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A Force Feedback Glove Based on Magnetorheological Fluid: Prototype Development and Evaluation

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***Abstract*—Magnetorheological Fluid (MRF) is a smart fluid which reversibly changes viscosity proportionally to an applied magnetic field. In an MRF actuator, this change in fluid properties results in a resistive force/torque, which can be used to provide passive force feedback in a haptic glove. In this work, the development of a force feedback glove based on MRF linear dampers is described. The paper also describes the development of the position sensing system for the glove as well as the development of simulation software for the glove. A first prototype of the glove, with force feedback and position sensing on the middle finger, has been constructed. This work reports on the testing and evaluation of this prototype. Finally a number of proposed improvements directed towards the identified drawbacks are presented.**

Keywords: haptic glove, magnetorheological fluid

I. Introduction

Over the years, the robotic community has aimed to develop robots that can perform work without any human assistance. These robots could be employed to perform tasks in hazardous or distant environments and other situations where a human operator would be put in danger or could not be in the required location. However, it was quickly acknowledged that these tasks could almost always be performed significantly better by humans [1]. The solution to overcome the needs and limitations of this situation is tele-presence. In such situations, both the human brain and the robot operator can work together and the advantages of both would facilitate successful performance of the required operations. This system is often referred to as a Robotic Master-Slave system where a human operator and a robot are the master and slave respectively. Haptic feedback is necessary in tele-presence since immersing the operator to the greatest extent possible in the remote environment greatly reduces the object manipulation time. Otherwise, the manipulation may require too much effort and may become imprecise [2]. Haptic feedback is also mandatory when the object being handled remotely is in the dark or no graphics are available [3].

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The haptic master device used in tele-presence to control the robot slave is in some cases in the shape of a glove since it can be easily worn on the human hand. The glove interfaces with the senses of the hand through force feedback. Applications of such systems include tele-surgery [4], space exploration, as well as assistance in police operations or fireman search and rescue missions [5]. 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 [6], as well as the training of surgeons [5]. Apart from these applications, haptic devices can be positively used in the art and entertainment industry, such as in the design and control of video game or cartoon characters [7], and to help people with special needs through sign language understanding and Braille learning and reading [8]. Also, similar to the latter is the use of a force feedback glove to help blind children in learning words, sounds and object forms [9] [10].

Amongst the popular haptic gloves one can find the Rutgers Master II [11], the CyberGrasp [12], MEMICA [13] and the glove created at the University of Tokyo [14]. A number of actuator technologies have been applied to power past master hands projects. The most common are electric and pneumatic actuators. Other actuators include electrorheological fluid, ultrasonic motors, shape memory alloys, and piezoelectric elements amongst others.

Amongst the less commonly used actuator technologies, one can find the magnetorheological fluid (MRF). MRF consists of micro-sized magnetisable particles mixed into an appropriate carrier fluid, the combination of which flows freely under normal circumstances with viscosity similar to motor oil. In the presence of a magnetic field, the micro-sized particles align and form a linear chain parallel to the field. This causes the yield strength and viscosity of the fluid to increase proportionately to the magnitude of the applied magnetic field, restricting fluid movement [15]. At a suitable magnetic field, the time necessary to obtain ninety per cent of the final viscosity of the MRF is equal to a few microseconds [16]. The largest change in the fluid properties occurs when the flow is normal in relation to the magnetic field direction [17]. The advantages of MRF may potentially result in a safe, lightweight, compact, high power to weight ratio, quick responsive actuator. This fluid is also an interesting choice since it provides infinite possibilities of viscosity values between its minimum and maximum.

Nonetheless, throughout the extensive literature search carried out about haptic gloves and about magnetorheological fluid, only three devices that combine the two researches together were found. The first of the three gloves was developed at the Washington State University Vancouver by J. Blake and H. Gurocak [18]. 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 [13]. 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 [19]. The performances, as well as the advantages and disadvantages of each of these three gloves have been compared in [20].

