Advanced modelling and preliminary psychophysical experiments for a free-hand haptic device

Nicola Sgambelluri, Enzo Pasquale Scilingo and A. Bicchi
Interdepartmental Research Center ”E. Piaggio”
University of Pisa Via Diotisalvi, 2
56126 Pisa, Italy
Email: bicchi@ing.unipi.it; n.sgambelluri@ing.unipi.it;
e.scilingo@ing.unipi.it

Rocco Rizzo, Marco Raugi
Department of Electrical Systems and Automation
University of Pisa Via Diotisalvi, 2
56126 Pisa, Italy
Email: rocco.rizzo@dsea.unipi.it, Marco.Raugi@dsea.unipi.it

***Abstract*— In this paper we report on a new improved free-hand haptic interface based on magnetorheological fluids (MRFs). MRFs are smart materials which change their rheology according to an external magnetic field. The new architecture here proposed results from the development and improvement of earlier prototypes. The innovative idea behind this device is to allow subjects interacting directly with an object, whose rheology is rapidly and easily changeable, freely moving their hands without rigid mechanical linkages. Numerical advanced simulation tests using algorithms based on finite element methods have been implemented, in order to analyze and predict the spatial distribution of the magnetic field. A special focus was laid on investigating on how the magnetic filed profile is altered by the introduction of the hand. Possible solutions were proposed to overcome this perturbation. Finally some preliminary psychophysical tests in order to assess the performance of the device are reported and discussed.**

I. INTRODUCTION

In tactile manipulation of real objects humans use their hands to grasp, squeeze, or indent the surfaces, and gather data from many sensory receptors lying in the skin. These receptors are ascribable to two broad functional sensory channels called kinesthetic and cutaneous sensors [7]. Kinesthetic sensors are responsible for detecting kinematic parameters, such as position, velocity and acceleration of joints, while cutaneous channels are elicited by the mediation of the mechanoreceptors innervating the derma and epidermis of the fingerpads. The synergistic combination of these two types of information gives rise to so called “haptic” perception [10]. Likewise, in designing artificial haptic interfaces both these channels should be addressed. In this paper we propose a novel concept of haptic interface allowing users to interact with 3D virtual objects moving freely their hands. Indeed, holding the hand unconstrained during manipulation and removing perceptual artifacts generated by wearing heavy and/or cumbersome exoskeletons or by dealing with rigid linkages softness discrimination is much better guaranteed. When instruments or rigid elements mediate tactile perception, the sense of touch is reduced as well as the dynamics and control of manipulation. In this paper we report on a new improved haptic interface based on MRFs, able to mimic the rheology of objects. MRFs are smart material, whose viscosity can be reversibly and quickly changed by an external magnetic field. Unlike kinesthetic displays present in literature the device here proposed allows a direct contact with an object whose compliance can be easily modulated. In this case both kinesthetic and cutaneous channels of the fingerpads are stimulated during the manipulation and tactile perception is augmented. Several prototypes based on MRFs have been already designed by the authors [2], [12]. Here the improved latest version is proposed and described.

MRFs consist of an oil-based solution in which micron-sized magnetically active particles are dispersed [4], [15]. In normal conditions particles are randomly distributed and the fluid exhibits a Newtonian behaviour [8], [9]. When an external magnetic field is applied, particles align themselves along ordered chains and the fluid assumes a near solid configuration. Rheologically this change is manifested in the development of a yield stress which can be modulated by the magnetic field [11]. This phase transition occurs in few milliseconds [3]. Indeed, turning off the magnetic field the fluid returns very quickly to its original (fluid) state. This interesting property suggested us the possibility of using these fluids to mimic the rheology of some viscoelastic materials and to realize haptic displays. A general immersive MRF-based scheme, so-called Haptic Black Box (HBB) display [13], [14], can be imagined as a box containing a given volume of the MRF in which a controlled and distributed magnetic field is suitably generated. An operator ideally can poke his/her bare hand inside the HBB and, without mechanical constraints, he can freely feel virtual objects materialized and moved under computer control in the environment. The viscoelastic properties of the MRF specimen can be modulated by an external magnetic field producing a desired object having different shape and softness. This interesting property suggested us the possibility of using these fluids to mimic the rheology of some viscoelastic materials, such as biological tissues [12]. In this way a field of application for MRFs-based displays could be surgical training, in open surgery and minimally invasive

