tacTiles - A Low-Cost Modular Tactile Sensing System for Floor Interactions

Jan Anlauff Tobias Großhauser Thomas Hermann
Cognitive Interaction Technology – Center of Excellence (CITEC)
Bielefeld University, Germany
janlauff@techfak.uni-bielefeld.de

ABSTRACT

In this paper, we present a prototype of a spatially resolved force sensing floor surface. The force sensors are based on conductive paper and grouped into modules called tacTiles. Due to the cheap and widely available materials used for tacTiles, the approach is suitable as a low-cost alternative for spatially resolved tactile sensing. The necessary techniques are shared as an open source and open hardware project to provide an affordable tactile sensing for smart environments. As an interactive application of these tacTiles, we present a detection of step direction algorithm used to count steps into and out of a room.

Keywords

tactile floor sensing, force sensing, HCI, modular systems, paper FSR, tacTiles, open source, open hardware

Categories and Subject Descriptors

H.5.2 [**Information Interfaces and Presentation**]: Input devices and strategies; B.4.2 [**Input/Output and Data Communications**]: Input/Output Devices

1. INTRODUCTION

Smart environments are in need of perceptual input to sense the location and the activities of humans. Such tracking may be accomplished by computer vision based systems. However, these systems raise serious privacy concerns and are subject to problems like visual occlusion and bad lighting conditions. Tactile sensitive surfaces avoid these problems and thus are a good complementary input and also offer information on the pressure distribution.

The following requirements were considered when designing tacTiles. The system should measure spatially resolved pressure over a dynamic range sufficient to detect footsteps. Real-time readout of the entire surface, meaning approximately 30 Hz, must be possible in order to support closed-loop interaction. The surface must be robust enough for people to walk on, and the system should be flat enough to be used on top of an existing flooring. We want the system to be modular and portable, making it versatile in use and allowing the modules to be arranged to cover exactly the surfaces of interest. Reproduction should be possible without special tools or materials and at reasonable cost.

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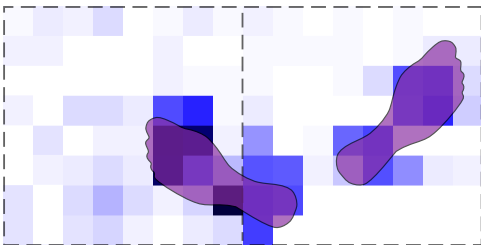


Figure 1: Example pressure reading from connected tacTiles.

The problem of sensing pressure distribution on floor surfaces has been topic of research in the last two decades. However, most approaches do not provide an acceptable tradeoff between spatial resolution and costs. Modular approaches are often hard to integrate into an existing environment, such as the AME Floor presented by Shrinivasan et al. [6], which requires a steel framework to be embedded into the floor. Other systems, such as the Z-Tiles developed by Richardson et al. [4], are based around special sensing materials that can be difficult to obtain.

In this paper, we present a low-cost[1] approach to a tactile sensing based on pressure sensors made out of black art paper. Our system may be reproduced without special tools at reasonable cost for smaller numbers of modules. The implementation details are freely available to foster further development and applications.

2. THE TACTILES SYSTEM

As the *sensing element*, a grid of paper-based force-sensing resistors (FSRs) was developed. Compared to standard commercial FSRs, they are much cheaper and more versatile, allowing us to merge the required wiring with the edges of each module. On each tile module, a microcontroller measures the resistance of the sensing elements. These *tacTiles* may either be connected to a host computer directly, or via a shared bus to a master that aggregates the measurement values and transfers them to a host computer. Figure 7 shows this information flow.

2.1 Sensor Principle

As our system's goal is to measure quasi-static forces, we can eliminate many alternative sensing techniques such as capacitive and piezoelectric.

[1]In the order of less than EUR 30 per 40×40 cm^2 module.

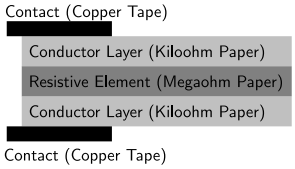


Figure 2: Paper FSR Layers.

In addition, our restriction to low cost design prevents the use of optical sensing, also due to its high power consumption. Therefore, we have adopted resistive force measurement since it is best suited to our design needs.

Given both the complexity of wiring discrete commerical FSRs and their prohibitive cost, we chose to develop our own paper-based sensors. Some types of black art paper are colored with carbon particles that conduct electricity. Custom force-sensing resistors (FSRs) can be built using this type of *conductive paper* as the resistive element. This was first proposed by Koehly et al. [2]. The advantages of using such custom *paper FSRs* include their low material costs[2] and the ability to build sensors of almost any shape.

