TANGIBLE DATA SCANNING SONIFICATION MODEL

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ABSTRACT

In this paper we develop a sonification model following the Model-based Sonification approach that allows to scan high-dimensional data distributions by means of a physical object in the hand of the user. In the sonification model, the user is immersed in a 3D space of invisible but acoustically active objects which can be excited by him. Tangible computing allows to identify the excitation object (e.g. a geometric surface) with a physical object used as controller, and thus creates a strong metaphor for understanding and relating feedback sounds in response to the user's own activity, position and orientation. We explain the technique and our current implementation in detail and give examples at hand of synthetic and real-world data sets.
Keywords: Model-based Sonification, Tangible Computing, Interaction, Exploratory Data Analysis

1. INTRODUCTION

Sonification allows users to experience their data in novel, acoustic ways, which is particularly interesting due to the continuously increasing growth of data which are collected in science, economy, production and society. It seems that the increase in complexity demands new ways to create awareness of the data in order to draw conclusions and get insights. Acoustic feedback is an intuitively appropriate option since it serves the same purpose also in our real-world experience of processes.

Human knowledge acquisition in the world is –besides observation– highly based on interaction with our natural, physical world. Often direct interaction, particularly with more complex structures or materials is the key to the discovery of before unknown properties [**?**]. Think for instance of the sound of shaking an opaque box of nails. We often forget how frequently we profit from the ubiquitious acoustic information in response to our actions. Data sets, however, are non-physical by nature. They originally do not reflect interactions by sound, and thus ways to intuitively interact with them need to be defined explicitely. This unfortunately brings in some arbitrariness which is somewhat difficult to remove. *Tangible Computing* [**?**] reintroduces physical objects (e.g. tools like a hammer or screwdriver) with all their intuitive and ubiquitous interaction qualities to the virtual world of digital manipulations. As guiding paradigm we regard that objects are not merely used as controllers, but 'become' the controlled virtual objects (e.g. interaction tools) by means of identification as described in [**?**, **?**].

This identification opens rich interaction possibilities and provides a strong connection between our intuitive interaction knowledge and the acoustic reaction of data in result to our interaction with them.

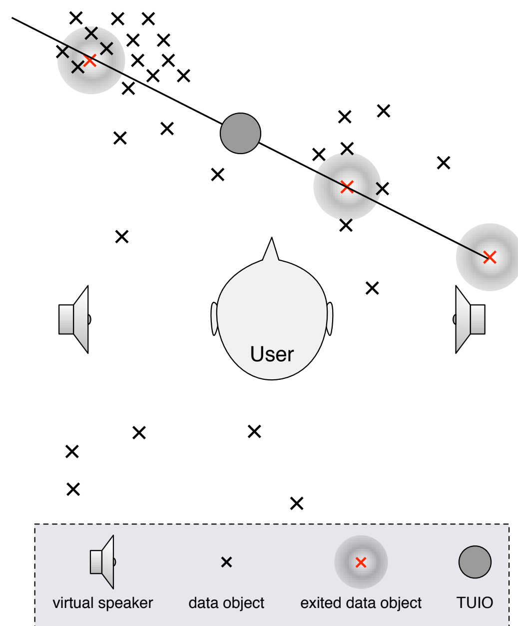

Figure 1: An overview of the system.

Our motivation is the extension of tangible computing paradigms towards sonification-based acoustic responses in exploratory data analysis. We regard this direction as highly promising for using sonification in a very productive way. Filling the gap between the user's manipulation skills and the system's manipulation modes via intuitive HCI-interfaces is important especially in data exploration tasks since they generally require advanced skills in handling the mechanisms as well as the knowledge about their specific benefits and drawbacks. The presence of physical properties such as position or extent as well as our human knowledge and experience facilitates the design of intuitive tangible user interfaces. Since Graphical User Interface do not have these physical properties it is much more difficult to achieve the same intuitiveness [**?**].

