The development of a novel haptic prototype using force input/kinesthetic feedback

Philip Feldman	Brian Frey	Kip Canfield	Ravi Kuber
Novetta Inc. / UMBC	UMBC	UMBC	UMBC
pfeldman@fgm.com	frey1@umbc.edu	canfield@umbc.edu	rkuber@umbc.edu

ABSTRACT

After many years where the mouse was the de-facto standard in human computer interaction, new interfaces such as multi-touch surfaces and gestural recognition are starting to become common. While gestural technologies can be used to improve interaction with a graphical user interface, haptic technologies enable the user to interact in a more immersive way, using the sense of touch. However, these devices are expensive, and are known to have their own limitations.

A system has been developed using force-input/kinesthetic feedback, with the aim of augmenting the experience when interacting with virtual objects. In this paper, we describe the iterative design of the system and its applicability to various contexts of use. This system senses force on the part of the user to move a remote or virtual actuator and provides the user with kinesthetic cues using small actuators as a means of informing the user of contacts in that environment. This technology would allow deep and complex interactions with virtual and telepresence environments but at low cost.

Author Keywords

Teleoperation, Virtual Reality, Tactile & Haptic UIs.

ACM Classification Keywords

H.5.2 Haptic I/O, Input Devices and Strategies, Ergonomics.

INTRODUCTION

Teleoperation, or the remote operation of devices, has become a day-to-day reality for thousands of people, ranging from soldiers to surgeons. The device sides of the equation – the surgical robots[1], pilotless drones[2], ground vehicles[3], submersibles[4] and their manipulators, have steadily become more complex and sophisticated. It is now possible to remotely control vehicles on other planets, at the bottom of the oceans, and in the skies above distant battlefields.

UIST'12, October 7-10, 2012, Cambridge, MA, USA.

However, the development of commercial interfaces for these devices has not kept pace with the development of the devices themselves. Current interface devices are either extremely simplistic, offering a limited range of haptic feedback (e.g. rumblepads) on the one hand, or extremely complex, where the interface may cost as much or more then the device it is controlling.

In this work, we set out to create a haptic interface device that lies between these two points, that is as close as possible to the fidelity of exoskeletal force feedback systems, while closer in cost to a gamepad. We call this form of interaction "Force Input / Kinethetic Feedback", or FI/KF. In the iterative process of evaluating this technology, we started with very a simple 1 DOF proof-of-concept system, and have progressed through interfaces of greater sophistication. We are currently in the process of refining an 8-DOF full hand interface for full evaluation and testing.

RELATED WORK

The reason for this problem is that historically, there have been either simple (open-loop) or expensive (closed-loop) ways to control a moving actuator. Open-loop extends the technology used for decades to control hobbyist model cars and planes. The user manipulates a set of knobs and actuators which in turn cause a motor to move on the remote device. No tactile feedback comes back to the manipulator (Figure 1).

Figure 1: Open Loop Interface [5]

Closed loop is far more sophisticated and complex. It is essentially a powered robot in its own right, designed to interact with the user by providing realistic tactile interactions with remote or virtual environments. The form of these robots can resemble exoskeletons [6] or modified traditional "industrial" robots [7] that apply opposing forces to the user. Here, the user moves a control that results in a matching move of the remote actuator. If the remote device encounters a barrier, an appropriate force is relayed back to the user, allowing for the haptic loop to be closed. An example of this can be seen in Figure 2. Unfortunately, this solution tends to be extremely expensive and fragile, and possibly dangerous[1].

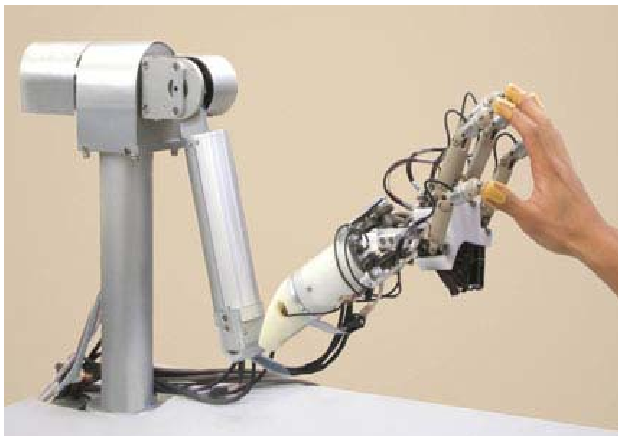

Figure 2: HIRO II, a full haptic (closed loop) Interface [7]

Because of the price and fragility of full haptic systems, the "joystick approach" is the style of control that is finding its way onto the vast majority of fielded robotic systems, particularly in the military. However, this results in a mismatch between the capability of the robot, and the ability of the user to control it. The builder of a sophisticated robot with many degrees of freedom (such as might be needed to disable an IED) is left with two unsatisfactory choices for control: Complex and unwieldy (but capable of sophisticated interaction), or simple and reliable (but nearly useless for more than the most simple and straightforward of control tasks).

