A Force Feedback Glove Based on Magnetorheological Fluid: Preliminary Design Issues

David J. Cassar, Michael A. Saliba *

Department of Industrial and Manufacturing Engineering, University of Malta
Msida, Malta

* michael.saliba@um.edu.mt

***Abstract*—This work first provides an overview of haptic gloves found in the literature, with a focus on their applications and their requirements. This information is then used to justify the use of Magnetorheological Fluid (MRF), a smart fluid which reversibly changes viscosity proportionally to an applied magnetic field, to effect the force feedback in a haptic glove. This is followed by the development of a linear damper to form part of the proposed glove, as well as a report on our selection of MRF through experiments performed on a number of fluids with different iron content, developed in-house. Finally, the paper describes the position sensing system and the preliminary design of the force feedback glove.**

I. Introduction

A popular concept in robotics is "tele-presence". In [1], tele-presence is defined as "the ideal of sensing sufficient information about the tele-operator and task environment, and communicating this to the human operator in a sufficient natural way, that the operator feels physically present at the remote site". Such a system is often referred to as a Robotic Master-Slave system. This allows the operator to perform tasks in hazardous or distant environments by knowledgeably guiding the robot slave from a safe distant location. For such operations to be successful, it is necessary to virtually immerse the human operator in the remote environment through haptic feedback, otherwise the manipulation requires too much effort and becomes slow and imprecise [2]. Haptic feedback is also mandatory when the object being handled remotely is in the dark or no graphics are available [3]. These haptic systems have a number of applications, such as tele-surgery [1], space exploration, as well as assistance in police operations or fireman search and rescue missions [4]. Moreover, haptic devices may also be used to simulate virtual environments. An example of such environments is their use in the medical field to aid the rehabilitation of a number of medical conditions [5], as well as the training of surgeons [4].

II. Requirements of a Force Feedback Glove and the Actuator Technology Used

There are a large number of different haptic device configurations as well as various technologies. In [6] however, three important properties are identified for haptic gloves so as to immerse the human in virtual reality manipulation. These are: i) Free space must feel free; ii) A solid virtual object must feel stiff; iii) Virtual constraints must not be easily saturated. Also, to truly immerse the user in the virtual environment, he/she must forget the real world. This, first and foremost, means that the force-feedback glove must be as lightweight as possible, a challenge which is very demanding when considering the number of actuators needed. Also, the user must not have any constraints to the natural movement of his hand. This can involve hand constraints, such as the making of a fist, a hand posture which is for example not allowed by the Rutgers Master II [7] due to its configuration. It can also involve constraints to the area to which the user is tied down due to cabelling or grounding of the haptic device. That said, if the device is grounded on the user's body, although it gives the user more freedom of movement, he must carry the weight of the glove himself and the simulation of certain effects such as of a virtual immovable wall cannot take place [6].

This means that the requirements of actuators in a haptic glove are many. The actuators must have very low friction when they are in the off-state, a high enough force in the on-state to convince a person that he is touching a solid object, as well as a low weight. Finally, the actuators used must be safe especially since their application is in proximity to human skin. A number of technologies have been applied to power past master hands projects. The most common are electric actuators, such as those used in the CyberGrasp [8] and the glove created at the University of Tokyo [9], and pneumatic actuators, such as those used in Rutgers Master II [7]. Other actuators include ultrasonic motors, Shape Memory Alloys, and piezoelectric elements amongst others.

III. The Use of MRF in Force Feedback Gloves

The advantages and disadvantages of each technology tend to characterise the particular master hand to which it is applied, and thus the choice of the actuator technology used is crucial. In this work, the potential of smart fluids is being investigated. This technology is less popular than other technologies, such as pneumatic and electric actuators, probably due to the relative lack of availability and experience in its use. Here, two smart fluids are being considered, the Electrorheological Fluid (ERF) and Magnetorheological Fluid (MRF). The most important property of these fluids is their ability to reversibly change viscosity when exposed to an electric field (in the case of ERF) or magnetic field (in the case of MRF). Such a change occurs from liquid to a semi-solid, the viscosity of which is proportional to the field, within milliseconds of exposure to the particular field. With the application of the field, the particles in the fluid align together forming a chain, thus resulting in an increase in yield stress. The typical maximum yield stress of MRF is 50 to 100 kPa, whilst that of ERF is only 2 to 5 kPa. In [10], both fluids are compared in great detail. Also, in [11], with improvements in the composition of the liquid, a maximum attainable yield stress close to 250kPa has been claimed. This results in very high potential forces with small devices.

