InformationSense: Trade-offs for the Design and the Implementation of a Large Highly Deformable Cloth Display

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Deformable displays can provide two major benefits compared to rigid displays: Objects of different shapes and deformabilities, situated in our physical environment, can be equipped with deformable displays, and users can benefit from their pre-existing knowledge about the interaction with physical objects when interacting with deformable displays. In this article we present *InformationSense*, a large, highly deformable cloth display. The article contributes to two research areas in the context of deformable displays: It presents an approach for the tracking of large, highly deformable surfaces, and it presents one of the first UX analyses of cloth displays that will help with the design of future interaction techniques for this kind of display. The comparison of *InformationSense* with a rigid display interface unveiled the trade-off that while users are able to interact with *InformationSense* more naturally and significantly preferred *InformationSense* in terms of joy of use, they preferred the rigid display interfaces in terms of efficiency. This suggests that deformable displays are already suitable if high hedonic qualities are important but need to be enhanced with additional digital power if high pragmatic qualities are required.

CCS Concepts: • **Human-centered computing → Graphical user interfaces**; **Haptic devices**;

Additional Key Words and Phrases: Deformable display; deformable digital surface; invisible marker; tracking; projection mapping; pragmatic and hedonic qualities; reality-based interaction; power versus reality trade-off

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1 INTRODUCTION

Rigid plane displays are the prevailing display type. However, during the last several years more and more display shapes have been researched and partly made their way into consumer products (e.g., smartphones with curved edges, curved TVs, and PC displays). Also, first attempts have been made to make displays deformable. Deformable displays are physical objects which can be physically manipulated in order to interact with digital content. These kinds of displays can provide two major benefits compared to rigid displays: First, arbitrary objects of our physical environment can serve as deformable displays, and second, they address multiple human senses, and allow users to draw from their preexisting knowledge about the manipulation of physical objects. Deformable displays can therefore potentially provide the means to "weave themselves into the fabric of everyday life until they are indistinguishable from it" [44]. Indistinguishable not only refers to their appearance and integration

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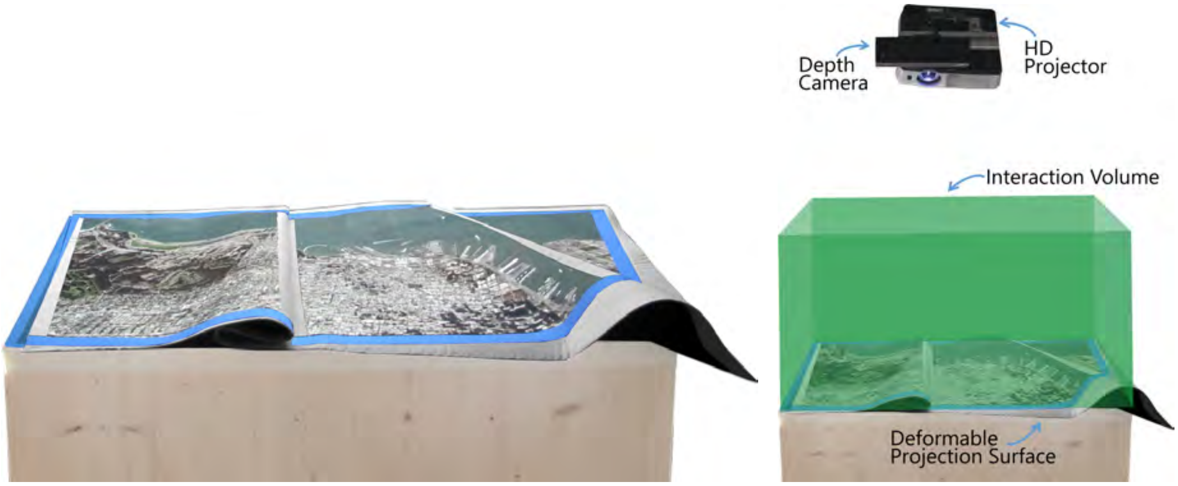


(a) Digital content can be mapped to the cloth. *InformationSense* allows for navigating the digital content through deformations of the cloth.

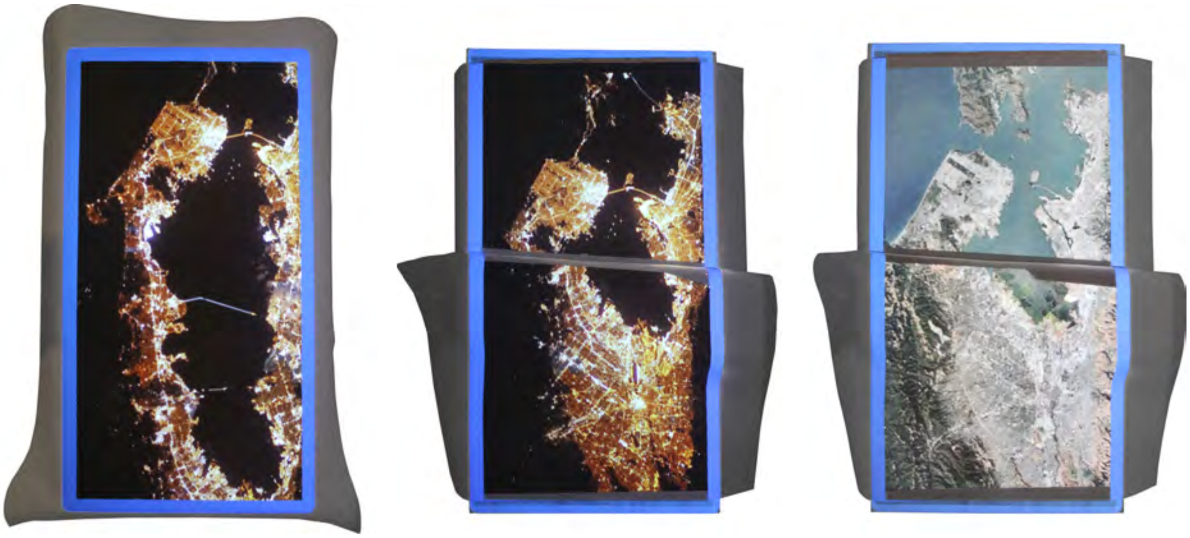
(b) A depth camera captures the shape of the cloth as well as invisible markers printed on the cloth. This allows for a precise projection mapping on the large cloth surface.

Fig. 1. *InformationSense*: An interactive volume is generated above a table. Within this volume, a cloth equipped with invisible markers, can be tracked. The cloth can be deformed but still augmented in real time. (content image source: Goggle Earth)

in our physical environment but also to the interaction with them. These devices can allow for a "rich set of interaction possibilities, involving many degrees of freedom, yet with very intuitive interaction" [40]. For example, navigating with a physical map, where one can grab, fold, unfold, rotate or move the interface within the physical environment, provides a richer set of interaction possibilities and addresses more human senses than panning and zooming interactions applicable when utilizing the digital counterpart (e.g., Google Maps). Deformable displays therefore inherit qualities from both the digital and the physical world.

The *Reality-based Interaction* framework [16] addresses the design of post-WIMP interfaces with respect to these two worlds. The framework proposes that the interaction with interactive systems should be in line with the pre-existing knowledge humans have about the interaction with physical objects. Although *Reality-based Interaction* could inform the design of deformable displays, the framework has not yet been applied to research in that field. However, the framework could help to design interactive systems which, in the sense of Mark Weiser's vision of Ubiquitous Computing, allow us to freely "use them without thinking and so to focus beyond them on new goals" [44].

In this article, we present *InformationSense,* a deformable display based on an augmented cloth (see Figure 1 and 2). *InformationSense* supports a very high degree of deformation and interaction like we know it from the interaction with the everyday object of a physical cloth. It is possible to grab, fold, or rotate the display in arbitrary ways, whereas the physical properties of the cloth are not influenced by the technical setting. In contrast to previous work, *InformationSense* therefore allows for unrestricted deformations and does not limit interaction to bending (e.g., [2, 9, 13, 22, 25, 33, 37]), stretching (e.g., [35, 41, 43, 46]) or predefined folding (e.g., [8, 18, 24]) of the device. The technical setting of *InformationSense* uses a depth camera and a projector mounted on the ceiling.



(a) Satellite image of San Francisco Bay at night: *InformationSense* provides a static mapping of digital content to a physical cloth. The digital content can be navigated by moving the cloth. (content image source: ESA)

(b) Multi-focus view of San Francisco Bay: The cloth of *InformationSense* can be deformed or even folded to create custom views of the space. (content image source: ESA)

(c) Satellite image of San Francisco Bay at daytime: Although the mapping is static in terms of the position awareness on the cloth the digital content is dynamic and can be replaced. (content image source: Goggle Earth)

Fig. 2. *InformationSense*: Exploring digital spaces through physical manipulations of the deformable display. *InformationSense* showing the San Francisco Bay from different perspectives.

The tracking approach generates an interactive volume above a table in which the position and deformation of the cloth can be tracked, and the cloth can be augmented in real-time. Within the interactive volume a 3-dimensional surface model of the cloth is generated. In addition, the cloth is equiped with invisible markers which are detected by the depth camera and used to achieve a static mapping of digital content to the 3-dimensional surface model. Following the vision of Ubiquitous Computing, the technical setting of *InformationSense* allows to integrate computational power in our physical environment while keeping the appearance as well as the interaction indistinguishable from the environment.

Based on that we elaborate different application scenarios for large, highly deformable displays. We further evaluated *InformationSense* in context of the *Reality-based Interaction* framework. The deformable *InformationSense* display, which allows for interactions *in* the real-world, was compared to interfaces which are running on a rigid display, but make use of real-world metaphors to virtually deform the information space *like* the real-world. The results give insights about how users interact with large deformable cloth displays and how they make use of pre-existing knowledge about the physical properties of the material to navigate, explore, and manipulate digital information spaces.

