Implants for Haptic Rendering

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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 body implantable haptic displays. Implantable haptics conceptualizes the idea that haptic displays can also be considered as permanent implants, which can be used to display haptic data or enhance human perceptual modalities using surrounding nerf-endings. We exemplify our concept with an example of such displays: subcutaneous magnetic vibrator implants and their potential in conveying haptic data or substituting non-haptic data into haptics.

Index Terms—Computer Society, IEEE, IEEEtran, journal, LaTeX, paper, template.

1 Introduction

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August 26, 2015

2 Background

2.1 The touch sense and cutaneous mechanoreceptors

In [1] K. Johnson analyzes the four mechanoreceptive afferent neuron types and their distinct perceptual functions in glabrous skin: The Pacinian are located in the deeper layers of the skin and are targeted at sensing fine surface detail as well as vibration and are therefore most sensitive to higher frequencies ($< 250Hz$). Rapidly Adapting afferents end in Meissner receptors which are targeted at roughly textured surfaces and therefore are most sensitive to lower frequencies ($30 - 50Hz$). Slowly Adapting type 1 end in Merkel disk receptors which are situated in the epidermis (superficial layers of the skin). They are sensitive to rough textures, shapes and edges and therefore deformation of the skin. Finally Slowly Adapting type 2 afferents are thought to end in Riffini receptors that are not well understood but most probably respond to stretch.

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 [2]. 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 [3]). In addition to the added complexity, mechanical systems face the issue of miniaturization and the difficulty to embrace the uneven nature of the human body. Nevertheless the more recent approach of using ultrasound interference to produce a stimuli on skin in mid-air [4] solves these issues and makes it possible to produce the sensation of 3D shapes in empty space [5]. We can also mention the air-jet technique although it's much less versatile compared to ultrasound [6]. Still, the ultrasound technique has its own limitations: The stimulation range is limited to tens of centimeters [7]. 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 [7] 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.

2.3 Sensory substitution through touch

In [8], sensory substitution is used to feed pre-processed audio information through vibrations on the surface of the skin. For that they use a bracelet containing the electronics and four evenly spaced vibration motors that lay flat against the skin.Effectively creating a one-dimensional display [3] Over a relatively short training period (28 days) deaf participants were capable of identifying and discriminate sounds with an impressive success rate.

It is also worthwhile mentioning that, even though sensory substitution is commonly accepted as the re-mapping of senses and has given encouraging results, it is neither fully understood or proven to do so. This is further explained in an interesting paper [9] where the author proposes an alternative explanation to the results we've seen in sensory substitution experiments. According to [9] the phenomenon is closer to the acquisition of reading skills in that it consists in building a second route, necessitating the existence of a first sensory route and parallels it. In this way sensory substitution is the progressive creation of an automated identification skill rather than the rerouting

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of information to an existing processing route. Sensory substitution may also be limited in the way that there are differences in spatial bandwidths between senses as mentioned in [9]. For example the touch sense alone might not be sufficient to fully substitute for a broader bandwidth sense such as vision.

3 Implants for Haptic Rendering

3.1 Concepts

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 suggest integrating technology directly to the body. This might sound dangerous and intrusive but as we see in this paper 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 great potential in haptics and human-machine interaction with relatively low risk and invasiveness.

3.2 Subdermal magnetic implants, SMIs

In the biohacking and body-mod communities magnetic implants have existed since the early 2000s. Their main appeal is that they give the implantee the ability to "touch" magnetic fields, although other uses exist, like integrated headphones with ear implants [10].

3.2.1 Implant design

3.2.1.1 Shape: 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 side. The M31 (3mm by 1mm disc) has become a standard because it is easily available on the market.

3.2.1.2 Magnet type: 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.

3.2.1.3 Bio-safe coating: Neodymium (like most materials) is unfortunately not bio-compatible and requires a coating. This is the main problem in the design of SMIs because the non-magnetic mass to 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 guaranteeing a decent durability in vivo and a very low permeability. With current manufacturing constraints, the possible options are as follows: silicone, glass, titanium and parylene. Each one with inherent advantages and disadvantages. With a growing demand it seems that titanium encasing is finally becoming affordable for manufacturers and is the best option as of 2021 although prices are still high when compared to it's predecessors.

3.2.2 Choice of location and implantation procedure

3.2.2.1 Location: 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 [11]. 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).

3.2.2.2 Implantation procedure: 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 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.

