CyberHaptics– Magnetic Implants as Haptic Devices

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Abstract—Haptic displays are multiple and diverse in technology. They can be found in the form of fixed, movable, portable, wearable, encounter-type and can display a subset of known haptic modalities. In this paper, we introduce a new category: human implant haptics. Implantable haptics conceptualizes the idea that haptic display systems can also be considered as permanent biocompatible implants in living organisms having touch sensing capabilities. They can be used to display haptic data or enhance perceptual modalities using surrounding nerf-endings. We specifically exemplify and investigate thus new concept, we termed cyberhaptics, with subcutaneous magnetic vibrator implants, and show how they can be used to convey haptic data or substituting non-haptic data into haptics.

Index Terms—Cyborg haptics, subcutaneous magnets, implant haptic displays.

1 Introduction

CYBERHAPTICS, a name composed from cybernetic or cyborg and haptics, designates any technology that enables providing or enhancing human haptics by implanting an artificial component of technology in a living organism. This type of haptic technology is not researched despite potential needs in terms of restoring human haptic sensations for amputees, and the new trend in human augmentation through various technologies (e.g. Google glass, mobile phones, etc.). Almost all existing haptic technologies are external devices that convey haptic data through direct contact on organism's skins. They can be found in the form of fixed or portable, graspable, wearable, touchable (encounter-type), pseudo-type and can display a subset of known haptic modalities, see recent reviews in [1].

It is however possible to envision haptic devices as biocompatible fully or partially implantable devices that are permanently part of the human body. This novel research in cyborg haptics, that we named *cyberhaptic technology* might offer tremendous perspectives and challenging investigations for new knowledge and applications. We are all cyborgs already as we relay and depends on several devices that enhance our perceptual, cognitive and strength capabilities. For being active by essence, haptic devices cannot be fully implantable as they still depend on an external source of information to be displayed. However, the mechanical transducer can be fully integrated and in various ways. In the future, we may expect advances in technology such that more sophisticated implants at different subcutaneous levels can serve the purpose of haptic displays to relay stealthily information.

In this paper, we investigate the use of sub-dermal magnetic implants or SMIs(see Section 2). Magnetic implants appeared in the early 2010's among the biohacking community and have since vastly evolved both in design and uses. They consist of a strong magnet encapsulated in a biocompatible material and are usually implanted right beneath the skin in the hypo-dermis. These have found many uses over the years as practical tools, entertainment or wireless earphones. The ones we will be focusing on are particularly small and placed in the fingertips to give the user a sense of magnetic fields: when the implant interacts with an external field, it moves or vibrates among the user's nerve endings. This simple system provides the ability to detect, touch and identify fields with surprising precision as studied in depth by I. Harrison [2].

What we aim to prove is the feasibility of using implantable magnets as haptic rendering device in concrete use cases, like feedback for virtual and augmented reality. Assuming this is the case, magnetic implants would provide a mechanically simpler and potentially scale-able approach to haptic rendering. Most importantly they introduce the possibility of haptics through sub-dermal, permanent technologies.

2 Background

2.1 Sub-dermal implants and cutaneous mechanoreceptors

Among the skin's mechanoreceptors, the nerve endings dedicated to tactile stimuli, it is the quickly adapting (QA) that are mostly involved in the perception of the implant (J. Hameed [3]). They are composed of Pacinian and Meissner corpuscles that are receptively sensitive to ranges of 200-300Hz and around 50Hz which loosely corresponds to the detectable frequency range of the implants [3].

Since they interact with the skin from the inside rather than through the epidermis, it is fair to expect a different response to a similar stimuli. Indeed when I. Harrison [2] compares superficial and implanted magnet performances we see some differences in particular in amplitude dis-

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crimination where implants showed a significantly higher sensitivity.

Additionally we must take into account the evolution of magnetic implants as they seem to have changed a lot during the last decade. Firstly the grades (strength) of the magnets used have increased and will probably keep increasing. The coatings used have also changed to be thinner further reducing the excess mass of the implant. Both these factors impact the sensitivity of the implant as they increase the effect that an exterior field can have upon it by reducing it's size and mass while increasing it's intrinsic field.

