‘ForSe FIE*lds*’ – Force Sensors For Interactive Environments

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Abstract In this paper we discuss the development of ‘Z-Tiles’ in conjunction with a sister project, ‘Self-Organising Sensors’ (SOS). Combined, these projects will result in a pressure sensitive, self-organising, interactive sensor design that can be embedded into appropriate environments. The shared objective of these projects is to further our understanding of movement and gesture. In this paper, we discuss the design and behaviour of a force sensing material, the physical design of the sensor encasement and the software that allows the sensors to communicate and self-organise. The issues of modularity and portability are also discussed in this paper, while consideration has also been given to the conceptualisation and development of a variety of prototypes; ranging from entertainment to potential therapeutic applications. Essentially, the Z-tiles sensor can be used in control surfaces where force, weight distribution or motion is used as control parameters.

1 Keywords

Gesture, effort, movement, weight, balance, force, sensor, resolution, sensor composition, sensor characterisation, physical design, sensor arrangement, signal processing, multiplexing, self-organising sensors, interfacing, visualisation, demonstration.

2 Introduction

Every minute of every day we require our bodies to behave in diverse ways to accomplish their various tasks, these physical efforts being as countless and complex as the motivations that drive them. However, subtle, embedded, sensing technologies can allow us to explore the use of the body as an inherently powerful communication medium. In recent times, gesture has received much academic attention as a possible interface between technology and users. While, in Asian cultures, body-centred art forms are esteemed as a useful means of encouraging an awareness of our physicality, improving balance, posture flexibility vigour, blood pressure, muscle strength and general well being [1].

So how can we become more aware of the body, in both it's realised and unrealised potential as communicator and reinforcer? In this technical note, we discuss the design and development of one possible tool that would allow increased insight into the paradigms of movement and gesture. This paper creates a historical context for the Z-tiles/SOS sensor, describing the pre-existing work in this area. We describe the concept, motivation, design, manufacture and implementation of the sensor and refer to some of its applications.

3 Background

In 1997, two almost parallel developments were taking place on both sides of the Atlantic. Paradiso et al (1997) developed the MagicCarpet [2], a floor space that detected people's footsteps in terms of location within the carpet and impact force, while Fernström and Griffith (1998) developed LiteFoot [3], a floor slab with embedded sensors that detected people's foot movements. The objectives of both groups were similar: to create a floor space as input device in ubiquitous computing or smart environments. Each group was aimed at a gesture sensitive device that could be used for artistic expression and control by dancers, as well as a device suitable for installations in public environments such as galleries and museums. In experimental use, the two different devices showed some interesting properties.

3.1 MagicCarpet & LiteFoot

The MagicCarpet is based on a matrix of PVDF cables whose capacitance changes when a force is applied to them. The cables are arranged as an approximate 10cm XY grid. The signals from the cables are multiplexed and scanned along the periphery of the space at 80 Hz. The MagicCarpet is quite responsive, but, due to the multiplexing, one foot can "hide" another, if they impact at the same time on the carpet. The MagicCarpet is rectangular, 1.8 by 3 metres and is easy to transport as it can be rolled up, just as a normal carpet.

The LiteFoot floor is based on infrared optical proximity sensors that detect an object if it reflects the infrared light near the surface of the floor. Almost 2000 optical proximity sensors are placed approximately 40 millimetres apart in a grid in a floor space, 2 by 2 metres. The architecture of LiteFoot is fully pixellated, i.e. all sensors operating in parallel, hence objects cannot "hide" each other. Attempts were made to make the LiteFoot force sensitive by having an accelerometer in one corner under the device.

The scan time of the LiteFoot is 100 Hz, as one of the design goals was to be able to deal with Irish tap dancing (the world record at the time was 28 taps per second.)

The LiteFoot floor is not easily transportable – it is a rigid floor slab weighing around 100 kg and quite cumbersome to get through doors, especially elevators!
Other interesting endeavours which have attempted to further understand motion and weight distribution on floor spaces, include the work of Addlesee et al (1997), the Active Floor [4], and the Smart Floor, [5]. Orr et al (2000), both floors employ load cells to identify and track people, by registering changes in weight distribution, vertical force and load variations.

