# A MALLEABLE DEVICE WITH APPLICATIONS TO SONIFICATION-BASED DATA EXPLORATION

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## ABSTRACT

This article introduces a novel human computer interaction device, developed in the scope of a Master's Thesis. The device allows continuous localized interaction by providing a malleable interaction surface. Diverse multi-finger as well as multi-handed manipulations can be applied. Furthermore, the device acts as a tangible user interface object, integrated into a tangible computing framework called tDesk. Software to convert the malleable element's shape into an internal surface representation has been developed. Malleable interactions are applied to a new Model-based Sonification approach for exploratory data analysis. High-dimensional data are acoustically explored via their informative interaction sound in result to the user's excitation.

**Keywords:** HCI, Malleable User Interface, Tangible Computing, Model-based Sonification, Exploratory Data Analysis, Continuous Interaction.

## 1. INTRODUCTION

In today's human-machine environments so-called human computer interaction (HCI) devices facilitate communication between human beings and the computer. Despite the overall rapid development in the information technology area, human machine interaction is still based on devices that emerged in the course of the personal computing paradigm, like mouse and keyboard.

If we compare the possible reservoir of especially haptic manipulations, we make use of every day, with actions primarily applied on common computer devices, we rapidly leave the scope of typing, dragging and clicking. Instead we observe a powerful set of complex actions like shaking, twisting, kneading, playing instruments, catching etc.. Typically, we receive direct responses from the objects we manipulate. Such responses occur in form of stimuli to our senses, like acoustic, tactile or visual feedback. In this context, human sound processing abilities are of particular importance. Our excellent sense of hearing significantly supports us in interacting and orienting in our environment.

Personal computing devices, meanwhile essential elements of our life, seem to conflict with forms and cultures we developed for living. We can hardly incorporate our above mentioned interactive and perceptual abilities into typical HCI systems based on mouse and keyboard interaction in graphical user interfaces.

New HCI approaches, like tangible computing (see [3, 4, 5]) promote an improved integration of computing entities into our environment. HCI frameworks originating from these research fields focus on real, physical entities as main interfaces in HCI scenarios. Not only systems accompanying our life can benefit from this paradigm shift, but also individual research domains,
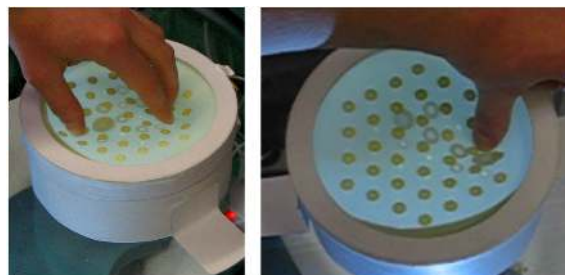


Figure 1: ***Elastable*** interface assembly. Interface offers a malleable interaction surface. Besides, it acts as tangible user object and allows direct visual display.

like exploratory data analysis. In this context, interactive sonification [6, 7] is particularly addressed. By advancing an integration of interaction into data exploration environments, it considers the human researcher's interaction and perception skills in a more balanced fashion. Approaches which couple e.g. tangible user interface (TUI) frameworks with multi-modal exploratory applications promise a significant improvement of data analysis.

This paper presents a physical human computer interaction interface (see Fig. 1), called ***Elastable***, which offers a malleable surface providing a large number of degrees of freedom for continuous, tactile interaction (see also [1]). The malleableness of the interface not only allows to activate but also to continuously control and determine internal processes. Additionally, the device is integrated as a TUI object into the tDesk [2] framework. Since the device does not provide any electronic components, it is equipped with specially featured markers, allowing external capturing hardware, in combination with implemented processing software, to perform object tracking as well as surface reconstruction tasks. A new sonification-based data exploration model incorporates the interface's functionality. Thereby, malleable interactions determine radii of virtual hyperspheres that are located around prototypes in model space. Collisions between hyperspheres and data sample objects are used as elementary acoustic excitations, that lead to *acoustic* feedback. Furthermore, a video projector directly displays model-depended information on the malleable surface providing *visual* display and feedback. As a result, the application combines novel physical interface development and data exploration approaches into a HCI loop of a powerful multi-modal exploration system (see Fig. 2).
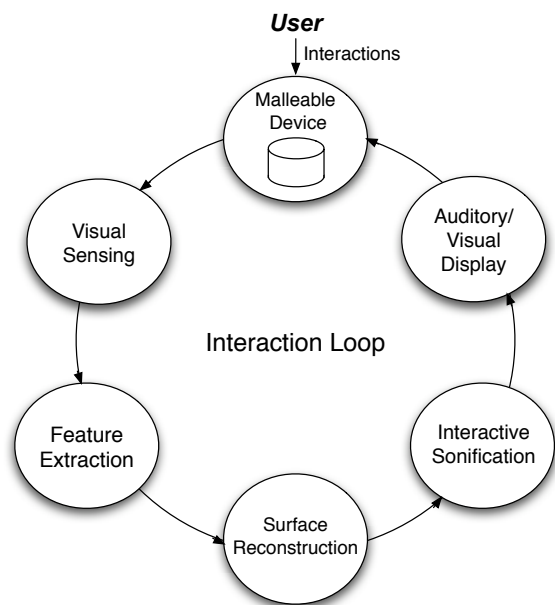
Figure 2: Module Diagram showing coarsely the implementation in a new data exploration application.