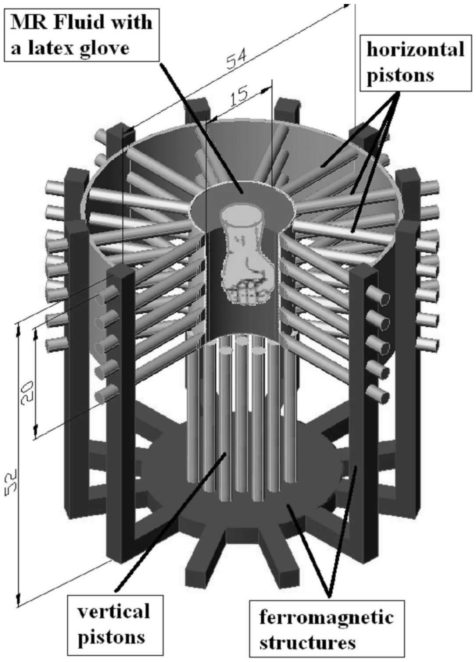

Fig. 1. Architecture of the new HBB-II device with main dimensions.

surgery.

II. ADVANCED MODELLING

On the basis of these considerations a new advanced device, which we called Haptic Black Box II (HBB-II) [1], capable of overcoming many limitations of the previous prototypes has been designed and built. The novel device presents a cylindrical-shaped plastic box containing the MRF and a series of ferromagnetic cores, positioned in aureole shape around the plastic box and used to dynamically address the magnetic flux inside the fluid. Furthermore, the presence of a latex glove inside the cylindrical plastic box allows to discriminate shapes and compliance of the virtual objects.

A. Hardware description

Figure 1 shows a schematic view of the new device with its main dimensions. The MRF is contained into a plastic box which is cylindrically shaped for the sake of symmetry of the system. Then, in order to allow subjects to freely handle the fluid, the box is internally equipped with a latex glove. However, the box has dimensioned to allow easy accessibility to the fluid, and, at the same time, minimize the magnetic reluctance. It has a circular base with a diameter of about 15 cm and a height of about 50 cm. The ferromagnetic structure is used to close and address the magnetic flux. It is composed of 10 vertical columns bolted to an iron circular plate and a series of 66 pistons, properly positioned in the system and free to move along a fixed trajectory with respect to the plastic box containing the MRF. Sixteen of such pistons are arranged in a matrix form of 4×4 below the box base; the remainder fifty, arranged in series of 10×5 are placed in aureole form around the lateral surface of the plastic box. They are constrained to run into special hollow cylinders placed at the top of each column. Cores are made of ferromagnetic material (carbon steel C40) with high magnetic permeability and with a high magnetic saturation threshold in order to reduce the transversal sections. Then, taking into account such a saturation threshold, the iron plate has a diameter of about 30 cm and a height of about 1.5 cm; each column has a base diameter of about 4.5 cm and a height of about 35 cm; and each piston has a base diameter of about 2 cm and a height of about 15 cm. The coils are arranged to produce the proper magnetic field for the energization of the MRF. In the system there are two types of coils. A group of coils are positioned around the inferior part of the columns and used to create the main magnetic field (the so-called primary-coils) and another group is placed around the 66 pistons and used for a fine control of the field resolution (the so-called secondary-coils). Each primary-coil is built with about 5300 AmperTurns of enamelled copper wire, with a low thermal resistivity, arranged in 11 layers of 50 turns around a hollow plastic cylindrical support of an inner diameter of 46 mm and total length of 110 mm.

The secondary-coils consist, instead, of about 2800 AmperTurns, arranged in 5 layers of 54 turns around a hollowed plastic cylindrical support of an inner diameter of 21 mm and total length of 150 mm. The electrical resistance of a coil is $0.25\ \Omega$ at 27^oC. All the coils are connected to an external electronic power system, described in the next section, to obtain the desired magnetic field in different regions of the fluid. Finally a control system manages the current flowing into each coil for a double purpose. On electrical side it adjusts the value of current for a direct modulation of the magnetic field; on mechanical side, the current in each coil allows to move the pistons within the plastic cylindrical guide. This stroke goes from the column to the lateral surface of the plastic box containing the MRF. The piston recovers its initial position by the effect of a return spring. In Figure 2 a picture of the device is reported.

