Vertibles: Using Vacuum Self-Adhesion to Create a Tangible User Interface for Arbitrary Interactive Surfaces

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ABSTRACT
We present Vertibles, a set of Tangible User Interface (TUI) objects employing a vacuum-based adhesion effect. This effect allows attaching them to arbitrarily inclined surfaces, bringing the benefit of TUIs to vertical interactive surfaces. In contrast to other vertically attachable TUIs, Vertibles stick to a wide range of surface materials and work with optical as well as electric object tracking techniques for interactive surfaces. We present an overview of approaches for sticking objects onto vertical surfaces, describe the technical principle and properties of our solution, and document implementation details of a number of Vertibles prototypes.

Author Keywords
Tangible user interface, non-horizontal surfaces, self-adhesion, vacuum.

ACM Classification Keywords
H5.2 [Information interfaces and presentation]: User Interfaces: Input Devices and Strategies.

General Terms
Design.

INTRODUCTION
Within the last decade, Tangible User Interfaces (TUIs) [3] have gained interest within the research community. They can offer advantages over traditional GUIs [2]. TUIs are especially suited for complementing interactive surfaces, supporting rapid and blind interaction with visualizations and enhancing the user experience (e.g. [5]) due to their intrinsic kinesthetic feedback.

So far, TUIs have been employed mostly on horizontal interactive surfaces. However, differently inclined surfaces are adequate for different tasks like reading on vertical and touch-interaction on horizontal surfaces [13]. While GUIs can easily be adjusted to different display orientations, gravity mostly forbids the use of traditional TUIs on non-horizontal displays. We have developed a TUI widget set called *Vertibles* (for *vertical tangibles*) that sticks to vertical surfaces. These employ vacuum-based adhesion, which allows attaching them to almost any surface material. As no additional holding mechanisms or consumable materials are needed, Vertibles can be used with a wide range of tracking and output technologies. Some of the Vertibles also have movable parts, such as sliders and knobs, which are not affected by the adhesion effect. The transparent acrylic body allows visual feedback and interface elements to be seen through the TUI.

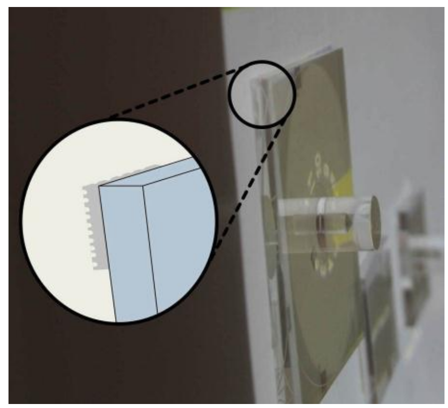

Figure 1: Working principle of Vertibles: An adhesive film underneath the Vertible utilizes microscopic suction cups to stick on an arbitrary surface.

In the following, we first describe and compare techniques for sticking TUIs to non-horizontal surfaces. We describe their respective working principles and limitations. From this comparison we derive why we chose our approach and how Vertibles and especially their adhesion layer are designed (see Figure 1). On this basis we discuss the potential of vacuum adhesion for the construction of other TUI components and possible limitations of our approach.

EXISTING APPROACHES
A number of TUI-related research projects have built tangible objects for non-horizontal surfaces. These can be grouped by the employed adhesion technology. A common approach for attaching objects to non-horizontal surfaces is using magnets. One of the first TUIs based on this technique were Tangible Bits by Ishii et al. [3]. Their transBOARD system employs magnet-backed cards on a vertical surface in combination with an embedded optical barcode scanner. Later Jacob et al. presented the Senseboard [4], which also used magnets for adhesion and

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RFID tags for position tracking. Recently, several projects presented tangible objects with embedded magnets like Madgets [12], Mechanix [9] or Geckos [8].

Van Laerhoven et al. [7] demonstrated a vertical notice board using a double-layer conductive surface. Objects can be attached to the surface with a special conductive pin. The system detects and identifies these pins but does not track their position. Similar to this Villar et al. presented VoodooIO, a system utilizing pins and conductive layers to create a malleable user interface [10].

Designer's Outpost by Klemmer et al. [6] is an approach that is technically very similar to Vertibles. It uses self-adhesive Post-It Notes, which are virtually augmented by a front-projection setup. Thus, they offer tangible interaction with their digital content. The Post-It notes stick to a wide range of surfaces but lose adhesion strength over time.

DESIGNING SELF-ADHESIVE TANGIBLE USER INTERFACES

In the following we will compare approaches for adhesive TUIs and discuss some of the design challenges involved. We propose self-adhesion based on vacuum-creating surface structures (e.g. microscopic suction cups) as a passive technique allowing TUIs to adhere on arbitrary surfaces. In this section we compare the suitability of different adhesion techniques concerning different input and output technologies used in today's interactive surfaces. We also look at some requirements caused by the underlying adhesion technique (see Table 1).

