Invention: **Tactile display / shape display**

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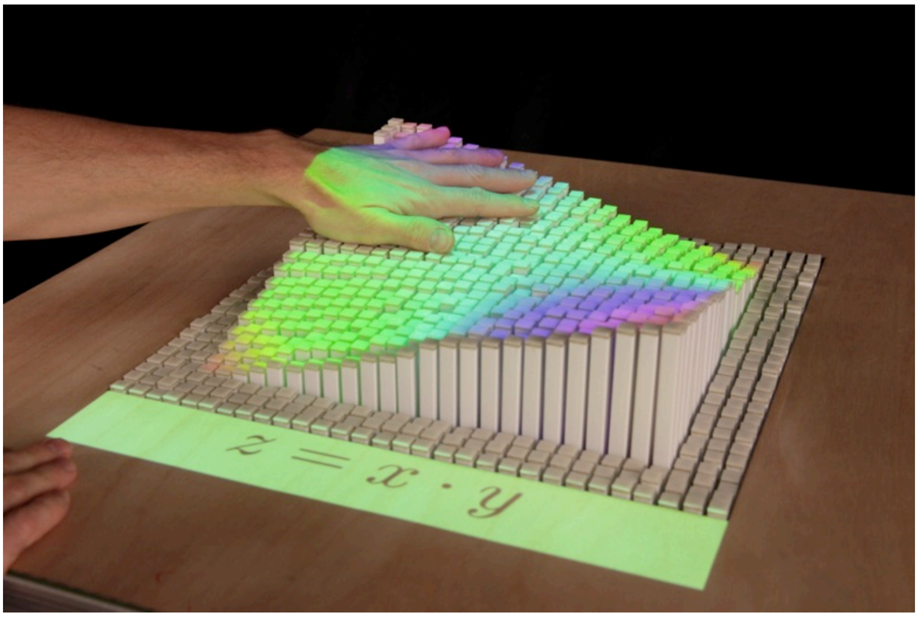
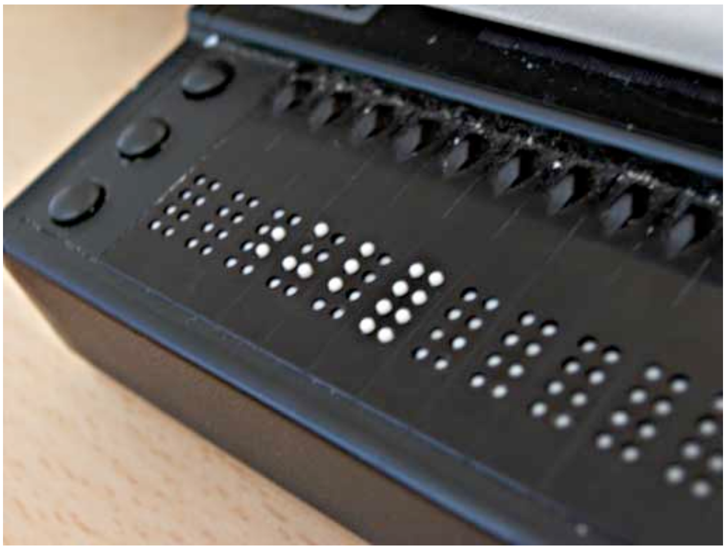
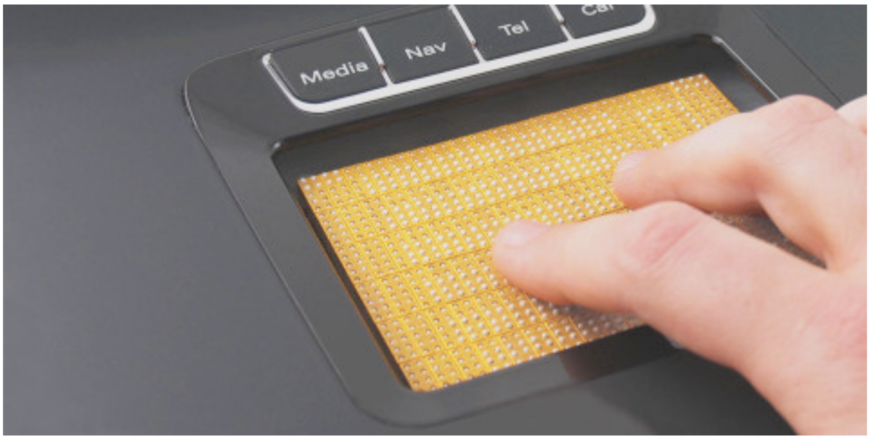
Aim of the invention: Construction of tactile resp. shape displays at lower costs compared to existing approaches. Such devices can be used for human-computer interfaces and in particular for presenting information to blind people.