II. Development of the Actuation System

Due to the relative novelty of this approach, and due to size limitations, it was not possible to purchase appropriate actuators for the glove. Guided by a lot of useful information found in the literature (e.g. [21] and[22]), an MRF actuator was developed. This development is documented in detail in [20], and here it is briefly summarised. The actuator consists of a magnetisable cylinder, a small piston head made of magnetisable material and wound by insulated copper wire (providing a magnetic field of 0.354 Tesla when at maximum current), an aluminium tube and cap, and an oil seal. The design of the actuator is illustrated in the CAD drawing in Figure 1. Further improvements to the design were implemented so as to eliminate fluid leakage as well as short circuiting of the coil, two conditions being faced at the early days of this work.

The fluid itself was also developed in-house, due to the lack of available suppliers, as well as unsuitable minimum order quantities. This required a large amount of information on MRF to be gathered from the literature, amongst which were [21], [23] and [24]. These describe in detail how a good MRF is developed. Although a fluid developed in house 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 fact, three fluids with different iron contents were developed. 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), in Fluid 2 it was 40% by volume (75% by weight), and in Fluid 3 it was 60% by volume (87% by weight).

Although the above allowed experimentation with fluids of different iron content and exposure to magnetic fields of different magnitudes, a third parameter to be investigated was the effect of the radial gap size. This refers to the gap between the piston head and the inner wall of the cylinder. Two iron cylinders were thus developed. Cylinder 1 had a gap of 1mm whilst Cylinder 2 had a gap of 2mm.

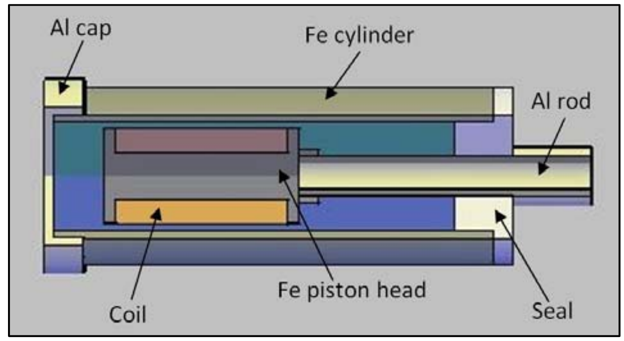

Figure 1: CAD drawing of the developed piston

The three fluids created were then 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 can carry without moving. The latter was done by hanging different amounts of calibrated weights to the piston. The results of the experiments are presented in Table I.

Through these results, one can clearly see through numerical values the effect of the size of the radial gap, the effect of iron content in the fluid, and also the effect of the magnitude of the magnetic field controlled by the current in the coil. These results were important to conclude the maximum forces of each cylinder/fluid combination, which demonstrates the true potential of the MRF technology. Moreover, these results also show the minimum force for each combination and thus were used as a guide to choose the best combination for the haptic system. Since a maximum force of 15N is sufficient for use in this application [25], four combinations fit this requirement. Of these, Cylinder 1/Fluid 3 combination has a maximum of 70N, however this results in a minimum force greater than 6N, which represents an unacceptable resistance to free motion of the glove when the force feedback is off. Cylinder 1/Fluid 1 combination does not allow a factor of safety as its maximum obtainable force is 15.2N. From the remaining two, Cylinder 1/Fluid 2 combination was chosen since this results in a slightly lower force at 0A. That said, the maximum force is lower than its alternative, however, the 22N maximum force of the chosen combination will be enough to simulate a solid object. A final advantage of this choice is that since the radial gap is 1mm, as opposed to the 2mm gap of its best substitute, the resultant actuator would have a slightly smaller total width.

The forces exerted by the MRF piston can be controlled by the current, as shown in Table I. 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 an op-amp LM324, transistor TIP122, as well as some other electronic components, an electronic circuit which allows the DAQ output to control the power fed to the piston from an external 5V power supply was developed.

Table I: The forces obtained by the six different cylinder/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

III. Development of the Position Sensing System

After evaluating a number of applicable sensor technologies, and comparing these through a decision matrix, resistive bend sensors were chosen as the main element to make up the position sensing system. This choice was made since these sensors are inexpensive, lightweight, thin and flexible, and require only basic circuitry. The sensors chosen have a length of 1 inch (~25.4mm). Through experimentation, the best positioning of the sensors was determined.

