Towards a Haptic Black Box for Free-hand Softness and Shape Exploration

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Abstract

In this paper we propose an innovative prototype of a haptic display for whole-hand immersive exploration. We envision a new concept of haptic display, the Haptic Black Box concept, which can be imagined as a box where the operator can poke his/her bare hand, and interact with the virtual object by freely moving the hand without mechanical constraints. In this way sensory receptors on the whole operator's hand would be excited, rather than restricting to just one or few fingertips or phalanges. To progress towards such a challenging goal, magnetorheological (MR) fluids represent a very interesting technology. These fluids are composed of micron-sized, magnetizable particles immersed 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. By removing the magnetic field, the fluid quickly returns to its liquid state. We briefly report on the design of this device, describe psychophysical experiments to assess performance for softness and shape exploration, and report on the experimental results.

1 Introduction

In many applications, the ideal haptic display would be such as to allow the operator to interact with the virtual object by freely moving his/her hand without mechanical constraints, and exciting sensory receptors on the whole operator's hand, rather than on just one or few fingertips or phalanges. Accordingly, a completely new approach to the design of haptic displays, the Haptic Black Box concept, can be envisioned. A HBB can be imagined as a box in which the operator can poke his/her bare hand, and where virtual objects materialize and move under computer control according to interactions with the operator and the virtual environment (see Fig.1). An application that would greatly benefit from the availability of a HBB display is clearly the training of operators to open surgery operations. An implementation of an HBB would consist of a controlled volume in which the material properties at each point can be tuned independently by some non-intrusive means. Clearly, the HBB concept is rather futuristic at this stage. However, to progress towards such a challenging goal, MR fluids represent a very interesting technology enabling at least some simplified form of HBB.

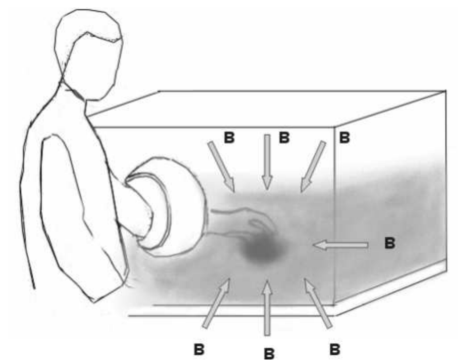

Figure 1: A schematic representation of a HBB MR fluid based display.

A magnetorheological (MR) fluid is a material that responds to an applied magnetic field with a change in its rheological behaviour. Typically, this change is manifested by the development of a yield stress that monotonically increases with the applied field, and with a change of viscoelastic properties of the material within the pre-yield state. Just as quickly, the fluid can be returned to its liquid state by the removal of the field. MR fluids are readily available on the market, although their application field is currently restricted to devices such as valves, brakes, clutches, and active dampers. We report here about the possibility to use MR fluids to mimic the compliance, damping, creep (in other terms the rheology) of different materials, in order to realize a haptic display. Usage of MR fluid for haptic displays can be a viable solution in a limited number of important applications: indeed, the range of viscoelastic parameters that can be mimicked by magnetically tuning the rheological properties of currently available fluids, closely resembles that encountered in biological tissues. Accordingly, an elective

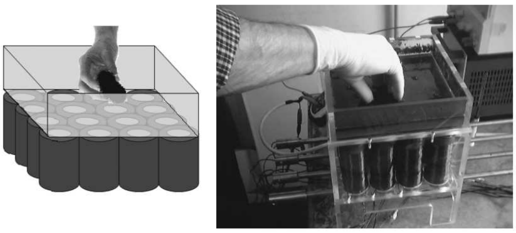

Figure 2: A Haptic Black Box preliminary implementation uses 16 solenoids arranged beneath the lower face of the box to excite the magnetic field in the HBB.

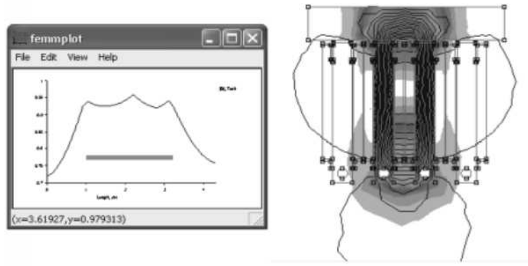

Figure 3: FEM-CAD simulation of the distribution of magnetic field in the region above two contiguous solenoids.

field of application for MR fluid-based haptic displays is surgical training, in both minimally invasive and open surgery. A possible implementation of MR fluids is addressed to open surgery simulators, whereby the operator would interact with his/her free hand with virtual replicas of whole organs or complex surgical environments. In this scenario, the operator's hand would be "immersed" in the virtual environment and would receive tactile information from all its parts, including the inner phalanges, palm, and back of the hand. After briefly reporting on the design of these devices, in this paper we describe psychophysical experiments to assess the capability of discriminating shape and compliance of virtual objects, and the experimental results thus obtained.

