Proceedings of SPIE's 8th Annual International Symposium on Smart Structures and Materials, 5-8 March, 2001, Newport, CA. Paper No. 4329-47

Virtual reality robotic telesurgery simulations using MEMICA haptic system

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ABSTRACT

There is increasing realization that some tasks can be performed significantly better by humans than robots but, due to associated hazards, distance, etc., only a robot can be employed. Telemedicine is one area where remotely controlled robots can have a major impact by providing urgent care at remote sites. In recent years, remotely controlled robotics has been greatly advanced and the NASA Johnson Space Center's robotic astronaut, "Robonaut," is one such example. Unfortunately, due to the unavailability of force and tactile feedback the operator must determine the required action by visually examining the remote site and therefore limiting the tasks that Robonaut can perform. There is a great need for dexterous, fast, accurate teleoperated robots with the operator's ability to "feel" the environment at the robot's field. The authors conceived a haptic mechanism called MEMICA (Remote MEchanical MIrroring using Controlled stiffness and Actuators) that can enable the design of high dexterity, rapid response, and large workspace haptic system. The development of a novel MEMICA gloves and virtual reality models are being explored to allow simulation of telesurgery and other applications. The MEMICA gloves are being designed to provide intuitive mirroring of the conditions at a virtual site where a robot simulates the presence of a human operator. The key components of MEMICA are miniature electrically controlled stiffness (ECS) elements and Electrically Controlled Force and Stiffness (ECFS) actuators that are based on the use of Electro-Rheological Fluids (ERF). In this paper the design of the MEMICA system and initial experimental results are presented.

Keywords: Haptic Interfaces, MEMICA, Virtual Surgery, Medical Training, Controlled Stiffness, ERF, Rheological Fluids

1. INTRODUCTION

The key to the development of the haptic system, MEMICA, is the use of liquids that change viscosity when subjected to electric field. Such liquids that are called Electro-Rheological Fluid (ERF) were known to exit for over fifty years. ERF exhibit a rapid, reversible and tunable transition from a fluid state to a solid-like state upon the application of an external electric field [Phule and Ginder, 1998]. Some of the advantages of ERFs are their high yield stress, low current density, and fast response (less than 1 millisecond). ERFs can apply very high electrically controlled resistive forces while their size (weight and geometric parameters) can be very small. Their long life and ability to function in a wide temperature range (as much as –40C to +200C) allows for the possibility of their use in distant and extreme environments. ERFs are also not abrasive, and they are non-toxic, and non-polluting (meet health and safety regulations). ERFs can be combined with other actuator types such as electromagnetic, pneumatic or electrochemical actuators so that novel, hybrid actuators are produced with high power density and low energy requirements. The electrically controlled rheological properties of ERFs can be beneficial to a wide range of technologies requiring damping or resistive force generation. Examples of such applications are active vibration suppression and motion control. Several commercial applications have been explored, mostly in the automotive industry for ERF-based engine mounts, shock absorbers, clutches and seat dampers. Other applications include variable-resistance exercise equipment, earthquake-resistant tall structures and positioning devices [Phule and Ginder, 1998].

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While ERFs have fascinated scientists, engineers and inventors for nearly fifty years, and have given inspiration for developing ingenious machines and mechanisms, their applications in real life problems and the commercialization of ERF-based devices has been very limited. There are several reasons for this. Due to the complexity and non-linearities of their behavior, their closed-loop control is a difficult problem to solve. In addition, the need for high voltage to control ERF-based devices creates safety concerns for human operators, especially when ERFs are used in devices that will be in contact with humans. Their relatively high cost and the lack of a large variety of commercially available ERFs with different properties to satisfy various design specifications made the commercialization of ERF-based devices unprofitable. However, research on ERFs continues intensively and new ERF-based devices are being proposed [Tao, 1999]. This gives rise to new technologies that can benefit from ERFs. One such new technological area, which will be described in detail here, is virtual reality and telepresence, enhanced with haptic (i.e. tactile and force) feedback systems and for use in, for example, medical applications.