What would be ideal would be the simplicity and ruggedness of a gamepad with the resolution and bandwidth of an something like the HIRO or CyberGrasp. Previous attempts at compromise between these two extremes have been problematic. Vibrotactile gamepads add some level of feedback to simple interfaces. Complex haptics can be simplified to the point where they are reasonably affordable, but that simplification Limits the range of applications that these are suitable for[2]. Zhu *et al* [20] have described the other challenges faced when interacting with low-cost devices, which may impact the quality of feedback perceived. Examples include the limited points of interaction with devices and difficulties presenting cutaneous feedback using these technologies [19].

Tactile/Kinesthetic Feedback research has endeavored to bridge this gap, producing a wide variety of innovative solutions. Minamizawa and Prattichizzo have worked with hand-mounted effectors that are capable of providing ungrounded sensation to the user [8][9]. These effectors are attached to the user and their position is tracked through space using non-contact means. If the user encounters an object, then the effectors apply squeezing or lateral forces to the user's finger. Grounded haptic sensations, such as weight can be provided by using attachments, such as a forearm fixture that is is in turn grounded. Moradganjeh has developed haptic feedback patterns to provide an additional channel of information to users of a logging crane [10].

Johnson, Zhai, May and Maglio [11] have adding vibrotactile feedback to an IBM TrackPoint force sensing joystick. The design goal was to provide tactile vibration with a very compact size and power consumption suitable for laptop computers. The task of the study was for users to steer the cursor through a "tunnel" using the enhanced TrackPoint. They ran several permutations of the test, with visual only, tactile only, and visual and tactile combined. The mean trial completion times under the visual and tactile condition was significantly shorter than each of the other three conditions [11]. They did not, however look into opposing kinesthetic motions as cues to the user.

Although the patent space regarding the concept FI/KF is quite sparse, there are some patents that touch on the concept. Most of these derive from Immersion Corporation's patents for their force feedback mouse that they tried to market in the late 1990's [12].

Inverting the paradigm of motion-input/force feedback to force-input/motion feedback may be a way to provide flexible, grounded kinesthetic feedback to users that does not require positional tracking, and can provide forceful, complex haptic patterns.

It has been shown that users are very comfortable with converting a force input to a motion output (where force is mapped to velocity). This is true even if the input device does not move. The use of force input for control is not new. The early-generation F-16s had a rigid force sensing joystick[13], and IBM used the force-sensing TrackPoint as a mouse substitute in their laptop keyboards for many years (and continued by Lenovo) [14]. What has been lacking is a way of providing feedback to the user from within the force-input context.

---

[1] For a force-feedback device to provide crisp forces, such as knocking on a door, the motors in the system must be very powerful, so that they can effectively mimic a hard impact with a stiff surface. Unfortunately, the forces sufficient to instantly decelerate a hand can also lead to injury in the case of malfunction.

[2] An example of an very simplified haptic system is the Novint Falcon. (http://home.novint.com/products/novint_falcon.php)

Through our pilot studies, we have identified that small amounts of motion, when presented in the appropriate context, can provide high bandwidth, fine resolution user feedback. We call this Force Input / Kinesthetic Feedback (FI/KF). In a FI/KF system, when the remote device encounters resistance to its motion, an open loop actuator mounted to the input device is moved a small distance in the direction of and proportional to the force produced by the collision. In other words, if a user is driving a robot forward with a force sensing joystick and the robot hits a wall, an actuator on the joystick moves towards the user some distance. The position of the actuator is based on the force acting on the robot's sensors, so if, for example, a robot continues to try to drive through a wall with a consistent force, the offset of the joystick will remain constant. If the robot's end effector encounters greater or lesser force, either through actions of the operator, or through the object moving with respect to the end effector, the joystick's offset will change in a proportional way. If the robot pulls away from the wall entirely, the force drops to zero, and the joystick returns to its neutral position. Although the fidelity of such an interaction may not be quite as high as a full force-feedback, haptic mechanism, it is quite capable of providing sufficient resolution and response for a user to distinguish shapes.

