Haptic Technologies for Direct Touch in Virtual Reality

http://mslab.es/SIG16Course

Miguel A. Otaduy, URJC Madrid

Allison Okamura, Stanford University

Sriram Subramanian, University of Sussex

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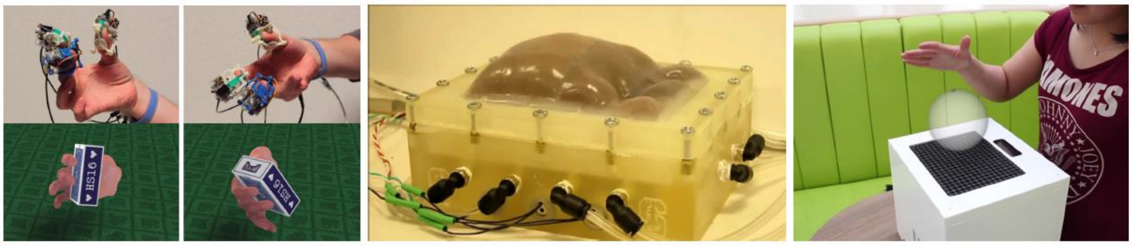
Introduction

Virtual reality (VR) is experiencing a renaissance thanks to technological progress in computer graphics and the commercial breakthroughs in head-mounted display and tracking technologies. Fully immersive VR requires virtual touch of comparably high quality, to allow bimanual interaction with the environment. However, current VR systems lack the ability to convey realistic haptic (kinesthetic and cutaneous) sensations, because traditional haptic technologies have focused on grounded, kinesthetic haptic interfaces that render virtual environments by outputting a force through a robotic end effector. They provide compelling simulations of tool-based interaction, but do not allow users to touch virtual content directly with their hands.

In line with the renaissance of VR, there is an explosion of novel haptic technologies too. In recent years, we have witnessed the advent of haptic technologies, both hardware and software, that enable compelling virtual touch directly with our hands. The novel available technologies employ diverse actuation principles, such as wearable robotic end effectors, active surfaces, or ultrasound haptic interfaces for mid-air feedback.



Novel haptic technologies open the door to many possibilities for computer graphics researchers and developers. While simulation and interaction methods for traditional kinesthetic haptic interfaces are well established, novel haptic interfaces exhibit many more degrees of freedom and multiple challenges for model and algorithm design. Similarly, they enable the design and development of so far unseen immersive VR applications.

Course Objectives

This course intends to disseminate the recent advances in haptic technologies among the computer graphics community. It will provide initial training on these technologies, so that computer graphics researchers and developers are ready to embark in the development of novel computational methods as well as immersive VR and AR applications with direct touch.

The course covers a broad range of topics relevant for research and development of direct touch solutions:

- **Fundamentals** on tactile perception and control theory relevant for application development, as well as tactile design considerations.

- **Actuation** technologies employed in direct-touch haptic interfaces, to understand the dimensionality, range, bandwidth, and resolution of sensations that can be produced. The different variants and their control mechanisms will also be discussed.
- **Software** methods for the connection of haptic actuators to VR simulations.

The course also covers three alternative haptic technologies, discussing particular aspects of each of them:

- **Wearable cutaneous devices** provide tactile feedback by stimulating skin directly with miniature electromechanical actuators, and eliminate typical workspace restrictions of haptic feedback. Several successful devices operate on the finger pad by translating and orienting a small mobile platform [Minamizawa et al. 2007; Prattichizzo et al. 2013], while others stretch skin tangentially to simulate frictional forces [Nishimura et al. 2014]. Tactile rendering methods control cutaneous devices to match contact configurations simulated in VR scenarios [Perez et al. 2015].
- **Active surfaces** enable direct exploration and palpation of dynamically varying shapes. Two successful approaches operate by controlling local shape through particle jamming with pneumatic actuators [Stanley and Okamura 2015], or modulating height fields using mechanically actuated pin arrays [Leithinger et al. 2015].
- **Mid-air haptic interfaces** enable both direct-touch and mid-air interaction, without the need to hold or wear any device. Different devices stimulate the skin using either air jets [Sodhi et al. 2013], vibrotactile feedback through localized ultrasound modulation combined with hand tracking [Long et al. 2014], or full spatial modulation of the ultrasound field [Inoue et al. 2015].

Intended Audience

The course is intended at general audience in computer graphics with an interest in research and development of VR applications. There is no prerequisite for course attendees. The course will start with fundamentals and will then evolve to technical content in connection with each actuation technology, but it will pay special attention to the big picture.

Speakers

The course gathers three lecturers who are currently at the forefront of research on haptic technologies for direct touch. In addition, their backgrounds span different areas, computer graphics, robotics, and HCI, contributing to a comprehensive coverage of the course.

- **Miguel A. Otaduy** is Professor of Computer Science at Universidad Rey Juan Carlos, Madrid. He received his MS and PhD from UNC - Chapel Hill, and was a senior research associate at ETH Zurich. His research covers from physics-based simulation to computational haptics, and is currently involved in two major European projects: Wearhap and the ERC Starting Grant Animetrics. He is/was program chair or editor-in-chief for the IEEE World Haptics Conference (2017 and 2019), the Symposium on Interactive 3D Graphics and Games (2014), and the Symposium on Computer Animation (2010). He is also co-chair of the Technical Committee on Haptics.
- **Allison Okamura** is a Professor of Mechanical Engineering and (by courtesy) Computer Science at Stanford University. She received her BS from UC Berkeley and MS/PhD from Stanford University. She has been editor-in-chief of the IEEE International Conference

on Robotics and Automation, associate editor of the IEEE Transactions on Haptics, and co-chair of the IEEE Haptics Symposium. Her awards include the IEEE Technical Committee on Haptics Early Career Award, the IEEE Robotics and Automation Society Early Career Award, and the NSF CAREER Award. She is an IEEE Fellow. Her research interests include haptics, teleoperation, virtual reality, medical robotics, neuromechanics, and education.

- **Sriram Subramanian** is Professor on Engineering and Informatics at the University of Sussex. Before joining Sussex, he was a Professor at the University of Bristol and a senior scientist at Philips Research Netherlands. He is specifically interested in rich and expressive input combining multi-touch, haptics and touchless gestures. He holds an ERC Starting Grant and has received funding from the EU FET-open call. In 2014 he was one of 30 young scientists invited by the WEF to attend their Summer Davos. He co-founded Ultrahaptics a spin-out company that aims to commercialise mid-air haptic using phased array of ultrasound transducers.

Agenda

The duration of the course is 1.5 hours, split in the following way:

- 30 min. Wearable cutaneous devices (Otaduy).
- 30 min. Active surfaces (Okamura).
- 30 min. Ultrasound haptic interfaces (Subramanian).

References

INOUE, S., MAKINO, Y., AND SHINODA, H. 2015. Active touch perception produced by airborne ultrasonic haptic hologram. In World Haptics Conference (WHC), 2015 IEEE, 362–367.

LEITHINGER, D., FOLLMER, S., OLWAL, A., AND ISHII, H. 2015. Shape displays: Spatial interaction with dynamic physical form. Computer Graphics and Applications, IEEE 35, 5, 5–11.

LONG, B., SEAH, S. A., CARTER, T., AND SUBRAMANIAN, S. 2014. Rendering volumetric haptic shapes in mid-air using ultrasound. ACM Trans. Graph. 33, 6, 181:1–181:10.

MINAMIZAWA, K., KAJIMOTO, H., KAWAKAMI, N., AND TACHI, S. 2007. A wearable haptic display to present the gravity sensation - preliminary observations and device design. In EuroHaptics Conference, 2007 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2007. Second Joint, 133–138.

NISHIMURA, N., LEONARDIS, D., SOLAZZI, M., FRISOLI, A., AND KAJIMOTO, H. 2014. Wearable encounter-type haptic device with 2-dof motion and vibration for presentation of friction. In Haptics Symposium (HAPTICS), 2014 IEEE, 303–306.

PEREZ, A., LOBO, D., CHINELLO, F., CIRIO, G., MALVEZZI, M., SAN MARTIN, J., PRATTICHIZZO, D., AND OTADUY, M. 2015. Soft finger tactile rendering for wearable haptics. In World Haptics Conference (WHC), 2015 IEEE, 327–332.

PRATTICHIZZO, D., CHINELLO, F., PACCHIEROTTI, C., AND MALVEZZI, M. 2013. Towards wearability in fingertip haptics: A 3-dof wearable device for cutaneous force feedback. IEEE Transactions on Haptics 6, 4, 506–516.

SODHI, R., POUPYREV, I., GLISSON, M., AND ISRAR, A. 2013. Aireal: Interactive tactile experiences in free air. ACM Trans. Graph. 32, 4, 134:1–134:10.

STANLEY, A., AND OKAMURA, A. 2015. Controllable surface haptics via particle jamming and pneumatics. Haptics, IEEE Transactions on 8, 1, 20–30.

Wearable Cutaneous Haptics

Devices and Rendering

Miguel A. Otaduy
URJC Madrid
http://mslab.es

Outline

1. Stimulation and actuation methods
2. Skin simulation
3. Tactile rendering

Wearable Cutaneous Haptics
Devices and Rendering

1. Stimulation and actuation methods

Wearable Haptics

- Devices grounded on the body

- No workspace limitations
- Passive vs. Active haptics
- Limited power
- Limited feedback

In contrast to traditional grounded haptic interfaces, wearable haptics propose interfaces that are grounded on the body of the user. This conceptual difference introduces other technological differences that affect the design of wearable haptic interfaces and their control algorithms. There are both advantages and disadvantages.

1. Wearable devices are not limited to a constrained **workspace**. Therefore, they allow users to move freely and perceive haptic feedback in a much larger range, much like in the real world.
2. Much of wearable haptic technology targets cutaneous actuation. The response of the body to cutaneous stimulation is **passive**, in contrast to the response to kinesthetic stimulation, which is active. Passive systems simplify the design and update rate requirements of rendering algorithms.
3. On the other hand, wearability introduces **power** limitations. Devices must be built with miniature technology, but actuation is limited due to weight and power consumption.
4. Wearability also introduces limitations in terms of the available **feedback**. The action-reaction principle limits feedback to the location of the body where the devices are grounded. For example, it is not possible to stop the whole body.

