Towards fast multi-point force and hit detection in tabletops using mechanically intercoupled Force Sensing Resistors

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ABSTRACT

Tangible tabletop musical interfaces allowing for a collaborative real-time interaction in live music performances are one of the promising fields in NIMEs. At present, this kind of interfaces present at least some of the following characteristics that limit their musical use: latency in the interaction, and partial or complete lack of responsiveness to gestures such as tapping, scrubbing or pressing force. Our current research is exploring ways of improving the quality of interaction with this kind of interfaces, and in particular with the tangible tabletop instrument *Reactable* . In this paper we present a system based on a circular array of mechanically intercoupled force sensing resistors used to obtain a low-latency, affordable, and easily embeddable hardware system able to detect surface impacts and pressures on the tabletop perimeter. We also consider the option of completing this detected gestural information with the sound information coming from a contact microphone attached to the mechanical coupling layer, to control physical modelling synthesis of percussion instruments.

Keywords

tangible tabletop interfaces, force sensing resistor, mechanical coupling, fast low-noise analog to digital conversion, low-latency sensing, micro controller, multimodal systems, complementary sensing.

1. INTRODUCTION

One of the promising fields in NIMEs is that represented by live music performances based on tangible tabletop interfaces, which allow for a collaborative real-time interaction. The *Reactable* [13], initially developed by the Music Technology Group of Universitat Pompeu Fabra, is an example of a NIME of this kind. The *Reactable* is based on a multi-touch tangible tabletop interface, exploiting a modular synthesizer approach and a dynamic visual data-flow programming language. The *Reactable* supports the detection of tangible objects on its surface, which are associated with various units of a virtual modular sound synthesizer. Finger touches and strokes are detected, and are used both to control the connections between the objects and to adjust some parameters related to each unit. The recognition of the position and rotation angle of the tangibles on the surface is achieved by tracking fiducial symbols located underneath them and visible to a computer vision system through the translucent surface of the table. The rest of the system is in charge of implementing the dynamic patching between the synthesizer modules, to produce the actual synthesis results, and to offer a spatially augmented reality feedback which is back-projected to the translucent tabletop surface.

The currently used computer-vision system relies on a low frame rate infrared camera connected to a computer, so gesture detection temporal granularity and latency are limited by the low sampling rate of the system (less than 50 FPS) and by the image data transfer and processing time. For this reason, while the *Reactable* already offers a wide enough spectrum of musical expression possibilities, the system is still unable to exploit gestures important for musical expression such as percussive impacts, continuous finger/hand pressure or other body movements with their nuances. We want to overcome these limitations by combining the already existing hardware and software system with further gesture sensing technologies, increasing the system's control intimacy.

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2. STATE OF THE ART

After recalling the idea of music instrument control intimacy, the existing solutions to track user gestures on surfaces will be reviewed, highlighting their respective advantages and their downsides with respect to musical control intimacy.

2.1 Music instruments and control intimacy

The notion of control intimacy when playing an instrument was introduced by Moore in [16]. A person having a high degree of intimacy with a device can communicate through it in an effective way, as if it was an extension of herself. This process is described by Fels as *embodiment* of the device [5]. Control intimacy has also been discussed by Wessel in terms of a system's latency and jitter (latency variation) in [23]. The upper latency bound is set by Wessel to $10ms$ and the jitter amount to $1ms$ in order to detect quick gestures like a drummer's flams. Other authors [14] set the upper bound for latency to a higher value of up to around $30ms$. For our system, we tried to achieve the lowest possible latency, in order to minimize the overall gesture-to-sound latency.

2.2 Position, Impact, and Pressure Sensing Technologies for Interactive Surfaces

The detection of user contact with the physical interface is fundamental in traditional musical instruments and can play a fundamental role when interacting with NIMEs. A quantity of techniques are available to sense hit intensity, position, and pressures on surfaces.