The inversion of force feedback to kinesthetic feedback results in several benefits when integrated into interfaces:

- Immersion – As FI/KF allows for many degrees of freedom, literally any level of interface from joystick to full exoskeleton can be achieved with only minor increases in complexity. This means that deep levels of immersion within a system are possible when using FI/KF technology.

- Safety – For traditional force feedback systems to not feel "spongy", powerful motors must be used to provide the strong forces that come with encountering a hard surface, such as a tabletop. This means that every haptic interface has to face a tradeoff between fidelity and safety [15]. Either the motors are powerful enough to cause injury if there is a malfunction, or the user can never feel a solid surface. In the FI/KF system, motors only move a small distance. This means that powerful motors can be used, and that they are mechanically safe, since they cannot move enough to cause injury.

- Ruggedness – The rigid frame of the FI/KF system is inherently tough. In addition, since it does not have the tight tolerances required for an interface with many moving parts, it can also be designed to be easily disassembled and reassembled for transport.

- Cost – As motion is used as a user cue rather than the basis of the interaction, the primary structure of the interface is rigid. Force measurement through the use of strain gauges is very inexpensive – only a few dollars per degree-of-freedom (DOF). Simple open loop actuators can be attached at certain points such as the fingertips, to provide the motion feedback component. These actuators can be simple, open loop actuators, such as linear voice coil motors which carry a cost of a few dollars each. Lastly, the cost to manufacture is greatly reduced over traditional force feedback, since there are far fewer moving parts

KINESTHETIC FEEDBACK COMPONENTS

A series of prototypes were built to develop the Kinesthetic Feedback concept. Initially it was thought that only two components – force input measurement and motion feedback would be needed. During testing, it became evident that an additional components were needed

- When an actuator that is in contact with a finger or some other part of the user moves, the initial movement is immediately apparant. However, after a relatively short period of time, the user loses track of where the actuator is if there is nothing to compare that position to. As such, there needs to be a means of providing a "relative ground" that the user can perceive the motion feedback in a useful way
- Even with relative ground, in the case of higher DOF systems, the user has difficulty maintaining awareness of the positions for each contact point. For example, in the case of all 5 fingers of one hand resting on a surface for a prolonged period of time, the user becomes used to the amount of motion offset that the actuators are providing. In this case, additional modalities such as vibrotactile actuators can augment the interaction, providing both tactile and auditory stimuli that helps to maintain the user's awareness of the interaction with the object.

Force Input

This can be measured in a variety of ways, ranging from mechanical, spring-based devices to capacitive touch screen sensors to piezoelectric load cells in a typical bathroom scale. Because of the low cost and ease in mounting and connecting them to our prototype, we chose to use semiconductor strain gauges for our initial systems. This type of sensor is capable of providing continuous, extremely precise changes in resistance that reflect the amount of deformation of the substrate they are mounted to. As these sensors are small in size, they can be mounted nearly anywhere on the mechanism that is suitable. Strain gauges are typically arranged in opposing pairs, located at the point of maximum flexion in the object to be instrumented. The amount of flex can then be measured as the difference in resistance between the pair. For a FI/KF system, each axis or degree of freedom is instrumented with force measurement.

Motion Feedback

Kinesthetic feedback depends on relatively simple actuator output. The actuator simply moves a small distance that is proportional to the amount of force that the end effector is encountering, either in a virtual or telepresence environment. This means that actuators can run open loop, and that they do not require any safety interlocks. After experimenting with small servomotors of the type used for remote control models, we used stepper motors in our prototypes, as they are reasonably inexpensive and very easy to control. In the control software for the proof-of-concept, the force that was sensed by the strain gauge was simply scaled and turned into a step offset for the stepper motor to move through. In other words, a 100-Newton force in one direction might result in a 10-degree rotation of the motor in the opposing direction.

IMPLEMENTATION

Breadboard

Several iterations were needed to develop a working implementation of a FI/KF system. The first was a minimal two-actuator/two sensor breadboard that allowed for a basic understanding of the issues involved with FI/KF. The second was a more sophisticated proof-of-concept system that implemented the lessons learned from the breadboard. Both systems shared much in the way of electronics and software, since the issues to be resolved were the subjective perception of physical interaction as it applied to this concept.

