Haptic interfaces based on magnetorheological fluids

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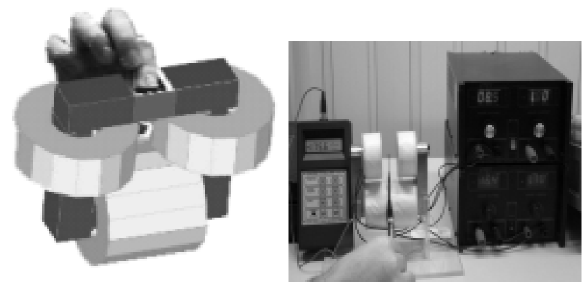
Abstract

In this paper we present an innovative application of magnetorheological (MR) fluids to haptic interfaces. These materials consist of a suspension of a micron-sized, magnetizable particles in a synthetic oil. Exposure to an external magnetic field induces in the fluid a change in rheological behaviour turning it into a near-solid in few milliseconds. Just as quickly, the fluid can be returned to its liquid state by the removal of the field. MR fluids are already present on the market, used in devices such as valves, brakes, clutches, and dampers. In this paper we investigate the possibility of using MR fluids to mimic the compliance, damping, creep (in other terms, the rheology) of materials in order to realize a haptic display and we propose two different implementations. Here we only outline the first scheme, whose experimental results have been reported in our previous work, and will describe the second one. In this latter scheme we set up a psychophysical protocol where a group of volunteers were asked to interact with the MR fluid duly excited and qualitative results are discussed.

1. Introduction

Magnetorheological (MR) fluids are materials that respond to an applied magnetic field with a change in rheological behaviour. Typically, this change is manifested by the development of a yield stress that monotonically increases with applied field. Just as quickly, the fluid can be returned to its liquid state by the removal of the field. MR fluids are already present on the market but their application field is restricted to devices such as valves, brakes, clutches, dampers.

We report here about the possibility to use MR fluids to mimic the compliance, damping, creep (in other terms the rheology) in order to realize a haptic display. Possible fields of application could be the surgical training in minimally invasive surgery and open surgery. This approach of using the MR fluid is justified by the observation that viscoelastic properties of the biological tissues could be mimicked by magnetically tuning the rhelogical properties of the fluid. In the case of minimally



(a) (b)

Figure 1. In the left side (a) the design used for the simulation is reported, while in the right side (b) the realized device during tests is shown.

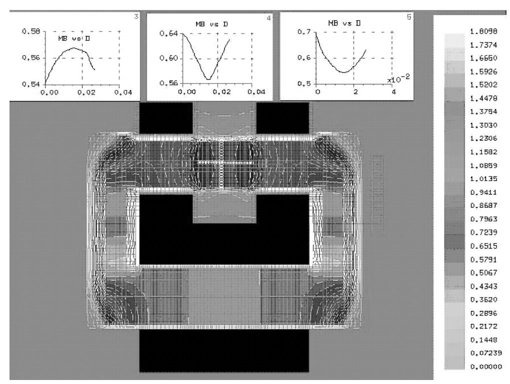
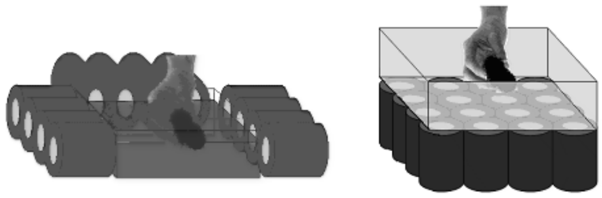


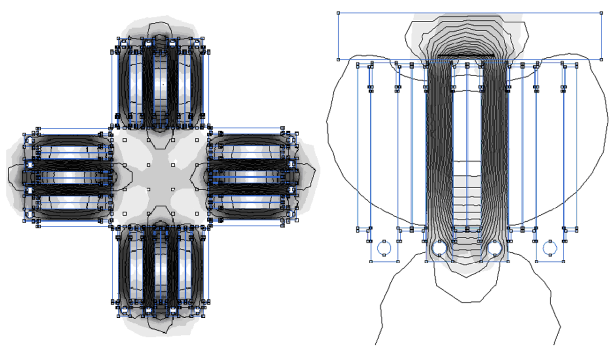
Figure 2. Simulation, through CAD analysis based on FEM, of the distribution of the magnetic field in the pinch grasp device.