## 2. RELATED WORK

Similar work has been approached by Vogt, Chen, Hoskinson and Fels [8] introducing a malleable touch interface. The interface was constructed from rubber sheet and fastened to a cut out border of a flat surface. In addition a camera was installed underneath the interface in order to capture surface clues provided by black dots on the surface[1].

In the project called "Liquid haptics" [9], computer interfaces were represented by containers, filled with liquids. Pillow shaped bladders, placed on the top of a container, were applied to "measure high bandwidth tactile information and deliver force feedback in the liquid itself".

Our work mainly differs from these projects in two regards. Firstly, besides providing malleable interaction facilities, *Elastable* operates as a tangible interface, so it can be moved/rotated on the tDesk. In addition, visual display is projected on the malleable surface itself. Moreover, none of the known interfaces were yet used in the context of interactive sonification.

## 3. THE TDESK - A SYSTEMIC CONTEXT

Recent research in the Bielefeld iLab[2] focuses on tangible computing and its use within data exploration. In this course, the so-called tDesk (tangible desk or gesture desk [2]) has been developed providing a desktop in form of a glass table for purposes of tangible computing. The tDesk is based on the elements shown in Fig. 3.

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[1]http://hct.ece.ubc.ca/research/malleable/
index.html

[2]Interaction Laboratory, part of the Neuroinformatics Group, Faculty of Technology, Bielefeld University, Germany,
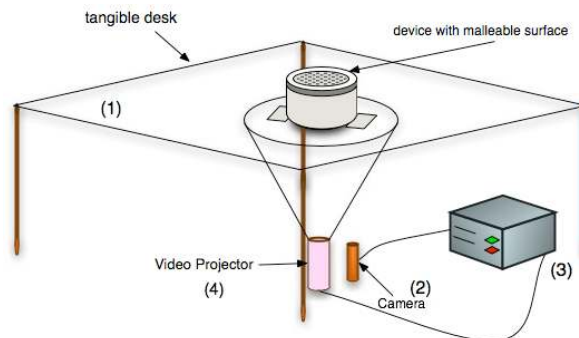http://www.techfak.uni-bielefeld.de/ags/ni/index\
_d.html

Figure 3: Components of the tDesk including (1) a transparent desk, (2) image capturing hardware, (3) a computing device and (4) a video projector. The integration of the *Elastable* interface is illustrated as well.
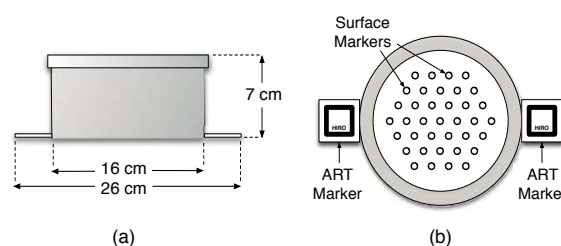
Figure 4: (a) Side view of the *Elastable* interface. (b) Bottom view illustrating alignment and design of surface markers and placement of ART markers.

The software developed for the interface is used in the tDesk environment and performs the following tasks:

1. Tracking of the *Elastable* interface on the tDesk's glass plate. As result, digital image data of the object is selected.

2. Object/Background segmentation and feature extraction of the segments by means of digital image processing.

3. Mapping of features to an internal model representing surface configurations of the malleable element.

4. Visual and auditory display to close the interaction loop.

Note that, as illustrated in Fig. 3, object tracking is realized by capturing the interface from below with the tDesk's capturing hardware located underneath the glass table. Visual display is performed by the video projector, also situated under the desk.

