HAPTIC INTERFACES FOR BIOMEDICAL APPLICATIONS

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Abstract: Recent developments in advanced interface technology allowed to implement new haptic devices for biomedical applications. Specifically, several innovative and more effective tools that allow people to interact by touch with virtual objects have been developed. Besides several applications such as gaming, entertainment, virtual reality, an important and promising field of application is the surgical simulation. Novice surgeons can be able to practice their first incisions without actually cutting anyone. Simulation for surgical training is a major focus for several research activity during the last few years. Simulating an organ is not easy, because is more complicated to model than is a common physical object, e.g. a ball. In this chapter we report several examples of haptic interfaces and introduce new technologies and paradigms to implement that.

1. Introduction

Tele-surgery, virtual surgery, minimally invasive surgery and in-the-body exploration and manipulation have becoming extremely important techniques for reducing costs, time of care and patient pain and discomfort. New generation of haptic interfaces are playing an important role in improving performance and extend functionalities of these new techniques.

In particular Minimally Invasive Surgery (MIS) has becoming increasingly widespread due to many benefits related to reduced trauma to the body, less anaesthesia, less post-operative pain and discomfort, smaller risk of infection, shorter hospital stay, faster recovery, and less scarring [1]. Nevertheless this promising technique still suffers from some important limitations due to the surgeon loss of tactile perception during palpation of internal organs. This is basically due to the mechanical transmission of the elongated tools used during operation. In order to overcome this limitation and provide surgeons with the flexibility of traditional open surgery while operating through tiny apertures, a haptic interface can be placed between the surgical tool and the surgeon, allowing delicate operations to be carried out from *within* the patient. In addition to MIS, haptic interfaces could be a viable solution also for surgical training in Open Surgery (OS). Indeed, although challenged by new developments in endoscopic technologies, traditional operative procedures often remain the only solution in most cases of surgical operations. Therefore surgical training in open surgery is very important. Just as commercial pilots train in flight simulators before they fly an aeroplane with real passengers, surgeons will be able to practice their first incisions without actually cutting anyone. A virtual surgical tool can be controlled via a haptic interface allowing the user to operate on a virtual patient. The operation could be completely artificially simulated and can be rerun many times until the trainee surgeon has learnt the technique. Alternatively the patient could be real and the surgeon could use a remote surgical tool to perform the operation. This provides a more efficient use of resources as the patient and the surgeon no longer have to be at the same physical location in order to carry out the operation. level of the handle, giving back to surgeon the lost tactile perception. These applications in teleoperation and virtual surgery call for the implementation of effective means of displaying to the human operator information on the softness and other mechanical properties of objects being touched. The ability of humans to detect softness of different objects by tactual exploration is intimately related to both kinesthetic and cutaneous perception, and haptic displays should be designed so as to address such a multimodal perceptual channel. Although accurate detection and replication of cutaneous information in all its details appears to be a formidable and challenging task for current technology some surrogating tactile information for softness discrimination can be however provided. Kinaesthetic information can be conveyed by means of force-position feedback of an actuator, based on specific technology, while cutaneous channel can be addressed either providing the surgeon with the rate of increase of contact area between fingerpad, or object or with the shape reconstruction of object being manipulated. Here we report some examples of haptic interface able to address also cutaneous channels.

2. Biological tactile sensing

When exploring rheological properties of an object such as stiffness, damping, hysteresis, etc., humans use their fingers to squeeze, stretch, probe or indent the surfaces, and gather data from many sensory receptors in the hand. These sensors can be classified into two broad functional areas, or sensory channels, namely kinesthetic and cutaneous sensors [2]. Kinesthetic information can be referred to geometric, kinetic and force data of the limbs, such as position, velocity and acceleration of joints, actuation forces, etc., which is mainly mediated by sensory receptors in the muscles, articular capsulae, and tendons. Cutaneous information is provided by pressure and indentation distributions, both in space (on the skin) and in time, and is mediated by mechanoreceptors innervating the derma and epidermis of the fingerpads. Information synergistically conveyed by the kinesthetic and tactile channels, and elicited by the central nervous systems, forms the object of `haptic', or touch-related, sciences and technologies [3].