Nowadays users of data exploration systems are rarely confronted with acoustic responses to their interaction with the data. From the perspective of ergonomy we expect sonifications to be most likely accepted if they come along as a non-obtrusive new element added to already existing interactions, so that users slowly become familiar with the additional information, and finally even rely on this channel of information. The key factors in such sonifications, however, are

Appropriate sound complexity All sound should be informative and as simple as possible in order to convey the information rather than masking it,

Directness The more direct sound responses reflect user–system interactions, the easier users can relate them to their actions,

Ergonomy The more interaction sounds follow principles we know from our real-world experience (e.g. harder interaction cause louder sounds), the less irritation are caused by the acoustic stream.

Model-based Sonification provides an approach which favors the coupled implementation of all the listed requirements, by defining dynamic systems and interactions on them [**?**].

In the Tangible Data Scanning Sonification Model (TDS) high-dimensional data can be explored by interacting with a particularly suited data driven 3D-representation which physically surrounds the user. This data-driven environment is then explored interactively by direct interacions with a *tangible user interface object* (TUIO) [**?**, **?**]. By identifying it with a virtual interaction tool, e.g. a plane or a sphere its movement causes intersections with data objects spatially embedded in the user's space. This leads in consequence to excitations which cause informative acoustic responses. The tight closure of the interaction loop enables the user to actively understand the spatial data distribution and even more complex features like their local density or topographic organization. In difference to other systems here quantitative information of the data are directly transformed into qualitative properties of the resulting sound. For instance, high or low data density due to the detailed coordinates are perceived as dense or sparse acoustic textures without creating this linkage explicitely.

We demonstrate the new sonification model at hand of our existing sensor equipment in our interaction Laboratory (iLab), namely the Lukotronic motion capturing system [**?**] which allows TUIO object tracking (6 DOF) at upto 100 Hz. As benchmark data sets we start with synthetically rendered 3D distributions to have precise control over the structure. This is followed by some real-world data sonification/interaction examples where the clustering structure can be understood from the interaction with TDS.

2. TANGIBLE DATA SCANNING

Before defining the TDS sonification model in detail, we briefly review Model-based Sonification as the more general design framework. The definition is followed by comments on the implementation and a discussion of scaling properties via performance scaling as introduced in [**?**].

2.1. Model-based Sonification

Model-based Sonification (MBS) [**?**] offers an unconventional way to create means of manipulating data: different from mapping based approaches, where data are turned into parameterized sounds, in MBS data are involved in the creation of a *process*, a dynamic system capable of a dynamic behavior that can be perceived as sound. Such an implemenation is called sonification model. The fundamentally different linkage between data and sonification puts the user and his interaction with the defined process into the fore and is rooted in the importance of interaction to explore the world. MBS delivers guidelines for required sonification model 'ingredients': system setup, dynamics, interactions, definition of the listener, and model-sound linkage. A key benefit of MBS is that it provides a generic linkage between data and the sonification, which means that for instance all sorts of high-dimensional data sets can be explored with a particular sonification model without any need of domain specific modifications. By this, the user can bring in auditory learning skills and gradually deepen his understanding of the sonification. For a detailed presenation and discussion of MBS see [**?**, **?**, **?**].

The conceptually most closeby sonification to TDS is the data sonogram model where in model space for each data item a mass-spring system is created [**?**]. Excitation occurs via spatially resolved impacts that cause shock waves to expand spherically through model space. In result, oscillations of the data objects are turned into acoustic responses that consitute the interaction-based sonification. With this background we now turn towards the discussion of the TDS model.

2.2. Model Description

Setup TDS is based on a spatial model. The model space is an Euclidean vector space $\mathcal{V} \subseteq \mathbb{R}^3$ in which objects

$$\mathcal{O} = \left\{ o_i = (o_{i[1]}, o_{i[2]}, o_{i[3]}, w_i)^\tau \mid i = 1 \dots n \right\} \quad (1)$$

reside. Every o_i has a specified location

$$v_i = (o_{i[1]}, o_{i[2]}, o_{i[3]})^\tau \in \mathcal{V} \quad (2)$$

and a weight $w_i \in \mathbb{R}$. The number n of objects and their characteristics are determined by a given data set

$$\mathbf{X} = \{\mathbf{x}_i \mid i = 1 \dots n\} \quad (3)$$

and a preprocessing function

$$f : \mathbf{X} \to \mathcal{V} \times \mathbb{R} \quad (4)$$

The mapping to model space is then achieved by applying the mapping function f to each x:

$$\forall\, \mathbf{x}_i \in \mathbf{X} :\ o_i = f(\mathbf{x}_i) \quad (5)$$

For example f maps a three-dimensional data set with data items out of two classes A, B

$$\mathbf{X} = \left\{ \mathbf{x} = (x_1, x_2, x_3, x_l) \in \left[\mathbb{R}^3 \times \{A, B\}\right] \right\} \quad (6)$$

to

$$\begin{aligned} f \mapsto f(\mathbf{x}) &= (x_1, x_2, x_3, w)^\tau \text{, with} \\ w &= \begin{cases} 0 & , x_l = A \\ 1 & , x_l = B \end{cases} \end{aligned} \quad (7)$$

In addition to the data objects, another special object T consisting of the vectors in the set

$$\mathcal{T} = \{\mathbf{v} | T_\theta(\mathbf{v}) = 0\} \subseteq \mathbb{R}^3 \quad (8)$$

with $T_\theta : \mathbb{R}^3 \to \mathbb{R}$ test function and θ meta-parameters is placed in the model space. This could be for example a plane T_p with

$$\begin{aligned} \mathcal{T}_\theta(\mathbf{v}) &= \mathbf{v}_t - (\hat{\mathbf{n}}_t \times \mathbf{v}) \\ \theta &= \{\mathbf{v}_t, \hat{\mathbf{n}}_t\} \end{aligned} \quad (9)$$

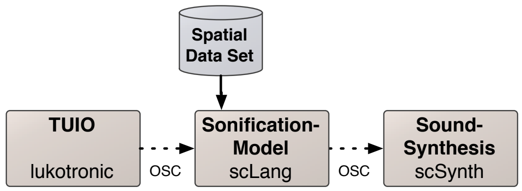

Figure 2: The implementation modules.

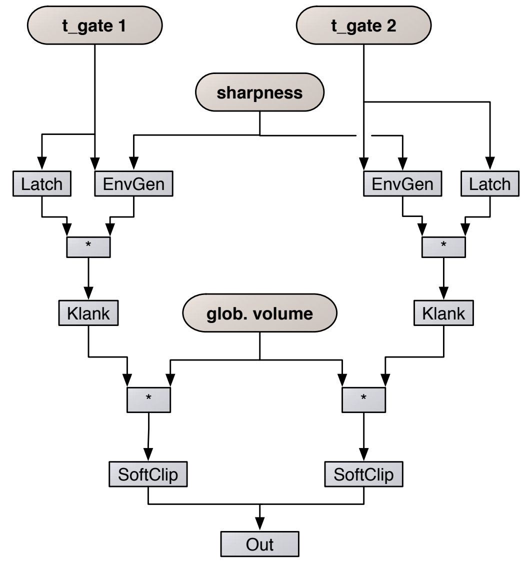

Figure 3: Schema of the used Synthesis Engine in stereo implementation.

Dynamics The user is able to adjust the given parameter set θ of T, especially its position, orientation or size. Any intersection of T and o_i will cause a damped excitation of the o_i depending on their weight.

Initial State All o_i's are in a state of equilibrium and do not produce any sound.

Excitation and Interactive Types The user is able to adjust the given parameters θ of T. This is done by a Tangible User Interface Object. which forces a direct interaction of the user with the system as motivated in Sec. **??**. Since the intersection-caused sound of the o_i's is damped, after a while TDS will again end in a state of equilibrium.

Model–Sound Linking There are at least two possibilities two describe the sound generation TDS. Both are based upon the collision of tool T and data objects o_i.

(a) The first approach expects the o_i's to be fixed in model space. The tool then is excited by each collision with a data item.

(b) The other point of view is to suppose a mass connected to each object o_i via a spring. When a collision of o_i and T appears, the connected mass is deviated from its origin. Its return into equilibrium is then an audible process.

Since both model approaches are equal in their spatial output, because the produced sound is located at the same point in space and depends on both interaction partners. For that reason it is possible to use the one which allows the simpler explanation of a specific issue.