## 4. CONSTRUCTION AND FUNCTIONALITY

The physical interface is built from a cylinder-shaped skeleton and a top cover with malleable element. The skeleton, as shown in Fig. 1 and Fig. 4, consist out of a cylindric, cookie box sized object that is made of paper board with two additional "wings", each holding an ARToolKit (ART) [10] marker. The top cover is designed as a malleable user interface, short MUI. It consists of a facet, cut out of a rubber glove that is clamped to a wooden ring. Similar to the skeleton, surface markers are attached to the MUI's flipside, as illustrated in Fig. 4 (b).
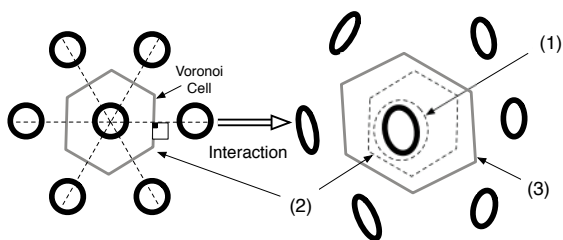
Figure 5: Transition from neutral marker alignment to expansion alignment caused through pressure at location (1). The original voronoi cell area (2) increases significantly (3), thus providing a suitable indication of surface displacement.

### 4.1. Feature Extraction

The goal behind the interface design is to allow implemented digital image processing modules, combined with external capturing devices, to

1. localize the interface within the camera image,

2. separate the image region, containing the malleable surface, from the background,

3. segment this region, i.e. separate markers on the skin, and

4. to extract the segmented objects' 2-dimensional coordinates.

The overall localization of the *Elastable* object on the tDesk is supported by ART markers. A region of interest containing the malleable interaction plane can be separated for further processing stages. The distinct appearance of a surface marker, providing two regions of high contrast gradients, can be extracted using a laplacian convolution operator followed by a thresholding operation. A postprocessing of the resulting binary image, using a morphological closing operation, brings out isolated, closed and orbital shaped objects. The last step of the feature extraction process addresses the localization of each isolated object in form of 2-dimensional coordinates. This problem is solved by using a contour retrieval operation. Mean vectors, each calculated from samples points of a corresponding contour, include the intended surface marker locations.

### 4.2. Surface Reconstruction

The surface marker locations provide the basis for extracting shape information of the malleable surface. Surface reconstruction is approached by calculating depth information of the surface from geometrical relations between surface markers. As shown in Fig. 5 on the left, except for border markers, each surface marker has 6 adjacent neighbors. The hexagon-wise alignment of the neighbors asserts equidistance between each adjacent marker in neutral position (that is, no external interaction). In case of surface interactions, the markers move away from each other, because the malleable material expands in opposite directions. In this context, each marker's Voronoi cell [11] is of special importance. A cell's area significantly increases proportional to vertical displacement (Fig. 5 depicts this phenomenon through the dashed hexagon).

In fact, changes in a cell's area will be used as clues for changes in depth of the malleable surface. For extracting such geometrical information from 2-dimensional vectors, representing each
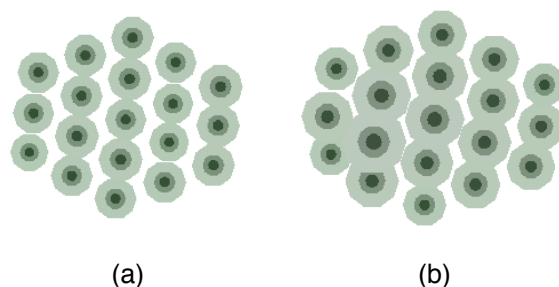


Figure 6: 2-dimensional surface reconstruction model. (a) No external interaction. (b) External malleable interaction. Surface vectors near to the interaction center exhibit the largest size.

marker's image position, a planar subdivision [11, 12] for marker-representing object vectors is computed, yielding vertices of corresponding Voronoi cells.

A suitable representation of the MUI shape can be embedded into 2-dimensional surface vectors $\mathbf{m}$, each representing a surface marker's 2-dimensional location inside the image. Furthermore, each surface vector consists of a corresponding depth (reconstruction) value $d$. Given a surface marker's image location $\mathbf{o}_l$ and its corresponding Voronoi cell area $a_l$, the corresponding surface vector $\mathbf{m}_l$ and depth value $d_l$ are defined as:

$$
\begin{aligned}
m_{l1} &= \alpha_1 \cdot o_{l1} \\
m_{l2} &= \alpha_2 \cdot o_{l2} \qquad\qquad (1) \\
d_l &= \beta \cdot a_l
\end{aligned}
$$

Thereby, $\alpha_{1,2}$ ad $\beta$ represent scaling factors. Fig. 6 illustrates a 2-dimensional surface reconstruction model, containing a number of $K$ spherical objects. Each corresponding object has the radius $d_l$ and is located at position $\mathbf{m}_l = (m_{l1}, m_{l2})^T$.

## 5. INTERACTIVE SONIFICATION BY MALLEABLE EXPLORER SPHERES

The new data exploration approach introduced here aims to apply malleable interactions to exploration of high-dimensional data. Malleable interactions combined with auditory display were firstly intended to provide local density information about the underlying data. Moreover, data space regions of similar structure can be compared by listening. The exploration model, depicted in Fig. 7 can be subdivided into individual components that in the following will be explained in terms of Model-based Sonification.

