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Natural Interactive Walking

Deliverable 2.2

Haptic Device Engineering for Walking Interactions: "Reproducible haptic device prototypes for integration in multimodal contexts"

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Contents

1 Introduction to Deliverable 2.2

1.1 Subminiature Actuators

Work has been directed toward the engineerings of haptic-capable actuators suitable to be embedded in shoes and other items in contact with wearers and users. The major challenges in the design of such haptic-capable actuators may be listed at follows:

1. The actuator must of size and of a form factor compatible with the dimensions of the components of a shoe. In practice, the actuator must be at least small enough to be embedded inside the sole of the shoe.
2. The actuator must be able to provide stimuli of a magnitude that is commensurate with the stimuli naturally occurring during waking.
3. The actuator must be sealed and crush-resistant.
4. The actuator must not consume a lot of power, aiming at an autonomy of 1 hour on a small battery.
5. The actuator, despite its small form factor, must be able to provide stimuli in the low frequency range, two requirements that oppose each other.
6. The actuator should be simple to manufacture and be of potentially low production cost.
7. The actuator must be very reliable and rugged.

Note: Since there is interest from a major corporation in the developed actuators, this part of the deliverable should remain confidential.

1.2 Scaling Law Theory for Such Actuators

The haptic actuators' operation is very sensitive to length scale. The performance, analogously to loudspeakers, is linked to the scale at which they are build since they operate from the basic physical (Newton's fundamental principle of mechanics, Maxwell's equations, and heat diffusion equations). Since there is interest in building them in several sizes, there is advantage in developing a scaling theory for these devices in order to predict performance. Such theory is outlined.

1.3 Haptic shoe prototypes

Several pairs of hapticized shoes were developed to the partners. A brief description of their design is provided.

1.4 Hapticized balance board

The balance board is device used in rehabilitation and entertainment (balance rehabilitation, home training for skaters and surfers, electronic variants Nintendo, etc.). There are many variants of such boards, but one of them is a circular disk 0.5 m radius having an hemispherical protrusion of radius 0.15 m. Such board was made haptically capable based on the structural suspension developed in D2.1 and delivered to AAU.

1.5 Fluid Actuator Concept

There is scientific justification in providing haptic feedback to the foot that covers both the tactile and the kinesthetic range [1]. While our research outlined above as shown that it is feasible from the energetic view point to provide tactile feedback to the feet, unfortunately such is not the case of kinesthetic feedback. We therefore oriented our research toward a different concept. Here, the actuating power is provided by the walker, as in real life, and the actuator is there to *passively*, i.e. without doing generative work (rate of energy transfer through a port). The goal is to modify the mechanical behavior of the sole, reproducing the behavior of different walking grounds.

Note: This invention was disclosed to the UPMC industrial office and a patent is now being written after positive search report of prior art.

1.6 Distributed actuator

The electronic system to drive 2 X 700 tactors from a single Arduino micro-controller constructed and tested; mechanical assembly under way.

2 Subminiature Actuators

Previous research have shown that the shoe sole can accelerate at up to 10 m·s^{-2}, see Fig. 2.1. It should be noticed that the highest accelerations are in the low frequency range of the spectrum, and that within the tactile domain — 20–1 000 Hz — the acceleration is below 1 m·s^{-2}. The explains why the 3 G actuators, see [2], used in the prototypes already delivered to the partners (see Deliverable D2.1, Section 2.2.4, and subsequent improvements) are capable of adequate reproduction of the tactile aspects of walking on materials despite the attenuation due to the indirect coupling the actuator to the glabrous skin of the volar regions of the foot. They are strong enough to tolerate an attenuation by a factor 3 to 10.

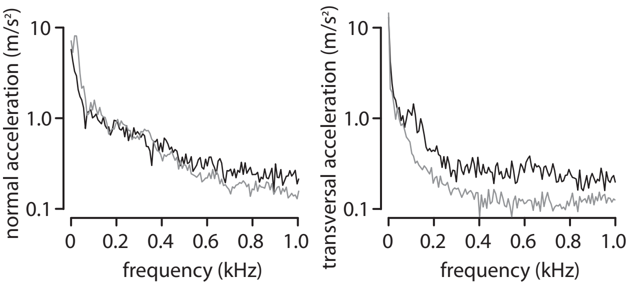

Figure 2.1: Average acceleration spectrum of a shoe sole elicited when walking on gravel or on wood. Data from [1].