The paper FSR principle is illustrated in Figure 2. Different variants of the conducting paper exist, with different resistance[3]. For the sensing layer, we used paper with a resistance in the low MΩ range refereed to as *MΩ paper*, for the connector layer a paper with a resistance in the kΩ range, referred to as *kΩ paper*. The quality of the contact between the resistive and conductive layers increases with pressure resulting in a corresponding increase in conductance, as found by Weiß and Wörn [8]. Pieces of copper tape with conductive adhesive are stuck on the paper and wires are soldered onto the copper tape to connect the sensor to the electronics. The resistance of a 4×4 cm^2 paper FSR ranges from approximately 700 kΩ to the high MΩ range.

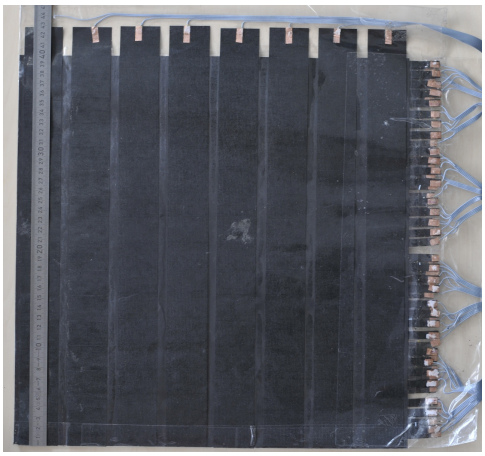


Figure 3: tacTiles sensing element.

We constructed a spatially resolved force sensing element out of such Paper-FSRs. It is 40×40 cm^2 in size and incorporates 64 custom FSRs in a 8×8 grid. We use conductive paper for the sensing element as well as for the connector layers. We combined a single piece 40×40 cm^2 of MΩ paper with a matrix readout. An insulation space of 1 cm separates each sensor element. Our tacTiles sensing element is shown in Figure 3.

[2]One 50 cm × 70 cm sheet of paper costs €1-2.

[3]All values for a distance of 3 cm between the ohmmeter's probes.

2.1.1 Sensor Readout

Because interference may occur between the different sensors in the matrix, for example when more than one FSR is loaded, they are decoupled with diodes, one per FSR. The diodes can not be integrated into the sensing element due to their height. They are aggregated on an external PCB, together with an Atmel ATMega microcontroller. We developed a scheme for densely wiring the individual FSRs in the sensing element that we call *ribbon paper* in analogy to ribbon cable. The opposite side of the sensing element with the ribbon paper is shown in Figure 4.

Figure 4: Ribbon paper on the back side of the tacTile.

The resistance of the FSRs is measured using a voltage divider and sampled by the microcontrollers internal analog-digital converter (ADC) with 10 Bit resolution. Time-multiplexing is used to sample the FSRs. A simplified circuit for 2×2 segment is shown in Figure 5. Only one of the digital output (D0, D1, ...) is switched to high level at a time, then each row is sampled by the ADC inputs. The electronics are shown in Figure 6a.

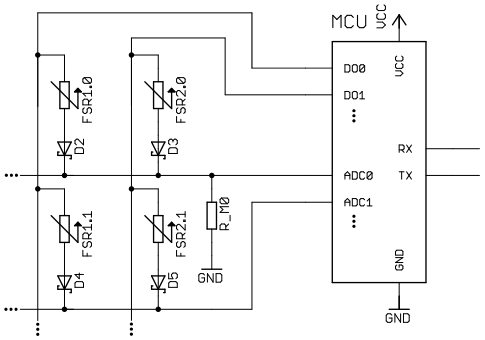


Figure 5: Circuit for a 2×2 Segment.

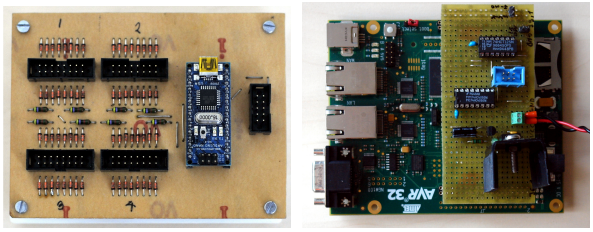
2.2 Communication Infrastructure

The tacTiles modules may either be connected directly to the host computer or through a bus system to a master controller unit, called *master* in the following.

We use a standard serial link to connect directly a host computer. This provides an easy and common programming and communication interface. The connection and the microcontroller bootloader is compatible with the Arduino environment [1].