invasive surgery the fluid could be incorporated in the handle of a surgical end-effector, whereas in the open surgery the operator would interact with a haptic box containing the fluid. Although challenged by new developments in endoscopic technologies, traditional operative procedures remain the only solution in most cases of surgical operation, therefore surgical training in open surgery is very important. Two possible schemes and two prototypal devices have been considered: pinch grasp and immersive configurations. In all prototypal devices we used the MR fluid marked as MRF-132LD by Lord Corporation® , Cary, NC, Usa.



(a) (b)

Figure 3. Design of the immersive scheme arranged in two configurations: HSM (Horizontal Solenoids Matrix) (a) and VSM (Vertical Solenoids Matrix) (b).



(a) (b)

Figure 4. Simulation of the distribution of the magnetic field in the active region of the HSM (a) and VSM (b) configurations realized by using a CAD analysis tool based on FEM.

2. Pinch grasp scheme and preliminary work

In this scheme the MR fluid is positioned in the air-gap of an electromagnet within a latex sleeve allowing the pinch grasp manipulation (see Fig. 1).

Preliminary work focused on the 3D simulation of the system by using dedicated CAD based on Magnetic finite elements algorithms. This simulation led us to define specifications relative to number of coils turns and current flowing into coils in order to produce in the air gap the maximum magnetic field resulting in the saturation phenomenon in the MR fluid. In Fig. 2 is reported a simulation, in which we used the real B-H curves of both MR fluid and steel and fixed 5100 At (Ampere-turns). The grey scale map shows the intensity of the magnetic field within the ferromagnetic core and the air gap. The simulation needed to find the optimal structural parameters and come to a fair compromise between the distribution of the magnetic field and the dissipated energy due to overheating. A comparison between the theoretical and experimental results has been performed. In particular we used a Gaussmeter to measure the magnetic field in the air gap at different levels of current

(a) (b)

Figure 5. Tactile interaction with the haptic box realized according to HSM scheme (a) and VSM scheme (b).

into coils and we compared the results with the behaviour given by the simulation.

Furthermore, preliminary work showed some evidence of the possibility of building a haptic display MR fluid based. In particular, a set of psychophysical tests were performed where a group of volunteers were asked to manipulate at the same time using both hands the biological tissue sample (chosen among brain, myocardium, spleen, liver, lower limb muscle and lung) and the MR fluid specimen duly excited with magnetic field. Regarding the brain, spleen and liver, results are very encouraging, while with respect to myocardium, lower limb muscle and lung the analogy was not satisfactory, because the magnetic field intensity needed to induce a compliance similar to these biological tissues, was beyond the saturation of the MR fluid we used. To overcome this limitation it is possible to use a MR fluid with higher saturation level. Studies in this direction have been performing.

3. Immersive scheme

The immersive scheme consists of a given volume of MR fluid placed within a Plexiglas box so that a hand can be introduced and interact with the fluid (Fig. 3).

The preliminary design envisioned was conceived as four walls of four solenoids placed side by side to form a box (Fig. 3a).