2.2 Haptic feedback and artificial tactile stimuli

When it comes to producing a tactile feedback many techniques have been proposed and used as seen in [4]. Nevertheless there are two main drawbacks we can see to most of the currently used systems: They involve a direct physical contact between the user (usually the finger tips) and the system, i.e. a device has to be worn, touched or held. Secondly the feedback devices usually involve more or less complex mechanical systems (With the exception of electro-tactile stimulation [5]). In addition to the added complexity, mechanical systems face the issue of miniaturization and the difficulty to embrace the uneven nature of the human skin. Nevertheless the more recent approach of using ultrasound interference to produce a stimuli on skin in mid-air [6] solves these issues and makes it possible to produce the sensation of 3D shapes in empty space [7]. We can also mention the air-jet technique although it's much less versatile compared to ultrasound [8]. Still, the ultrasound technique has its own limitations:

- The stimulation range is limited to tens of centimeters [9].
- Ultrasounds do affect the human body and the haptic devices exceed the recommended 110 dB for continuous exposure. They are safe as long as the head is kept at a normal distance from the device [9] but this seems like an issue for both children and animals.
- Finally the technology requires advanced hand tracking and uses ultrasound waves meaning that any obstruction, either external or by the users body, will disrupt the feedback.

With implantable technology we hope to solve a majority of those issues.

3 Implants for Haptic Rendering

3.1 Sub-dermal magnetic implants, SMIs

So far, haptic rendering is facing the main issue of practicality. Even in the most advanced implementations the user is either constrained in their movement or ability to use their hands in other ways. This drawback makes haptics unfit for regular or continuous usage in everyday life. To solve this we propose integrating technology directly to the body. This might sound dangerous and intrusive but as we see in this paper 3.1.2 it can be extremely simple both from an engineering and a medical point of view.

Implants are not a novel concept and have been used extensively for decades in the medical field. Surprisingly though implant technology is rarely considered outside of the medical realm and has only recently gained in popularity in both aesthetics and the biohacking community. Indeed the type of implant we're interested in comes from said biohacking community and we believe has potential in haptics and human-machine interaction with relatively low risk and invasiveness.

3.1.1 Implant design

The implant being placed under the skin it must of course be small. The second criterion influencing the chosen dimension is the influence of the mass of an object on the quantity of energy necessary to move it. In fact, the smaller a magnet (and therefore less massive) the more easily it will be moved by low intensity fields and higher frequencies. As the implant is placed in a delicate environment, it is preferable to avoid sharp edges and corners in order to avoid any pinching or friction with the surrounding anatomy. However its movement(i.e. rotation) must be able to cause a deformation of the surrounding tissues definitively eliminating the sphere. Usually a disc shape is chosen, with a pole on each face. The M31 (3mm by 1mm disc) has become a standard because it is easily available on the market.

The impact of a field on the magnet is also defined by the strength of the magnet itself. For this application we therefore use the strongest type of permanent magnet available, neodymium N52 (and more recently N55). We can see that in earlier studies [3] N48 was used and therefore we can expect significant differences in sensitivity.

Neodymium (like most materials) is unfortunately not biocompatible and requires a coating. This is the main problem in the design of SMIs, because the non-magnetic mass / total mass ratio must at all costs be minimized in order to optimize the system. The coating must therefore be as thin as possible while ensuring a long life in the face of wear. With current manufacturing constraints, the possible options are as follows: silicone, titanium nitride, glass, parylene and more recently titanium. Each with inherent advantages and disadvantages.

3.1.2 Choice of location and implantation procedure

In order to optimize the sensing, the implant must be placed in an area with a high density of sensory nerve endings. It turns out that the area of the human body with the highest density is the hand especially the fingertips which are also quite convenient for this use. Initially this type of implant was placed in the tip of the finger opposite the nail as can be seen in [3]. However, practices have since evolved and nowadays we prefer the side of the finger pad so as to avoid daily inconvenience (pinching the implant between the bone and a held object).