In this paper, we describe a novel ERF-based haptic system called MEMICA (remote MEchanical MIrroring using Controlled stiffness and Actuators) [Bar-Cohen, et al, 2000a]. MEMICA is intended to provide human operators an intuitive and interactive feeling of the stiffness and forces in remote or virtual sites in support of space, medical, underwater, virtual reality, military and field robots performing dexterous manipulation operations. MEMICA is currently being sought for use to perform virtual telesurgeries as shown in Figure 1 [Bar-Cohen, et al, 2000a&b] and it consists of miniature Electrically Controlled Stiffness (ECS) elements and Electrically Controlled Force and Stiffness (ECFS) actuators that mirror the stiffness and forces at remote/virtual sites.

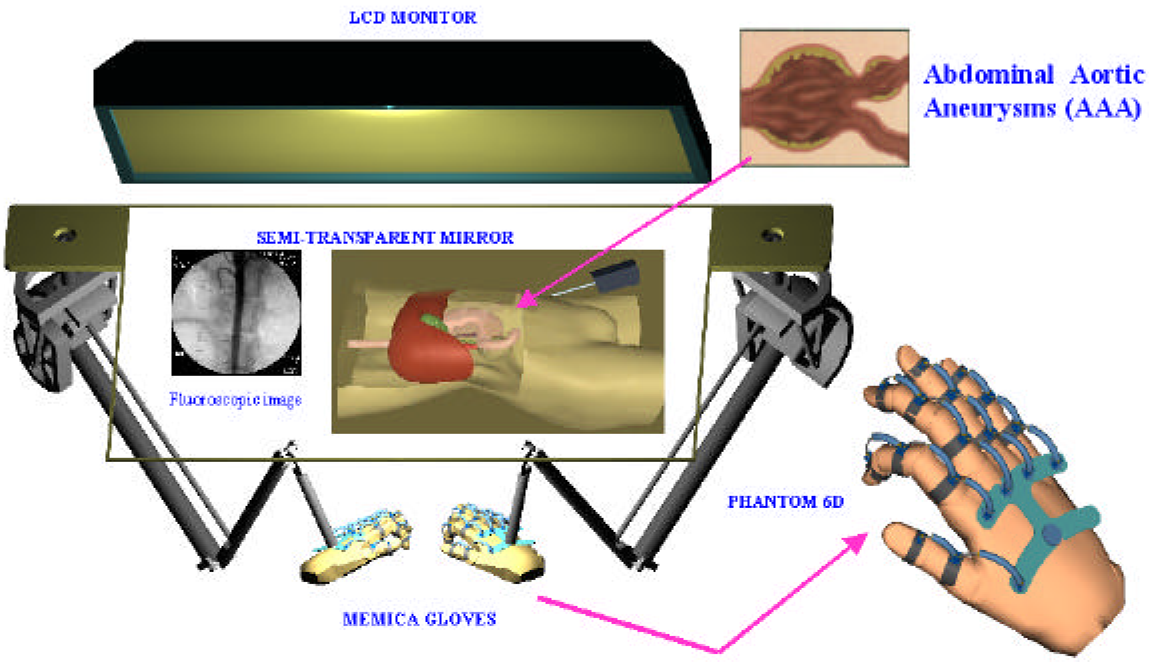

FIGURE 1: Performing Virtual Reality Medical Tasks via the Electro-Rheological Fluid Based MEMICA Haptic Interface.

2. HAPTIC INTERFACES AND ELECTRORHEOLOGICAL FLUIDS

Haptic (tactile and force) feedback systems are the engineering answer to the need for interacting with remote and virtual worlds [Burdea, 1996] and currently it is a less developed modality of interacting with remote and virtual worlds compared with visual and auditory feedback. Thus, realism especially suffers when remote and virtual tasks involve dexterous manipulation or interaction in visually occluded scenes. A very good description of the current state-of-the-art in haptic and force feedback systems can be found in [Burdea, 1996; Bar-Cohen, et al, 2000b].

Tactile sensing is created by skin excitation that is usually produced by devices known as “tactile displays”. These skin excitations generate the sensation of contact. Force-sensitive resistors, miniature pressure transducers, ultrasonic force sensors, piezoelectric sensors, vibrotactile arrays, thermal displays and electro-rheological devices are some of the innovative technologies that have been used to generate the sensation of touch. While tactile feedback was conveyed by the mechanical smoothness and slippage of a remote object, it could not produce rigidity of motion. Thus, tactile feedback alone cannot convey the mechanical compliance, weight or inertia of the virtual object being manipulated [Burdea, 1996]. Force feedback devices are designed to apply forces or moments at specific points on the body of a human operator. The applied force or moment is equal or proportional to a force or moment generated in a remote or virtual environment. Thus, the human operator physically interacts with a computer system that emulates a virtual or remote environment. Force feedback devices include portable and non-portable interfaces. Force feedback joysticks, mice [Immersion Corp., 1999; & Haptic Technologies, 1999] and small robotic arms such as the Phantom [Sensable Technologies, 1999] are non-portable devices, that allow users to feel the geometry, hardness and/or weight of virtual objects.