The final data glove consists of a thin glove to which eight bend sensors (two for every finger with the little finger excluded) were attached. The sensors were placed at the surface of the Proximal Interphalangeal (PIP) joint and at the bottom of the Metacarpophalangeal (MCP) joint as seen in Figure 2. To convert the change in resistance that occurs when the sensor is bent into a change in voltage, a simple voltage divider circuit was constructed. A DAQ was used to input the potential difference between the two resistances of the circuit to the computer.

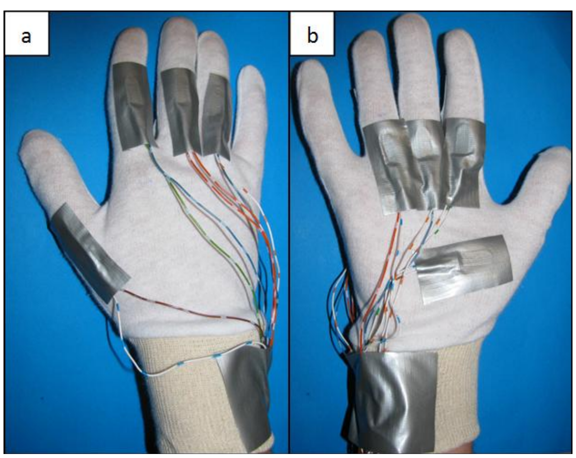

Figure 2: Data Input Glove a) back and b) front

IV. Prototype Development

The force feedback system consisting of MRF pistons, the position sensing system, as well as the electronic interfaces, were then combined to develop a prototype of a haptic glove. The first step is the decision between an exoskeletal and an endoskeletal design. Two popular haptic gloves, the CyberGrasp and the Rutgers Master II, mentioned in Section I, have an exoskeletal and an endoskeletal configuration respectively. With the size of the MRF piston developed, both configurations are possible and thus both were considered.

The greatest advantage of an exoskeletal design is that with such a configuration, complete fist closure is allowed. Through rough estimation it was calculated that if an endoskeletal configuration were to be adopted, the size of the piston developed, having a length of approximately 60mm when fully retracted, would allow the user's hand to only be closed two thirds of the way. With this constraint, virtual air as well as small objects can never be simulated since the user is not allowed to close his/her hand to form a fist.

The lack of available space for the force feedback system is a major concern when using an endoskeletal design. The long term primary goal of this project is the development of a haptic glove with which an anthropomorphic robot hand, focusing mainly on the RIAL Robot Hand [26] and [27], can be interfaced in a tele-presence system. Since this robot hand has two degrees of freedom for every finger, it is essential that the glove also has a minimum of two degrees of freedom for every finger to be able to convey the forces experienced by the robot hand. This is also required so as to allow the user to control the robot hand with adequate precision when wearing the force feedback glove. This is not possible with an endoskeletal design since such a configuration would not result in enough space for two pistons for every finger.

An exoskeletal design was thus opted for. This meant that a transmission system is needed to transmit the force produced by the linear movement of the piston to the rotary movement of the human finger joint. The transmission system can be made either of rigid, semi-flexible, or flexible bodies. Through experimentation it was concluded that a flexible transmission system is the best option since this eliminated fluid leakage and the unnatural motion experienced by the user as he/she opens his/her hand, conditions which were both present when using the other transmission systems. Also, this system allowed the user to adjust the glove to better suit his/her hand size. However, with such a system, a spring is needed so as to return the piston head to its original position when the user's hand is opened. The concept design displayed in Figure 3 was developed to make up the prototype of the force feedback glove. This is made up of two MRF pistons, one transmitting feedback to the MCP joint of the finger and the other to both the MCP and the PIP joints of the same finger.