Listener The model aims at spatially surrounding the listener with object-caused impact sounds propagated to him directly from the intersection positions. To achieve this, a *virtual listener*, is introduced into the model space and characterized by the head location v_l and its orientation. As a basic choice, the listener is located in the origin of the model space with the ears aligned with the first axis.

Sound Synthesis In order to stay as close as possible to the model's description, a physically inspired damped oscillator would have to be implemented for each possible intersection point. Against this stands the fact that TDS unfolds its strength particularly when exploring data sets containing at least 150 or more data items.

Unfortunately, it is unavoidable to test for each data object o_i, if a intersection with T takes place. This necessarily includes a matrix multiplication for every o_i. The computation of both, intersection and resulting sound is much too expensive for current computer systems. Therefore we choose a computational cheap but still complex sound. By adding virtual pick-up microphones at specific places into the space and directly rendering its input, we abstract from "one sound object per data impact" to "one sound object per pick-up microphone" (see Fig. **??** for positioning in a stereo setup). Each microphone is represented by a damped resonator bank (*Klank*) excited by triggered envelopes. Their inputs are triggers, whose amplitude corresponds to the location of the data impact. A simplified stereo version is shown in Fig. **??**.

Data–Model Assignment As described in **Setup**, every object o_i in model-space corresponds to a data item $\mathbf{x}_i$ by applying the transfer function $f(\mathbf{x})$ to it.

2.3. Implementation

TDS is implemented in SUPERCOLLIDER 3 [**?**]. As shown in Fig. **??** the system can be divided into 3 parts running in separate processes:

Tangible Object The user navigates the plane via a tangible object. Both its position and its orientation are tracked via active markers processed at approximately 40 Hz by a Lukotronic Marker Tracking System [**?**].

sonification model When loading the data set into the model, it is scaled to the interval $[-1, 1]$ in all dimensions. After that the sonification model is computed out of the given data and the TUIO's position. This is in particular the computation of the tool's state θ and possible impacts.

As an example here the detailed computation for an exploration plane with two virtual pickups in model space located at the sites of the user is shown: Let O be the basis of the model space, P_t be the basis of the exploration tool at time t. ${}^{O}\mathbf{T}P_t$ defines the homogene transform from O to P_t. Each time step Δt

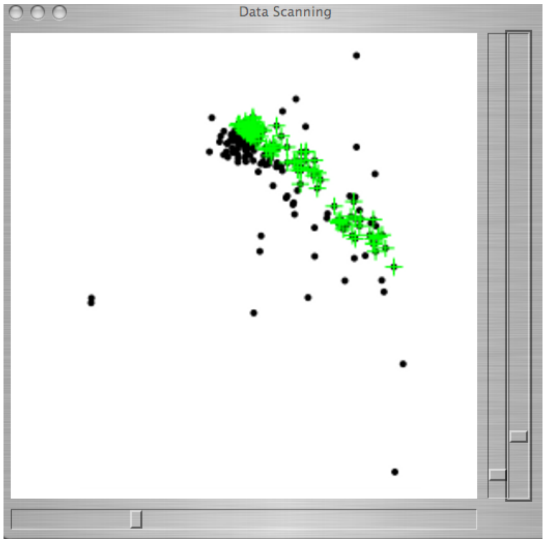

Figure 4: The Glass data set in use with TDS. The green data objects are currently excited by the on-moving plane $\mathcal{T}$ which is navigated by the user.

1. Get the current position of the TUIO and compute homogene transformation ${}^{P_t}\mathbf{T}_O$
2. $\forall o_i$: compute its positions $\hat{o}_i^{(t)} = {}^{P_t}\mathbf{T}_O o_i$ with respect to P_t.
3. Get the set of indices which penetrate the plane in the time interval Δt:
$$\mathcal{I}_t = \left\{ i \,\middle|\, \text{sgn}\left(o_{i[3]}^{(t)}\right) \neq \text{sgn}\left(o_{i[3]}^{(t-\Delta t)}\right) \right\} \quad (10)$$
where sgn : $\mathbb{R} \rightarrow \mathbb{R}$ is the signum function.
4. $\forall i \in \mathcal{I}_t$: compute onset time $t + \Delta_i t$, with
$$\Delta_i t = \Delta t \left\| o_{i[3]}^{(t-\Delta t)} \right\|_2 \quad (11)$$
5. Get the amplitudes for the virtual microphones by using the $o_{i[1]}$ coordinate of the original data object.
6. Trigger all events at precomputed time $t + \Delta_i t$ with its amplitude.

