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Reference
Usability evaluation and comparison of prototypes of tangible acoustic interfaces

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Abstract. This paper faces two problems: (1) the comparison of two different technologies for the characterization of acoustic propagation patterns and the positioning of acoustic sources in tangible acoustic interfaces (TAI) and (2) the usability evaluation of two different prototypes of TAI. In the framework of the EU-IST project TAI-CHI (Tangible Acoustic Interfaces for Computer-Human Interaction), two different prototypes of tangible acoustic interfaces have been designed, based on the TDOA (Time Delay Of Arrival) and the TR (Time Reversal) approaches.

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1 Introduction

This paper presents an evaluation of two different prototypes of tangible acoustic interfaces, developed in the framework of the EU-IST STREP project TAI-CHI (Tangible Acoustic Interfaces for Computer-Human Interaction, http://www.taichi.cf.ac.uk), funded by the European Commission in the Sixth Framework Program. This project explores how physical objects, flat or complex surfaces and walls can be transformed into natural, seamless, unrestricted touch surfaces. The ultimate goal is to design multimodal tangible acoustic interfaces (TAI) that employ physical objects and the surrounding space as media to bridge the gap between the virtual and the physical worlds.

We report a brief description of the first public event in which interactive TAI installations realized in the framework of the TAI-CHI project have been evaluated with the aim to help TAI developers to improve their prototypes.

The first interactive TAI installation took place at the “Casa Paganini”, research center on music and new multimedia technology in Genova (Italy), which includes a new site of the DIST InfoMus Lab, from the 25th to the 29th of July 2005, during first S2S² EU Summer School, organized by the EU IST Coordinated Action S2S² – Sound to sense, sense to sound (www.s2s2.org), aiming at setting up the roadmap on the technology research on sound.

This event gathered a number of researchers and scientists from all around the world on multimodal interfaces, which have been exposed to the installations developed in TAI-CHI and available during the whole duration of the EU Summer School.

A set of installations from the various partners of the TAI-CHI project have been presented to participants at the S2S² Summer School: two of them, based on TDOA (Time Delay Of Arrival) and TR (Time Reversal) techniques, have been chosen for an evaluation of the participants. Evaluation has been scheduled so that a group of 23 participants had to compile a questionnaire, provided by Prof. Klaus Scherer and his staff at the Geneva Emotion Research Group (GERG, Department of Psychology, University of Genève). GERG carried out a statistical analysis of
the collected data. Results and interpretation are being presented in this paper, in terms of comparison of the two TAI prototypes and of what usability dimensions are of most importance for the users.

In addition, TDOA (Time Delay Of Arrival) and TR (Time Reversal) techniques, that is the two technologies laying the foundations for the development of the presented TAI prototypes, are being compared.

## 2 Description of the interactive TAI installations

The developed TAI prototypes are based on the principle that interacting with a physical object modifies its surface acoustic patterns, due for instance to the generation of acoustic vibrations (passive method) or the absorption of acoustic energy, proportional to the contact pressure, at the points of contact (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. By visualising and characterising such acoustic patterns, it is possible to transform almost any object (for example, a wall, window, table top, giant screen, or arbitrary 3D object) into an interactive interface, opening up new modes of computer-user interaction for responsive environments.

The TAI prototypes installation, organized during the S2S EU Summer School held in Genova, has been scheduled so that a set of installations from the various partners has been presented to participants: two of them, designed by the staff of CeTT (Centre for Engineering and Technology Transfer, Yverdon Technology Parc, Switzerland) and LOA (Laboratoire Ondes et Acoustique, Institut pour le Developpement de la Science, l’Education et la Technologie, Paris, France) partners, have been chosen for an evaluation of the participants.

Both installations have been implemented in the new version of EyesWeb ([www.eyesweb.org](http://www.eyesweb.org)) (Camurri et al., 2000 and 2004) released in TAI-CHI, platform of TAI-CHI, with the support of DIST-InfoMus Lab staff for their development.

The principle of the evaluation is that the two installations selected for the evaluation task are characterized by a similar task: in such a way, the evaluation can compare the different solutions proposed. The task that has been selected for the evaluation is related to the application of interactive table and can be defined as "To navigate on some content (web browser, computer program, etc) projected on a table". This means that, by tapping on the table, the cursor on the projected image should move to the position of finger and generate a click (the beamer is above the table). The mapping is therefore quite straightforward, the detected position is used as input for Windows events controlling the position of cursor and generating clicks (the system is more or less simulating a mouse). DIST provided the module in EyesWeb that does that.