3.2.3 Author A. Fougues' right hand SMIs

Axel's two finger implants that were implanted prior to this research (25/09/2019) for personal augmentation. As expected they provide the ability to sense magnetic fields at close proximity. For the locations, he chose the right side of the tip on his right middle and index fingers 2. These fingers were chosen for being the most intuitive way to feel something (Axel is right-handed). They are both on the right sides so that they would not stick to each other, which could become annoying on the long run.

As clearly visible in the full hand X-Ray the two small disks have settled in a different orientation. Although they are free to rotate under a strong force it seems that they still default to this position two years later. This can be explained by the process of encapsulation, where the surrounding tissue grows back to form a capsule around the implant. This capsule having taken a specific shape can deform but will usually push the implant back to a default position. Although this almost 90 deg divergence in orientation

Fig. 1. X-Ray of Axel's right hand (16/10/1019) showing the two identical finger SMIs and a larger glass-encased magnet between the thumb and the index.

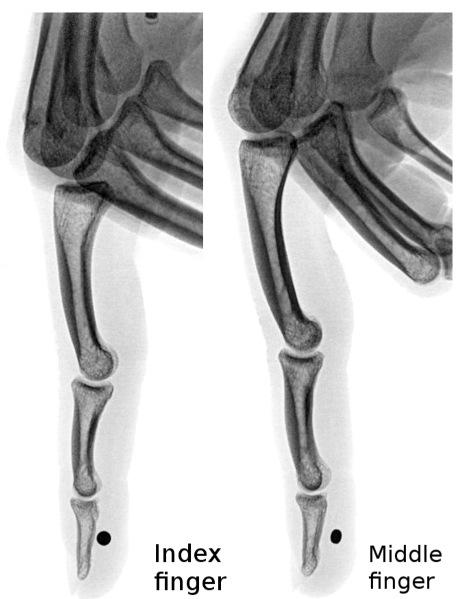

Fig. 2. Side-view X-Ray of Axel's 2 finger SMIs (16/10/1019).

has produced a very slight difference in sensitivity when sensing magnetic fields depending on their orientation, the contrast is barely noticeable.

It is worth mentioning that a larger magnetic implant is present in the soft tissue between the thumb and the index 1. This implant, commonly referred to as xG3, is a 15mm by 3mm Neodymium rod axially magnetized within a glass capsule. Due to its increased mass and friction it requires much stronger fields to be moved and the location is not ideal for sensing. So we won't be focusing on this one even though it might be stimulated too as a byproduct. It would nevertheless be interesting to consider it's properties in further research as its shape and mass should respond better to lower frequencies.

3.3 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 shape of the field.

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.

In this first article on the subject of magnetic implants [11] Hameed et al. establish the concept of sub-dermal magnetic implants as well as some properties such as field strength sensitivity and frequency sensitivity. Although there were only two participants in the study it effectively demonstrates the principle of stimulating an implant through an external coil and gives us an idea of the results to be expected.

In a following paper [12] Harrison I. et al. proceed to compare these magnetic implants to surface mounted implants in tests involving amplitude detection, amplitude discrimination, frequency discrimination, temporal discrimination and temporal gap detection. They demonstrated an advantageous increase in sensitivity for SMIs and a much finer sensitivity on lower frequencies (20-50Hz). They also discovered a lessened frequency discrimination on frequencies higher than 100Hz possibly due to the overlap of sensed frequency ranges between Meissner and Pacinian corpuscles.

A possible omission in both papers on SMIs [11] [12] is the importance of the implant's design (magnet-to-coating ratio, mass and shape) for the sensitivity in higher frequencies or lower currents. In both cases the magnets used are common 1mm by 3mm disk implants that are made this way due to coating procedures and cost limitations. As magnet manufacturing evolves and implantables become more common SMIs are prone to evolve too, improving their performance.

In fact in our tests on Axel's implants we found some notable differences. The tests were done in a similar manner using a Kramer PA-240Z amplifier and a coil. A Hirst Magnetics GM07 was used for the magnetic flux measurements. For a reliable detection at 200Hz we measured a threshold lower than 0.005mT as opposed to about 0.03mT in [12]. The large difference can be explained by the upgraded implants (grade N52 instead of N48 and parylene coating rather than silicone) but also by the fact that our results were measured rather than approximated. Also we could not get more precision on the threshold as we were reaching the instrument's resolution limits.

