Tangible Acoustic Interfaces and their Applications for the Design of New Musical Instruments

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ABSTRACT
Tangible Acoustic Interfaces (TAI) rely on various acoustic-sensing technologies, such as sound source location and acoustic imaging, to detect the position of contact of users interacting with the surface of solid materials. With their ability to transform almost any physical objects, flat or curved surfaces and walls into interactive interfaces, acoustic sensing technologies are the most promising way to bring the sense of touch into the realm of computer interaction. Because music making has been closely related to the sense of touch during centuries, an application of particular interest is the use of TAI’s for the design of new musical instruments that matches the physicality and expressiveness of classical instruments. This paper gives an overview of the various acoustic-sensing technologies involved in the realisation of TAI’s and develops on the motivation underlying their use for the design of new musical instruments.

Keywords
Sound source localization, new musical instruments design.

1. INTRODUCTION
In the past two decades, research on interfaces for Human Computer Interaction (HCI) has focused mainly on audio and video analysis aimed at making the interaction with machines as natural as possible. More recently the attention has turned toward multi-modal interfaces, where signals of various nature are jointly and synergistically used to convey as much information as possible between humans and machines in a bi-directional fashion. One class of signals that have not been considered as much as audio and video, are those produced by the tactile interaction with objects. The interest in such signals is, however, very strong, as they carry a formidable amount of information and could enable novel forms of expressiveness [1]. This particular area of research is addressed in depth by the European project IST-507882 TAI-CHI (Tangible Acoustic Interfaces for Computer-Human Interaction) [2]. What we present in this paper are the initial results of HCI research within the TAI-CHI project in the context of detection and classification of tactile interactions with tangible interfaces. The final goal of the project is to gain a wide and versatile “vocabulary” of interactions modes involving gesture analysis and interpretation. In this sense it is not surprising that the TAI-CHI project was inspired by the use of tangible acoustic interfaces in the context of electronic music and artistic performance [1].

Tactile interaction involves the generation of vibrational wavefronts or patterns, depending on the interaction modality. Such vibration take place on the object’s surface and the corresponding signals are acquired through contact sensors (typically piezoelectric sensors) applied to the surface itself. The variety of acoustic waves produced by the possible interactions provides the user with a potentially very wide, articulated and versatile vocabulary of signals that can be used for a variety of control purposes.

Different methods for the detection of interactions can be considered. These methods can be grouped into two families, active and passive. The former is based on the evaluation of the acoustic energy that is absorbed at the points of contact, when the object is excited with ultrasound. These techniques are regarded as in-solid acoustic Holography. The latter relies on the analysis of the acoustic vibrations generated at the points of contact, when tapping or moving a finger or some tool on the surface of an object. Within this approach many techniques of source detection, localization and characterization can be developed. One example is given by the Time Reversal Process [3], based on the comparison and identification of the interaction signal with respect to a pre-recorded (learning phase) set of interaction signals. Another possibility is given by the Time Delay of Arrival
(TDOA) estimation, based on the analysis and comparison of signals detected by a number of sensors arranged in an array [4]. In our work we consider TDOA-related methods.

The literature on sensor array processing is rich with solutions and results that are suitable for the localization of sound sources in the context of in-air environments of various sorts [4], [5], [6]. On the other hand, not as many results are available for sensor array analysis in the case of in-solid acoustic propagation, not only, but mainly in the Non-destructive Evaluation field [7], [8], [9], [10]. Although intimately related, the two application scenarios exhibit very different problems. One of them is related to the phenomenon of dispersion of wavefronts in rigid surfaces. This means that the propagation velocity within the means changes with the frequency. In other words, the acoustic waveform can rapidly become distorted by the presence of several frequency components traveling at different speeds, and through contamination by reflections and mode conversions.

The solutions available in the literature that study the response of microphone arrays can be coarsely classified into three broad categories: those based on the concept of Steered Beamforming (SB) [5]; those based on High-Resolution Spectral Estimation (HRSE) methods, which analyze and process the data covariance matrix of the array sensors [5], [6]; and those based on direct estimation of Time-Difference Of Arrival (TDOA) [11], [12].

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The following section will give an overview of the various technology approaches for the realisation of TAI’s. Section 3 will develop on the motivation underlying their use for the design of new musical instruments and section 4 will focus on the mapping issues related to TAI’s.