In thinking of virtual reality applications and assuming that the participants can carry a 10 Whr battery (the battery capacity of a high-end compact camera), it can concluded that for an autonomy of at least one hour, the actuation system of two shoes should be consume more than 10 W on a continuous basis, including the losses in the amplifier. The present actuators consume 5 W. So they fit the fill. The more advanced design described later is even more efficient.

2.1 Principle of Operation and Construction

Previous research has shown that due to thermal effects, iron saturation, and progress in the permanent magnet technology, the miniaturization of permanent magnet machines could benefit from "iron-less" designs, where the magnetic circuit includes significants air gaps that are not filled with iron. This observation has triggered much research in the design and construction of iron-less permanent magnet machines, especially in the small scales [3, 4, 5, 6, 7, 8].

For a transducer to be able to operate within the required bandwidth, the use of the Laplace force is the preferred option over variable reluctance approaches, because it can be used to construct linear transducers whereas variable reluctance machines are inherently nonlinear. It permits to achieve arbitrarily large strokes whereas variable reluctance transducers are limited by the geometry of the air-gap. The downside is that transducers based on the Laplace force, like loudspeakers, introduce limits in achieving high specific power and trust.

These constraints prompted us to study Laplace transducers that would have favorable thermal properties, that is, those where the windings are *outside* the magnetic circuit so that heat can be evacuated. To compensate for the absence of an iron armature to concentrate the field lines emanating from a permanent magnet we found an arrangement that was able to focus these lines within a small space by stacking cylindrical magnets so that their poles oppose each other and by optimizing the gap there-in-between. Please see Fig. 2.2, where the field generated in a quarter-space of the permanent magnet magnetic circuit can be viewed after extensive geometrical optimization.

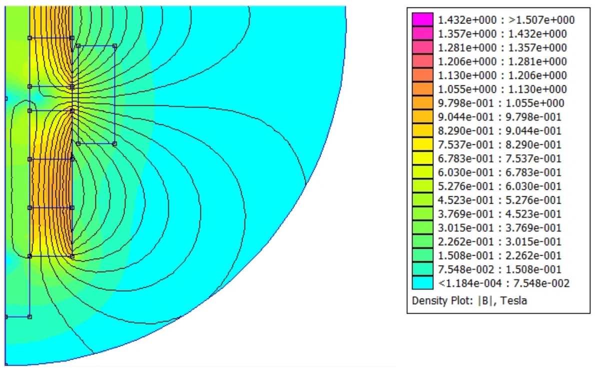

Figure 2.2: Quarter space geometry of field lines in the newly introduced iron-free inverted permanent magnet circuit.

It can be seen that even with very small 4 mm magnets, it is possible to achieve concentrated fields of nearly 0.8 Tesla in air. It must be realized that to achieve linear operation, there are two options available to the designer: Either the high-field region is smaller than the coils so that the output is decoupled from the relative displacement of the moving parts, or the opposite option where the coil must be much smaller that the uniform field region. The latter design have been used in some high-end speakers where the super-linearity requirement prevails over the huge magnet bulk and cost that these designs require. But here, efficiency prevails to the expense of perfect linearity and the former design is selected. It can be seen that this design is very efficient since there are hardly any stray lines escaping either inside the core or on axially.

The next innovation we introduced was to eliminate the mandrel on which coils are ordinarily wound. At the millimeter scale at which we design, this gain is highly significant since the device is very small. It allowed us to reduce the air gap below a fraction of a millimeter, something that would be impossible to achieve with the conventional approach where a 1 mm thick mandrel would have been necessary. But of course the coils cannot stay in place in "thin air" and must be secured with high geometrical accuracy.

To the end, we devised a manufacturing process based on gravity molding. Future, more advanced designs could therefore be based on injection molding which is industrially appealing. Referring to Fig. 2.3, a silicone RTV mold was fabricated to contain the three (or more, depending on the design) pre-fabricated coils separated by four tubular non-ferromagnetic spacers.

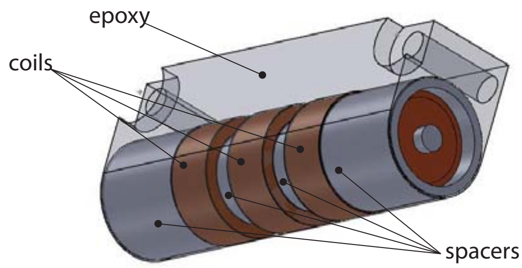

Figure 2.3: Mandrel-free molded assembly concept.