The contribution of this article is twofold. First, we introduce a technical solution for an absolute position aware augmentation of cloth with digital content and report on findings of a technical evaluation. The technical evaluation clarifies trade-offs which can guide the implementation of projection based deformable displays. Second, we report evaluation results in terms of efficiency, joy of use and users' interactions to inform further directions in the design of interfaces for large highly deformable displays. The results of the UX evaluation contribute to the understanding of the trade-off between the reality-based interaction with deformable displays and the often higher digital power of rigid display interfaces.

2 RELATED WORK

In this section, we approach the topic of deformable displays from two perspectives: We first survey the interaction with deformable displays. Finally, we give an overview of technical approaches applied to implement deformable displays.

2.1 Interaction with Virtually Deformable Interfaces and Physically Deformable Displays

Deformable interfaces can be separated into two classes: those digitally simulating deformations and those allowing for actual physical deformations of the interface. According to the interaction framework of *Reality-based Interactions* [16], these two classes can be described as interfaces providing interactions *like* the real-world and interfaces providing interactions *in* the real-world. In the further we review virtually deformable interfaces in terms of interfaces providing interactions *like* the real-world and physically deformable displays in terms of interfaces providing interactions *in* the real-world.

Virtually deformable interfaces: *Like* the real-world interfaces, which emulate the deformation of digital surfaces with metaphors, address humans' real-world knowledge to guide the interaction. Information Cloth by Mikulecky et al. [26] is an emulation of a physical cloth on a multi-touch table. The digital cloth can be draped over virtual objects, pulled, stretched or folded. It therefore allows navigating the digital information space and creating multi-focus views. ClothLens [19] extends this idea and facilitates the creation of multiple focus regions in the form of lenses on top of a virtual cloth surface. Butscher et al. introduced *SpaceFold* [3], a system inspired by Mélange [7] and past work on multi-touch document folding [5]. It supports the folding of a digital space with touch gestures. The interactions are based on the real-world metaphor of folding a piece of paper. All introduced interfaces offer real-world metaphors and enhance them with digital power like zoom or distortions of the digital space. However, they only mimic the real-world and do not provide the haptic qualities of physically deformable materials.

Physically deformable displays: *In* the real-world interfaces, in terms of physically deformable displays provide the means to facilitate these haptic qualities. Most of the proposed physically deformable displays are limited to predefined folding, bending, or stretching of the display. Roudaut et al. [34] introduced the concept of Morphees. Morphees are self-actuated deformable devices that allow for limited deformations. They further proposed a framework to make physcially deformable displays comparable. Lee et al. [21] elicited deformation-based user gestures by observing users interacting with A4-sized, artificial, deformable displays with various levels of flexibility (plastic, paper, and cloth). They found that with higher device flexibility, there were more gesture agreements, as well as better results, in terms of intuitiveness and user preferences. Some work made use of projected interfaces to simulate a higher flexibility of the display (e.g., [24]). For projected interfaces, different materials were investigated. Steimle et al. presented FlexPad, [40] a system which allows the transformation of sheets of plain paper or foam into physically deformable displays. Lo and Girouad [25] created a physically deformable display by projection on a device constructed from a layer of flexible plastic substrate, bidirectional bend sensors and a flexible circuit in order to investigate the application of bend gestures in gaming. Other work made use of cloth as a projection surface. Lepinski and Vertegaal [23] devised ClothDisplay, a small, cloth-based interface which supports folding, draping, stretching, and touching. Troiano et al. [41] presented a guessability study in which they identified gestures that users prefer when using an elastic display attached to a wooden frame.

Whereas most *like* the real-world interfaces provide additional digital power like zoom functionalities, *in* the real-world interfaces are closer to reality because display deformation represents an interaction to manipulate digital content. According to the framework of *Reality-based Interaction,* interfaces have to consider trade-offs between power and reality. The framework proposes that reality should only be given up in favor of digital power to gain desired qualities necessary to meet particular design requirements [16]. However, in the context of deformable displays, this trade-off is underexplored. *In* the real-world as well as *like* the real-world interfaces provide advantages and disadvantages which should be analyzed and compared in order to identify appropriate trade-offs for deformable interfaces.

2.2 Technical Implementations for Physically Deformable Displays

The technical implementation of most physically deformable displays is based on projection mapping. The important part of a precise projection mapping is a reliable tracking of the projection surface. There are several different approaches capturing the position and deformation of physical objects. Approaches can be clustered into three groups: sensor-based, depth-based and vision-based tracking. Sensor-based systems like Gummi [37], Twend [11], or Bendy [25] utilize bend sensors. With these sensors, limited deformations can be tracked, but not movement along the X, Y and Z-axes. Furthermore, senor-based systems affect the cloth consistency and weight and are limited in terms of the trackable deformability.

Some existing work utilize depth cameras in order to capture the position and deformation of physical objects (e.g., [24]). However, most of these approaches do not support deformation capture in real-time. Depth-based systems use the information provided by a depth camera to create a 3-dimensional model of the object being tracked. FlexPad, [40] for example, uses an algorithm to generate a detailed, geometrical model of the object in real time. Although this approach captures deformations in high detail and does not require any kind of markers or visible texture, it does not allow for overlaps, or for tracking when the objects do not entirely fit into the area tracked by the depth camera. Vision-based methods include systems based on passive markers (e.g., AR-marker), the tracking of visible features [42], or optical flow algorithms [12]. However, most methods need a visible texture or markers on the object to be tracked. Cloth Display by Lepinski and Vertegaal [23] uses stereo cameras and infrared reflective dots to generate a model of the cloth surface using a physics engine. Whereas the infrared dots are only slightly visible to humans they cannot be differentiated. Therefore, only a rough approximation of the surface and limited interaction is supported (e.g., no rotation). With HideOut, Willis et al. [45] presented a system based on the tracking of AR-markers printed with IR-absorbing ink. However, the approach is not applicable for tracking deformations. Furthermore, the still slightly visible, IR-absorbing ink diminishes over time, which leads to a decrease in tracking reliability. Narita et al. [27, 28] developed a high speed vision based approach for projection mapping on objects. The approach is based on the tracking of a dot marker array printed with infrared ink. Whereas this approach provides good mapping results it requires an expensive high speed camera and was only investigated for A4-sized mappings.

Several approaches allow capturing the position or deformation of objects. However, none of them allows for capturing a large deformable surface which provides the same degree of freedom as a "normal" cloth while still being easily accessible. Previous research mainly focused on either small, bendable and foldable objects or on larger stretchable materials. We present an approach for a highly deformable display. With highly deformable we mean displays which do not limit deformations to predefined folding, bending or stretching but allow for free deformation interactions. Our approach is capable of capturing the position and deformation of an object that can be manipulated in nearly arbitrary ways (e.g., it allows for overlaps). At the same time, the object is not required to fit entirely within the trackable area and therefore our approach allows for augmenting objects of almost arbitrary size. In contrast to previous work which contributed more precise tracking and augmentation approaches (e.g., [27, 28]) for small physically deformable displays we focus on a low-cost approach for large physically deformable displays that is easily accessible and reproducible.

3 INFORMATIONSENSE APPLICATIONS

InformationSense is a large physically deformable cloth display which is tracked within an interaction volume above a table and provides output by projection (see Figure 1). The cloth has a size of 121 x 68 cm and addresses many human haptic senses during interaction. The interaction with *InformationSense* is indistinguishable from the deformation of a “normal” cloth and therefore users can apply their pre-existing knowledge of the real-world and utilize their physical perception.

These particular characteristics make highly deformable displays like *InformationSense* especially suitable for domains like exhibitions (creation of exhibition objects or as part of the scenographic design), education (e.g., tool for imparting physical effects) or the prototyping of physically deformable displays (e.g., testing deformable displays for mobile devices).

3.1 Exhibitions: Viewing scenes from different perspectives

The scenography in exhibitions and museums already makes extensive use of cloth. Cloth is, among other things, used to create separate spaces, to cover walls through curtains and for projection surfaces. In scenography, cloth is often utilized because it feels more alive and provides a warmer atmosphere as rigid plane walls or other surfaces. *InformationSense* opens up new possibilities for the scenography. Instead of using static cloth, the visitor experience can be enhanced by the possibility for interacting with the cloth and making it react to the visitor’s input. To illustrate this, we designed an exhibition object which allows users to view geographic areas from different perspectives. Different images are mapped to the cloth of *InformationSense* and can be explored by

(a) *InformationSense* maps an aerial photograph of Glendale to the physical cloth. The first perspective provides a view before industrialisation in 1937. The image can be explored by physical manipulations of the cloth.

(b) By pressing a physical button the perspective can be changed. *InformationSense* now shows an aerial photograph of Glendale after industrialisation in 1957. The cloth remains the same deformation and therefore shows the exact same areas as before.

Fig. 3. InformationSense as exhibition object: Exploring Glendale from different perspectives. (content image source source: Wikimedia Commons)

physical deformations and movements of the cloth (see Figures 2 and 3). A multi-focus view can be created by folding the cloth. In this manner, areas lying far apart can be viewed simultaneously. The current implementation of *InformationSense* does not allow for an alternative input modality like touch. Therefore, a board with two buttons mounted behind the *InformationSense* table serves as a control panel for the selection of the perspective on the scene. By pressing one of the two buttons, the perspective changes to the selected view. *InformationSense* allows for a haptic and reality-based exploration of digital spaces. Especially in the context of exhibitions and museums, this provides strong benefits because visitors are instantly able to interact with the system without the need for an introduction.

Applications for exibihitons, or in general applications which aim at entertaining users, seem especially suitable for physically deformable displays as they focus on users engagement instead of efficiency. Therefore, already Steimle et al. [40] presented two entertaining applications for deformable displays: an application to animate virtual paper characters and an application to slice through time in videos.

3.2 Education: Experience physical effects by deformation

A second concept which can be realized with *InformationSense* is designed to allow children to experience physical effects and support them in their understanding of properties from our physical world based on the manipulation of a landscape model. Two scenarios could be supported. In the first scenario digitally projected balls are mapped onto the cloth. By deforming the display, the balls move over the surface with different speeds. Additional information about the physical movement of the balls (e.g., velocity, rotation velocity) are projected in proximity (see Figure 4a). The digital representations of the balls allow for altering the characteristics of the balls (e.g., size, friction, weight) and also the characteristics of the landscape the balls are placed on. The influences of these

(a) *InformationSense* as tool to simulate the influence of surface deformations and physical properties on ball movements. Additional digital power like the visualization of movement characteristics (e.g. speed) and additional functionalities like slow motion and playback can be integrated.