2. TECHNOLOGY OVERVIEW

2.1 Basic Principle

Any physical contact with a solid object or a surface (wall, table, etc.) is modifying its acoustic pattern by the way acoustic energy is distributed in the object and on its surfaces. Such perturbation of the acoustic pattern can be caused in two ways. First, by the acoustic vibration generated at the points of contact when tapping or moving a finger on the surface of the object (passive method). Second, by the acoustic energy that is absorbed at the points of contact (proportional to contact pressure) when the object is activated with ultrasound (active method). As acoustic vibration propagates well in most materials, this means that the information about the interaction can be conveyed to a remote location, using the structure of the object itself as a transmission channel and suppressing the need for any overlay or any other intrusive device over the area one wishes to make sensitive.

Generally, the TAI technologies are determining the geometric position of the acoustic sources (or sinks), which correspond to the points of contact on an object. Moreover, the additional information about the nature of the sound can bring extended control capabilities, as well as helping to eliminate false triggering due to ambient noise, or to operate selective tracking (for instance, a surface might be sensitive to the contact of a pen but not to a finger). It will thus be possible to determine how and where an object is touched or manipulated, providing a complete description of the interaction. The following subsections give an overview of the various technology approaches for detecting the contact position, that is, to locate where the object is touched.

2.2 Time Reversal

Time reversal in acoustics is a very efficient solution to focus sound back to its source in a wide range of material including reverberating media [3]. It is based on the principle that the impulse response in a chaotic cavity is unique for a given source location. The method that is employed here is a particular case of the Time Reversal technique and consists in detecting the acoustic waves in solid objects generated by a simple human touch. The detection is a two steps process. The first one is the acquisition of the impulse response: a short pulse is emitted by tapping on the surface of the object, which propagates toward the solid cavity and reflects inside. The echoes are collected by a contact transducer working as a receiver. The duration of the response depends on the absorption of the material and on the energy radiation property of the cavity. In the second step, the information related to the source location is extracted from a virtual time reversal experiment in the computer. The number of possible touch locations at the surface of objects is directly related to the mean wavelength of the detected acoustic wave.

Figure 2. Time Reversal – Training Step.

Figure 3. Time Reversal – Detection Step.

2.3 Time Delay of Arrival (TDOA)

TDOA-based locators are all based on a two-step procedure applied on a set of spatially separated microphones. Time delay estimation of the source signals is first performed on pairs of distant sensors. This information is then used for constructing hyperbolic curves that describe for each couple of sensors (the
foci of the hyperbola) the location of all points that correspond to
the estimated delay. The curves drawn for the different pairs of
sensors are then intersected in order to identify the source
location.

**Figure 4. Basic Principle of TDOA estimation.**

This constitutes the very simple abstract and geometrical
approach to the problem. However, a number of physical
phenomena has to be considered in order to make the method
reliable. Obviously, the performance of TDOA-based solutions
depends very critically on the accuracy and the robustness of the
time delay estimation (TDE). One can identify three major
problems for TDOA methods for the in-solid case: background
noise, reflections (multiple sound propagation paths) and,
especially, dispersion. The most crucial problem of in-solid
localization is given by the phase velocity dispersion occurring
with in-solid wave propagation. Generally speaking, waves in
solid plates propagate in different ways: longitudinal and
transversal waves, denoted as BAW (Bulk Acoustic Waves) and
Reyleigh waves, denoted also as SAW (Surface Acoustic Waves).
In thin plates one finds also other kinds of SAW: Love and Lamb
waves (see for instance \[10\], \[14\]). The direction of oscillation
of the particles in each one of these families of waves as well as
the velocities of propagation are different. Also, each one of these
types of waves can be excited according to different modes and
each mode has its own dispersion curve. Thus, according to the
physical interacting point on the surface and the frequency
content of the excitation, different modes can be excited with
significantly different propagation velocity. This makes the
estimation of TDOA’s a complex task and the TAI-CHI project is
investigating different solutions to override this problem.

### 2.4 Acoustic Holography

Methods for locating and visualising acoustic sources and
intensity patterns are well developed for in-air applications. They
are usually referred to as “Acoustic Holography” \[25, 26\]. Any
sound field descriptor, such as sound pressure, sound intensity or
particle velocity, can be calculated as a function of position and
time. Results are typically displayed as animated maps to
illustrate how a specific property changes as a function of time
\[27\]. Acoustic holography is sometimes referred to as an
“acoustic camera” \[28\] because it allows an image of the sound
sources to be visualized, in a similar way that an IR camera
allows one to see sources of heat. The great innovation brought by
the TAI-CHI project is to further develop Acoustic Holography
for in-solid wave propagation. This means that measurements are
executed directly on the object itself, using surface wave
transmission. In this case, the reconstruction of acoustic patterns
is only desired for a plan, so recording of acoustic waves need
only to be taken along a line, using a mono-dimensional
microphone array.