The high degree of dexterity which characterizes grasping and manipulative functions in humans, and the sophisticated capability of recognizing the features of an object are the result of a powerful sensory-motor integration which fully exploits the wealth of information provided by the cutaneous and kinaesthetic neural afferent systems.

Tactile functions are most effective at the fingertips, where detection of the surface texture of an object and discrimination of its fine form are performed by a large number of elaborate corpuscular and free nerve endings sensitive to mechanical stimuli (mechanoreceptors) (see Fig. 1).

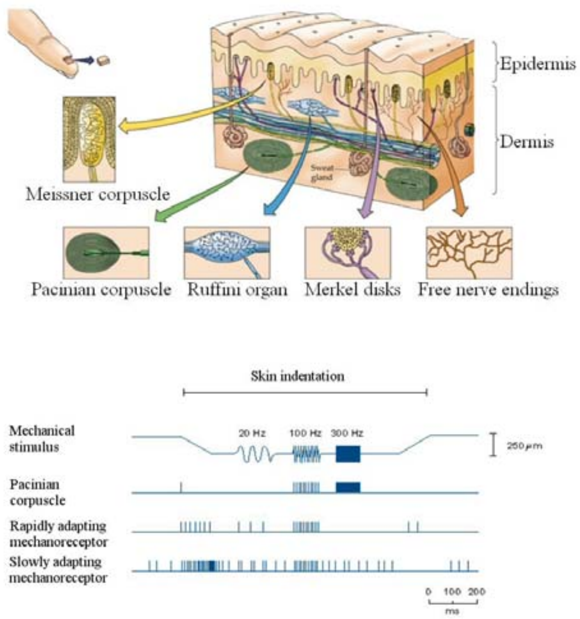


Figure 1: Organization of mechanoreceptors in the skin (upper) and firing rate of mechanoreceptors following an external mechanical stimulus.

3. Minimally invasive surgery

In minimally invasive surgery the role of advanced technology for providing tactile feedback is perhaps more important than in other field. In a laparoscopic operation, the surgeon operates through small openings (between 3 and 12 mm) in the abdominal wall of the patient. An inert gas (usually CO^2) is introduced to distend the peritoneal cavity. One of the openings is used to introduce a miniature camera (including a cold light source). Camera images are shown on a monitor while the camera is guided by an expert operator. The head physician and his assistants operate using a set of elongated slim rigid tools endowed with a couple of jaws at the tip. Jaws are opened and closed using the handle of the tools. The transmission of force and motion from the handle to the tip is actuated by means of levers. There are still many problems related to the use of this technique; for example, an important effort is devoted to the research and the design of new tools for complex purpose, such as suture or pinching. An important attention is posed in surgeon training for mini-invasive operation, using virtual reality and telepresence tools. Research in new surgical or training techniques should keep into account the human factor, namely their acceptability to the surgeon staff. Zucker *et al.* [4] resume the problem with the phrase: "general surgery, however, is a conservative discipline, an attribute that once served is well. General surgeons also tend to trust their visual and tactile senses more than *technology"*. Minimally invasive surgery is still afflicted with important limitations. The most important one is the surgeon loosing of both tactile and kinesthetic sensibility due to friction and backlash present in the transmission mechanism of the elongated tools. The surgeon may manipulate patient viscera only using long tools, observing actions and movements on a monitor visualizing abdominal environment [5]. He can not either touch or see viscera directly and that restricts the application of this technique only to some specific fields, such as resection and removal of organs (appendectomy, cholecystectomy and so on). Diminished tactile sensibility causes a loss of surgeon palpation evaluation capability, in particular with regard to tissue compliance and viscosity. These effects are so important that it becomes very difficult to discriminate the anatomical nature of the manipulated tissue. This is true, in particular, if the camera images are not sufficient or absent. In such cases, losses on perception may cause important lesions. It is not unusual that during the intervention of cholecystectomy a traumatic event on the gall bladder due to the losses of perception of the surgeon assistant occurs. Such an event is painless, since gall bladder has to be removed, anyway, a better sensibility may diminish the incidence of these events and optimize grasping force during manipulation.