2 The MRF-HBB prototype

The MR HBB prototype realized in our laboratory consists of a volume of MR fluid placed within a Plexiglas box where a hand can be introduced (through a sealed glove opening) to interact with the fluid. The viscoelastic parameters of the fluid in different regions of the control volume can be changed by suitably controlling the modulus of the magnetic vector field in that region. Although MR fluids only allow one-degree-of-freedom variations in their rheologic behaviour, this is sufficient to create differentials in compliance and plasticity, which can trigger the sensation of touching different objects within the HBB. Clearly, the realism of the display varies with the resolution by which we can control the intensity of the magnetic field in each point of the box. Our current, preliminary implementation only addresses the display of simple 2-D patterns by controlling the magnetic field in the MR fluid using 16 solenoids arranged underneath the lower side of the box (see Fig.2). In Fig.3, results from the simulation of the magnetic field distribution are reported. Crucial aspects of the design were mechanical and electrical sizing, to focus the magnetic flux into specific regions of the MR fluid, maximizing the magnetic field energy in this region and minimizing energy loss through stray paths, avoiding overheating, and limiting currents. In this paper we investigate the ability to create tactile images of different shapes, and discriminate different levels of compliance in a single region.

3 Experimental results

Experiments aim at exploring the HBB display to be able to provide tactile sensations in order to discriminate shape and compliance of virtual objects. 50 volunteers were asked to interact with the HBB display from time to time and required to describe sensations perceived. In the first phase the capability from the HBB display to allow subjects to recognize different shapes of objects variously oriented is assessed. Next, volunteers were asked to identify different level of virtual compliance. Finally, few psychophysical parameters have been evaluated.

3.1 Position Recognition

A preliminary experiment introducing the experimental session relative to the shape discrimination was performed. The goal was to locate a point perceived as stiffer within the matrix of the HBB. Since workspace can be represented as a 4x4 elements of a matrix, each point is identified by a solenoid. In order to avoid providing helpful cues, a point within the box, but far from boundaries of the box was chosen by chance and the corresponding solenoid was activated. A group of 50 volunteers was asked to interact with the fluid and identify coordinates of the point perceived as stiffer. In this preliminary version of the prototype the spatial resolution is quite rough. On this account, we expected from this experiment successful results. Indeed the percentage of correct recognition was 100%. Moreover, subjects answered quickly and doubtless.

3.1.1 Discussion

This experiment is of preliminary nature for probing the capability of the device to allow subjects to univocally identify one point. The quite low spatial resolution of the display minimizes the probability to make a mistake in locating the point, but the entirely successful results act as a launching pad for next promising developments.

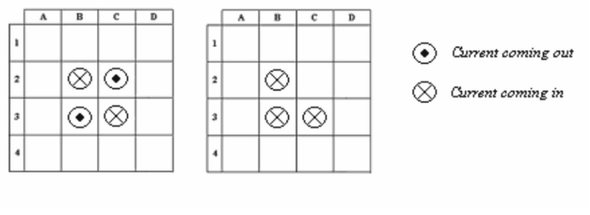

Figure 4: Set of solenoids activated in order to produce different shapes.

3.2 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 combination of solenoids. Volunteers were asked to manipulate the HBB display 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.4). Actually, the real figure is an intermediate shape between square and circle. Subjects were asked to freely describe the figure perceived 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 referring to a geometric shape having these properties. In particular we can consider equivalent, in this context, circle, square and rectangle. We can tolerate the mistake between square and rectangle, since 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. 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.5), but much work has to be done in order to increase the spatial resolution. Afterwards, we excited three solenoids such as in Fig.4. The shape of the figure so realized could be described as a triangle, L-shaped or trapezium. By assuming equivalent responses like these we obtained results depicted in Fig.6. Even in this case, results can be considered satisfactory. Adding the percentages of the responses relative to L-shape, triangle and trapezium we obtain 75% of correct answers.

