# TableHop: An Actuated Fabric Display Using Transparent Electrodes

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## ABSTRACT

We present TableHop, a tabletop display that provides controlled self-actuated deformation and vibro-tactile feedback to an elastic fabric surface while retaining the ability for high-resolution visual projection. The surface is made of a highly stretchable pure spandex fabric that is electrostatically actuated using electrodes mounted on its top or underside. It uses transparent indium tin oxide electrodes and high-voltage modulation to create controlled surface deformations. Our setup actuates pixels and creates deformations in the fabric up to ±5 mm. Since the electrodes are transparent, the fabric surface functions as a diffuser for rear-projected visual images, and avoid occlusion by users or actuators. Users can touch and interact with the fabric to experience expressive interactions as with any fabric based shape-changing interface. By using frequency modulation in the high-voltage circuit, it can also create localized tactile sensations on the user's fingertip when touching the surface. We provide simulation and experimental results for the shape of the deformation and frequency of the vibration of the surface. These results can be used to build prototypes of different sizes and form-factors. We present a working prototype of TableHop that has 30×40 cm$^2$ surface area and uses a grid of 3×3 transparent electrodes. It uses a maximum of 9.46 mW and can create tactile vibrations of up to 20 Hz. TableHop can be scaled to make large interactive surfaces and integrated with other objects and devices. TableHop will improve user interaction experience on 2.5D deformable displays.

## Author Keywords

Human-computer Interaction; Shape-changing Displays; Deformable Displays; Actuated Surfaces; Actuated Tangible Interfaces; Haptic Feedback, Electrostatic Actuation

## ACM Classification Keywords

H.5.2 User Interfaces: Graphical User Interfaces, Haptic I/O, Interaction Styles, Prototyping, Screen Design, User-centered Design


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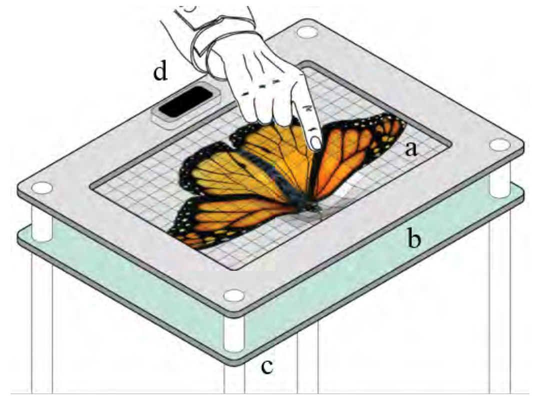


**Figure 1. TableHop consists of (a) a top layer of fabric glued to an ITO array, (b) an ITO and glass bottom layer, (c) a projector for back-projected contents (not shown), and (d) gesture sensor for interaction.**

## INTRODUCTION

Elastic deformable devices are increasingly used as physical user interfaces for both information input and output. A driving vision behind shape-changing interfaces is creation of a display surface that can both actuate itself and at the same time allow users to touch and manipulate it. These displays transform our interactions by exploiting inherent physical affordances. Instances of this vision include information displays [52] where maps or landscapes can be molded by the user's hands, physical visualizations of time-series data [41], and drawing applications that use physical extrusions to show texture.

Current approaches to create table-sized shape-changing surfaces use pin-actuators [14, 19]. inForm [14] uses 900 pins to create an actuated surface. Transform [23], an architecture similar to inForm, uses two sets of 400 pins to create a telepresence system. Pin-actuated devices suffer from large power consumption and limited scalability. For example, inForm can use 700 W during operation [14], and this power consumption will go up with scaling. Furthermore, pin-actuated surfaces do not afford touch-based user input - users cannot move their fingers freely on the surface of these devices as one may with any touch tablet.

A key aspect of shape-changing devices is the expressivity of the interaction that they allow through surface deformation. For example, users can stretch, twist or fold surfaces to manipulate 3D models [60]. This partly explains the popularity of using elastic fabric for user-input [60, 64]. Pin-actuated surfaces offer rigid deformations but have limited elasticity, whereas fabric based surfaces offer rich elasticity but lack the ability to keep deformations rigid.

In this paper, we present TableHop, which offers an elastic surface with the advantage of providing semi-rigid deformations using electrostatic actuation that are held in place as long as it is connected to a power source. It also combines independent tactile feedback using the same actuation mechanism. The tabletop surface, shown in Figure 1, is made of a highly stretchable fabric. Two indium tin oxide layers serve as electrodes that can pull and deform the surface (see Figure 1). We created a prototype to demonstrate the concept and explain how the system can be manufactured and scaled. The power consumption of our prototype with 3×3 array of electrodes is 9.46 mW, and a 30×30 array of electrodes would theoretically consume 946 mW.

The key contributions in developing TableHop are:

- using transparent thin-film indium tin oxide layers to create an elastic display that can actuate ±5 mm and is scalable to an order of 10 actuation points per $cm^2$,
- showing applications using static/dynamic deformations,
- supporting sensing of touch and user-driven deformations through depth-sensing and capacitive sensing, and
- supporting automated calibration procedure and algorithm for showing shapes.

## RELATED WORK

Many types of interactive displays that can deform and change their shape have been proposed in the HCI literature. Broadly, these devices can be thought of as *user-deformed* or *self-actuated* devices, and are mainly used as *input* or *output* device, respectively. Most of the deformable devices can also provide haptic feedback. Poupyrev et al. [49] provide an overview of use of actuation for shape-change in user interfaces. Coelho et al. [8] provide a survey of smart-materials used for shape-change. However they do not include the actuation mechanism of TableHop. Here, we review the literature on user-deformable and self-actuated surfaces that are related to TableHop, which is a new technology for creating an actuated fabric display that combines the advantages of user-deformable and self-actuated fabric displays.

*Elastic* user deformable surfaces without actuation have been explored for simultaneous visual and haptic feedback using transparent flexible sheet in front of a LCD [22] or with rear-projection [64]. The interaction scenarios and gestures for such systems have been extensively explored [60]. Examples of user deformable devices used as input devices with force feedback are deForm [12], Trampoline [18, 17], SinkPad [33] and GelForce [62]. A list of such displays is provided in [60], along with materials and gestures used for applications such as multi-layered data visualisation [41], 3D modeling, entertainment, gaming and rehabilitation.