### 2.5 Comparative Characteristics

Each of the different techniques that have been described above
has its own advantages and disadvantages. This is very important
to take into consideration when choosing which one is the most
appropriate for a certain application. Here are a few guidelines
concerning the comparative characteristics.

Cross-correlation techniques are the easiest to use in practice
because only one or two sensors are necessary, with the only
restriction that they should not be positioned along the symmetry
axes of the object they are fixed to. Another important advantage
is that they are compatible with the largest variety of objects and
complex shapes are even a benefit to get a unique acoustic
signature for each of the considered points. On the other hand,
their main drawbacks is the necessity of a learning phase, which
limits the interaction to a fixed number of points, and a relatively
big delay in the response, especially in reverberant materials (up
to 100-500ms).

TDOA techniques are the fastest in their response (typically, a
few ms) but they are limited to uniform surfaces of homogeneous
material, such as glass, PVC or metallic plates. A calibration
phase is necessary but then the number of detectable points is
only limited by the resolution of the system (typically 1 to 4
centimetres). Two sensors are necessary for mono-dimensional
detection (using a rod or a handrail, for instance) and four for bi-
dimensional detection on plates and surfaces.

In-solid acoustic holography is still at an early stage of
development but it shows promising perspective because of its
ability to track several points of contacts simultaneously and
continuously. This is a unique feature of holography, which might
not be feasible with other techniques. On the other hand the
practical aspects are less favourable for this technique, as it
requires an array of contact microphones attached to the surface
of the object that one wants to make interactive.

### 3. MUSICAL APPLICATIONS

Tangible Acoustic Interfaces lead to a very large number of
applications in the field of Human-Computer Interaction. As
already mentioned, they were originally conceived as new
interfaces for musical expression \[1\]. This section explains the
reasons that motivated their development in the context of
musical applications and in particular for the design of new
musical instruments.

#### 3.1 The Model of Classical Instruments

Classical musical instruments are characterized by the fact that
the performer interacts closely and most of the time directly with
the source vibration (ex guitar, violin, etc). This is due to the
symbiotic nature of the interface, which features a close
integration of sound generation and control, and results in highly
expressive capabilities. However, with the development of
computer music and new interfaces for musical expression
(NIME), we have observed a separation of the musical
instruments into two separate interfaces:

- The gesture controller (movement-sensing device)
- The sound generator (usually the computer)

Therefore, the main goal of using TAI technologies for musical
applications is to re-unify the sound generation and the control
over the sound in the same interface. In other words, the goal is to
use the acoustic waves generated by the interaction with an object as a sound source and to employ, at the same time, the same acoustic vibrations to extract control information for processing the sound by means of a computer. This way, it is possible to keep the original essence of classical instruments, but with new gestural interactions and extended control capabilities.

3.2 Extended Control
Compared to classical musical instruments, TAI based instruments offer two kinds of controls over the sound:
- The control over the generation of the sound (the way the vibration is produced, by tapping, rubbing, scratching, etc).
- The control over the simultaneous processing of the sound (by extracting control parameter from the above vibration).

To be complete, the latter require not only a localization of the interaction but also a refined characterization and interpretation of the interaction itself, based on pattern recognition techniques and gesture interpretation. Thanks to this, one could aim to recover a clear perceptual mapping similar to that of traditional instruments, i.e. to recover a clear correspondence between a physical gesture and the sound response produced by it. In a wider perspective, this approach will allow a tremendous expansion of the gesture scope and an unlimited freedom in the definition of movements that can communicate expressive details, without the usual constraints of traditional instruments. In this way, it becomes possible to conceive an interface according to a desired human gesture instead of adapting the gesture to a given interface.

3.3 Instrument Design
A key aspect of TAI technologies is that they are not delivering a specific interface but a mean to transform a large variety of objects into interactive interfaces. For this reason, the final application will not be a specific NIME but rather an experimental kit, which enables people to transform almost anything into a musical instrument, giving a new freedom in the design of new musical interfaces. Objects of any form, shape and dimension can become an interface. Ergonomic issues, in terms of what we could call tactile design, will play a relevant role. Moreover, a new expressive dimension for musical instrument is introduced by the possibility to communicate a message not only with the sound, but also with the symbolic nature of the object that is chosen for the interface. In that sense, the creative dimension for the design of new musical instruments based on this technology is getting close to the art of sculpting and plastic art, in general.