The installation operation is relatively short and not very intrusive because it is superficial. First a small incision is made on the side of the finger then using a flat tool the skin is lifted so as to form a pocket a little larger than the size of the implant. The implant is slipped into it and an optional stitch can be made. Under good circumstances the finger can be used normally again after a week. However, encapsulation (reconstruction of the tissues around the implant) can take 3 to 6 months and is not superficially noticeable. It is only at the end of this period that the implant will produce

Fig. 1. X-Ray showing the two identical finger SMIs and a larger glass-encased magnet between the thumb and the index.

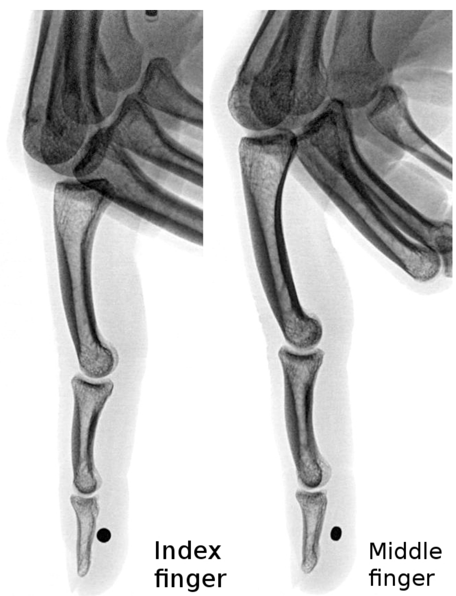

Fig. 2. Side-view X-Ray of 2 finger SMIs that have settled in different orientations.

consistent final results. So any experimental measurement within this period should therefore be considered with caution as it might not reflect the actual performance when healed completely.

3.2 Artificially stimulating an SMI

Stimulation is done by creating a magnetic field around the implant. For this we use one or more electromagnets. It is then possible to vary the following parameters in order to vary the feedback:

- The strength or amplitude of the signal.
- The type of signal: sine, square, audio...
- The frequency, for periodic signals.
- The field's shape.

These variations allow information to be communicated to the user through the signal. The information can be spatial because the magnetic field is continuous in space and the user can touch it and explore its shape.

Due to the nature of this process, there are in theory two ways of transmitting information by a magnetic field to an SMI:

In a first case, the field is fixed. For three-dimensional information, its shape is manipulated to reflect the information. For example a magnetic field in the form of a virtual object is projected into space and the user is free to touch it. For non-three-dimensional information, it suffices to make the field uniform and to vary the signal according to the information. For example for Morse code the signal varies between two frequencies and can be felt uniformly throughout the space. The works of Q. Zhang, H. Dong and A. El Saddik [10] come close to this technique. In their version a virtual surface is created by an array of electromagnets and can be explored using a glove with magnets on it. However, this example is based on a continuous field and the repellent effect of on the glove. A comparable version for SMIs would rely on alternating fields and the ability of SMIs to detect them even at low intensity. While this option is ideal for large-scale 3D display applications, it inherits all of the issues associated with the formation of large and complex shaped magnetic fields.

In this second case, the field is fixed relative to the implant. In the case of our SMIs it can be produced by a ring or a bracelet for example. This time, to produce three-dimensional information, the position of the fingers will have to be monitored in real time in order to determine the appropriate stimuli in relation to their movement in space. This method has the disadvantage of having to equip yourself with a device. However, the shape of the field does not matter as long as it encompasses the implant and there can be full control of each individual implant at all times. In addition, the magnetic field to be produced is of much smaller scale, which makes the material much easier to design. In a way this is similar to the uniform fixed field but with the advantage of individual control of the implants.

We therefore opted for the second option for the control it offers and the simplicity of its design. However, our conclusions may apply in both cases.

4 Wearable stimulator design

In order to be able to experiment with our ideas, we had to create the device that will transform our signal into a magnetic field. For this we have considered many options, including a device in the form of a bracelet. This bracelet could consist of a single large electromagnet encompassing all the implants of the hand in a single field or of a set of electromagnets arranged in a circle. This second option would theoretically have allowed the creation of complex shaped fields, essentially forming a "magnetic display" (similar to that of Q. Zhang [10]) around the hand.