(b) *InformationSense* as tool to simulate the water level based on surface deformations. Through the dynamic digital content simulations it is for example possible to realize tides.

Fig. 4. *InformationSense* as educational tool: Experiencing physical effects by deformation

characteristics can be experienced and compared while shaping the terrain and observing the balls. Furthermore, the digital power of *InformationSense* could provide additional functionalities like slow motion or playback.

The second scenario simulates water on an landscape. A lake can be created and the user experiences how a deformation of the landscape changes the flow of the water (see Figure 4b). In addition a simulation of tides could be integrated. The water line could automatically rise and fall while shaping the terrain. In contrast to other educational tools based on videos, pictures or simulations, *InformationSense* provides a haptic experience, is easy to interact with, and provides a 3-dimensional and perspective view. Already with Illuminating Clay [31] Piper et al. showed the benefits of combining the tangible immediacy of physical objects with computational simulations and their dynamic capabilities.

3.3 Prototypes: Size adjustable and deformable displays

The *InformationSense* approach can be used for the quick creation of physically deformable display prototypes in different shapes and sizes. With a smaller version of *InformationSense* a screen could be simulated whose size can be changed during the interaction by folding (see Figure 5). Therefore it can, for example, be used to simulate dynamic changes of display sizes from a smartphone-sized screen to a tablet-sized screen. This facilitates the exploration of interfaces which adapt to the shape of the display or even displays whose shape can be dynamically altered to meet the current requirements of the task best. *InformationSense* provides the means to research interaction and visualization techniques which will facilitate users' work with future deformable displays. Still, it is cheap to produce, easy to transport and simple to assemble. However, to actually use the *InformationSense* concept as an approach to investigate size adjustable displays it should be enhanced with further input modalities

(a) A text input interface optimized for a smartphone-sized display.

(b) The text input interface can automatically adapt to the change in size and orientation.

(c) The size and the proportions of the display can be selected depending on the task at hand. For text input on the move a wide format could be suitable.

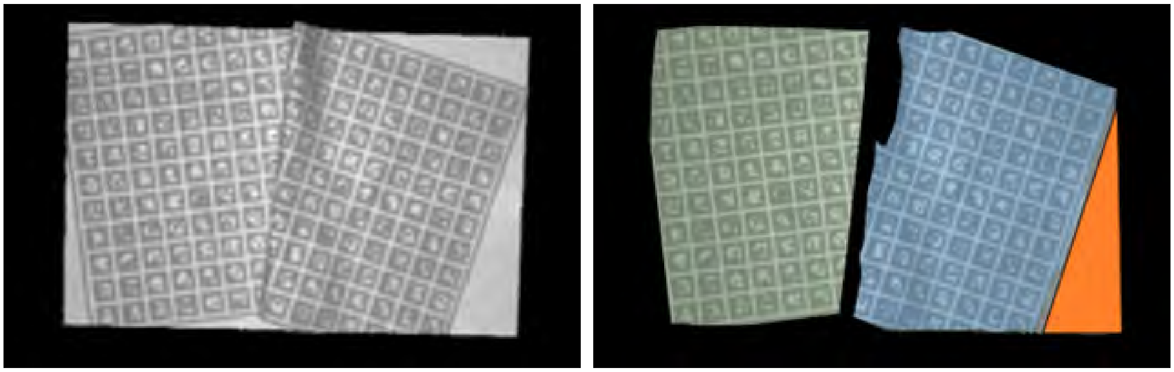
Fig. 5. *InformationSense* can be used as prototyping environment for adaptive interfaces for alternative display shapes. The size, the proportions and the shape of the display can be changed by the user. The interface can be automatically adopted to these changes.

like touch [30]. This would allow to not only change the size of the display but also to interact with the interface and investigate the user experience.

4 INFORMATIONSENSE IMPLEMENTATION

The *InformationSense* tracking approach generates an interactive volume above a table in which the position and deformation of objects and surfaces can be tracked, and the items can be augmented in real-time. The tracking approach combines the generation of a 3-dimensional surface model of the items within this volume with the detection of invisible markers printed on the items (see Figure 6).

The system consists of a depth camera, a projector, and the cloth which is equipped with invisible AR-markers based on the ARToolKit. The depth information is used for tracking the deformation of the projection surface and, if overlaps exist, detect the different segments of the surface. The invisible markers are used to unambiguously identify the areas on the projection surface for the mapping of digital content. Therefore the markers provide the means for a global position determination of the currently visible area of the cloth. Capturing the depth



(a) Tracking of invisible markers in the IR spectrum

(b) Cloth segmentation based on depth information

(c) Mesh generation with Kinect Fusion [15]

(d) Texture mapping based on markers and mesh

Fig. 6. *InformationSense* processing pipeline: The pipeline combines the detection of invisible markers (a), the segmentation of the cloth in different areas (b), the generation of a 3-dimensional mesh of the cloth (c) and finally the projection mapping (d).

information as well as tracking the invisible markers is performed using a single depth camera which is operating in the infrared spectrum. This allows for tracking and augmenting large blank materials and does not interfere with the projection.

The depth camera and the projector are mounted on the ceiling above a table which is used to place and interact with the deformable display. A semi-automatic calibration detects the table, and maps the coordinate systems of the projector and the depth camera to each other. This semi-automatic calibration enables a quick and easy setup of an interaction volume. Whereas the size of the interaction volume is limited by the depth camera and the projector, the size of the objects to be tracked is limited only by the number of available AR-markers. Different materials can be used as a projection surface. *InformationSense* uses a neoprene cloth. Neoprene can be folded and crunched very easily, but has a higher stiffness than other materials and does not retain creases when unfolded.

To make our setting reproducible we provide a detailed description of the technical implementation. In the following, we explain (1) the approach to create and track invisible markers, (2) the segmentation of the deformable projection surface using depth information, and (3) the mesh generation in combination with the previous two methods to perform an absolute mapping of digital information (see Figure 6).

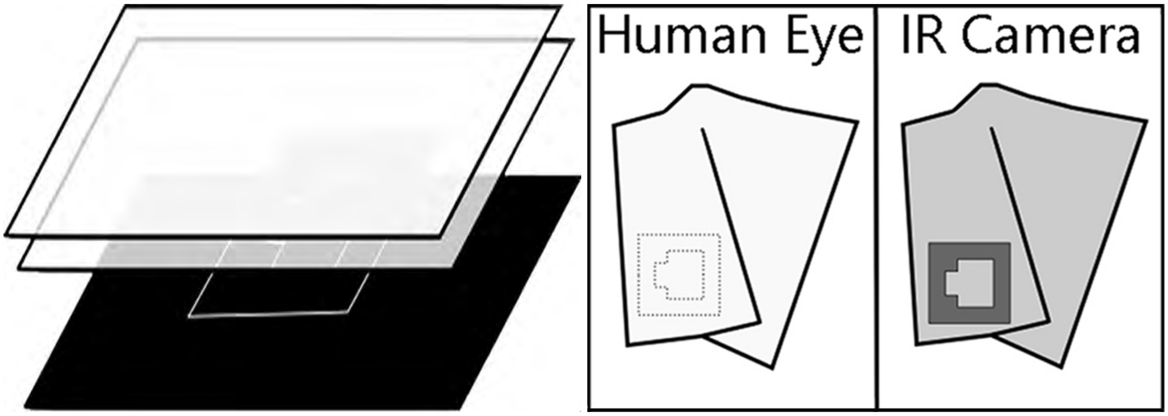
4.1 Marker-Tracking

For the creation of invisible markers, we made use of the fact that black materials can either absorb or reflect infrared light. A black cloth with black markers printed on it is used as projection surface. Whereas the cloth absorbs the infrared light, the ink used to print the markers reflects the infrared light. The markers can be adhered using a printing template and a brush or a screen printing approach. With this technique, the markers are only visible to infrared cameras like the Microsoft Kinect 2 and are nearly invisible to humans. Projection works best on white surfaces. To keep the surface white, a coarse-pored infrared translucent white fabric is adhered (with an iron-on fabric adhesive) to the top of the black cloth (see Figures 7a and 7b). The high contrast in the infrared frame, achieved with this approach, allows for a high tracking accuracy of the markers (see Figures 7c and 7d). To further improve the detection, the infrared frame is processed using the inverse square law. This normalizes the hue of the pixels depending on the distance to the camera and therefore reduces the divergence of brightness values across the detected image. For the final marker detection, the infrared frame is converted to a binary image. For the conversion an adaptive thresholding is applied, because more or less infrared light is reflected to the camera lens, depending on the angle and distance of the AR-markers to the camera. Markers which are not lying flat on the table reflect less infrared light and appear darker in the infrared frame (see Figure 8a). Utilizing adaptive thresholding on a frame results in the binary image, displayed in Figure 8b.

In contrast to previous methods for invisible markers based on infrared reflective ink, (e.g. [29]) our approach provides several advantages. It is cheap and simple to produce, it allows for high tracking precision, because the reflective black ink does not produce a glow effect like infrared reflective ink does and therefore the edges between the reflective ink and the absorbing fabric are very sharp. Finally, in contrast to infrared reflective ink, which diminishes over the course of several days, our method is resistant and insensitive to daylight.