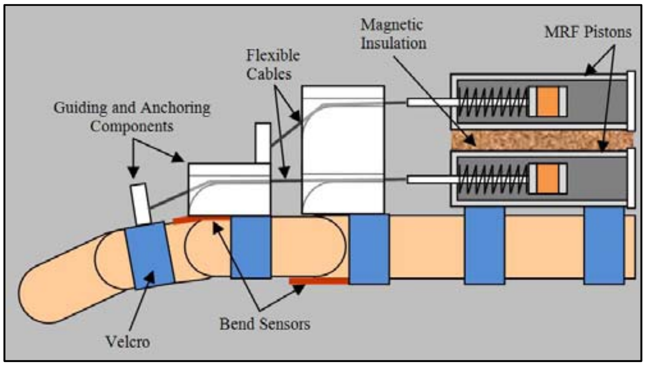

Figure 3: Conceptual design of the force feedback system

Based on this prototype, a conceptual design of the entire haptic glove was completed. The prototype presented here was created to test the system on only the middle finger, and was constructed in a way that adequate space is left for the remainder of the force feedback system on the other fingers. The prototype is shown in Figure 4. The exoskeletal frame, where the two pistons transmitting force feedback to the middle finger are housed, can fit two other pistons at the bottom and another two at the top. These six pistons would be used to transmit force feedback to the MCP and PIP joints of the index, middle and ring finger. The pistons to transmit force feedback to the thumb can be placed on the side of the hand. No force feedback to the little finger shall be provided.

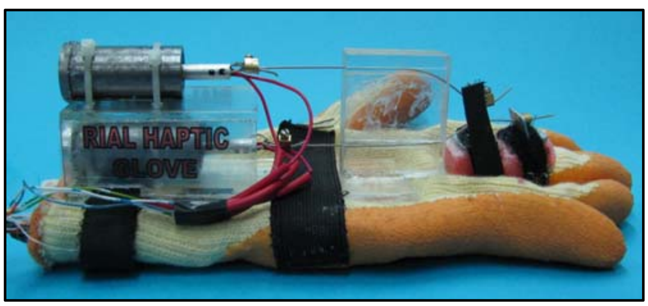

Figure 4: The developed force feedback glove prototype

V. SIMULATION SOFTWARE FOR THE GLOVE

Before implementing computer software, one must first consider the inputs and outputs involved in this system. These can all be seen in Figure 5. In this diagram, one can see that the positions of the user's hand joints are inputted from the haptic glove to the computer system. This involves a number of steps so as to convert the change in angle from degrees to a voltage input. When the virtual object is touched, meaning that the true angles of the user's finger joints match the size of the virtual object, the computer system outputs the elastic properties of this object through force feedback so that the user can feel the object being grasped. This is done by converting the voltage output into a change in the magnetic field of the actuator, thus resulting in a change in force transmitted to the user. If the haptic glove were to be used in a remote environment through tele-presence, the properties of size and elasticity of a real object are determined by the sensors of the robotic hand (rather than being generated by the computer system), the position of which is controlled by the glove.

Computer software to manipulate these inputs and outputs was developed using Labview [28], a graphical based computer language by National Instruments. The two programs created will now be described.

Simulation of grasping a solid real object: This software has the capability to simulate a real object as if it were being grasped in real time by a robotic hand in a remote environment. The user is first asked to grasp a real object when wearing the haptic glove and angles of the fingers at contact with the object are recorded. In the second part, the real object is put aside and the user starts to close his/her fingers around empty space. When the readings of the bend sensors match the values recorded earlier, object contact is simulated by switching on the force feedback actuators. This software also allows the user to create a library of object dimensions and load them when required.

Simulation of virtual objects of different sizes and elasticities: When choosing the actuator technology for the haptic device to be developed, one of the major features which led to the selection of MRF was its ability to change to different viscosities, thus making it possible to display objects with different elasticities. Since it was not possible to display this effect with the first software, another program was developed which simulates balls of different sizes and elasticities.