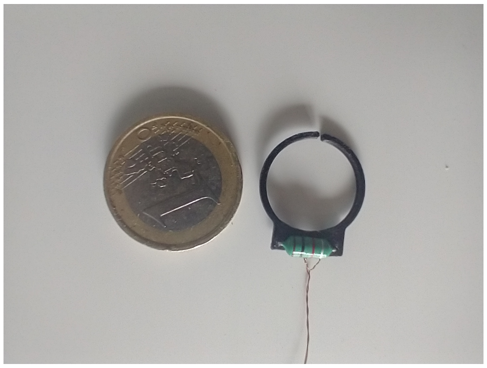

Fig. 3. A ring design utilizing a single axial inductor on a 3D printed base.

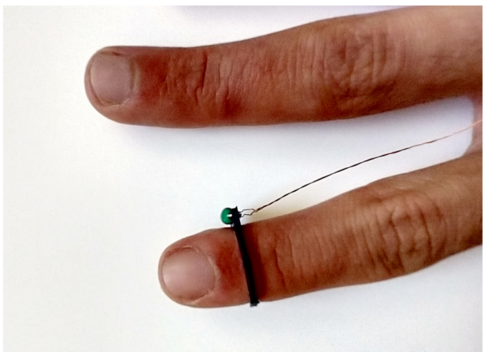

Fig. 4. Ring worn at close proximity to the implant.

The alternative considered was that of rings whose body constitutes the electromagnet. In order to test all these different configurations and the ways to optimize the magnetic flux, we used simulations. We used a finite element analysis software (Finite Element Method Magnetics). Unfortunately, obtaining the sufficient field range for this application would have required the manufacture of complex custom-made coils with metal cores and the final format did not necessarily meet our criteria.

Finally we have chosen a new system in the form of rings using an unshielded axial inductor to produce the signal. The support rings are modeled and printed in PLA 3.

Given the desired frequency and intensity range we have decided to treat our signals as standard audio. The disadvantage of this method is that the production of frequencies below 50Hz is often limited by the hardware. However, it offers the advantage of being able to use the existing protocols and audio channels of our devices (bluetooth, aux outputs, etc.).

The rings are therefore connected to the outputs of a portable audio amplifier. Initially we considered the use of custom rolled coils however the use of inductors proved to be more compact and more coherent while the loss in performance is negligible. Due to their small size and the nature of the inductor used, bands must be worn at implant level 4.

The inductor is chosen such that its resistance limits the maximum current that can be produced by the amplifier so that it corresponds to the maximum current supported by the inductor. In this way no additional components are needed and the inductor is used to its full potential. We can of course use the two stereo channels to control two rings separately. For our rings, a 5W two-channel amplifier proved to be sufficient. Therefore the amplifier is only a few centimeters. We use power cable and audio-jack cable for signal input. The rings are connected to the outputs of the amplifier by very fine wires of about 1 meter.

This system meets our main criteria:

- At least two fingers can be stimulated independently.
- The fabrication is easy and the performance of each ring is consistent.
- The device is discreet and is not restraining the user.

5 Haptic rendering of a virtual environment

Based on the limitations and advantages of this method here is an overview of potential use-cases at the moment divided into three categories We propose to use SMIs as a haptic feedback device in virtual environments, augmented reality and robot control. They would provide pressure and texture feedback while retaining an extremely low mechanical complexity and low constraint for the user. We will be using Unity to construct a VR scene and a LeapMotion to keep track of the user's hands within this scene. The previously designed device will produce a feedback corresponding to the hand's (more specifically the fingertip) overlap and movement relative virtual objects. From the 3D virtual interaction we first extract the depth of penetration of the fingertip in the object perpendicularly to the closest object surface point. This value will directly correlate to the felt pressure. The pressure will be defining the amplitude of the feedback signal. In this simple scenario the signal is sine-wave of low frequency (around 50 Hz)for a finer amplitude discrimination [2]. Every material has a default ”surface thickness” that defines the depth at which maximum amplitude is reached. This simulates the softness of the fingertip. An additional value can be added to represent the object's softness.