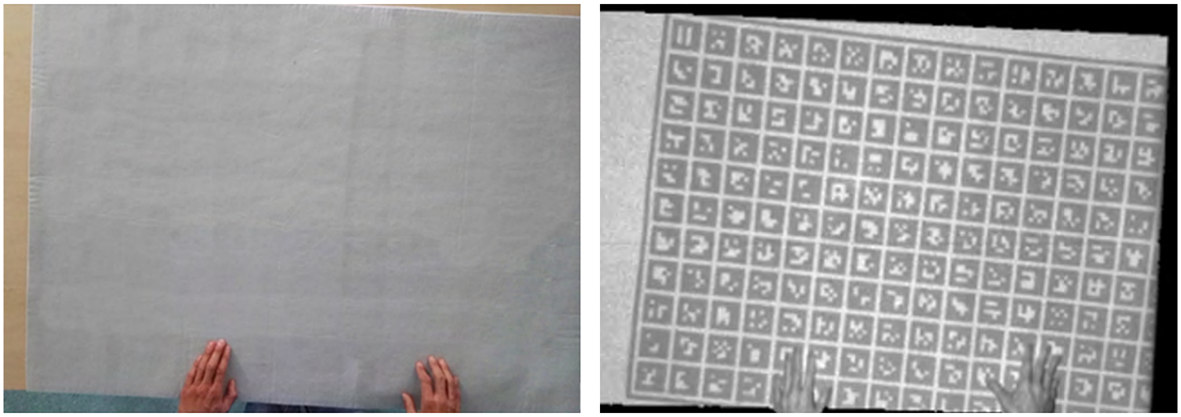
4.2 Segmentation

A folded cloth consists of different segments which have to be textured separately. The fold lines provide edges which can be used for the segmentation of the cloth surface (see Figure 6b). To extract edges, an approach presented by Hulik et al. [14] is applied. Hulik et al. compared different approaches for plane segmentation in depth maps and showed that an edge detection based on depth accumulation in combination with the watershed algorithm provides good performance in terms of a low runtime while still producing a good segmentation result. First, the depth accumulation in combination with an edge detection algorithm is applied to highlight the edges



(a) Construction of invisible markers by printing IR-reflective black ink on an IR-absorbing black cloth.

(b) The Marker are invisible for humans but provide a good contrast in the IR-spectrum.



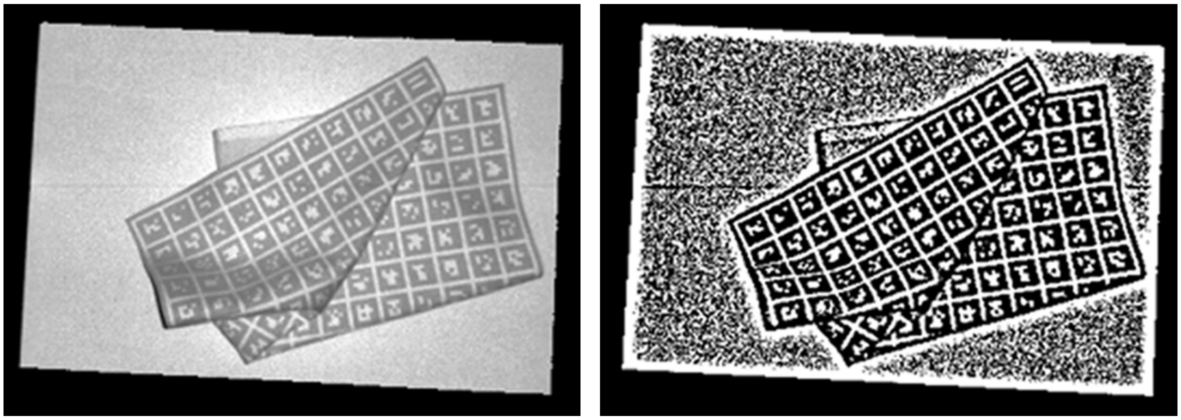
(c) The coarse pored white cloth which is added to the black cloth generates a nearly white surface which is suitable for projections.

(d) A low cost depth camera is sufficient to get a high contrast image of the markers in the IR-spectrum.

Fig. 7. Creation of persistent invisible AR-markers by making use of different IR-reflection characteristics of black materials

on the depth image and second, the watershed algorithm provides the segmentation result based on the enriched depth image.

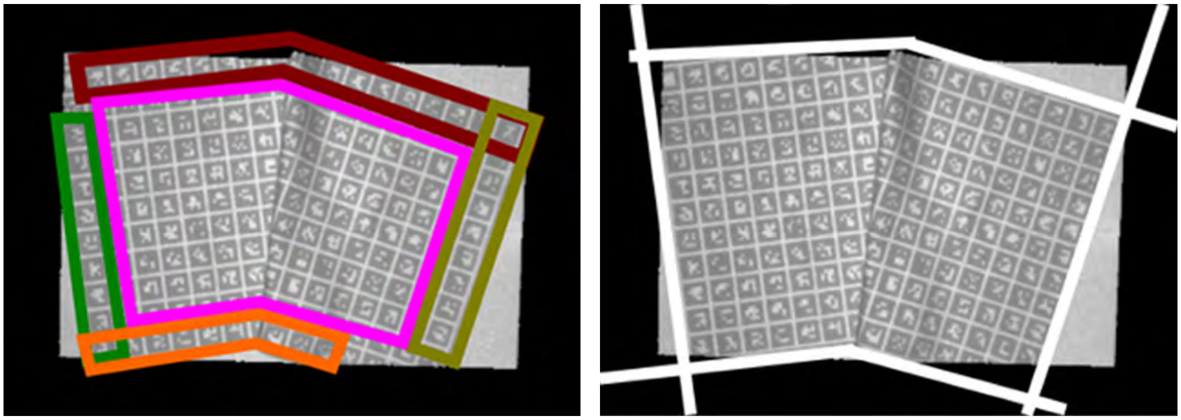
For the depth accumulation the neighboring depth information around each pixel is captured, and the difference between their depth values is computed. The number of neighboring pixels which have a higher depth difference than a threshold is counted. The higher the number of neighbors with a depth difference above the threshold, the more likely there is an edge at the given position. To eliminate noise from the image, smoothing with a median filter is applied. Afterwards the canny edge detector [4] as well as a fast contour line detection are processed. This results in a contour image which shows the folds' edges. The borders of the cloth are determined by a different approach. The segmentation is based on depth only and requires a height difference above a certain threshold



(a) The invisible markers have different IR-reflection characteristics based on their angle and distance to the camera.

(b) An adaptive thresholding is applied to generate a binary image which takes the different IR-reflection intensities into consideration.

Fig. 8. Marker detection: The IR-image is transformed to a binary image for the AR-marker detection.



(a) In the first step the AR-markers at the cloth boarders are detected.

(b) In the second steps the positions of the markers are used to calculate the cloth boarders.

Fig. 9. Border detection: The difference in hight between the cloth and the table is to small to be reliably detected by the depth camera. The *InformationSense* apüproach uses the AR-markers to detect the cloth border.

to work. The difference in height between the table and a cloth border lying flat on it is not large enough to detect an edge reliably. To incorporate this information, the border lines which were computed by the marker tracking are taken into account (see Figure 9). Eventually, the combined result of the contour image and the cloth border detection algorithm are overlaid over the raw depth map. The resulting image therefore provides depth information in terms of a gray-scale image with highlighted edges and is well suited as input for the watershed algorithm.

The segmentation approach is optimized for planar regions, which is sufficient for most of the cases. However, the approach tends to segment strongly curved areas of the cloth into several segments although there is no fold edge. This still allows for a projection mapping on the curved areas, but introduces visible edges between the segments.

4.3 Mesh Generation & Projection

The Kinect Fusion API [15] is used to generate a 3-dimensional mesh model of the deformable projection surface (see Figure 6c). In order to display the digital content onto the cloth, the generated mesh model is split according to the previously identified segments. The detected markers are used to map the texture to the segments. For each marker, its original position on the cloth, as well as the UV coordinates on the texture, are known. Furthermore, the markers' 3D coordinates, as well as the 3D coordinates of the other points on the mesh, are given. In order to find the UV coordinates of the points on the mesh, for each mesh segment, the 3D coordinates of the markers detected within it are projected into 2D space. Afterward, a homography matrix between the projected coordinates and the known UV coordinates is calculated. Finally, the 3D coordinates of the mesh segment are projected to 2D space and the calculated matrix is utilized to compute their UV texture coordinates (see Figure 6d).

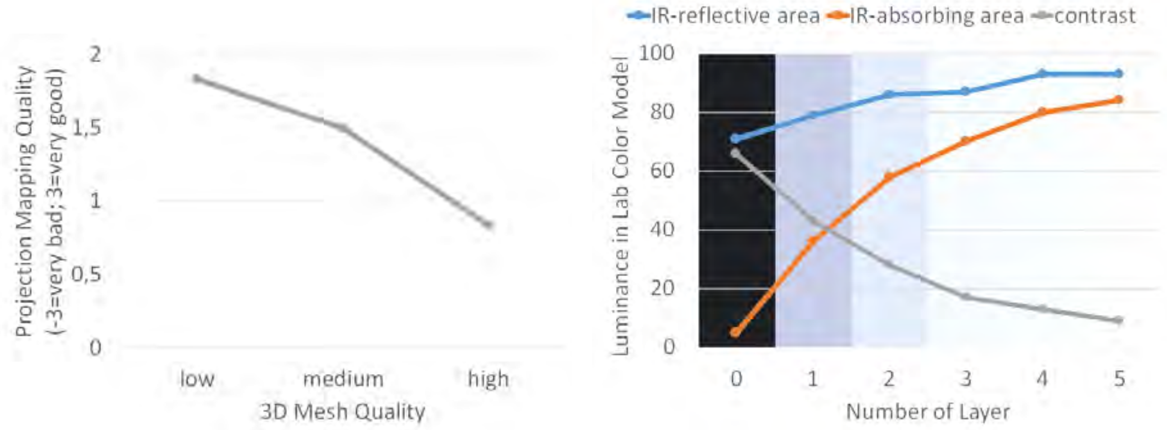
The combination of tracking invisible markers and a 3-dimensional mesh based on depth information complements existing approaches. The tracking approach utilized for *InformationSense* provides (1) sufficient tracking precision, and (2) global 3D position determination. Still, it (3) preserves the "cloth-feel," (4) provides an undistracted visual output, and (5) facilitates large projection surfaces. Furthermore, the tracking approach is (6) scalable because the absolute positional awareness allows for a combination of multiple sets of depth cameras and projectors to increase the tracking and projection volume. However, the approach faces difficulties in strongly bent or crumpled areas. In these areas a reliable augmentation of the cloth is not supported. To further improve the mapping quality the *InformationSense* approach could be combined with approaches for the generation of meshes which allow for occlusions. These approaches are base on detailed geometrical models [40], physics engines [23], or as-rigid-as-possible (ARAP) modeling [32, 39]. This would allow to overcome difficulties with the plane segmentation approach that can occur for strongly bent areas and difficulties with the marker detection approach that can occur for small areas and areas with a huge angle deviation to a perpendicular orientation to the camera.