Devices in the images: [Solazzi et al., Proc. of IEEE RO-MAN 2010; Chinello et al., Proc. of IEEE Haptics Symp. 2012; Leonardis et al., Proc. of IEEE World Haptics Conf. 2015]

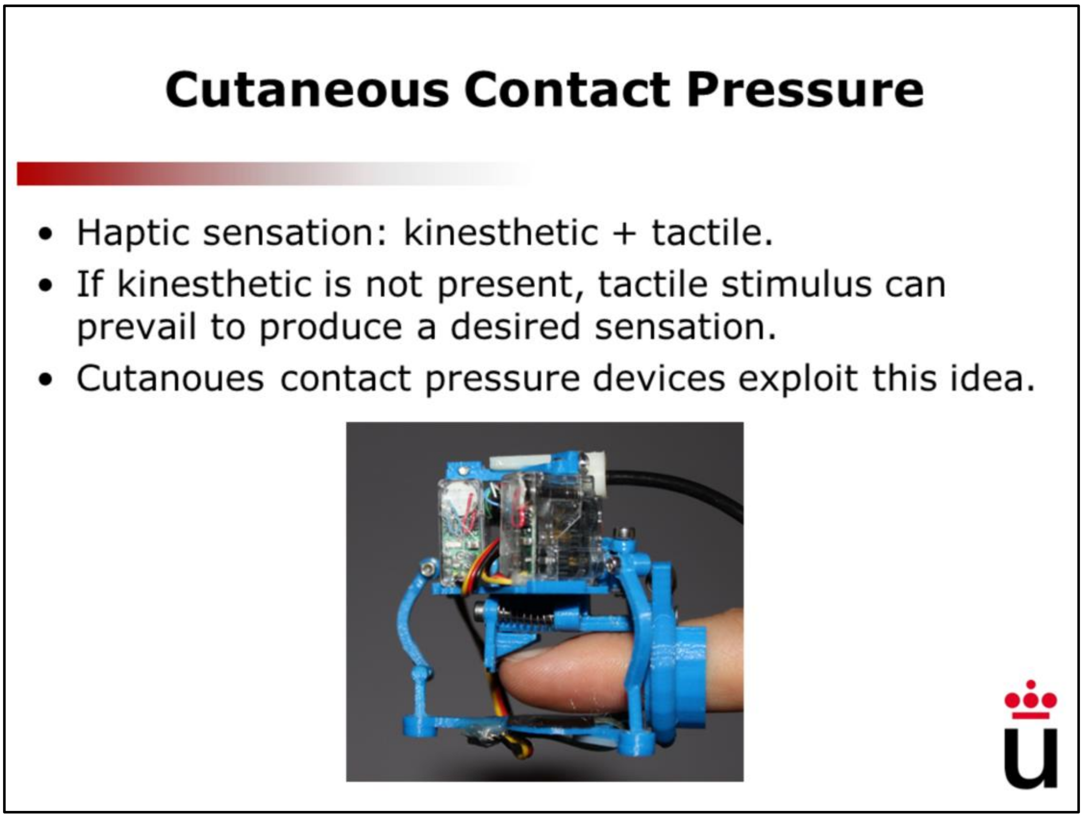
Kinesthetic Stimulation - Exoeskeletons

- Antropomorphic devices to act on body DoFs.
- They constrain relative motion.

Exoskeleton devices are more or less antromorphic, to provide forces on natural degrees of freedom of the body.

They are grounded on one part of the body (e.g., the forearm) to provide feedback on a different part (e.g., the fingers). Thanks to this setup, they succeed to constrain relative motion.

Devices in the images: Dexmo F2 by Dexta Robotics; [Lucas et al., Journal of Robotics and Mechatronics 2004]



When exploring a bump, the object geometry produces forces (i.e., kinesthetic stimulus), but the local shape also produces skin deformation (i.e., tactile stimulus). The brain interprets the combined haptic stimulus [Wijntjes et al. IEEE Trans. on Haptics 2009; Drewing and Ernst, Brain Research 2006]. Exploiting this observation, some devices provide cutaneous stimulation only, which is interpreted as a full interaction with a Surface.

Such devices modulate contact pressure against the skin, typically at the finger pad. Some devices are built as a pin array that enables a local approximation of an arbitrary surface, others consist of a small platform that is controlled as the end effector of a robotic structure. The devices may also vary in terms of their control strategy, based on position control or force control.

Device in the image: [Chinello et al., Proc. of ASME/IEEE Intl. Conf. on Advanced Intelligent Mechatronics 2015]

Contact Area

- Contact produces a change in contact force and contact area. Their relation indicates object softness.
- Some prototypes expose a controllable membrane.

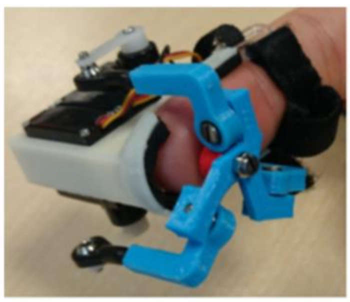
When contact on takes place on the skin, both contact force and contact area vary. The relationship between these two magnitudes provides information about object softness. [Bicchi et al., Brain Research 2008].

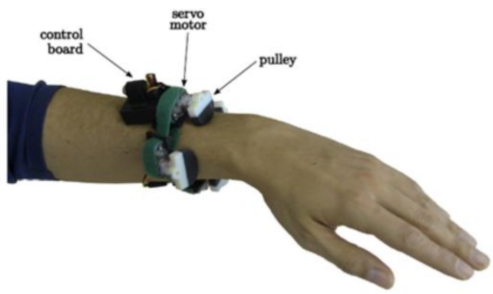
Some wearable devices exploit this observation to render contact on finger pads using controllable soft membranes.

Device in the image: [Battaglia et al., Proc. of IEEE Haptics Symp. 2016]

Skin Stretch

- Skin stretch can be exploited in two ways:
  - It can replace normal forces, due to the coexistence of skin stretch during normal contact.
  - It is a natural sensation under frictional contact.





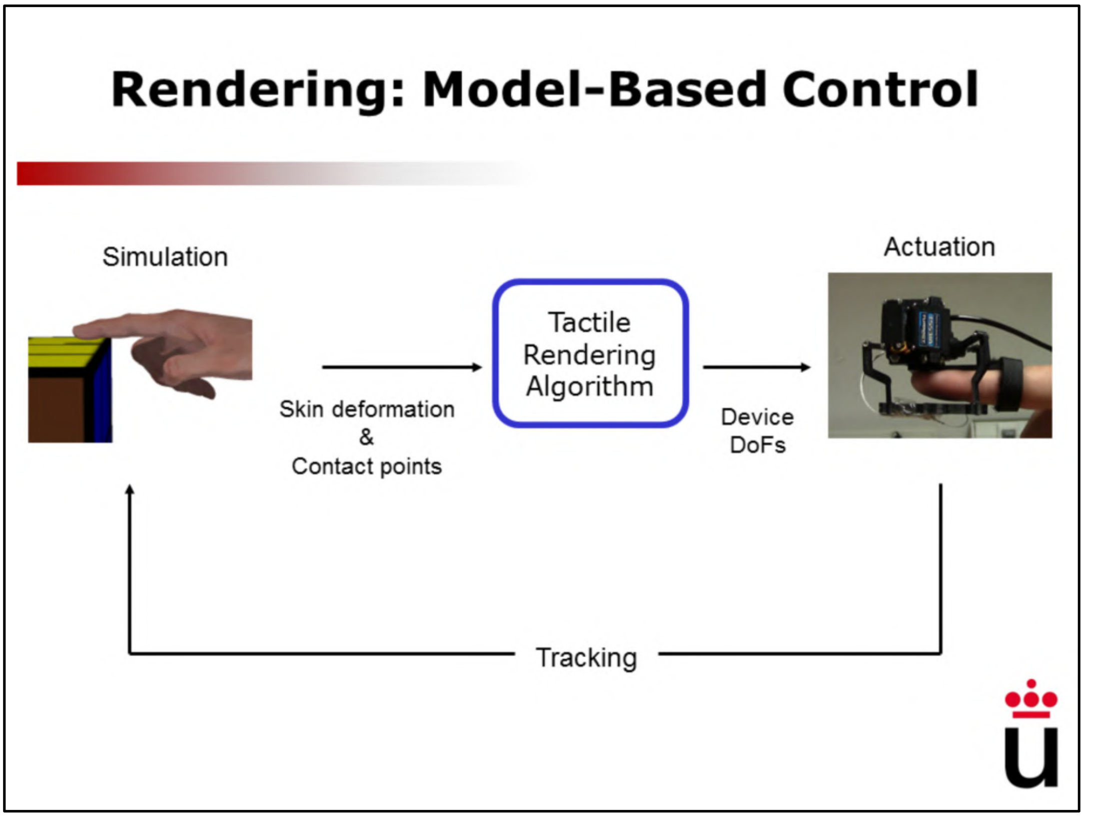
Similarly to contact area and force, under normal contact skin is also stretched. Then, it is possible to convey normal contact without actually applying normal forces, just by tangentially stretching skin [Hayward and Cruz; IEEE Haptics Symp. 2000].

In addition, lateral skin stretch is a natural way to convey tangential friction forces.

Devices in the image: [Leonardis et al., Proc. of IEEE World Haptics Conf. 2015; Chinello et al., Proc. of IEEE Haptics Symp. 2016]

