Empowering Materiality: Inspiring the Design of Tangible Interactions

Magdalena Schmid
BMW AG
Knorrstr. 147, Munich, Germany
Magdalena.Schmid@bmw.de
+49 89 382 60947

Sonja Rümelin
BMW Research and Technology
Hanauerstr. 46, Munich, Germany
Sonja.Ruemelin@bmw.de
+49 89 382 51985

Hendrik Richter
University of Munich (LMU)
Amalienstr. 17, Munich, Germany
Hendrik.Richter@ifi.lmu.de
+49 89 2180 4687

ABSTRACT

Tangible user interfaces utilize our ability to interact with everyday objects in order to manipulate virtual data. Designers and engineers usually follow the rule “form follows function”, they support an existing interaction with a purpose-built interface. Still, we do not fully exploit the expressiveness of forms, materials and shapes of the non-digital objects we interact with. Therefore, we propose to invert the design process: we empower materiality to inspire the implementation of tangible interactions. Glass objects were chosen as an example of culturally and structurally rich objects: in a three-month workshop, these glass objects were transformed into interactive artefacts. In the paper, we present three resulting contributions: First, we describe our inverted design process as a tool for the stimulation of multidisciplinary development. Second, we derive a list of material-induced interactions. Third, we suggest form-related interactions as a means of designing future tangible interfaces.

Author Keywords

Design; Prototyping; Materiality; Glass; Interaction; Tangible user interface; Organic user interface; Natural user interface; Guides; Craftsmanship; Immateriality.

ACM Classification Keywords

H5.2.User interfaces: Prototyping.

INTRODUCTION

Historically, interaction design has primarily been constrained by available input- and output-mechanisms such as keyboards, mice or 2D screens and the fact that one tried to bridge atoms and bits [19]. Often, graphic designers are “formgivers” of screen-based two-dimensional interface solutions. On the other hand, product and industrial designers also deal with the design of interfaces, but non-virtually connected ones: e.g. cups with a handle to indicate where to grab them.

Figure 1: Glass objects inspire novel forms of multimodal interaction through their form and materiality.

Nowadays, designers are faced with the demand of giving 3D objects a meaning and right to exist by connecting them to digital information and virtual space. As an apparent consequence, more and more displays are integrated in our environment. Flat displays fail to express values incorporated in the form and materiality of physical objects as they are often just cut in or added onto the object, rather than making use of the designed form and material properties. The use of tangible user interfaces addresses this problem, but often results in a detached remote control, rather then implementing the function or information in the surface and materiality of the object itself. Researchers build a representation of the digital mass as an object, but struggle to enrich the tangible interaction with authentic use of material.

In order to cope with these challenges, we have to take the material’s attributes and restrains into consideration [15]; we have to get in touch with the materiality of interaction and bits. In order to enhance the user experience, the design of seamless transitions will be crucial to reduce the gap between real and virtual [19]. In our process, we use materiality to add value to the tangible interaction. Therefore, we turned the usual process of developing the use case and then giving it a physical form, upside down.

Glass volumes are an example of cultural and structural rich objects. We implemented our approach in a three-month workshop setting incorporating industrial designers, HCI

TEI 2013, Feb 10-13, 2013, Barcelona, Spain.

students, engineers and traditional craftsmen, resulting in 5 interactive installations (see Figure 1). Blown glass objects carry different time-dimensions as the liquid hot material freezes a moment in time during its origination process when it cools down. On one side, the craftsman blowing the glass implements his knowledge, on the other side the material has its specific limitations e.g. if it gets too cold, the blowing process has to be stopped. Both result in an object with an individual form, which therefore has its own personality.

In our case study, we researched the characteristics of form and material in order to design the interaction personalized on each glass body. At the same time, we tried to breathe life into the objects by extracting their embedded interaction onto their non-flat surface. In doing so, we realized that not only the form, but also the material affords specific interaction. We aim to create interactions resulting from form and materiality as a basis for future TUIs. Our results can enrich and broaden the future development of tangible and organic interactions by enhancing their expressiveness with material authenticity.