Safety issues are also a major consideration needed to justify the use of MRF in a haptic glove. The most important issue is that MRF produces a passive force, which is highly desirable in a haptic glove, since as in the case of the electric actuators used in the CyberGrasp, the fact that the fingers are pulled backwards by cables raises safety concerns since the user can be hurt in cases of malfunction (as reported in [7]). Secondly, MRFs have very low power requirement and are thus safe to be used in proximity to the human hand. Also, the fluid itself does not pose any risk in case of leakage [12] .

Although the use of MRF is gaining popularity in the automotive field through active suspensions and steer-by-wire, as well as in the structural engineering field through seismic motion control devices [13], its use in haptic gloves is minimal. In fact, after an intensive search on haptic gloves and magnetorheological fluid in the literature, only the three devices listed below were found to combine the two together. This means that the knowledge on the use of MRF in haptic gloves is very limited and that there is scope for significant further work in this area. We emphasise again here that in order to more accurately provide a tele-presence experience, the actuators in a haptic glove should produce a (passive) force or torque to impede finger movement, rather than actively provide a backward pull on the fingers (as does the Cybergrasp [8]). Thus, a system based on MRF actuators is potentially an ideal candidate for such an application.

The first of the three gloves being reviewed here was developed at the Washington State University Vancouver by J. Blake and H. Gurocak [14]. This glove makes use of a number of MRF rotary brakes to apply torques to different joints on the human hand. The second device is the MagnetoRheological Actuated Glove Electronic System, known as MRAGES [12]. The third of these haptic devices has a particular shape since its basis is a computer mouse. In fact it is not called a haptic glove but Smart Mouse [15]. This device is particular because it is a ground-based type haptic device. However, unlike some ground-based type haptic device developed in the past, such as the Phantom [6], the actuators in this glove do not follow the fingers. In other words, all of the fingertips must be placed at a certain plane when grasping. The performances, as well as the advantages and disadvantages of each of these three gloves have been compared in Table I.

TABLE I
COMPARISON OF BLAKE/GUROCAK GLOVE [14], MRAGES [12], AND THE SMART MOUSE [15].

	Blake/Gurocak Glove	**MRAGES**	**Smart Mouse**
Glove basing type	body-based type	body-based type	ground-based type
Actuators positioning	exoskeleton type	exoskeleton type	endoskeleton-type
Glove Weight	not available	part glove weighs 160g	not available
Actuators			
No. of actuators	4 small, 2 large	5	5
Type of Actuator	rotary brake	piston	piston
Weight per actuator	not available	16 grams each	52 grams each
Maximum Force	93 N-mm - 191 N-mm	6N to fingertip	26N
Friction Force	5 N-mm for both sizes	1.4 N to 1.9 N	5.54N
Travel	not applicable	31.75mm	20mm
Power Requirements	0.1 to 1.0 A	0.33 A at 5 V	3A
No. Of Turns	150 turns - 250 turns	350 turns	not available
Estimated Magnetic	0.66 T - 0.75 T	0.25 T	not available
Force feedback on every finger	1 @ MCP, 1 @ PIP coupled with DIP	1 @ fingertip	1 @ fingertip
No. Of fingers	3	5	5
General			
Response Time	67 ms - 100 ms	not available	42.8ms
MRF used	MRF-240BS (LORD Corp.)	MRF-22ED (LORD Corp.)	MRF-132AD (LORD Corp.)
Position Sensing	CyberGlove	linear potentiometer	Hall-effect sensor
Force Sensing	not available	force gauge at back of	film-type force sensor
Transmission	stainless steel gears	cable transmission	nil
Greatest advantage	serpentine magnetic flux path crosses MRF gap many times	very portable and lightweight	weight of device is insignificant since device is ground-based
Greatest disadvantage	device probably very heavy due to transmission systems	very low maximum forces	fingertips must be placed on a certain plane when grasping