Acoustic sensing techniques

Tactile interfaces based on acoustic detection techniques are usually referred to as Tangible Acoustic Interfaces (TAIs). Acoustic sensing techniques for tracking object hits and knocks on interactive surfaces of large dimension have been developed by Ishii and Paradiso [9, 17]. In this system a set microphones was used both on the interaction surface and in its vicinity to detect various types of hits on the surface. Additional microphones were used to filter out excitations coming from outside the surface. A proper signal processing system was able to track knock intensity and locations with latencies within $65ms$ and a spatial precision of about $2 - 3cm$.

Several techniques and tools for transforming daily life objects into tactile interfaces have also been explored in the context of the *TAI-CHI* European project [1], aimed at improving the knowledge and use of TAIs. One of the latest outcomes in this research line has been presented by Crevoisier in [2] with an achieved spatial precision of about $1cm$ [2]. In comparison with Paradiso's system, a much more advanced hardware is used.

The main advantage of TAIs is that they offer flexibility on the shape and type of the interaction surface or object. The limitations are the need for elaborated hardware and processing to achieve high spatial resolutions, the fact that continuous pressures can't be sensed, and that simultaneous multi-contact input is not possible.

Computer vision techniques

In the particular case of back-projected tabletop surfaces, multiple contact points positions and pressures can be detected by using computer-vision algorithms, using various kinds of optical set-ups based on techniques such as frustrated total internal reflection (FTIR), diffuse illumination (DI), diffuse surface illumination (DSI) [20], or laser light plane (LLP) [3].

Such vision-based system can provide high spatial resolution. However there are various drawbacks: sensitivity to lighting conditions, the need of costly high frame rate cameras and proper processing hardware/software to achieve low enough latencies in interaction (for instance, a 200 FPS camera would be needed for a $5ms$ sampling interval). These are the same limitations encountered in the *Reactable* system, which uses a DSI setup.

A way of overcoming the frame rate and cost problems has been presented by Crevoisier et al. in their Multi-Touch Everywhere system (MUTE) [3] which uses a multi-touch high-speed tracking system based on the combination of an infrared LLP setup with a low-cost high-speed smart-camera produced by *NaturalPoint* [4], able to perform blob-tracking directly on the camera's specialized hardware at 100 FPS, thus saving data transfer bandwidth, latency, and processing time. This system is reported to have latencies of about $10ms$ [5]. This computer-vision system is combined with surface vibration sensing to generate control data for the sound synthesis system, however single or multiple point pressures are not detected.

Resistive and capacitive touch-screens

Two technologies commonly used in commercial touch-screens are those based on resistive sensing and on capacitive sensing [20]. While this kind of input devices is insensitive to illumination conditions, can achieve high frame rates (around 200 Hz), and offer multi-touch input at low latencies, they suffer from reduced sensitivity to pressure and their cost can be high, especially in the case of the projected capacitive technology, as in the high-performance screen models offered by 3M [6]. Another problem is that custom tactile overlays would need to be fabricated for the *Reactable* , which has a circular shape.

Dense surface sensor arrays

These techniques rely on arrays of discrete sensors of various nature directly disposed along the whole interaction surface. The density of the sensing elements can vary from few to many units per unit surface area, influencing the achievable spatial resolution and hardware complexity.

One of the first commercially available devices of this kind has been offered by *Tactex* [7], whose devices are based on optical fibers used to measure the compression of a translucent compressible foam. *Tactex* hardware has been used by NIME researchers in [23, 12].

Another existing technique for capturing high-quality anti-aliased pressure images at high frame rates from a surface has been presented by Rosenberg et al. in [18]. This technique is based on a novel sensor, the Interpolating Force Sensing Resistor (IFSR). The system is claimed to be rugged, durable, scalable, having a wide dynamic range, and being capable of capturing even subtle variations in gesture pressure.

Jones et al. presented in [11] a capacitive force sensing solution based on an interleaved array of conductors. An enhanced version of this system called *Soundplane A* has now been made commercially available [7].

Amongst all the reviewed techniques, these last two methods are those who get closer to what we are trying to achieve with our system. The only downside appears to be the necessity of fabricating custom circular versions of these sensors, with properly adapted hardware.