4. Hardware solutions

4.1. Sensing

In order to overcome the limitation of loss of tactile perception in minimally invasive surgery and provide surgeons with the flexibility of traditional open surgery while operating through tiny apertures, the elongated tool can be suitably sensorized and actuated. Concerning the sensorization of the laparoscopic tool, different solutions can be envisaged. One of these was implemented by [6]. The commercial tool, laparoscopic pliers, has a very simple mechanical structure: a rigid beam is actuated by the handle. Its forward-backward movement closes and opens the jaws. Module sensor was positioned near the handle, to respect the simplicity of the original mechanism. The sensors were able to measure the applied force and the jaws position. The force sensor was realized applying two strain gauges to an aluminium ring: the ring deformation causes gauge resistance variation. The position sensor is realized using an optical position sensing device (PSD). It is a semiconductor optical device on which a light emitting diode (LED) is placed. Light injection causes the generation of two currents: the difference of these currents is a linear function of the LED position above the PSD. The LED is integral with the rigid beam which actuates the opening and closure of the jaws, hence its position is an indirect measure of the jaws angles (see Fig. 1). These signals can be used to identify the rheology of the biological tissues manipulated by the sensorized laparoscopic tool and convey them to a suitable display which has to be controlled to replicate the rheology.

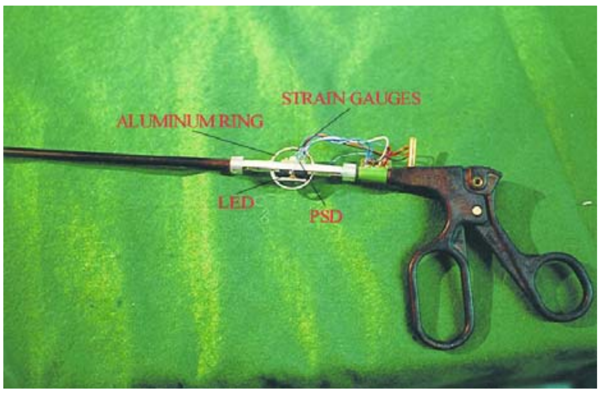


Fig. 1: Force and position sensors placed directly on a commercial laparoscopic tool.

4.2. Haptic display technology

Communication of haptic information involves both sensing performed at the remote end of the loop, and display on the operator side. In full generality, both kinesthetic and tactile information should be sensed at one end, and displayed at the other end. As a matter of fact, at the present state of the art and technology most remote haptic systems only implement the kinesthetic channel. Indeed, the parts of a haptic system that refer to cutaneous tactile information are the most difficult to realize. Although there have been prototypal implementations of such sensory and displaying systems, such as e.g. those described by [8] and [9], the need for miniaturization, simplicity, economy, and ruggedness of many applications, makes the display of tactile information indeed a formidable task. On the other hand, the tactile component of haptics is by no means of secondary importance. In fact, in the psychophysical literature, it has been firmly established by the fundamental work of [10] and [11] that loss of the tactile channel reduces human capability of haptic discrimination dramatically. To illustrate a particular, but important example of a remote haptic system, let us refer to the case of a system for remote palpation of tissues in minimally invasive laparoscopy. This application, which has been considered by several authors, is still one of the most promising for the new haptic technologies. As already reported, imperfections and mechanical disadvantage in conventional forceps may substantially impair the surgeon capability of tissue discrimination by palpation. This is particularly unfortunate in operations where camera information alone is not sufficient (for instance, nodular lesions of the lung have the same visual appearance as normal pulmonary tissue). Purely kinesthetic sensors and devices can be implemented rather easily for this application. On the contrary, tactile sensing should be implemented right on the small tips of the forceps jaws in the form of an array of distributed pressure sensitive elements, with the relative harnessing problems; and tactile actuation should be realized by an array of micromechanical indenters, acting on the operator fingerpad. Although possible, such realizations may result too costly and not robust enough for large volume applications. An effective strategic line can be to simplify tactile sensors and displays to an extent which may represent a realistic tradeoff between what is needed perceptually and what can be provided technologically. Here, we propose several technological solutions which comply with this latter requirement. As preliminary feasibility study, we designed and realized a haptic interface embedded into a laparoscopic tool. It consists of a rotational solenoid placed within the handle of the tool. The axis of the solenoid was linked to a trigger which can be easily and ergonomically touched by the surgeon (see Fig. 2). The sensorization module was devoted to acquire signals relative to force and strain imposed on the biological tissues manipulated by the tool. These signals were suitably processed to identify the rheology of the biological tissue. The solenoid was hence controlled to replicate the identified compliance.