The device can be then fabricated in just two steps. In the first step, epoxy is poured to secure the three coils/five spacers in one single operation with high geometrical accuracy, sparing the hollow cavity where, in a second step, the moving assembly will be inserted. Because of the freedom of shape creation afforded by molding, the device can also be provided with mounting holes for fasteners and routings for the coil leads, while protecting sensitive areas.

The second step can be better understood by reference to Fig 2.4. The key elements are the suspension membranes. As these actuators are scaled down, in order to conserve the output level and simultaneously extend the response in the low-end, it is necessary to provide increasingly large moving part excursions from the rest position.

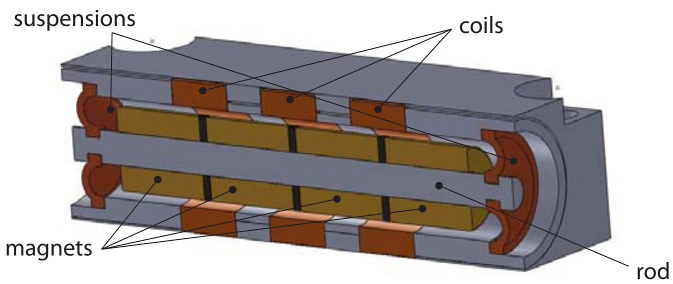

Figure 2.4: Cutaway view showing the inner arrangement.

In previous, larger designs, the suspensions were made of laser-cut rubber disks that were simple to manufacture and were not strongly limiting factors because of their diameters. With the 8 mm design under discussion, however, simple disk-suspension would have greatly limited performance and introduced distortion at high amplitudes. With therefore set out to design new membrane geometries that could provide adequate radial stiffness, high axial compliance, and above all distortion-free large excursions. The result of the optimization were half-tori membranes that were moldered out of natural rubber, a material that is very durable. This design achieves a 6 mm stroke before bottoming and leaves room for improvement. Finally, a central rod constrains and align the four magnets axially and insert directly inside the membrane by snapping without the need for fasteners or clips.

The whole system is therefore very simple: three coils, four cylindrical magnets, two small spacer, two large spacers, one rod, and two membranes, all straightforward parts. The entire assembly is achieved without fasteners, by molding and clipping, and yet guarantee high geometrical accuracy and structural integrity.

Preliminary tests confirm that the performance of these 8 mm actuators is similar or even exceeds that of the previously employed 14 mm actuators which have more parts and that all the objectives outlined in Section 1.1 have been achieved or exceeded. We are preparing a batch of 50 to 100 units for distribution to the partners.

3 Scaling Law Theory

It is important to develop a scaling theory so that that the performance of motors of different sizes and geometries can be predicted from a few sample points in the design space, of which we have now three. The construction of a motor is driven by the following parameters, see Fig 3.1:

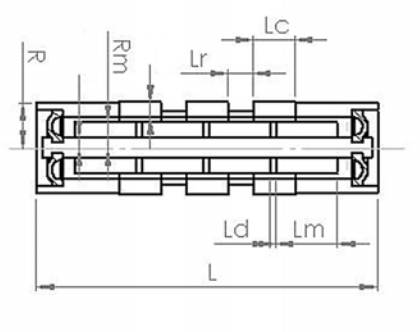

Figure 3.1: Construction parameters.

1. L: Motor length
2. L_m: Magnet length
3. R: Motor radius
4. R_m: Magnet radius

Starting from the basic laws of physics that govern the behavior of these devices, Maxwell's equations, heat diffusion laws, conservation of momentum, it is possible to predict that:

1. Motor constant $\left[\mathrm{N}/\sqrt{\mathrm{W}}\right]$: $K_m \propto R^2 L$
2. Motor time constant [s]: $T_c \propto R^2$
3. Moving parts inertia [kg]: $m_v \propto R^2 L$
4. Thermal resistance [°K·m/W]: $T_r \propto 1/LR$
5. Intermediate disc Length [m]: $L_d \propto L_m R$

6. Coil length [m]: $L_c \propto L_d R$
7. Coil thickness [m]: $Hc \propto R_m L$
8. Lowest cut-off frequency [Hz]: $F_0 \propto L^{1/2}$
9. Dissipated Power [W]: $P \propto RL$

Although this theory is its initial stage of development, it is already possible to conclude that our intuition was correct: in scaling down the device, there is an efficiency advantage in making long and skinny, rather than disk-like.