IV. The Development of an MRF Piston

Due to the relative novelty of this approach, and due to size limitations, it was not possible to purchase appropriate actuators for the glove. Thus, our first task was to develop an MRF piston and cylinder. We were guided in this work by a lot of useful information found in the literature (e.g. [16] and [17]). Our design consists of a magnetisable cylinder, a small piston head made of magnetisable material and wound by insulated copper wire, an aluminium tube and cap and a nylon bearing, illustrated in the CAD drawing in Fig. 1.

The operation mode of the device is quite simple. The piston head separates the cylinder in two chambers connected by a narrow gap, i.e. the radial gap between the piston head and the inner wall of the cylinder. In the off-state, when translation of the piston occurs, MRF fluid flows through this gap from one chamber to the other. When a current is fed to the magnetic wire coil, a magnetic field proportional to the current is generated. This field passes through the piston head, the MRF and the cylinder, thus it directly influences the viscosity, and so the flow, of the MRF through the gap, causing resistance to piston translation. The piston is more efficient if the magnetic gap is narrower; however, this increases off-state resistance as will be seen in the results of the experiments performed (see Section VI). Presented in Fig. 2 are the components making up the developed piston.

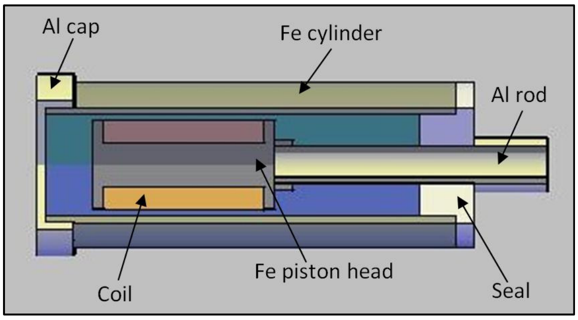

Fig. 1. CAD drawing of the developed piston

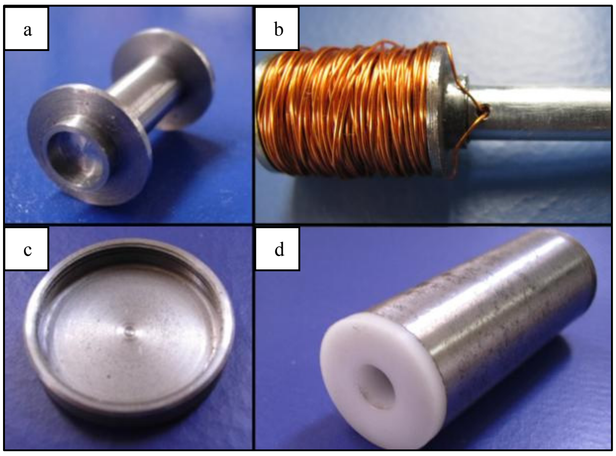

Fig. 2. a)iron piston head;b)piston head coiled with magnetic wire and assembled to aluminium rod;c)aluminium cap;d)iron cylinder and nylon seal

To develop an effective MRF piston there are a number of parameters which should be taken into consideration [17]. In this project, the values of most of these parameters were dictated by the size which would allow assembly to the human fingers, as well as the travel needed. From a number of experiments performed in [18], it can be concluded that the average width of the metacarpal digit of the human hand is 20mm. Also, as indicated in [19], the gap between the piston head and the cylinder should be between 1 and 2 mm. To allow ease of experimentation, a single piston head with an outer diameter of 14mm was developed. It was coiled with approximately 310 turns of insulated copper wire (27SWG). Two cylinders were then developed, one having an inner diameter of 16mm and the other having an inner diameter of 18mm. In the following paragraphs, these cylinders will be referred to as Cylinder 1 and Cylinder 2 respectively. Cylinder 1 provided a gap of 1mm whilst Cylinder 2 provided a gap of 2mm. Both cylinders have a wall thickness of 1mm.