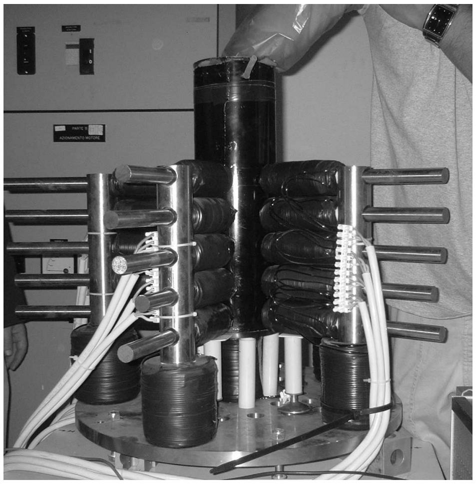

Fig. 2. Picture of the HBB-II during an experimental trial.

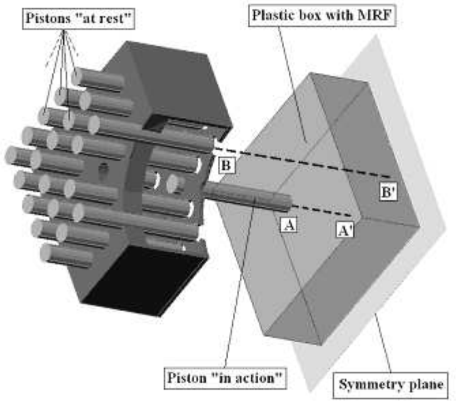

Fig. 3. MRF energization principle of HBB-II: particular of piston mechanism.

B. Working principle

The advanced version of the haptic device operates in the following way. Let us suppose to create a figure such as a little hemisphere of MRF at the basis of the box, or along its lateral surface, or a cylinder of MRF with the axis along the radial direction at different height in the plastic box, or whatever else. To obtain the desired geometry, a set of neighboring solenoids has to be activated, by injecting impulsively current into the relative coils. Thus, tuning the current in the coils belonging to the cores which compose the magnetic path, it is possible to change the rheology of the fluid and obtain different compliance. When all the pistons are at rest (far from the plastic box), the reluctance of the magnetic path, closed along the line B-B' and shown in fig. 3, is very high and the value of flux in the fluid is neglectable; on the contrary, when two or more pistons are ”in action” (close to the plastic box), the gap along the magnetic path A-A' is reduced implying an increase of magnetic flux in the volume of fluid corresponding to the active pistons. In summary, the modulus of the magnetic field in a specified portion of the MRF and its spatial resolution can be controlled acting both electrically, varying the value of the current flowing into some coils, and mechanically, moving the pistons. In such a way, it is possible to reconstruct many objects of different shapes in different zones inside the box containing the fluid.

III. ADVANCED SIMULATION

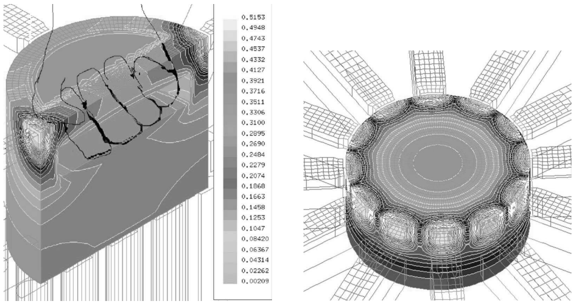

Fig. 4. Numerical simulation of HBB-II display: Flux density at the middle plane of the fluid when 2 opposite pistons operate (on the left side) and when all the pistons of the plane operate (on the right side).

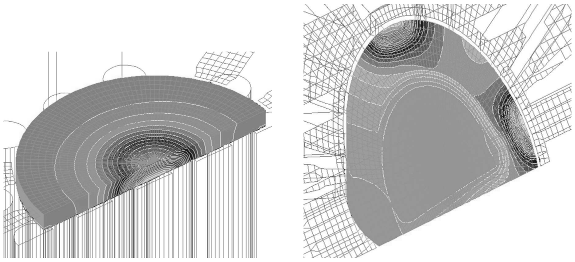

Fig. 5. Numerical simulation of HBB-II display: Flux density at the base of the fluid when the central vertical piston operate (on the left side) and when two non-adjacent pistons are activated (on the right side).