2.2.1 Force and position detection using few force sensing elements

An example of position and force sensing device based on few sensing elements is the one developed by Wessel et al. in [22], where various 2-D arrays of pressure sensitive touchpads (Interlink VersaPad) disposed into a matrix layout are connected with custom high scanning-rate hardware and drivers (from 200 Hz up to 6000 Hz per touchpad/channel) to a software synthesis system handling various types of musical control structures.

A contribution similar to our implemented system is the work of Schmidt et al. [19] where four strain gauges are used to detect the forces present at the four corners of an horizontal surface. The magnitude of these forces is used to determine the 2-D position of objects and user pointing interaction on the surface, however for its construction this system can only sense a single point of contact.

[1] Tangible Acoustic Interfaces for Computer-Human Interaction

[2] no explicit information about the achieved latencies of the system has been found in literature or on-line.

[3] NUI Group Community Book - *Multi-Touch Technologies*, available at `http://nuigroup.com/log/nuigroup_book_1/`

[4] `http://www.naturalpoint.com/`

[5] `http://www.future-instruments.net/fr/mute.php`

[6] `http://solutions.3m.com/wps/portal/3M/en_US/TouchSystems/TouchScreen/Solutions/MultiTouch/`, accessed on february 6^{th} 2012.

[7] `http://madronalabs.com/`

3. SYSTEM CONCEPT AND IMPLEMENTATION

Our aim is to enhance the sensing capabilities of the *Reactable* hardware by means of force, impact, and sound sensing devices interfaced with the host PC by mean of a micro-controller. The guidelines in developing the system have been: low implementation costs (hardware complexity and price), embedding factors, and effectiveness in gesture detection (sensitivity, low latencies).

Early prototypes involved the use of blob-tracking computer-vision system combined with sound picked up from the interaction surface by mean of a contact microphone, used to control a digital wave-guide sound synthesizer, however due the low frame rate of the camera the system proven to be inadequate for rhythmical tapping interaction. In our latest prototype, we directly use the positional data coming from the sensing system in combination with the signal picked up by a contact microphone.

3.1 Force sensing element

We decided to use Force Sensing Resistors (FSR) due to their mechanical ruggedness and low cost [24]. FSRs have often been used for the construction of NIMEs [21, 15] and are already found in commercial game-pads, drum-pad controllers, and in middle-end or high-end MIDI controller keyboards to provide global or individual key pressure information (respectively the parameters *channel after-touch* and *polyphonic key pressure* in the MIDI standard). A useful report on the performances of commercially available FSRs is presented by Hollinger and Wanderley in [6].

3.2 Characteristics of a force sensing resistor

For our prototypes, an Interlink FSR force sensing resistor was chosen (Part No. 406 – 1.5 " Square). The guide provided by Interlink [8] enumerates the various the sensor characteristics such as sensing accuracy, force sensing resolution, and aids in the basic steps of setting up the FSR system. In particular the aspects kept into consideration are:

- *Sensing accuracy*: a FSR is not accurate as a strain gauge, but for the use made this accuracy was considered to be sufficient.
- *Force sensing resolution*: force resolution is ± 0.5 % of full use force. This enables the capture of detailed gestural data.
- *Force sensing range*: the sensing range of the used FSRs covers up to 3 orders of magnitude, from $10g$ up to $10Kg$ or more. This allows the detection of both subtle nuances and of gestures like strong hits and presses.

3.3 Mechanical coupling between sensors and tabletop surface

An optimal mechanical coupling between the sensors and the interaction surface is the first step needed for providing the best possible dynamic range and sensing response. During the construction of the system, the following aspects had to be kept into consideration for the sensing system to work properly:

- FSR response is very sensitive to the distribution of the applied force. To keep the force distribution more consistent, a thin elastomer can be used.
- The FSR needs to be laid on a firm, flat, and smooth mounting surface. This is the case in our implementation, being the sensors laid on tabletop perimeter, which is flat.
- During installation, special care is needed to avoid the presence of even very small kinks or dents in the FSR active area, that can cause false triggering of the sensors.