### Deformable Handhelds and Tables

Many deformable handheld devices have been developed to provide novel functionality, interaction and experience. Inflatable Mouse [31] works like a regular mouse, but additionally provides haptic feedback and can be deflated and stored in the PC card slot. SinkPad [33] also provides haptic feedback using an elastic material in addition to regular mouse functionality. Trampoline [17] is a handheld input device that provides haptic feedback using an elastic touch surface. MorePhone [15] provided physical notification by bending the edges of an elastic thin-film e-paper display on a handheld device. However, improving user experience requires more functionality [47].

Relief [37] is an actuated tabletop display that is able to render and animate three dimensional surfaces. FEELEX [25] combined haptic sensation with computer graphics on a tabletop. Harrison et al. created dynamic changeable physical buttons on a visual display for tactile feedback [20]. inForm [14] provides dynamic physical affordance by deformation of the Tabletop. Troiano et al. presented user-defined gestures for interaction with large elastic deformable displays [60]. Emerge [57] provides physically dynamic bar charts and new interactions for exploring and working with datasets rendered in dynamic physical form on a Tabletop. ShapeClip [19] allows users to transform a LCD screen into a three dimensional surface display, and produce dynamic physical forms.

Many unique abilities and applications of these deformable devices such as haptic feedback, physical affordance, small form-factor and three dimensional interaction can be realized using TableHop.

### Elastic and Fabric based Surfaces

Interaction and gesture studies on elastic deformable surfaces have been widely carried out using fabric-based surfaces [60]. eTable [32] is such an elastic tabletop display for three dimensional interaction with haptic feedback. User can explore multi-dimensional data using ElaScreen [67].

Many types of actuation mechanisms have been used to make self-actuated deformable devices such as pneumatic actuation [20, 31, 56, 13, 66, 44], magnetic actuation (ForceForm [61], MudPad [26], BubbleWrap [3]) and mechanical pin-actuation (Releif [37], Sublimate [36], inForm [14], Transform [23], ShapeClip [19], Emerge [57], KineReels [58] and Shade Pixel [30]). Smart-materials, such as shape memory alloy (SMA) have been used to make deformable surfaces [8, 42, 53]. For example, SMA was attached to different flexible surfaces such as thin E-ink display [15] and paper/origami [50] to make them self-actuated to output physical notification and create physical animation, respectively. However, our literature search did not reveal use of electrostatic actuation to make an elastic interactive surface.

Actuated deformable surfaces such as Relief [37] and inForm [14] use front-projection that the users' hands partially occlude during interaction. Such projection does not allow satisfactory visual feedback, especially during collaboration. Occlusion can be avoided using multiple rear projectors if the actuators are sparsely distributed so that their shadow can be eliminated [54]. Using self-illumination such as Lumen [48], TAXEL [34] and Emerge [57], occlusion can be avoided. However, such approaches do not offer continuous deformable surfaces for high-resolution visual output, or require special flexible displays [34].

## TABLEHOP OVERVIEW

TableHop is a tablet or table-sized shape-changing surface. The surface of TableHop is made of a fabric that is elastically deformable through user manipulation and self-actuation. It combines rear-projection and self-actuation, which enables new user experiences. For the first time, users can interact with a display that is *elastic* and *actuated* in one system.

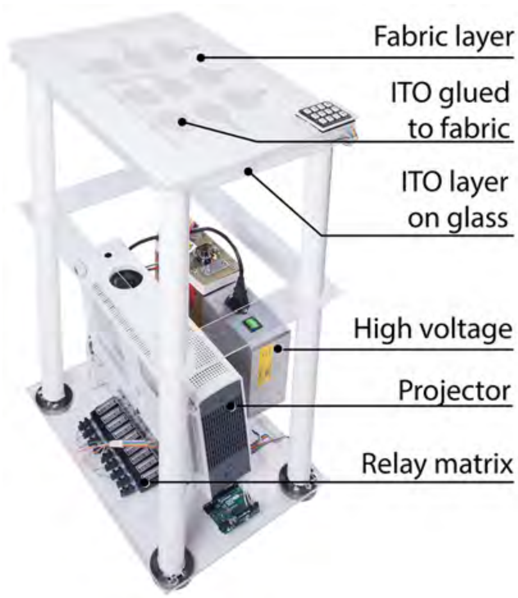


**Figure 2. TableHop consists of a top layer of fabric with an ITO array, an ITO and glass bottom layer, high-voltage supply, relay matrix, micro-controller, a rear projector, and a user tracking device for interaction.**

TableHop combines the advantages of elastic surface displays and actuated surface displays, i.e., non-occlusion using rear-projection, and visual and haptic feedback using actuation. For an actuated surface display, the user experience will improve significantly by avoiding occlusion, which will remove distraction and confusion due to useful information blocked by users' hands. This is particularly useful in an collaborative environment, where users do not occlude information to each other. For an elastic surface display, the users can now experience the advantages of an actuated surface, e.g., indirect interaction using implicit input (i.e., physical notification).

An overview of the TableHop hardware is shown in Figure 2. The elastic fabric carries an array of thin-film transparent indium tin oxide (ITO) electrodes. Another set of electrodes on a transparent substrate (glass or acrylic) is placed below the fabric. The fabric is actuated using electrostatic force by applying a high voltage between the electrodes. A relay matrix and microcontroller is used to switch different electrode pairs. A projector is placed below the actuation system to project content for the user. A compact tracking device is embedded on the top frame to enable user interaction.

### Tactile Feedback

TableHop provides a new way of tactile feedback using its electrostatic actuation mechanism. Apart from the usual haptic force feedback from the elastic fabric, it provides tactile feedback by vibrating the fabric in addition to the physical deformation. Simultaneous visual and haptic feedback is achieved. A higher frequency voltage signal is added to the voltage signal used for inducing deformation, which is typically a low frequency signal. It is a mechano-tactile communication technique that relies on the fast adapting Meissner's corpuscles (cutaneous) mechanoreceptors in fingertips which respond to mechanical stimuli from vibration in the frequency range of 2–40 Hz [16, 28]. The vibration for tactile feedback in TableHop is generated in this range.

## ENABLED APPLICATIONS

The existing elastic displays suffer from lack of actuation. The existing malleable displays suffer from occlusion. There is no self-actuated elastic or malleable display that does not suffer from occlusion. TableHop can address these issues, and is able to remove these limitations. Many applications of rear-projection elastic displays such as 3D modeling and multi-layered data exploration can be implemented on a TableHop display. Likewise, many applications of actuated malleable displays such as 3D animation and data physicalization can be implemented using it. Here, we present unique application scenarios that are enabled by TableHop, and are provided in the supplementary video. Note that the self-actuated malleable displays use front-projection and suffer from occlusion, which is avoided by elastic displays by using rear-projection.