RELATED WORK

According to Norman [13], an affordance is the design aspect of an object, which suggests how the object should be used. He later retracted this definition and called that visual clue of an object "perceived affordances" [12]. He adds that other aspects, like cultural constraints and conventions, may also influence our ability to interact with objects. This definition was translated to the interaction with digital data by Ishii in his first announcement of tangible bits in 1997 [8]. He states that there is a need for something to "bridge the gaps between both cyberspace and the physical environment, as well the as the foreground and background of human activities", and a lot of effort has been spent to explore this field of research.

Later, TUIs have been used a lot in combination with interactive surfaces to manipulate digital data like music [11] or graphics [3]. Underkoffler [17] presented Urp, where representations of architectural models were enhanced by projecting additional information on normal tables. These TUIs rely on an augmented environment. Other types of TUIs represent digital data themselves, and can for example contain display space to present them to the user [2]. Hemmert et al. [6] did not even display information visually, but translate possible output in tangible interaction.

Another trend is to enhance arbitrary objects with the ability to sense how the user interacts with them, e.g. how they are manipulated or grasped, and adjust interaction implicitly [20]. Depending not only on what we do and what we want to achieve, but also on what we see, shape and form influences how we interact with objects [16]. Flatters et al. could even show that the texture of objects has an effect on how we grasp them [4].

Over one decade after his first statement, Ishii still advocates the thesis that "TUI is one of the most promising paths to his (Mark Weiser's [18]) vision of invisible interfaces" [9]. Lately, TUIs have been evolved to be even more than representations of digital data. Due to technical improvements, they can now be organic, i.e. shape changing according to the current state of data [10]. Deformation can be output only, dependent on implicit or explicit input, but shape-changing input can also result in remote output [14]. Moreover, Rasmussen et al. [14] state in their overview the possible functional aims of shape change: communicate information, provide dynamic affordances, give haptic feedback, serve practical reasons or allow construction.

In summary, the form of TUIs is a valuable parameter to control interaction with objects. Now we want to start to inspire new forms of interaction by exploring the properties of glass regarding its form and material factors.

DESIGN SPACE

Looking at the expressivity of glass as a raw material, we found it to be rich, versatile and highly association-evoking [7], similar to an object's affordance according to Norman: It can be used for its visual, haptic, auditory, capacitive and conductive domain. Furthermore, glass can even transmit data when used as glass fiber. The various benefits of the material and its process of origin inspired us to examine its material specific process, form, structure and context, in order to approach new ways of material induced interactions.

Processing Analogies

The material affordances include the knowledge of glassblowers as well as the post processing treatment. While being processed from its pure fluid form to an object, the craftsmen influence the volume and surface of the glass object from inside with air and outside with tools and water. The applied knowledge, technique or information is stored in the result (see Figure 2). After the glass has cooled down, different textures can be achieved by finishing it with tools. Finally the use of glass in its cultural context leaves traces on the way a material is perceived and accepted.

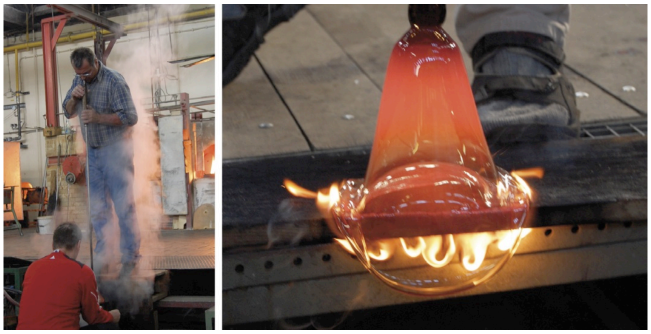

Figure 2: Hot glass gets shaped with tools.

Architectural Factors

Blown glass can have different shapes originated from molds or by blowing free forms. The architectural properties of blown glass objects are a specific result of the process: The surface builds the static structure, which means there is no addition of other materials needed to keep it in shape. Blown volumes imply lightweight thinking as their initial material is of the same physical mass as their final product, but encloses more space.