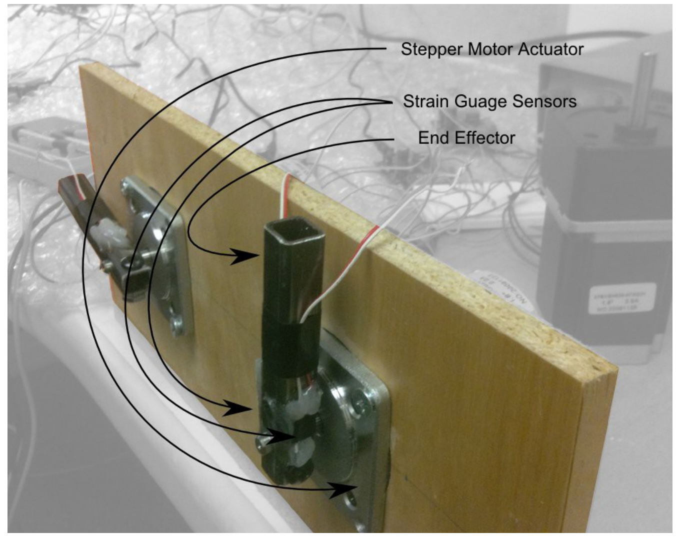

Figure 3 – Initial Breadboard

The breadboard initially consisted of the following:

- Two NEMA-23 standard bipolar stepper motors with an associated Phidgets [16] Stepper 1063 motor controllers
- Two mild steel end effectors clamped to the drive shaft of the motors, each with two 1.3k ohm semiconductor strain gauges. The strain gauges are connected to a wheatstone half bridge. The bridge is converted to 0.0 – 5.0 volts by an IndustroLogic [17] SGAU strain gauge amplifier to a Phidgets Precision Voltage Sensor 1135.
- One Phidgets InterfaceKit 1018 communicates with the motor controllers and the voltage sensors, and then provides a single USB connection to the host computer.
- The host was a Dell laptop running Vista. The programming environment was MSVC 8, using the Phidgets C/C++ and OpenGL/GLUT libraries.

The breadboard was able to interact with both a simple virtual and a simple physical object.

The initial virtual environment was a simple end effector (a circle with an arbitrary radius and mass) moving along a single axis colliding with a fixed “wall”. The simulation runs in a simple sampled environment running at approximately 60hz. The motion of the end effector is determined from the force read from the strain gauge as the user pushes it against the holding torque of the motor. This force is then used to calculate the size of the end effector’s motion vector based on the mass. In each iteration of the simulation loop, the motion vector is added to the end effector, and a collision test is performed with respect to the position of the wall and the radius or size of the end effector.

The amount of penetration of the end effector radius into the wall determines a collision vector that is both added to the position of the end effector and fed back to the stepper motor, scaled and used to provide the kinesthetic feedback to the user.

In the case of the initial physical environment, the force applied to one end effector was scaled and used to set the position of the actuator holding the other end effector. A fixed object was placed in the way of the other end effector so that when the end effector contacted it, the force resulting from that collision would in turn be scaled and used to provide the kinesthetic feedback to the first motor. In this case the host computer needed only to read the forces from the two respective sets of sensors scale the values and use them to set the positions of the actuator motors. The OpenGL graphics subsystem in this case was only used to display the values of the sensors and the positions of the actuators.

Although this configuration worked as intended, the subjective reactions from our pilot studies revealed that the kinesthetic feedback presented was poor. The initial collision was quite noticeable, but determining anything beyond that was difficult at best. Instead, it felt as though the input device was simply moving randomly, and not in a way that was intuitively connected to the behavior of the end effector.

At first, this was thought to be a sensitivity problem, so a new set of end effectors made of 1/8" sheet steel were made. Since the cross section of the stock was far thinner than the original rods, the increase in flex made for a much greater change in resistance from the strain gauges. Unfortunately, although the improvement in sensing was noticeable, it did not affect the overall lack of proper "feel" of the FI/KF system. It was difficult to determine when a collision had occurred, and how much resistance was being encountered by the virtual end effector. It turned out that what was needed was some kind of relative ground that the user could compare the motion too. For example, kinesthetic feedback at the fingers needs to be experienced relative to a "fixed" palm, while motion feedback of the hand needs to be experienced relative to a "fixed" forearm or shoulder and so on. For example, motion at the fingers can be felt precisely if the motion is experienced relative to the palm of the hand, the motion of the hand is experienced relative to the forearm and so forth. Once the concept of a relative ground was implemented in the second prototype, subjects were able to distinguish subtle interactions with the virtual test environment.