The basic idea is related to the localization, realized by means of sensors, of the points touched and consequent generation of events. In particular, the processed recorded acoustic wave signals can be back-projected on an image plane to reconstruct the image of the acoustic wave pattern.

Two different technologies laying the foundations of the developed TAI prototypes, TDOA (Time Delay Of Arrival) and TR (Time Reversal) techniques, have been used for the characterisation of acoustic propagation patterns and the positioning of acoustic sources. TDOA and TR techniques are two main techniques emerged from TAI-CHI up to now. They are complementary: TDOA faster but more difficult to get high precision, TR slower (slightly higher latency due to computational load, but allowing more precision).

## 3 TAI prototypes based on TDOA algorithm: the “memory game” and “Sound Rose” applications

CeTT staff presented two different demos: the first one implements an sort of “memory game”, whereas the second one is an artistic installation called “Sound Rose”.

In the “memory game” installation (see Fig.1) users had the possibility to tap different locations on a table, where each of them corresponds to the visualization of a specific image/card. The tapping on a specific location was detected and translated to a mouse click on the specific card to be turned. The aim of the task consists of finding two subsequent identical images: in this case the system provides an acoustic feedback to users. This application is based on the TDOA (Time Delay of Arrival) algorithm: starting from several sensors embedded in the system, the algorithm consists of computing the time employed by the tap to reach 2005).
The second installation is an interactive artistic installation integrating the TAI technology realized by Alain Crevoisier and Sei Matsumura. Entitled “Sound Rose”, this installation (see Fig.2) consists of a touch sensitive table with images projected from the ceiling. When users tap on the table, rose-like graphics are displayed at the point of contact and the raw sound created by the impact is processed in real-time in order to produce more elaborated sounds. Parameters such as the force of impact is controlling the size of the roses. Different sounds and graphics can be selected by tapping on visual buttons at the four corners of the table. Both impact positions and sounds are in loops, allowing the users to create complex visual and sonic patterns. Another button at the bottom of the table allows to erase the loop.

### 4 TAI prototype based on TR algorithm: LOA installation

LOA staff proposed a demo in which users could, by tapping on eight different points on a table, manipulate buttons to activate the Media Player by means of the functions Play, Stop, etc. This second installation is based on the Time Reversal (TR) algorithm, that consists of computing the correlation between the response functions of each points trained by the system (Crevoisier et al., 2005; Ing et al., 2001). This method is characterized by a slightly longer latency with respect to the TDOA algorithm. In recent years, time reversal interactive experiments were developed in the Laboratoire Ondes et Acoustique (LOA). In the experiment shown within the S2S event in Genova, a simple table desk was transformed in an interactive surface, more precisely in a six buttons remote control. Then, a simple touch on this set of buttons allowed one to control a media player software just as a normal keyboard would. The six virtual button functions, marked with tapes on the table were:

- Start (start the media player software)
- Play (play the selected music)
- Stop (stop the selected music)
- Next (select the following piece of music)
- Previous (select the previous piece of music)
- Close (close the media player software)
The material needed for such experiments is very light, standard and easy to implement. The acoustic sensor is a cheap Murata PKS1-4A type, with a working bandwidth ranging from 0.1 to 5 kHz. It is glued or taped anywhere on the interactive surface and connected to the input line of a portable personal computer, 700 MHz with a 256 Mo RAM. Typically, 100 ms acoustic signals are digitized by a standard sound card, with a 44.1 kHz sampling rate and a 16 bit dynamic.

The general physical concept of the time reversal interactive experiment is summarized in the following paragraph:

The first step of the experiment is a training step. It consists in acquiring a reference library, that is to say a set of impulse responses in memory. As illustrated in Fig.3, three arbitrary chosen “tactile” points B, C, D are sequentially touch and the three corresponding impulse responses (or acoustic signature), \( h_{BA}(t) \), \( h_{AC}(t) \), \( h_{AD}(t) \) are detected by the sensor (point A) and recorded in the computer.

In a second use step, as one of the previous points is touched again, say C, the new impulse response \( h_{AC}'(t) \) detected by the sensor is transferred to the computer. Then, a time reversal experiment is processed in the computer. The new impulse response is time reversed and virtually reemitted by the accelerometer as if it was able to act as a source, Fig.3. The acoustic field that one would observe with accelerometers on points B, C, D is represented on the right hand side of Fig.3:

\[
S_I(t) = h_{AC}'(-t) \otimes h_{AI}(t) \tag{3}
\]

\( I \) is the point index, \( I = B, C, D \) and \( h_{AC}'(-t) \) holds for the emitted signal from A. Consequently the reversibility property of the wave equation implies that a maximum of energy is found on the point where the source was. Thus, the computation do identify point C as the touched point among the three tactile points, Fig.3. Because time reversal process was shown to be a spatio temporal matched filter, a second and quite straightforward interpretation should be highlighted. The signal processing of Eq.3 is a correlation. Thus computing the correlation between a new signal \( h_{AC}'(t) \) and each reference signal of the library gives a maximum close to unity (0.98 in Fig.3) when a pair of signals resemble each other. It happens during the use step, when the same point as in the training step is touched again. Thus from a signal analysis point of view, the training step is the acquisition of a set of match filters whereas the use step is a recognition process based on correlation computing.