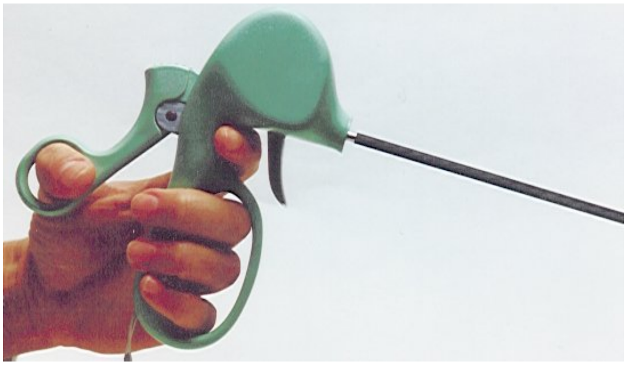
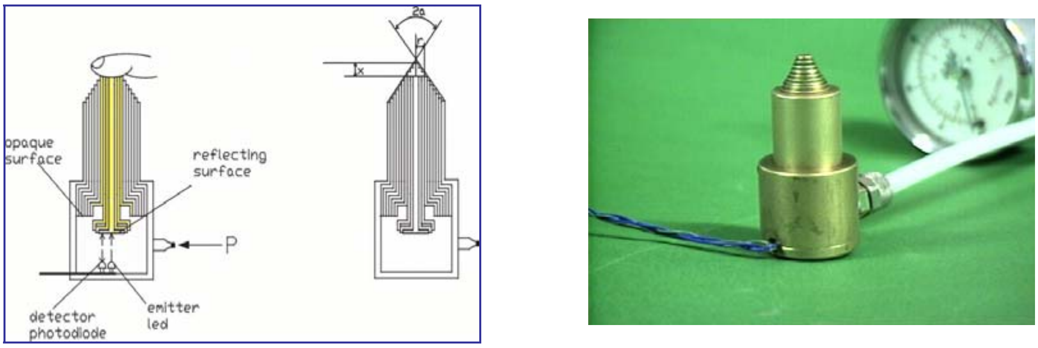


Fig. 2: Early prototype of actuated laparoscopic tool.

In the scheme of a haptic remote system for minimally invasive surgery applications, the sensing part is placed on the laparoscopic tool and signals acquired can be suitably conditioned and used for controlling haptic display able to replicate softness of the biological tissues. As above mentioned, the ability of humans to detect softness of different objects by tactual exploration is intimately related to both kinesthetic and cutaneous perception, and haptic displays should be designed so as to address such multimodal perceptual channel.

In literature there are several attempts to implement devices capable of providing, in addition to kinaesthetic information, cutaneous information, e.g. by means of shape and/or vibration feedback, or conveying thermal data. Here, we proposed two different technologies. The first one refers to a new conjecture [7] based on surrogating detailed tactile information for softness discrimination with information on the rate of spread of the contact area between the finger and the object as the contact force increases, while the latter one is based on smart materials, such as magneto-rheological fluids.

The new conjecture we proposed relies on the paradigm that a large part of haptic information necessary to discriminate softness of objects by touch is contained in the law that relates resultant contact force to the overall area of contact, or in other terms in the rate by which the contact area spreads over the finger surface as the finger is increasingly pressed on the object. We called this relationship the CASR. Clearly, such a conjecture does not imply that all other aspects of tactile information (such as, e.g., the shape of the contact zone or the pressure distribution in the contact area) are not relevant to the task; rather, it suggests that, in the lack of better resources, the CASR information might be an acceptable surrogate for the complete sense of touch. A further motivation for such a hypothesis is given by Hertz modeling theory of contact between elastic bodies [12]. This theory provides a relationship among the interaction force between two bodies coming into contact, the contact area and the compliance of the two bodies. Although this theory applies to homogeneous, isotropic bodies of size much larger than that of the contact area, and this is not usually the case in many remote haptic system applications (such as, e.g., in laparoscopic surgery), still it is interesting to verify that our hypothesis makes sense in this case.



(a) (b)

Fig. 3: Description of the principle (a) and prototype (b) of CASR display.