The breadboard was modified so that one actuator/sensor assembly was used as the force input and the relative ground. A linkage was added to the other actuator so that the end of the linkage rested on the top of the first assembly (Fig 4).

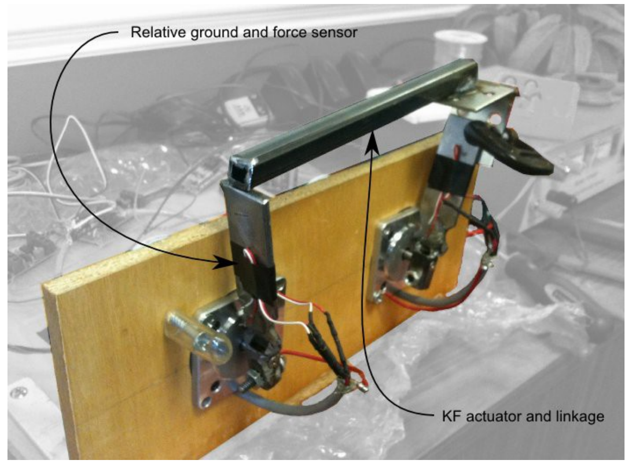

Figure 4 – Improved Breadboard

The force sensor was held fixed, while the second actuator moved the linkage in response to collisions in the virtual environment. The user then, by resting a finger or two of one hand on the linkage and applying force to the "relative ground" of the first assembly with another finger or two could now sense and discriminate between the speed and forces of various collisions. Using this configuration it was possible for users to approach contact slowly and exert a light touch on the virtual target, even if the target was moving towards or away from the virtual end effector. It was also unnecessary for the user to look at the monitor while performing these tests.

Proof-of-concept

Based on the success of the modified breadboard, work began on a proof-of-concept system that would allow multiple degrees of freedom interaction with an environment, and more thoroughly test the concept of relative ground. This proof of concept system is shown in figure 5, below.

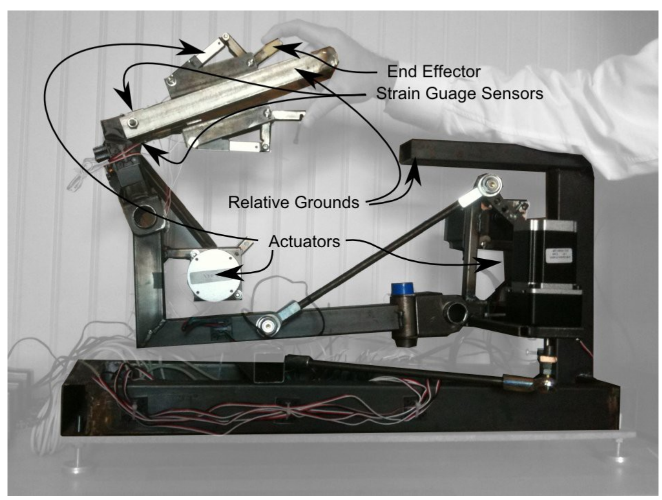

Figure 5 – Proof-of-Concept

The proof of concept system has two relative grounds, one for the forearm and one for the palm. It has two sensor/actuator assemblies that allow the user to perform gripping actions, and assemblies that allow for input and feedback in the horizontal and vertical axis.

A more detailed view of one of the finger interfaces is shown below in figure 6. Here the components of a FI/KF system can be clearly seen. Attached to a common base are both the relative ground and the force sensor. The actuator is then attached to the force sensor, and an end-effector is then mounted to the actuator. By fixing both the sensor and actuator to the same frame as the relative ground, no unwanted artifacts are entered into the interaction between the user, the actuator, and the force sensor. Additionally, the proximity of the relative ground to the actuator allows for the user to more clearly interpret the motion of the actuator.