Source: http://tangible.media.mit.edu/project/inform



Refreshable Braille device (https://en.wikipedia.org/wiki/Refreshable_braille_display)



State of the art: Haptic touchpad, for further information see:
https://www.researchgate.net/publication/220584804_Haptisches_Touchpad_zur_Infotainmentbedienung

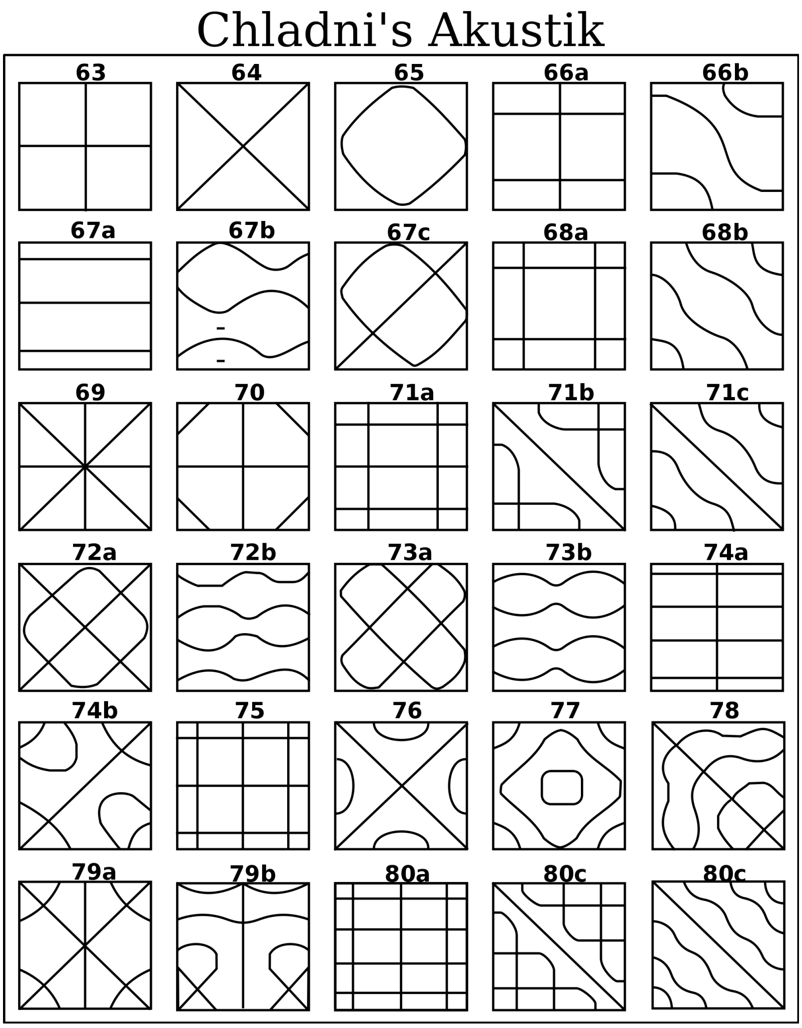
State of the art: Ultrasonic haptic feedback: http://spectrum.ieee.org/tech-talk/consumer-electronics/gadgets/ces-2015-hands-on-with-ultrahaptics-ultrasonic-tactile-display