The device was simulated by means of algorithms based on finite element methods[5][6], in order to know which solenoids have to be activated to produce a specific magnetic field distribution. Different 3D simulations were implemented. Figure 4 reports on the left side the numerical simulation of the HBB-II display when two opposite solenoids in the middle of the box are activated. The flux density distribution shows that a cylinder, which can be grasped by the hand, is achievable. The chromatic scale on the left side displays the intensity of the magnetic field in the region facing the two solenoids. On the right side of the same figure is shown how the magnetic flux density is distributed in the space when all the pistons lying on the same plane are stimulated. In this case, several lateral lobes, one for each solenoid, running along the circumference of the box are distinguishable. Further simulation test results are reported in Figure 5. Here, on the left side, the flux density at the base of the box when the central vertical piston operates is represented. The figure generated by this configuration is a concentrated central region with higher magnetic field. Finally, on the right side of the same figure the flux density in a generic plane of the fluid when two non-adjacent pistons are activated is depicted. In this case two stiffer bumps are created in the proximity of the two active solenoids.

The simulation tool has played a twofold role. It helped us to optimize size and distribution of solenoids in order to maximize the magnetic field and reduce losses, but also represented an effective mean to identify which solenoids have to be activated to produce a given magnetic field distribution resulting in a figure having assigned shape and compliance.

A. Interaction between the operator hand and the MRF

The MRF-based device, as described in the previous sections, is equipped with a latex glove allowing an unconstrained interaction between the operator hand or fingers and the fluid inside the box. However, as the hand (wearing the glove) and the MRF have different magnetic characteristics, it is necessary to verify what happens during the interaction. For the sake of simplicity and taking into account that the formulation of the problem can be easily extended to a more general case, we focused our analysis on an earlier simplified prototype, which

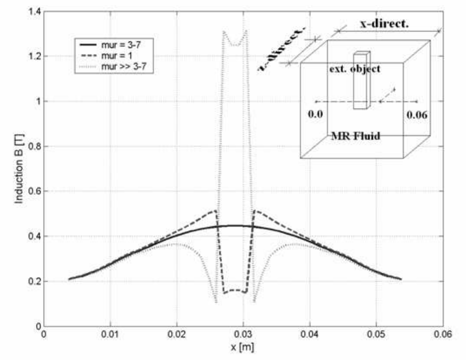

Fig. 6. Induction B along x-direction when an object with different magnetic permeability is inserted in the fluid.

allows subjects to use their thumb and index finger in pinch grasp manipulation [14]. In this prototype, the MRF is placed within the air gap of an electromagnet, inside a plastic tray. Before investigating the hand-MRF interaction, a preliminary analysis has been performed simulating the insertion in the fluid of a little object with magnetic characteristics different from those of the fluid. From a magnetic point of view, the MRF magnetic permeability varies in a range between about 3 and 7, depending on the operating point. When an external object is inserted into the fluid, the magnetic path is perturbed inducing an increase or decrease of the magnetic flux density in the regions surrounding the object. Figure 6 shows the three profiles of the magnetic flux density B in the central zone of the fluid, obtained with three objects having $\mu_r = 1$, μ_r ranging from 3 to 7 and $\mu_r \gg 7$, respectively. The magnetic permeability $\mu_r \in [3, 7]$ refers to the fluid, hence is equivalent to the configuration without the object. The figure reports the behaviour of the flux density along the direction parallel to x axis. As it can be seen, when an external object having magnetic permeability different from that of the fluid, the magnetic field is dramatically modified. In order to investigate a more realistic case, the system has been analyzed simulating the insertion in the fluid of two operator fingers ($\mu_r = 1$) during a pinch grasp manipulation as schematically shown in Figure 7. Figure 8 and 9 show the profiles of the magnetic field along two orthogonal directions for the simulated model. As it can be seen, the difference between the values of field in the ideal case (absence of fingers inside the fluid) and in the analyzed case (two fingers inside the fluid) is about $20-22\%$. As the device should satisfy the requisite of a good field uniformity, also under different conditions, the perturbation due to the presence of objects in the fluid has to be attenuated.