	Vacuum	Magnets	Glue	Electro-Adhesion
Optical Sensing	✓	✓	✓	✓
Resistive Sensing	✓	✓	✓	✓
Capacitive Sensing	✓	-	✓	-
Inductive Sensing	✓	-	✓	-
Front-Projection	✓	✓	✓	✓
Rear-Projection	✓	-	✓	✓
LCD	✓	✓	✓	*
Transparent	✓	-	✓	-
Passive	✓	✓	✓	-
Movable	-	✓	-	✓
Re-usable	✓	✓	-	✓

Table 1: Suitability of various techniques for vertical tangibles with regard to input and output technologies of interactive surfaces. (*A first test did not show interference between electro-adhesive pad and LCD. However, the pads did not stick either.)

Sensing

We considered different sensing technologies - optical sensing as well as several electric sensing approaches – in our comparison of adhesion techniques. While optical and resistive sensing both work well with all tested adhesion techniques, capacitive and inductive sensing were influenced by magnets and electro adhesion. These techniques did not allow for sensing position of an object with these adhesion techniques or even prevent tracking at all. Therefore magnets and electro adhesion are not applicable for displays like Apple's iPad or large multi-touch overlays and foils utilizing capacitive sensing.

Output

We compared three prevailing output technologies concerning their compatibility with adhesive TUIs. In contrast to sensing the output of an interactive surface is much less affected by adhesive objects. Front-projection works for all discussed adhesion techniques while rear-projection only can't be used with a magnetic surface as it is not transparent. The third output technology we looked at was LCD. It uses an electric field to align small crystals within the display in combination with a backlight. LCD worked well with all tested adhesion techniques, only our electro-adhesion test failed on LCD as we didn't notice any adhesion nor did it influence the output. Therefore we can only conclude that electro-adhesion does not work on an LCD with rather low voltages.

TUI Characteristics

Beside limitations concerning the underlying sensing and display technology there are also implications on the design of an adhesive TUI. The most obvious implication is on visual feedback within the tangible object. As magnets or electronic components of electro-adhesive objects are not transparent they cause visual limitations. Therefore they rely on front-projection for visual feedback on the object or visual feedback next to it. Electro-adhesion also comes along with another drawback: as it is an active technique based on continuous power consumption it needs an internal battery or an external power supply. The electronic circuits also make these TUIs heavier and error-prone. Technically, electro-adhesion can also be integrated into the interactive surface instead of the object. Though this reduces the object's complexity, it also makes everything else stick to the surface and interferes, for example, with capacitive sensing (see Table 1).

Although passive adhesion based on vacuum or glue doesn't suffer from these limitations it is constrained in terms of movability and re-usability. Whether vacuum-based adhesion nor glue allow moving an object across the surface without detaching it while magnets or electro-adhesion allow moving an object attached to a surface easily. Glue-based adhesion also doesn't allow many re-attachments of the object as the adhesive strength fade over time due to pollution of the glue. Vacuum-based adhesion doesn't suffer from this as the adhesive film can be cleaned with pure water restoring the original adhesion strength.

Vacuum-creating surface structures

Based on these facts we decided to use *vacuum-creating surface structures* for the creation of adhesive tangible objects. Prior to the object construction we tested different materials utilizing vacuum-based adhesion differing in terms of transparency, adhesion strength and cleaning effort. All use special structures to create a vacuum between the adhesive material and the surface, increasing friction. The adhesion strength varies according to the surface structure. We evaluated an adhesive film with artificially created microscopic suction cups. These cups work like small plungers, which create a vacuum between the material and the underlying surface (see Figure 2).

Although each small vacuum on its own only offers a very small adhesion force, the sum of all suction cups creates a strong adhesion effect over the entire contact area. In our first tests, 1 cm^2 of transparent adhesive film (display foil for iPad2 from mumbi[1]) held a weight of about 20g on a Rosco projection screen at an angle of 75° for more than four days. Other adhesive materials like 'Nano-Pads'[2] offer a much stronger adhesion and lower cleaning-effort at the cost of transparency and thickness. No matter which material is used this type of adhesion works especially well with interactive surfaces, as they already need to be reasonably smooth in order to ease dragging. In contrast to glue, however, all of these materials can simply be cleaned with water to restore their full strength. We finally decided to use the display foil mentioned above as it offers the best tradeoff between adhesion strength, easy re-positioning, transparency and a high re-usability.

CONSTRUCTION OF VERTIBLES

Vertibles consist of two layers: an *object* layer and an *adhesive* layer. The *object layer* is the object's acrylic body, which can incorporate moving parts. Similar to SLAP widgets [11] or the reacTable TUIs [5], Vertibles are both translucent due to the use of the transparent adhesion technique and light. The object layer can provide special interaction affordances through its shape or moving parts (see Figure 3). Since the moving parts must move freely, they may not be covered with adhesive film. Therefore, adhesive pads may only be attached to static parts of a *Vertible*.