In the first prototype a nylon bearing was used to seal the cylinder. The sliding against the seal of the aluminium rod attached to the piston head resulted in a friction force of 1.4N. However, there was leakage of the fluid at high pressures, resulting in considerable inconsistency in results. The nylon bearing was then replaced by a wiper ring seal. No leakage of MRF took place in the experiments that followed, not even at high pressures, however, the friction force resulting from the interfacing of the rod and this seal was of 2.3N.

A second problem faced was the short circuiting of the coil. Damage to the insulation of the wire was exposing the highly conductive copper to the MRF. Being mostly composed of iron particles (as described in detail in Section V below), the MRF is a conductive fluid, resulting in short circuiting of the damaged coil, reduced magnetic field and thus less resistance to motion of the piston. This was addressed by the addition of a step to the surface of the piston head to ensure that the wire does not hit the seal at the end of the piston travel. Other features of the design also prevented the damage of the wire during the assembly of the piston components. Finally, the coil was covered with chemical metal, a hard, non-magnetic electrical insulator. Such a coating was needed since through observation it was seen that the abrasive MRF was resulting in damage to the coil. The chemical coating resulted in the needed hardness to prevent any damage through rubbing against the fluid, as well as electrically insulating the coil from the fluid without resulting in any magnetic changes.

V. The Development of MR Fluid

The performance of the device is also greatly dependent on the magnetorheological fluid itself. Due to the lack of available suppliers, as well as unsuitable minimum order quantities, it was decided to develop the fluid in-house. Although this fluid may not be expected to be as good as a commercial one, the inexpensive mixture of ingredients allowed for experimentation with fluids of different iron content.

In the first mixture, multi-purpose oil and iron filings were mixed together, the combination of which became a solid when exposed to a magnetic field. Although a success, it was quickly realised that due to the difference in densities between the two components, gravitational settling of the particles to the bottom of the fluid occurred. Although with a few piston strokes, original properties were restored, by time, the performance of the fluid started to deteriorate, the reason being that agglomeration started to take place. This means that the iron particles that settled at the bottom of the fluid started to stick permanently together, turning into hard sediment. Hence the most important avoidable feature is not the gravitational settling of the particles but the agglomeration which follows this, since the fluid cannot be returned to its original condition when it is moved again [20]. A number of alternatives described in [11] and [21] can be used to reduce this problem, the simplest of these being the addition of grease or other thixotropic additives to the fluid. Other additives may also be used, the details of which are given in [16] and [22]. As a result, the second mixture created included grease. This additive has resulted in a very effective resolution of the agglomeration problem.

Following the above work, investigations about the iron particles and carrier fluid were made. There are a number of attributes of the magnetisable particles which affect significantly the properties of the MRF, since the particles are the component which cause the increase in yield stress under the influence of a magnetic field. The information that was gathered from [11], [19] and [23] regards the material, size, and shape of the particles used, as well as the use of different carrier fluids. Finally, a very important factor is the ratio of the mixture. The volume concentration of particles in the fluid plays an important role in determining the magnetic field at which the fluid saturates. This does not mean that a good MRF must necessarily have a high volume concentration. Although the flux density at which magnetic saturation takes place increases with the increase in the iron volume fraction in the fluid [17], thus resulting in larger field-induced shear stresses, this occurs at the cost of a higher viscosity when the fluid is in the off-state.

The above information led to the development of three fluids with different iron contents. All the fluids were mixed using multi-purpose oil, grease, and iron extra pure reduced particles with an average size of 10µm. The approximate iron content of Fluid 1 was 20% by volume (53% by weight), 40% by volume (75% by weight) in Fluid 2, and 60% by volume (87% by weight) in Fluid 3.