What remains to be done is derive a few more of these relationships to predict some other characteristics that are directly relevant to haptics, such as the lowest frequency and the largest force achievable for a given scale and geometry. Next we need to proceed with measurements with our prototypes to validate the theory.

4 Haptic shoe prototypes

Several types of haptically enabled shoes were developed and delivered to the partners. One type is of open, sandal type. The objective was to provide the shoe with the means to measure the foot-ground interaction forces and to respond to the pressure applied with a mechanical response effected by the haptic transducers.

Referring to Fig. 4.1, the necessity for small actuators can be appreciated. In this design, the actuators are embedded in the sole (two in the hell, two in the front). Once bonded to the foamy material of which the soles are made, the vibration propagate with sufficient intensity to provide the illusion of walking on difference grounds once the pertinent algorithms simulating interaction with solid or aggregate materials are employed [9, 10].

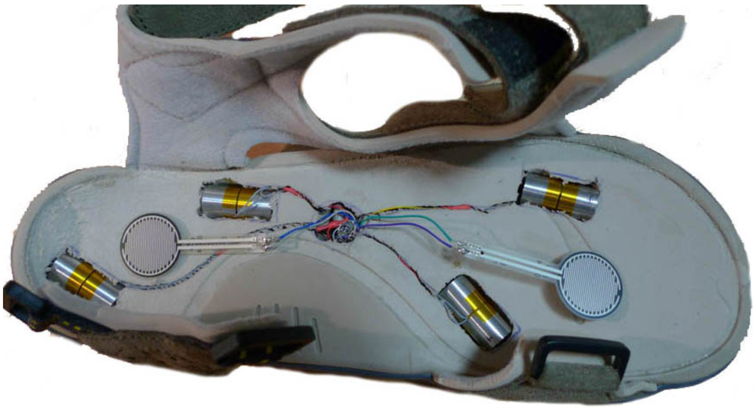

Figure 4.1: Exposed soles showing the sensor and actuators embedded in the foam. There is one sensor for the heel and one for the ball of the foot and four actuators.

In order to provide both audio and haptic feedback pairs of light-weight sandals were selected (Model Arpenaz-50, Decathlon, Villeneuve d'Ascq, France). This particular model has light, stiff foam soles that are easy to gouge and fashion. Four cavities were made in the thickness of the sole to accommodate four vibrotactile actuators. Two actuators were placed under the heel of the wearer and the other two under the ball of the foot. There were bonded in place to ensure good transmission of the vibrations inside the soles. When activated, vibrations propagated far in the light, stiff foam. In the present configuration, the four actuators were driven by the same signal but could be activated separately to emphasize, for instance, the front or back activation, according to balancing behavior of the wearer, or to realize other effects such as modulating different, back-front signals during heel-toe movements.

The sole has two force sensitive resistors (FSRs) pressure sensors aimed at detecting the pressure force of the feet during the locomotion of a subject wearing the shoes. The two sensors are placed in correspondence to the heel and toe respectively in each shoe.

Figure 4.2 shows the overall system organization. A cable exits from each shoe, with

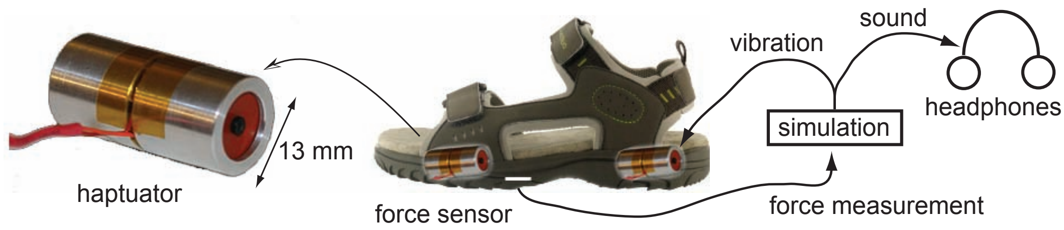

Figure 4.2: Overall audio-haptic simulation system.

the function of transporting the signals for the pressure sensors and for the actuators. Such cables are about 5 meters long, and they are connected through DB9 connectors to two 4TP (twisted pair) cables. One 4TP cable carries the sensor signals to a breakout board which contains trimmers, that form voltage dividers with the FSRs, which then interfaces to an Arduino board. The other 4TP cable carries the actuator signals from a pair of Pyle Pro PCA14 mini 2 × 15 W stereo amplifiers, driven by outputs from a FireFace 800 sound-card. Each stereo amplifier handles four actuators found on a single shoe, each output channel of the amplifier driving two actuators connected in parallel. The PC handles the Arduino through a USB connection, and the FireFace sound-card through a FireWire connection. The connection among the different elements of the system is illustrated in Fig. 4.3.