This second software starts off by asking the user if the ball in the simulation is to be small, medium or large and also the elasticity of the ball. Numerical values within the software are associated with each choice. The total output voltage of the force feedback system is then calculated using the formula:

$$V = C\left[\left((\Theta_r - \Theta_s) * k\right) + T_i\right]$$

where V is the output voltage, Θ_r is the real-time angle value of the user's finger joint, Θ_s is the joint angle for contact with the simulated ball, k is the stiffness of the simulated ball as reflected at the joint, T_i is an initial joint torque to simulate the moment of contact, and C is the constant of proportionality in V/Nm. Both Θ_s and k are determined from the user's selection, and C is obtained through calibration. One must note that with this formula, the resistive force of the actuation system is increased to display the increase in object hardness as it is squeezed. This rate of increase is determined by the selected elasticity.

From the above description, one can see that the two programs developed have the potential necessary to use the haptic glove and its features. By combining some of the features of these two programs and performing some minor changes, one may develop software with which the haptic glove can be used to operate an anthropomorphic robot hand through tele-presence in a master-slave robot system.

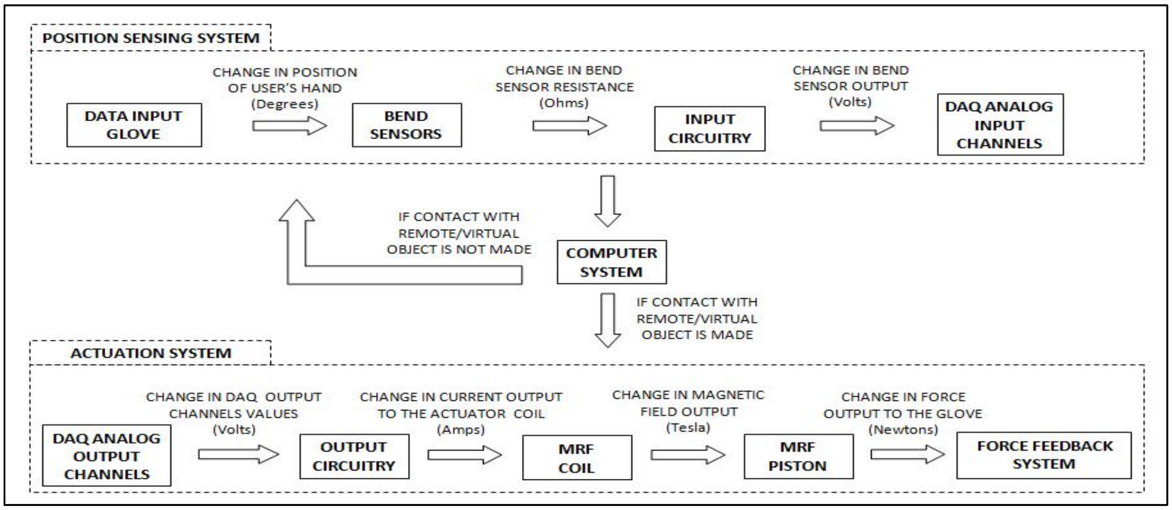

Figure 5: Detailed illustration of the communication system

These two programs demonstrate the use of the glove in a virtual environment. However, one must understand that the development of the virtual environment does not have any limitations. One may create a whole library of objects of different shapes, sizes and elasticities. Also, the visual aspect of the virtual environment can be developed, so that the user is immersed further into this world by seeing and feeling the virtual object.

VI. Evaluation and Testing

During testing and evaluation, the requirements deemed necessary for a successful haptic glove together with the requirements of actuators and sensors suitable for these gloves were reviewed. These will be presented below.

A solid object feels solid: The selected cylinder/fluid combination is able to achieve a force of 21.8N at 0.8A. When attached to the final prototype, the resistive force exerted by the piston is enough to stop the movement of the human finger, thus providing the feeling of a true solid object. This force can only be overcome if the user puts in extra effort to exert a force that is uncomfortable for his/her finger.

No resistance when "touching virtual air": The problem of unwanted resistance to movement is one which is common amongst haptic gloves. Glove developers aim to achieve insignificant resistance to movement at the off-state so as to be able to convincingly simulate what is known as "virtual air". Unfortunately this is not an easy task when using MRF based actuators especially since enough resistance in the on-state is required to simulate a solid object.