In this configuration named with acronym HSM 4x4 (Horizontal Solenoids Matrix 4x4), work space is a Cartesian plane with 16 quantized points. Each point is identified by the intersection between the extensions of the axes of four facing solenoid. The dimensioning has been realized so as to focus magnetic flux into specific regions of the MR fluid, maximizing the magnetic field energy in this region and minimizing the energy lost in the other regions. In particular, solenoids are dimensioned in according to mechanical, thermal and electrical criteria. Mechanical aspects concerned the size and the shape of the steel core. Thermal considerations have been done in order to avoid overheating inconveniences. Electrical evaluations aimed at estimating the resistance and inductance of the coil such that the current density flowing into coil was under limitations foreseen by regulations. By tuning the current into each coil, figures with a given shape and compliance have been realized. This configuration exhibits an inconvenience due to the fact that the region closer to the walls is exposed to a greater magnetic field. This is due to the fact that the magnetic field generated by a solenoid is concentrated in a nearly uniform field inside the solenoid, while the field outside is weaker and decreases with the distance from the axis. In this way, the figures we can reproduce are constrained to be stiffer at the edges. In Fig. 4a, a simulation of the distribution of the magnetic field is reported and in Fig. 5a the realized system during a tactile manipulation task is shown. It is worth noting that figures such as cross or shape running from an edge to the other are well defined and easily reproduced. Indeed, in Fig. 4a a cross is simulated, in which four facing solenoids are activated. To overcome this limitation we adopted a second configuration named VSM (Vertical Solenoids Matrix) where 16 solenoids are vertically placed below the box. In this case every quantized point is simply identified by the ideal prolongation of the solenoid's axis in the box and the magnetic field may be distributed throughout over the box surface. In Fig. 4b a simulation of the distribution of the magnetic field through CAD analysis tool based on FEM is reported. In particular a frontal plane is illustrated, where two contiguous solenoids are excited. The magnetic field is maximum at the top of each solenoid and slightly decreases at the transition zone between the two solenoids. Fig. 5b shows the realized system where a volunteer performs a tactile manipulation test.

4. Hardware equipment

In both configurations every solenoid is comprised of 305 turns of an enamelled copper wire, marked Autovex 180, with a low thermal resistivity made by Pirelli, arranged in 5 layers of 61 turns around a cylindrical core made of carbon steel AISI 1015. The ferromagnetic core is commonly used for screws and bolts production. Indeed, it shows a good magnetic relative permeability around thousand, an high saturation level (about 2.3T) and low hysteresis. These properties arise from low carbon level (typical value is about 0.15%) and negligible nickel level.

Turns are not into direct contact with the core, but they are separated by a rubber support covered with a layer of Nomex which is a special insulating material for voltage transformers. This precaution assures a good thermal and electrical isolation. In order to minimize the dispersed flow beyond the workspace and to guarantee the safety of the user, the solenoids are connected together by means of a AISI 1015 steel ring. By separately tuning the current flowing into the 16 coils, it is possible to reproduce figures with desired shape and compliance.

A roughly control system is obtained by manually acting on 32 switches: every couple of switch allows to establish the current direction in the coils and to turn on and off each solenoid.

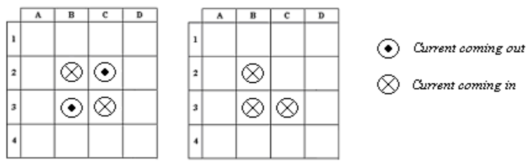
A real time control is obtained by using two acquisition cards interfaced to a computer. One is used as input card to acquire signals from Hall sensors and the other as output with 16 analogic channels. The output signals are used to drive a power circuit able to generate high current values for the solenoids. Basically, the circuit is a voltage-current converter, where a high gain operational amplifier supplies a final push-pull section implemented by using C-Mos components. As Hall Sensor we chose UGN3503U, produced by Allegro for reliability and cheapness. Moreover, it provides a voltage signal proportional to the magnetic flux enclosed by the sensors plan. The calibration of the system is performed by placing Hall sensors at 16 quantized points. Such a configuration can be realized either in air or in the fluid; in the latter case Hall sensors have to be previously protected.

5. Experimental tests

We performed several psychophysical tests in order to qualitatively assess performances of the system. Experimental results are only of preliminary nature but intend to show promising requirements for a next quantitative investigation which will be done in future developments. The experimental protocol is based on 50 volunteers which were asked to perform a manipulation task and the scheme used is the VSM. All volunteers wear a latex glove and can immerse their hand in the haptic box interacting with the MR fluid duly excited. Each subject did not undertake preliminary training, but came for the first time into contact with the fluid while performing tests.