A bus system is required to combine multiple tacTiles into one coherent sensing surface. We developed a bus based on the Myrmex system by Schürmann [5], as it provides a high performance interface compatible with most operating systems. In this system, the master, acting as a USB Video Class 2.0 compliant device, aggregates the pressure readings from the connected tacTiles and transmits them as a grayscale video stream to the host computer. This transmission method allows high speeds and easy analysis of the pressure map, for example using computer vision software. An example readout of two connected tacTiles is shown in Figure 1. The darker the blue shade, the more pressure was measured on the corresponding FSR.

The bus is based on the Serial Peripheral Interface (SPI) standard, as it allows high transfer speeds. The regular SPI standard



(a) Electronics of an tacTile Module

(b) NGW100 board with bus adaptor electronics.

Figure 6: Electronics of the tacTiles system.

uses a slave-select line for each bus slave, but this would require a dedicated line to each module. Instead, we developed a custom protocol that implements addressing. We extended the system to power the slaves modules via power supply lines integrated into the bus connection. Each tacTile has a peak power consumption of approximately 50 mA.

An NGW100 AVR32 32-Bit microcontroller development board, shown in Figure 6b, is used as the master controller and SPI bus master. Voltage regulation and level-shifting electronics are necessary to connect to the tacTiles bus. They were designed as a module that can be stacked simply on top of the NGW100 board.

Using a bus clock of 250 kHz, we achieved an update rate of 430 Hz for one module. Given a stable bus clock, additional modules will simply divide this update rate amongst themselves. Tests with a total of four meters of cable between the master and the tacTiles did not show any transmission problems. Thus, the current bus clock speed seems safe and may even be increased.

From the host computer, the pressure readings can be transmitted over the network to other applications as Open Sound Control (OSC) protocol [9] messages. OSC presents a well-supported, high performance network transport format.

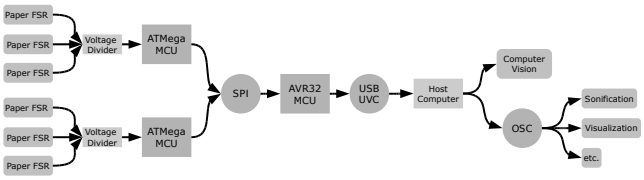


Figure 7: Information flow in the tacTiles system.

3. EVALUATION

3.1 Sensor Characteristics

We evaluated the characteristics of the paper FSR sensing element to compare their performance to a commercial FSR from Interlink. These measurements required a test system that can provide a reproducible and clearly defined loading of the sensors while measuring the actuation force. Such a system can also be used to simulate mechanical wear by repeated actuation.

3.1.1 Test Setup

We based our test setup on an three axis linear table by Isel. It has a maximum downward z-axis actuation of approximately 200 Newtons, with a peak actuation of over 300 Newtons. The actuation force is measured with a ME Systems KD140 beam force sensor with a force range of $\pm$ 100 Newtons. Different pads can be mounted on the actuation end of the sensor to match the size and shape of the FSR sensor. The FSR sensor values were measured with an 80 kΩ reference resistor in the voltage divider. Both, the amplified analog readings from the beam force sensor and the FSR readings, are sampled with the internal ADC of an ATMega microcontroller at 10 Bit resolution. Figure 8 shows the test setup.

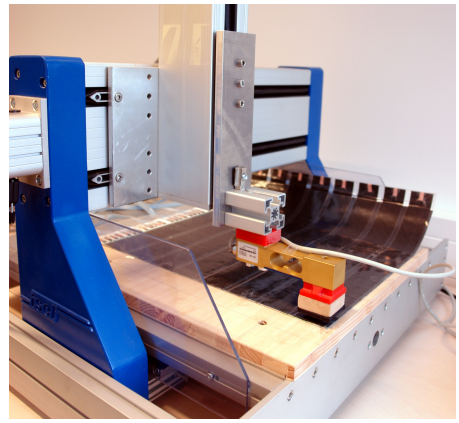


Figure 8: Sensor test setup: Linear table with tacTiles element.

3.1.2 Results

The force versus conductance plots, are generally preferred for reference, as they are invariant for a given sensor regarding the supply voltage and reference resitor. Plots for three sample FSRs in the sensing element are shown in Figure 9. The individual pads respond differently because of variations in the length of the electrical path through the kΩ paper. Since changes in path length change the overall resistance of each circuit non-trivially, the relationship between the FSR and the measurement resistor in the voltage divider is affected. However, since the effect is linear, we are able to model and predict its effect. A plot of the fitted curve constants a and b is shown in Figure 9.