3.4 Mechanically intercoupled force sensing resistors

In our prototypes, sixteen force sensing resistors are laid out on the perimeter of the table at regular distance. Thanks to its elasticity, the plastic perimeter acts as a force distributing mechanism: a force applied in a point of the sensing perimeter will only be detected by the sensors nearest to it.

In the first prototype the sensors were located beneath the circular tabletop surface and a thin elastomer completely covering the sensors was used to provide the needed mechanical coupling and force distribution. A thin layer of expanded polyethylene foam was found to offer the best mechanical coupling, with fastest response and nearly no hysteresis. However this first setup was not able to detect subtle touches: it was later found that the circular tabletop surface ($6mm$ thick, *Plexiglass* material) was taking the shape of a concave meniscus under the effect of its own weight, thus lifting the area of contact on the border with the elastomer of some fraction of millimeter, nulling in this way lower gesture forces which instead had to compensate for the concavity of the surface before of actual force detection.

Having discovered this phenomenon, we decided to leave the elastomer only on the sensors areas instead that on the whole table perimeter. While this choice had the effect of making the sensors able to detect soft pressures, another negative side-effect appeared: the tabletop surface was now free to vibrate when excited by an abrupt gesture hit, thus basically making the system nearly unusable for tracking abrupt gestures.

For this reason we switched to a further variation of the mechanical setup. In this latest prototype, a matte *Plexiglass* $6mm$ thick annulus has been cut to just cover the perimeter of the table (fig. 1). The annulus is currently secured to the table perimeter by mean of duct-tape in way that pressure detection is not affected. The matte finishing has the potentially useful characteristic of generating sound when scrubbed. This sound can be detected by the contact microphone and be used to control physical modelling based sound synthesis models. Another important change is that

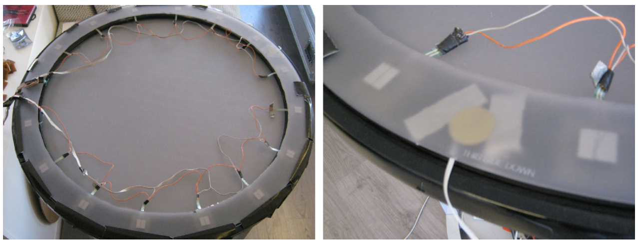

Figure 1: A top view of the tabletop annulus. On the right a detail of the contact microphone.

the thin elastomer has now been replaced with pairs of plastic coupling items (fig. 2) that provide direct excitation of the sensor in a way that makes the force sensing resistors act more like actual force measuring devices, a technique based on [10]. With this last type of mechanical setup the minimum detectable weight is of about 40 grams, comparable in magnitude with the force of a soft touch. However, mechanical crosstalk is still present when the annulus is hit due to its mechanical characteristics. We believe that by substituting the annulus with a thinner plastic material, and coupling it with the lower part of the structure by means of an elastomer, will improve mechanical damping and drastically reduce false triggering, allowing for true concurrent hits detection.

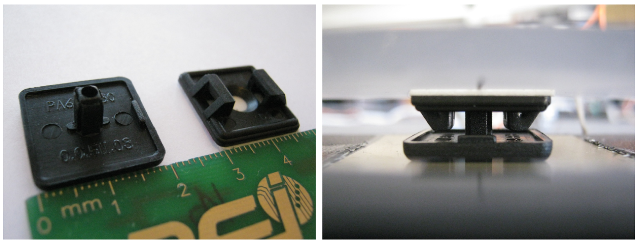

Figure 2: The used plastic coupling items and their disposition between the annulus and FSR.

3.5 Acquisition system setup

The sensors are connected by mean of a multiplexing circuit to a signal conditioning circuit to prepare the signal for the analog to digital conversion on the micro-controller. The micro controller samples the analog signals and converts the values to a lightweight serial protocol sent to the host computer where further signal processing is carried out to extract the final gesture information.

3.6 Impedance to voltage conversion

FSR resistance (impedance) is inversely proportional to the applied force. We can infer the applied force by using proper circuitry transforming resistance into a voltage. Two of the possible alternatives are a voltage divider, and a current to voltage converter circuit.