3.2.1 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 the display to give 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. Generally, shape information is easily extracted by visual means, whereas to gather this information haptically requires execution of the "contour following" exploratory procedure. Our system aims at improving the softness discrimination task proving further information about the shape and the texture.

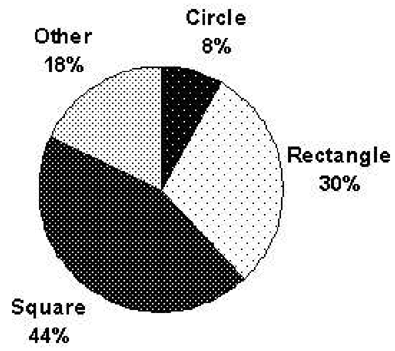

Figure 5: Pie chart showing the percentage of shapes recognized by volunteers when four contiguous solenoids are activated.

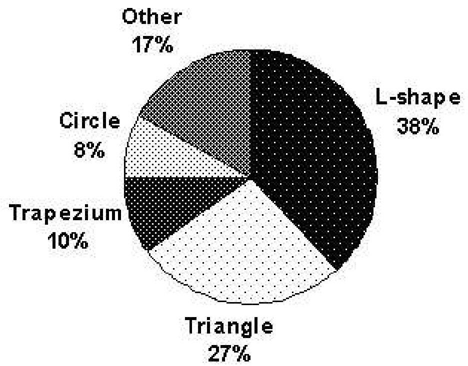

Figure 6: Pie chart showing the percentage of shapes recognized by volunteers when three contiguous not aligned solenoids are activated.

3.3 Shape and orientation recognition

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 the choice had to be made within a predetermined set of figures (Fig.7). Also subjects were required to indicate the orientation of the figure which could be different from that represented in Fig.7. Referring to Fig.7 shapes reproduced were I, II, IV, V, VII and VIII. The percentages of correct recognition of the shape

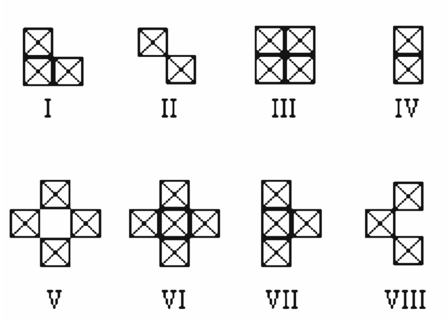

Figure 7: Set of figures from which subjects could choose the perceived shape differently oriented during the tactile manipulation of the MR fluid.

Figure 8: Experimental Setup: training on 4 specimens.

and orientation were 76%, 96%, 85%, 80%, 81% and 93%. Results are very satisfactory.

3.3.1 Discussion

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, hence some uncertainty was easily removed by exclusion. However, this test is very significant and promising because the changed orientation could deceive and make mistakes.

3.4 Compliance recognition

This experiment aimed at assessing the capability of subjects to discriminate different virtual objects by their softness. Four specimens at different compliance (Fig.8) have been chosen. Since texture is a relevant cue for discriminating materials, specimens were coated with a thin layer of latex (Fig.9). We used two different type of foam, a flock of cotton and a small ball of steel wool, all cut in the same size and shape (about 2cm x cm). The group of 50 volunteers could preliminary manipulate specimens without seeing them and he was asked to rank them in terms of compliance. 100% of subjects recognized the correct stiffness scale. Next, volunteers were asked to touch the MR fluid displays while an assistant gradually changed the magnetic field. In order to focus the attention only on the compliance property disregarding the shape, just one location was excited corresponding to one solenoid (Fig.10). Subjects indicated

Figure 9: Experimental Setup: softness blind recognition.

the closest level of compliance perceived for each specimen. Through this empirical approach we obtained a set of four virtual objects mimicked by MR fluids-based display. Once completed the calibration phase, virtual objects were submitted to volunteers in random order. To make the experiment as general as possible subjects were informed that they could be presented with virtual objects that did not belong to the specimen set, and that one repetition of the same specimen was allowed. Each trial sequence, therefore, implied 6 virtual objects presented to each volunteer. In Fig.11 the percentage of successful recognitions of the six virtual objects is reported.

3.4.1 Discussion

Results are rather good for both devices. Percentage of successful recognition is on the average more than 70% for all virtual objects. Next developments aim at combining shape and compliance enhancing softness discrimination tasks.