Basically, the initial model setup combines the internal malleable surface shape representation (Sec. 4.2) with a self-organizing map (SOM) [13]. SOMs are a special models of artificial neural networks and are used for projecting high-dimensional data sets into a lower dimension under preservation of the data's topology.
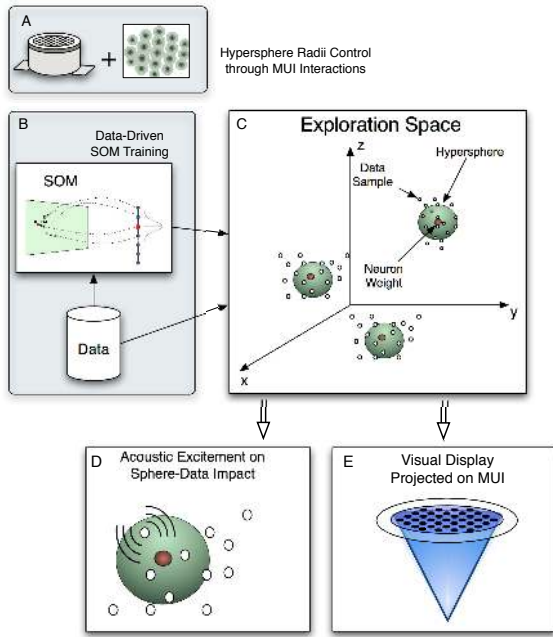
Figure 7: Structure of application components. MUI interactions will change radii of hyperspheres surrounding SOM weights in data space. Impacts between hulls of hyperspheres and data samples will excite sounds. Additionally provided visual feedback will be projected on the MUI's surface.

The SOM contains:

1. A data set $X = \{\mathbf{x}_i, i = 1...L\}$, given each $\mathbf{x}_i \in \mathbb{R}^d$.

2. A set $N = \{\mathbf{r}_j, j = 1...I\}$ of neurons framing a 2-dimensional layer grid. The vector $\mathbf{r}_j = (r_{j1}, r_{j2})^T \in \mathbb{N}^2$ declares the grid-location of the corresponding neuron.

3. A set $W = \{\mathbf{w}_{\mathbf{r}_j}, j = 1...I\}$ containing weight vectors $\mathbf{w}_{\mathbf{r}_j} \in \mathbb{R}^d$, representing localized neuron prototypes in data space.

Malleable interactions will be described using the formalism given in Eq. 1 yielding:

1. A set $M = \{\mathbf{m}_l, l = 1...K\}$ of surface vector locations $\mathbf{m} = (m_{l1}, m_{l2}) \in \mathbb{R}^2$.

2. A set $D = \{d_l, l = 1...K\}$ of depth values corresponding to the surface vectors.

## 5.1. Exploration Model Setup

In the scope of the exploration space, the following components are introduced:

1. A set $O = \{\mathbf{o}_i, i = 1...L\}$ of data objects, given each $\mathbf{o}_i$ located at $\mathbf{x}_i$.

2. A set $N = \{\mathbf{n}_{\mathbf{r}_j}, j = 1...I\}$ of neuron objects, given each $\mathbf{n}_{\mathbf{r}_j}$ located at $\mathbf{w}_{\mathbf{r}_j}$.

3. A set $S = \{s_{\mathbf{r}_j}, j = 1...I\}$ representing radii of hyperspheres, each located around $\mathbf{n}_{\mathbf{r}_j}$.
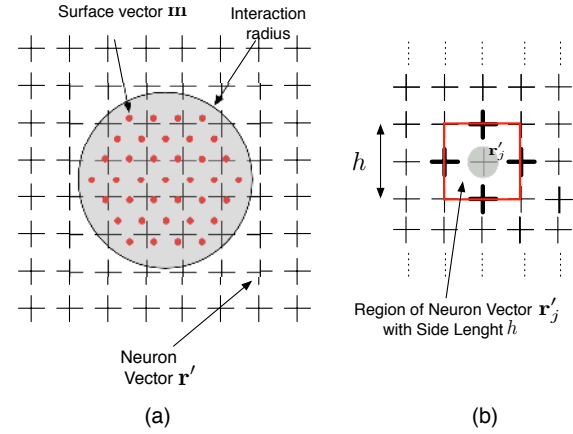


Figure 8: (a) Result of transforming neuron locations into a 2-d vector space. The transformation enables to extract neighboring relations between surface vectors (red dots) and transformed SOM neurons (black cruxes) in order to determine hyperspheres radii in exploration space. (b) Region of a neuron vector $\mathbf{r}_i'$ (red quad).

