ForceForm: A Dynamically Deformable Interactive Surface

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ABSTRACT
We present the design and implementation of ForceForm, a prototype dynamically deformable interactive surface that provides haptic feedback. We use an array of electromagnets and a deformable membrane with permanent magnets attached to produce a deformable interactive surface. The system has a fast reaction time, enabling dynamic interaction. ForceForm supports user input by physically deforming the surface according to the user's touch and can visualise data gathered from other sources as a deformed plane. We explore possible usage scenarios that illustrate benefits and features of the system and we outline the performance of the system.

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Tangible interaction; interactive surfaces; tactile feedback

ACM Classification Keywords
H.5.2 Information Interfaces and Presentation: User Interfaces - Interaction Styles

INTRODUCTION
Touch surfaces have become common devices in both mobile and tabletop scenarios. However, these surfaces are usually flat and unable to be physically altered, providing little flexibility to the user interface designer beyond changing the visual information communicated to the user via software.

ForceForm provides direct input by allowing the user to alter a surface by touch. The deformations that the user has made can be persistent, as illustrated in Figure 1. Allowing the persistent state to be viewed makes ForceForm suitable to larger scale touch surfaces with multiple users, and tangible modelling tasks. As ForceForm has a fast response time, this interaction occurs dynamically. Furthermore, ForceForm can provide haptic feedback to localised points of the surface, which eases visual overload and preserves screen real estate. The system is standalone, so the user is able to interact using relatively minimal effort as no extra tools such as pucks [13], or the fabrication of physical buttons [4] are needed.

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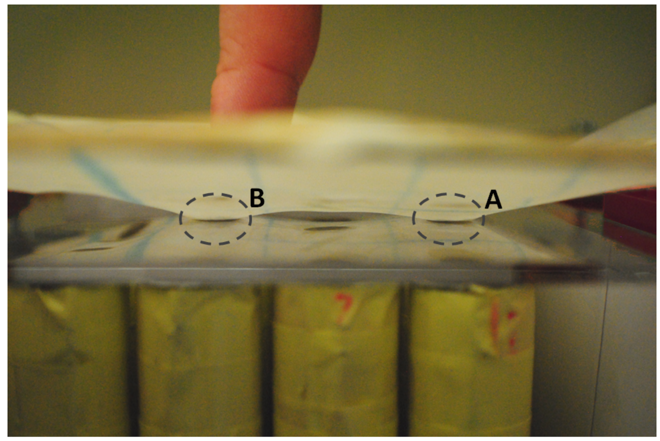

Figure 1. Side view of ForceForm. The user has made an indent (A) and is now making a second indent (B) by pressing down on the surface.

Possible uses for the system include approximating terrain data, with a focus on rolling hills as opposed to jagged mountainous peaks. Users can directly interact with and visualise the terrain data in a tangible manner rather than on a computer screen or by using a 2D contour map. ForceForm can be used for the visualisation and interaction with surface constrained 3D data that has organic properties, with relief from the ubiquitous flat surface.

We see ForceForm as being useful for both direct user input and output. It also enables interesting new haptic feedback enabled interaction techniques when used as an interactive touch surface.

RELATED WORK
Several previous systems use magnetic forces for different goals and functionalities, for example, to actuate objects [13] or magnetic fluid [6, 8]. MudPad [8] consists of a pouch of opaque magnetic fluid that is used as a touch surface in conjunction with a projected display. The fluid is able to be stiffened using an underlying grid of electromagnets. The resulting change in viscosity is used to provide haptic feedback while the user is touching the surface. This haptic feedback focused system does not allow for deformable interaction.

Pin arrays have been used to produce actuated tabletop displays. Feelex [7] is an early implementation, consisting of an array of linear actuators that are used to raise and lower rods which deform a white nylon cloth surface. Relief [9] consists of aluminium pins that are actuated using a potentiometer. Recompose [2] builds upon Relief to enable both direct interaction by pushing and pulling the pins up, and gestural interaction by making gestures above the surface. Shape memory alloy (SMA) wires have also been used to actuate pin arrays [11]. Pin array displays give a different interaction experience when compared to ForceForm. ForceForm feels like a soft surface that the user is able to push down with nothing immediately underneath. In contrast, in a pin array system, the user pushes down a rigid rod. Furthermore, ForceForm allows the user to push down on the surface from an angle, rather than solely from directly above and it is unclear whether this can be achieved using pin arrays.