VI. The Experiments, Results and Analysis of the Cylinders and Fluids Combinations

The three fluids created were tested in the two cylinders developed. This was done by increasing the current in the coil, in steps of 0.1A, to a maximum of 0.8A (to prevent coil overheating), and finding the maximum weight that the piston could carry without moving. The latter was done by hanging different amounts of calibrated weights to the piston. The results of the experiments performed are presented in Table II.

TABLE II
THE FORCES OBTAINED BY THE SIX DIFFERENT PISTON AND FLUID COMBINATIONS AT DIFFERENT CURRENTS

Current (A)	Force (N)					
	Cylinder 1 (1mm gap)			Cylinder 2 (2mm gap)		
	Fluid 1	Fluid 2	Fluid 3	Fluid 1	Fluid 2	Fluid 3
0	3.2	3.6	6.3	2.7	3.6	4.1
0.1	3.6	3.6	6.3	2.7	3.6	4.1
0.2	4.5	5.4	19.2	3.2	4.1	7.1
0.3	5.8	8.5	31.7	3.6	4.5	9.0
0.4	7.6	11.2	40.6	4.5	5.4	13.4
0.5	9.8	14.3	43.7	4.9	7.1	16.1
0.6	12.0	16.9	51.3	6.3	7.6	18.3
0.7	13.4	18.8	61.1	7.1	8.5	21.8
0.8	15.2	21.8	70.9	8.1	10.7	26.7

A number of important conclusions can be drawn from the results obtained.

Size of gap: The size of the gap between the piston head and the inner cylinder wall is a crucial parameter. When in the off-state, the fluid must flow easily through this gap. One can notice that the force is consistently higher in Cylinder 1 than in Cylinder 2 for identical currents and fluids, due to the narrower gap. Since this gap acts as a closed valve when the coil is switched on, much more force is needed with the small gap since the flux density is much higher and thus the resultant fluid viscosity is greater.

Iron content: As the iron content of the fluid rises, so does its viscosity. In fact, the mixture containing 60% iron content can be better described as slurry rather than a fluid. This explains the high friction force of this mixture in the off-state, especially in Cylinder 1. One can note the higher forces obtained with a higher iron content fluid by comparing the results of the different fluids for each cylinder.

MRF potential: From the results obtained one can immediately notice the high forces attained by the 60% iron mixture in Cylinder 1. A force of 70N was obtained from a cylinder with a mass of only 72g. This means that the cylinder can hold a force almost 100 times its own weight. However, one must also note the high friction force at the off-state. This latter force is too high to be used in a haptic glove. This means that both the piston and the fluid must be designed to satisfy the particular needs of the system to reach its full potential. Thus when using this fluid, one must compromise between the minimum and maximum forces obtainable.

No saturation: All combinations in Table II show an increase in force with an increase in current, thus magnetic saturation was not reached during our experiments. This means that if the magnetic field were to be increased (through better magnetic wire selection or more space allocated for the coil), an increase in the forces attainable would follow. Alternatively, since no saturation with the present magnetic field and cross-sectional areas of the magnetic components of the piston occurred, minor reductions to the dimensions of these components, such as the cylinder wall thickness, can be performed, resulting in lighter and smaller actuators.

VII. Development of the Position Sensing System

Unlike force actuation, the roles of the position sensing system in virtual and remote manipulation are quite different. In virtual manipulation, the position sensing system acts as a switch which triggers the force actuators when the virtual object is "touched". On the other hand, the position sensing system in remote actuation acts as an input system which feeds the required angles to the robot slave. Imprecision in this system means that the user does not truly understand the dimensions of the virtual object, or worse, damages the real object. Moreover, the position sensing system is required to be lightweight, robust and frictionless. Some technologies which fit these criteria include strain gauges, Hall effect sensors, fibre-optics, pneumatics, and textile based-conducting electroactive polymers. In this work, the position sensing system will be made up of a number of bend sensors. This choice was made since these sensors are inexpensive, lightweight, thin and flexible, and require only basic circuitry. Also, bend sensors have already been used in other projects in our lab, and we are therefore already familiar with their operation and performance characteristics. We chose sensors that are manufactured by Flexpoint [24]. This is because, as claimed in [25], this manufacturer provides sensors which show little decay over time. In [25], it is also suggested that bare sensors are more accurate. Nonetheless, we used overlaminated sensors to ensure robustness of the system even with frequent experiments and changes to the glove. Also, this supplier offers bend sensors in three different lengths, the smallest being only 1 inch (~25.4mm). Such sensors are ideal to measure the positions of the different joints of the human hand since their size results in no overlapping between two digits of the human finger. This means that the reading of every sensor is solely dependent on the particular joint it is attached to. This results in a more accurate system.