Voltage divider

A common approach for impedance to voltage conversion relies on using a voltage divider type of circuit (fig. 3a). The relationship between the FSR resistance values and the output voltage is represented by the equation:

$$V_{out} = V_{in} \frac{R_2}{R_1 + R_2} = \frac{V_{in}}{1 + \dfrac{R_1}{R_2}} \quad (1)$$

With a voltage divider circuit the force to voltage relationship is not linear, and the voltage range has to be traded with sensitivity [8]. To interface the voltage divider with the ADC, an operational amplifier should be used to buffer the voltage before of the analog to digital conversion in order to minimize the ADC sampling capacitor settling time, which is influenced by the source impedance.

Current to voltage conversion

In our latest prototype we use a current to voltage converter type of circuit (a topology also known as transimpedance or transconductance amplifier) which is able to convert the force-voltage relationship into a quasi-linear one, more suitable for measuring actual forces used in the subsequent gesture computing phases. The output voltage for the used circuit topology (fig. 3b) is given by the following formula:

$$V_{out} = V_{ref} \left(\frac{R_f}{R_{FSR}} + 1 \right) \quad (2)$$

V_{ref} is set to about $0.8V$ by mean of a buffered and bypassed voltage divider, this reduces the voltage drop on the FSR offering a better compliance with Interlink's integration guidelines which set the maximum current across the sensor to $\frac{1mA}{cm^2}$. To maximize the use of the ADC's dynamic range, V_{ref} is also used as negative voltage reference for the ADC via an additional bypassed buffer. The value for R_f ($3.3K\Omega$) has been chosen to allow resolution at low forces, setting the upper force bound to about $3.5N$.

[8] A useful tutorial on the optimization of the voltage divider circuit can be found at `http://cnmat.berkeley.edu/` search engine terms: "optimizing voltage divider".

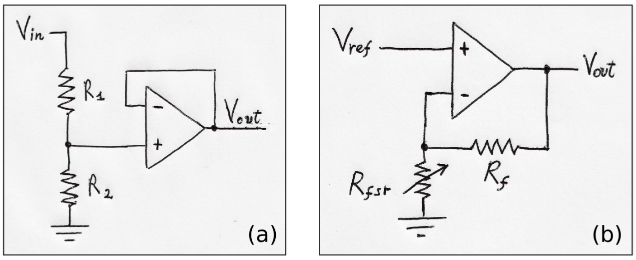

Figure 3: Voltage divider (a) and transconductance amplifier (b).

Fast multiple-channel sensing

In our first prototypes we used a very simple circuit in which a pair of 8 channel multiplexers (HEF4051) was used to cyclically connect each one of the FSRs to one of the two halves of a buffered voltage divider circuit (one per multiplexer). While this approach offered good results for low sample rates, at higher sampling rates there was significant channel crosstalk, and noise levels where too high. This was not an immediately evident problem since the first prototype used an *Arduino 2009*, which due to limitations in the FTDI virtual serial port system bandwidth, was only able to achieve a sampling rate of about 360 Hz per sensor.

In our latest prototype we decided to switch to the *Pinguino* platform[9], based on the PIC 18F family of microcontrollers produced by Microchip. *Pinguino* is nearly equivalent to *Arduino*, but with a lower price and components count, simplifying the construction of quick prototype platforms. The used PIC chips have embedded USB communication functionality so no additional interfacing chips are needed. Also, clock speed is higher (48 MHz instead of 16 MHz) offering more computing power. When connected to the host computer, the *Pinguino* microcontroller appears as an USB CDC class device. Data is sent using bulk transfers, with an achievable frame-rate of 1000 Hz per channel (bound to the maximum USB packet size of 64 Bytes, with a granularity of 1 packet per millisecond). With this system the measured gesture-to-sound latency is below 20 ms (the audio output buffer size being set to $7ms$).