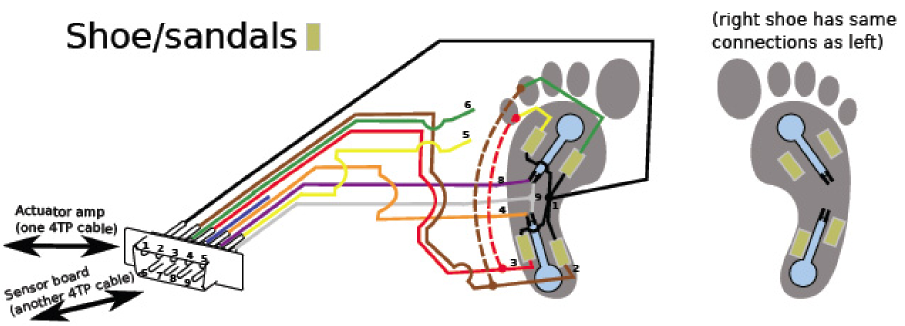

Figure 4.3: System interconnections.

Further details and experimental results can be consulted in the cited references [9, 10].

5 Haptically Enabled Balance Board

These ideas can be applied to artifacts on which we stand other than shoes. A good example is the so-called "balance board". These devices have multiple applications ranging from recreational activities and home training to rehabilitation, with the goal of restoring the sense of postural balance in patients with vestibular or motor deficits. In essence a balance board is a board on which one stands resting on a fixed or rolling pedestal of different geometries to adjust the level of difficulty of the exercise, see Fig. 5.1a,b.

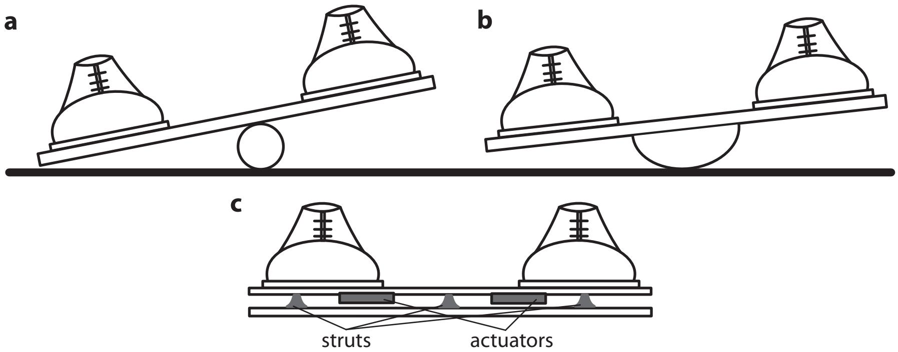

Figure 5.1: Main types of balance boards (**a**). Hapticized balance boards featuring specifically optimized structural elements that permit the haptic stimuli to be transmitted to the foot while supporting the weight of a person (**b**).

Next, there is abundant literature showing that tactile stimulation to the foot has both an effect on the physiology of balance and on sensorimotor learning in healthy and impaired subjects [11, 12, 13, 14]. On the other hand similar principles that were used to simulate foot-ground interactions could be used to stimulate the foot during the act of balancing with the difference that now the sensor is no longer a pressure sensing but a sensor sensitive to inclination, that is, an accelerometer.

Following this idea, a haptically-enabled balance board was designed, implemented and delivered to the partners. To provide for tactile stimuli, we employed the larger actuator developed during the previous period and adapted to a new use the structural technique that enabled us to decouple the vertical stiffness from the lateral stiffness by means structural struts represented on Fig. 5.1c. This is achieved by giving a particular profile to the supporting rubber struts, which upon optimization can achieve very high normal stiffness to support the weight of a person and very low lateral stiffness to enable the actuators to provide stimulation to the feet. Once the board is equipped with an accelerometer it is possible to relate its movements to tactile stimuli.

This device opens the possibility for many new applications and studies. Figure 5.2 shows the device in the course of assembly.