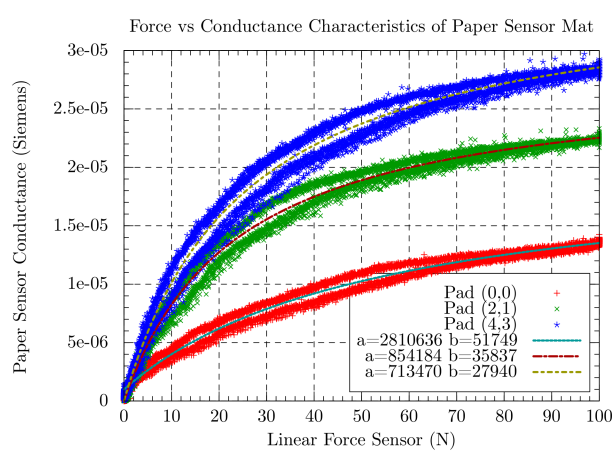


Figure 9: Force vs. conductance plots for three paper FSR sensor pads with overlaid fitted curves for parameters a and b.

The sensors feel very responsive when actuated by hand. An evaluation of the timing characteristics has been conducted with the linear table, but the readings do not show any significant delay

with regard to the actuation. A much faster actuation and sensing system would be required to determine the response time. Koehly et al. measured the time-response of their paper FSR with an oscilloscope. It took 75 ms for the paper to recover from a 3 kg load [2]. According to the Nyquist theorem, this equals six sensed impulses per second.

We conducted a preliminary test on the durability of the paper FSR sensing element by having the linear table actuate single pads 2000 times in a row. No significant difference of force to resistance relationship could be seen in the resulting plots. Either a the number of actuations was not high enough, or another factor is limiting, such as the total time being compressed. According to personal communications with Koehly, the paper FSRs in the T-Stick musical input device [3] start to degrade slowly after a year of heavy use and hundreds of practice sessions.

Our analysis showed that while the paper sensors have a lower saturation pressure and are not as linear as the Interlink FSRs, they show otherwise comparable characteristics, such as drift, time response, force sensitivity and resolution in the usable range. This agrees with the findings of Koehly et al. for their paper FSRs [2].

4. TACTILES-BASED STEP DETECTION

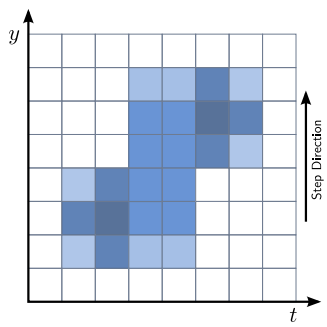


Figure 10: Step visualized in time. Each pixel represents a row sum at time t.

An application for the tacTiles system could be to assess the number of persons in a room. We here present an analysis of the pressure profile over time to detect steps and their direction on the tacTiles. If these are placed in the entrance of a room, the number of persons in it can be determined by simply counting the in-/ and outward steps.

Let $I(x, y, t)$ be the intensity at location (x, y) at time t, and

$$I(y, t) = \sum_x I(x, y, t)$$

the x-marginal. For a typical footstep in the direction of increasing y, the space-time plot appears as in Figure 10. The center of pressure is

$$\vec{c} = (\bar{y}, \bar{t}) = \frac{1}{N} \sum_{y,t} (y, t) \cdot I(y, t), \text{ where } N = \sum_{y,t} I(y, t).$$

Then, the sign of the linear correlation coefficient $\hat{r}$ is

$$\operatorname{sgn}(\hat{r}) = \operatorname{sgn}\left(\sum_t \sum_y (t - \bar{t}) \cdot (y - \bar{y}) \cdot I(y, t) \right)$$
$$= \begin{cases} 1 & \text{step in direction of increasing y} \\ -1 & \text{step in direction of decreasing y.} \end{cases}$$

On our website [7], we provide a demonstration video that shows such an analysis and counting of persons entering and leaving a room.

5. CONCLUSION

We have presented a low-cost modular system for spatially resolved sensing of pressure profiles in real-time for applications in smart environments. Our current prototype is flexible and delivers spatially resolved pressure readings at a frame rate of 430 Hz for one tacTile, but the latency of the paper-based FSRs limits the usable refresh rate per individual sensor to approx. 12 Hz. The tacTiles system uses only low-cost material, and we expect that one module will cost less than EUR 10 in sensor materials, and about EUR 20 for an integrated PCB with the electronics. The building time of one sensing element was measured to be approximately 8h. We will provide building plans and the software for the tacTiles system as an open source and open hardware project on our website [7]. We are confident that tacTiles provides a solid basis for the covering of larger surfaces in smart environments, and for many applications beyond, ranging from interactive games to assistive feedback-systems for rehabilitation.

6. ACKNOWLEDGEMENTS

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