Most of all, glass is transparent. We can access internal information visually, or even look through the information contained. It can be tinted, colored and fade seamlessly from transparent to opaque, from bright to dark. The volume enclosed by glass is resonating sound and glass filters UV radiation, turning it into heat.

Surface Structures

As Bronstein et al. point out: "Analysis and understanding of shapes is one of the most fundamental tasks in our interaction with the surrounding world" [1]. How we perceive things according to their shape evokes associations that in turn induce different actions. The following list of properties is not exhaustive but gives an idea of what elements can be used to deign interactions.

Edges & Indentations: We can interact "along" those structures without losing track

Holes: Holes afford to grasp into.

Texture: Different areas can have different textures and can therefore be localized by sensing. Texture can target towards a direction.

Changes in structure: Larger structure can alternate with smaller structure. An abrupt change can alternate with continuous transitions.

By locating information on certain architectural points on the surface it gets less arbitrary.

Metaphors and Meaning

The rich characteristics of glass are not only built on material and form. Due to the fact that we know glass from different environments e.g. windows, bottles, sandglass, glasses etc., it is helpful to use existing cultural links in order to extract the range of possible interactions.

Metaphors for glass objects induce certain material specific properties. How we use glass can be inspiring and translated into culturally embedded interactions. In our everyday life we use glasses to fill them, mix, contain and store liquids. When looking at this process on a metaphorical level, we translated "liquids in glass" to "immaterial information in a given volume". This perspective allows us to interact with information in material specific ways. For example, one can pass information by pouring parts of information from one object to the other. Or delete it, which would relate to emptying a glass. Other possible interaction metaphors can display information e.g. damping on surface to write on it, or the change of value over time in a sandglass. When used as a mirror, glass adds a reflective layer to interaction.

WORKSHOP

Key component of the workshop was the combination of expertise. We merged together industrial design, educational craftsmanship and academic computer science for two main reasons: First, we intended to benefit from synergetic effects. The three parties complemented each other in their knowledge and work process. Second, we consider multidisciplinary collaboration as fundamental for interface design and HCI research. Knowledge from different fields helps to come up with new metaphors and work processes, which inspires the design and implementation process.

Participants

Three parties were involved in the process:

The raw glass objects were created by the BMW **design team** Munich. Working on volumes, geometry design and new materiality, it is also engaged in exploring the expressiveness of novel multimodal interactions with design objects.

Ten **master students** (4 female) from the media computer science department of the University of Munich[1] took part in the workshop. The students were selected based on their motivation and previous knowledge of interface design and hardware prototyping. A PhD student from the HCI group of the University of Munich organized and supervised the weekly meetings and provided technical support.

Technical input and support came from the ***Glasfachschule Zwiesel*** *(technical college for glass manufacturing)*[2], a traditional manufacturer for glass art, technical glass objects and optical instruments. Several visits to the *Glasfachschule* helped the students to familiarize with the material glass and the artistry of forming and reworking it. Furthermore, the craftsmen at the *Glasfachschule* adapted the glass objects according to the students' plans. The glass objects originally were created in a creative workshop at *Theresienthal Kristallglasmanufaktur* in Zwiesel, using the local expertise in glass blowing technics.

Process

The workshop was organized as a 4-hour weekly meeting in an on-campus lecture room. Later on, the students worked on their prototypes in the electronics-lab. Over the three months we covered three entwined phases: Input/ Related Work, Brainstorming/ Ideation and Prototyping/ Implementation. Several ideation and brainstorming

---

[1] http://www.medien.ifi.lmu.de/

[2] http://www.glasfachschule-zwiesel.com/

methods from interaction design and HCI research were used in the process. The course of action is described in the following.

In the first two meetings with the students, the designer and the organizer defined the topic and discussed the implications with the students. A number of non-interactive glass objects served as a basis for discussion. Graphical representations help to define the design space (see Figure 3).