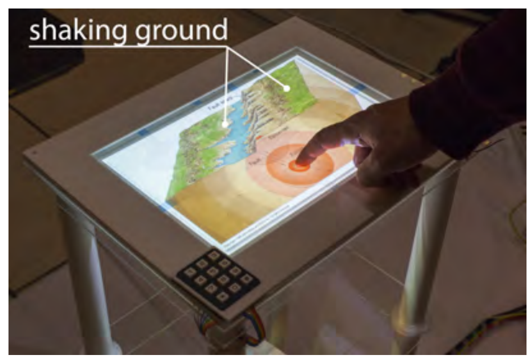


**Figure 3. A user initiates a simulation with a touch gesture, and all users view the dynamic display without occluding each other, and can touch it to feel the simulation.**

In the data visualisation and animation application shown in Figure 3, a static image of an earthquake scenario is shown on TableHop. One user initiates earthquake simulation by performing a gesture such as pushing, pulling, sliding or pinching the fabric which is possible on an elastic display, and not on a malleable display that is rigidly attached to the actuators. In response to the user gesture, the image becomes dynamic and the ground starts shaking to emulate earthquake at the affected locations. This is possible with a self-actuated display, but not existing elastic displays. Other users can see the earthquake visually, as well as feel the shaking ground by touching the surface. This is possible using a self-actuated malleable display. But, using TableHop the users do not occlude the projected media to themselves or to others.

In Figure 4, the application of personal notification in a collaborative scenario is shown. A static image is shown on


**Figure 4. (Background removed) A user is exploring tall buildings by pinching and pulling the display with one hand, and simultaneously receiving peripheral visual and tactile notification at the other hand.**

TableHop. One user is describing one of the tall building by pinching and pulling the TableHop fabric using one hand without suffering from occlusion, which are possible on an elastic display, and not on a malleable display that is rigidly attached to the actuators. At the same time, the user receives a personal notification below the other hand at which location TableHop vibrates to provide visual cues that is not possible due to occlusion in a malleable display, and to provide tactile cues that is not possible using an elastic display.

TableHop enables unique interaction scenarios, which are not possible either by a flexible display or a malleable display, in one system without occlusion for better multi-touch and collaborative user experience.

A TableHop system can be solely used as an output device, for example, to *play back* previously recorded media. In this case, either the deformation information is embedded in the media, or it is obtained in real-time by analyzing the media. One use of no-interaction operation of TableHop is *physical animation* of media used for advertisement or documentary. However, TableHop offers various interaction possibilities which are presented next.

### Interaction scenarios

A range of interactions described in [52] can be achieved using TableHop systems, such as *Indirect interaction* using implicit input. For example, users can receive *physical notifications* using deformation of TableHop fabric, i.e., restaurant locations on a map can physically pop-up, or the geographic elevation information can be physically portrayed to the users.

*Direct interaction* can be achieved using existing touch sensing and gesture recognition technologies such as a 3D depth cameras [55], which can be seamlessly incorporated into TableHop systems. *Action and reaction* type of interaction can be achieved because TableHop can recreate *push*, *pull*, *bend* and *slide* types of gestures. Such actions can be recorded and played back. After withdrawing user induced deformation, the TableHop fabric can restore back to its equilibrium deformed state, because it is elastic.

TableHop facilitates simultaneous and independent interaction at different locations as it uses an array of electrodes to actuate the fabric at independent locations. *Input and output* that are not directly related can be achieved simultaneously with action and reaction type of interaction, at independent locations. For example, when a user presses a deformed-fabric button at one location, a physical pop-up notification can be delivered at another location. A range of such interactions including remotely merging input and output can be achieved using TableHop.

TableHop offers more expressive and efficient visualization and communication of information, and dynamic affordances using self-actuation and tactile feedback. The TableHop architecture can be used as a toolkit to implement with other exploratory and hedonic systems to evoke emotion and stimulation, while not compromising aesthetics.

## DESIGN PARAMETERS

### Safety

EEEL safety rules [45] for high-voltage recommend operation below 2 mA AC or 3 mA DC when the voltage exceeds 1 kV rms or 1 kV DC, respectively. The stored energy should not exceed 10 mJ. We recommend using commercial high-voltage supplies, which have such safety mechanisms. This recommended limit is slightly below the startle response threshold. Interested researchers and designers must be careful to evaluate the stored energy between the electrodes in large TableHop systems that could potentially exceed 10 mJ.

### Stable operation limits

Electrostatically deflected elastic systems may suffer from *pull-in* or *snap-down* instability. It occurs when the applied voltage is increased beyond a certain critical voltage, leading to higher electrostatic force that cannot be balanced by the elastic restoring force of the fabric. Assuming that the fabric behaves like a linear spring, stable operation is achieved when the maximum deflection of the fabric $w_{max}$ is less than one third of the initial (unforced) separation $d_0$ between the fabric and the electrode, i.e.,

$$w_{max} < d_0/3. \tag{1}$$

The electrostatic force is nonlinear. It is also nonuniform in our case when the electrodes deform. The maximum allowable *pull-in* voltage $V_{PI}$ for stable operation when $w_{max} = d_0/3$ is given by [51]

$$V_{PI} = \sqrt{\frac{\frac{d_0}{3}\left(\frac{64D}{R^4} + \frac{4\sigma t}{R^2}\right) + \frac{128\alpha D}{t^2 R^4}\left(\frac{d_0}{3}\right)^3}{\varepsilon\left(\frac{5}{6d_0^2} + \frac{4}{3\pi R d_0} + \frac{1.918}{\pi R^2}\right)}}. \tag{2}$$

$R$, $t$, $D$, $\sigma$ and $\varepsilon$ are the radius, thickness, flexural rigidity, residual stress and permittivity of air, respectively. $\alpha = (7505 + 425\nu - 2791\nu^2)/35280$ is a Poisson ratio ($\nu$) dependent empirical parameter.

If TableHop is operated with $V_{max} > V_{PI}$, then the fabric can collapse and get stuck to the bottom electrode. In practice, the stiffness of the fabric, electrostatic field and Poisson ratio are increasingly nonlinear with further stretching, and the limit of stable operation region can be as high as $d_0/2$. In this work, we limit our operation to $w_{max} < d_0/3$.