Lumen [14] also uses SMA technology to move cylindrical objects up and down in slow and smooth motions. SMAs have also been embedded in foam to be used as a deformable surface [3]. However, SMAs have a slow reaction time and are not comparable to the dynamic interaction of ForceForm.

Smith et. al. [16] developed Digital Foam, which supports clay like sculpting and modeling operations, however Digital Foam caters for different tasks as it does not keep persistent state information as ForceForm does.

Recently, air pressure has been used to provide dynamically changing functions to a surface. Aihara et. al. [1] developed a surface that is able to be rigid or soft, with adjustable height, depending on the air pressure used. Harrison et. al. [4] developed button overlays that consisted of inflatable buttons, however, the buttons cannot be altered once the overlay has been made. Additionally, each button requires a pneumatic pump to be able to operate independently.

There are numerous previous works focused on handheld and mobile interaction, of which Gummi [15] is an example. However, we have focused on previous work that is aimed at deformable surfaces in a tabletop interactive surface setting, as this is most related to our current work.

USAGE SCENARIOS

We introduce two possible usage scenarios which illustrate the features and benefits of ForceForm. The *On Screen Keyboard* usage scenario describes the use of ForceForm for haptic feedback and the *Terrain Modelling* usage scenario is an example of how ForceForm could be used for input and output in the form of data visualisation.

On Screen Keyboard

Studies have found that haptic feedback significantly improves performance with keyboards on touch surfaces [5]. ForceForm is well suited to a virtual keyboard application this application as the surface can spring back up after being pushed down, resembling the keys of a keyboard. The study also found that text entry is further improved by providing localised haptic feedback as opposed to feedback from a single actuator which vibrates the whole screen. ForceForm is able to provide haptic feedback in a manner which is localised to the region of each electromagnet. The possibility of keys that have varying levels of stiffness could also be explored.

Terrain Modelling

Upon consultation with scientists in a local Soil and Landscape Science group, we found that those who perform terrain analysis currently use computer programs to produce a model of remotely sensed datasets from a number of sources. This information could be fed into ForceForm and modelled in a tangible manner. This would allow the scientists to readily visualise the landscape and easily gather extra information, such as line of sight. As well as providing output in the form of information visualisation, the user could provide input to the system by directly pushing down or pulling up the hills and valleys formed. It is also common practice for scientists in the group to use play-dough to aid in visualising surfaces. Sand and soil beds are also used for modeling surface water flow and erosion. Both of these current methods could be complemented with the use of ForceForm.

SYSTEM DESIGN

ForceForm consists of a latex surface *(a)* that has been augmented with a grid of neodymium permanent magnets, 6mm in diameter with 1mm thickness, which are arranged in phase. An underlying grid of computer controlled electromagnets *(c)*, similar to that of the Actuated Workbench [13], is used to attract and repel the neodymium magnets, deforming the surface at localised points. There is one permanent magnet per electromagnet in our prototype system. Figure 2 illustrates the hardware of the ForceForm system.

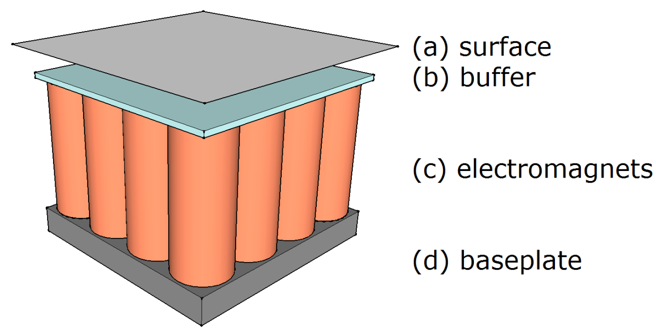

Figure 2. A scale diagram of the structure of the system.

Similar to what was discovered by the Actuated Workbench [13], the ferrous steel cores of the electromagnets would attract the permanent magnets attached to the surface. This prevents the system from functioning as intended, as once a permanent magnet was touching an electromagnet core, it required a greater force to detach, resulting in the system requiring non-linear forces. Our solution is to place a sheet of 2mm thick Perspex *(b)* between the deformable surface and the electromagnets to prevent touching the cores.