We also were interested in sensitivity over a larger range of frequencies and signals. Again testing in similar condi-

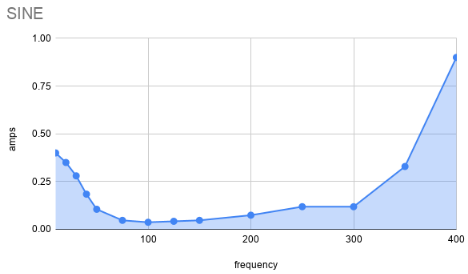

Fig. 3. Relative sensitivity to a sine wave over a 10-400Hz frequency range.

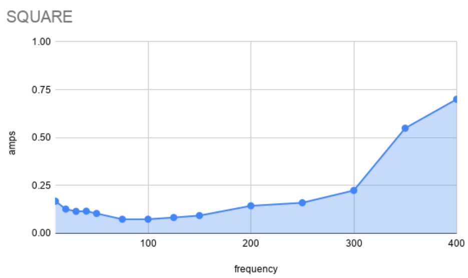

Fig. 4. Relative sensitivity to a square wave over a 10-400Hz frequency range.

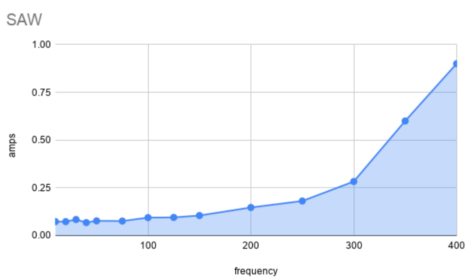

Fig. 5. Relative sensitivity to a sawtooth wave over a 10-400Hz frequency range.

tions we ended up with three different sensitivity curves for a sine, square and sawtooth signal.

As you can see used amps as an indicator of sensitivity. In the following estimation of the field strength $B = \mu n I$ both μ (permeability) and n (turn density) are constant so the current I is proportional to the field strength B. Since we can easily and accurately measure I we can therefore use it here as an indicator of sensitivity and the vertical axis is effectively the amount of amps necessary to reach the threshold with an identical setup. For this experiment both fingers were used and there was no significant difference in sensitivity.

The results are visibly different for each signal. The most sensitive range overall being 50-300Hz as expected. Also all signals lose sensitivity rapidly over 300Hz. On low frequencies (¡100Hz) the sharp polarity changes in the square and saw waves make them stand out more while the sine wave tends to fade out.This makes sense, in lower frequencies the sharp drops in the saw wave produce a fast change in polarity that can be assimilated to a pulse signal and be felt more easily even in very low frequencies. In the mid-range (100-300Hz), the sensitivity threshold is similar for all waves. Above 300Hz we can see that the square wave does not fade as quickly as the other two. As the frequencies get higher above 300Hz the changes in polarity become too close to be sensed. We can see that the square wave is slightly more less affected. It is difficult to explain but we can suppose that the square wave (and saw to some extent) should be felt better in the higher frequencies as the changes in polarity are further apart and sharper. The reason saw waves are less sensitive than square waves in high frequencies might be that the sharp polarity change is always in the same direction and contrary to low frequencies the implant does not get enough time and/or energy to move all the way back. In [12] amplitude detection was only tested on two frequencies, here we test them over a range. Nevertheless the higher sensitivity at 200Hz than 20Hz (Amplitude RL results) is similar in our results.

As tested and proven in [13] tactile stimuli also has the advantage of producing much faster response times than it's visual and auditory counterparts with no significant influence from the position of the stimuli.

Describing the sensations produced by the stimulation is very subjective but a general idea can be given. As such we have categorized the sensations:

Incoherent	I	Hard to recognize the signal. Noise or a continuous signal with spikes in amplitude. Like holding a bee.
Continuous	C	Feels like lightly sliding the finger across smooth fabric or very soft fur.
Vibration	V	A soft vibration of discernible frequency, not very localized and fades throughout the finger. Can feel like rough fabric.
Buzz	B	A sharp vibration that reverberates through the bone. A pull on the magnet's area can be felt at the same time. Feels like touching a running engine or running your fingers along the bars of a fence.
Tapping	T	A sensation of being hit or tapped at the implant's location at a speed equivalent to the frequency used.
Deformation	D	Feels like something is crawling under the skin, similar to rubbing the finger on a surface of small beads or pressing on a small ball bearing.
Pull	P	Very localized feeling of the implant being attracted in a direction (the direction can be hard to determine). It is a continuous version of ”Tapping” but the mechanoreceptors get used to it so quickly that it takes a lot of power to be felt reliably.