The overall *exploration space* is defined as the Euclidean vector space with the same dimensionality as the data space, in which neuron objects and corresponding data objects are located. Module C of Fig. 7 completes the exploration space by introducing virtual hyperspheres with radii $s_{\mathbf{r}_j}$, which one surrounds a *neuron object* $\mathbf{n}_{\mathbf{r}_j}$.

## 5.2. Excitation

Malleable surface interactions that affect the radii of hyperspheres are represented by surface vectors, defined in Sec. 5. Thereby, the connection between physical interaction and virtual exploration space is provided through the following functions:

1. A function $t_\gamma(\mathbf{r}_j) : \mathbb{N}^2 \rightarrow \mathbb{R}^2$, transforming neuron grid positions $\mathbf{r}_j$ into a 2-dimensional vector space. Thereby, the coefficients of $\mathbf{r}_j$ are scaled by $\gamma$. The resulting vectors will be denoted as *neuron vectors* $\mathbf{r}_j'$. Thus, $t_\gamma(\mathbf{r}_j)$ yields:

$$t_\gamma(\mathbf{r}_j) = \mathbf{r}_j' = \begin{pmatrix} \gamma \cdot r_{j1} \\ \gamma \cdot r_{j2} \end{pmatrix} \qquad (2)$$

2. A function $z(\mathbf{r}_j) : \mathbb{R}^2 \rightarrow \mathbb{R}$, calculating neighborhood relations between all surface vectors $\mathbf{m}_l$ and single neuron vectors $\mathbf{r}_j'$ via kernel regression [14]:

$$z(\mathbf{r}_j') = \frac{1}{K} \sum_{l=1}^{K} d_l \cdot H \left( \frac{\mathbf{r}_j' - \mathbf{m}_l}{h} \right) \qquad (3)$$

The function $t_\gamma(\mathbf{r}_j)$ maps neuron locations into a vector space in which surface vectors $\mathbf{m}_l$ are situated (Fig. 8 (a)). Consequently, relations between surface vectors $\mathbf{m}_l$ and neuron vectors $\mathbf{r}_j'$, used for creating links between malleable interactions and hyperspheres' radii, can be calculated. This is done by the $z$ function that uses a multivariate normal kernel $H \propto \exp\left(-\mathbf{r}_j'^2/2\right)$. The resulting value of $z(\mathbf{r}_j')$ represents the hypersphere radius $s_{\mathbf{r}_j} = z(t_\gamma(\mathbf{r}_j))$, associated with $\mathbf{r}_j'$ and can be interpreted a measure for the interaction activity taking place in a defined region around the neuron vector $\mathbf{r}_j'$.
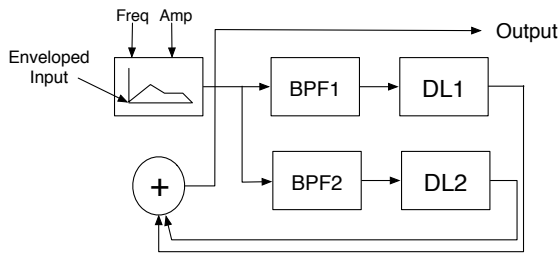
Figure 9: Diagram of a simple banded waveguide. An input source's modes are modeled through a bandpass filter and a delay line. The input source can for instance be represented by a short-time envelope of a sine wave.

### 5.3. Dynamics

As dynamic system, the data driven objects $\mathbf{o}_i$ are given dynamical properties (e.g. define localized potentials in model space). By this, any excitations may drive them from equilibrium and induce acoustic responses. Here we abstract from a detailed implementation to an explicit interaction sound modeling. The data objects $\mathbf{o}_i$ are assumed to exhibit abilities of sounding objects, oscillating on excitation. Impacts between the hyperspheres' hulls and data objects cause acoustic responses, which constitute the sonification (see component D in Fig. 7). Each object $\mathbf{o}_i$ features a stiffness constant $k_i$, which determines its pitch of the sound that indicates a hypersphere-data impact.

### 5.4. Model-Sound Linking and Sound Synthesis

The sound synthesis is implemented by using banded waveguide models [15, 16], each responsible for the sound generation of a single sounding data object. Each banded waveguide circuit is built from three elements as illustrated in Fig. 9, namely an *input source*, a *bandpass filter* (BPF), and a *delay line* (DL). For the input source an enveloped sine wave with a variable frequency and amplitude is chosen. In addition, the input source is modulated by a two-pole filter providing initial mode characteristics. The frequency parameter is used to convey information about a hypersphere-data collision. The bandpass filter's and delay's parameters are adjusted such that for lower input frequencies short-time xylophone-like sounds are generated, while sounds of with higher input frequencies, can be compared with a spoon striking a tea cup.