Wearable Cutaneous Haptics
Devices and Rendering

2. Skin simulation

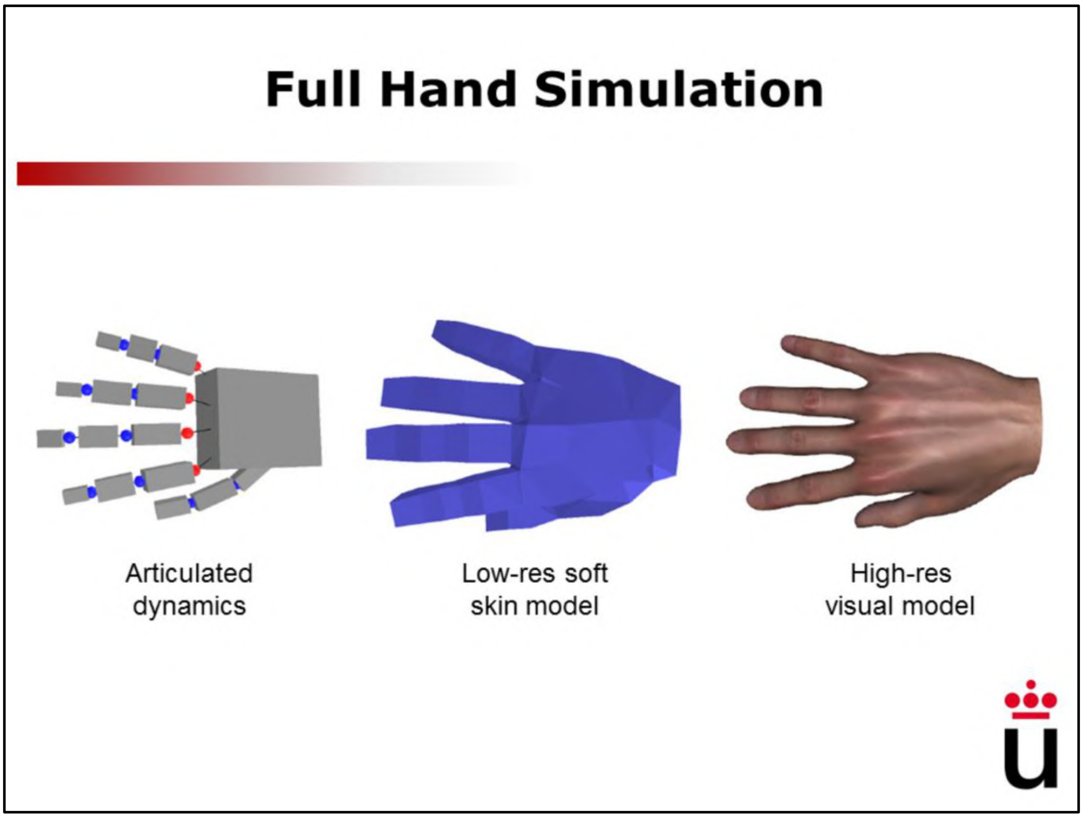


Haptic rendering can be regarded as a model-based approach to control haptic devices. The virtual environment executes a simulation of contact with virtual objects, and contact information from this simulation is used to control the configuration (position or force) of the haptic device [Otaduy et al., Proc. of IEEE 2013].

In tactile rendering, we can follow the same strategy, but in this case it is necessary to simulate contact between a model of the skin and virtual objects. Taking as input skin deformation and contact points/forces, the tactile rendering algorithm will decide the configuration of the cutaneous device.

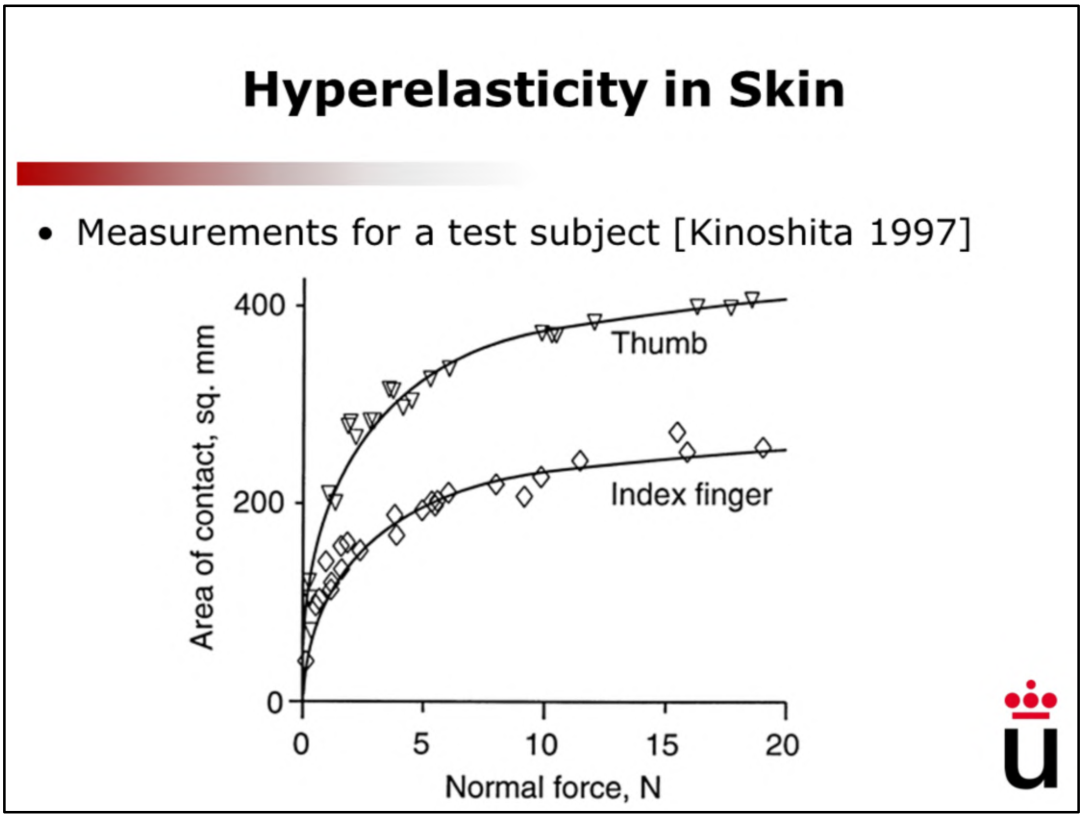
The rendering loop is closed by tracking the motion of the user, which is used as a goal input in the virtul simulation.

To achieve high fidelity tactile rendering, it is necessary to simulate an accurate model of skin.

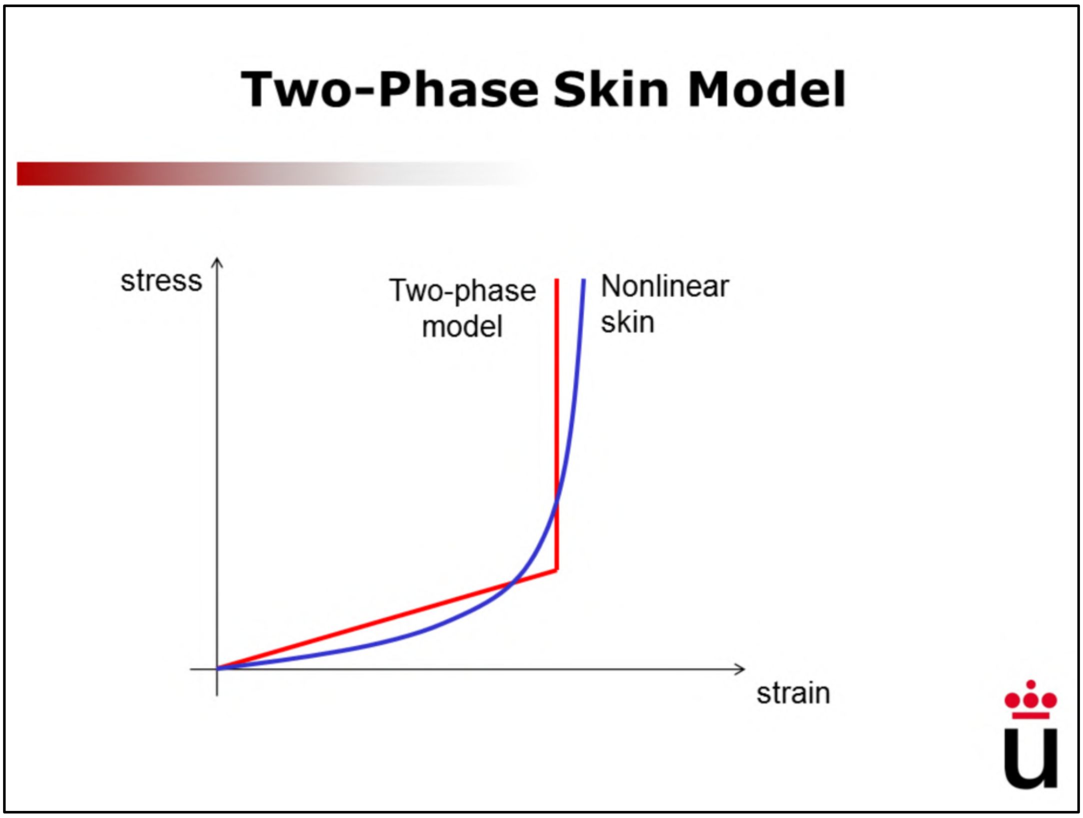


Humans use mainly their hands to explore, manipulate, and interact with the world through touch. As a result, tactile rendering has mostly focused on providing tactile feedback on the hand. In the simulation-based rendering strategy mentioned in the previous slide, this requires a simulation of the full hand.

From the computational point of view, a full-hand simulation requires: articulated skeleton dynamics, soft flesh deformation, and two-way coupling between them [Garre et al. IEEE World Haptics Conf. 2011].

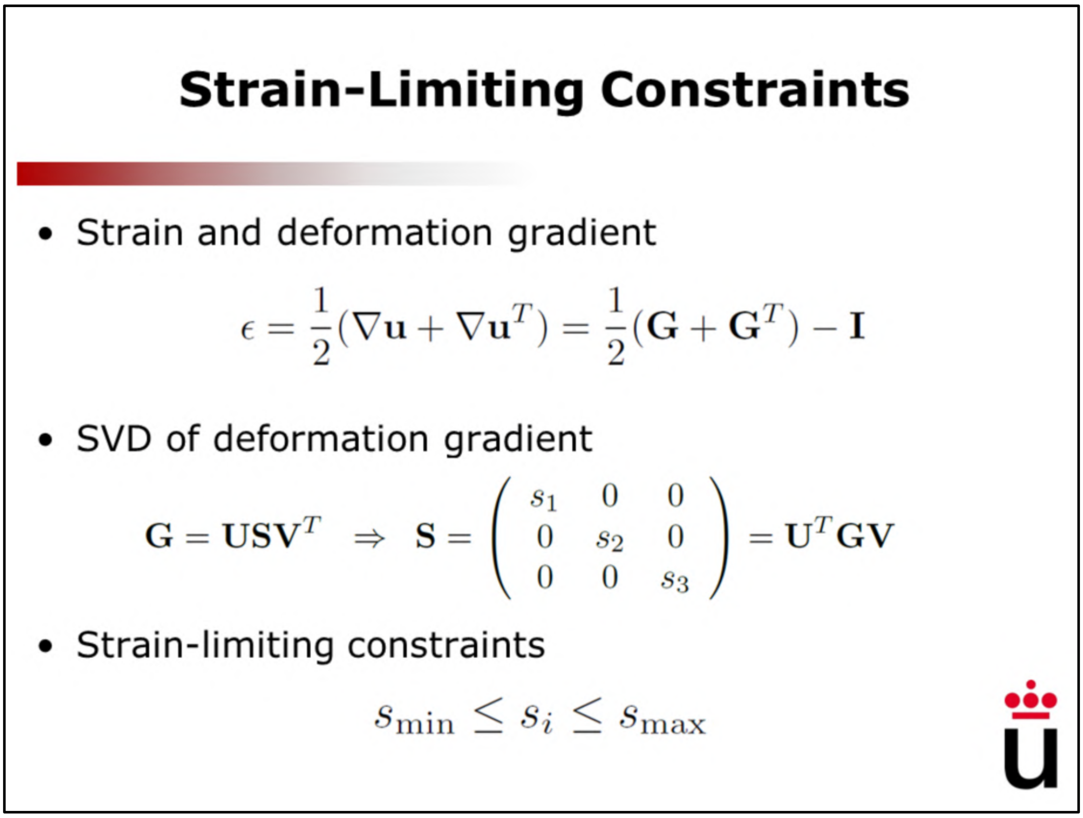


One of the major sources of complexity in the simulation of the hand is the hyperelastic behavior of skin. This is evident from measurements of force vs. contact area [Serina et al. Journal of Biomechanics 1997; Kinoshita et al. Journal of Neurophysiology 1997]. At initial contact, under small contact forces, skin is very compliant and the contact area grows rapidly. This is benefecial for our interaction with the environment, as a large contact area enables a more stable grasp. But as forces grow, skin reaches incompressibility and contact acts against the underlying rigid bone. Forces grow while contact area remains practically fixed.