This prototype system uses 16 custom made electromagnets of 21mm diameter that each operate at DC 12 volts and 1.2Amps. A custom made electronic circuit board provides a power operational amplifier for each electromagnet and takes input from a digital to analog converter device connected to a computer, which regulates the power to each electromagnet, enabling bi-polar control.

The user's finger position is tracked by using a Cyclotouch T-series touch overlay. The glass has been removed, leaving a frame that we have situated above the system. The user's finger position is determined when the user's finger passes through the frame. This could alternatively be achieved by visually tracking the finger, or by using a resistive touch pad as with MudPad [8].

Interaction Characteristics. The surface of ForceForm feels soft and so offers a different interaction experience than previous systems such as Feelex [7], where the user is pushing down on rigid rods. The surface of ForceForm feels similar to human skin or playdough.

When an electromagnet is positively charged, the permanent magnets on the latex move upwards, away from the electromagnet. This deforms the surface above the electromagnet into a dome shape, with the size of the dome dependent on the strength of the charge. Conversely, when the polarity is switched, the permanent magnets on the latex move downwards, towards the electromagnet, deforming the surface downwards and creating an indent. The depth of this indent can currently only be adjusted by adjusting the space between the deformable surface and the electromagnets. This occurs because when a permanent magnet is attracted downwards, it moves closer to the electromagnet, decreasing the space between them and resulting in the permanent magnet 'snapping' down to the electromagnet.

Thus, for each electromagnet, the surface can currently achieve one state where the permanent magnets are attracted downwards, another neutral state where the electromagnet is off, and multiple states where the electromagnet is repelling the permanent magnets upwards at different strengths. The range of motion between the peak and trough is around 25mm with our current prototype system.

Haptic Feedback. Haptic feedback provided only to a user's fingertip has been described as a huge bandwidth reduction on the haptic channel when the number of haptic receptors in the body is considered [18]. ForceForm can provide a full hand tangible experience rather than being bound to the fingertip [17] or the muscles involved in holding a stylus [10]. Switching the polarity of an electromagnet enables the corresponding permanent magnet to be vibrated, providing an interesting sensation to the user when the user is in direct contact with the surface. This is affected by the tautness of the surface and the speed of the polarity switching.

PERFORMANCE

We outline the performance of the prototype system.

Speed. Well designed systems reduce the time it takes for the user to perform a task [12] and thus we have placed emphasis in developing a system with a fast response time. Due to the inductance of an electromagnet, it takes time for the current and, therefore, the magnetic field to build up. Using an oscilloscope and current sensing resistor, we measured the current response of our electromagnets, and obtained a time constant of 6ms. This indicates that it takes 6ms for the magnetic field to reach 63.2% of its final strength, and 12ms to reach 86.5% of its final strength. More precisely, the current is given by $i(t) = Ifinal * (1 - EXP(-t/T))$ where $i(t)$ is the current as a function of time, t is the time in seconds, $Ifinal$ is the final current in Amps, and T is the time constant in seconds, 0.006 for our electromagnets. In general, the magnetic field changes at a slower rate than the electrical current due to eddy currents within the unlaminated steel core of the electromagnet. An inductive pickup coil was used to directly measure the time response of the magnetic field, which was also found to be 6ms. Therefore, eddy current effects are negligible in this case and the electrical current is an accurate reflection of the magnetic field. This quick response time means that system interaction appears to occur dynamically.

Magnetic Field. We have mounted our electromagnets on a steel base, illustrated in Figure 2, *(d)*, which differs from implementations in previous work. The steel base plate increases the magnetic field strength by 70%, by providing a flux linkage path between the steel cores, without extra power consumption or a larger footprint. This is a significant improvement, at essentially no cost or increase in complexity.

As we are moving a surface up and down, the vertical component of the magnetic field strength is relevant to ForceForm. We have modelled the vertical component using a finite element magnetic modelling program and can be seen in Figure 3. The vertical component of the field strength at a position 10mm above and centred between two repelling electromagnets, indicated by the white area in Figure 3, is 0.043 Tesla. At a position 10mm centred directly above a repelling electromagnet, the vertical component is 0.050 Tesla. This illustrates that the magnetic forces are still present a distance above the electromagnets. The forces are stronger above the electromagnets than in between, but not by a significant amount, meaning that the surface is almost flat when adjacent electromagnets are repelling.