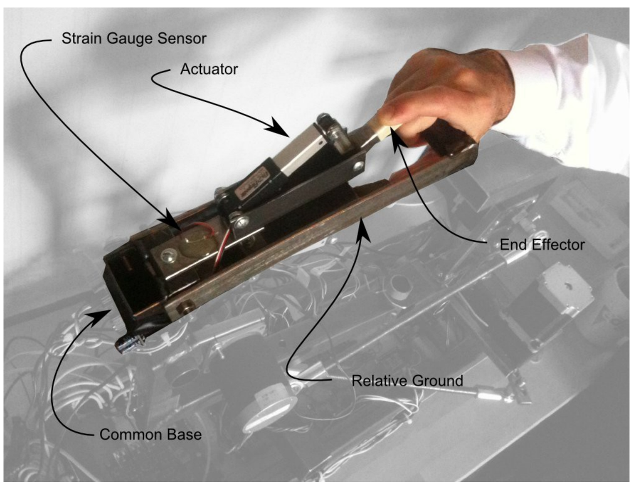

Figure 6 – Finger Interface Detail

Since building or buying a corresponding robot to control with the device was prohibitively expensive, the virtual environment was extended to provide more opportunities for interaction. This environment is shown in Figure 7.

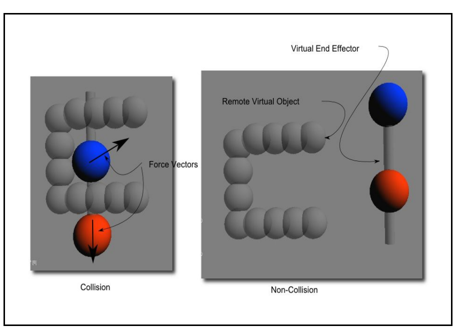

Figure 7 – Proof-Of-Concept Virtual Environment

In this particular example, the target's position is fixed. The virtual end effector consists of two connected spheres that are constrained to move together within a vertical range. The up and down motion of the individual spheres are under the control of the finger-controlled "gripper" assembly of the proof-of-concept system. The horizontal motion is controlled by the user pushing and pulling on the relative ground that connects with the palm. Vertical forces from the contact of the individual spheres with the target are sent to the respective finger interface. If the force vector is positive[3], the actuator will move upwards in a proportional way to the force. If the vector is negative, the actuator will similarly move downwards. Horizontal forces from the contacts of both spheres are sent to the actuator that moves the palm relative ground (with its associated assemblies). This motion is in turn interpreted relative to the ground that the forearm is resting on.

When using this prototype system, it was possible for the user to control the virtual end effector with a high degree of precision, and with very good tactile feedback. It was possible to grip an object tightly or loosely, to feel the shape of the surface that is being gripped, and even to feel if an object slides out of the end effector. And as opposed to a force-feedback system, hard surfaces were very easy to differentiate from softer surfaces, even when high amounts of force were being applied.

Prototype

Based on the success of this proof-of-concept, a more in depth prototype was built that designed to work with an entire hand, rather than just two fingers. As with the earlier proof-of-concept, the concept of relative ground was incorporated to near the fingertips to provide better accuracy in the sensing of motion feedback. This interface is shown in figure 8.

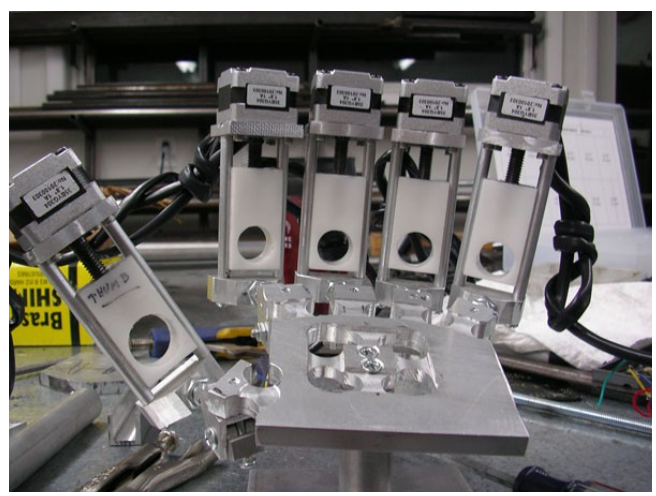

Figure 8 - Initial Hand Prototype

This prototype used the same types of components as the earlier systems (Strain gauges, stepper motors and Phidgets

[3] In the local coordinate frame

controllers) and the same software to provide the virtual environment as described above. The environment was enhanced to provide collision detection and response for each of the five fingers.