State of the art:
- inForm project at MIT: Array of bars that can be controlled individually to generate programmed patterns, e.g. computed or scanned surfaces.
- Audi haptic touch, https://www.designaffairs.com/de/audi-haptic-touch/
- Braille devices (e.g. based on amplified piezoelectric actuators)
- Ultrasonic haptic feedback (the device, which uses ultrasound to generate air pressure waves, allows touchless haptic sensations)

Description of the invention:

The current inForm like approaches require many active mechanical components for presenting feature-reach surfaces – at least one control element per surface element, e.g. a (small) electric motor or valve. The key idea of the invention is to use an oscillating membrane as realized by a loudspeaker, for example, or a plate instead. It is well known that a plate shows oscillation patterns corresponding to its geometry and the excitation frequency. For not too strong excitations, the response to a multitude of frequencies is given by a linear superposition of the patterns of the individual frequencies - an idea known from Fourier analysis and synthesis of signals. The mathematical foundation of linear superposition is given by linear algebra. Using this superposition approach, nearly arbitrary patterns can be displayed, if the possible range of excitation frequencies is large enough. The achievable relatively small amplitudes will be sufficient to use the plate as a tactile display. The shape of the plate is not limited to a square, but could also be curved or of arbitrary shape.

For large amplitudes needed for shape displays (cf. inForm project at MIT), the oscillation of the membrane could be amplified by an array of levers, which transforms the motion of the membrane into a motion of an array of bars (this idea is inspired by the „pinart“ nail board, cf. figure below). The advantage of hollow bars (tubes) would be that their motion requires less force. One general side-effect of the invention is the generation of acoustic noise, which allows to differentiate between shapes by hearing, but can be unwanted in many cases. Therefore it is suggested that the oscillating plate moves bars from a resting position into the desired positions. When these positions are reached, the oscillation of the plate can be stopped. A ratchet meachanism could prevent the bars from falling into the null position, while allowing an intended reset of all bars.



Chladni figures for a quadratic plate exposed to a periodic excitation at different frequencies; the plate shows no oscillation along the shown lines, called nodal lines (https://de.wikipedia.org/wiki/Chladnische_Klangfigur)

Nail board „pin art“ (https://en.wikipedia.org/wiki/Pin_Art)

Alternatives to a ratchet mechanism (different kind of “shape memory”):

- The membrane could shape a material like modeling clay to preserve the oscillation pattern. A compromise is needed regarding the stiffness of the deformable material: It must be soft enough so that the force of the membrane is sufficient for achieving the deformation and it must be hard enough to withstand touching by the user. The deformable material could also consist of spheres filled with little magnets. It is possible to use a mechanical pusher for resetting the shape, i.e. flattening the material [a further, related invention would be to use oscillating membranes to generate shapes of granular media, like sand; this might require real-time feedback and solving non linear equations].
The advantage of this storage mechanism is that the smooth surfaces can be presented.

- “Freezing” of the position of the nails, which shall move through guidance tubes. The patterns of the nail board can be preserved by a (electro) magnet, which is mounted at the sides of the nail board. This requires that the nails (or hollow tubes etc.) be made at least partially from a ferromagnetic material so that the nails can be magnetized. A second (electro) magnet could be used to reset the pattern. If the nails are oriented vertically (with respect to the direction of gravity) it is suggested that the guidance tubes are filled with a viscous medium to prevent the nails from returning to their ‘ground state’ to fast. The operation of the haptic display could comprise the following steps:
1) The oscillation of the membrane is switched on for a sufficiently long period of time (until all nails are in the desired target position)
2) Electromagnets at the sides are switched on, which “freeze” the nail positions.

3) The oscillation is switched off.
4) Switching off the magnets at the sided is sufficient for resetting the pattern if the nails are oriented vertically, otherwise an electromagnet behind the nail board pulls back all nails.

Instead of electromagnets permanent magnets could be used whose distance from the nails can be varied, e.g. by mounting the magnets on a turnable arm, to choose between dropping or holding the nails.

A device constructed according to the invention without "shape memory" could be placed in an evacuated space, to minimize the acoustic noise. This will rule out the use of the device as a tactile display, but it could still be used for visual presentation of surfaces.