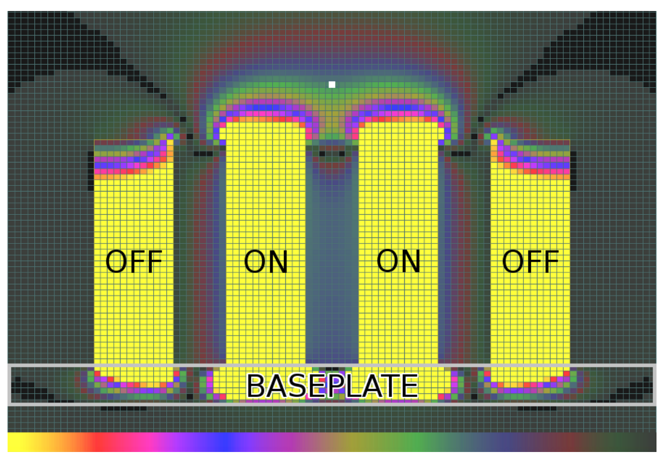

Figure 3. Diagram showing strength of the vertical component of the magnetic field, when two adjacent electromagnets are positively charged. The bar below indicates the strength, where yellow is the highest strength area.

Temperature. As with the Actuated Workbench [13], each electromagnet in our current implementation is only on for a relatively short period of time for current applications, but if many electromagnets were to stay on for a long amount of time, cooling may need to be considered. Our initial thermal measurements of the temperature of the winding show that, for any power dissipation, the temperature is halved due to the heat-sinking action of the steel baseplate, which is a significant improvement.

DISCUSSION

Pangaro et. al. [13] suggested, in their Actuated Workbench paper, that a grid of electromagnets is theoretically capable of levitating magnetic objects above a surface. However, implementation of this is difficult when Earnshaw's Law is considered, which states that a stable configuration of static magnets is incapable of maintaining levitation. ForceForm sidesteps this problem by providing magnetic levitation in a tethered manner: the levitated permanent magnets are tethered along a plane by being attached to the latex surface, thus they are held in place above the electromagnets and prevented from flipping over and attracting to one another.

As ForceForm is a prototype system, there are a number of hardware parameters that can be altered in order to improve various performance metrics to suit the application. These include the size of the electromagnets, the power used, the size and shape of the permanent magnets, the material used for the deformable surface, whether it is slippery or has grip, and the tension of the surface. ForceForm can be scaled to achieve a finer resolution than our prototype model achieves and the number of electromagnets can be increased to suit the size of surface required.

By using an opaque membrane in place of the semi-transparent latex used in our current implementation, ForceForm can be projected upon to create a deformable display surface. Projecting onto an opaque surface provides interesting applications in spatial augmented reality. For example, one might project terrain upon the deformable surface, and have the projected terrain adjust to fit the surface as the user deforms it. Ideally, a light, thin, bendable touch display could be fitted to the surface to prevent occlusion from projecting to an area where the user is touching, but we are unaware of a suitable product currently available.

When ForceForm is implemented with a transparent surface, an underlying thin LCD display can provide annotations in place of where the Perspex sheet is currently located. However, the surface will not be completely transparent due to the small permanent magnets attached to the surface in the current implementation. Parallax errors will be introduced, and so we suggest that only simple annotations may be possible, such as the colour of a broad region: for example, green for land and blue for sea.

CONCLUSION AND FUTURE WORK

We have presented the design, implementation and discussion of a prototype dynamically deformable interactive surface with numerous features including a fast reaction time, user input and persistent output, and the ability to provide localised haptic feedback. These features have been illustrated by several usage scenarios. We have also outlined the performance of the system, including how the use of a steel baseplate allows our electromagnets to be 70% more powerful without extra power consumption or requiring a larger footprint.

We have focused on making a magnetic surface that is as flexible as possible and exploring possible applications that this technology is broadly suited to. In future we would like to focus on a specific application and tailor the ForceForm system to optimise it for that application. We would also like to experiment further with interaction techniques that use this type of deformable surface, as we feel that ForceForm invites interesting interaction possibilities. For maximum flexibility, it would be ideal to create a dynamic deformable surface that can be uniformly deformed at any arbitrary point, and have a magnetic surface that is magnetic all over, rather than just above each electromagnet.

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