Counterintuitively, this prototype did not provide as effective a sensation of interaction as the proof-of-concept or the breadboard. To explore this result, only one finger at a time was enabled. In this configuration, the users were able to report that their subjective sensation of interaction was quite good. The best sensation of interaction came from when the thumb or pointing finger interface was enabled. Based on this result, more fingers were enabled and subjects were queried as to the quality of sensation. Once more than two fingers were activated, users reported a subjective loss in the ability of being able to sense the motion feedback. It appears that the ability of the user to sense motion feedback as accurate haptic feedback is limited by how much attention the user can devote to each interface point. This may be a form of "Change Blindness" that can exhibit in tactile as well as visual displays[18]. We are currently exploring ways to enhance this interaction, such as adding acoustic and vibrotactile drivers.

DISCUSSION

It appears, based on subjective reports if interaction with the breadboard, proof-of-concept, and prototype iterations described above, that FI/KF has many of the benefits of force feedback and open loop systems with few of the drawbacks. As with more traditional force-feedback devices, it is capable of letting a user interact with virtual or remote objects. A user can "feel" a surface, grip an object firmly or gently, and interact with a virtual environment in an effective way without requiring visibility at all times. As with open-loop systems, the technology is reasonably inexpensive and robust. No actuator appears to need to move more than a centimeter or so, which enables simple linkages and allows open-loop actuators to run safely. As with open loop systems, the system appears to be capable of being built inexpensively and ruggedly, allowing for practical use. This differs dramatically from the traditional force feedback systems, where motion is measured and forces are applied to restrict the motion, yet the initial users of the system report that their interactions compare favorably to more conventional force feedback systems.

FUTURE WORK

Currently, the prototype system is only a few weeks old and still being tested and evaluated. In future work, we intend to examine how the use of FI/KF affects the speed and accuracy of user interaction with test 2D and 3D environments, seeing how such interaction correlates with Fitts' Law. Another study will be a comparison of traditional force-feedback and open-loop devices with FI/KF devices against a common set of tasks.

Based on what we have learned, the next step will to explore how additional modalities such as acoustic and vibrotactile actuators can enhance the basic FI/KF user experience. This will allow us to evaluate how effectively FI/KF can be used for prolonged, complex interaction, and also allow us to evaluate the degrees-of-freedom required for a non-trivial application. Based on the success of these evaluations, we will then look at making a low-cost equivalent of the hand interface. Our current target is manufacturing costs of $50 to $100, and for the system's performance to compare favorably with more traditional systems such as the CyberGrasp [5], which costs tens of thousands of dollars.

Virtually any interface that would already use more sophisticated interaction if it were economical is a target market for this technology. What follows is a list of potential FI/KF system applications;

- Civilian – Many remote and dangerous environments, ranging from hazardous waste cleanup to the space station could benefit from more effective user interfaces and the resultant increase in capabilities that such robots could achieve. For example, with the proper interface, it would have been possible to send a robot to repair the Hubble, instead of sending an expensive and far riskier mission involving humans.
- Consumer – Although game platforms have increased in power many times since their introduction, the primary interface, the gamepad has not changed in any meaningful way since its introduction[4]. A simple example of this could be the replacement of the existing thumbsticks on a game controller with FI/KF thumbsticks, which would provide greater precision in the game, as well as the ability of the user to feel, for example if they backed up against a wall, or if the safety on their gun was on. Another possibility would be to add FI/KF to touchscreen interaction -- since touchscreens can measure force, it would only take the addition of a set of actuators to provide motion feedback to the user. This could be particularly useful with mobile devices.
- Commercial Teleoperation – once a cost-effective, sufficiently sophisticated interface is developed, the applications within the commercial sector are quite widespread. For example, equipment in dangerous environments such as mines could be effectively operated by remote control, eliminating the risk to humans and also the expense of mine safety equipment.
- Military – One of the obvious uses for this technology is in the improvement of robots currently used for the neutralization of IEDs. Current robots use an open-loop interface that most resembles that for a model car with additional controls for the arm and end-effector. By

[4] An exception to this are the Microsoft Kinect and the Nintendo Wii, which are exploring the user interaction defined by motion tracking without force feedback.

integrating a FI/KF controller with an enhanced end-effector that can measure force, it should be possible for the operator to engage in far more dexterous interaction with the device, enhancing the chances for neutralizing the device without explosion.