The whole sonification model is implemented as a class extension in SUPERCOLLIDER language making use of SONENVIR [?], the JITLIB [?] and other self-developed software building blocks.

Sound Synthesis As mentioned in Sec. **??** the sound design of TDS is constrained by two major aspects; firstly the possibly high number of data items and therefore high computational load in the sonification model, and secondly the willing to stay as close as possible to the sound of excited vibrating objects.

Since the inter process communication is done by OSC messages [?] the resulting system can be distributed to several processes resp. computers connected via network.

As an extension of the current implemented system it is also possible to add performance scaling abilities to the exploration tool [?]. This can be achieved by computing tool intersection only for a random subset of data items each time step. The computational load will be decreased whereas the relative information e.g. about local density is preserved. Nonetheless information about the data set will be lost. For example an outlier detection with TDS and performance scaling is rather difficult since data objects might not produce sound at every impact.

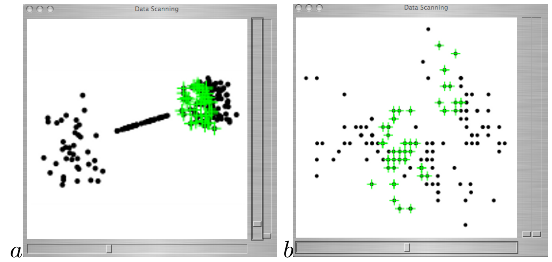

Figure 5: (a) The synthetic and (b) the iris data set in use with TDS. See text and caption of Fig. **??** for details.

3. TDS INTERACTION EXAMPLES

For qualitative evaluation we have used a synthetic data set which consists of 3 clusters in series. One cluster is sparse, the second one is only one-dimensional and the third one is dense in all three dimensions. In addition we try to understand the clustering of glass types in the MCI glass data set and the clustering of the well-known iris data set which both may be acquired at [?].

As exploration tool we choose a plane connected to the TUIO so that its normal vector points right out of the palm of the user's hand. Sound examples of these interactions may be downloaded at [?].

Synthetic When moving the plane along the third axis in which all data clusters are lined up, both the cluster borders and the dimensionality of each cluster is nicely separated by silence. The user is able to find class boundaries by moving the plane until it reaches a location at which no sound is produced.

The local density of the data set can be judged by interactively scanning different regions of the it. Regions with high local density produce a dense sonic grain cloud, whereas sparse regions are rendered to more sparse clouds.

The dimensionality of the cluster can be determined by the spatial spreading of the sound scape. At the moment it is necessary that the change in dimensionality is only in the first ordinate $o_{i[1]}$ since the yet-implemented system is only stereophonic. This constraint can be fixed by implementing the system with a spatial speaker setup or with an HRTF encoder.

An example visualizing the data–tool interaction in the synthetic data set is shown in Fig. **??**a.

Glass Since the glass data set is 9-dimensional, but TDS in its current implementation is only able to display three-dimensional data, we choose to explore the projection of the glass data set onto its first three principal components [?] rather then using three arbitrarily chosen axes. This way the maximal data variability is preserved.

The interaction as shown in Fig. **??** enables the user to explore the different densities of the data. Here TDS shows its strength also in outlier detection; they are nicely separable from the region with many data objects.

Iris As described at [**?**], the iris data set consists of three classes, where one (A) is easily (and linear) separable from the others, whereas the other two classes form a lengthy cluster (B, C). By using the plane tool, A can be easily separated from B, C and located at the upper front of the model space. A clear separation of B and C is possible, but this is also not possible in visual displays such as a scatter plot of the data.

Fig. **??***b* shows the interaction of a user with this data set.

4. RELATION TO OTHER DESIGN PRINCIPLES

In Sec. **??** we have described TDS in terms of Model-based Sonification. A physically inspired description technique is one approach to define an interactive sonification system and to motivate the interaction methods and the resulting sound.