D. Gembris

Dresden, August 1st , 2017

Keywords: Haptic display, shape display, human computer interaction, membrane, Chladni figures, vacuum, granular media

Appendix:

Open questions:

- Which is the highest frequency a membrane can tolerate? What is the highest amplitude?
- Dependence of approximation error on maximum frequency?
- What is the best material for the membrane?

Wave physics:

The propagation of waves is described by the wave equation, a partial differential equation (PDE) of second order (v: wave velocity):

$$\frac{\partial^2}{\partial t^2} = v^2\left(\frac{\partial^2 u}{\partial x_1^2} + \frac{\partial^2 u}{\partial x_2^2}\right)$$

In the following a membrane of rectangular shape is considered with dimensions $a \times b$. It is clamped at the edges, i.e. $u(0,y,t) = u(a,y,t) = u(x,0,t) = u(x,b,t) = 0$.

This PDE can be solved by separation of variables using the following function:

$$\begin{aligned} u(x,y,t) &= af(x)g(y)h(t) \\ &= ae^{jk_x x}e^{jk_y y}e^{j\omega t} \end{aligned}$$

Inserting this expression into the PDE gives: $\omega^2 = v^2\left(k_x^2 + k_y^2\right)$ -

To ensure that the solutions fulfill the boundary conditions at $x = 0$ and $y = 0$, the exponential functions f(x) and g(x) are replaced by:

$$\sin kx = -\frac{i}{2}\left(e^{ikx} - e^{-ikx}\right).$$

The boundary conditions at x = a is met, if the spatial frequency k_y is an integer multiple of π/a:

$$k_1 = \frac{n_x \pi}{a}, \quad n_x = 1,2,\ldots$$

For the second coordinate, the following function is obtained:

$$g(y) = \sin(k_y y), \quad k_y = \frac{n_y \pi}{b}, \quad n_y = 1,2,\ldots .$$

The equations above lead to the following eigenmodes:

$$u_{n_x n_y} = \sin\left(\frac{n_x \pi x}{a}\right)\sin\left(\frac{n_y \pi y}{b}\right)e^{i\omega_{n_x}\omega_{n_y}t}$$ with the eigenfrequencies:

$$\omega_{n_x n_y} = v\pi\sqrt{\left(\frac{n_x}{a}\right)^2 + \left(\frac{n_y}{b}\right)^2} \;.$$

The boundary conditions thus result in a discrete frequency spectrum.

The general solution of the PDE for the rectangular membrane is the superposition of all eigenmodes:

$$u(x,y,t) = \sum_{n_x,n_y=1}^{\infty} \left\{ A_{n_1,n_2} \sin\left(\omega_{n_x n_y} t\right) + B_{n_1,n_2} \cos\left(\omega_{n_x n_y} t\right) \right\} \cdot \sin\left(\frac{n_x \pi}{a} x\right) \sin\left(\frac{n_y \pi}{b} y\right)$$

The expansion coefficients are obtained from the scalar product of the initial condition for the elongation and the spatial functions of $u(x,y,t)$ (the desired surface of the shape display):

$$B_{n_x,n_y} = \frac{4}{ab} \int_0^a \int_0^b u(x,y,0) \sin\left(\frac{n_x \pi}{a} x\right) \sin\left(\frac{n_y \pi}{b} y\right) \mathrm{d}x \mathrm{d}y$$

$$A_{n_x,n_y} = \frac{4}{ab\omega_{n_x,n_y}} \int_0^a \int_0^b \dot{u}(x,y,0) \sin\left(\frac{n_x \pi}{a} x\right) \sin\left(\frac{n_y \pi}{b} y\right) \mathrm{d}x \mathrm{d}y$$

These coefficients can be calculated by numerical integration. The input signal of the loudspeaker should thus consist of sine and cosine waves with the stated eigenfrequencies and amplitudes A and B. A necessary preparation step is to measure the wave velocity v, e.g. to determine some eigenfrequencies experimentally.

Literature:
https://e3.physik.uni-dortmund.de/~suter/Vorlesung/Physik_III_WS10/3.6_Wellen.pdf (in German)