Apart from mechanical instability, electrical instability may occur due to electrostatic discharge. The dielectric strength of air $E_{max}$=3 kV/mm, above which it breaks down and loses its electrical insulation property. As a result, an electrostatic discharge or electric spark can occur. The nanoscale conductive coating on the transparent electrode can evaporate, and the transparent dielectric insulator can crack and lose transparency due to the spark. To avoid it, the electric field at maximum deformation of the fabric must be less than the breakdown electric field $E_{max}$, i.e.,

$$3V_{max}/2d_0 < E_{max}, \quad (3)$$

where $V_{max}$ is the maximum voltage applied between the top and the bottom electrodes. For example, if $V_{max}$=10 kV, then the initial separation $d_0 > 5$ mm to avoid electric discharge that can occur when the fabric deforms by $d_0/3$. If the initial separation between the electrodes is 15 mm then the fabric can be deformed by 5 mm without encountering mechanical (snap-down) and electrical (break-down) failures.

### Energy consumption

In TableHop, the top and the bottom transparent electrodes form the two-plate capacitor configuration, however, with one plate being flexible. From parallel plate capacitor theory, an upper limit of energy consumption is given by,

$$U_{max} = \varepsilon A_{max} V_{max}^2 / 2d_{min}. \quad (4)$$

$A_{max}$ and $d_{min}$ are the maximum area and minimum separation between the electrodes. $V_{max}$ the maximum applied voltage. $d_{min} = 2d_0/3$ is the corresponding limiting separation. $C_{max} = \varepsilon A_{max}/d_{min}$ is the maximum capacitance between the electrodes. For $A_{max}$=200×300 mm$^2$ area electrodes separated by $d_0$=15 mm, $C_{max}$=53.1 pF. Using $V_{max}$=10 kV, the maximum energy consumption $U_{max}$=2.65 mJ. This energy can be harvested during the discharging of the electrodes.

The working energy consumption that induces deformations is lower. For example, to induce deformation of 5 mm, i.e., to change separation from 10 mm to 15 mm, only 0.85 mJ energy is required. Assuming zero leakage current, the energy required by the electrodes to maintain their shape is 0 mJ. Care must be taken to limit the size of TableHop so that the energy stored between the electrodes *does not exceed 10 mJ.*

### Elastic fabric

Initially, deformable surface was realized using sponge rubber sheets [21]. White nylon clothes were attached on top of the rubber sheets to make deformable *malleable* displays [25]. Later, silicone rubber and latex rubber were used [61, 20, 56]. The common choice for *elastic* display is spandex blended (with nylon, cotton, polyamide etc.) fabric [64, 60]. Spandex blended fabrics are commonly available in the market. They are elastic, and at the same time strong. Their elastic deformation is limited as the spandex content is maximum 20%. They can be stretchable by up to 50% with full elastic recovery. *Pure spandex* fabric, on the other hand, can stretch by more than 500% without breaking[11]. It can make full elastic recovery for stretch up to 300% [24]. Pure spandex fabric is not suitable to make clothes due to comfort and allergy concerns, and is not commonly available.

The 100% spandex elastic fabric can be modified to improve its optical and electrical properties. A fabric with pattern of a dense-net can be used for better elasticity. The small vacant spaces in the netted-pattern allows light from the projector to pass through directly. This will limit the gain and viewing angle, and reduce the contrast of image formed at the fabric. The vacant spaces can be filled with diffusing materials to use the flexible fabric effectively as a rear-projection screen. Front-projection screens use materials that enhance diffused reflection. Rear-projection screens require materials that enhance diffused transmission. Quartz and polytetrafluoroethylene (PTFE or teflon) powders are recommended as they offer good diffused transmission. In order to improve contrast, the fabric can be embedded with a dark tint that absorbs the ambient light striking the fabric. However, caution must be taken as it can also absorb the light from the projector, which can reduce the light transmission and, therefore, the gain.

### Dielectric material

The electrostatic pressure is given by

$$Q(r) = \varepsilon V^2/2d^2, \quad (5)$$

with $\varepsilon = \varepsilon_r \varepsilon_0$, where $\varepsilon_0$ is the permittivity of vacuum, and $\varepsilon_r$ is the relative permittivity or dielectric constant of the medium. $Q(r)$ can be increased by inserting a transparent dielectric sheet above the bottom electrode to increase $\varepsilon$. Polymethylmethacrylate (PMMA or acrylic) sheets are a suitable transparent dielectric material, which have typical $\varepsilon_r = 3.6$. Other materials such as transparent PVC (polyvinylchloride), polystyrene or polyethylene terephthalate (PETE) sheets can be used as well, which have similar dielectric constants.

The breakdown voltage of the transparent dielectric sheets is usually high. For example, the breakdown electric field $E_{max}$ of PMMA is 30 kV/mm. They provide a protective shield for the bottom electrode, and prevent electrostatic discharge.

### Pixel addressing

In TableHop, the top and bottom electrodes form a capacitor, which stores or maintains its charge when its connection is floating. This leads to deformed electrodes (pixels) maintaining their shapes during operation. Passive matrix or active matrix addressing scheme can be used, which significantly reduces the complexity of connections to the electrodes, and makes TableHop *scalable*.

Two passive matrix driving circuits are shown in Figure 5, which require $m + n$ control signals for a pixel array of $m$ rows and $n$ columns. The pixels are addressed serially one at a time by selecting corresponding row and column among the top and bottom arrays, respectively. In Figure 5 (a), the driving circuit uses an *unselect* voltage (HV/2). It leads to cross-talk with adjacent pixels. In Figure 5 (b), the driving circuit uses the high-impedance mode where the unselected rows and columns are floating, and it reduces cross-talk significantly. This circuit is difficult to test due to the floating electrodes.

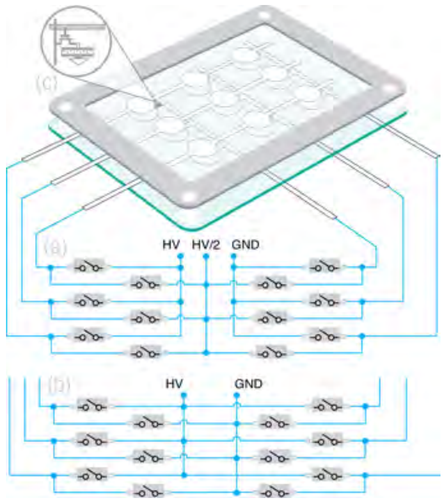


**Figure 5. Passive and active matrix driving circuits for TableHop are shown. An unselect voltage HV/2 and high-impedance mode are used in (a) and (b), respectively. The thin-film fabrication required for active matrix implementation is shown in (c).**

The HV power supply can be regulated linearly and a desired voltage can be applied to each pixel. The ground voltage (GND) connection goes to the bottom electrodes. The bottom electrode panel can be manufactured with a transparent thin film transistor and capacitor to connect to the ground signal and to retain charge, respectively as shown in Figure 5 (c) and an active matrix driving circuit can be implemented.