4.4 Technical Trade-offs

Systems like *InformationSense* put special requirements on the technical setting and the projection mapping. For the implementation of a projection mapping system different trade-offs have to be considered. In the following we elaborate on the identified trade-offs and report on findings from three initial technical evaluations we conducted in order to determine suitable properties for each trade-off. The trade-offs and our results can be used as a guide for further technical evaluations of comparable systems. The trade-offs were analyzed on a desktop PC with a Core i7-4770K with 3.50 GHz, 16 GB RAM, and a GeForce GTX 760 graphics adapter.

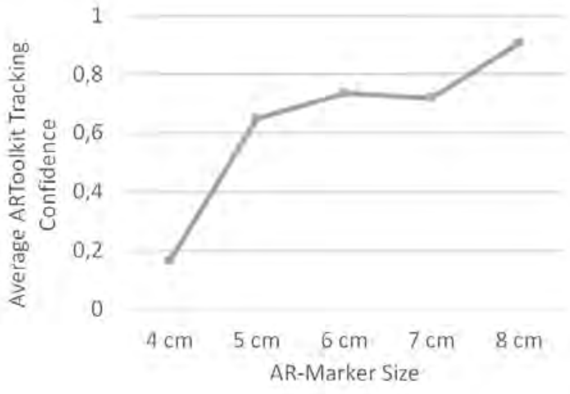
- **Trade-off 1 - latency vs. 3D model accuracy:** The 3-dimensional model accuracy can be controlled by Kinect Fusion settings (voxels per meter for X, Y and Z-axis). The 3-dimensional model accuracy defines how well the distortion of the digital space approaches the real-world shape of the projection surface. However, the better the 3-dimensional model accuracy the higher the latency. We tested three different accuracy settings for Kinect Fusion (low accuracy: 96 voxels for all settings; medium accuracy: 192 voxels; high accuracy: 384 voxels) and investigated the projection output. Although the Kinect Fusion algorithm works with the mentioned voxel settings for the mesh generation only every third voxel was considered. This results in a mesh with 1,024 vertices for low accuracy, 4,096 vertices for medium accuracy, and 16,384 for high accuracy. 6 participants were asked to provide a random deformation of the cloth. A checkerboard pattern was mapped to the cloth and participants gave their subjective assessment about the quality of the projection mapping (seven-point Likert scale from -3 = very bad to 3 = very good). The participants' rating for the quality of the projection mapping showed that the lowest accuracy was even perceived best (low accuracy: $M = 1.8$, $SD = 0.9$; medium accuracy: $M = 1.5$, $SD = 0.8$; high accuracy: $M = 0.9$, $SD = 1.1$; see Figure 10a). Already the low settings provide a mapping which fits the real-world shape of the cloth well. A more fine grained mapping does not lead to a better perceived quality, but even adds some noise to the projection. The coordinates of each vertex contain an error. When mapping the texture these errors are mainly visible at the edges between the vertices. This is especially true when mapping textures with strait lines which get some jitter due to the errors. The more vertices a mesh has, the more edges it has and therefore also the more errors are visible. A low accuracy mesh does not match the actual shape of the cloth as good as a high accuracy mesh, but straight lines appear clearer due to the less vertices. However, the participants mentioned that the perceived differences where very small. In contrast, the 3-dimensional model accuracy had a huge influence on the latency in terms of frames per second (fps). With high accuracy only 32 % the frames for low accuracy were achieved (low accuracy: 22 fps; medium accuracy: 16 fps; high accuracy: 7 fps). As a result for the latency vs. model accuracy trade-off *InformationSense* accepts a lower model accuracy in favor of a low latency. It became apparent that a fine grain tracking of the 3-dimensional shape of the cloth is not necessary for a projection mapping that is perceived as being of high quality.

- **Trade-off 2 - surface color vs. IR contrast:** The *InformationSense* tracking approach is based on a black cloth and AR-markers printed in black. To achieve a close to white surface a course pored white fabric is attached to it. The number of white layers influences the resulting color of the surface (the more layers the whiter) but also negatively influences the IR-translucency (see Figure 10b). A high IR-translucency is crucial for the reliable AR-marker tracking. To identify a good trade-off between color and tracking accuracy we tested six different numbers of layers (0 layers to 5 layers) attached on top of an AR-marker. To measure the level of contrast in the IR spectrum we captured an IR-frame for each sample using the Micosoft Kinect 2. We calculate the average color for IR-absorbing and IR-reflecting areas to get a measurement of contrast. Results show that even with one layer the color of the cloth is usable for projections but still provides a very high contrast image in the IR spectrum. With two layers the contrast in the IR spectrum is still high compared to the results for IR-absorbing ink provided by Willis et al. [45] Thus, two layers provide a good trade-off between a close to white color of the projection surface and a still high contrast in the IR spectrum which is suitable for marker tracking.
- **Trade-off 3 - marker size vs. marker detection confidence:** The trackable minimal segment size is a crucial factor for a suitable projection mapping. The trackable size of the segments defines the supported augmentation of deformations. The minimum segment size corresponds to the size of the AR-markers printed on the cloth. At least one AR-marker has to be detected within a segment and therefore has to fit into the segment. To identify appropriate marker sizes we compared five different sizes (4 to 8 cm with 1 cm interval). We made use of a 4 x 4 marker configuration which allows for a large number of different markers and therefore for a large projection surface. For each size, six of these 4 x 4 markers were printed on a sheet of paper. The colors of the markers were adjusted in a way to produce the same contrast in the IR-spectrum as AR-markers printed on the cloth and covered with two layers of course pored white fabric. The marker tracking confidence for each configuration was calculated as the average detection confidence provided by the ARToolkit (see Figure 10c). The results show that a marker size of 6 cm provide a good trade-off between the allowed minimum segment size and the tracking confidence. To



(a) Latency vs. 3D model accuracy: A higher model accuracy does not lead to a higher perceived projection mapping quality. A lower model accuracy and therefore a lower latency should be preferred over a higher model accuracy.

(b) Surface color vs. IR contrast: Two layers of course pored white cloth provide a good trade-off between the color of the projection surface and the contrast of the AR-markers in the IR-spectrum. The background of the chart corresponds to the color of the projection surface.



(c) Marker size vs. marker detection confidence: AR-markers with 6 cm provide a good trade-off between a reliable marker tracking and a small minimal segment size.

Fig. 10. Technical trade-offs of *InformationSense*: The trade-offs can be used as a guide for the implementation and evaluation of related systems.

lower the minimum segment size a more powerful infrared camera (higher resolution, higher sensitivity, more fps) could be used, to provide reliable tracking with smaller markers.

5 EVALUATION

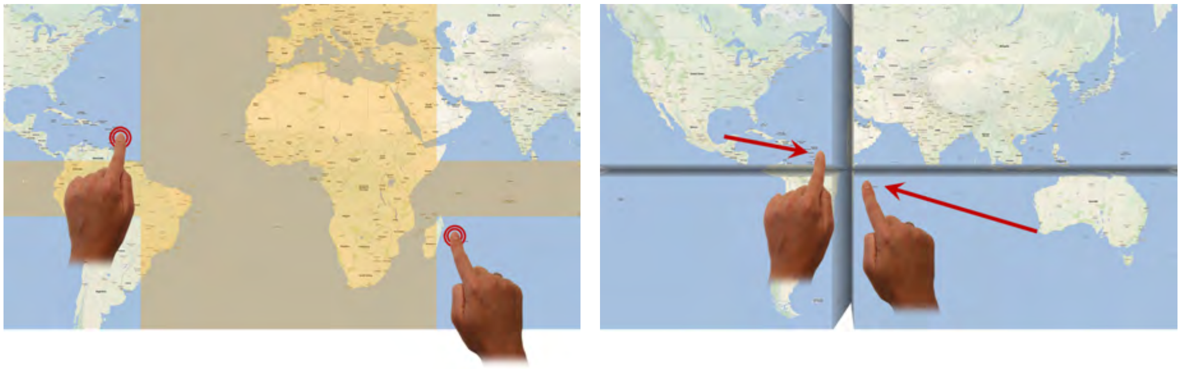
Physically deformable displays provide the means to be integrated into our physical environment and allow for interaction with digital space through physical manipulations of the display. Although users can make use of their pre-existing knowledge about the manipulation of objects, it has to be explored if the interaction with digital spaces through augmented deformable surfaces provides similar pragmatic and hedonic qualities as state-of-the art interaction paradigms on rigid surfaces. In our evaluation we compared *InformationSense*, a physically deformable display, which offers interactions *in* the real-world, to virtually deformable interfaces which emulate real-world behavior and therefore allow for interactions *like* the real-world, but offer more computational power to the users.

The evaluation focused on deformations and movements of the interfaces which correspond to the navigation in digital information spaces. All interfaces support panning and folding interactions. We made use of a search and compare task to force users to navigate (search) the digital space and carry out deformations (compare). The goal was to measure participants performance and inquire about their preferences, as well as identify strategies that users pursue in order to complete the tasks. The questions we wanted to answer are related to the trade-off between power and reality described by the *Reality-based Interaction* framework:

- **RQ1**: Does the additional power of a *like* the real-world interface outperform the flexibility and the haptic qualities of a reality emphasizing interface that allows for interactions *in* the real-world.
- **RQ2**: Is an interface based on interactions *in* the real-world preferred over the increased digital power of an interface based on interactions *like* the real-world?
- **RQ3**: How do people manipulate a large physically deformable display that provides a very high degree of freedom and do they draw from their pre-existing knowledge?