The *adhesive layer* contains the (optical) marker pattern used for object tracking as well as the self-adhesive pads. To permanently attach these pads we used superglue to affix them to the bottom side of the *Vertibles*. This construction allows attaching and removing *Vertibles* easily without damaging or losing one of the self-adhesive pads.

[1] http://www.mumbi.de/

[2] http://www.nano-pad.com/en/index.html

The adhesive layer also includes multiple white pads. These pads create a static marker pattern for each Vertible, which is recognized and tracked by our tracking software. Marker pads attached to the dynamic parts of a *Vertible* also allow to track the position of the respective part without any further sensing effort. In Figure 3, such marker pads can be seen under turning and sliding knobs.

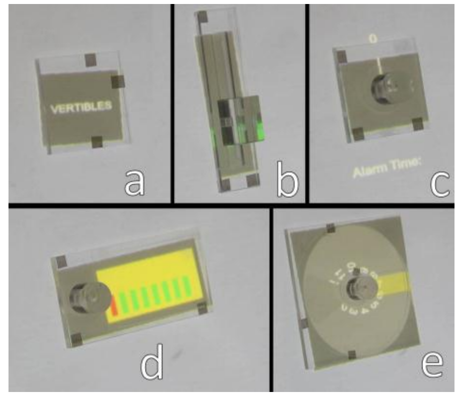

Figure 2: Our set of Vertibles: (a) plate, (b) slider, (c) turning knob, (d) scroll box, (e) selection box. Each is augmented with an interaction menu projected through the acrylic object.

Based on this basic construction principle, we created a set of acrylic interface widgets, each featuring an adhesive layer. While their intended functionalities were inspired by GUI widget sets, their shapes were designed carefully for the intended use on interactive display surfaces. The smallest and simplest *Vertible* is a *plate*, which can be placed on the surface. Its adhesion layer just contains a marker pattern. Next, we designed a *turning knob* as a dynamic part of several objects, for example in the center of a plate (see Figure 3(c)) for simple scrolling or zooming tasks. Combining such a turning knob with an additional viewing area let the user scroll text or use an equalizer (see Figure 3(d) or offers a large preview area in a list selection task (see Figure 3(e)). Another object borrows from the common *slider* widget (see Figure 3(b)). The sliding trench provides enough friction for the slider to keep its position even when mounted vertically.

These objects work on vertical as well as horizontal surfaces. Neither the turning knobs nor the sliders are influenced by gravity. The constructions described above bring tangible interaction to practically all non-horizontal touch-sensitive surfaces. Our marker design works with optical tracking (diffuse illumination) and a blob tracking approach, but other tracking targets, such as visual markers for camera tracking from above, metal foil for capacitive tracking, or even RFID tags can easily be substituted.

Preliminary Observations

We gathered first insights on the use of Vertibles in a preliminary user study with four participants. They were asked to control a small music player application with Vertibles on an inclined screen (e.g. to select a song). No participant had problems placing the Vertibles on the screen to control the application. At no time there was fear that a Vertible might fall down or could not be removed. None of users complained about fatigue after the study, which took about 20 minutes. Therefore we assume that the vacuum-based adhesive film we used is a promising approach for sticking tangible objects to arbitrary surfaces in terms of usability, re-attachment and fatigue.

CURRENT LIMITATIONS OF VERTIBLES

Due to the inherent properties of vacuum-based adhesion, *Vertibles* suffer from some limitations. One is the immobility of the object once attached to a surface (see Table 1). In order to move the object, the user needs to detach and replace it instead of simply dragging it to another location. While testing different vacuum-based self-adhesive materials we found out that thin adhesive films work less well on rougher surfaces. Thicker adhesive films mitigate this problem, but are less translucent, thereby impairing the quality of the visual feedback. This trade-off has to be considered for the construction of a self-adhesive TUI and the underlying surface and calls for different types of visual feedback. Another drawback is the problem of dirty surfaces as it lowers the adhesion effect over time. Though this only happens after multiple attachments and can be solved by simply wiping the objects pads, the surface should be as clean as possible to start with, to avoid a continuous need for pad cleaning.

FUTURE WORK AND POSSIBLE EXTENSIONS

One of the obvious next steps is an evaluation of TUI usage on non-horizontal surfaces. We will conduct a study to investigate how it differs from the well-known usage on horizontal surfaces. Possible differing factors could be the precision in terms of exact placement and the fatigue occurring after some time. Another (positively) influencing factor could be the absence of the orientation problem known from shared tabletops.

A possible hardware extension is to make Vertibles movable in at least one dimension. This could possibly be achieved by adding a self-adhesive cylinder, which has a surface with microscopic suction cups. Though a first test was promising, this construction will require a complete re-design of Vertibles as the adhesive layer will then also include dynamic parts. Another hardware improvement could lead to stacks of multiple objects on arbitrary surfaces similar to Lumino [1]. Though this would allow to combine different Vertibles it also requires an increased adhesion force for each object. Therefore it will be necessary to balance the possible levels of stacks and the required adhesion force to keep the interaction with Vertibles easy and avoid fatigue.

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