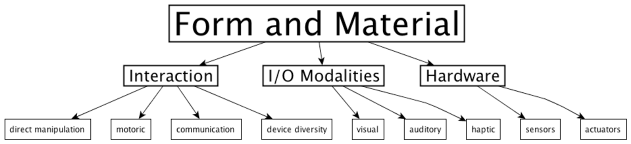

Figure 3: Defining the design space: Form and material of the objects determine interaction, input and output modalities and feasible technical solutions for interactivity.

In the next meeting, we had invited talks from both in-vehicle interface research and materiality design. Again, the goal was to deepen the understanding of the diversity of the field. Constant discussion in the group finally lead to the definition of five main topics of the intended interactive installations:

- Materiality: As stated before, the form and materiality of the objects provide a basis for the interaction.
- Communication: The objects could communicate with the visitor/user or with each other.
- Personalization: The objects could react to the user's characteristics and reflect own personality.
- Input: The objects could have a vast variety of input modalities, defined by form and materiality.
- Output: Accordingly, the objects could draw on their natural properties to emit information.

The results of several brainstormings on the five topics were sorted using a graphical idea cluster.

In the next meeting, the students chose two out of the several project ideas as a potential candidate for implementation. Their decision was based on the strength of the design metaphor, the technical feasibility and their motivation to work on the object. Based on their choices, the students divided into groups of two.

Thereafter, the students discussed their topics and decided for one. We used the 10 plus 10 exercise [5] to widen the design space and - in the long run - to further descend into the design funnel: First, the design challenge was stated. Then, at least 10 different design concepts that address the same challenge were generated. An in-group discussion helped to reduce the number of design concepts. The students chose the most promising of the resulting design concepts and produced 10 details or variations of this concept. Finally, the best idea(s) were presented and discussed in the group. In general, regular presentations in front of the group were given during the whole workshop. These presentations helped to rethink and sharpen the story and to work out a strong design metaphor. Subsequently, the students decided on a project and a corresponding glass object. Again, short presentations (i.e. 'elevator pitches') with 3-5 slides were given by each group.

After this brainstorming / ideation phase, we visited the *Glasfachschule Zwiesel* several times. The students had the chance to learn about the history of glass manufacturing, to discuss the numerous ways of producing and reworking glass objects and to try these methods by themselves (see Figure 4).

Figure 4: Left: Learning methods to manufacture glass (glassblowing). Center: Discussion in the group. Right: Taking part in the process (glass polishing).

The students learned about concepts and methods such as differing glass materialities which support or inhibit polishing or cutting the material. During the subsequent prototyping phase, this knowledge helped the students to design the input and output modalities of their objects and take the underlying materiality into account. For example, due to structural stress, most glass objects can't be cut into thinner or lighter parts of their structure, because they would crack or split completely. This knowledge was incorporated into the prototyping process. In a second visit to the *Glasfachschule*, the students presented their ideas and the selected glass objects to the craftsmen. Both parties discussed the technical feasibility of modifying the glass objects according to their plans (see Figure 5).

The selected glass objects stayed at *Zwiesel* for several weeks and were modified according to the plans. Meanwhile, the students continued to work on the implementation of their prototypes. Additionally, the weekly meetings were used to prepare the final presentations. The intended two minute pitches contained the underlying metaphor, the process of the interaction and technical principles.

Figure 5: Left: The second meeting at the *Glasfachschule* was used to discuss the feasibility of the intended modifications of the glass objects to the craftsmen. Center: Changes such as grindings or holes were planned and registered (right).

After 3 weeks, the finished glass objects returned to the lab. Now, the electronics were implemented into the objects (see Figure 6). The resulting interactive installations are described in detail in the next chapter.