5.1. Position recognition

This experiment is provided for evaluating the spatial discrimination of a point stiffer than the others ones. Workspace can be represented as a 4x4 elements of a matrix. Each point is identified by a solenoid. A point within the box was chosen and the corresponding solenoid was activated. The selection is made by chance avoiding choosing a point near the boundaries of the box in order for not providing helpful cues. The group of 50 volunteers was asked to identify the coordinates of the point perceived as stiffer. The surface of the box is 18cm x 18cm, while the diameter of a single solenoid is 4.5cm. Of course, the resolution is rough, but the percentage of correct recognition was 100%. Moreover, subjects



(a) **(b)**

Figure 6. Simulation of the distribution of the magnetic field in the active region of the HSM (a) and VSM (b) configurations realized by using a CAD analysis tool based on FEM.

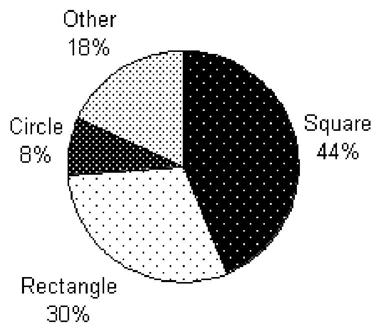


Figure 7. Pie chart showing the percentage of shapes recognized by volunteers when four contiguous solenoids are activated.

answered quickly and doubtless. To excite the fluid we chose a middle value of magnetic field because we aimed at identifying the shape and not at discriminating the softness.

5.1.1. Discussion. This experiment has no pretensions to have high relevance for evaluating the resolution of the system, because the diameter of each solenoid is too big with respect to the overall dimension of the box. It was very hard to make a mistake in locating the point, but the entirely successful results act as a launching pad for next promising developments.

5.2. Shape recognition

Another test was based on the ability of the system to produce a given shape. Two simple figures were selected and reproduced by suitably exciting a certain number of solenoids. Volunteers were asked to manipulate the MR fluid and freely describe the shape perceived without receiving suggestions. The first figure reproduced was a square obtained activating four solenoids in the middle of the box (see Fig 6a). Indeed, the real figure is an intermediate shape between the square and the circle. Subjects we asked to freely describe the figure perceived

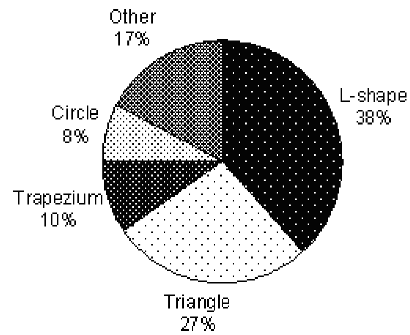


Figure 8. Pie chart showing the percentage of shapes recognized by volunteers when three contiguous not aligned solenoids are activated.

without reference frameworks. Results have to be interpreted on the basis of qualitative considerations.

The figure we would reproduce was regular and symmetric and as the spatial resolution is quite low, we can accept as good all answers of the subjects that refer to a geometric shape having these properties. In particular we can consider equivalent the circle, the square and the rectangle. We can tolerate the mistake between the square and the rectangle as an uncertainty on the length side of the figure depends on the tactile artefact during the manipulation. Summarizing, 82% of the subjects recognized a figure similar to that one produced. The remaining volunteers described a regular figure but quite unlike the real figure, such as hexagon, parallelogram, rhombus, or triangle. Results are very encouraging (see Fig. 7), but much work has to be done in order to increase the spatial resolution.