The choice of the glove plays an important role in the accuracy obtained by the position sensing system. Ideally, the sensors are physically attached to the human hand. For obvious reasons, this is not practical, thus the sensors are instead stuck to a glove. Unfortunately the glove provides an additional source of error since as the hand is closed, the surface of the glove may take different contours on different occasions. This inaccuracy tends to increase in thicker gloves. This is because the resistance of a bend sensor is not only affected by the angle that it is bent in but also by the radius of the curvature of bending. Attached to a thin glove, the bend sensors being used resulted in a resistance of 2.5kΩ when the hand was in a flat position, and a resistance of about 30kΩ when the hand was closed in a fist, exact values dependent on the particular joint.

VIII. Electronic Interfacing of the System

The electronic interfacing of the position sensing system can be achieved using very simple circuitry. It consists of a voltage divider with a fixed resistor, the value of its resistance being approximately equal to the minimum resistance of the bend sensor (resistor of 2.7kΩ), with the bend sensor acting as a variable resistor. This circuit is supplied with a 10V supply, and the voltage value present between these two components is fed to an analog input channel of a data acquisition card (DAQ) which allows interfacing to a PC.

In Section VI, it was shown that the forces exerted by the MRF piston can be controlled by the current, all other parameters left unchanged. A typical graph plotted with the values obtained during the experimentation of the Cylinder 2 / Fluid 3 combination, discussed in Section VI, is shown in Fig. 3. The relationship of the current and force can be determined and the equation of this plot can be used to calibrate the output. The current supplied by a DAQ analog output channel is not sufficient to power the coil of the piston. Through the use of the op-amp LM324, transistor TIP122, as well as some other electronic components, the electronic circuit shown in Fig. 4 allows the DAQ output to control the power fed to the piston from an external 5V power supply.

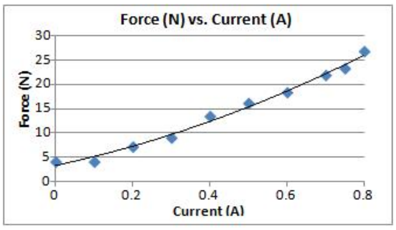

Fig. 3.Graph of Force(N) vs. Current(A) for Cylinder2/Fluid3 combination

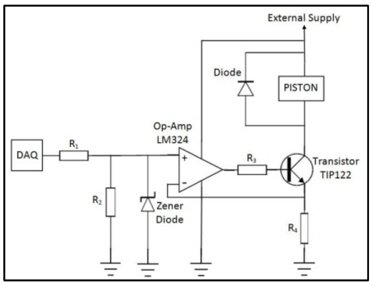

Fig. 4. Electronic diagram of the piston current control circuit

IX. Preliminary Glove Design

The results in Section VI indicate that the mean off-state force of the developed MRF actuators is 3.6N. This value is comparable to those obtained in [12] and [15]. However, by performing further experiments on the Cylinder1/Fluid2 combination, the friction force was reduced to 1.8N. Although this friction force was low enough to allow the weak forces exerted by the backward motion (opening) of the human finger to push the piston head to its original position, springs with a low stiffness constant were added to the actuators as this resulted in a more natural motion of the human hand as it is opened. The conceptual design for the force feedback system of one finger is illustrated in Fig. 5. Two MRF cylinders transmit passive force to the first two flexion joints of the human finger. The bottom cylinder applies passive force feedback to the first joint, while the top cylinder applies the feedback to both joints. This set-up is sufficient to reproduce the force effects of most grasping situations.