Then we try simulating texture. For that we assign each material a spatial period representing the coarseness of it's texture. We then calculate the tangential velocity of the fingertip to the object's surface and with the following formula [11] we deduce the feedback frequency: $F = tangentialvelocity/spatialperiod$ This frequency can the be applied as an amplitude modulation on our previously described signal or can directly replace the 50Hz base frequency. Sadly the calculation of the tracked finger's velocity introduces a lot of unwanted noise as opposed to the simple collision tracking used for the pressure simulation. This is of course due to the tracking precision of the LeapMotion controller but also to the natural shaking of a hand in empty space (the shaking would not be present when touching an actual physical object due to friction). In the optimal lighting condition for the hand tracking and by filtering the values with a rolling average we still get spikes in absolute velocity of up to 6 mm/s. This can be reduced by further filtering but then the input delay becomes noticeable. This means we can either threshold the texture simulation to a minimum velocity which gives inconsistent feedback on slow movements or the feedback can be left as is but the feedback for a static touch will remain noisy. We found the second option much more distracting.

Add section on characteristic feedback here (buttons and other recognizable punctual feedbacks)

6 HAPTIC RENDERING OF ALTERNATIVE SOURCES

When considered as less disrupting alternative to visual (screens) or audio(speakers) input SMIs can be envisioned as a new discrete information streaming route from digital devices to the brain. In this first idea the device could be connected to sensors of any type effectively creating what is referred as sensory substitution. A common example is using an ultrasound range finder to aid in the navigation of blind people. In this example a feedback is given relative to the distance of the person to an obstacle. In a similar way a microphone can be used for the deaf. This last example has been tested extensively using surface of the skin vibration with very conclusive results. With training participants were capable to recognize and differentiate sounds in [12]. This is good evidence that similar results if not better could be achieved with SMIs. The interesting lead on this option is to think of all the possible "artificial senses" one could learn. The "North Sense" trans-dermal implant is also a great example of what can be done through sensory substitution. Created and used by Liviu Babitz, it constantly notifies the user of their orientation through a vibration on the chest. Over time users have reported being intuitively aware of their geographical orientation without consciously paying attention to the implant.

7 EXPERIMENTS

7.1 Material and methods

The experiments on haptic rendering will be done using Unity combined with a Leapmotion controller placed flat on the desk in front of the user. For the stimulation the device detailed earlier will be used.

7.1.1 Shape recognition and scale

We want to test how effective the 3D feedback is at giving the user information about the virtual objects he is touching. For that we will be asking the subject to discriminate between three simple 3D shapes by touch alone. We will be varying the scales of the objects at each round.

This is how we will proceed: The test subject will be equipped with our stimulation device. Ideally two rings will be used on two implants unless the subject only has one in which case only one will be used. The subject will be seated at an empty desk with just the Leapmotion controller in front of them.

At each turn three shapes (a sphere, a cube and a cylinder?) will be presented to the subject. Their scale will be randomly selected (uniform for the three shapes). The subject will be given time to touch them and try to tell which is which. The experiment will be repeated with a variety of scales.

This experiment will hopefully give as clues as to the effectiveness of the feedback in 3D while taking into consideration the limitations in spatial accuracy that the hardware and software could give rise (by keeping track of the scale). We will of course be monitoring the answers to the test in relation to the scale but we will also be logging the finger trajectories that could be interesting to analyze thereafter.

7.1.2 Hardness/force discrimination

In testing hardness we wish to determine if the simulation of different material properties can effectively be rendered through the SMIs.

In this effect three cubes will be presented in a similar fashion to the previous experiment 7.1.1 except this time the subject will have a visual representation of the cubes and his hand(s) on a screen as this should not impact the experiment and helps with finding the objects. The cubes will be visually identical.

At each turn, a randomized hardness will be attributed to each cube (different for each). The subject will be asked to rank them (from softer to harder) by touch.

With this experiment we hope to demonstrate the variability of pressure feedback and hopefully determine a discrimination threshold.

7.1.3 Effectiveness of punctual recognizable feedback

The simplest stimulation we can produce in a virtual environment is a simple short pre-recorded signal, yet it might be hugely effective, especially if it is a tactile response that the user is familiar with. We want to determine the effect of such a feedback on the precision and dexterity increase of a user when the feedback expected from real world circumstances is produced through the SMIs.