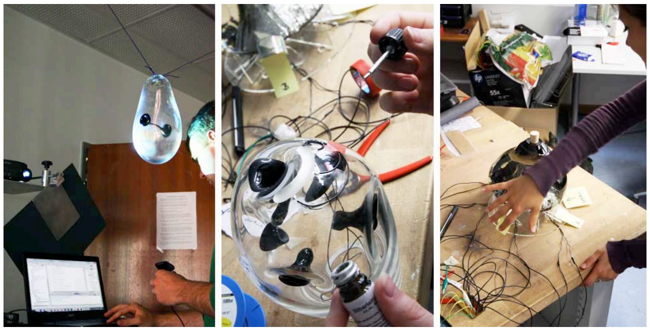

Figure 6: Implementing electronics. Left: Adjusting the image that is projected on the glass. Center: Applying conductive ink on the glass surface. Right: Setting up the *Kinect* for tracking.

PROTOTYPES

During the workshop we created five interactive prototypes, focusing on their individual material induced interaction. The given glass objects cannot deal with all variations of the design spaces, but try to get into detail for certain aspects of the material.

1. AUDIOSPHEAR - feeling music

Inspired by the sound qualities of glass harps, AUDIOSPHEAR is reaching out to make use of the volume enclosed by the blown glass object (see figure 7). By connecting the glass to a smartphone via Bluetooth, the user can control the content by interacting with the surface and shape of the glass object speaker. Linear functions like skipping through the track list are directly implied on the surface by angled engravings on the glass. Haptic feedback is provided through the texture of the material. The hole on top of the object, resulting from the blowing process, is used to control the volume of the speaker. Circular touch input in both directions regulates the acoustic output. By closing the hole with the whole hand, the speaker is put in mute. To visualize the audio signals the glass body is floating in water, which is reacting on individual tones, relating to the distance between glass and the container - its context.

Figure 7: Left: Prototype 1 AUDIOSPHEAR glass body raw. Center: Glassharpe using volume to create sound. Right: Final object in use.

2. 3D BLACKBOX - visualizing time

The shape of a sandglass is a well-known metaphor for time and its constant flow. In order to get this shape, two single bubbles were blown into each other. During this fusion it is essential to melt them at the right moment and state of aggregation, as well as to stop the blowing at the right time. It takes a lot of process-related information to blow the shape. This context is used and adapted to the interaction with the object (see figure 8). By touching it at its significant waist - the crucial point of the object - one can control the action inside the top bubble: Little colored spherules contained in two bottles start to roll through the body and eventually fall into the lower part. There they are creating a layered picture visualizing the actions in the past. This colored code, similar to layers of soil and stones, provide chronological feedback to the user helping him to reflect his personal actions and experiences like a diary.

Figure 8: Left: Prototype 2 3D BLACK BOX glass body. Center: Concept of glass related interaction: sandglass. Right: Interaction on glass.

3. TIME FREEZE - capturing moments

The material itself dominantly determines the moment the glass object is finished: Once it is cooled down its basic form cannot be altered anymore. We experienced this moment as a captured moment in time displayed in the object like a message sent from the past (see figure 9). This effect was an inspiration for the interaction on the glass surface. By plugging the finger into the two significant holes the user is taking a picture and displays it on the sandblasted glass surface. Optical effects of the material blur the picture, blending the rear projected photo with the shape of the object. The person now seems to be inside the glass - an individual relation between the user and the 3D-object is created. Furthermore the user can tint the object in a color of choice by filtering the main color in the picture taken. In order to reset the object, the information is "poured" out like a glass.

Figure 9: Left: Prototype 3 TIME FREEZE glass body. Center: Metaphor for glassrelated interaction: message in a bottle. Right: Final prototype with taken picture.

4. LIQUID NUMBERS - visualization beyond numerical values

When speaking of glass, transparency is the most common used quality. The fact that you can look right through an object reveals all of its content and helps to understand the context surrounding it. Value in its raw state is often displayed in numbers, which not always offers the needed information at first sight, e.g. temperature shown in degrees. The installation LIQUID NUMBERS reaches out to make use of the transparency, using the enclosed volume as a container for a mix of water and a liquid metal (see figure 10). The magnetic attributes of the fluid are used to display numerical values by rising and falling as well as moving around in the 3D space. Just like the rise and fall of the tide is giving information about time and the constellation of the moon, the 3D visualization of values can provide information beyond the numerical content at a glance. It displays the value in relation to its context. Free-hand gestures are used to control the values in the prototype. The choice of input is particularly lending itself towards the interaction as it makes use of the 3D space around the object.