Portable systems are force feedback devices that are *grounded* to the human body. They are distinguished as *arm-exoskeletons* if they apply forces at the human arm and as *hand-masters* if they apply forces at the human's wrist and/ or palm. Portable hand masters are haptic interfaces that apply forces to the human hand while they are attached at the human operator forearm. In most cases, these systems look like gloves where the actuators are placed at the human forearm and forces are transmitted to the fingers using cables, tendons and pulleys. The CyberGrasp is an example of such a system, which is a lightweight, force-reflecting exoskeleton glove that fits over a CyberGlove and adds resistive force feedback to each finger via a network of tendons routed around an exoskeleton [Virtual Technologies, 1999]. The actuators are high-quality DC motors located in a small enclosure on the desktop. The remote reaction forces can be emulated very well; however, it is difficult to reproduce the feeling of "remote stiffness". To date, there are no effective commercial unencumbering haptic feedback devices for the human hand. Current "hand master" haptic systems, while they are able to reproduce the feeling of rigid objects, present great difficulties in emulating the feeling of remote / virtual stiffness. In addition, they tend to be heavy and cumbersome with low bandwidth, and they usually only allow limited operator workspace.

During the last ten years, some researchers proposed the use of ERFs in an effort to improve the performance of haptic interfaces. There are many properties of ERFs that can greatly improve the design of haptic devices. Their high yield stress, combined with their small sizes can result in miniature haptic devices that can easily fit inside the human palm without creating any obstructions to human motion. ERFs do not require any transmission elements to produce high forces, so direct drive systems can be produced with less weight and inertia. The possibility of controlling the fluids' rheological properties gives designers of ERF-based haptic system the possibility of controlling the system compliance; and hence, mirrors accurately remote or virtual compliance. Finally, ERFs respond almost instantly, in milliseconds, which can permit very high bandwidth control important for mirroring fast motions. The only concern that a designer of ERF-based haptic interfaces may have is the need for high voltages to develop the forces and compliance required. This has two consequences: a) it increases the complexity of the electronic system needed to develop the high voltage and b) it raises safety concerns for the human operator. Both issues can be solved easily with modern electronic circuit design techniques. Nowadays, low power, small size circuits can be used to generate the required high voltage using a very low current on the order of micro-amps. Consequently, the required power becomes extremely low, in the order of mWatts, posing no hazard for human operators.

Kenaley and Cutkosky were the first to propose the use of ERFs for tactile sensing in robotic fingers [Kenaley and Cutkosky, 1989]. Based on that work, several workers proposed the use of ERFs in tactile arrays used to interact with virtual environments [Wood, 1998] and also as assistive devices for the blind to read the Braille system. The first to propose this application of ERFs was Monkman [Monkman, 1992]. Continuing this work, Taylor and his group at the University of Hull, UK, developed and tested experimentally a 5x5 ERF tactile array [Taylor, et al, 1996]. Professor Furusho and his group at Osaka University in Japan, developed an ERF-based planar force-feedback manipulator system that interacts with a virtual environment [Sakaguchi and Furusho, 1998 a&b]. This system is actuated by low-inertia motors equipped with an ER clutch. An ERF-based force-feedback joystick has been developed in Fraunhofer-Institut in Germany. The joystick consists of a ball and socket joint where ERF has been placed in the space between the ball and the socket. The operator feels a resistive force to his/her motion resulting from the controlled viscosity of the ERF [Böse, et al, 2000]. Finally, MEMICA that is described in this paper, which is being developed by researchers at Rutgers University and JPL, employs ERF-based force-feedback gloves [Bar-Cohen, et al, 2000a, b & c; Mavroidis, et al, 2000a,b&c; Pfeiffer, et al, 1999].