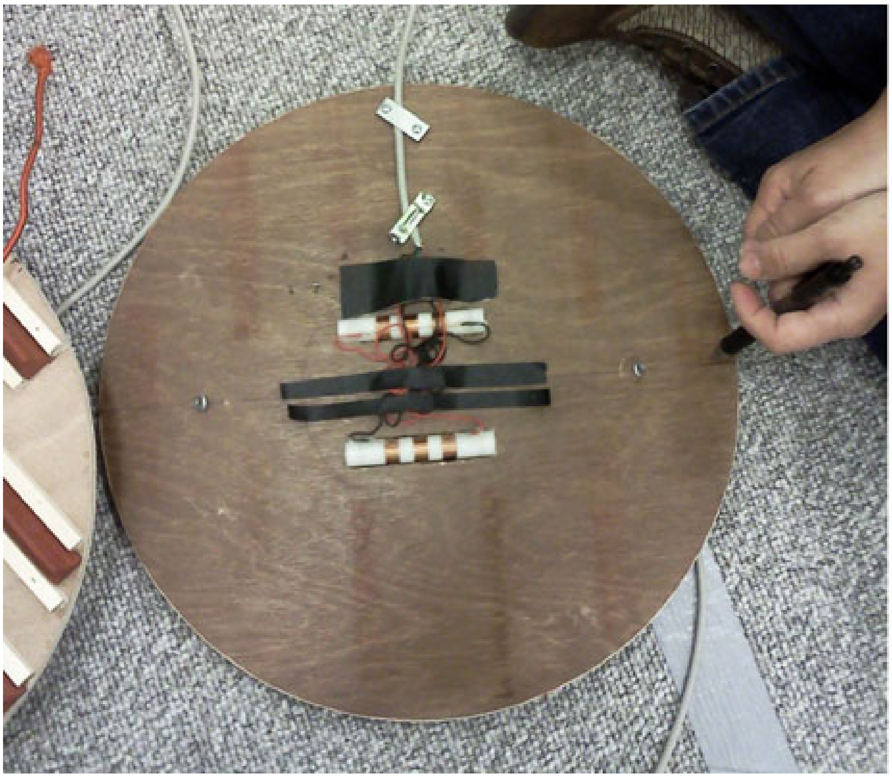

Figure 5.2: Upper board with actuators that rests on the lower board with struts.

6 Fluid Actuator Concept

We also explored a new haptic shoe concept that is able to: (a) operate on very low power, (b) provide strong tactile stimuli, (c) provide kinesthetic stimulation as well despite the high forces involved. The initial idea is to consider two elastic cavities connected by a duct. One cavity is placed under the heel and the other under the ball of the foot. The overall form factor is compatible with ordinary shoes. The cavities are filled with a fluid. The flow in the duct is controlled by a high bandwidth valves. A pressure sensor is located in each cavity as illustrated in Fig 6.1.

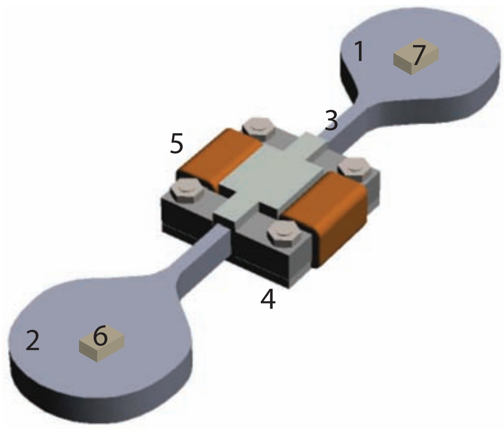

Figure 6.1: Actuated Fluidic Sole.

The sole comprises two deformable chambers (1,2) that are connected by a duct (3). Upon pressure imbalance between the two chambers the fluid is forced through the high bandwidth valve (4) actuated by magnetic motor (5). Pressure sensors (6,7) allow an embedded computer to command activation patterns corresponding to the simulation of ground materials. Promising valve technologies include magneto-rheological fluid-based monolithic valves and water-based variable reluctance needle valves.