5 TDOA and TR algorithms: comparison of performances

TDOA-based localisation systems 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.

This constitutes the very simple abstract and geometrical approach to the problem. However, a number of physical phenomena have 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 Rayleigh waves, denoted also as SAW (Surface Acoustic Waves). In thin plates one finds also other kinds of SAW: Love and Lamb waves. The particles oscillation direction in each one of these families of waves as well as the propagation velocities is 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 a complex task and the TAI-CHI project is investigating different solutions to override this problem.

The acoustic time reversal algorithm uses the signal produced by a sound wave emanating from a source and acquired with one sensor placed on the surface of a board. The algorithm needs an initialisation phase where signatures obtained by tapping specific locations are recorded. During the functional phase, the signals acquired when the surface of the board is being tapped on are compared to the recorded signatures. As a result, it is determined if the tap is located on one or another previously recorded location or not. The TR algorithm offers similar difficulties as the TDOA algorithm.

The advantage of the acoustic time-reversal method is clear: one single sensor is needed. Its disadvantage relies in the need to record the signatures as an initialisation phase. The method is excellent when a relatively small number of interaction points are needed. The TDOA method is more versatile but it needs more sensors. It offers the possibility to locate an impact without initialisation phase and at any location.

The demonstration suggests that the TR method is more reliable than the TDOA method. That is probably true. But the comparison is not so good as the applications demonstrated are so different. We will have to implement the same demonstrations with each kind of method to show which solution is more advanced.

6 The usability evaluation phase

The evaluation phase of the presented TAI prototypes included the definition of the exact parameters of usability and human factors to take into account to assess the effectiveness of the TAI interfaces developed by the project. The collaboration with professor Klaus Scherer and his staff of Geneva Emotion Research Group led to the definition of an evaluation questionnaire that has been used for the evaluation.

The evaluation was spread over 5 days, and included 23 participants. They were all S2S attendee with a professional background on Interfaces Design or Human-Computer Interaction. 11 participants evaluated CeTT installation, whereas 12 participants focused on LOA installation. This evaluation was a first attempt to determine what dimensions of the interfaces were most sensitive, and regarded as most important by experienced users. The aim was also to compare the two interfaces, CeTT and LOA, that apply the same concepts but use different techniques (TDOA and TR), and to determine why users would prefer one interface over the other.

The questionnaire that we built compiled 21 scale questions, belonging to three categories (cf. annex section):

- The "Overall" category comprised questions regarding the general feeling of the user when using the interface, and her or his first impressions.
- The "Usability" category comprised more technical questions regarding various aspects that we thought could be critical to assess the effectiveness of the interfaces, and to allow a direct comparison of usability between the two interfaces.
- The "Emotional involvement" category comprised questions with regard to the personal feeling of the user when using the interfaces.

For each question, respondents were asked to circle a 1-to-9 scale, bounded by explicit labels, were appropriate. Questionnaires were anonymous, but respondents could leave their email address and personal information to the members of the staff who were present at the exhibition if they wanted to be kept updated about future developments.
Two kinds of analysis were conducted by Geneva Emotion Research Group on the quantitative data that was collected.

First, a Pearson correlation analysis on all questions, for each category, allowed us to show the implicit links that users drew between the dimensions expressed in the questionnaire. In the "overall" category, the results showed that how users liked using the interfaces was strongly linked with how the interfaces met their expectations ($r= .836, p<.01$). Similarly, the ease with which the users experienced using the interface was strongly linked with how long it took them to actually master the interface ($r= .824, p<.01$).

With regard to "usability", precision, sensitivity, coherence of behavior, and reactivity showed the strongest correlations, pairwise, with Pearson's coefficients significantly rising above .79. No significant correlations were found for the "emotional evolvement" category.

The results of the questionnaires were then analyzed using Student $t$ tests, comparing the two interfaces on the basis of the dimensions measured by the questionnaire, and verifying Levene's test for equality of variances.