3. MEMICA HAPTIC GLOVE

The key aspects of MEMICA are miniature ECS elements and ECFS actuators that mirror the forces and stiffness at remote/virtual sites. The ECS elements and ECFS actuators which make use of ERFs to achieve this feeling of remote / virtual forces are placed at selected locations on an instrumented glove to mirror the forces of resistance at the corresponding locations in the robot hand.

a. Electrically Controlled Stiffness (ECS) Element

The stiffness that is felt via the ECS element is modified electrically by controlling the flow of ERF through slots on the side of a piston (Figure 2). The ECS element consists of a piston that is designed to move inside a sealed cylinder filled with ERF. Electrodes facing the flowing ERF while inside the channel control the flow rate electrically. To control the "stiffness" of the ECS element, a voltage is applied between electrodes facing the slot, affecting the ability of the liquid to flow. Thus, the slot serves as a liquid valve, since the increased viscosity decreases the flow rate of the ERF and varies the stiffness felt. To increase the stiffness bandwidth from free flow to maximum viscosity, multiple slots are made along the piston surface. To wire such a piston to a power source, the piston and its shaft are made hollow and electric wires are connected to electrode plates mounted on the side of the slots. The inside surface of the ECS cylinder surrounding the piston is made of a metallic surface and serves as the ground and opposite polarity. A sleeve covers the piston shaft to protect it from dust, jamming or obstruction. When a voltage is applied, potential is developed through the ERF along the piston channels, altering its viscosity. As a result of the increase in the ERF viscosity, the flow is slowe[...] [...]nd [...] forces increases.

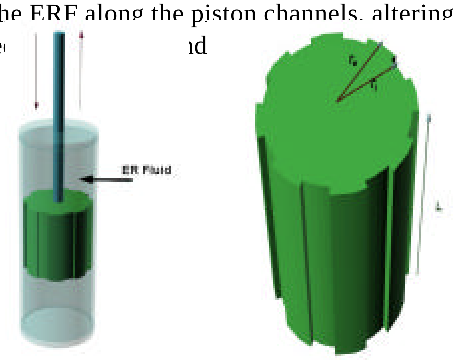

FIGURE 2: ECS Element and Its Piston.

b. Electrically Controlled Force and Stiffness (ECFS) Actuator

To produce complete emulation of a mechanical "tele-feeling" system, it is essential to use actuators in addition to the ECS elements in order to simulate remote reaction forces. Such a haptic mechanism needs to provide both active and resistive actuation. The active actuator can mirror the forces at the virtual/remote site by pulling the finger or other limbs backward. This actuator operates as an *inchworm* motor (as shown in Figure 3) and consists of active and passive elements, i.e., two brakes and an expander, respectively. One brake locks the motor position onto a shaft and the expander advances (stretches) the motor forward. While the motor is stretched forward, the other brake clamps down on the shaft and the first brake is released. The process is repeated as necessary, inching forward (or backward) as an inchworm does in nature.

Using the controllability of the resistive aspect of the ERF, a brake can be formed to support the proposed inchworm. A schematic description of the ECFS actuator is shown in Figure 4. The actuator consists of two pistons (brake elements) and two electromagnetic cylinders (pusher element). Similar to ECS, each piston has several small channels with a fixed electrode plate. When an electric field is induced between the piston anode and cylinder cathode, the viscosity of the ERF increases and the flow rate of the fluid though the piston channel decreases securing the piston to the cylinder wall. Each of the electromagnetic cylinders consists of a coil and a ferromagnetic core integrated within the piston. When a current impulse is passed through the winding, an electromagnetic field is induced and depending on the current direction, the cylinder moves forward or backward.

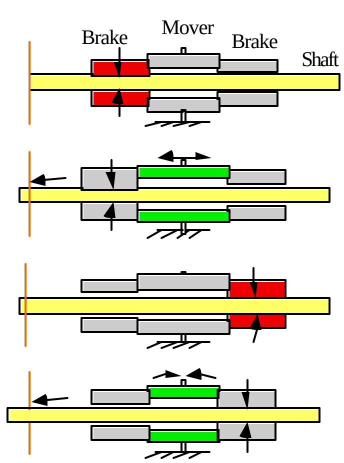

FIGURE 3: Concept of the Inchworm Motor.