5.1 Interfaces

We compared the "in" the real-world interface *InformationSense*, which emphasises reality over digital power, to the "like" the real-world interface *SpaceFold* [3], which decreases reality in favour of digital power. For



(a) The fold mechanism of *SpaceFold* is activated by tapping and holding the information space at two positions.

(b) The folding of the space can be controlled by altering the distance between the touch points. Horizontal and vertical folds can be created simultaneously.

Fig. 11. *SpaceFold*: A *like* the real-world interface which allows for digital deformations of information spaces by using the metaphor of folding a sheet of paper.

InformationSense the digital content is statically mapped to the physical cloth and can only be navigated by moving or deforming the cloth. *SpaceFold* is a pan/zoom interface enhanced with a distortion-based visualization technique. The multi-scale-navigation technique allows for digital deformations of a digital space based on the metaphor of a folded sheet of paper (see *Figure 11*). Users are able to create vertical or horizontal folds by placing their fingers on the multi-touch table. A dwell time activates the folding mechanism, and moving the fingers closer to each other creates a fold. By placing the fingers diagonally on the screen, the interface facilitates the creation of a horizontal and vertical fold simultaneously (cross fold). Existing folds can be modified by activating the folding mechanism and moving the two fingers closer to each other to push texture into the fold that is laying between the fingers or moving the fingers away from each other to pull texture out of the fold. If multiple folds are placed between the two fingers and the user moves the fingers towards each other, the folds are merged.

Although *SpaceFold* does not address the tactile sense, it makes use of users' pre-existing real-world knowledge about folding a sheet of paper. This potentially eases interaction and facilitates the visual interpretation of a fold as the depth and the shading of a fold corresponds to the space that is aggregated. Furthermore, it enhances the real-world metaphor with additional power, which is that zooming is enabled and that the deformation of the space is performed in a structured way (e.g., only horizontal and vertical folds, automatic merge to limit the number of folds, no overlaps). For *SpaceFold* we investigated two variants: with zoom and without zoom. Zoom, because zooming is a powerful functionality that we want to isolate for further investigation.

5.2 Task

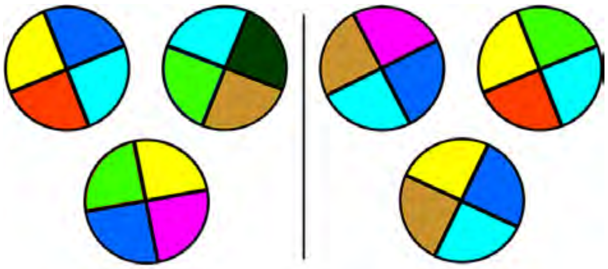
A search and compare task was used to force users to navigate the virtual landscape and perform deformations of the digital space *in* or *like* the real-world. Our task was based on previously existing compare tasks (e.g., [3, 17]) but was altered due to differences in the study setup. *InformationSense* supports cloth rotation. Therefore the compare task had to be independent of the orientation. Furthermore, whereas most previous tasks allowed for the comparison of two objects, we wanted to investigate different task complexities, which were represented through different numbers of objects to compare.

Participants had to search and compare circular colored objects with each user interface (see Figure 12). The objects were randomly rotated and placed on a white background. Each object was colored with four out of eight colors. The colors were selected to be very easily distinguishable in order to minimize the influence of different display properties (brightness, saturation, contrast, sharpness) when comparing projection mapping to a LCD display. Participants had to determine if one color was given in all of the circle objects and lock their answer by pressing one of two highlighted keys on a keyboard which was placed on a separate table on the right side of the participant. To force users to examine all objects, a pair of objects always had at least one color in common, but only in some cases one color was present in all of the objects. Additionally, two different task distances were investigated. We distinguished between tasks, in which participants may see all of the circle objects at once without folding or zooming (short distance tasks) and tasks in which this was not feasible (far distance tasks). For interfaces in which zooming was enabled, the colors of the objects were only visible at a zoom level of 1:1. When zoomed out, the objects were still visible but the colors were covered. The same procedure was used for the folded areas of *SpaceFold*.

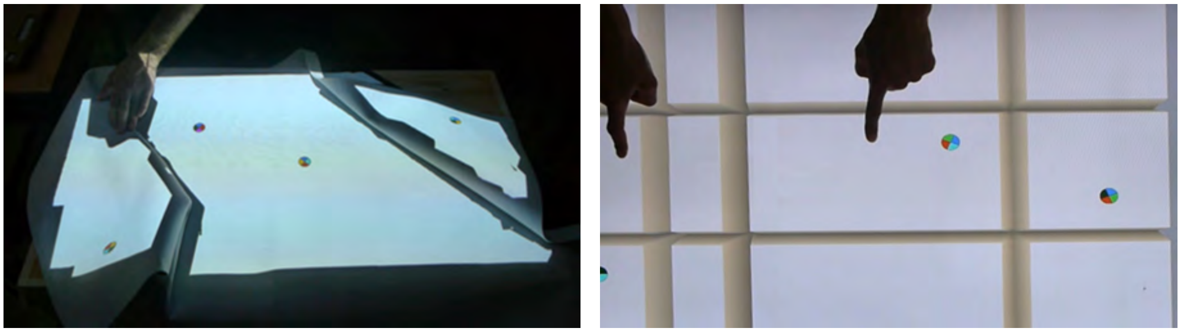
5.3 Experimental Design

The experiment was conducted as a within-subject factorial design with three independent variables:

- User Interfaces: *InformationSense*, *SpaceFold* with zoom, *SpaceFold* without zoom
- Task Complexity: low (two compare objects), medium (three compare objects), high (four compare objects)
- Distance of objects: short (no folding mandatory to view all compare objects at once), far (folding or zooming is necessary to see all compare objects at the same time)



(a) Compare task with three objects: (left) unequal - no color in all three objects; (right) equal - turquoise quarter in all objects



(b) Task conduction with *InformationSense*

(c) Task conduction with *SpaceFold*

Fig. 12. Study task: The space has to be folded in order to compare different numbers of circular objects

Dependent variables collected during the study were task completion time and the individual actions performed by the participants. Task completion time was defined as the time between pressing a key on the keyboard to start the task and the time when users locked their answer. For the *SpaceFold* interfaces the actions performed were logged for each trial for later statistical analysis. For *InformationSense* the actions were identified trough a manual video encoding. In addition the User Experience Questionnaire (UEQ) [20] was applied to compare the subjectively perceived pragmatic and hedonic qualities of the interfaces.

5.4 Apparatus

The *InformationSense* system implemented for the evaluation consisted of 209 (19x11) AR-markers. Each of the markers was 6x6 cm in size. The pattern was printed on top of the 2 mm thick neoprene textile and covered with two layers of thin, infrared translucent white cloth. This resulted in a light gray projection surface (see Figure 8c). The final system has an approximate size of 135x85 cm. A 93x52 cm large and 90 cm high table was used for cloth placement and also to define the interaction volume in which the cloth is augmented. The resulting space had an aspect ratio of 16:10. A full HD projector and a Microsoft Kinect 2 depth camera were placed 1.4 meters above the table to track and augment the cloth.

SpaceFold was run on a 55 inch multi-touch table (Citron DreamTouch) with a resolution of 1920x1080 pixels and a size of 121x68 cm. To limit the interaction space to the same size that was supplied by *InformationSense*, a black border was displayed and the size of the interface was reduced to the same physical size as the table used for *InformationSense* had. Also, the height of the multi-touch display was the same as for the table of *InformationSense*. The real-world size of the visualized digital space corresponded to the dimensions of the *InformationSense* cloth. Thus, the landscape used for *SpaceFold* had the same physical size as cloth when visualized at a zoom level of 1:1. The software for all interfaces ran on the same PC as for the technical evaluation (Core i7-4770K, 16 GB ram, GeForce GTX 760).

5.5 Participants

Participants were recruited among students and staff of the university. A total of 18 persons participated (8 females and 10 males). The average age was 21.9 years (SD = 2.3, aged 19 - 26). Only two of the participants studied computer science. The others were matriculated in various different subjects, ranging from other technical majors like electronics, mechanical engineering, and civil engineering to subjects like humanities, architecture, teaching and artistic sciences. None of the participants was physically impaired or had a color vision deficiency. Therefore the participants did not face difficulties with respect to the physical effort needed to manipulate the cloth or the employed color coding.

5.6 Procedure

Half of the tasks in each block were short-distance and half far-distance tasks. The tasks were conducted in a continuous sequence without a reset of the deformation (either physical or digital) between tasks. Therefore, participants continued with the deformation state of the previous task. Although this makes task completion times less comparable we dispense with a reset because we assume, that an initial deformation, as it would also occur in a real setting, strongly influences the interaction behaviour. After participants completed the task set for an interface they answered the User Experience Questionnaire. After all interfaces, we conducted a semi-structured interview in order to ask participants about the strategy that they employed to solve the task and the perceived advantages and drawbacks of the interfaces in terms of the power versus reality trade-off. Each session lasted about 1.5 hours in total, and participants had to stand while solving the tasks. They were paid 12 Euros as compensation.

5.7 Findings & Discussion

In this section we report on our findings and discuss them in relation to our research questions. We focused on the differences between the *in* and *like* the real-world interfaces in terms of users' performance (RQ1), the user preferences (RQ2), and the participants' interactions with the interfaces (RQ3).

Non-parametric tests were used when the assumption of normality was violated. To analyze the interaction behavior of participants when using *InformationSense,* we applied a coding scheme to our video recordings. We placed the focus on the individual actions performed by the participants and compared them to the logs which were automatically generated for the *SpaceFold* interfaces. An inter-coder reliability test was conducted for more than 10% of the video data. Cohen's Kappa showed a high inter-coder reliability (K = 0.81).