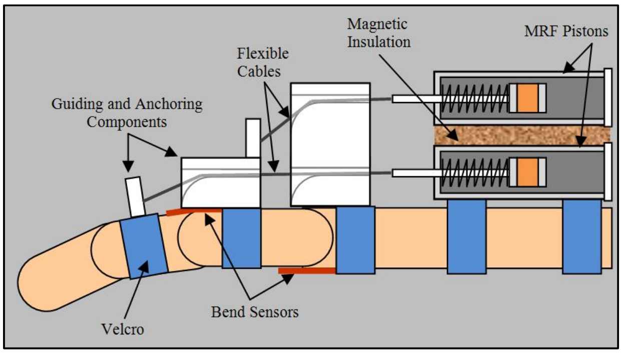

Fig. 5: Conceptual design of the force feedback system

Computer software to interface with both the electronic systems of the actuators and of the position sensors is being developed using Labview [26]. This software provides the necessary control to simulate the grasping of an object. The software first asks the user to grasp the real object and, through the position sensing system and its electronic interfacing, the reading of each bend sensor is obtained. The real object is then put aside and the user starts to close his fingers around empty space. When the readings of the bend sensors match the values stored in the previous step, current is passed through the piston coil to simulate object contact. Another program being developed alters the current in the coil so that the user is able to feel objects with different hardness. With further programming and calibration, the haptic glove can be used to operate an anthropomorphic robot hand through tele-presence in a master-slave robot system.

X. Conclusion and Future Work

In this work, we contribute further information on the use of Magnetorheological Fluid, a smart fluid with reversibly changeable viscosity. Three different fluids and two cylinders have been developed and evaluated, resulting in a quantification of the effect of changes in the iron content in the fluid used, as well as of the dimension of the gap between the piston head and the inner cylinder wall. With these results, the potential use of this fluid in haptic gloves as well as in other demanding applications is clearly indicated. The use of short bend sensors to create a position sensing system with insignificant weight, and the electronic interfacing of both systems were also described. Finally, a preliminary design of a new haptic glove based on MRF cylinders has been presented.

The construction of the whole force-feedback glove is currently underway. This will be followed by testing and evaluation of the device. Further testing and improvements to reduce the friction of the piston in the off-state will also be conducted. Future work includes improvements to the ease of wearing the glove, its comfort and its robustness. Further improvement may include the testing with more MRF compositions as well as the integration of a tactile display system at the fingertips.

References

[1] R. J. Stone, "Haptic Feedback: A Brief History from Telepresence to Virtual Reality", *Proceedings of the First International Workshop on Haptic Human-Computer Interaction*, p.1-16, Aug. 31- Sept. 01, 2000.

[2] P. Lemoine, M. Gutierrez, F. Vexo, D. Thalmann, "Mediators: Virtual Interfaces with Haptic Feedback", *In Proceedings of EuroHaptics,* 5th-7th June, Munich, Germany, pages 68-73, 2004.

[3] V. Popescu, G. Burdea, M. Bouzit, "Virtual Reality Simulation Modeling for a Haptic Glove," *Computer Animation* 1999.

[4] A. Fisch, C. Mavroidis, Y. Bar-Cohen, J. Melli-Huber, "Chapter 4: Haptic Devices for Virtual Reality, Telepresence and Human-Assistive Robotics", Department of Mechanical and Aerospace Engineering, Rutgers University, The State University of New Jersey.

[5] D. De Rossi, F. Lorussi, E.P. Scilingo, F. Carpi, A. Tognetti, and M. Tesconi, "Artificial kinesthetic systems for telerehabilitation.", *Stud Health Technol Inform,* 2004.

[6] T.H. Massie, and K.J. Salisbury, "Phantom haptic interface: a device for probing virtual objects," *Proceedings of the 1994 International Mechanical Engineering Congress and Exposition,* vol. 55-1, 1994.

[7] M. Bouzit, G. Burdea, G. Popescu, and R. Boian, "The Rutgers Master II-New design force-feedback glove," *IEEE/ASME Transactions on Mechatronics*, vol. 7, no. 2, pp. 256-263, 2002.