Afterwards, we excited three solenoids such as in Fig. 6b. The shape of the figure so realized could be described as a triangle, L-shaped or trapezium. By assuming equivalent the responses of these types we obtained results depicted in Fig. 8. Even in this case, results can be considered satisfactory because by means of a tactile manipulation, subjects freely described a shape very similar to that desired one. Adding the percentages of the responses relative to L-shape, triangle and trapezium we obtain 75% of correct answers.

5.2.1. Discussion. This experiment is performed in support of the possibility of reproducing an object by a given shape. The rough resolution does not help to accurately define contours, but even in this case our goal was to test the ability of giving an idea of the shape. Further improvements will led us to have an higher resolution and a better discrimination. It has been shown in literature that during haptic exploration information regarding object properties are remarkably defined by global shape cues.

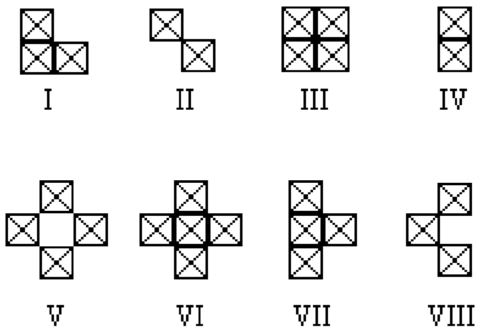


Figure 9. Set of figures from which subjects could choose the perceived shape differently oriented during the tactile manipulation of the MR fluid.

Generally, shape information is easily extracted by visual means, whereas to gather this information haptically requires execution of the "contour following" exploratory procedure (EP) (Lederman & Klatzky, 1987) [15]. Our system aims at improving the softness discrimination task proving further information about the shape and the texture.

5.3. Recognition of the shape and orientation

This experiment is strictly correlated to the previous one. Even in this case subjects were asked to recognize the shape produced by the MR fluid, but now they have to choose among a predetermined set of figures (Fig. 9) with the addition of indicating the orientation of the figure which could be different from that represented in Fig. 9. Indeed, the reproduced shape could be rotated and subjects were required to indicate the orientation degree as well. Referring to Fig. 9 shapes reproduced were I, II, IV, V, VII and VIII. The percentages of correct recognition of the shape and orientation were 76%, 96 %, 85%, 80%, 81% and 93%. Results are very satisfactory.

5.3.1. Discussion. Some considerations have to be done. Figures II and VIII are multiply connected. Generally, a curve C in the complex plane is said to be simple if it does not cross itself. It is said to be simple closed if it is simple and its starting point and terminal point coincide. A region D in the complex plane is said to be simply connected if every simple closed curve C in D encloses only points of D, otherwise the region is said to be multiply connected. Figures multiply connected are more easily identified than those simply connected. This is due to the ability to distinguish the geometry of different parts linked to few points. The high percentages of successful recognition are due to the fact that the shape perceived could be compared with a set of figures, since some uncertainty was easily removed by exclusion. However, this test is very significant because the changed orientation could deceive and make mistakes. Therefore results are very promising for next developments.

6. Conclusions and future work

The system we have described is a prototypal device of a haptic interface. Unlike kinesthetic displays present in literature our system allows a direct contact with a compliant object. In this case both kinesthetic and cutaneous channels of the fingerpads are stimulated during the manipulation and tactile perception is augmented. Psychophysical tests, even though of preliminary nature, show that system is promising. Much work has to be done in order to better control the system such as to provide desired shape and compliance and increase the spatial resolution. Next developments will concern the increasing of the number of solenoids and the reduction of their sizes that will result in a higher spatial resolution. Moreover a quantitative characterization of the system and an implementation of different control strategies will be performed. Our goal is to realize a system able to simulate in real time the rheology of a virtual object by acting both on the shape and the softness. To do this, the control strategy will tune dynamically the magnetic field generated by solenoids placed in suitable positions. Also, a quantitative study from a psychophysical point of view has to be done. Several parameters have to be evaluated such as PSE (Point of Subjective Equality), JND (Just noticeable Difference) or Psychometric Function in order to give utmost accuracy to psychophysical investigation.

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