Another system for task–oriented sonification design is TADA, introduced in [**?**]. In TADA a linkage between the exploration task and a sound-related everyday experience has to be established which in consequence helps to find an appropriate sonification system. Since our approach is not bound to a specific domain where it should be used, we restrict the description to the so-called *Ear Benders* [**?**] and show the possible linkage of the there-given description to TDS.

Ear Bender Analogon: Musical Clock

The main parts of a musical clock are a rotatable disc or cylinder equipped with many small pins, a fixed metal comb standing upright to the plate and a crank with which the player can rotate the disc and produce little songs. Rotating the disc or cylinder causes the pins to deviate teeth of the comb and excite them. The onset and timbre of the resulting sound depends on the position of the pin on the plate. The winding behavior of the user mainly affects the resulting sound under the given pin positions. The following principles can be observed:

- The more pins are on the cylinder, the more sounds appear.
- The faster the cylinder rotates, the more dense occur the resulting sounds.
- Geometrical structures correspond to acoustic patterns.

We can interpret the dataset as the disc of our musical clock. Obviously, the single data item then corresponds to a pin on the plate. The comb which is handled by the user corresponds to a plane in the data-space and so to the TDS object. Now, the user is able to move the plate through the data space. Each time it passes a data item, this produces a sound in the plane.

These considerations imply the analogy that controlling the exploration tool (in this case the *comb-like metal teeth* of the musical clock) single data items (*pins*) of the data (*plate*) cause the system to produce a grain-like sound corresponding to the user's interaction and the data itself.

By extending the model– (and data–)space to three dimensions, it is possible to use other tools than a plane, e.g. a sphere or a racket with defined but adjustable center and radii.

In this sense Earbenders provide a highly suited source of inspiration for sonification model design, or the other way Model-based Sonification provides practical implementation techniques to transfer Earbender stories to the problem under investigation.

5. DISCUSSION

We have introduced a new Model-based Sonification approach called *Tangible Data Scanning sonification model* (TDS). This highly interactive sonification makes use of the benefits of tangible computing by using a tangible user interface object as input source.

Benefits of TDS are its simplicity in design and usage. By using a tangible object as data tool, the user binds his immediate environment to dedicated points in model-space and therefore constructs a virtual map of the data itself. In this process of data-user communication the data's inherent complexity is preserved. Complex data sounds complex whereas simple data such as collinear arranged data items remains simple in their sonic representation.

Unfortunately TDS in its natural form is not able to display data with more than three dimensions. This drawback complies with the constraints of other well-known spatially indexed data display systems like a scatter plot. One solution of this problem is to use common dimension reduction techniques e.g. Principal Component Analysis as preprocessing. An example of this exploration chain is shown in the exploration examples given in Sec. **??**.

TDS differs in its exploration qualities –the structures which could be observed– from standard data displays. Here the user is able to detect local features such as differences in local densities or dimensionality in a natural form. The grounding data has not to be projected to a two-dimensional plane.

The strong reliance on direct interaction enables the user to immerse into the data in a simple way compared to visual representations which require head-mounted displays or at least stereo-glasses and a Virtual Reality environment.

Different from standard data sonifications for similar data domains like the sonic scatter plot as used in [**?**] here all axes are mapped onto spatial dimensions and are therefore equivalent to each other by means of interaction.

We plan to extend the system by making use of Performance Scaling as introduced in [**?**]. It is also easy to extend TDS with almost all extensions currently used in a scatter plot, these are for example differing colors (here: differing pitch), differing shapes (here: timbre) and so forth. Another direction is to look for physically inspired features such as "the faster a data object passes the exploration tool, the louder is the resulting sound". This kind of system reaction need no explanation to the users since it is familiar to almost every impact interactions around us. The naturalness of TDS can also be increased by adding rendering spatial sound. In order to make TDS more portal we plan to add support for other input systems like a *SpaceMouse* or TUIO's in our tangible Desk system [**?**]. It is also possible to identify the origin of the model space with a TUIO rather than binding it to the origin of the coordinate system. This way the user is not immersed by the model space itself, but enabled to interact with the data set as if it where just a physical object which has to be examined with the exploration tool.

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