3.5 Just Noticeable Difference (JND)

The Just Noticeable Difference, or simply JND, is a measure of differential sensitivity, i.e. the smallest in-

Figure 10: In the compliance recognition experiment, a small volume of MR fluid is controlled by one of the solenoids and probed directly by the subjects.

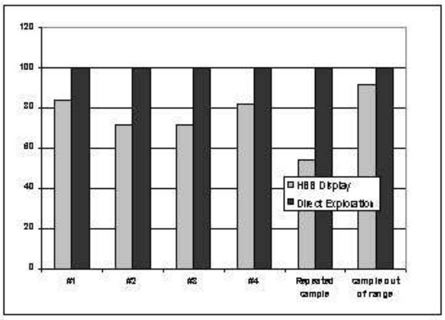

Figure 11: Compliance estimation: percentage of successful recognition on 6 virtual objects.

crement or decrement of stimulus for a difference to be perceived by the subject. The methodology consists in presenting a couple of stimuli and evaluate the appreciation of the difference in sensation. In order to experimentally estimate the JND versus the intensity of stimulus we used the Method of Adjustment (MOA) in which the subject adjusts the intensity until the difference in sensation is judged to be "just noticeable". For both devices, we divided the operating range of the magnetic field into 10 points. Stimulus intensity in this experiment ranged from zero to the saturation level of the MR fluid. Starting from each point, the magnetic field was continuously varied recording the value indicated by the subject as soon as he perceives a discrimination in sensation. Mean JND and its standard deviation for each reference stimulus was calculated for each subject, and data were averaged over the 50 subjects. Results are presented in Fig.12 along with the corresponding error bars. Through linear interpolation of the middle part of the curve, it is possible to evaluate a Weber constant of 0.08. Average values of Weber's constants are available in the

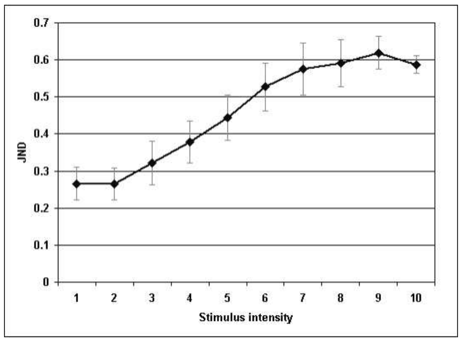

Figure 12: Just noticeable difference versus stimulus intensity for HBB display. Standard deviation relative to average value is reported as well.

psychophysical literature for most common perceptual channels, among which the two most relevant to our purposes here are = 0.013 for diffused tactile stimuli, and k=0.136 for punctual tactile stimuli (this numbers indicate the rapid saturation of receptors involved in single-point tactile perception). Weber's fraction we have found is hence compatible with values available in literature.

3.6 Psychometric function

Another parameter on which we focused our attention is the psychometric function, a measure of sensorial resolution widely used in psychophysical studies. The experiment consists of asking volunteers to compare virtual compliance of MR fluid in two successive trial. The working range of the magnetic field was segmented into 10 points. In the first trial, volunteers were asked to manipulate the HBB display excited by the middle stimulus in the range and this is referred as reference stimulus. In the latter volunteers were asked to tell whether the compliance perceived by touching the MR displays when excited by a magnetic field chosen by chance within the working range, was "harder" than the reference stimulus. The number of positive answers divided by the total number of answers is denoted by the probability that the perceived stimulus was greater than the reference stimulus. As the current stimulus was varied from lower to higher values than the reference stimulus, the psychometric function was obtained. In the ideal case of an infinitely fine resolution in the sensory channel, the psychometric function would be a step function. Results are reported in Fig.13.

3.6.1 Discussion

In order to avoid that the subject knows which intensity of the stimulus to expect from trial to trial (e.g. either a slightly stronger stimulus, in ascending series, or a slightly weaker one, in descending series we adopted the Method of Constant Stimuli (MOCS). In this case the order of presentation of the stimulus

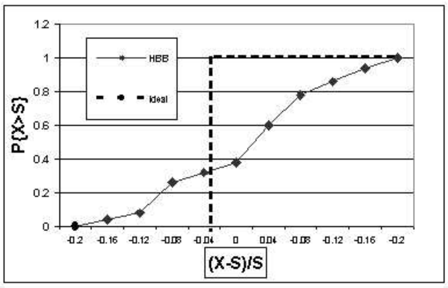

Figure 13: Psychometric Function of HBB displays level S is the reference stimulus and X is the current stimulus to be compared.

is randomized, so the subject cannot guess in advance the intensity of the stimulus. The discrepancy between the ideal step function and the experiments can be quantified by the sum of the squares of deviations from the ideal, stepwise curve, namely by the figure

$$D = \sum_{i=1}^{5} P_i^2 + \sum_{i=6}^{11} (1 - P_i)^2$$

In ideal case this figure is equal to zero. In real case a device is as effective about sensorial resolution as this figure approaches zero. The HBB display shows a parameter equal to 0.55.