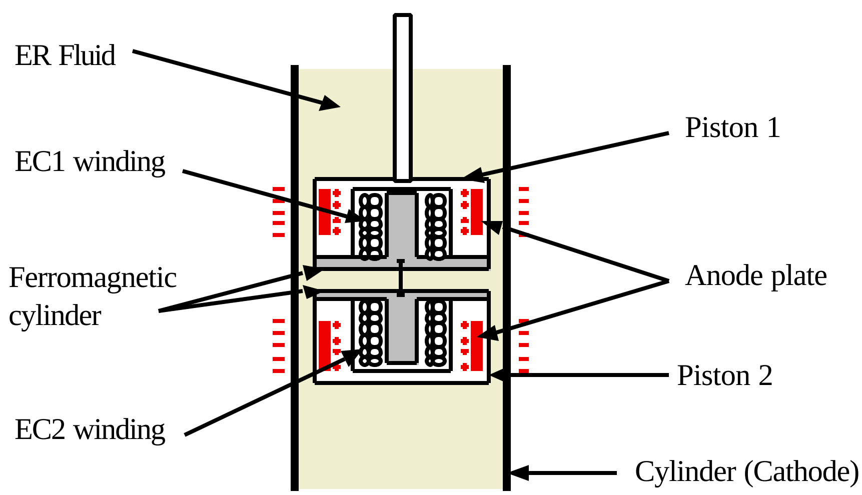

FIGURE 4: ECFS Actuator Configuration

At each cycle, the pistons move forward or backward with very small displacement (<1.5mm). The duration of each cycle is close to a millisecond, corresponding to the response time of the ERF. The ECFS actuator can then reach a speed higher than 15-cm/s with a piston displacement equal to 0.5-mm at 3-ms cycle duration. The electromagnetic cylinder is designed to produce the same force as the resistive force of the piston inside the ERF, which is about 15N.

c. MEMICA Haptic Glove and System

A haptic exoskeleton integrates the ECS elements and ECFS actuators at various joints. As shown in Figure 5, the actuators are placed on the back of the fingers, out of the way of grasping motions. The natural motion of the hand is then unrestricted. Also, this configuration is capable of applying an independent force (uncoupled) on each phalange to maximize the level of stiffness/force feedback that is "felt" by the operator. Different mounting mechanisms are currently being evaluated where the most ergonomic seems to be the use of an arched actuator providing a better fitting with the finger motion and geometry. Since the ERF viscosity is higher than air, there is no need for tight tolerance for the ECFS piston and its cylinder. The second proposed solution uses curved sliding rail, which is also suitable for a finger motion. The third solution uses a flexible tendon connected directly to the piston inside the cylinder where the tendon length can be adjustable to the user phalange length. The integrated MEMICA system that combines the ECS and ECFS using an exoskeleton system is shown graphically in Figure 6.

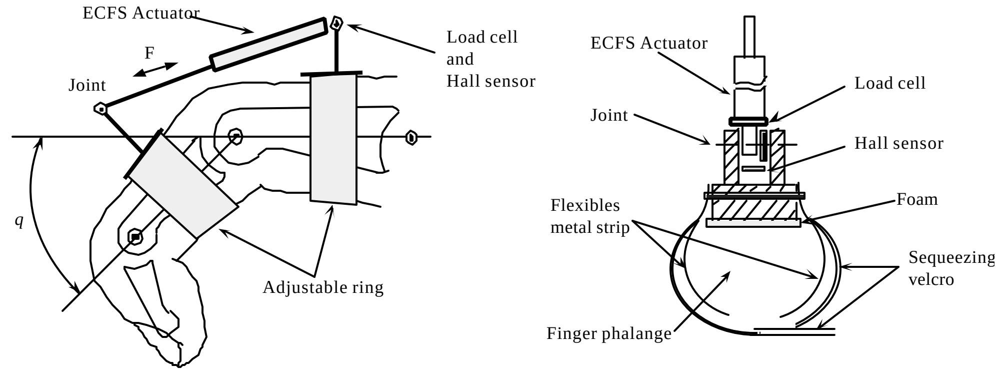

FIGURE 5: Mounting of an ECFS Actuator on the Finger Phalange.