The order they are in loosely correlates to the frequencies they correspond to with very high frequencies tending towards I and low ones towards P but over all different signals tend to intensify different sensations. For example a sawtooth wave will produce a very distinct T while a sine will be much closer to a D. It is also important to mention that depending on both signal type and frequency each of these sensations can feel sharper or smoother while still belonging to the same category. Effectively making it possible to differentiate one signal type from another even though the produced sensations are similarly named.

3.4 SMI key benefits and drawbacks for haptic rendering

By comparing to existing methods we can deduce the strengths and flaws of our implant-based technique. Of course we take into account the constraint of having to have one or more implants placed. However, in view of the trends [14] and the potential of body hacking we will remain optimistic about a future where (non-medical) implants are widespread and accepted.

Benefits:

- As with the ultrasound method, our technique does not require physical contact.
- Our method allows higher and finer force feedback (as opposed to the weaker ultrasound feedback).
- The system is simple and therefore compact, versatile and scalable.
- Magnetic fields are unobstructed by the vast majority of bodies and materials (again as opposed to ultrasound). They are also not noticeable by humans and the majority of living beings.

Drawbacks:

- SMIs only stimulate at one point (each), therefore we do not have the resolution of a mechanical system or the ability to cover an area like the ultrasound-based system.
- The range of a magnetic field is limited. A magnetic field follows the inverse cube law (R^{-3}). This can be compensated to a certain extent by a more powerful system.

4 WEARABLE STIMULATOR DESIGN

In order to conveniently test our theory and the practicality of using SMIs in various circumstances we will have to design and create a stimulating device accordingly. The goal of the device is being capable of stimulating the full sensitivity range of the implants, it will therefore be usable in any use-case. We will be designing our device so that it takes full advantage of the method's strong points. It will therefore make use of the scalability of this technology and be designed to be as wearable, discrete and compact as possible. The goal being to obtain a device that is practical in daily use over long periods of time without restraining the user as this seems to be one of the main obstacles haptic feedback is facing.

4.1 Electromagnet coil geometry

After comparing a bracelet and a ring configuration we opted for the rings as they were much more feasible when it comes to range and power. Our stimulation coil would

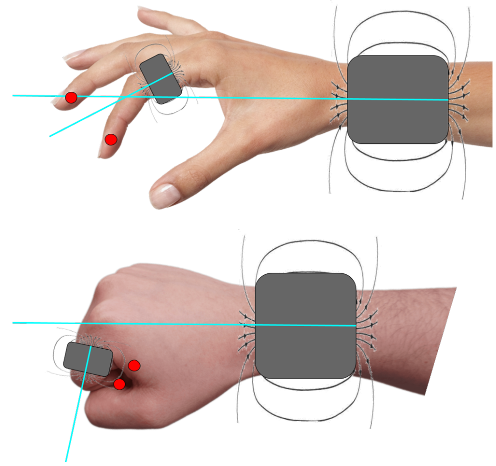

Fig. 6. Demonstration of the relative position of magnet implants (red dots) to the electromagnets (wrist and ring configuration) in different hand positions. The blue lines represent the z-axis of the electromagnet and it's field.

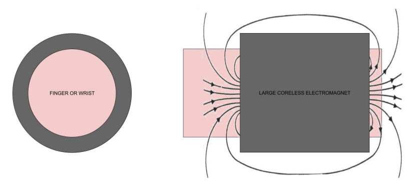

Fig. 7. A ring design utilizing a single air-cored electromagnet with a crude representation of the field lines. Front view on the left and side view on the right.

therefore be worn around the finger and would have to be in reasonable dimensions.

It is worth mentioning that the hand's position can move the implants relatively far from that axis but given the capsule-like shape of the magnetic fields of solenoids the implants should remain within the field. Nevertheless this means the stimulation strength will vary as the user moves their fingers as the implants will get closer or further from electromagnets.

A simple coil wound around the finger and was used in [11] but air-cored are capable of a much lesser magnetic field when compared to iron-cored (human anatomy can be considered as water that has a magnetic permeability close to 0, like air). Therefore a air-cored wrist design would be highly inefficient due to the large distance to the SMIs. We designed a bracelet of similar proportions constituted of parallel cylindrical iron-cored electromagnets forming a ring.