Two possible solutions were proposed to attenuate this perturbation. The first one is based on using magnetic field sensors which can be positioned in the fluid and employed in a feedback control system. In this way, it is possible to modulate the current flowing into the excitation coils to compensate the field variations due to the introduction of some objects. Although such a solution is quite general (it should be used either for $\mu_{r_{obj}} < \mu_{r_{MRF}}$ or $\mu_{r_{obj}} > \mu_{r_{MRF}}$) its

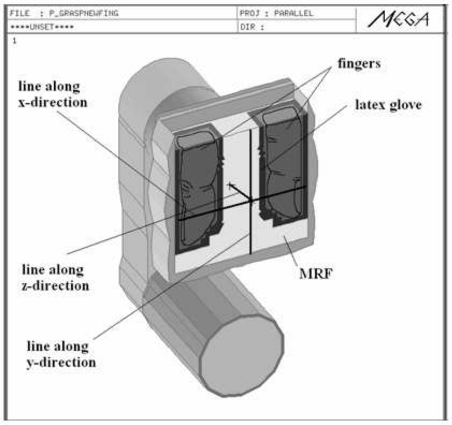

Fig. 7. Model of PG manipulation with two fingers inserted inside the fluid.

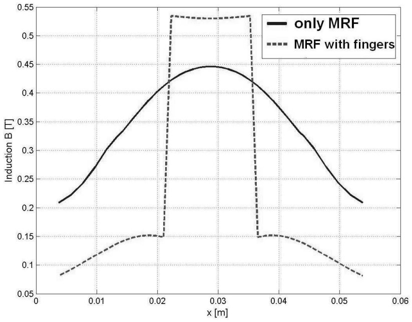

Fig. 8. Induction B along x-direction when two fingers are inserted in the fluid.

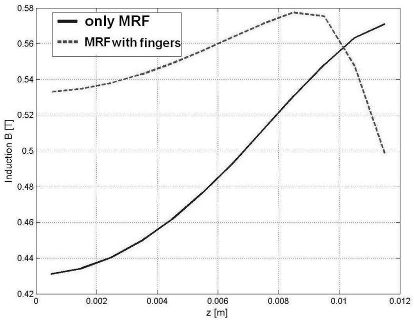

Fig. 9. Induction B along z-direction when two fingers are inserted in the fluid.

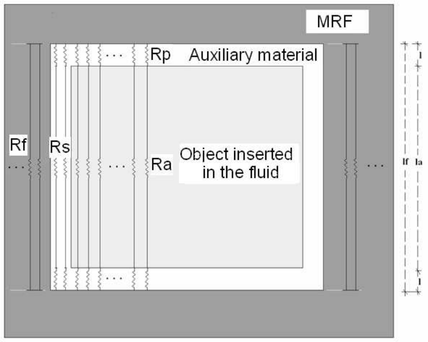

Fig. 10. Bi-dimensional model of the system used to characterize the magnetic permeability of the auxiliary material.

implementation requires an auxiliary control system that could be extremely complex due to the difficulties in positioning the magnetic sensors. The latter solution, instead, is based on a proper choice of the material which covers the inserted object. If such a material is able to make the reluctance of magnetic paths around the object equal to that of the MRF, the insertion of the object will not perturb the magnetic field. This solution is only applicable to objects with $\mu_{r_{obj}} <> \mu_{r_{MRF}}$ (that is the case of the operator fingers). The problem is thus reduced to find an auxiliary material (with a suitable magnetic permeability) that will be used to cover the object to be inserted in the fluid. In particular, considering the operator hands, it is necessary to find a proper material to manufacture the glove. The value of the magnetic permeability μ_r of such an auxiliary material has been calculated using the bi-dimensional scheme of Figure 10. Let us consider a domain of fluid that completely surrounds the object covered by an unknown magnetic permeability μ_{r_x}. The domain can be subdivided into several flux tubes (48 subdomains in our case). Then, the magnetic reluctance of each subdomain which includes both the object and the auxiliary material was calculated and set equal to the reluctance of the subdomain composed of the only MRF. This approach leads to a quadratic equation where the unknown is the magnetic permeability μ_{r_x} and the constants K_n take into account the geometry and the physical characteristics of the system:

$$K_1\mu_{rx}^2 + K_2\mu_{rx} + K_3 = 0 \tag{1}$$

The solutions of such an equation are: $\mu_{r_{x_1}} = 10.7$ and $\mu_{r_{x_2}} = -0.23$, with the obvious choice for the first one.