To do so we take the example of a simple and familiar mechanical button click. The subject will be seated in front of a screen and the Leapmotion controller. On the screen will be represented the virtual environment consisting of an array of five large buttons on a wall facing the user and a representation of the user's hand in that space. Each of the buttons has a corresponding light over it. The buttons are animated and can be "pressed" by the user. At each turn the buttons will be producing a feedback or won't. We will then ask the subject to quickly turn all the lights on.

We expect the absence of a feedback to confuse the user into pressing the buttons too much or too little effectively loosing time. We hope that the familiar response of a button clicking when sufficiently pressed will allow for the task to be done more cleanly and quickly. We will be tracking the fingers to analyze the depth and consistency of the presses. [I would like to find 1 or 2 other examples than buttons]

7.1.4 Evolution of sensitivity thresholds

It would be interesting to test the lowest detectable amplitude of a 200Hz sine so that we can compare the results with [2] I. Harrison's and therefore know if changes in design of the implant in the last years make a significant difference in sensitivity. To do so we would use a fixed coil of similar dimensions as in [2] Harrison's paper. On the bottom center of the coil we place a gaussmeter probe and we also monitor the drawn current. The subject then places their finger in the center of the coil and either no signal or a signal of randomized amplitude is sent through the coil. Each time the subject says if the stimuli was felt. We expect lowest thresholds around 0.005 mT instead of the

0.03 mT average found previously. Also the gaussmeter will allow us to validate the estimated field strength as we expect that there is a significant difference between estimated and measured values.

Additionally the previous experiment could be repeated with varying frequencies for a sine, square and sawtooth wave to obtain sensitivity curves for each **??** in a more reliable way. This might take some time though as there is 42 frequency-signal type configurations to be tested.

Finally we could validate my categorization of sensations **??** by giving a series of stimuli to the subject and asking them to assign a category to each. If the results match between subjects then the description can be considered as accurate.

7.1.5 Alternative feedback sources

For this second set of experiments we wish to test the understanding of basic information when transmitted through SMIs.

Firstly we would like to experiment with the transfer of continuous information such as provided by most environmental sensors. We will use the on-board compass of the android device to keep the subject aware of their current cardinal orientation. We hope that the subject will be capable of keeping track of their orientation independently of visual cues and memory. To test this the subject will be equipped with the android device in a frontal or rear pocket making sure that it will be held firmly against the body and not rotate relative to the body. They will then be equipped with the stimulating device and blindfolded. The subject is told to memorize their orientation. We finally proceed to spin the subject around and ask them to face back to their original orientation. This will be repeated five times without any stimuli and five times with it.

[I would like to add a second navigation-related experiment here...]

7.1.6 Results

7.1.7 Discussion

7.2 Further research

7.2.1 Long term sensory substitution

We're interested in exploring the extents of sensory substitution through this new medium. An idea would be to use audio signal of sound or speech to the stimulate the implants. To get the best results the signal would have to be remapped in the frequency domain from it's original range to something close to our tactile sensitivity. Of course remapping the full audible spectrum (20-20,000Hz) to our limited sensitivity of 10-300Hz would lead to an extreme loss of resolution but simple sounds such as speech use a much more reasonable range. Hopefully, through extensive training, simple sounds or speech could be understood. Alternatively method's like the ones used in the Neosensory Buzz [12] might be applied. If it ever turns out that such complex information can be interpreted through this medium it's design simplicity and convenience will shine in many fields like helping with disabilities, discreet communication, information streaming in high stress scenarios [13] and of course augmented reality.

7.2.2 Shaping the magnetic field

An other lead that we hinted at earlier is the use of this technology on much larger scales. Assuming it is possible to produce fully controllable room-sized magnetic fields then a user within that space could be provided with information while being completely free of any equipment. This could in theory be used to render full scale tactile virtual environments, establish silent and targeted communication or even 3D guidance. An obvious use for that would be in VR entertainment but it could also be used in dangerous or high stress workplaces. Of course the use of SMIs in such a large scale depends largely on our ability to produce and manipulate magnetic fields which is an ongoing filed of research to this day.

8 Conclusion and future work

The conclusion goes here.

Acknowledgments

The authors would like to thank...

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