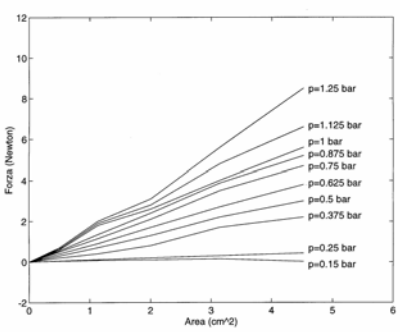
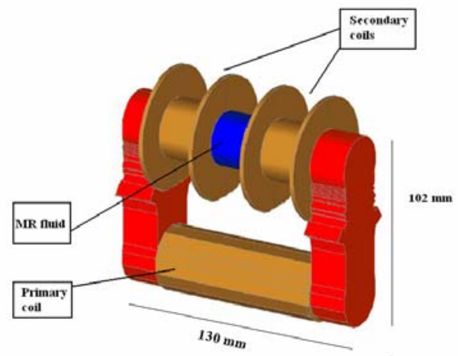


Fig. 4: Force/Area response of the prototype CASR display with costant pressure.

A possible implementation of a device which replicates the rate at which the contacting area of the probed material spreads on the surface of the remote probing finger consists of a set of cylinders of different radii in telescopic arrangement. Regulated air pressure acts on one end of the cylinders, and the operator finger probes the other end of the display. The length of the cylinders is arranged so that, when no forces are applied by the operator, the active surface of the display is a stepwise approximation of a cone whose total angle at the vertex is. When the probing finger is lowered by an amount, an area of contact approximately evaluated as is established. Correspondingly, the force opposed to the finger is given by the pressure established in the inner chamber by the external regulator. An optoelectronic sensor placed within the chamber allows measurement of the displacement, while a servo pneumatic actuator regulates the chamber pressure based on the desired CASR profile to be replicated. A laboratory prototype of the CASR display, with ten concentric cylinders, is shown in Fig. 3, while Fig. 3 shows the experimental characterization of the CASR effect as measured with several different values of constant pressure. As it is apparent from Fig. 3, the CASR curves of this display at constant pressure are roughly linear. To match typical CASR curves (which are nonlinear), the haptic display is operated in feedback by controlling pressure in the inner chamber as the display displacement is changed, in such a way as to track the CASR function measured on the specimen under exploration. A pneumatic servo valve is employed to this purpose.

Several psychophysical tests have been performed to validate the hypothesis that when a display conveys the information related to the growth of contact area when an object is touched is more effective and provide a more accurate tactile perception for a better discrimination [13].

Another innovative technology for implementing haptic displays is based on smart materials, Magneto-Rheological (MR) fluids. MR fluids consist of an oil-based solution in which micron-sized magnetically active particles are dispersed. In normal conditions particles are randomly distributed and the fluid exhibits a Newtonian behaviour. 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. This phase transition occurs in few milliseconds [14]. 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, such as biological tissues, and to realize haptic displays.



(a)

(b)

Fig. 5: Model (a) and realization (b) of the Pinch Grasp (PG) display.

Several architectures of MR-based haptic displays have been envisaged [15][16][17]. The first prototype was realized for pinch grasp manipulation. The MR fluid is positioned in the air-gap of an electromagnet within a latex sleeve allowing pinch-grasp manipulation. The scheme of the device is reported in Fig. 5. Performance of this display, in terms of capability of mimicking rheology of biological tissues, was quantitatively and psychophysically assessed. More precisely, four samples of bovine biological tissues were selected: brain, spleen, liver and bone. Each sample has been reduced to the same size of the MR fluid specimen in order to remove artifacts due to differences in geometry. A descriptive model of MR fluid and biological tissue was formulated. Results showed that each of these four biological samples as well as the MR fluid can be described by a generalized third order Kelvin model, having five parameters, three springs and two dampers. In addition to the five parameters the MR fluid is described also by the magnetic field. In order to identify the most suitable magnetic field to apply to the MR fluid to make it similar in compliance to the biological sample, a set of psychophysical experiments was performed.