3.4 Mapping
As mentioned before, in addition to the information about the position of contact on the object-interface, sound analysis allows extracting high-level parameter for extended control and interaction. The following table gives an overview of the parameters that can be used to control further sound processing.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>[x, y]</td>
<td>TDOA / Acoustic Holography</td>
</tr>
<tr>
<td>Position</td>
<td>Point index</td>
<td>Time Reversal</td>
</tr>
<tr>
<td>Pressure</td>
<td>[z]</td>
<td>Active Acoustic Holography</td>
</tr>
<tr>
<td>Volume</td>
<td>[v]</td>
<td>Amplitude follower</td>
</tr>
<tr>
<td>Action Type</td>
<td>Tapping, Scratching, Rubbing, etc</td>
<td>Pattern Recognition</td>
</tr>
<tr>
<td>Contact Type</td>
<td>Hard / Soft</td>
<td>Spectrum Analysis</td>
</tr>
</tbody>
</table>

Using the [x, y] information about the position, for instance, it is possible to draw a certain number of zones on the interface and assign them MIDI events, such as Note numbers and continuous controllers. The following diagram shows an example of interface with various zones drawn on a flat object.

Figure 5. Two design examples for TAI instruments.

Figure 6. Mapping example with a flat object. Zones are drawn on the surface and assigned to MIDI Note # and Continuous Controlers.

4. IMPLEMENTATION
The following sub-sections give a summary of the experimental setups and results for the various technologies. Originally implemented on separate platforms, the algorithms are progressively ported on the EyesWeb software platform [29].

4.1 Time Reversal
The method has been successfully tested in various situations and with various objects. The example shown in figure 7 consists of a single piezo transducer attached to a blackboard and connected to the microphone input of a laptop. A grid of 9x6 points spaced of...
4cm is drawn on a piece of paper fixed to the board. The red dot on the computer screen corresponds to the detected point.

4.2 TDOA
At present the investigation has been limited to the simple case of flat surfaces. Two kinds of materials were tested, glass and plexiglass, i.e. isotropous materials. The tables used were of three sizes 130x100 cm2, 70x100 cm2 and 50x50 cm2, homogeneous with no discontinuities.

The measurable criteria of the proposed technical approaches are in terms of spatial resolution of localization. Currently, the obtained resolution is of less than +/- 1 cm on a surface of about 15x15 cm2 (see Fig. 8) Improvements on this target performance will depend on the refinement of the present methods and on the integration of the new methods under study.

The experimental set-up consists in a prototype acquisition system and a set of contact sensors. The acquisition system is formed by a PC Pentium IV 2.1 GHz, a Multi-Track hard-disk recorder a Terratec EWSMT88 sound card 8IN/8OUT working at a sampling rate of 96 KHz. New tests at a higher sampling rate of 512 KHz by means of an ultrasound acquisition card are planned for the next future. At present, a sampling rate of 96 KHz provides a linear resolution of about 1.75 cm for a plexiglass surface (mean acoustic wave propagation velocity \(\sim 2600\) m/s).

For what concerns the sensors, at present we used both a set of high quality sensors (Knowles BU-1770) and a set of 4 low-cost piezo-electric sensors.

4.3 Acoustic Holography
In different series of tests, theory and algorithm of Acoustic Holography were applied. The investigated objects were a metal-plate, a board of wood and a glass-ceramic hob with different dimensions. On them, an impulse-hammer respectively through taps have created an acoustic signal (Figure 2). The used sensors were ICP accelerometers of PCB and the recording of the measured signal was done with an OROS signal analyser. Finally, the measurement data processing for the localisation was computed with a MATLAB scipt, where the Rayleigh-Sommerfeld algorithm was evaluated.

5. CONCLUSION
One truly exciting idea about sound controllers is the possibility of transforming almost any object into an interactive interface. No extra technology is needed for the interface; only inexpensive piezo contact sensors and a few audio inputs for the computer are sufficient. Building low-cost, custom interfaces which offer a high degree of expressiveness is the real challenge of TAI controllers. This opens the door for a vast area of exploration. From small
resonant objects to big structures, the potential to invent original interfaces is unlimited. In addition, the sound of the interface can be used not only to control other processes but also as a natural source for further manipulation, live sampling and processing. This gives this kind of NIME an even larger scope of creative development. Definitely oriented for further growth in the age of advanced technology, TAI based instruments bring back the historical unity of traditional instruments with the well-integrated duality of musical control and sound generation.

6. ACKNOWLEDGMENTS
Our thanks to all the participants of the TAI-CHI project who are contributing to the development of this promising technology, making possible the exciting musical applications presented here.

7. REFERENCES
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