In the development of this glove, this unwanted resistive force has been faced throughout the whole project. The initial resistive force of the actuator developed at 0A was decreased from 3.6N to 1.8N by reducing the diameter of the rod which interfaces with the oil seal. However, during the development of the final prototype, a spring was added to the components to facilitate the finger opening stroke. This increased the resistance to finger closure to a total of 4N. With such a force opposing the hand movement when no object is being simulated, the user cannot truly feel that he/she is "touching virtual air". Then again, as the user is opening his/her hand, no resistant forces are present since the piston returns back to its original position with the aid of the spring. Also, if the user's hand is opened faster than the speed with which the piston returns to its original position, the flexible cable allows the user to do so unopposed.

Lightweight: A major concern in any haptic glove is its weight. Based on the prototype developed, the estimated weight of the conceptual RIAL Haptic Glove is 0.86kg. This estimation is based on a glove which provides force feedback to the thumb and three fingers, with two degrees of freedom for each. This is considered as being heavy when compared to the light Rutgers Masters II weighing 0.13kg and the heavier CyberGrasp being 0.45kg. Nonetheless, to make a fair comparison, one must keep in mind the number of actuators being included in this estimate. In fact, if the number of actuators is matched to these gloves, the resultant estimated figure is comparable to that of the CyberGrasp, a commercial haptic glove.

Comfortable: Although the glove needs to be tightly attached to the human hand as well as rigid so as to result in a convincing simulation of a solid object, comfort is still desired. To ensure that the glove is as comfortable as possible, a thick rubber glove was used in our work. Also, Velcro was used as the primary material to fasten the glove and its components to the user's hand. Some foam was added to increase the cushioning layer between the anchoring components and the human hand.

Accuracy: Experiments were conducted in which the voltage readings obtained by the position sensing system at particular angles were recorded for calibration purposes as well as to deduce the average accuracy for each joint. For these experiments, the readings for both the MCP and the PIP joints were taken. Throughout the experiments, the user was wearing the final prototype developed, including all the fastening components of the force feedback system. The true angle was then read using an angle measuring device as shown in Figure 6. The data obtained were then plotted and an equation for each joint was derived by curve fitting. The curve for the MCP joint is shown in Figure 7. The readings previously obtained and the equations derived from the graphs, were then used to estimate the margin of error of the position sensing system at each joint. The values obtained resulted in an average error of 2.79^0 for the MCP joint and an average error of 3.24^0 for the PIP joint. These results indicate that the developed system has the capability to adequately sense the positions of the finger joints.

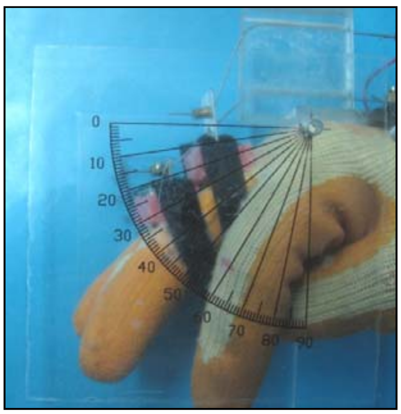

Figure 6: Experimental setup for true angle reading

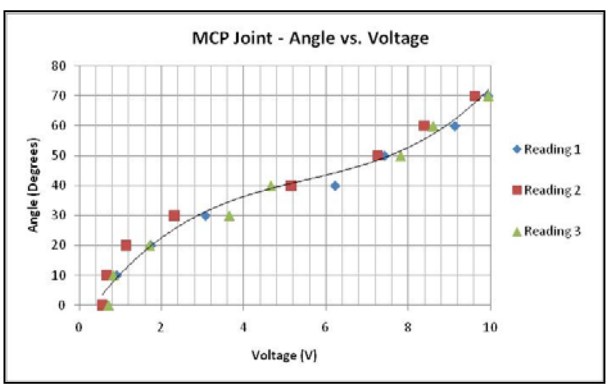

Figure 7: Graph for MCP joint

Realistic Simulation: The final criterion which was used to evaluate the prototype developed as well as the potential glove is the ability to achieve a realistic simulation. This is the most important criterion since it is the main objective of this project and it also incorporates all the requirements of a haptic glove.