B. Simulation results

The solution has been numerically verified by a suitable simulation. The system in Figure 7 was simulated in the configuration of two fingers covered by a glove made of a material having magnetic permeability $\mu_{r_x} = 10$. Figures 11, 12, and 13 show the profile of magnetic induction B, in the central zone of the MRF, respectively along the x, y and z direction, when two fingers are inside the fluid. As it can be seen, the value of B is not perturbed with respect to the ideal case (absence of fingers in the fluid). Figure 14 reports the field maps inside the fluid.

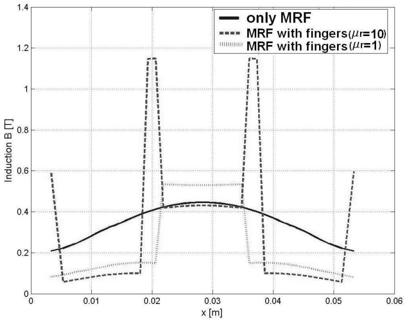

Fig. 11. Induction B along x-direction when two fingers covered with a material of magnetic permeability=10 are inserted in the fluid.

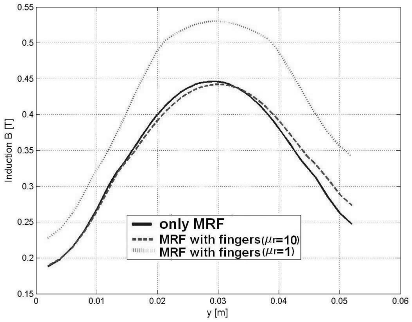

Fig. 12. Induction B along y-direction when two fingers covered with a material of magnetic permeability=10 are inserted in the fluid.

Although results have shown a good attenuation of the perturbations of the magnetic field when an extraneous object is introduced within, the proposed solution should be deeply analyzed with reference to the increased tactile capability of the operator. In other words, the magnetic field inside the MRF can be effectively predicted with a low error margin if subjects wear a glove made of a material having the relative magnetic permeability equal to 10 while interacting with the fluid.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A set of psychophysical experiments, even though of preliminary nature, have been performed in order to assess the improvements of the HBB-II with respect the previous prototypes. The experimental session entailed tests on the capability of recognizing different shape and compliance of virtual objects variously oriented. It is worthwhile pointing out that it is not possible to create an isolated stiff region inside the fluid. This is due to the fact that the magnetic field is solenoidal, i.e. $\nabla \cdot B = 0$ or the equivalent integral form $\int\int_A B \cdot dA = 0$. In other terms given any volume element, the net magnitude of the vector components that point outward from the surface must be equal to the net magnitude of the vector components that point inward. This means that the

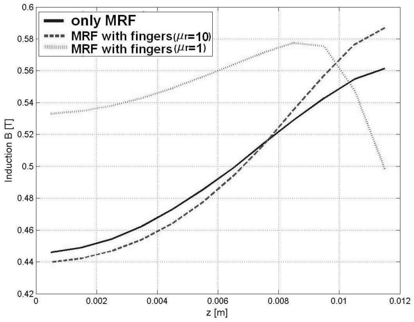

Fig. 13. Induction B along z-direction when two fingers covered with a material of magnetic permeability= 10 are inserted in the fluid.