### 5.5. Visual Display

Module E of Fig. 7 provides visual feedback, projected on the MUI's surface. Visual pointers indicate how far several MUI regions contribute to changes in hyperspheres' radii (see also Fig. 1). Since movements of the ***Elastable*** interface on the tDesk translate the surface vectors relative to the neuron vector grid, the visual display, moreover, provides orientation in exploration space.

### 6. SONIFICATION AND INTERACTION EXAMPLES

The exploration setup was evaluated on two data sets namely the iris and glass data set, both obtained from UCI [17][3]. For each ex-

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[3]University of California at Irving, Machine Learning Repository http://www.ics.uci.edu/~mlearn/MLRepository.html
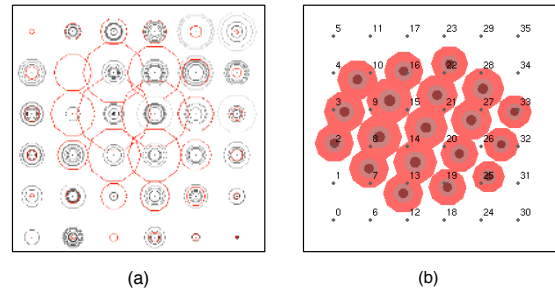


(a)                                    (b)

Figure 10: (a) Distance map. Each concentric circle is located around a neuron in SOM layer space and displays the distance between data object and the corresponding neuron object as radius. Additional red circles represent radii of corresponding hyperspheres. (b) Interaction map containing neuron vectors and surface reconstruction model. Both illustrations describe the same interaction scenario.

ploration example, a SOM training algorithm was applied on the corresponding data set. Weight-data distance sets, for each individual weight, were created and projected upon the SOM neuron layer in form of concentric circles. Thereby, each data sample $\mathbf{x}_n$ has been assigned to its corresponding weight vector $\mathbf{w}_{\mathbf{r}_j}$ to which the data sample had the minimal distance relative to all other weight vectors.
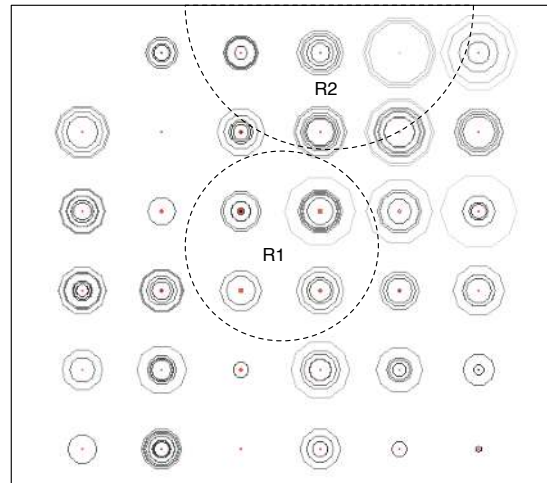


Figure 11: The distance map of the iris dataset. The dashed circles outline explored regions $\mathbf{R}1$ and $\mathbf{R}2$, that exhibit similar sound patterns in their corresponding sonifications.

An interaction map, containing surface reconstruction model and neuron vector grid and a distance map, representing weight-data distances projected upon SOM neuron layer space have been created for a better understanding and orientation (see Fig. 10). The sound files the text will refer to can be obtained from [18].

### 6.1. Exploration Example: Iris Data Set

For the first exploration example, the iris dataset that describes properties of iris flowers has been used. A record description includes a feature vector $\mathbf{x}^{Iris} \in \mathbb{R}^4$. Fig. 11 shows the distance
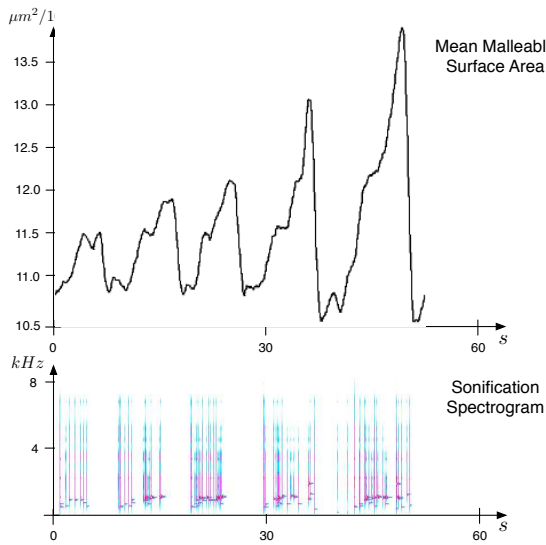
Figure 12: Both, mean area of all surface markers' voronoi cells (top) and sonification spectrogram (bottom) have been plotted along the time axis of the described interaction. The mean area is representative for the malleable interaction intensity.

map explained in Sec. 6. The overall exploration process contained two cycles, each including five interactions applied to the center and upper right region (regions denoted as **R**1 and **R**2 in Fig. 11) of the neuron vector grid respectively. At the beginning of the cycle small sized hyperspheres were generated, whereas larger ones appeared at the end.