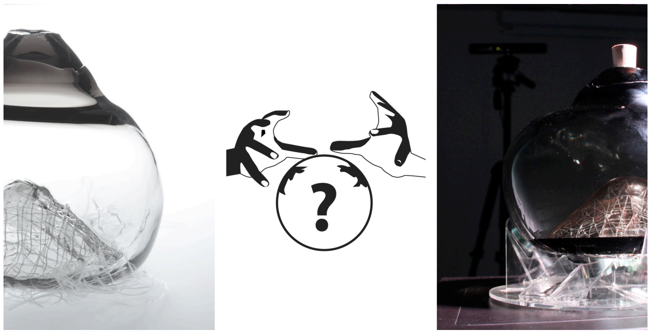

Figure 10: Left: Prototype 4 LIQUID NUMBERS glass body. Center: Glass related context: reading the future in a crystal ball. Right: Information visualized with metal fluid

5. NEBULA ORB - aggregation displays information

The glass object is significant for the different aggregation and temperature states the material has to go through in its production process. Colored glass spots where pot on the surface and then pushed inside in order to explore the volume visually (see figure 11). Those haptic spots are used as points of interest in the interaction. Depending on the combination of fingers touching the dents different aspects of the function can be controlled. The choice of function here is a climate control unit. To display the airflow the body is filled with circulating steam lightened up in color to show the temperature. The airflow can be controlled by the distance between the hand over the object. Other functions relating to a dent each represent temperature and climate zones - they can be modified with multi-touch gestures.

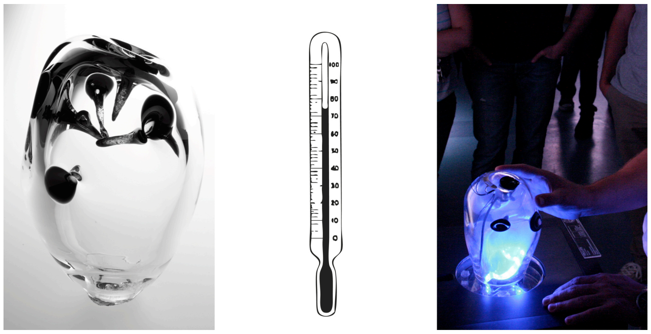

Figure 11: Left: Prototype 5 NEBULA ORB glass body. Middle: Thermometer: visualization with different aggregation states.. Right: Interaction on final glass object.

CLASSIFICATION OF RESULTING INTERACTIONS

Analyzing process and prototypes, we now present how the single aspects of the objects and their means of interaction correspond to each other (see Figure 12).

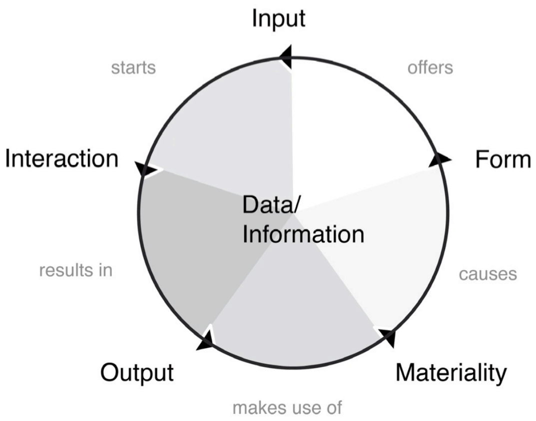

Figure 12: Material induced interaction: the material implies a specific function, input and output.

The material and how it has been processed cause the form and appearance of each object. Cultural constraints and conventions, as well as former experiences with form and material then imply specific interaction and possibly even relate to a concrete function. Therefore, the objects encourage communication with them. We used this syntax to connect and affect to a counterpart in the “sea of bits”. Virtual world in this context is not only digital data, but also immaterial values like worth, time and token gestures. The manifestation of the interaction finally takes into account the object’s form and material to make the resulting output accessible to the user.