4 Conclusions and future work

In this paper we explored the possibility of implementing haptic interfaces by using magnetorheological fluids. Unlike kinesthetic displays present in literature this type of haptic interface would allow 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. We envisioned a prototype of MR fluid-based haptic display. Although results are very satisfactory much work has to be done in order to make the display able to simulate in real time the rheology of a virtual object by acting on both shape and softness. Indeed, 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. Next developments will progress towards this direction.

References

[1] G. Ambrosi , A. Bicchi, D. De Rossi, and P. Scilingo, "The Role of Contact Area Spread Rate in Haptic discrimination of Softness", Proceedings of the 1999 IEEE International Conference on Robotics and Automation, Detroit, Michigan, may 1999, pp. 305-310.

[2] A. Bicchi, E.P. Scilingo, N. Sgambelluri, and D. De Rossi, "Haptic Interfaces based on magnetorheological fluids", Proceedings 2th International Conference Eurohaptics 2002, Edinburgh, july 2002 , pp.6-11.

[3] G. Bossis and E. Lemaire, "Yield Stresses in Magnetic Suspensions," Journal of Rheology, 1991, Vol. 35(7), pp. 1345-1354.

[4] G. Burdea, and P. Coiffet, Virtual Reality Technology. John Wiley and Sons: New York, NY.

[5] J.D. Carlson, "The Promise of Controllable Fluids." Proc. of Actuator 94 (H. Borgmann and K. Lenz, Eds.), AXON Technologie Consult GmbH, 1994, pp. 266-270.

[6] J. C. Falmagne: "Psychophysical Measurement and Theory", in Handbook of Perception and Human Performance, K. R. Roff, L. Kaufman, and J. P. Thomas, USA, eds., Wiley Interscience Publ., 1986, Vol. I, chapt. 1, pp 1-66.

[7] Fedorov, "Features of Experimental Research into the Characteristics of Magnetorheological and Electrorheological Shock Absorbers on Special Test Stands." Magnetohydrodynamics, 1992,Vol. 28, No. 1, p. 96.

[8] A.M. Kabakov, and A.I. Pabat, "Development and Investigation of Control Systems of Magnetorheological Dampers." Soviet Electrical Engineering, 1990,Vol. 61, No. 4, p. 55.

[9] B.E. Kashevskii, "Relaxation of Viscous Stresses in Magnetorheological Suspensions" Magnetohydrodynamics, 1990, Vol. 26, No. 2, p. 140.

[10] W.I. Kordonsky, (1993a), "Elements and Devices Based on Magnetorheological Effect." Journal of Intelligent Material Systems and Structures, 1993a, Vol. 4, No. 1, p. 65.

[11] W.I. Kordonsky (1993b), "Magnetorheological Effect as a Base of New Devices and Technologies." Journal of Magnetism and Magnetic Materials, 1993b, Vol. 122, No. 1 / 3, p. 395.

[12] S. J. Lederman, and R. L. Klatzky, "Hand movements: a window into haptic object recognition", Cognitive Psychology, 1987, 19:342-368.

[13] E.P. Scilingo, A. Bicchi, A. De Rossi, A. Scotto, "A magnetorheological fluid as a haptic display to replicate perceived compliance of biological tissues", 1st Annual International IEEE-EMBS Special Topic Conference on Microtechnologies in Medicine & Biology, Lyon, France, October 12-14, 2000.

[14] B.F. Spencer, S.J. Dyke, M.K. Sain and J.D. Carlson, "Phenomenological Model of a Magnetorheological Damper", Journal of Engineering Mechanics, ASCE, 123, 1997, 230-238.

[15] M.A. Srinivasan, R.H. LaMotte, "Tactile Discrimination of Softness", Journal of Neurophisiology, 1995, Vol. 73, No. 1, pp. 88-101.