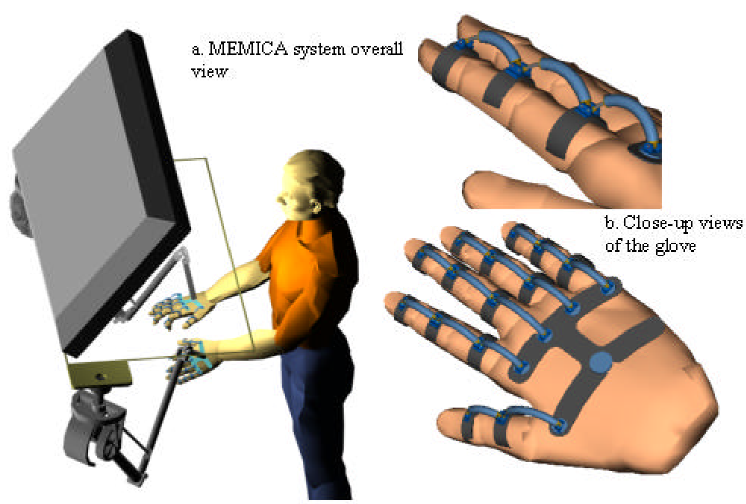

FIGURE 6: 3D View from the MEMICA System and Close-up View of the gloves with the ECFS actuators.

4. EXPERIMENTAL ECS SYSTEM AND RESULTS

To test the concept of controlling the stiffness with a miniature ECS element, a larger-scale testbed has been built at the Rutgers Robotics and Mechatronics Laboratory. This testbed (Figure 7) is equipped with temperature, pressure, force and displacement sensors to monitor the ERF's state. The cylinder is mounted on a fixed stainless steel plate to maintain rigidity during normal force loading. The top plate is also stainless steel and serves as the base for the weight platform. Beneath the platform, around the stainless steel shaft, is a quick release collar that allows the force to be released by the operator. The shaft, which transmits the force down into the cylinder, is restrained to only one-dimensional motion through a linear bearing mounted to the top plate. At this junction there is a load cell and flange bracket mounted for the wiper shaft of the displacement sensor. Within the chamber, the experimental piston is attached to the shaft with e-clips secured at the top and bottom of the piston. The chamber itself is a one-inch internal diameter beaded Pyrex piping sleeve, six inches in length. Pyrex allows visual observation of the ERF during actuation. In order to apply voltage to the fluid, supply wires are run down through the hollow shaft and into the piston, where the electrical connections are made to the channel plates. Threaded into the bottom plate of the chamber is the dual pressure and temperature sensor. The final sensor is mounted along side the chamber and affixed with a flanged bracket to the chamber.

Six system parameters are measured during experimentation: voltage, current, force, displacement, pressure and temperature. All sensor signals are interfaced directly to Analog-to-Digital boards located in a Pentium II PC and are processed using the Rutgers WinRec v.1 real time control and data acquisition Windows NT-based software. In addition, all sensors are connected to digital meters located inside the interface and control box. Sensor excitation voltages are supplied by five volts from the PC or by the meter provided with the sensor itself.

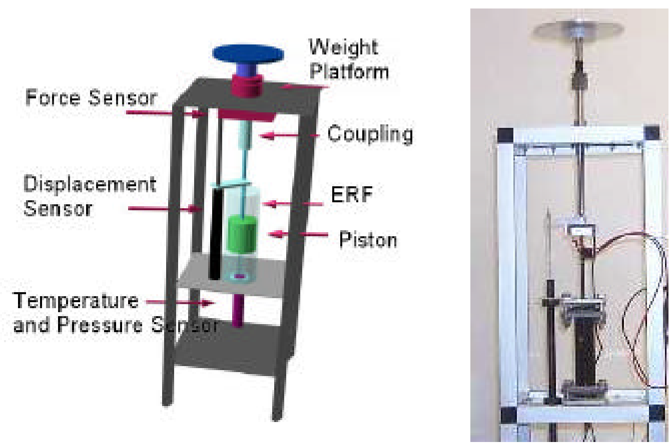

FIGURE 7: Schematic and actual prototype of the experimental Testbed.