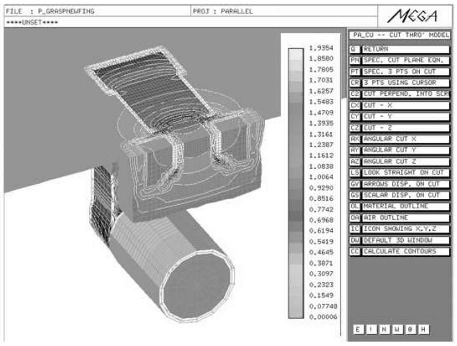

Fig. 14. Magnetic field maps inside the fluid when two fingers covered with a material of magnetic permeability=10 are inserted in the fluid.

magnetic field lines must be closed loops, or equivalently that there exist no magnetic monopoles. Another qualitative test was based on the ability of the system to produce a given shape. The same simulated objects in Fig. 4 and 5 were reproduced by exciting the same solenoids activated during the simulation. Volunteers were asked to manipulate the fluid and freely describe the shape perceived without receiving suggestions. Results are very encouraging and well agreed with the simulation results. In particular, volunteers recognized without doubt the cylinder positioned at different orientations or radial patterns and they were able to identify all the other figures with a high recognition percentage. The final experiment aimed at assessing the capability of subjects to discriminate different virtual objects by their softness. Being the novel architecture of HBB-II capable to attain the saturation level of MRF, the full dynamic range of MRF was exploited, thus allowing a fine discrimination of a high number of objects having different softness.

V. CONCLUSIONS

Psychophysical tests, even though of preliminary nature, and simulation results showed that the new device, HBB-II, is more effective than the earlier prototypes. The most important novelty concerned the possibility of creating 3D virtual objects with an augmented tactile perception. Performance of the new device has been assessed, showing satisfactory results. Simulation tests have been performed and results provided the guidelines for creating virtual objects having different shape and compliance. A special focus was laid on investigating the interaction between the operator hand and the MRF. When the hand is introduced within the box containing the MRF, the magnetic field distribution is perturbed. Different solutions were envisaged in order to remove this artefact, and enhance tactile perception capabilities without altering the field. Further work has to be done towards an improvement of the control strategy, introducing magnetic sensors in the feedback loop, and thus enhancing the capability of perceiving more effectively 3D complex objects.

VI. ACKNOWLEDGMENT

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REFERENCES

[1] A. Bicchi, M. Raugi, R. Rizzo, and N. Sgambelluri, "Analysis and Design of an Electromagnetic System for the Characterization of Magneto-Rheological Fluids for Haptic Interfaces". *IEEE Transactions on Magnetics*, 41(5):1876 - 1879, 2005.

[2] A. Bicchi, E. P. Scilingo, N. Sgambelluri, 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] J.D. Carlson, D.N. Catanzarite and K.A. St Clair, "Commercial Magneto-Rheological Fluid Devices", *Proceedings 5th Int. Conf. on ER Fluids, MR Suspensions and Associated Technology*, W. Bullough, Ed., World Scientific, Singapore,1996, 20-28.

[5] GE Medical Systems (ed): MR Safety and MR Compatibility: Test Guidelines for Signa SPTM Version 1.0 , http://www.ge.com/medical /mr/iomri/safety.htm , October (1997).

[6] J. Jian-Ming, "Electromagnetics in Magnetic Resonance Imaging", *IEEE Antennas and Propagation Magazine*, v. 40, n. 6, December 1998, pp. 7-22.

[7] R.S. Johansson and G. Westling: "Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects", *Experimental Brain research*, 56, pp. 550–564, 1984.

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

[9] 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.

[10] J. M.Loomis and S. J. Lederman: "Tactual perception", *Handbook of Perception and Human Performance*, Wiley, 1986, Vol. II, chapt. 31, p. 1-41.

[11] A.I. Pabat, "Controlled Magnetorheological Shock Absorbers." *Magnetohydrodynamics*, 1993, Vol. 26, No. 2, p. 222

[12] 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.

[13] E.P. Scilingo, N. Sgambelluri, D. De Rossi, and A. Bicchi. "Towards a Haptic Black Box: Magnetorheological fluid based display for softness and shape discrimination", *In Proc. IEEE Int. Conf. on Robotics and Automation*, Taipei, Taiwan, pages 2412-2417, May 2003.

[14] E.P. Scilingo, N. Sgambelluri, D. De Rossi, and A. Bicchi, "Haptic Displays Based on Magnetorheological Fluids: Design, Realization and Psychophysical Validation", *In Proc. 11th Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 10–15, 2003.

[15] 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.