4 Z-tiles/SOS Concept

In a new collaborative project that started in 2001 under the auspices of Media Lab Europe in Dublin, Fernström and Paradiso initiated the development of a new modular device, based on previous experiences. Over a number of design discussions, the concepts evolved into Z-tiles and SOS (Self-Organising Sensors).

Z-tiles is a design for a fully scalable, self-organising, force sensitive surface. The Z-tiles detect x/y location as well as the force applied (the z-axis). Based on our experiences with the MagicCarpet and Litefoot, we aimed for a fully pixellated surface area that could detect both location and force in real-time. The device described in this paper allows us to consider not only how we move our physical mass around, but also the physical 'effort' involved in monitoring and controlling our movements, and expressing ourselves. We decided to try a modular design where each tile would have its own built-in computational power. Latterly, in SOS, we developed a communication protocol that allows modules to use high-level sensor data, as well as the ability to self-organise.

5 Understanding Effort

A considerable flaw in many existing systems is their inability to detect – with appropriate detail - weight distribution and transference in movement, the complex dynamic of "physical effort". The iterative design process of Z-tiles/SOS has involved working alongside a variety of departments in both the University of Limerick and Media Lab Europe. Graduates in Contemporary Dance at UL, and a Tai Chi instructor worked with the research team in an attempt to describe and catalogue the richness of human motion patterns.

Understanding the nuances of effort directly affects the design of a sensor system in terms of sensitivity, durability, applicability and usability. Areas of interest included the exploration of contact area, transference, weight distribution, posture, torsion, as well as the subtleties of timing, give, and relaxation.

6 Sensor Design

We have developed a mixture of silicon rubber and carbon granules that showed interesting properties for inexpensive force sensors. The sensor works on a simple premise; the electrical resistance of the mixture changes with applied force, and this change can be measured.

6.1 *Plubber* – Sensor Material

After a period of experimentation, the most suitable carbon granules were estimated to be of the order of 500 microns in diameter. Carbon granules were crushed and sieved, leaving carbon particles with sizes between 300 and 600 microns. The granules were then used in the manufacture of the sensor mixture. We call the resulting sensor material *Plubber*. Fig.1 shows the sensor polymer being applied to a circuit board. We tried applying *plubber* of varying compositions and thicknesses. Our testing revealed a mixture with the repeatable properties.

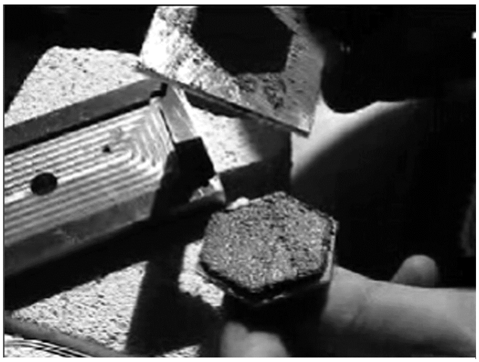

Figure 1. Freshly made 'plubber' being applied to circuit board.

6.2 *Prexels* – Pressure Elements

The pressure sensitive elements that our system employs are continuously being developed. In their current form, *prexels* are hexagonal circuit boards with a *plubber* coating. Changes in force exerted on the *plubber* layer results in a change in electrical resistance between the contacts (see Figure 2).

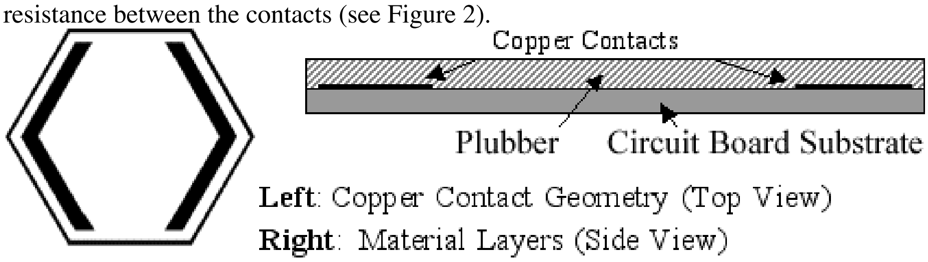

Figure 2 *Prexel* Design.

The relationship between resistance and force is a power function. Our preliminary characterisation has shown that the dynamic range of a *prexel* is quite large, ranging from 30N to at least 900N. Due to the elasticity of the sensor material, the *prexels* show a clear hysteresis (see Figure 3).