In order to achieve as fast as possible ADC settling times during the array scanning, we also recurred to the use of a per-channel transimpedance amplifier. While this increases components count and overall price, channel crosstalk and noise are considerably reduced.

Low noise circuits and analog front-end

The SNR of the sensed values is lower at low forces. For this reason low-noise signals and signal measurement are important factors to obtain a stable position calculation with fast response times (no digital low-pass filtering of the values). Various books and application notes give useful guidelines regarding these issues, such as those written by Bonnie Baker (for instance [1]). Reduced noise levels were obtained by interposing a passive RC lowpass filter ($R = 100\Omega, C = 100nF$) between the op-amp and the ADC to create a charge reservoir for the ADC, and to avoid op-amp output oscillations. Even if we are still using breadboards for our prototypes, we found that implementing these techniques significantly reduced noise levels,

[9] `http://www.hackinglab.org/`

reaching performances close to 10 bits precision for a single channel setup. Precision is slightly worse in the multi-channel case, with about 8.5 usable bits of information. At current we are using a MCP6024 quad op-amp, a single-supply, low-noise, high GBWP, and low-cost model produced by Microchip. A $1\mu F$ bypass capacitor has been put in parallel with the supply pins of each op-amp to improve stability.

4. PROCESSING OF THE SENSED SIGNALS

4.1 Force sensing range and value adjustment

Test weights (fig. 4) were used to measure the force to ADC value relationship The results for a single (multiplexed) sensor are visible in fig. 5, showing a quasi-linear relationship between applied weights and resulting ADC values. The

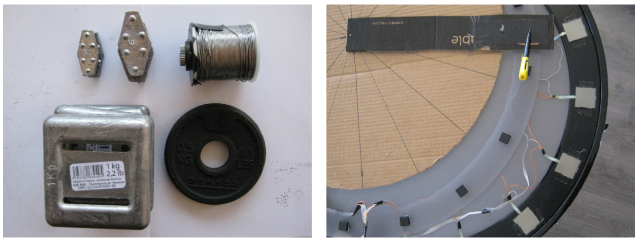

Figure 4: On the left the used test weights. On the right the used jigs, annulus, and sensors.

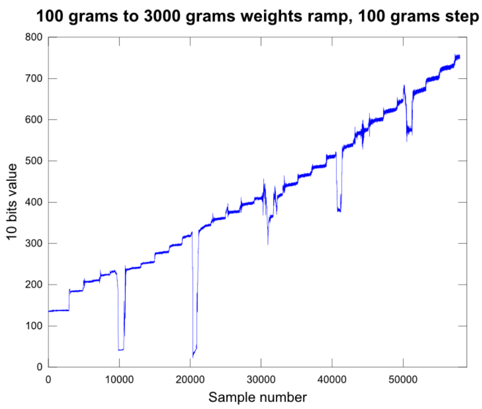

Figure 5: The weight to ADC value ramp. Jumps are due to the changes in test weights combinations.

other sensors also present this quasi-linear relationship, with slightly different initial offset values and force to value ratios.

4.2 Contact points tracking, hit detection

After having removed each sensor's baseline value and adjusted the output range, a simple algorithm is used to detect continuous pressures on the whole tabletop perimeter by computing and tracking the centroids of the force values present across the 16 values array. With optimal mechanical coupling it should be possible to resolve up to 8 points separate (at the distance of 2 sensors). We found that with the latest setup, at least 5 separate points can be resolved.

Hit detection currently works by applying a sensor signal value delta positive threshold to each channel, followed by a delta zero-crossing detection. When the delta value crosses zero the actual signal value is taken as a maximum. Hit position is then computed as the centroid of the recorded hits peak values. As previously mentioned, short hits tend to generate false cascaded triggering. It is anyway possible to track single consecutive hits if the finger does not loose contact force with the surface once the impact has taken place. Our hit detection algorithms still needs to be refined, and we are also limited by the mechanics of the currently used setup.