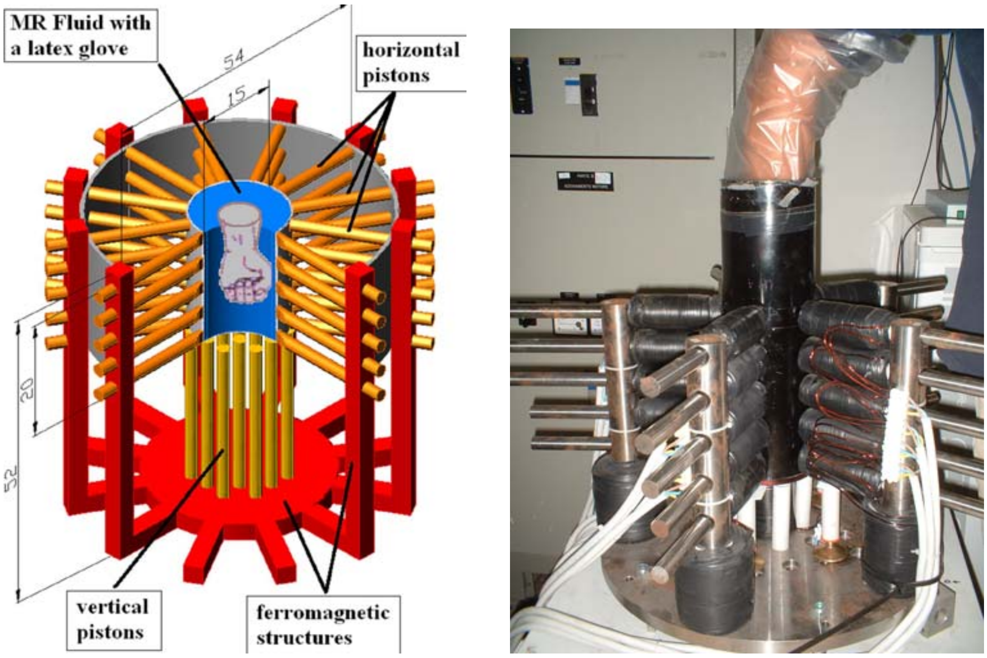
Fifteen volunteers were asked to manipulate at the same time, using both hands, the biological tissue sample and the MR fluid specimen duly excited with magnetic field. The magnetic field was changed by an assistant till subjects perceived a good resemblance in compliance between the MR fluid and the sample of biological tissue. When volunteers perceived the same tactile sensation from both biological tissue sample and MR fluid specimen, the corresponding magnetic field was recorded. Tests were repeated more times for each volunteer in order to calculate the average magnetic field necessary to excite the MR fluid specimen and to induce a compliance similar as much as possible to the corresponding biological tissue sample. Results are very encouraging and open new perspectives in realizing a haptic display for surgical training in minimally invasive surgery and open surgery applications. The technical evolution of this display led us to implement a new architecture capable of reproducing 2D and 3D virtual objects. The general scheme refers to a Haptic Black Box (HBB) concept, intended as a box where the operator can poke his/her bare hand, and interacts 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. Two architectures were envisaged: HBB I and HBB II. A crucial aspect during the design phase of these displays was the arrangement of the electromagnetic system for properly energizing the MRF. The simplest way to create a controllable magnetic field is to use more electromagnets suitably arranged to optimize the interface between the device and MR fluid. These devices must guarantee a low reluctance flux paths (e.g. through steel) to focus magnetic flux into region of active magnetic fluid, starting from liquid (without field) until the range of magnetic field saturation (commonly 0.5-0.6 T); a magnetic field inside the MR specimen should be as uniform as possible, maximizing the magnetic energy in the fluid gap and minimizing the energy lost in the ferromagnetic cores and other regions (according to safety criteria); and, finally, an easy accessibility to MRF specimen should be assured. Since the behavior of both MRF and ferromagnetic cores is highly nonlinear, an analytical method cannot perform an accurate investigation, therefore a 3D Finite Element code was used. The first configuration, called HBB-I, implies a distribution of 16 solenoids underlying the box which contains the MRF, arranged in a matrix form of 4x4 and placed below a plastic box with a square base of 18cm x 18cm and a height of 4cm. Each ferromagnetic core is equipped with a coil of 305 AmperTurns of enamelled copper wire marked Autovex 180, with a low thermal resistivity made by Pirelli, arranged in 5 layers of 31 turns around a cylindrical core made of carbon steel AISI 1015 and able to support a maximum DC current of 10 A.