Typical elasticity models in computer graphics cover only linear materials, i.e., with a linear strain-stress relationship. A linear material largely simplifies computations, which is particular important in the context of haptic rendering methods. However, neither soft elastic nor stiff elastic materials provide the desired behavior.

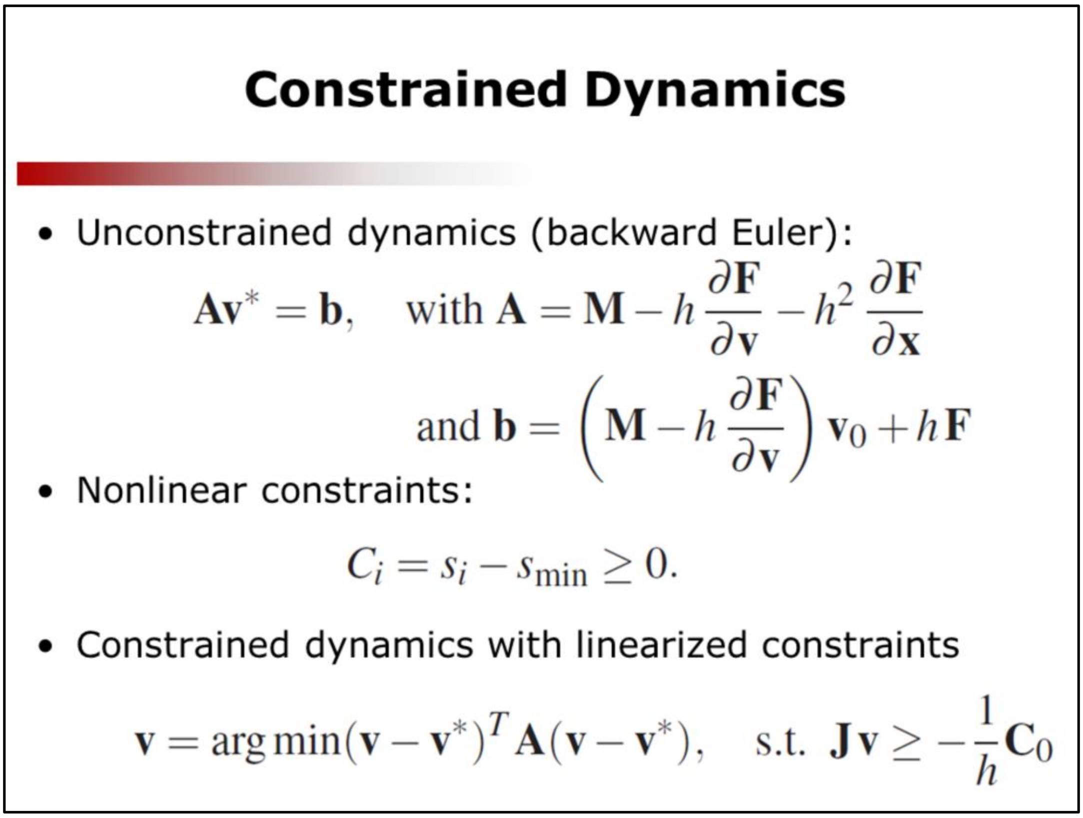
As an alternative, we can use a two-phase model, soft linear elastic under small strains, and with strain-limiting constraints once a certain deformation is reached. For very stiff behavior, it is computationally advantegeous to model hard constraints instead of stiff energies.



Several different strain-limiting models have been developed in computer graphics, particularly for cloth [Thomaszewski et al., Eurographics 2009; Wang et al. ACM SIGGRAPH Asia 2010].

Instead, here we describe a strain-limiting approach that fits within constrained dynamics [Pérez et al., IEEE World Haptics Conf. 2013], and can be solved together with other constraints (e.g., due to frictional contact) using constrained optimization solvers.

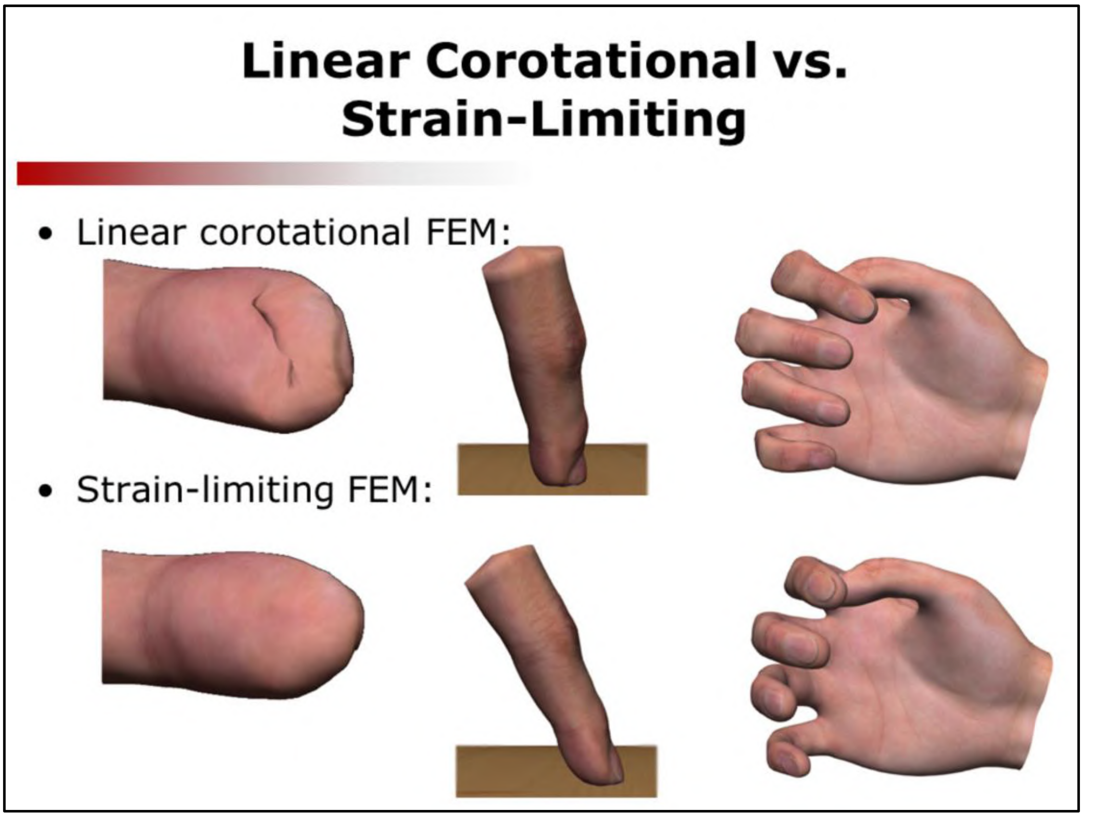
The core idea is to limit the amount of strain, by limiting the deformation gradient G. In practice, the method computes the singular values of the deformation gradient, and applies stretch and compression constraints on each singular value independently. On a tetrahedral discretization, this method amounts to formulating up to six constraints per tetrahedron.



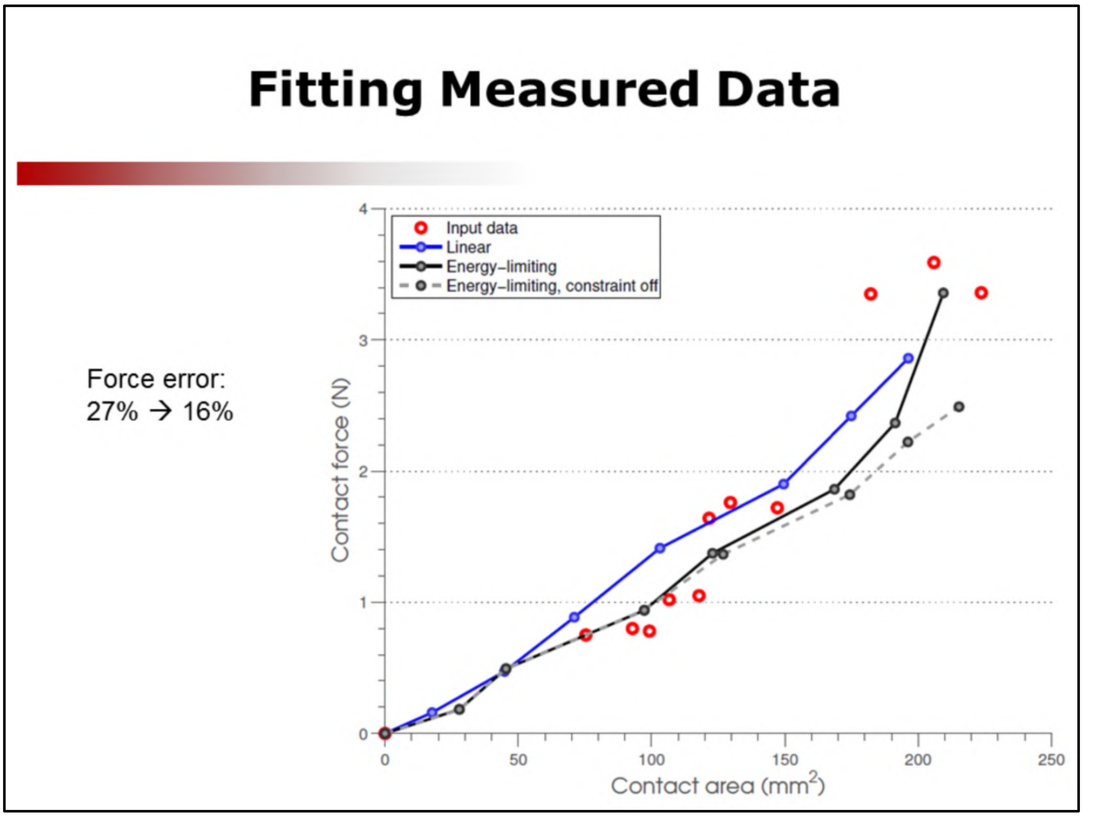
By combining discretized dynamics (e.g., using backward Euler implicit integration) together with strain-limiting constraints, we obtain a formulation of deformation dynamics as a constrained optimization problem.