[8] VR Logic, Cybergrasp,[Online], Available: http://www.vrlogic.com/html/immersion/cybergrasp.html.

[9] S. Nakagawara, H. Kajimoto, N. Kawakami, S. Tachi, and I. Kawabuchi, "An Encounter-Type Multi-Fingered Master Hand Using Circuitous Joints," *Proceedings of IEEE International Conference on Robotics and Automation*, Barcelona, Spain, pp. 2667-2672, 2005.

[10] Lord Corporation, "Engineering Note: MR vs ER", [Online]. Available: www.lord.com/Portals/0/MR/MRvsER.pdf

[11] J.M. Ginder, L.D. Elie, and L.C. Davis, "Magnetic fluid-based magnetorheological fluids", U.S. patent 5,549,837, 1996.

[12] S.H. Winter, and M. Bouzit, " Use of Magnetorheological Fluid in a Force Feedback Glove", *IEEE Transaction on Neural System and Rehabilitation Engineering,* Vol.15, Num.1, March 2007.

[13] J.D. Carlson, and B.F. Spencer Jr., "Magneto-Rheological Fluid Dampers for Semi-Active Seismic Control", *Proc. 3rd Int. Conf. on Motion and Vib. Control,* Chiba, JP, Vol. III, pp. 35-40, 1996.

[14] J. Blake, and H. Gurocak, "Magnetorheological fluid brake for a force feedback glove for virtual environments", *Proc. of IDETC/CIE 2005: ASME 2005 Design Engineering Technical Conferences and Computers and Information in Engineering Conference,* Sept 2005.

[15] K.H. Kim, Y.J. Nam, R. Yamane, and M.K. Park,"Smart Mouse: 5-DOF Haptic Hand Master Using Magneto-Rheological Fluid Actuators" *Proceedings of the 11th Conference on Electrorheological Fluids and Magnetorheological Suspensions,* 2009.

[16] G. Aydar, C.A. Evrensel, F. Gordaninejad, and A. Fuchs, "A Low Force Magneto-rheological (MR) Fluid Damper Design, Fabrication and Characterization", *Journal of Intelligent Material Systems and Structures,* 2007.

[17] M.R. Jolly, J.W. Bender, and J.D. Carlson, "Properties and applications of commercial magnetoreological fluids", *Journal of Intelligent Material System and Structures,* Vol. 10, pp. 5–13, 1999.

[18] M.A. Saliba, F. Farrugia, and A. Giordmaina, "A Compact Glove Input Device to Measure Human Hand, Wrist and Forearm Joint Positions for Teleoperation Applications", *Proceedings of the IEEE/APS Int. Conf. on Mechatronics and Robotics*, Aachen, Germany, Sept. 2004.

[19] G. Yang, "Large-Scale Magnetorheological Fluid Damper for Vibration Mitigation: Modeling, Testing and Control," Ph.D dissertation, University of Notre Dame, 2001.

[20] I. Vessonen, "MR fluid-based damping force control for vehicle cabin vibration suppression", *Journal of VTT SYMPOSIUM,* Vol. 225, 2003.

[21] J.D. Carlson, "What Makes a Good MR Fluid?", *Journal of Intelligent Material Systems and Structures*, Vol. 13, No. 7-8, 431-435, 2002.

[22] J.D. Carlson, "Low-cost MR fluid devices.", *Proceedings of the 6th International Conference on New Actuators,* Bremen 17–19 June 1998.

[23] J.D. Carlson, and B.F. Spencer Jr., "Magneto-rheological fluid dampers: scalability and design issues for application to dynamic hazard mitigation." *Proc. 2nd Workshop on Structural Control: Next Generation of Intelligent Structures,* Hong Kong,1996.

[24] Flexpoint webpage. [Online], Available: http://www.flexpoint.com/

[25] L.K. Simone and D.G. Kamper, "Design considerations for a wearable monitor to measure finger posture". *Journal of NeuroEngineering and Rehabilitation,* 2005.

[26] NI Labview webpage. [Online],Available: http://www.ni.com/labview/