(a) (b)

Fig. 6: Model (a) and realization (b) of the Haptic Black Box (HBB)-I display

This ferromagnetic core is commonly used for screws and bolts production. Indeed, it shows a good magnetic relative permeability around thousand, a high saturation level (about 2.3T) and low hysteresis. 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. Fig. 6 shows the architecture of the new device.

When a given solenoid is activated, the magnetic field flux goes through the MRF which becomes harder near the core. According to compliance and shape of the object to be replicated, one or more solenoids are, statically or dynamically, excited. Two critical aspects of this configuration limit strongly performance. The first one regards the paths of the magnetic flux that close themselves in air increasing the magnetic reluctance and, consequently, decreasing the magnetic field inside the MRF. Indeed, the highest value of magnetic field intensity which can be created is lower than the saturation level of MRF. The latter aspect is the impossibility of reproducing 3D object, as virtual objects are constrained to be confined to the bottom of the box. These considerations have been the propelling thrust to conceive a new architecture, called HBB-II. In this new configuration, in order to reduce the reluctance of the magnetic path, opportune ferromagnetic yokes and cores have been introduced at strategic positions. To increase the spatial resolution, more solenoids, having smaller sizes has been added, suitably arranged into a three-dimensional architecture in order to create 3D virtual objects. A further improvement concerned with the choice of special materials whose nonlinearity is more attenuated. Fig. 7 shows a schematic view of the new device, the HBB II, with its main dimensions. It is possible to decompose the whole system in 4 main parts. The plastic box is used to contain the MRF and it is cylindrically shaped for a better symmetry of the system. Then, in order to allow to freely handling the fluid, the box is internally equipped with a latex glove.



(a) (b)

Fig. 7: Architecture (a) and realization (b) of the HBB-II display

However, since the dimensions of the box have to respect a compromise between an easy accessibility to the fluid, and a reduction of 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 to 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 x 4 below the box base; the remainder fifty, arranged in series of 10 x 5, is placed in aureole form around the lateral surface of the plastic box. They are constrained to slide in special holes present in the superior part of each column. All the used cores are composed of ferromagnetic material (carbon steel C40) with a 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 coil system needs to produce the proper magnetic field for the energization of the MRF. In the system there are two types of coils: the one positioned around the inferior part of the columns and used to create the main magnetic field (the so-called primary-coils) and the other positioned around the 66 pistons and used for a fine control 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 hollowed 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. 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. The control system controls the current in each coil for a double purpose. From an electrical point of view it adjusts the value of current for a direct modulation of the magnetic field; from a mechanical point of view, the current in each coil allows to move the piston, inserted in the plastic cylindrical support as in a classical solenoid with a plunger inside it, along a fixed trajectory starting from the column and ending at the lateral surface of the plastic box containing the MRF. The piston returns to its initial position by the effect of a constrained spring.

The architectures of MR fluid based haptic interfaces here presented can be used as device standing near the sensorized laparascopic tool, but not integrated with it. Possible developments can progress towards a possible integration with the laparoscopic tool. Indeed, the fluid can be placed within the handle of the laparoscopic tool, suitably modified to lodge the system able to create a local distribution of the magnetic field.

5. Discussion and Conclusion

In this chapter we showed some examples of haptic interfaces for biomedical applications. Starting from the conjecture, supported by experimental evidence, that, in addition to kinaesthetic channels, also cutaneous information should be conveyed to the operator, we proposed new technological solutions where force-position feedback is enriched by additional cutaneous sensing cues to augment haptic perception. Indeed, it has been firmly established in the psychophysical literature that the ability of discriminating softness by touch is intimately related to both kinesthetic and cutaneous tactile information in humans. In replicating touch with remote haptic devices, there are serious technological difficulties to build devices for sensing and displaying fine tactile information. We endeavored to overcome these difficulties, finding innovative technical solutions, supported by quantitative and psychophysical experiments. In particular we proposed a new conjecture for implementing new effective haptic displays in order to surrogate the detailed phenomenology of cutaneous perception with a simplified paradigm implying to replicate the growth of contact area during tactile interaction. Moreover, we exploited an innovative technology based on smart fluids to implement new haptic interfaces allowing users to freely handle their hands without rigid linkages or constraints.

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