Extensive experimental tests are currently underway to determine the relationship of the reaction force to the applied voltage, human motion, temperature and pressure changes and verify the predictions that were made using an analytical model developed by the team. Representative results from these tests are shown in Figures 8a and b. In Figure 8a no voltage is applied to the device. Four different weights equal to 2.75lb., 5.50lb., 8.25lb. and 11lb. are placed individually on the weight platform. Each time the quick release collar is released, the piston displacement induced by the weight is recorded. A very fast descent of the piston is observed for all the weights. In Figure 8b, the same procedure is followed but this time a voltage of 2kV is applied on the ERF. It can clearly be seen that the piston is showing a very slow descent and for the lightest weight (i.e. the 2.5lb.) no motion is observed. This experiment shows that when the electrical field is enabled, the viscosity of the ERF is such that the ECS element can resist the gravity forces from the weights. Using electro-active polymers as smart materials can enable the development of many interesting devices and methodologies. Using such EAP fluids one may be able to construct a system that allows to “feel” the environment compliance and reaction forces at remote or virtual robotic manipulators. The ability to have human operator controlling a remote robot in the sense of telepresence is addressing the realization that there are some tasks that can be best performed by human but may be too hazardous for physical presence. Using such haptic interface as described in this paper allows human operators to perform the tasks without the associate risks.

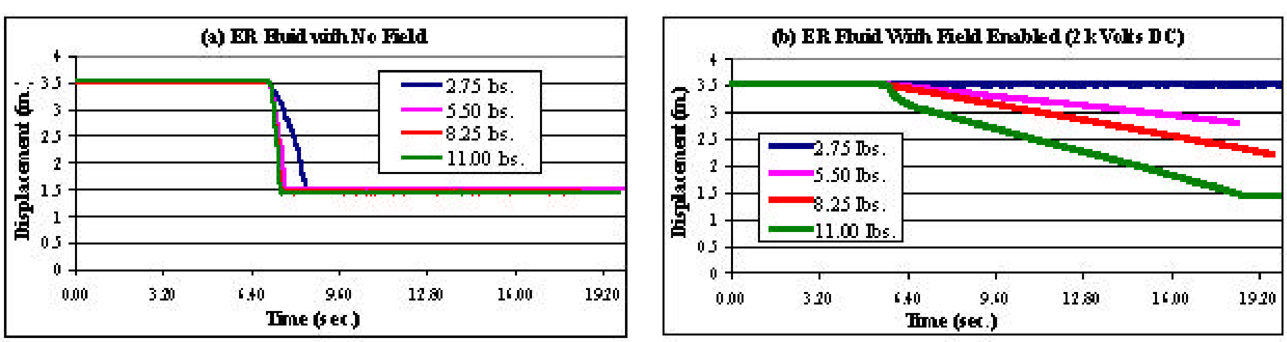

FIGURE 8: Piston Displacement.

5. CONCLUSIONS

A haptic mechanism was described that can allow operators to sense the interaction of stiffness and forces exerted on a robotic manipulator. A key to the new haptic interface is the so-called electrically controlled stiffness (ECS) element, which was demonstrated in a scaled size experimental unit proving the feasibility of the mechanism. A conceptual novel ERF-based haptic system called MEMICA that is based on such ECS elements was described. MEMICA is intended for operations in support of space, medical, underwater, virtual reality, military and field robots performing dexterous manipulations. For medical applications, virtual procedures can be developed as simulators to allow training doctors, an exoskeleton system can be developed to augment the mobility of handicapped or ill persons, and remote surgery can be enabled.

ACKNOWLEDGMENTS

Work at Rutgers University was supported by NASA's Jet Propulsion Laboratory (JPL) and CAIP - the Center for Advanced Information Processing. Research at JPL/Caltech, was carried out under a contract with National Aeronautics Space Agency. The author would like to thank Mr. Charles Pfeiffer, Mr. Alex Paljic, Ms. Jamie Lennon, Ms. Sandy Larios and Ms. Sarah Young, Rutgers University, for providing assistance during the development of the MEMICA concept.

REFERENCES

Bar-Cohen Y., C. Pfeiffer, C. Mavroidis and B. Dolgin, "MEMICA: a Concept for Reflecting Remote-Manipulator Forces", *NASA Tech Briefs*, Vol. 24, No. 2, pp. 7a-7b, 2000a.

Bar-Cohen Y., C. Mavroidis, C. Pfeiffer, C. Culbert and D. Magruder, "Haptic Interfaces", Chapter in *Automation, Miniature Robotics and Sensors for Non-Destructive Testing and Evaluation*, Y. Bar-Cohen (Ed.), The American Society for Non-destructive Testing, Inc. (ASNT), pp. 461-468, 2000b.