We implemented a *segment* driving circuit. It uses one large bottom electrode, which is simpler. The top electrodes are connected individually, and different deformation patterns are created by switching them independently.

### Shape of deformation

Here, we present an analysis that can be used to describe the shape of deformation produced by a TableHop system.

The shape of deformation in a TableHop system is given by the deflection and deformation of the transparent electrodes that are attached to the fabric. Figure 6 shows two different configurations the transparent electrodes can be attached to the fabric. When they are attached below the fabric facing the bottom transparent electrode directly, a uniform force is exerted on them. When they are attached above the fabric facing the bottom transparent electrode through the fabric, a nonuniform force is exerted on them. The shape of the fabric in these two configurations is analyzed next.

The fabric used in TableHop can be considered as a *diaphragm*, and its deflection and deformation can be obtained using the *membrane theory* of continuum mechanics [59]. Because the deformation of the fabric is many times its thickness, the large deflection theory is applicable. The fabric around the electrodes is not attached to a rigid support – the boundary condition for the fabric is that of a simply supported diaphragm. In the first case, where the transparent electrodes are attached at the bottom of the fabric and directly face the fixed ground electrode, we can assume that the electrodes do not deform, and a uniform electrostatic force is applied at the center of the diaphragm.

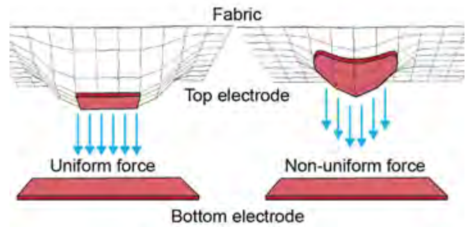


**Figure 6. Two possible cases of electrode placement are shown with the electrode attached to below (left) and above (right) the fabric. The electrostatic force exerted on the fabric is uniform and nonuniform over the area of the electrode, respectively. We used the arrangement on right.**

The equations describing the deformation of a thin circular elastic diaphragm is given in [1]. We followed the analysis of these differential equations as given in [27]. The results describe the deformation of any shape of electrodes under any distribution of load. In this paper, we present the solution for circular electrodes and the two cases of force distributions as shown in Figure 6.

The shape $w(r)$ of a circular electrode is given by,

$$\frac{dw}{dr} = \sum_{n=3,5} C_n(\beta_n \rho^n - \rho), \tag{6}$$

ignoring the higher order terms. $r$ is the radial position on the electrode. $\beta_n = (1+\nu)/(n+\nu)$ for $n = 3$ and 5. $\nu$ is the Poisson ratio of the electrode. The constant of integration to get $w$ is equal to the maximum deformation $w_{max}$ at the center of the electrode (i.e., $r$=0).

$$C_3 = \frac{-12 w_{max}(\beta_5 - 1)/R}{3(\beta_3 - 2)(\beta_5 - 1) - 2(\beta_3 - 1)(\beta_5 - 3)}, \quad \text{and} \tag{7}$$

$$C_5 = -C_3(\beta_3 - 1)/(\beta_5 - 1). \tag{8}$$

The corresponding shape of deformation when the transparent electrode at attached below the TableHop fabric under uniform load is shown in Figure 7-a. The initial gap between the electrodes $d_0$=15 mm. The maximum deformation is considered as $w(r = 0) = d_0/3$=5 mm for stability consideration, which is presented earlier.

When the transparent electrodes are mounted above the fabric, the electrostatic pressure exerted on the fabric (diaphragm) is a nonlinear and non-uniform load as shown in Figure 6. An analytical solution describing the shape under such nonlinear and non-uniform load condition is unavailable in the literature. In [51], the nonlinear electrostatic force is linearized at a given deformation location $w(r)$ and the resultant force is assumed to exert a uniform pressure on a virtual diaphragm. The corresponding shape of deformation when $w(r = 0) = d_0/3$=5 mm is shown in Figure 7-b.

The analytical shapes of deformation is useful for graphic designers. For example, using thicker transparent electrodes at-

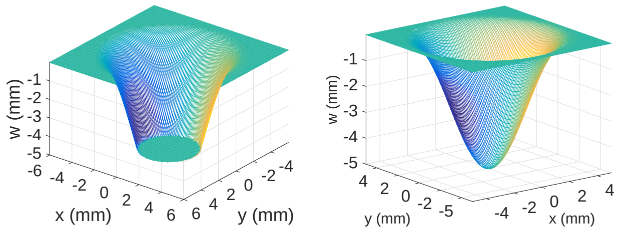


**Figure 7. Shape of deformation of 6 mm radius is shown (a) from below when a uniform pressure is applied using an electrode of 1 mm radius attached at the bottom, and (b) from above when a nonuniform pressure is applied over the entire area at the top.**

tached to the bottom of the fabric, flat bottom shapes can be created. Using thinner transparent electrodes mounted on the top of the fabric, smooth shapes can be created.

TableHop designers and users can customize the shape, size and position of electrodes, and separation ($d_0$) between individual electrodes to create user-defined deformations. Safe and stable operation can be ensured using the technical limits presented in the paper. Using the analysis presented above the shape of such deformations can be modeled. Designers will have the freedom to make custom effects on the go by physically moving the electrodes.

### *Spline functions*

The shape of the fabric can be described by a power series. We considering the first two terms in the power series as shown in Equation (6), which is similar to a cubic spline function. In general, the shape of fabric can be described using spline functions as they are used to describe the deformation of elastic structures. In fact, the bending of elastic structure is related to the foundation of spline theory. The fabric of TableHop can be visualized as the mesh used in spline theory. The deformation of the fabric due to the loads can be described by the deformation of the mesh using spline functions.

## System Resolution

The *shape resolution* of shape-changing devices has been described using non-uniform rational B-splines (NURBS) [53]. The 10 features of shape resolution in this framework are (i) area, (ii) granularity, (iii) porosity, (iv) curvature, (v) amplitude, (vi) zero-crossing, (vii) closure, (viii) stretchability, (ix) strength and (x) speed.

(i) The ares of TableHop can be increased by increasing the size of the fabric and using more electrodes. A suitable projector can be used for a large area TableHop system.