Exploration of design space

Throughout the installations, we tried to explore the design space of glass-specific interaction. In the following, we present an overview over characteristic design aspects in respect to the categories we introduced before.

Processing Specific Interaction

Prototype 5 picks up the ***process of change*** between liquid and cooled down state. It uses the artifacts, the holes in the surface as a connection to the inside, and cites the fluid state of glass by bringing in a new, cloudy material – steam. Capturing a moment in time via a photo in prototype 3 refers to the ***moment of cooling down*** while processing. Finally, the ***airflow*** used as feedback modality in prototype 5 goes back to the initial work step during the creation of the glass body. Where the craftsmen blew to create, it blows to represent its current, virtual state.

Architectural Specific Interaction

In prototype 1, the glass body is used to resonate music. Its ***volume*** inside supports the sound by giving it space and by motivating the ***surface*** which takes the sound waves and reproduces the sound in its own style.

Surface Specific Interaction

Installations used **texture** to identify different areas. Prototypes 3 and 5 used specific areas for activation of functions. ***Directional texture*** in prototypes 1 and 5 was found to be useful to control continuous values like track order and temperature. ***Transparency*** was used in prototypes 2, 4 and 5, where adjustments of the virtual world were presented visually inside the objects with spherules, ferrofluids, and steam. ***Holes*** afforded to grasp into, and to easily locate a function. They were used in prototypes 3 to trigger and 5 to choose a certain functionality. More general, ***openings*** were used to control the transition from inside to outside; in prototype 1 to mute music when the opening is covered, in prototype 3 to allow users to pour content out of the object via the top opening. Interaction along ***indentations*** was used in prototypes 1 and 2 to control volume and amount (of spherules), respectively, giving the user guidance and orientation to not leave the interaction space. The structure is useful to not lose track, and to be taken as an orientation.

Material Specific Interaction

Prototype 1 picks up the metaphor of ***closing*** the object’s opening with the hand, so that nothing can get out and no music is played. Prototype 2 refers to the process of ***pouring*** out of a glass body to empty. The mechanism of pouring is used to delete a former taken picture. The picture of using glass as a body to ***store*** liquid material inside is reflected in prototype 4, where ferrofluid, an untouchable material, is filled in and now accessible.

DISCUSSION

Glass has a lot to offer when used for prototyping. Its material qualities in surfacing and the fact that it is transparent, encourages interaction naturally. Its richness of metaphors offers several possibilities of facing interaction design within a historical and cultural context.

Challenges of Glass

Working with glass was a new experience for most of the workshop’s participants. Therefore, examining the material was required as a first step to understand how the material can be used. Some ideas of realizing interactivity proved to not be realizable and thus had to be rejected, like cutting certain parts of the glass bodies. It also happened that a glass body broke. It was possible to reproduce it almost identically, however, the rework caused a delay not comparable to exchanging a broken cable.

Challenges of the workshop

The specific properties and especially the sensitivity of glass demand the consultation of craftsmen, which promotes collaboration outside the usual research environment. The multidisciplinary team of academics, design professionals and craftsmanship also requires a higher level of communication due to different backgrounds. Different ideas of an ideal design of both craftsmen and designers provoked discussions unusual for all parties. It was crucial to fix a time frame and spend face time regularly. Researching outside the box helped us to have a better understanding for each other, but also quickened creativity beyond the known context.

FUTURE WORK

Future implementations of this type of workshop should comprise other rich materials such as wood, plastic or metal. This would help to further substantiate the comprehensive consistency of form and texture for interactions. Our explorational approach allows for the translation and implementation of the resulting interactions into a context of choice. In the next step, we will implement selected interactions in the contexts of automotive and tangible user interfaces.

CONCLUSION

In summary, we learned that we can empower the materiality to inspire more meaningful and richer interactions by looking beyond use-case-scenario-based designs. With more material induced interaction, we can generate more elaborate guidelines and revise how functionality is represented by different materials. We encourage designers and researchers in the field of tangible and embedded interaction to make use of the power of materiality, for inspiration, but also to create future interactions.