5.7.1 RQ1: Efficiency of physically deformable and virtually deformable interfaces. We analyzed the differences in user performance between the interfaces in terms of task completion time (see Figure 13). Task completion time for *SpaceFold* without zoom (M = 21.9 sec, SD = 14.9) was lower than for *SpaceFold* with zoom (M = 22.3 sec, SD = 14.0) and *InformationSense* (M = 24.6 sec, SD = 18.2). A Friedman's ANOVA showed a significant main effect between interfaces (χ^2 = 7.81, p = 0.02). Post-hoc, Wilcoxon Signed-Rank Tests in line with Bonferroni Correction indicated that the median task completion time for *SpaceFold* without zoom, was significantly lower than for *InformationSense* (Z = -2.58, p = 0.03). The differences between the other interface pairs were not significant (p > 0.05). Another Wilcoxon Signed-Rank Test revealed that the median task completion time for short-distance

Fig. 13. Task completion times separated by object distance (* indicates significant differences with significance level of 0.05)

tasks was significantly lower than for far-distance tasks (Z = -19.2, $p < 0.01$). We further analysed task completion times for the interfaces separately for short and far distance tasks. Task completion times for short distance tasks did not reveal a significant effect ($p > 0.05$). For far distance tasks, the test showed a significant main effect ($\chi^2 = 14.6$, $p < 0.01$). For far distance tasks the task completion times for *SpaceFold* with zoom (M = 28.4 sec, SD = 14.8) and *SpaceFold* without zoom (M = 28.5 sec, SD = 16.0) were lower than for *InformationSense* (M = 34.0 sec; SD = 19.6). A pairwise comparison revealed that the median task completion time for *InformationSense* was significantly higher than for both versions of *SpaceFold* (with zoom: Z = -4.38, $p < 0.01$; without zoom: Z = -3.76, $p < 0.01$). The comparison of the two *SpaceFold* based interfaces indicated no significant difference ($p > 0.05$).

The results showed that for far distance tasks, for which a deformation of the landscape was indispensable, the *SpaceFold* interfaces outperformed *InformationSense* in terms of task completion time. Six participants (*P2, P4, P9, P11, P15, P17*) explicitly stated in the interview that the additional digital power, e.g., zooming the interface for an overview or the ability to perceive objects lying within folds, facilitated their work and especially sped up their search for the objects. Achieving an overview over the information landscape was equally important for all interfaces. Participants applied the same search strategy for all interfaces. This strategy stood in close relation to the Information Seeking Mantra [38] which is overview first, zoom and filter, then details on demand. To manipulate the space, users tried to get an overview, then developed a deformation strategy, and finally deformed the space to explore the details. This process was applied iteratively. For short distance tasks, getting an overview in order to develop a deformation strategy was less important because folding was not necessary. For these tasks, no significant differences in task completion times were identified.

Finding 1 The additional digital power of *SpaceFold* provides a higher efficiency in terms of task completion time. The digital power therefore outperforms the flexibility and the haptic qualities of *InformationSense*. The difference in task completion time is due to the better overview of the *SpaceFold* interface which facilitates the search process and the development of a deformation strategy. For navigation tasks in which a deformation of the space is not required, no significant difference in efficiency can be found between the interface providing additional digital power *(SpaceFold)* and the interface which does not incorporate additional digital power (*InformationSense*).

5.7.2 RQ2: User Preferences. We analysed the participants ratings on pragmatic and hedonic qualities collected with the User Experience Questionnaire. The lower task completion times for *SpaceFold* are already an indicator of a higher pragmatic quality of the interfaces. This is also underpinned by the participants' ratings (see Figure 14). The *Attractiveness* scale showed no significant effects ($p > 0.05$). However, we found a significant difference in the ratings of the pragmatic qualities: *Perspicuity* ($\chi^2 = 12.7$, $p < 0.01$), *Efficiency* ($\chi^2 = 10.8$, $p < 0.01$) and *Dependability* ($\chi^2 = 6.1$, $p < 0.05$). Post-hoc comparison showed that *SpaceFold* with zoom was rated significantly better than the *InformationSense* interface for all three dimensions (*Perspicuity*: $Z = -3.00$, $p < 0.01$; *Efficiency*: $Z = -3.13$, $p < 0.01$; *Dependability*: $Z = -2.78$, $p < 0.01$). For *SpaceFold* without zoom only the scale *Efficiency* was scored significantly higher than for *InformationSense* ($Z = -3.00$, $p < 0.01$). Between the two touch-based interfaces, only the dimension *Perspicuity* showed a significant difference ($Z = -3.00$, $p < 0.01$). The system which supports zooming was rated higher. Therefore, related to the interfaces pragmatic qualities, most participants preferred the *SpaceFold* interfaces due to their additional digital power.

When looking at the hedonic qualities, the statistical analysis revealed significant effects for the dimensions *Stimulation* ($\chi^2 = 13.6$, $p < 0.01$) and *Novelty* ($\chi^2 = 15.6$, $p < 0.01$). Post-hoc pairwise comparisons showed that *InformationSense* was rated significantly better for both scales, when compared to *SpaceFold* with zoom (*Stimulation*: $Z = -3.22$, $p < 0.01$; *Novelty*: $Z = -3.19$, $p < 0.01$) and SpaceFold without zoom (*Stimulation*: $Z = -3.22$, $p < 0.01$; *Novelty*: $Z = -2.90$, $p < 0.01$). During the task and in the interviews, participants mentioned several reasons for the higher hedonic qualities of *InformationSense*. One participant exclaimed during her work with the system: *"That's really cool. I think that [to use InformationSense] is a lot of fun!"* (*P17*) Another one said: *"That [to use InformationSense] was just the most fun for me. It was something new."* (*P9*). Participants further reported that they liked the high degree of freedom provided by the cloth surface. They also found the interface modern and new (*P2-P5, P9, P10, P13-P17*), valued its haptic qualities (*P2, P5-P8, P13, P17, P18*) and described it as natural, human, real or direct (*P2, P5, P8, P10, P13, P15, P17*). One of them said: *"Everything you did with your hands actually happened."* (*P17*) Furthermore, some participants mentioned that the system was beautiful, refreshing, interesting or fascinating (*P7-P9, P13, P14*), that it feels good (*P1, P6, S08*) or that it had a playful character (*P1, P9, P10, P13*).

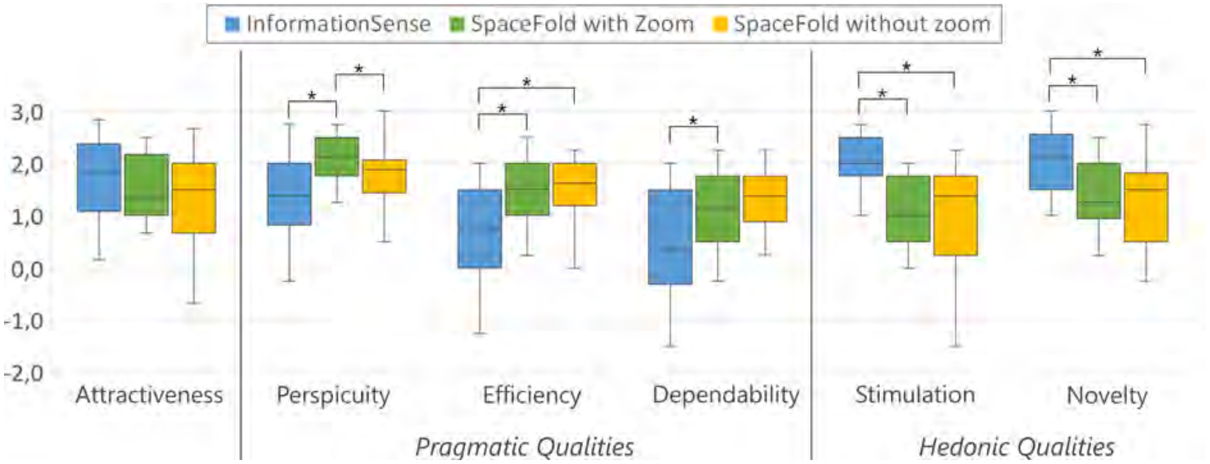


Fig. 14. Results from the User Experience Questionnaire (* indicates significant differences with significance level of 0.05)

Finding 2. The trade-off between the emphasized reality of *InformationSense* and the power of *SpaceFold* showed that the raised emphasis of reality comes at the cost of pragmatic qualities but increases the hedonic qualities. Users appreciate the direct manipulation and the natural feeling of the physically deformable display and mentioned numerous use cases which can benefit from the hedonic qualities of *InformationSense*, ranging from architecture and fashion design to games and teaching. In terms of pragmatic qualities the additional digital power of *SpaceFold* is preferred over the direct manipulation and natural feeling of *InformationSense*.

5.7.3 RQ3: Interaction behavior. The analysis of video recordings and log files revealed information with regard to interaction types which were utilized by participants while conducting the search and comparison tasks (see Figure 15). In the following section we elaborate on the expressive power of the interfaces.

Approximately 30% of all interactions conducted with the interfaces corresponded to actions to create a deformation (*InformationSense*: 26%; *SpaceFold* with zoom: 27%; *SpaceFold* without zoom: 31%). For *InformationSense* only 17% of these deformations correspond to a horizontal or vertical folding as it is also supported by *SpaceFold*. Most deformation actions performed with *InformationSense* are based on users' pre-existing knowledge about what interaction possibilities a cloth provides. Users created diagonal folds, crumbled the cloth, stacked folds over each other, or grabbed an object to place it at another position on the table.