(ii) Granularity measures the density of physical actuation points. This concept describes well the pin-based mechanical actuation systems such as FEELEX [25], Popup [43], Lumen [48], BMW kinetic sculpture [5], Relief [38], Tilt displays [2] etc. Similar to actuated devices such as Surflex [7], Programmable blobs [63], the granularity of TableHop is constant, but is not well defined. There is no available system that can change granularity on demand.

(iii) The porosity of TableHop systems is nonzero as the screen is implemented using an elastic fabric, which has net-like pattern. The porosity can be changed by changing the fabric, and it cannot be changed on demand.

(iv) The curvature in [53] is proposed to compute by removing $\pi$ from the angle between three consecutive control points. Because TableHop uses electrodes to create curved surfaces, the control points are not defined well as in pin-actuated systems. In TableHop, a curved surface with the maximum angle is produced when the fabric deforms by the maximum allowed normal deflection of $w = d_0/3$. From Figure 7, the maximum angle is calculated from the slope of the curve, i.e. $w' = dw/dx$, that is approximately equal to 59.8°.

From Equation (5), the electrostatic pressure (force) is proportional to the square of potential difference ($V$) between the electrodes. The electrostatic force between two opposite electrodes is always attractive when a voltage signal is used to actuate them. When electrodes are placed below the fabric carrying the other pair of the electrodes, *concave* surfaces are created. By using another set of electrodes above the fabric, *convex* surfaces can be created.

In geometry, curvature $\kappa$ at a point is defined as the inverse of radius of the arc that best approximates the curve at that point. The radius of curvature (i.e. inverse of curvature) is calculated using the formula $\frac{1}{\kappa} = \left|\frac{(1+w'^2)^{3/2}}{w''}\right|$. From Figure 7, the minimum radius of curvature at the bottom of the deformed fabric is approximately 0.83 mm, which also describes the *sharpness* of deformation in our TableHop system.

(v) The amplitude of TableHop is dependent on the flexural rigidity $D$ of the fabric and the maximum voltage $V_{max}$ applied between the electrodes. Using 100% spandex fabric and $V_{max}$ = 10 kV, we achieved an amplitude of 5 mm.

(vi) The deformations created by TableHop systems are similar to wavy patterns, allowing it to portray *zero-crossing* features. Each electrode can produce one wavy pattern. The exact shape of the waves are given by Equation (6).

(vii) Out of the ten features of shape resolution, “closure" is the only feature that TableHop does not offer.

(viii) The TableHop system achieves deformation of the screen by stretching the fabric. The stretchability can be increased by using a more stretchable fabric. Due to the constraints for stable operating condition, the fabric is not allowed to stretch beyond a limit. Given a shape of the deformation, the stretching of the fabric can be calculated numerically. From Figure 7 the stretching of the fabric is numerically calculated assuming linearly connected points as approximately 341.7%, i.e. the deformed fabric is approximately 3.4 times its original length. Pure spandex fabric can stretch by more than 500% without breaking [11].

(ix) The force exerted on the TableHop fabric to induce a desired deformation depends on the separation of the electrodes (see equation (5)). It is a nonlinear force that varies during the deformation process. For any possible shape, the TableHop fabric is at equilibrium, i.e., the electrostatic force exerted on the fabric is counterbalanced by the restoring elastic force of the fabric. A minimal external force is required to trigger further deformation.

The *strength* of a TableHop system is described by the energy needed to modify the fabric from flat position to the maximum deformed position. Zero energy is stored when the fabric is flat. Maximum energy is stored when the fabric is deformed maximum, i.e., $w_{max}(0) = d_0/3$, and is given by $U = \frac{1}{2}C_{max}V_{PI}^2$, where $V_{PI}$ is given by equation (2). When the electrode is attached below the fabric as shown in Figure 6, the capacitance is given by $C_{max} = 3\varepsilon A/d_0$, where $A$ is the area of the electrode. When the electrode is mounted above the fabric, the capacitance is given by $C_{max} = 2\pi\varepsilon \int_{r=0}^{R} \frac{rdr}{d_0 - w(r)}$, where $w(r)$ is given by equation (6).

An upper bound (over-estimate) of energy of our TableHop implementation is given in subsection "energy consumption", i.e., 2.65 mJ, where it is assumed that the entire fabric is deformed by the maximum allowable value $d_0/3$. An estimate of average force ($F_{est}$) can be made assuming $U = F_{est} \times d_0/3$, giving $F_{est} = 0.53$ N for $d_0$=15 mm.

(x) The *speed* of a TableHop system is determined by the response-time of the fabric and the speed of high-voltage power supply. The response time of the fabric is dictated by the Young's modulus, density, diameter and the length of the fabric fibers. These parameters can be estimated carefully from the mechanical vibration measurements. Response time of fabric fibres (Nylon, woll, etc.) is in tens of milliseconds (10s of Hz) [35]. Response time spandex can be expected to be similar. We observed that the fabric responded instantaneously to low-frequency voltage input below 20 Hz.

## EVALUATION OF IMPLEMENTATION

We implemented a TableHop prototype (see Figure 2) based on the design parameters discussed earlier.

A 100% pure spandex fabric was used for maximal elasticity and deformation using low force. Indium tin oxide (ITO) coated polyethylene terephthalate (PET) sheets from Sigma Aldrich were used as transparent electrodes. An entire ITO-PET sheet (1 ft×1 ft) was used as the bottom electrode. The top-electrodes were precisely laser-cut from the ITO-PET sheets. The protective cover of the electrodes were removed at the end. We used nine 40×60 mm$^2$ elliptic electrodes.

A projector (Sanyo PLC-XU111) was placed below the fabric (see Figure 2). We used a commercial 10 kV and 1.5 W high-voltage supply (Glassmann MJ10P1500), which offers high-voltage output waveform regulation by user defined low-voltage input signal, as well as user adjustable current limit. It also provides the output voltage and current monitor signals as low-voltage signals. A high-voltage H-bridge switching circuit was developed to switch between the electrodes. The size of the working area on the fabric was 200 mm × 300 mm. The volume of the entire prototype was 30 cm × 40 cm × 80 cm. A laptop computer was used to operate the projector and an oscilloscope (Agilent DSO-X-3024A) that controlled and monitored the high-voltage supply.

Next, we present the experimental evaluation of the performance of our TableHop implementation. It can be easily repeated to evaluate other TableHop systems using a stably mounted camera. We presented the *static analysis* of the shape of deformations earlier in the section on design parameters.