This problem is comparable to typical constrained dynamics problems used for contact handling, which are formulated as Linear Complementarity Problems (LCPs) and solved using relaxation methods (e.g., projected Gauss-Seidel).

However, deformation constraints exhibit high nonlinearity in contrast to contact constraints, and solvers based on linearization suffer bad convergence. An alternative is to design solvers for nonlinear problems, such as line-search Jacobi relaxation [Pérez et al., IEEE Haptics Symp. 2016].



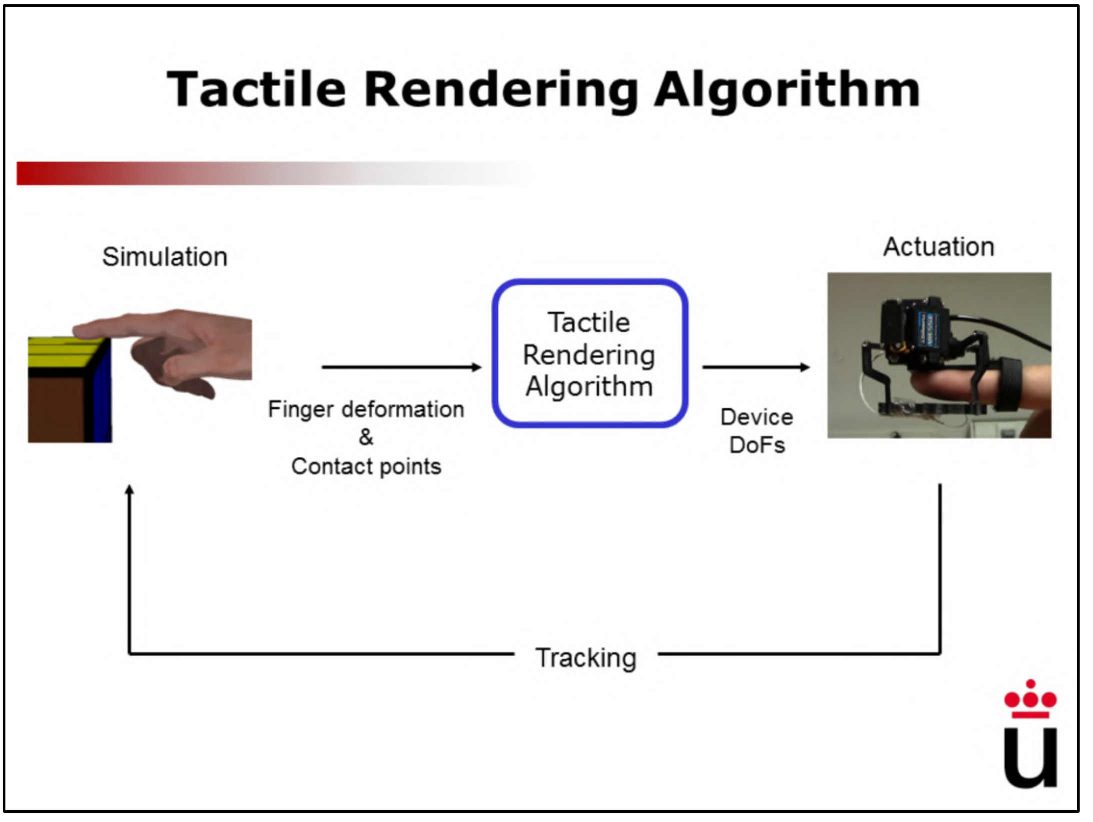
The images compare real-time simulations of a soft linear corotational model vs. a strain-limiting model. Under small forces both behave similarly and exhibit the soft deformation present in real skin. However, under larger forces the soft linear corotational model suffers various types of artifacts, not present in the strain-limiting model: inversion of elements under friction forces, collapse of the finger under high pressure, and extreme deformation of finger joints.



The strain-limiting nonlinear skin model also fits well data measured from actual subjects. Using force-area data collected in controlled experiments [Miguel et al., IEEE World Haptics Conf. 2015], a linear material model makes a compromise between the initial softness and the highly constrained behavior. The two-phase nonlinear model, on the other hand, fits better both regimes. The overall force error is reduced from 27% down to 16%.

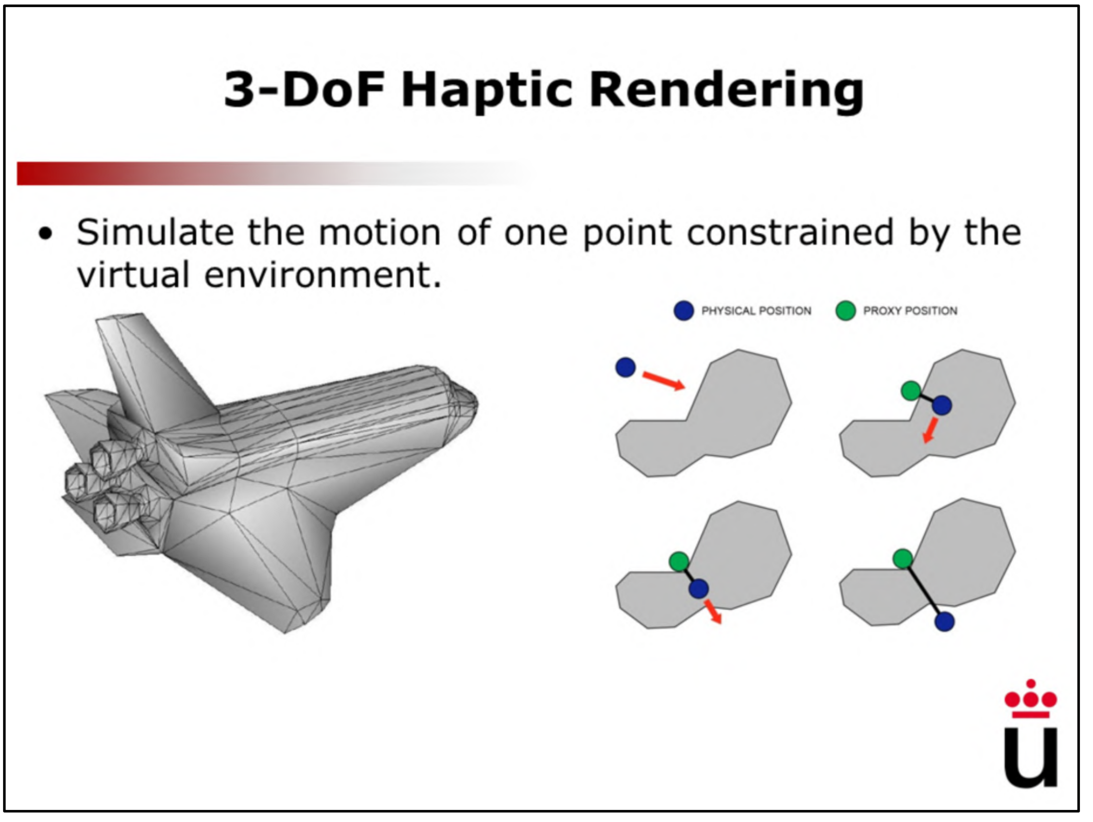
Wearable Cutaneous Haptics
Devices and Rendering

3. Tactile rendering



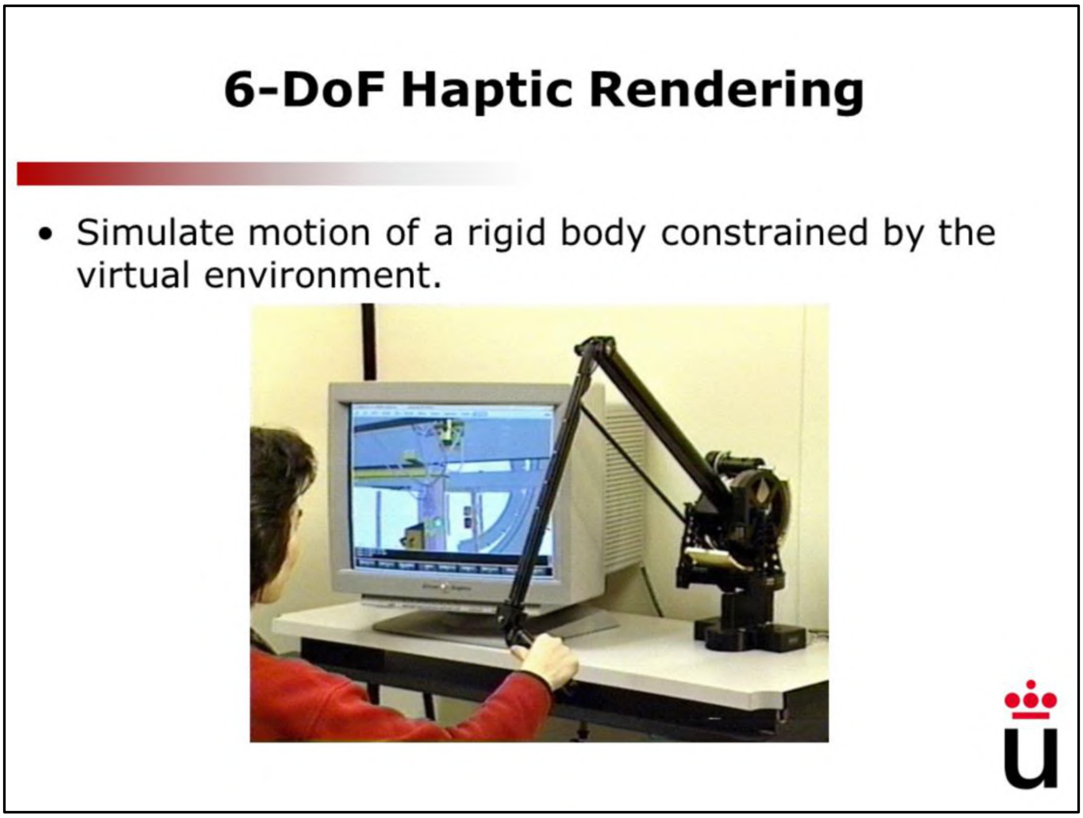
Let’s recall the complete tactile rendering framework. Given a simulation of the interaction between a skin model and virtual objects, the rendering algorithm is in charge of computing the command configuration of the tactile device.