CONCLUSIONS

We have presented a new approach to computer interfaces that inverts the paradigm of conventional force feedback systems and shown how iterative design can be performed resulting in the development of a more sophisticated low-cost haptic prototype Rather than measuring motion and responding with force, the Kinesthetic Feedback system measure force and responds with motion. Several prototypes have been built to evaluate this concept and have discovered that in addition to force input/motion feedback, a relative ground is require for the user to perceive kinesthetic feedback effectively, and that the actuator and force sensor must be mounted together on the relative ground to eliminate artifacts that would come from the case where these were decoupled. Work on this concept is continuing, with the next step being the refinement of the 8 DOF hand interface. This interface will allow for more flexibility, widening the range of applications which the device can lend itself to.

We believe that FI/KF represents an opportunity to develop a new branch of computer interfaces. Simple FI/KF systems have the capacity to be as inexpensive as the traditional mouse, and can scale into sophisticated, immersive interfaces.

ACKNOWLEDGMENTS

We'd like to think Novetta inc for supporting this project with Phil's 20% time and funds, Tom DeVito for helping to assemble the prototypes and Powergrid Fitness in all its incarnations for giving Phil the background to do this.

REFERENCES

1. Intuitive Surgical, da Vinci Surgical System http://www.intuitivesurgical.com/products/davinci_surgicalsystem/index.aspx
2. General Atomics MQ-1 Predator - http://en.wikipedia.org/wiki/General_Atomics_MQ-1_Predator
3. iRobot Packbot http://en.wikipedia.org/wiki/General_Atomics_MQ-1_Predator
4. Remotely Operated Underwater Vehicle http://en.wikipedia.org/wiki/Remotely_operated_underwater_vehicle
5. SuperDroid Robots - LT-F with custom controller - http://superdroidrobots.com/LT.htm
6. CyberGlove Systems CyberGrasp - http://www.cyberglovesystems.com/products/cybergrasp/overview
7. Haruhisa Kawasaki et al (2005) Development of Five-Fingered Haptic Interface: HIRO-*II ACM Proceedings of the 2005 international conference on Augmented tele-existence* Vol 157, pp 209 - 214.
8. Minamizawa, et al (2010) Simplified Design of Haptic Display by Extending One-point Kinesthetic Feedback to Multipoint Tactile *Feedback IEEE Haptics Symposium 2010*
9. Prattichizzo, et al (2010) Using a Fingertip Tactile Device to Substitute Kinesthetic Feedback in Haptic Interaction *EuroHaptics 2010, Part I, LNCCS 6191*, pp 125-130
10. Moradganjeh, Amid (2009) Implication of haptic interface for complex interaction in specialized vehicles *Proceedings of SIDeR 2009* http://www.flirtingwiththefuture.com/proceedings/implication_of_haptic_interface/17-Implication%20of%20Haptic%20Interface.pdf
11. Johnson, et al (1999) What you Feel Must be What you See: Adding Tactile Feedback to the TrackPoint *Proceedings of INERACT 99*, IOS Press, pp 383-390 (http://www.almaden.ibm.com/u/zhai/papers/interact99/interact99.pdf)
12. Rosenberg, Louis - Isotonic-isometric force feedback interface (United States Patent 6259382) and Isotonic-isometric haptic feedback interface (United States Patent 7102541)
13. General Dynamics F-16 Fighting Falcon http://en.wikipedia.org/wiki/F-16#Flight_controls
14. Lenovo TrackPoint description - http://www.pc.ibm.com/ww/healthycomputing/trkpnt.ht

1.

15. Human Science Group, Health and Safety Laboratory (2012) Collision and injury criteria when working with collaborative robots
16. Phidgets, Inc http://www.phidgets.com/
17. Industro Logic, http://www.industrologic.com/
18. Gallace, et al (2006) The failure to detect tactile change: A tactile analogue of visual change blindness. *Psychonomic Bulletin & Review*, Springer New York pp 300 – 303
19. Brewster, S.A., 2005. Chapter 30: The impact of haptic 'touching' technology on cultural applications. In: Hemsley, J., Cappellini, V., Stanke, G. (Eds.), Digital Applications for Cultural Heritage Institutions. Ashgate

Press, UK, pp. 273-284.

20. Zhu, S., Kuber, R., Tretter, M. & O'Modhrain, M.S. 2011: Identifying the Benefits of Haptic Devices for Non-Visual Access to the Web. Interacting with Computers 23, 565-581.

21.

2.