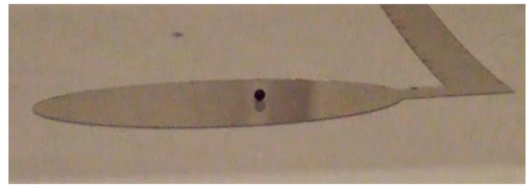

**Figure 8. An expanded polystyrene bead of 2 mm diameter was attached on the electrode to evaluate the mechanical response experimentally.**

*Dynamic analysis* of TableHop is presented here. In order to be able to evaluate the bending of the fabric, we attached an expanded polystyrene bead of 2 mm diameter on top of an electrode. The bead can be attached to the fabric if the electrodes are attached below. The position of the bead was recorded using a high-speed camera at a speed of 120 frames per second. A circle-tracking algorithm was used to calculate the position and motion of the bead from the video-recordings. The bead was painted black for easy tracking using binary image conversion. Using a spherical bead of known diameter, the recording system was calibrated. The motion of the bead, i.e., the deflection of the fabric was converted to millimeter. The experimental results presented below used this technique.

### Calibration

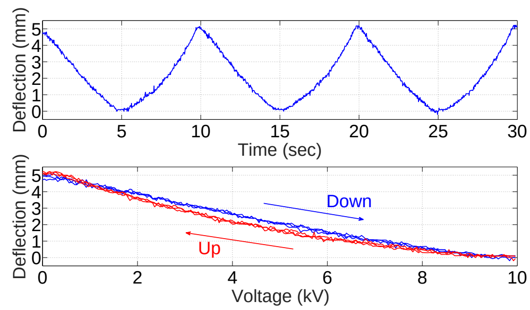


**Figure 9. The deflection ($w(0)$) of the fabric (top) and the nonlinear relation between the applied voltage ($V$) and the deflection (bottom) are shown. A 100 mHz and 0–10 kV voltage was applied. $d_0$=15 mm.**

The electrostatic pressure is nonlinear (see equation (5)). The bending of the fabric $w(r)$ is expected to hold a nonlinear relationship with the applied voltage $V$. We performed the *up and down* movement of the fabric to calibrate our TableHop system. A ramp voltage signal of 0–10 kV peak-to-peak and 0.1 Hz frequency was applied using an electrode of 50 mm diameter. The separation $d_0$ was 15 mm. The corresponding deflection of the fabric $w(0)$ (see Figure 9) was nonlinear and repeatable as expected. However, the nonlinearity was different for upward and downward directions. In other words, the fabric shows *hysteresis*, which can be calibrated using the proposed technique.

### Speed

The *speed* of our TableHop implementation was measured experimentally. This technique can be used to evaluate the speed of other TableHop systems.

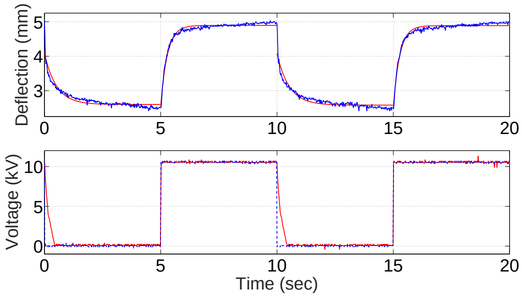


**Figure 10. (Top) Experimental (blue) and fitted (red) step response of our TableHop implementation are shown. The estimated time constant is ≈ 280 milliseconds. (Bottom) The input reference voltage (blue) and the measured output voltage (red) of HV power supply are shown.**

The *speed* of a TableHop system is determined by the speed of high-voltage power supply and the response-time of the fabric. The rise and decay time specifications from the datasheet of our high-voltage supply are maximum of 100 milliseconds (10 Hz), and typically 50 milliseconds (20 Hz). The voltage is applied directly to the electrode with a resistor, eliminating low-pass RC filtering.

We measured the response time of the fabric experimentally using the bead and camera technique presented above. A square wave reference signal of 0–10 V peak-to-peak range and 100 mHz frequency was applied to the high-voltage supply (see Figure 10, bottom, blue). The measured high-voltage output of the supply is shown in Figure 10, bottom, red. The rise-time of the voltage-supply was excellent, but the fall-time was low. The diameter of the electrode was 50 mm and the separation $d_0$ was 15 mm. The measured response of the fabric is shown in Figure 10, top, blue. The data was corrected using the hysteresis response presented above. First order rise and decay models were fitted to the response of the fabric (see Figure 10, top, red). The maximum time constant of the fabric response is estimated at approximately 280 milliseconds (3.6 Hz). The slow (fall) speed of high-voltage supply used in our implementation affects the speed of our implementation. The speed can be increased using a faster voltage supply. Correspondingly, the peak running power requirement for 280 millisecond speed operation of our TableHop system is estimated at approximately 2.65/0.28=9.46 mW. The maximum working power, i.e., to change the maximum deformation from $d_0/3$ to 0, is estimated at approximately 0.85/0.28=3.04 mW.

### Tactile Feedback

The tactile feedback ability of TableHop was evaluated experimentally using the bead and camera technique presented above. Unlike the above experiments, a high-speed camera is required for speed measurement.

A sinusoidal voltage signal of 1 kV peak-to-peak amplitude and 10 Hz frequency was applied to the electrodes. The motion of the bead was video-recorded using a high-speed camera (Exilim ex-zr400) at 120 frames-per-second. The frequency was varied from 10–20 Hz in steps of 1 Hz, and the corresponding videos were recorded. The vibration of the fabric was calculated in millimeters using the bead and camera technique presented above. The frequency response of the fabric in our TableHop implementation is shown in Figure 11. The vibration of the fabric peaks at 12 Hz, and the corresponding peak amplitude is 1.8 mm. We employed tactile feedback at this frequency and amplitude.

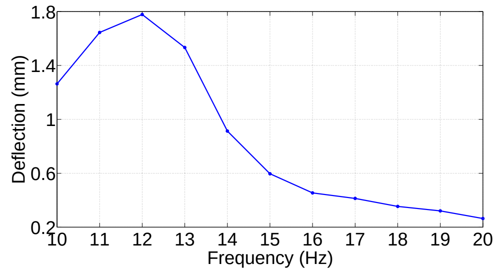


**Figure 11. The vibration of TableHop fabric in response to 1 kV sinusoidal voltage at different frequencies is shown. For tactile feedback, the fabric was vibrated at peak frequency 12 Hz.**

Higher vibration amplitude can be achieved by applying >10 kV voltage signal. However, it may affect the visual perception of the dynamic shapes that the user might want to experience simultaneously. A faster power supply with bandwidth >20 Hz is required to use the full 10 kV range, which was a hardware limitation in our prototype. The efficiency of vibrating the fabric reduces at higher frequency due to lower gain. To create larger vibrations, higher voltage is required. It is possible to vibrate the TableHop fabric at higher frequency at higher amplitude using higher voltage. An appropriate high-voltage supply, for example, a Tesla coil can be used to generate high voltage and high frequency.