As we will see next, some of the rendering algorithms simplify the problema by computing a simulation with just as many degrees of freedom as the device, while others compute an accurate simulation and then reduce the response to the domain of the device.



Before jumping to tactile rendering, let us describe classic haptic rendering algorithms, due to their similarity.

The earliest approach in haptic rendering, called 3-Degree-of-freedom (DoF) haptic rendering, simulates contact between a point and objects in the virtual environment [Zilles and Salisbury, IROS 1995; Ruspini et al., ACM SIGGRAPH 1997]. This point is constrained by the surfaces of the virtual objects while it tries to reach the configuration tracked by the device (a.k.a. haptic interface point, HIP, or haptic probe). Haptic feedback is obtained by computing a force as a function of the vector difference between the haptic interface point and the constrained point.

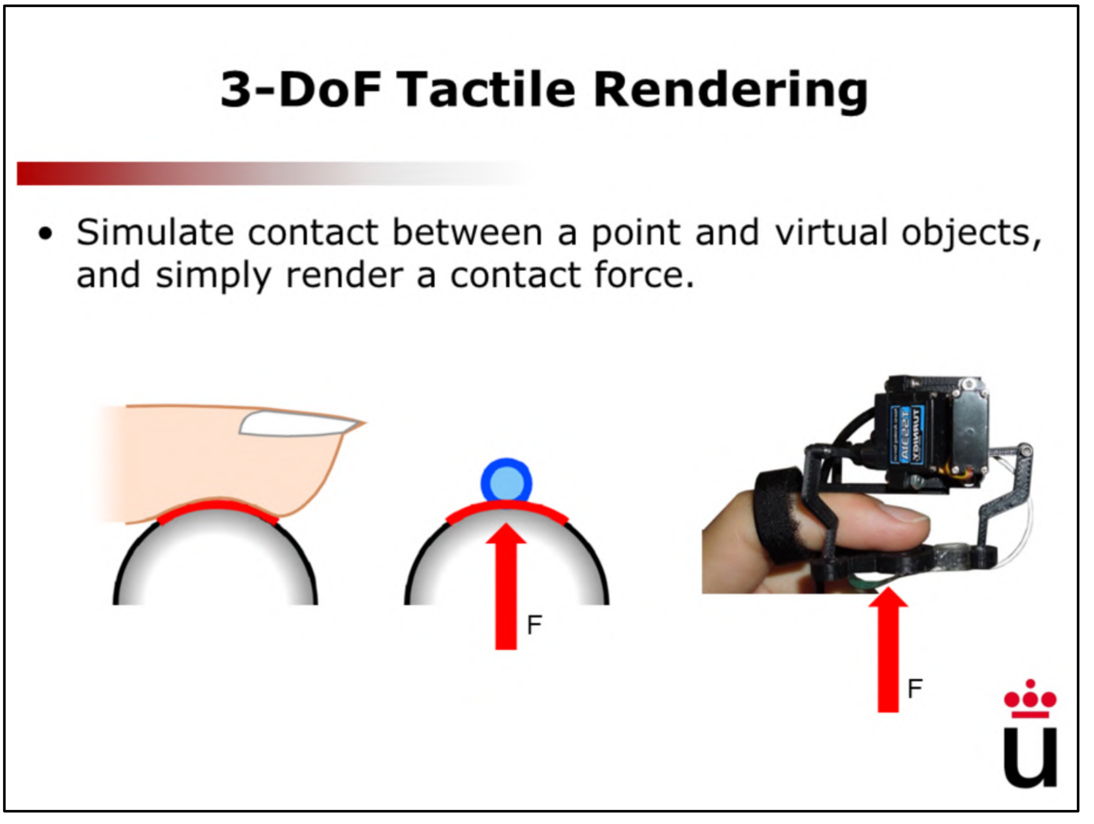


The next step was to simulate contact between a rigid body and the virtual environment, and constrain the motion of the body to object surfaces. This approach is called 6-DoF haptic rendering. Haptic feedback is obtained by computing force and torque as a function of the traslantion and rotation difference between the constrained body and the configuration tracked by the device [McNeely et al., ACM SIGGRAPH 1999].

This approach allows haptic feedback of tool-object interaction, but it is not suited for direct touch.

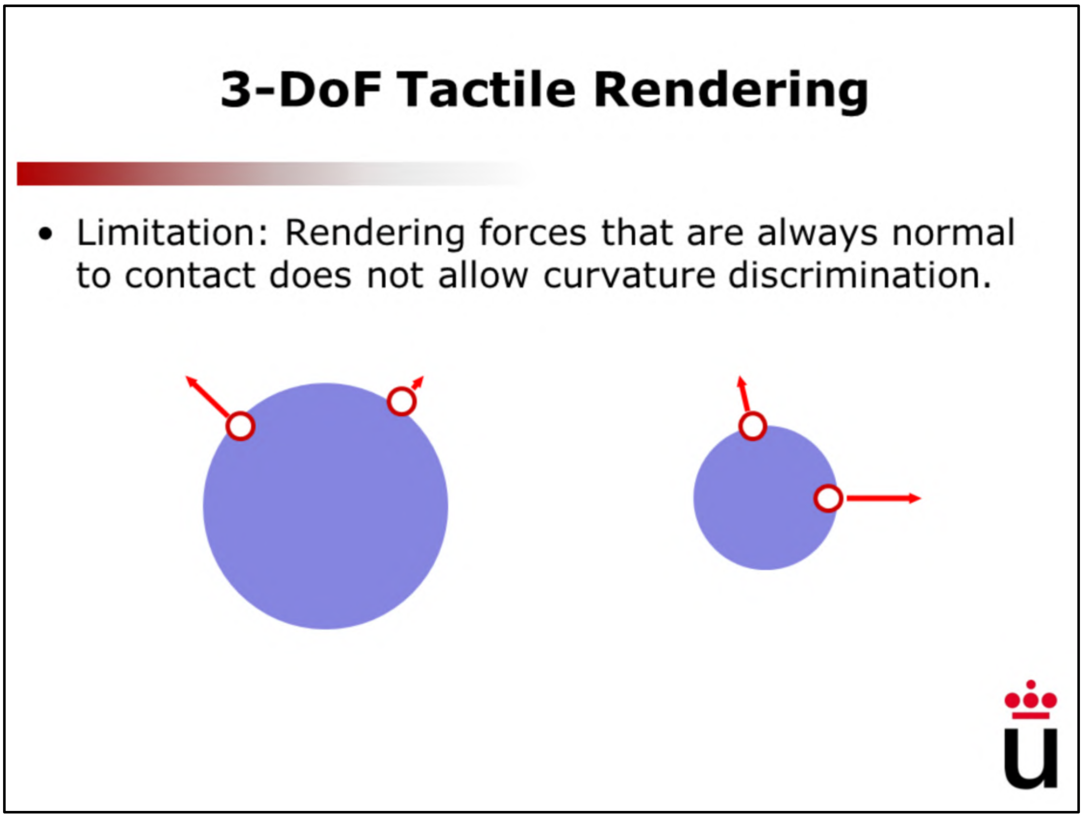
The various cutaneous devices described in section 1 use different stimulation methods, and hence their rendering algorithms also vary.

Here, we describe rendering algorithms for devices that employ contact surface modulation as stimulation method.



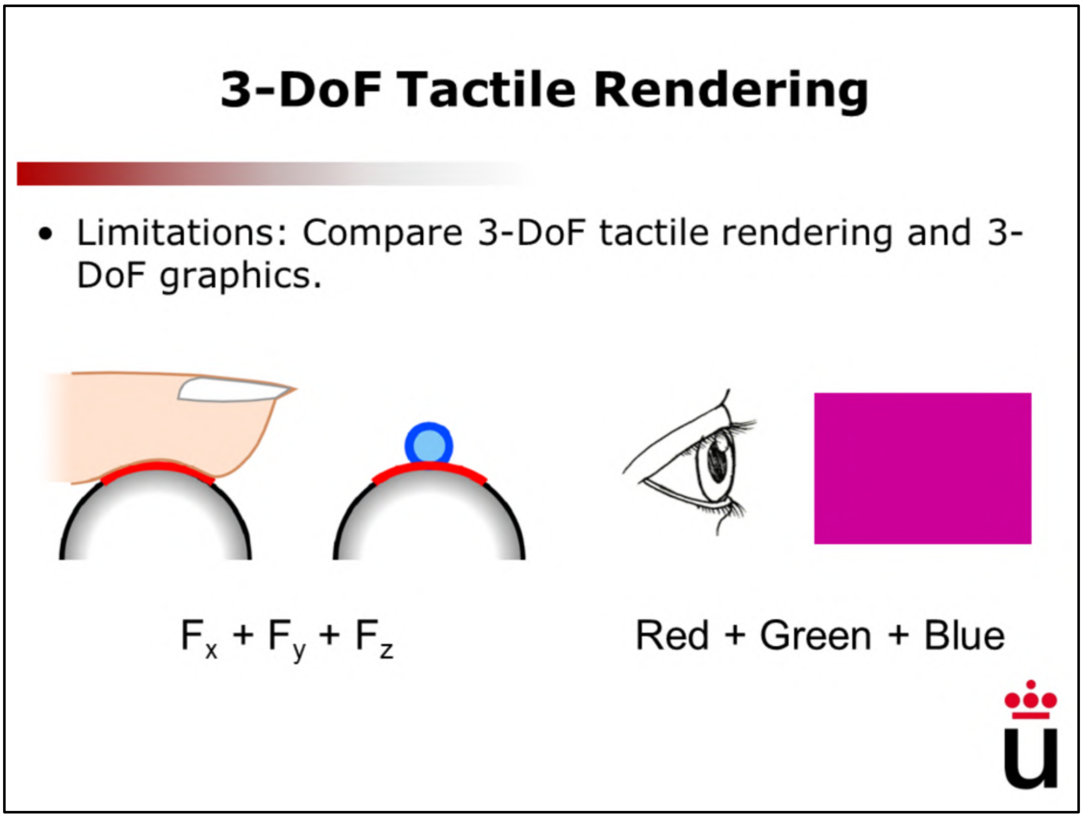
Wearable cutaneous devices based on controllable platforms are so far limited in the dimensionality of their motion space. Taking advantage of this dimensionality, it is possible to simulate contact between just one point and virtual objects. This single point represents the centroid of the finger pad.