Bar-Cohen Y., C. Mavroidis, M. Bouzit, C. Pfeiffer and B. Dolgin, "Remote Mechanical Mirroring using Controlled Stiffness and Actuators (MEMICA)", Rutgers Docket Number 99-0056 A US and International PCT patent application has been filed by Rutgers University in September 2000c.

Böse H., J. Berkemeier and A. Trendler, "Haptic System Based on Electrorheological Fluid," *Proceedings of the ACTUATOR 2000 Conference*, 19-21 June 2000, Bremen GERMANY.

Burdea, G., *Force and Touch Feedback for Virtual Reality*, New York: John Wiley and Sons, 1996.

Haptic Technologies, http://www.haptech.com/prod/index.htm, 1999.

Kenaley G. L. and M. R. Cutkosky, "Electrorheological Fluid-Based Robotic Fingers With Tactile Sensing," *Proceedings of the 1989 IEEE International Conference on Robotics and Automation*, Scottsdale AR, pp. 132-136.

Mavroidis C., C. Pfeiffer and Y. Bar-Cohen, "Controlled Compliance Haptic Interface Using Electro-Rheological Fluids," *Proceedings of the 2000 SPIE Conference on Electro-Active Polymer Actuators and Devices (EAPAD 2000), SPIE 7th Annual International Symposium on Smart Materials and Structures*, Newport Beach, CA, March 5-9, 2000a, Volume 3987, pp. 300-310.

Mavroidis C., C. Pfeiffer, J. Celestino and Y. Bar-Cohen, "Design and Modeling of an Electro-Rheological Fluid Based Haptic Interface," *Proceedings of the 2000 ASME Mechanisms and Robotics Conference*, Baltimore MD, September 10-13, 2000b, Paper DETC2000/MECH-14121.

Mavroidis C., Pfeiffer C., Lennon J., Paljic A., Celestino J., and Bar-Cohen Y., "Modeling and Design of an Electro-Rheological Fluid Based Haptic System for Tele-Operation of Space Robots," *Proceedings of the ROBOTICS 2000 Conference: The 4 th International Conference and Exposition/Demonstration on Robotics for Challenging Situations and Environments*, February 27-March 2, 2000c, Albuquerque, NM, pp. 174-180.

Mavroidis D., Y. Bar-Cohen, and M. Bouzit, "Haptic Interfacing via ElectroRheological Fluids," Topic 7, Chapter 19, Y. Bar-Cohen (Ed.), "Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges," SPIE Press, (In print - Expected the end of February 2001).

Monkman G. J., "Electrorheological Tactile Display", *Presence*, MIT Press, Vol. 1, No. 2, 1992.

Pfeiffer C., C. Mavroidis, Y. Bar-Cohen, B. Dolgin, "Electrorheological Fluid Based Force Feedback Device," *Proceedings of the 1999 SPIE Telemanipulator and Telepresence Technologies VI Conference*, Boston, MA, September 19-22, 1999, Vol. 3840, pp. 88-99.

Phule P. and J. Ginder, "The Materials Science of Field-Responsive Fluids," *MRS Bulletin*, August 1998, pp. 19-21.

Sakaguchi M. and J. Furusho, " Force Display System Using Particle-Type Electrorheological Fluids," *Proceedings of the 1998 IEEE International Conference on Robotics and Automation*, Leuven, Belgium, May 1998a, pp. 2586-2590.

Sakaguchi M. and J. Furusho, "Development of ER Actuators and Their Applications to Force Display Systems," *Proceedings of the 1998 IEEE Virtual Reality Annual International Symposium (VRAIS)*, Atlanta, GA, 1998b, pp. 66-70.

Sensable Technologies, http://www.sensable.com/products/desktop.htm, 1999.

Taylor P. M., A. Hosseini-Sianaki and C. J. Varley, "Surface Feedback for Virtual Environment Systems Using Electrorheological Fluids," *International Journal of Modern Physics B,* Vol. 10, No. 23 & 24, 1996, pp. 3011-3018.

Virtual Technologies, http://www.virtex.com/ 1999.

Wood D., "Editorial: Tactile Displays: Present and Future," *Displays-Technology and Applications*, Vol. 18, No. 3, 1998, pp. 125-128.