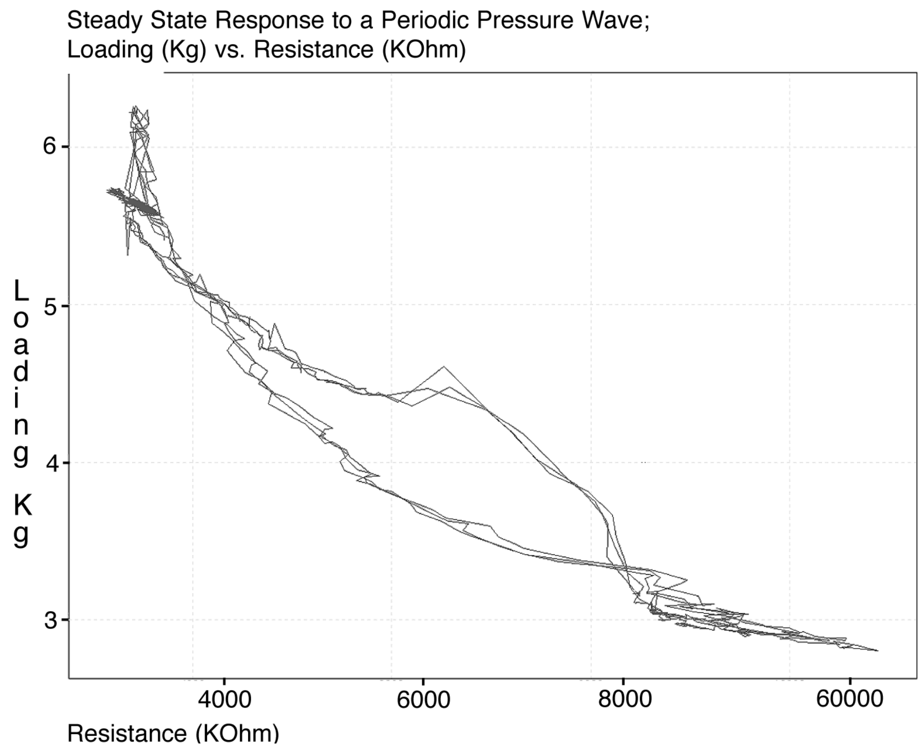

Figure 3.

Preliminary testing of the *prexels* has provided us with an initial understanding of their properties, and additional tests and further characterisation is necessary. Initially, the prexel seems to need to be "warmed up" for a period of at least a few seconds. Once warmed up, recognition is fast (delay is not directly perceptible => less than .1 sec). Recovery time, on the other hand, is considerably slower. Resistance continues to change for seconds after pressure is removed - the change appears to be asymptotic to an unloaded resistance value, however, this has not been verified. At the time of writing we are continuing to investigate sensor design and characteristics.

7 Modular Tile Design

We derived our individual sensor geometry by arranging a series of hexagons into a module shape – a *Z-tile*. This shape directionally interlocks and self-holds, as shown in figure 4. In our prototype, the spatial resolution is 40 millimetres. Each Z-tile has an upper and lower circuit board. The upper has 20 *prexels*, individually covered by *plubber*, while the inside of a tile houses microcontrollers and connections. Each Z-tile has four connection points along its perimeter where data and electrical power can be transferred. See Figure 5.

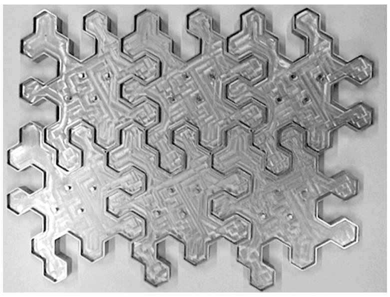

Figure 4.

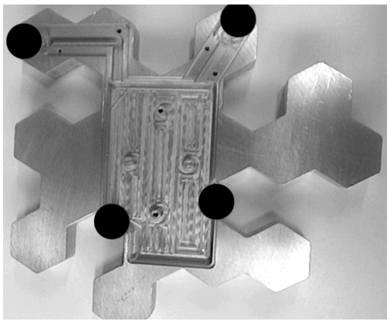

Figure 5.