Then, the force computed for the single point is directly rendered by the device.



Unfortunately, 3-DoF tactile rendering suffers many limitations. A clear limitation is the inability to convey curvature information, because a point contact does not allow a representation of relative orientation between the finger pad and virtual objects.

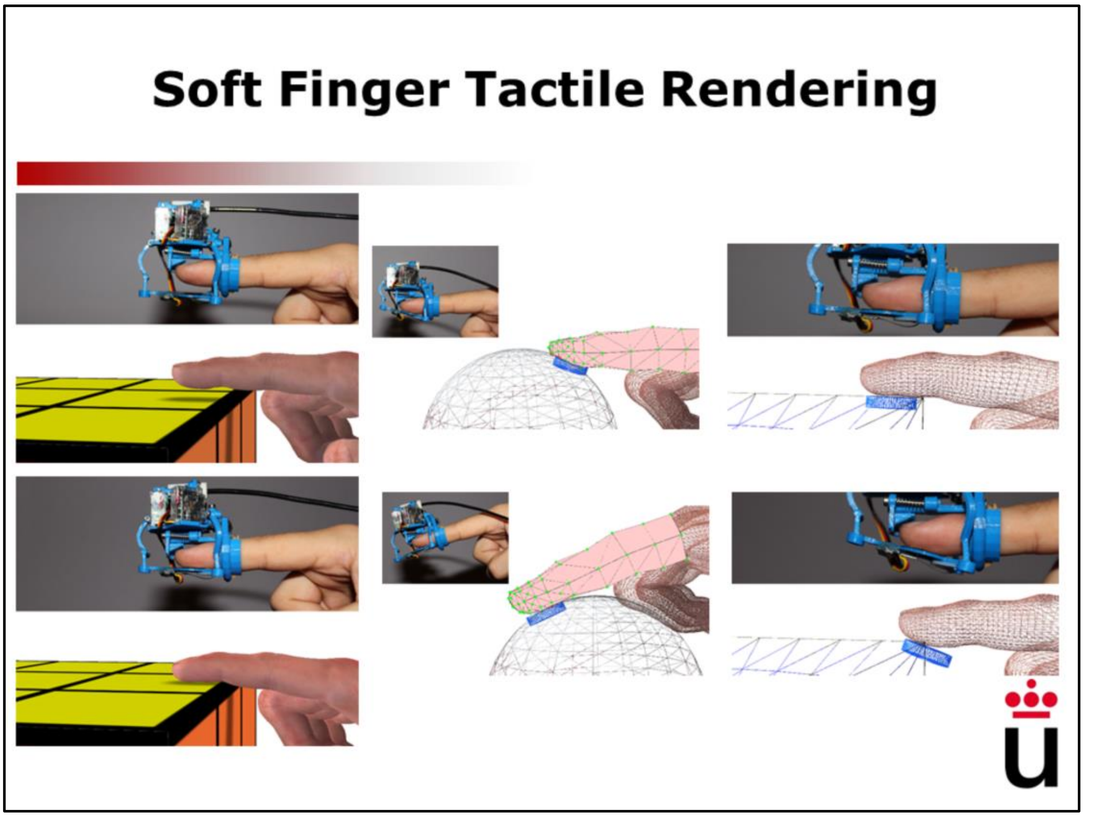
Proprioception would help us to perceive shape in the real world, but this is not possible from cutaneous feedback, due to the inability to constrain the absolute motion of the fingers.



The truth is that tactile sensing is a high-dimensional phenomenon, and cannot be approximated in a 3-DoF space.

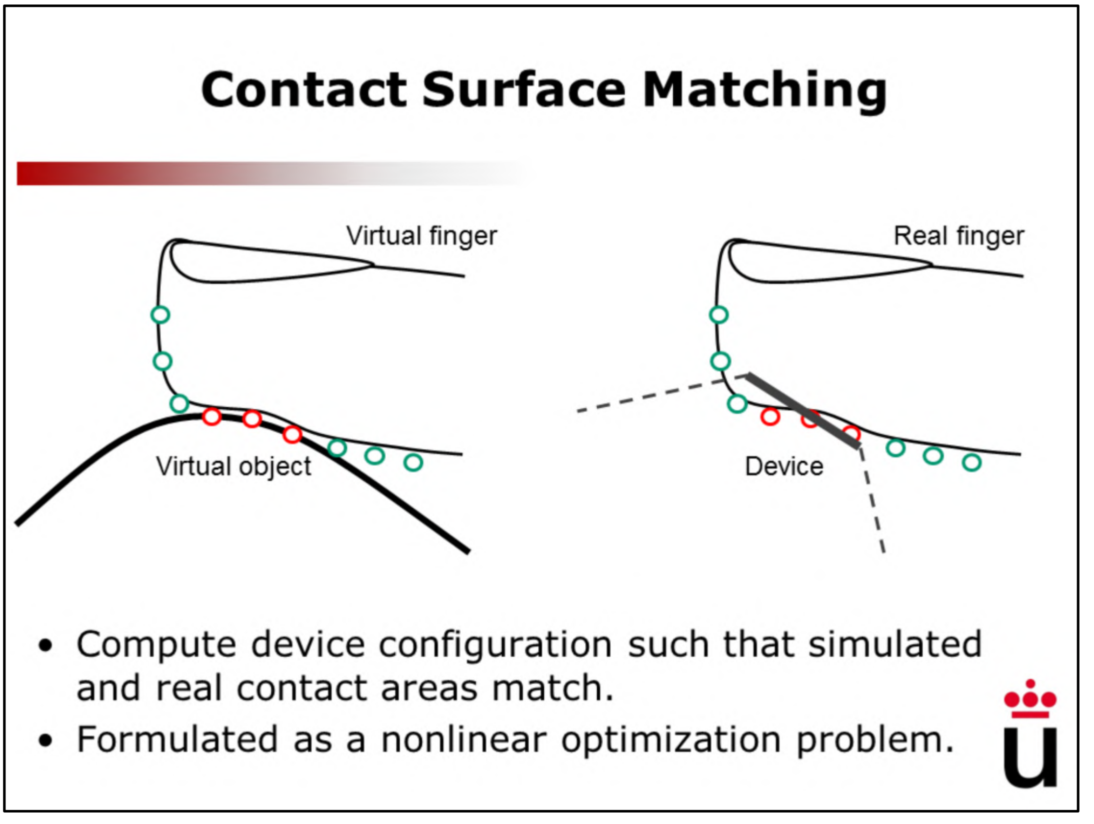
Consider the following comparison to computer graphics. A 3-DoF graphics would consist of displaying an image with a single color. We would only be able to change this color in time.

The accuracy of tactile rendering can be enhanced by simulating a high-dimensional contact problema between an accurate model of skin and virtual objects (as shown in section 2), and then computing an optimal reduced output specific to each particular device.



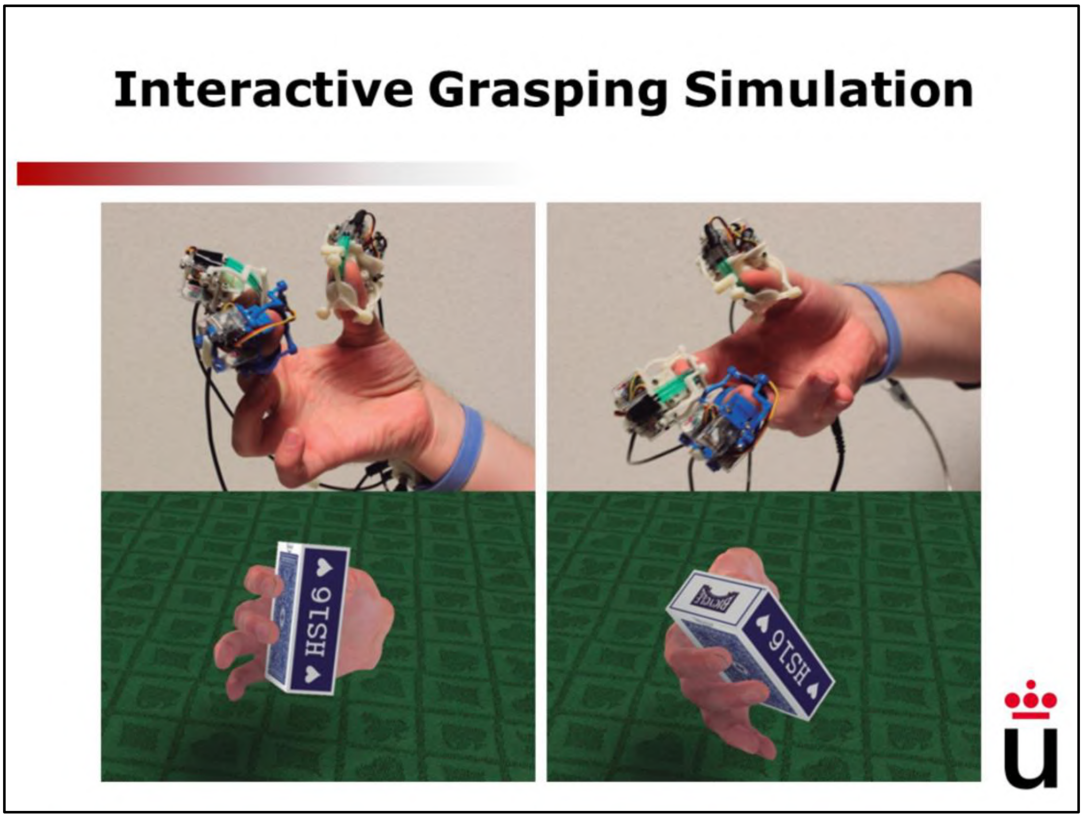
In soft finger tactile rendering, the configuration of a wearable tactile device is governed as a function of full contact between a nonlinear soft finger model and virtual objects. So far, this approach has been followed for the design of tactile rendering algorithms for contact surface modulation devices. In addition, it has only been applied on 3-DoF devices, but it could be extended to others.

Full contact information between a finger model and virtual objects allows to account for contact location as well as relative orientation between the finger and virtual objects. Moreover, this information could also be used to account for pressure distribution and for tangential friction forces on future higher dimensional devices.



Once full contact between the finger model and virtual objects is computed, the rendering algorithm is based on the principle of contact surface matching. This is formulated as an optimization problem, where the configuration of the device is computed such that the contact areas in the virtual environment and between the device and the real finger are as similar as possible [Pérez et al., IEEE World Haptics Conf. 2015].

Formulating tactile rendering as an optimization problem is a powerful tool. It handles both forward and inverse kinematics, for devices that are either open-loop mechanisms or parallel mechanisms. It also allows a seamless extension to handle workspace constraints, in the context of constrained optimization. In addition, the formulation of the objective function allows different weighting of desired properties.