The peak vibration frequency of the fabric can be increased by mounting the fabric with pre-stretching to increase the stiffness. However, this would reduce the peak-amplitude of deformation that can be generated for the visual feedback.

In our pilot-study, we obtained feedback from two users with experience in midair haptics (Ultrahaptics [6]) and four users with no prior experience. The user-group consisted of four males and two females, and age varied from 23–35. The users were not allowed to look at the display and asked to wear a headphone. All the users experienced immediate mild increase in tactile feedback when vibration was turned on while touching the fabric softly. They were also able to perceive when the vibration was turned off, albeit not instantly. We concluded from visual cues from the zoomed view through a camera that the users reduced the vibration of the soft fabric with their touch, which correspondingly led to reduced and slow sensation. In TableHop, the vibration induced for tactile feedback can provide visual cues, which is intended to be simultaneously experienced by the users with the media displayed. A carefully designed study for user-centric evaluation is required.

Note that TableHop allows users to interact with the fabric display directly with physical touch even when it is actuated to deform and create static and dynamic shapes. The fabric is displaced locally due to the user interaction force. However, it recovers to the (electrostatic) forced equilibrium position quickly due to high elastic recovery force and fast response [24]. If the fabric is stretched beyond 300% then it can recover up to 95% quickly and then recover further slowly.

## DISCUSSION

The pin-actuated systems such as inFORM [14], Relief [37], ShapeClip [19] and Emerge [57] can have higher resolution and linear range, and better haptic (force) feedback than TableHop. For example, inFORM and ShapeClip have linear pixel size of 3.175 mm and 20 mm, and linear range of ±5 cm and ±30 mm, compared to 50 mm and ±5 mm of our TableHop implementation. The advantages of TableHop are low power consumption, smaller foot-print (volume and weight), i.e., scalability and portability (with no recalibration) and low-noise operation. inFORM and ShapeClip require 3 W (315 $mW/mm^2$) and 2.7 W (6.75 $mW/mm^2$) power per actuator pin, compared to our TableHop that requires 6.32 mW for $200 \times 300$ $mm^2$ electrode area leading to 0.16 $\mu W/mm^2$ power consumption. In a given TableHop system, increasing the resolution (i.e., reducing the pixel size) leads to lower maximum amplitude of operation, which requires higher voltage supply and more stretchable fabric to compensate.

The shape of the deformation in a TableHop system can be calibrated in three dimension using a projector and camera setup [55]. First, the projector and camera system can be calibrated by projecting a grid pattern onto the fabric. Then, the deformations can be calibrated using an image processing algorithms such as one given by Ferrier et al. [10] for a given choice of fabric, electrode shape and size, and separation between the top and bottom electrodes.

The TableHop systems can be deployed in many different form-factors such as a tabletop or a large wall-mount display. Large TableHop systems require larger fabric, which may impose mounting challenges in order to reduce bending due to its own weight in spite of it being light-weight. Tighter mounting of the fabric with pre-load (pre-stretching) can reduce the bending. It should not affect the elastic deformation of the fabric, similar to standard springs that exhibit same differential compression or extension independent of their compressed or extended length. However, it will reduce the maximum achievable deformation of the fabric.

The TableHop systems do not allow very sharp deformable physical features, similar to other elastic and malleable displays. Electrodes attached to the bottom of the fabric can create flat bottom features. The size of the electrodes can be reduced to sub millimeter level. Higher elasticity fabric and smaller electrodes may be used to increase the sharpness of deformation. However, smaller electrodes will lead to lower force and smaller deformation.

Because the fabric is a continuous piece, the induced deformation at one location can interfere with the deformation induced at another location. To eliminate or reduce the interference between different locations, the fabric can be mounted on a transparent grid of rigid (glass or plastic) or elastic (spandex threads or silicone band) sheet. The deformation of the fabric in each section will be bounded by the clamped or simply supported boundary condition depending upon rigid or elastic attachment between the fabric and the grid.

The TableHop systems can incorporate tactile-feedback technologies such as TeslaTouch [4] and Corona [40] that do not need any mechanical actuation. The electrodes of TableHop can be used to incorporate technologies such as electrovibration [39, 4] that uses electrostatic tactile communication [29] and electrostatic discharge [40] that uses electro-tactile (electrocutaneous) communication.

The TableHop systems can integrate gesture sensors such as LeapMotion for interaction as shown in Figure 1. Vision-based detection of finger touch [22] can be used. We did not prefer using external systems outside the TableHop box to enable interaction. Capacitive touch sensing such as DiamondTouch [9] and [65] can also be integrated by reconfiguring the electrodes for multi-touch capacitive sensing [46]. User-centric development of unique interactive applications that TableHop can enable using such sensors is a future work.

Our TableHop implementation has a foot-print of $30 \times 40 \times 80$ $cm^3$. The height of the actual actuation system in TableHop is very low, i.e. less than 25 mm in our prototype. The overall height can be further reduced using a short-throw wide-angle pico-projector. Apart from the projector and the translucent fabric, the entire TableHop system can be made almost transparent using glass or acrylic frames. The small and *compact* size of TableHop offers unique opportunity to product designers and for *ubiquitous* deployment.

## CONCLUSIONS

We presented TableHop, the first elastic display surface that is self-actuated and uses rear-projection, and can be used for tablet and tabletop applications. It provides an additional tactile feedback to an elastic interactive surface. It enables interaction with deformable surfaces without user induced occlusion. The technological advantages are small form-factor, low-power, scalability and integratability.

We used transparent indium tin oxide electrodes and high-voltage modulation to create controlled surface deformations. Our prototype had a 30×40 cm surface area and uses a grid of 3×3 transparent electrodes. It achieves ±5 mm deformation using 10 kV supply using pure spandex fabric. It consumed a maximum of 9.46 mW and creates haptic vibrations of up to 20 Hz. We showed implementation, evaluation and analysis that can be used to build prototypes of different sizes.

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