To help in this evaluation, using one of the programs developed, the user grasps a real object whilst wearing the device developed. The position values of this object are then recorded. When the user removes the real object, he/she is restricted from forming a fist by the simulation of the real object previously grasped. This exercise was conducted on a small red ball as seen in Figure 8.

When performing this exercise the user is not given the full simulation of the ball since only the middle finger has haptic feedback. Thus with the current prototype it is difficult for the user to truly understand the exact shape of the object being simulated. Nonetheless, even the middle finger on its own gives the user the sense of grasping a round solid object. A slight delay between the time the MRF pistons are switched on and the time their resistive forces are acting at a maximum exists. This makes the simulated ball feel slightly smaller than the real ball. However, this can be easily compensated through software by switching on the pistons slightly earlier than is really required. It is thus believed that the simulation on the middle finger resulting from the final prototype developed has a good level of realism, a property which can be drastically increased once force feedback on all fingers is successfully implemented.

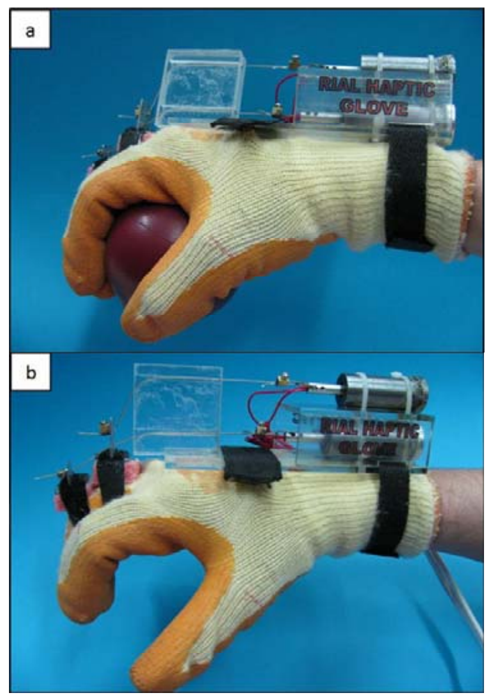

Figure 8: Ball simulation exercise: a) real object, b) virtual object

Although the addition of springs increased the resistance to movement when the MRF actuator is in its off-state, it was also noted that if the cables are adjusted properly, the springs would take any slack that the system may have. This means that force feedback can potentially be applied to any angle of the finger joint movement.

VII. PROPOSED IMPROVEMENTS

Through the evaluation it was understood that the greatest drawbacks of the prototype developed are the resistance to movement as the user is "touching virtual air" as well as the issue of weight. In view of this, a number of modifications aimed at decreasing these disadvantages are proposed here.

Decreasing resistance to movement: The decrease of the resistance to movement when the actuators are in the off-state is an issue which requires continuous improvement since the ideal resistance at this state is zero. The latter is not possible. However, if this force is low enough, the user can be made to believe that he/she is touching virtual air.

The first proposed improvement is the re-designing of the piston head. The proposed design aims at maintaining the positive results of the maximum forces achieved by the developed design whilst reducing the minimum forces. In this design, the top of the piston head is in the shape of a cone so as to allow easier motion when the piston head is pulled forward. Also, the bottom of the piston head is circular so as to decrease the force needed to push the piston head into its original position. This means that if a spring is used, a lighter spring (than the one currently being used) would provide enough force to push the piston head with the new design backwards. With a lighter spring, the resistance to forward movement is also decreased. As can be seen in Figure 9, when compared to the old design, the proposed design has better hydrodynamic properties, thus it has the potential of decreasing the resistance to movement greatly. That said, the added features to the original design may have to be manufactured using a non magnetic material so as not to alter the magnetic field and path present in the current prototype.