In accordance with an interaction cycle, the sonification of the overall process contains five separate sequences of sound events, each representing a performed interaction. Fig. 12 illustrates the interplay between malleable interaction intensity and sonification. As can be seen, in this case the degree of expansion of the malleable surface is proportional to the number of hypersphere-data collisions, reflected by acoustical events. The pitch of each sound event corresponded to the distance between data sample, stroked by the hypershpere, and its corresponding weight vector.

The sonification example for **R**1 (sound file **ET_Exp1_R1**), starts with short, percussive and low-pitched impact sounds, representing hyperspheredata collisions close to their nearest neuron objects. From the second sequence on, the number of initiated high-pitched sound events increases, representing more distant collisions. A distinctive melodic sound pattern repeats in sequence two, three and five. This acoustic pattern can be considered as representative for the explored region. In addition, the ending parts of sequence four and five indicate a high-pitched grain. This sound event obviously represents a collision between a hypersphere and a significantly distant data object. In fact, in Fig. 11 this phenomenon is depicted through the furthermost ring of the upper right circle constellation inside **R**1.

The second sonification, describing the exploration of region **R**2 (sound file **ET_Exp1_R2**), begins with single sound events increasing in pitch. Again, towards the end of sequences four and five, high pitched grains occur (please compare with **R**2 in Fig. 11).

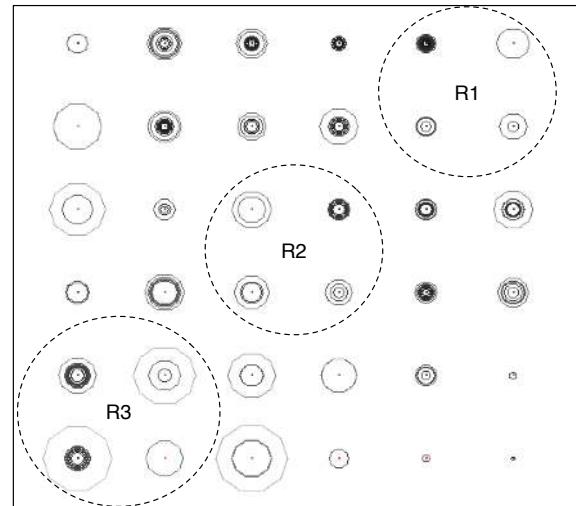Especially the third sequence of each sonification has similar



Figure 13: According distance map for the glass data set. Again, the explored regions are marked by dashed circles.

pitch structure in the beginning. In addition, at the end of the last two sequences, high pitched sound events are produced, what implicates similarities between those two regions.

### 6.2. Exploration Example: Glass Data Set

The second exploration was based upon the glass data set. The data set describes chemical properties of cullet and contains 214 records, each represented by a vector $\mathbf{x}^{Glass} \in \mathbb{R}^9$. The resulting distance map for the data set can be seen in Fig. 13. Three regions (denoted as **R**1, **R**2 and **R**3) were explored for the purpose of demonstration. However, in this particular case the exploration focused on extracting the class information of data samples. Explorations of different regions should give information about the occurrence of certain glass classes in the neighborhood of the corresponding neuron object. A single MUI interaction was performed for each explored region, providing a single an short sound sequence.

One of six predefined sounds was displayed on hypersphere-data collision, representing the data sample's class by its frequency. Tab. 1 shows the relationship between class label and frequency value. A compact sound representation for an explored region allowed to easily compare sound sequences representing different regions.

| Class | Sound Event Frequency (Hz) |
|-------|----------------------------|
| 0 | 300 |
| 1 | 600 |
| 2 | 900 |
| 3 | 1200 |
| 4 | 1500 |
| 5 | 1800 |

Table 1: Correspondence between class label of a data sample and frequency value of its representing sound event.

Fig. 14 depicts the relationship between malleable surface ex-

pansion and generated sonification (please compare with Fig. 12) for a single interaction, as applied in this exploration session. The sonification describing the exploration of region **R**1 (sound file **ET_Exp2_R1**) includes sound events mainly representing the first three classes. In the beginning, sound events associated with class 1 dominate the interaction. The middle part exhibits an equal number of grains according to class 0 and 2 occurs. At the end of the sequence, a single sound event representing class 5 is audible. Similar to the exploration of the iris data set, this high-pitched event can be clearly assigned to a ring in the distance map.