8. Software

To create a modular device, we decided to use distributed processing where each tile has its own computational power, and the floor space is able to connect to the outside world along its perimeter through an adaptor. The software on the micro-controllers of each individual Z-tile fulfils a number of criteria: it accurately reads the force values from the twenty *prexels* on each tile, using 12-bit resolution and a latency of less than 10 ms, it can output force readings to an external device (a computer connected to a Z-tiled floor via a normal serial or USB port); and it routes data to and from interconnected tiles. As well as these direct requirements, a Z-tiled floor space adapts to changes in its physical shape while in use, by adjusting its routing of information as tiles are added or removed from any part of the floor space. As well as this, the floor space can potentially have more than one externally connected device, and always uses the shortest route from any tile to its nearest external connection point.

In order to fulfil all these requirements, a floor space of Z-Tiles self-organises, so that each tile in the floor knows its position relative to the rest of the floor space. It also knows in which direction it must output pressure information in order to reach an external connection with minimum delay. The self-organising network is formed and maintained by passing messages between neighbouring tiles. The network is formed by the propagation of an initial set-up message from an external connection to each tile in the floor. Once each tile has received the set-up message it knows how to route its data. When the network is in operation, messages are constantly transmitted between neighbouring tiles and because of this, tiles added or removed can quickly be recognised and the routing can be adjusted as necessary. After a new tile is added to the floor, the addition is detected when the tile begins sending out *keepalive* messages, and, once recognised, its neighbours send out set-up messages to it. The tile accepts the message with the shortest route to the external node, and propagates this on to its other neighbours, thus providing them with a new route.

When a tile removal is detected - due to the absence of *keepalive* messages - any neighbouring tiles which used the removed tile to route data and broadcast out reset messages, thereby triggering a regional reconfiguration of all affected tiles.

9 Scenarios and Applications

In the first Z-tiles scenario, we used a tile as an input device for controlling a MIDI module, i.e. as a musical controller. We used direct mappings between location-pitch and force-loudness.

In a second scenario (McElligott et al 2002)[6] a device with only four *prexels* measured the movements and motions of a performing musician, by allowing the musician to stand or sit on the sensor arrangement. The device was designed to extend the musician's control over any given instrument, through audio signal processing controlled by the sensor data.

A third scenario involved using a Z-tile as an input device for navigating a virtual reality world by "surfing". A virtual reality program, OpenVR (Savage 2001)[7] was used as a prototype test for the tile. The user, with a head-mounted display for visuals, stood on the tile. We demonstrated that a weight distribution profile could be extracted from the tile. For example, a high force at the front of the tile would indicate a vector pointing forward. If standing upright, the user would remain stationary in the virtual world, while leaning forwards, backwards or sideways would move the user in that direction with a speed proportional to the difference in weight distribution over the tile. This interface was reported by users to feel both natural and highly engaging.

The Z-tile sensors have also been used as a volume control for "The Cardboard Box Garden", a musical installation by Ferris (2001)[8]. A section of "The Cardboard Box Garden" consists of a series of stacked boxes. The Z-tile pressure sensors are placed on the floor under the boxes. The sensors respond to the changes in the weight of the boxes, by triggering an increase or decrease in the volume level of audio.

We are currently working on possible scenarios that illustrate the practicality of re-configurable floor sensors. Initial developments are focused on using the sensors for artistic performance so that the performance space can be dynamically rearranged. Also, this dynamic re-arrangement capability will provide a safeguard should a tile fail in use, enabling the system to continue functioning. These features allow us to potentially build custom-made, dynamic and resilient interactive spaces.

10 Conclusion

In this paper, we have described the development of a force sensing material (*plubber*) that can be screen-printed onto circuit boards. The sensor material shows interesting possibilities in terms of the range of force that can be detected, making it suitable, for example, for making interactive floors. We have also described the development of a modular sensor arrangement with local computational power that can be used for building larger, force sensitive, floor spaces. The physical shape of the resulting Z-tiles and the embedded software makes larger interactive floor spaces self-configuring. We have briefly described our initial application prototype scenarios.

We need to do further testing of the sensor material to fully reveal the characteristics of the *plubber*. Further mechanical design of the tiles is ongoing, as is re-evaluation of connectors, circuit design and layout, and experiments in microcontroller architecture.

In our scenario development, we are now exploring ideas of using Z-tiles, for example, for Tai Chi and other movement therapies for Arthritic and Multiple Sclerosis patients.

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