LOA was found to receive significantly better results than CeTT for the dimensions of precision ($t=-3.252, p<.01$, respective means of 4.55 and 6.92), sensitivity ($t=-2.795, p<.05$, respective means of 4.55 and 6.67), coherence of behavior ($t=-2.284, p<.05$, respective means of 5 and 6.83), reactivity ($t=-4.662, p<.001$, respective means of 4.45 and 7.33), and predictability ($t=-2.222, p<.05$, respective means of 6.45 and 7.75).

Interestingly enough, the analysis did not yield to any significantly better results for CeTT over LOA.

7 Conclusions

To conclude, these analyses allowed us to determine what usability dimensions were of most importance for the users, i.e. where the emphasis should be put in terms of research/development.

We identified a number of such dimensions, namely the easiness of use, the coherence of the interface behavior (that allows predictability), as well as the precision, the sensitivity and reactivity.

Similarly, we were able to compare the two interfaces on a number of these dimensions, showing a clear preference of the users for LOA, over CeTT, with regard to the dimensions of precision, sensitivity, coherence of behavior, reactivity, and predictability. A model of questionnaires have been used is showed in the Appendix below.
APPENDIX

MODEL OF QUESTIONNAIRE:

Interface number: (1=CeTT, 2=LOA)

Background

This is a test of prototypes of tangible acoustic interfaces.

Instructions

You are presented with several interfaces. Each one of them is using different technologies, and we would like to gather your impressions about their usability, as well as your personal feelings about this innovative way to interact with a machine. Please answer the following questions, circling where appropriate.

These questionnaires are anonymous. Should you require more information, please do not hesitate to contact a member of the staff.

We thank you for your time and support.

Overall

<table>
<thead>
<tr>
<th>Question</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Overall, how much did you like using this interface?</td>
<td>1 2 3 4 5 6 7 8 9 Very much</td>
</tr>
<tr>
<td>2. Overall, did this interface meet your expectations?</td>
<td>1 2 3 4 5 6 7 8 9 Very much</td>
</tr>
<tr>
<td>3. Overall, how easy was it to use this interface?</td>
<td>1 2 3 4 5 6 7 8 9 Very easy</td>
</tr>
<tr>
<td>4. Overall, how intuitive did you find this interface?</td>
<td>1 2 3 4 5 6 7 8 9 Very much</td>
</tr>
<tr>
<td>5. Overall, how long did it take to learn how to use this interface?</td>
<td>A long time 1 2 3 4 5 6 7 8 9 No time at all</td>
</tr>
</tbody>
</table>

Usability

<table>
<thead>
<tr>
<th>Question</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>6. How precise is the interface?</td>
<td>Not at all 1 2 3 4 5 6 7 8 9 Very much</td>
</tr>
<tr>
<td>7. How sensitive is the interface?</td>
<td>Not at all 1 2 3 4 5 6 7 8 9 Very much</td>
</tr>
<tr>
<td>8. How coherent to your moves were the reactions of the interface?</td>
<td>Not at all 1 2 3 4 5 6 7 8 9 Very much</td>
</tr>
<tr>
<td>9. How useful was the feedback provided by the interface?</td>
<td>Not easy 1 2 3 4 5 6 7 8 9 Very easy</td>
</tr>
<tr>
<td>10. Would you have needed more feedback from the interface?</td>
<td>Not at all 1 2 3 4 5 6 7 8 9 Very much</td>
</tr>
<tr>
<td>11. How fast was the interface to react to your moves?</td>
<td>Too slow 1 2 3 4 5 6 7 8 9 Fast enough</td>
</tr>
<tr>
<td>12. Did you manage to do what you aimed for?</td>
<td>Never 1 2 3 4 5 6 7 8 9 Always</td>
</tr>
<tr>
<td>13. How easy was it to recover from an unexpected situation?</td>
<td>Very easy 1 2 3 4 5 6 7 8 9 Very hard</td>
</tr>
</tbody>
</table>
14. Is the display of the interface easy to use? | Very easy | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Very hard

**Emotional involvement**

| 15. How appealing is the interface? | Not at all | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Very much |
| 16. How stimulating is the interface? | Not at all | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Very much |
| 17. How satisfying is the interface? | Not at all | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Very easy |
| 18. How odd/bizarre was it to interact with the interface? | Not at all | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Very easy |
| 19. How much command/control does this interface offer? | None at all | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | A lot |
| 20. Would you be ready to use this interface on a daily basis? | Not at all | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Very much |
| 21. How predictable is the behavior of the interface? | Not at all | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Very much |

**Open comments**

Feel free to provide us with additional comments, suggestions, critics, or even congratulations, regarding the interfaces.
References