ACKNOWLEDGMENTS

We thank Hans Wudy and Gunther Fruth (Glasfachschule Zwiesel), Max Hannes (Theresienthal AG), Thierry Boissel (Akademie der bildenden Künste München), Martina Starke and Oliver Heilmer (BMW AG) and from the University of Munich LMU: Frederik Brudy, Marion Koelle, Verena Lerch, Denys Matthies, Simon Mang, Sven Osterwald, Felix Praschak, Hanna Schneider, Jeannette Schwarz, Fabius Steinberger, Prof. Andreas Butz.

REFERENCES

1. Bronstein, A. M., Bronstein, M. M., and Kimmel, R. *Numerical Geometry of Non-Rigid Shapes*. Springer Science + Business Media, New York, NY, USA, 2008.
2. Butz, A., Groß, M. and Krüger, A. Tuister: A Tangible UI for Hierarchical Structures. In *Proc. of IUI*, ACM (2004), 223-225.
3. Fitzmaurice, G. W., Ishii, H., and Buxton, W. Bricks: laying the foundations for graspable user interfaces. In *Proc. of CHI*, ACM (1995), 442-449.
4. Flatters I. J., Otten, L., Witvliet, A., Henson, B., Holt, R. J., Culmer, P., Bingham, G. P., Wilkie, R. M., Mon-Williams, M. Predicting the effect of surface texture on the qualitative form of prehension. *PloS one 7*, 3 (2012), e32770.
5. Greenberg, S., Carpendale, S., Marquardt, N. and Buxton, B. (2012), *Sketching User Experiences - The Workbook.* Academic Press.
6. Hemmert, F., Hamann, S., Löwe, M., Wohlauf, A., and Gesche, J. Shape-changing mobiles: tapering in one-dimensional deformational displays in mobile phones. In *Proc. of TEI*, ACM (2010), 249-252.
7. Holman, D. Glassblowing: forming a computational glass material, In *Proc. of TEI*, ACM (2012), 379-380.
8. Ishii, H. and Ullmer, B. Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms, In *Proc. of CHI,* ACM (1997), 234-241.
9. Ishii, H. Tangible bits: beyond pixels. In *Proc. of TEI*, ACM (2008), xv-xxv.
10. Ishii, H. The tangible user interface and its evolution. *Communications of the ACM 51*, 2 (2008), 32-36.
11. Jordà, S., Geiger, G., Alonso, M. and Kaltenbrunner M. The reacTable: exploring the synergy between live music performance and tabletop tangible interfaces. In *Proc. of TEI*, ACM (2007), 139-146.
12. Norman, D. Affordances and Design. 2004. http://www.jnd.org/dn.mss/affordances_and.html
13. Norman, D. Affordances, Conventions, and Design. *Interactions* 6, 3 (1999), 38-41.
14. Rasmussen, M. K., Pedersen, E. W., Petersen, M. G., and Hornbæk, K. Shape-changing interfaces: a review of the design space and open research questions. In *Proc. of CHI*, ACM (2012), 735-744.
15. Rosner, D. The material practices of collaboration. In *Proc. of CSCW*, ACM (2012), 1155-1164.
16. Sartori, L., Straulino, E., and Castiello, U. How objects are grasped: the interplay between affordances and end-goals. *PloS one*. 6, 9 (2011), e25203.
17. Underkoffler, J. and Ishii, H. Urp: a luminous-tangible workbench for urban planning and design. In *Proc. of CHI*, ACM (1999), 386-393.
18. Weiser, M. The computer for the 21st century. *Scientific American* 265, 3, (1991), 94-104.
19. Wiberg, M. and Robles, E. Computational Compositions: Aesthetics, Materials, and interaction design*. International Journal of Design* 4, 2 (2010), 65-76.
20. Wimmer, R., Baudisch P. Modular and deformable touch-sensitive surfaces based on time domain reflectometry. In *Proc. of UIST, ACM (*2011), 517-526.