Therefore, participants made extensive use of the physical and haptic properties and the additional freedom for interaction that the cloth provides. They argued that free deformations provided them with more possibilities like the creation of small partial folds or to fold edges over (*P1, P8-P10*). Three participants said that they needed fewer work steps when they deformed the cloth without restrictions (*P3, P10, P15*). Others argued that it felt intuitive and natural (*P4, P5*) and one reported that folding did not require him to think about his interactions at all (*P10*). One participant said: *"With this material [cloth] I have it [the ways to interact with it] in my own hands. That's because I can manipulate and deform it as I want and my interactions are transferred one to one."* (*P18*)

While users reported that they strongly appreciated the freedom for interaction when using the physically deformable display they also stated that restrictions (only vertical and horizontal folds) helped to control the interface on the rigid display. 14 of the participants mentioned that free deformations would not work well in combination with the touch-based interfaces. Most of them stated that they would prefer it to keep the restrictions. They argued that the risk of slips (trigger wrong action) would be high (*P3, P5, P17*) or that unrestricted deformations would feel unintuitive in a 2-dimensional environment. They deemed folding on the

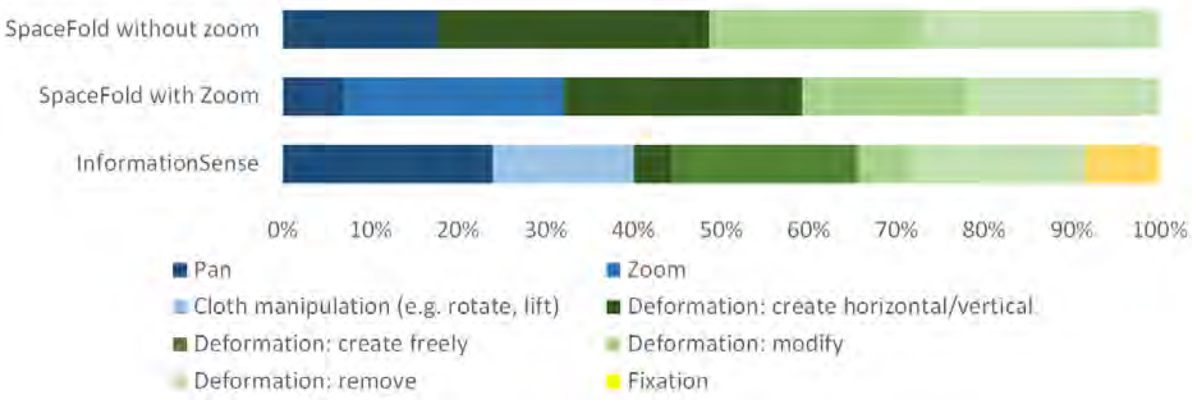


Fig. 15. Actions conducted with each of the interfaces

touch surface less complex and simpler to understand when only a limited set of possible interactions is supported and the interactions are constrained (*P7, P14*).

Finding 3.1 Users make extensive use of the high degree of freedom of the physically deformable display. The physically deformable display provides a high expressive power which allows users to easily perform complex deformations. Users apply their pre-existing knowledge and are intuitively aware of the possibilities to push a cloth together to create a fold, to crumple it, to lift it in the air, grab it on its borders to move it or flip an existing fold over to look under it. Physically deformable displays therefore provide the means to use them without thinking about the interaction.

Finding 3.2 A lower degree of freedom is appreciated for the virtually deformable interface on the rigid display. For rigid displays, which do not address the haptic sense, the reduced degree of freedom can help users to control the complexity of deformations.

5.8 Limitations

In terms of the study protocol, we decided to take a continuous task sequence with no reset of the deformation between tasks. This makes results for task completion time less comparable. However, task completion time was not the focus of our research. Instead we focused on external validity in terms of fluent interaction, which would also occur when using such a display in real settings. Furthermore, we limited the task to searching and comparing objects without directly interacting with them. Further research should investigate physically deformable displays which offer a combination of interaction through deformation and other input modalities like touch. To do so *InformationSense* could be combined with touch sensitive cloth like FlexTiles [30]. In this first evaluation we limited the interaction to the navigation in digital spaces without investigating the manipulation of digital objects within these spaces.

6 IMPLICATIONS

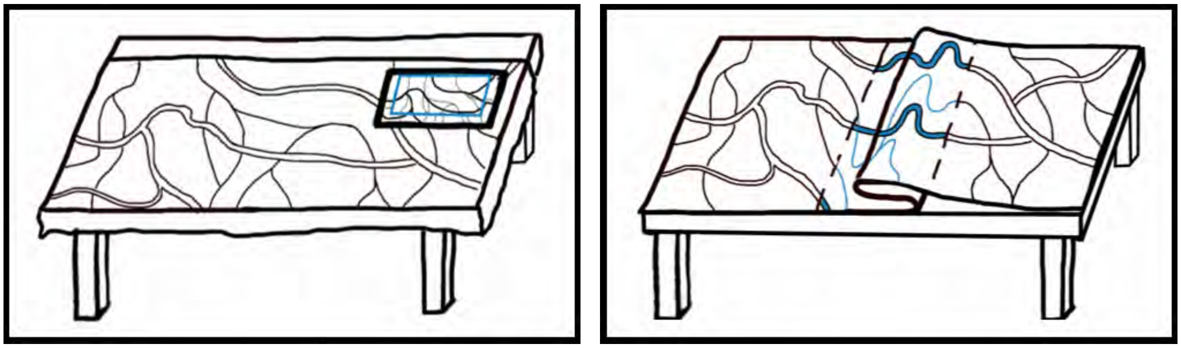
The implications of this work inform two major areas in the context of deformable displays: the technical implementation as well as the design of interfaces for deformable displays.

InformationSense is based on a novel tracking approach which supports (1) a sufficient tracking precision and (2) a global 3D position determination. It (3) preserves the “cloth-feel,” (4) provides an undistracted visual output, (5) facilitates a large projection surface and (6) is scalable. The utilized markers are created from persistent materials and thus, in contrast to markers based on infrared ink [45], support long term use. Although not as precise and robust as other more complex and expensive solutions (e.g., [27, 28]), our tracking approach can be applied by practitioners to design low cost physically deformable displays that do not decrease in tracking performance over time. Thus, the tracking approach is also usable for in-the-wild settings like for example in museums. Further, we elaborated three technical trade-offs: lateny vs. 3D model accuracy, surface color vs. IR contrast, and marker size vs. marker detection confidence. The trade-offs can be used as a guide for the implementation and evaluation of related systems which have the potential to be integrated in our physical environment - integrated in terms of the visual appearance but also in terms of the interaction.

The results of our UX study can inform the design of interfaces for deformable displays as well as unveil further research directions. The results show that *InformationSense* as a physically deformable display provides qualities which differ from the qualities of rigid displays. The physically deformable display, which allows users to explore digital information spaces by physical manipulations of the display, has shown significantly higher hedonic qualities than the virtually deformable interface.

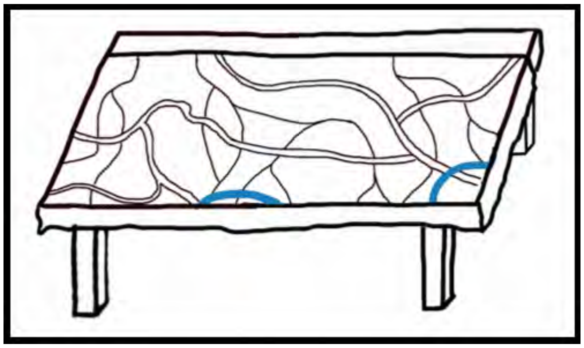
UbiComp experiences where displays are integrated in our physical environment can benefit from high hedonic qualities. Users have pre-existing knowledge about how a cloth can be manipulated and are able to apply this knowledge when interacting with physically deformable displays. The increased expressive power of physically deformable displays makes a huge set of possible interactions easily manageable without the need for introduction. Therefore systems like *InformationSense* allow users to experience digital content without thinking about the necessary interactions. Especially tools for educational purposes or exhibitions and museums could benefit from these qualities of physically deformable displays.

However, the emphasis on realism during the design of the physically deformable display came at the cost of pragmatic qualities. For application scenarios, like control rooms or office work, where the performance in terms



(a) Overview+detail design pattern: An overview of the entire space could facilitate the orientation.

(b) Focus+context design pattern: Distortion overlays in folded areas could facilitate the orientation in folded spaces.



(c) Cue-based visualizations: Halos could facilitate the navigation to objects which are out of the interaction volume or which are covered by folds.

Fig. 16. Large physically deformable displays can be enhanced with additional digital power to increase their pragmatic qualities.

of task completion time, or the development of a task completion strategy, is crucial, deformable displays like *InformationSense* need to be extended with additional digital power in regard to the *Reality-based Interaction* framework. The study results helped to identify leverage points where the pragmatic qualities of physically deformable displays can benefit from additional digital power. The two main issues of *InformationSense* are the missing zoom functionality and the loss of information situated in folds when the space is deformed. These reality-based properties of the physically deformable display hamper users in getting an overview and creating a mental map of the space. Such a mental map is essential for creating a deformation strategy and for modifying existing deformations. Problems with creating an overview and building a mental map are well known and researched for rigid display interfaces. Approaches which proved valuable to overcome the problems for rigid displays could be adapted and researched for the use with physically deformable displays. For example, overview visualizations (e.g., [6]), distortions which show content situated in folds in an aggregated form (e.g., [7, 36]) and off-screen visualizations (e.g., [1, 10]) could be implemented (see Figure 16).

7 CONCLUSION

In this article we presented *InformationSense*, a large, highly deformable cloth display. The article contributes to two areas in the context of deformable displays: It presents an approach for the tracking of large, highly deformable surfaces, and it reports on findings of one of the first UX analyses of cloth displays that will inform the design of future interaction techniques for this kind of displays.

The cloth tracking of *InformationSense* is based on a novel approach for the creation of invisible markers. In this context we examined three technical trade-offs which have to be considered when tracking deformable surfaces using markers and mapping content to it. The resulting system can be used in several application domains. We presented three use cases which can benefit from the hedonic qualities of large, highly deformable displays.

Furthermore, we reported on study results which contribute to a better understanding of the advantages and disadvantages of physically deformable displays in context of the power versus reality trade-offs. In particular, we focused on the objective user performance, users' subjective preferences, and participants' interaction with the interfaces. Results show that users perform faster and prefer the increased digital power of the virtually deformable interface in terms of pragmatic qualities. However, they prefer the physically deformable display in terms of hedonic qualities. Users like the high deformability and are able to control it based on their pre-existing knowledge. The physically deformable display provides a high expressive power which facilitates the effortless creation and modification of complex deformations.

We can conclude that highly deformable cloth displays can provide higher expressive power and higher hedonic qualities than rigid displays. Nevertheless, further research is required to investigate how the pragmatic qualities of physically deformable displays can be increased by adding digital power without decreasing the expressive power.

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