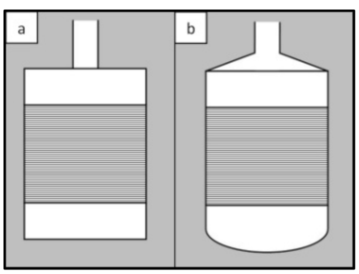

Figure 9: Piston head designs: a) design developed, b) design proposed

The springs also play an important role in the actuator. By using customized springs, the force provided may be just enough to push the piston head in its original position. Thus, through customization, the lightest springs which provide the necessary force and the least resistance may be chosen.

One can also try to improve the fluid itself. By doing so, the range of forces obtainable can be widened. This means that the radial gap can then be increased accordingly to achieve a maximum force similar to the one obtained in this work (since this force was enough to stop the motion of the human finger, increasing this maximum force would be futile) and thus a lower minimum force is attained.

The actuator design also plays a very important role. If a more efficient design is developed, the range of forces obtainable can again be increased. Since a higher maximum force is not required, an increase in efficiency can then be directed at obtaining a lower minimum force by using a less viscous MRF.

Weight Reduction: The second important feature of the haptic glove developed that can be improved is its weight. Although the final prototype developed is just over 0.3kg, the estimated weight of the final glove is approximately 0.86kg, a weight which may tire the user after prolonged usage. Presented below are some improvements aimed at diminishing this problem.

One of the design concerns in an MRF piston is magnetic saturation. This occurs when the cross sections of the components making up the magnetic path are too small to sustain the magnetic flux density generated by the electromagnet. This also results in saturation of maximum force, meaning that an increase in current is not followed by an increase in force. Through the results obtained in Table I, one can see that saturation does not occur with the present actuator design. Also, since the maximum force obtained is enough to simulate a solid object, there is no intention of increasing the magnetic field further. Thus the cross sections of the components making up the magnetic path can be reduced to sizes which are just enough to hold the magnetic flux generated. Such reductions in the component sizes would help in reducing the total weight of each actuator.

Another improvement may be that of locating the return spring outside the actuator. Due to its superior magnetic properties, iron is the chosen primary material of the MRF actuator. Unfortunately, iron also happens to be one of the heaviest materials. If the spring had to be assembled on the outside of the cylinder, the actuators developed can be smaller by a value equal to the length of the compressed spring, decreasing the weight.

One may note that the proposed improvements aim at reducing the weight of the actuator since every reduction is then multiplied by the number of actuators installed in the glove. It is believed that with the proposed improvements, the total weight of the RIAL Haptic Glove may be reduced significantly. Nonetheless, a force feedback glove made of eight MRF actuators can never be light. Thus, one may also consider making the whole haptic device ground-based for certain prolonged applications. By doing so, the weight of the glove is supported by the desk or wall that it is mounted to, and so the weight of the device becomes insignificant. That said, this constrains the user from moving around whilst wearing the device, thus reminding him/her of the real world and limiting the immersion in the simulated one. A solution may be to provide a mount with which the user may optionally ground the device whilst striving to achieve the lightest weight possible to improve usage when the glove is user-based.

VIII. CONCLUSION

In this work, an innovative actuation technology for a haptic glove based on magnetorheological fluid was successfully developed. This actuator was within the size limitations imposed by the hand geometry. The chosen cylinder/fluid combination can develop a resistive force of up to 22N exceeding the design requirement of 15N. Moreover, work on this actuator technology clearly showed the potential of MRF in a quantitive manner. A position sensing system for the glove with an adequate degree of accuracy was also developed.

Both systems and the respective electronic and computer interfacing were integrated with an exoskeletal frame and an adjustable transmission system to make up a first prototype of the glove. This prototype transmits force feedback to two degrees of freedom of the middle finger. This feedback is done in a way that the user can be convinced that he/she is grasping a solid or very stiff object. Through the computer software developed, the prototype can also simulate a real object and allows the creation of an object library, as well as simulate balls of different sizes and elasticities. Finally, a conceptual design as well as evaluation of the whole haptic glove based on the prototype were presented.

This project and the successfully developed prototype provide the necessary groundwork for developing a good haptic glove based on MRF technology and can be operated in a tele-presence mode and in a virtual environment.

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