The according sonification for the exploration of the region denoted by **R**2 in Fig. 13 (sound file **ET_Exp2_R2**) exhibits a balanced occurrence of all classes. The sequence begins with low-pitched sound events representative for class 0, 1 and 2. In this context, the number of data items corresponding to class 1 dominates. In the middle of the sequence a high-pitched grain, representing class 5 occurs followed by sound events associated with class 3 and 4.

The third region **R**3 (sound file **ET_Exp2_R3**) significantly differed from the previously explored regions in its acoustical representation. In this case, data samples from class 5 occurred most frequently. Single representatives of class 3 and 4 can be heard in the beginning and middle part of the sonification.

Comparing the three underlying sonifications, a transition of class occurrences can be extracted between **R**1 and **R**3. **R**1, for the most part, contains data items, associated with the first there classes with the exception of one single representative of class 5. **R**2 exhibits a balanced number of representatives of all classes, while data samples from **R**3 predominantly belong to class 5 (except a few data items from class 3 and 4). In the course of these observations, the assumption can be made that the first and last three classes respectively constitute groups of correlated data.

## 7. CONCLUSION

We introduced a new physical HCI interface called ***Elastable***. The interface serves not only as a TUI object but additionally provides interactive degrees of freedom by consisting of a malleable surface. A new Model-based Sonification application presented novel facilities for exploring high-dimensional properties of data. The general concept of the application was to enhance a projection-based algorithm with virtual dynamic hyperspheres that were coupled with malleable interactions in order to force collisions between hypersphere and data objects.

The malleable interaction surface of the interface facilitates a variety of new *continuous* interaction forms. Integrated into HCI environments, the malleableness of the interface not only allows to activate processes but also to *continuously control* and determine them. The interface's continuity is reflected by the malleableness itself. Interactions applied to the interface's surface, cause the surface to fade to preferred shapes. Moreover, the surface allows to target different regions of either small or large areas for interaction. Thus, the interface provides a high number of degrees of freedom to the user and significantly differs from HCI interface devices, which are mainly characterized by a predetermined number of discrete states.

We regard the fusion of a malleable interface's properties, projection-based data exploration techniques and Model-based Sonification as a promising route for the development of interactive data exploration.

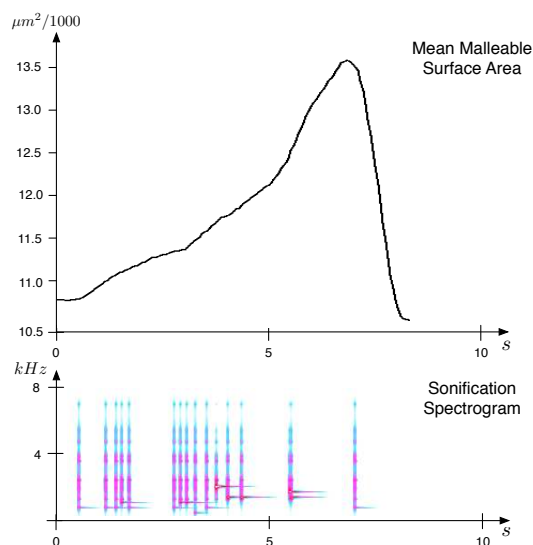In the first exploration example the pitch of each generated



Figure 14: Mean area of all surface markers' voronoi cells (top) and sonification spectrogram (bottom). Note that in this case the exploration cycle consist of just one interaction.

sound was coupled with the distance between excited data object and their associated neuron object. In combination with interaction forms, provided by the malleable interface, sequential exploration of regions of interest was enabled. As a consequence, acoustic patterns have been discovered, making distance structures of data samples located in the neighborhood of corresponding weight vectors perceivable for the user. The properties of a single sound event not only allowed to distinguish between sounds occurring in parallel but also to integrate individual sounds into patterns that identify a given exploration region. Thus, similarities between different exploration regions have been recognized by comparing.

Since, in the second example the sonification was used for conveying information about classification, the MUI more and more adopted the task of communicating hypersphere radii to the user by its degree of expansion. In other words, the malleable surface's characteristics provided tactile feedback about the exploration model's internal configurations. This recapitulation shows, how proper exploration model and physical interface complete each other.

In both sonification examples the rhythmical structure of the sound (assuming a constant interaction velocity) reflected data density information at a given hypersphere radius.

The incorporation of deformable, elastic and malleable devices into HCI systems establishes new paradigms and perspectives for the future. In our daily life we are used to interact with such devices in different ways. For instance, we check the pressure of a football by pressing it or we use squeeze bread to check its age. The interaction on such objects is not characterized by a single, almost discrete event, but rather by a continuous motion towards a resistant state. A successful integration of similar interaction forms into HCI will contribute to a more task oriented communication with computing devices. The fusion of tangible computing frameworks, novel auditory displays and the discussed device is the scope of our ongoing research in this field.

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