5. CASE STUDIES

The dataflow programming language *Pure Data* has been used to prototype various sound synthesis patches to be controlled by our system. A custom software has been written in Java to handle the serial communication with the micro-controller and to offer a visualization of the sensed values and computed gestural data. The software sends the computed gestural data via *OpenSoundControl* to *Pure Data* , which in turn uses the received information to control sound synthesis parameters.

5.1 Collective synthesis control

One of the simplest possible forms of interaction with the multi-channel force detection system is that of using a generic mapping of the sensed force values to control the parameters of a synthesizer. We decided to divide the table in two equal halves, and to use the sum of the forces of each zone to control three synthesis parameters of a custom programmed synthesizer. The interesting aspect of this approach is that the force values can be mapped so that the only way of fully exploring the timbre and dynamic palette of the synthesizer is that of pressing on all the sensors at the same time, thing which is not possible for a person alone.

5.2 Simple pitch-amplitude control

The second experiment has been that of controlling the pitch and amplitude of an oscillator, mapping its pitch to the angular position of the touch and its intensity and timbre to pressing force. With this basic setting it is possible to play simple melodies using fingers and one or two hands. The quality of the interaction is comparable with that of a capacitive ribbon controller, with the addition of pressure force sensitivity. While due to the system mechanics polyphony is not possible for near contact points, slide portamento and vibrato controls are easily achievable by sliding a single finger or using two fingers to vary the computed centroid position.

5.3 Scratch interaction

Another experiment we tried is that of controlling the live-scratching of a sample. For this task a spinning turntable-record metaphor was chosen, where the record is free to spin when no finger force is applied, and the revolution speed gradually slows down when the applied finger force increases. Virtual turntable motor traction and pressing force influence on spinning speed can be tuned in the synthesis patch to adjust the interaction. Additional nearby sensors can be used to control sound output volume, to approximate the scratch "chopping" control. While the haptic feedback typical of turntables is absent, thanks to the matte surface's low friction, to the low latency and high frame rate of the system, fast and subtle control can be achieved.

5.4 Hit detection and control of physical modelling based synthesizer

The last and more ambitious experiments involves hit detection on the annulus in combination with a contact microphone completing the sensing of an hit. The signal coming from the contact microphone is used to excite a physical model of percussive instrument based on banded waveguide synthesis, as proposed in [4]. The positional data is used together with the hit tracking system to determine the tuning of the virtual instrument and to trigger the sound. Proper delays have to be used to synchronize the audio stream coming from the microphone with the stream coming from the FSR system. The experiment confirmed that the hit detection and the mechanical systems still need improvement, anyway the sensitivity proven to be high enough to finely control the timbre and tuning of the instrument.

6. SYSTEM LIMITATIONS AND FUTURE STEPS

As previously mentioned, the first aspect that we need to improve is the mechanical interaction layer, which presents crosstalk problems with hit gestures. Another area of improvement is the signal conditioning and ADC circuitry. Noise should be reduced when we'll pass from breadboards to circuit prototypes based on a printed circuit board that uses a proper ground-plane and low-noise layout techniques. Once the system will present sufficient reliability, it will be integrated with the *Reactable* software and hardware. Also, the addition of visual feedback will aid the artist in the use of the new system and will offer a representation of the detected gestures, enhancing the perception of gestures and performance for the public.

7. CONCLUSIONS

A prototype multi-point pressure and hit detection system based on mechanically intercoupled force sensing resistors has been presented. The system is able to detect both subtle gestures and forces up to $3.5N$ in multiple simultaneous points with low latencies and a frame-rate of $1KHz$. The mechanics and electronics of the system have been exposed, and some case studies have been described.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

[1] B. Baker. *A Baker's Dozen: Real analog solutions for digital designers.* Newnes, 2005.

[2] A. Crevoisier and C. Bornand. Transforming Daily Life Objects into Tactile Interfaces. In *Proceedings of the 3rd European Conference on Smart Sensing and Context (EuroSSC)*, pages 1–13. Springer, 2008.

[3] A. Crevoisier and G. Kellum. Transforming ordinary surfaces into multi-touch controllers. In *Proc. of the Conf. on New Instruments for Musical Expression (NIME)*, 2008.