This layout can be compared to a simple array reminding us of [15] and raising the possibility of shaping the produced field in a similar but simpler way.

4.2 Simulate and test various electromagnet types and configurations

For this first part we can start obtaining and testing various setups of electromagnets. They can be tested in two ways:

The first step will be to reproduce the amplitude experiments from [12] as the modern magnet implants are about

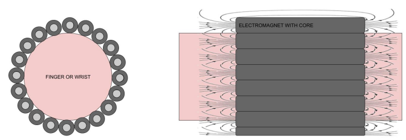

Fig. 8. A ring design utilizing a chain of parallel cylindrical iron-cored electromagnets with a crude representation of the field lines. Front view on the left and side view on the right.

20% stronger (Grade N50 as opposed to the grade N48 used in [12] and [11]). We expect the detection threshold to be slightly lower.

Then we will be able to simulate and test physically the variety of selected electromagnets to determine their specifications, range and field shape. From that data we will be able to determine the best ring and/or bracelet setup as well as the power requirements.

This testing will focus on determining the maximum usable range but also that the pain threshold is not surpassed on close range. The goal being to validate our theoretical design 8. By using both methods of testing we also confirm that the values found in [12] match the experimental results we will have with our implants.

To verify how the electromagnets we choose interfere in close proximity (ring formation 8) we can try using a simulation software.

5 Rendering use-cases

Based on the limitations and advantages of this method here is an overview of potential use-cases at the moment divided into three categories

5.1 Haptic rendering in VR and AR

This first type of usage would be centered around haptic feedback. When controlling a robot for example, a precise sensation of pressure and maybe even texture could be given through SMIs. This is already one of the major focuses of haptic feedback especially on medical robots. Another similar field is haptic feedback in a XR environment where touching a virtual object could be made more convincing if the user could feel it. Again our device could be combined with a common VR setup to provide this kind of feedback while also leaving the users hands free for hand tracking or using controllers.

5.2 Sensory augmentation and substitution

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.

5.2.1 Sensory augmentation based on external sensors

In this last option 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. Essentially giving them the lost basic form of ultrasound echolocation. 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 [8]. 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 worn 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.

Finally, assuming it is indeed possible to shape the field produced by the multiple cored electromagnet configuration, the device could be use as a wearable haptic display. This could be used in all three use-cases to create the illusion of movement or even basic individual SMI stimulation in a 3D environment without advanced finger tracking.

5.2.2 Media and digital sense

We spend hours interacting with the digital world and that interaction usually fully engages at least on of our main senses making it difficult or impossible to execute another task at the same time. We would like to use our auxilary information channel to free the user's hands, ears and eyes while still streaming information to them. On the most basic level, for example, the device is connected to a users phone and relays notifications and ringing through the SMIs. On a much more advanced level, complex information (sound, speech, directions) could be streamed to the user continuously without impeding them of full sensory capacity (hearing, looking, touching) and mobility (using their hands) like holding a phone would. This concept can be difficult to imagine but basing ourselves on existing research on sensory substitution through touch and concepts like brain plasticity it should be possible to an extent.

6 Experiments

6.1 Haptic rendering

6.1.1 Material and methods

For this category we can try to give basic touch feedback in a simple VR/AR environment. Using simple geometry and existing hand tracking technology. 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 relative to the hand's overlap with virtual objects. The experience can then be compared with SMIs, with superficially placed magnets and without feedback at all. As the experience and immersion are subjective and difficult to evaluate we could instead evaluate the performance in doing a difficult task, like moving objects to a precise location. This would allow us to compare how much more aware and efficient a person is within a VR environment with the feedback.

6.1.2 Results

6.1.3 Discussion

6.2 Sensory augmentation and substitution

The most simple and probably the first example to be tested is blind navigation using an ultrasound range finder. The output of the sensor will be converted into input for the device hopefully allowing a person to navigate a simple space while blindfolded. A simple app can be coded to interact wirelessly with the device in order to communicate game feedback or notifications. The ground work for this (software) has already been done in prior personal research.

6.2.1 Material and methods

6.2.2 Results

6.2.3 Discussion

6.3 Further research

6.3.1 Transition to on-board signal processing

It will probably be interesting at this point to transition to an on-board signal processing and finalize the device as a standalone system.

6.3.2 Shaping the magnetic field

Assuming it is possible with a ring of electromagnets we can try to simulate shapes, movement...

7 CONCLUSION AND FUTURE WORK

The conclusion goes here.

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