While this concept is very appealing and is appropriate for concept testing, it has the downside that no stimulation is possible at the moment when the pressure is equal between the two chambers. A second concept is more complicated to realize but does not have this drawback. It is illustrated in Fig. 6.2. The two chambers (4,5) are now stacked on each other and are made to have different diameters. The valve is now immersed in the fluid, in the upper chamber. It has an orifice (1) and electromagnetic coil (2) with a magnetic gap (3). In addition it has a check valve (6) to allow the return the fluid in the upper chamber. When one steps on this “haptic cushion” the fluid is forced from chamber (6) to chamber (5) because they have different surfaces and similarly to the previous concept, haptic stimuli can be commanded through the valve during the fluid migration. When pressure is released, the check valves allows the initial equilibrium to be rapidly restored.

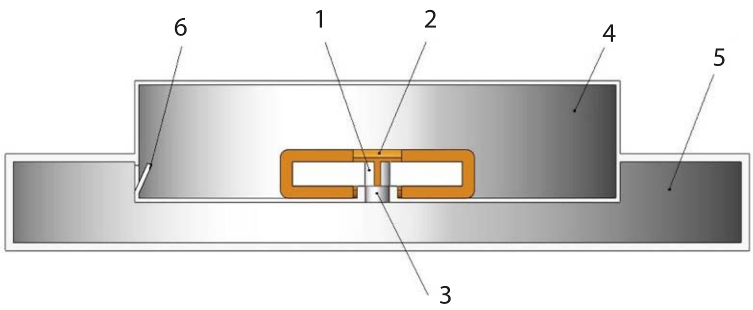

Figure 6.2: Haptic cushion concept.

The main advantage is that now the device is one single unit. One unit can be located under the heel and the other under the ball of the foot, can be independently activated to provide kinesthetic sensations even if they are equally loaded by a step.

7 Distributed Actuator

We have also made significant progress toward the realization of a high resolution distributed sole stimulator with 768 tactors per foot, see Fig. 7.1. Each tactor is a small 5 mm coil would around a vertical mandrel containing a cylindrical magnet. Upon activation, the magnet is propelled upward colliding with the foot sole and providing a high contrast tactile stimulus even through a sock.

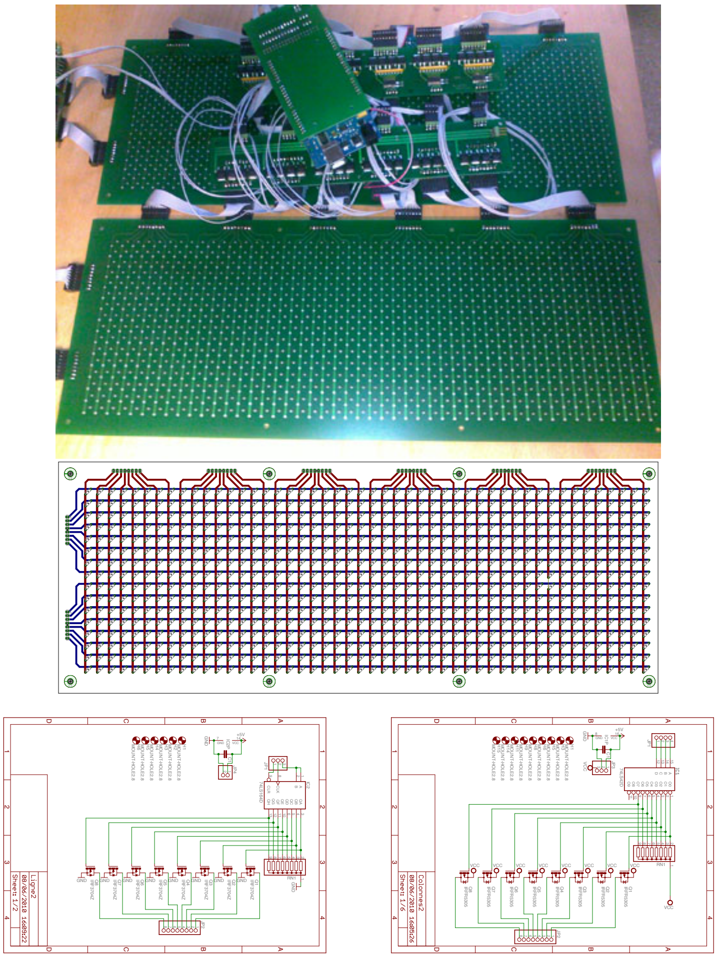

Figure 7.1: Circuitry (partial) for driving the 768 tactors. The circuit to drive a 8 × 8 sub-matrix is shown. This circuit is duplicated as many times as required, that is 48 times yielding drive for $48 \times 16 = 768$ actuators.

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