[4] G. Essl, S. Serafin, P. Cook, and J. Smith. Musical applications of banded waveguides. *Computer Music Journal*, 28(1):51–63, 2004.

[5] S. Fels. Designing for intimacy: Creating new interfaces for musical expression. *Proceedings of the IEEE*, 92(4):672–685, 2004.

[6] A. Hollinger and M. M. Wanderley. Evaluation of Commercial Force-Sensing Resistors. Input Devices and Music Interaction Laboratory (IDMIL) Report, January 2006. Music Technology Schulich - School of Music, McGill University Montreal, QC, Canada.

[7] T. C. Inc. Tactex Smart Fabric Technology, www.tactex.com.

[8] Interlink Electronics. FSR integration Guide and Evaluation parts Catalog. http://www.interlinkelec.com/, 2000.

[9] H. Ishii, C. Wisneski, J. Orbanes, B. Chun, and J. Paradiso. PingPongPlus: design of an athletic-tangible interface for computer-supported cooperative play. In *Proceedings of the SIGCHI conference on Human factors in computing systems: the CHI is the limit*, pages 394–401. ACM New York, NY, USA, 1999.

[10] T. Jensen, R. Radwin, and J. Webster. A conductive polymer sensor for measuring external finger forces. *Journal of biomechanics*, 24(9):851–853, 1991.

[11] R. Jones, P. Driessen, A. Schloss, and G. Tzanetakis. A force-sensitive surface for intimate control. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME)*, pages 236–241, 2009.

[12] R. Jones and A. Schloss. Controlling a physical model with a 2D force matrix. In *Proceedings of the 7th international conference on New interfaces for musical expression*, pages 27–30. ACM New York, NY, USA, 2007.

[13] S. Jordà. On stage: the reactable and other musical tangibles go real. *International Journal of Arts and Technology*, 1(3):268–287, 2008.

[14] N. Lago and F. Kon. The quest for low latency. In *Proceedings of the International Computer Music Conference*, pages 33–36, 2004.

[15] M. T. Marshall. *Physical Interface Design for Digital Musical Instruments.* PhD thesis, McGill University, March 2009.

[16] F. Moore. The dysfunctions of MIDI. *Computer Music Journal*, pages 19–28, 1988.

[17] J. Paradiso, C. Leo, N. Checka, and K. Hsiao. Passive acoustic sensing for tracking knocks atop large interactive displays. In *Proceedings of the 2002 IEEE International Conference on Sensors*, volume 1, pages 521–527, 2002.

[18] I. Rosenberg and K. Perlin. The UnMousePad: an interpolating multi-touch force-sensing input pad. In *ACM SIGGRAPH 2009 papers*, page 65. ACM, 2009.

[19] A. Schmidt, M. Strohbach, K. Van Laerhoven, and H. Gellersen. Ubiquitous interaction-Using surfaces in everyday environments as pointing devices. *Lecture notes in computer science*, pages 263–279, 2003.

[20] J. Schöning, P. Brandl, F. Daiber, F. Echtler, O. Hilliges, J. Hook, M. Löchtefeld, N. Motamedi, L. Muller, P. Olivier, et al. Multi-touch surfaces: A technical guide. *IEEE Tabletops and Interactive Surfaces*, 2008.

[21] M. Wanderley and N. Orio. Evaluation of input devices for musical expression: Borrowing tools from hci. *Computer Music Journal*, 26(3):62–76, 2002.

[22] D. Wessel, R. Avizienis, A. Freed, and M. Wright. A force sensitive multi-touch array supporting multiple 2-D musical control structures. In *Proceedings of the 7th international conference on New interfaces for musical expression*, pages 41–45. ACM New York, NY, USA, 2007.

[23] D. Wessel and M. Wright. Problems and prospects for intimate musical control of computers. *Computer Music Journal*, 26(3):11–22, 2002.

[24] S. Yaniger. Force Sensing Resistors: A Review Of The Technology. *Electro International, 1991*, pages 666–668, 1991.

[10] `www.gencat.cat/agaur/`