In this example, soft finger tactile rendering is used in the context of a grasping simulation. The user perceives the strength of the grasp, as well as the relative orientation between the finger pads and the object being grasped.

More complex devices, with additional degrees of freedom, would also allow feeling tangential forces, and therefore slipping friction.

Future Work

- Higher-dimensionality devices
- Cutaneous – kinesthetic integration
- Optimization-based formulations of rendering

The changes in wearable haptics are enormous, and the field is making progress at a fast pace. At the same time, there is room for many future improvements. Some of them include the design of devices of higher dimensionality, which would allow combined perception of rich friction and normal forces, the integration of wearable cutaneous and kinesthetic feedback, and the evolution of tactile rendering algorithms toward richer optimization-based formulations, e.g., incorporating perceptual metrics into the objective function.

Haptic Technologies for
Direct Touch in Virtual Reality

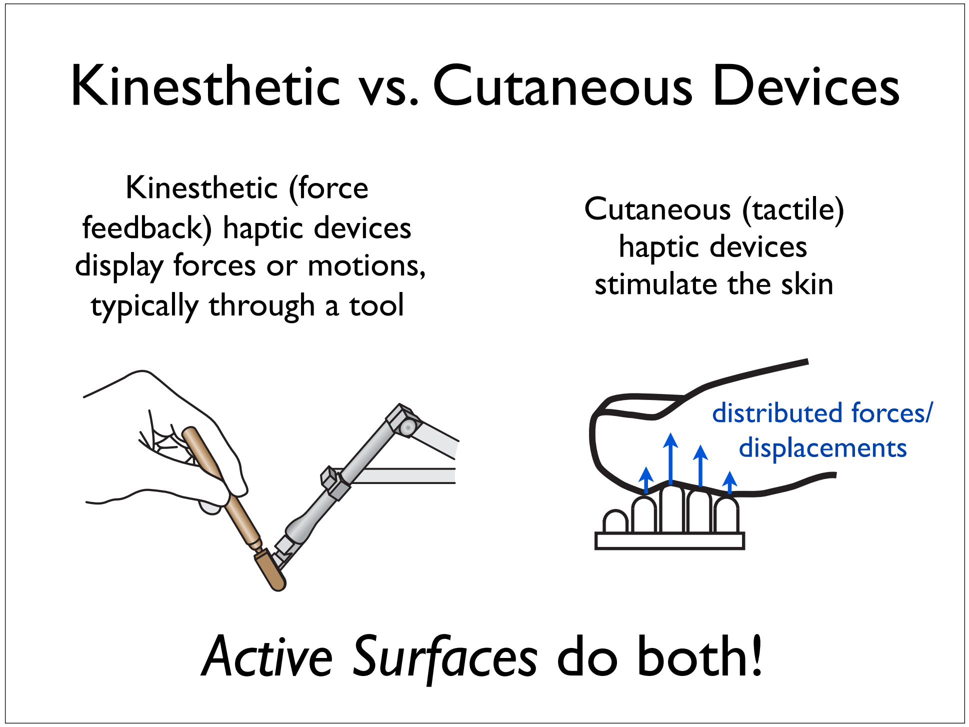
Active Surfaces

Allison M. Okamura

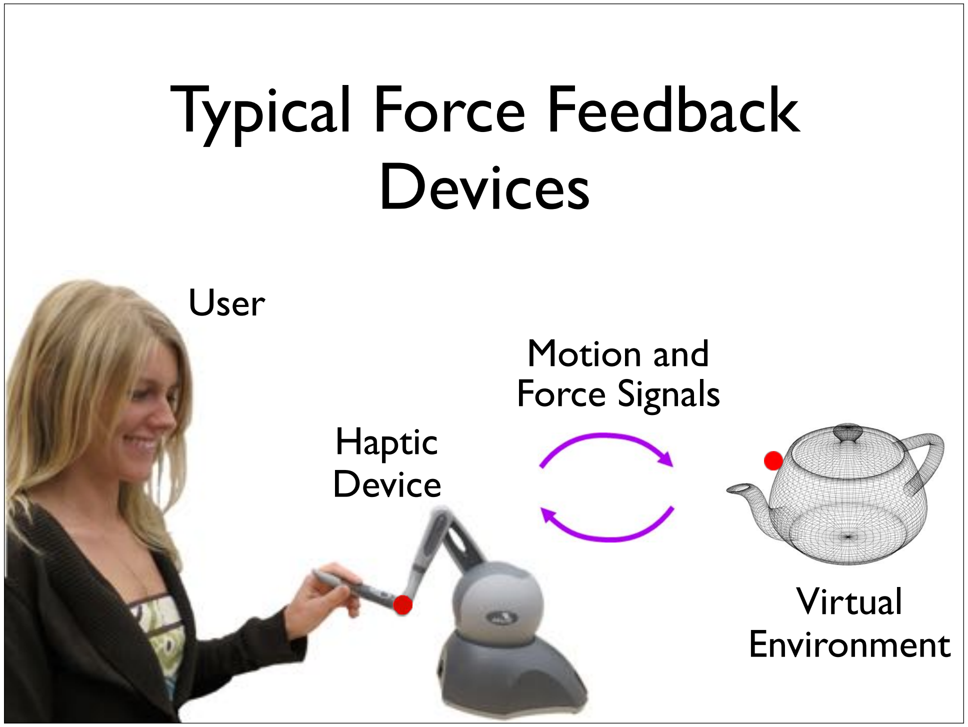
Department of Mechanical Engineering
Department of Computer Science
Stanford University
http://charm.stanford.edu

Materials contributed by Andrew Stanley

Human cognitive processes evolved alongside the ability to manipulate complex objects and tools. This makes it particularly striking that our interaction with computer systems is currently limited to simple, abstracted interfaces such as touch screens, keyboards, mice, and open-air gestures. The full sensing and manipulation capabilities of the hand are largely ignored in human-computer interfaces. Active surfaces are an alternative: solid, 3D, holdable interaction devices that change shape and mechanical properties while sensing and responding to human touch and/or recreating desired objects. Such devices have the potential to revolutionize human-computer interaction, by allowing humans to manipulate and take full advantage of spatially embodied cognition. While numerous devices have been developed for haptic feedback and human-computer interaction through touch, the ability to generate and allow users to manipulate truly 3D solids and vary their mechanical properties is a relatively new approach for haptics and HCI.

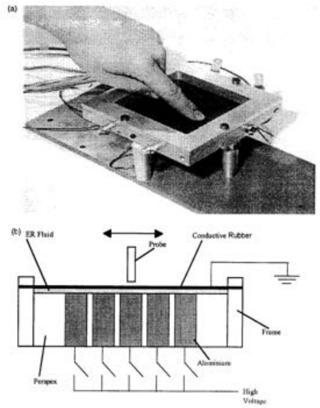


In the field of haptics, devices are typically divided into two main categories: kinesthetic and cutaneous devices. Kinesthetic devices display resolved forces to the hand, typically through a held tool attached to an actuated manipulandum. Exoskeletons also fall into this category. Cutaneous devices are stationary or wearable devices that aim to stimulate the skin. This presentation is about Active Surfaces, which aim to provide distributed tactile information to the skin, while also communicating larger-scale forces and shape to the whole hand.

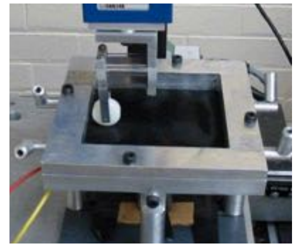


Typical force feedback devices (of the so-called impedance type) record the user's movement, then a virtual environment with a programmed impedance determines the amount of force to be displayed to the user. The haptic device then pushes on the user with that force.

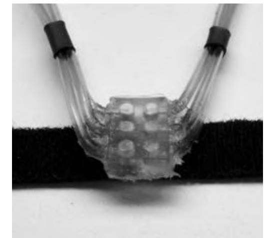
Tactile Displays



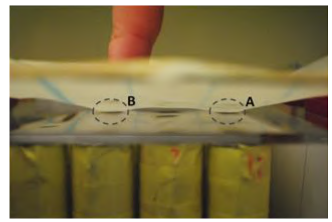
Taylor et al. 1998



Liu et al. 2005



King et al. 2008

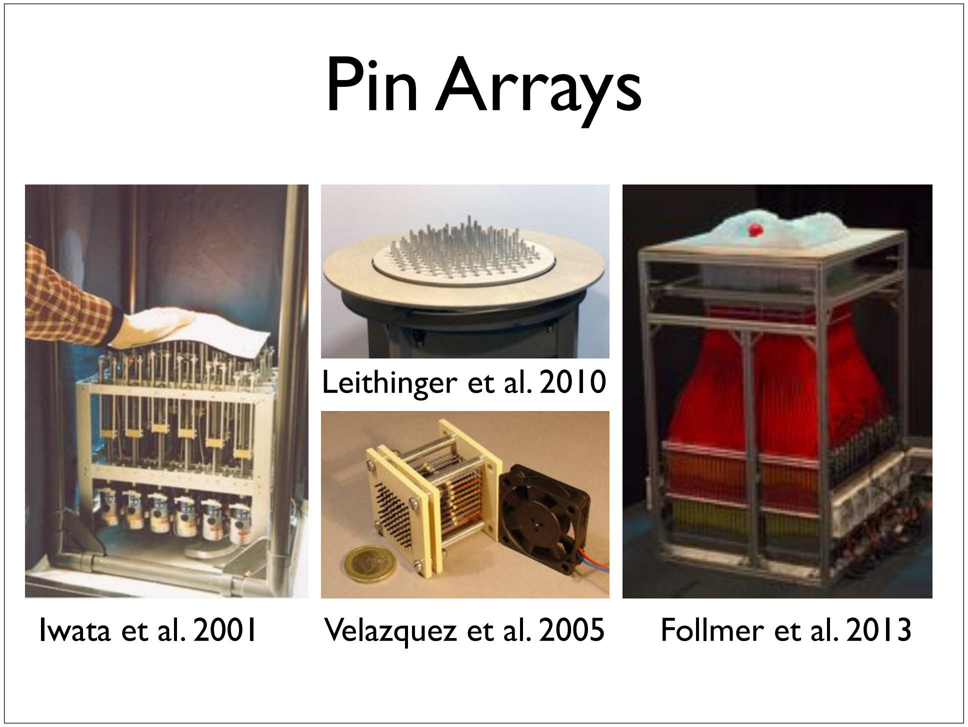


Tsimeris et al. 2013

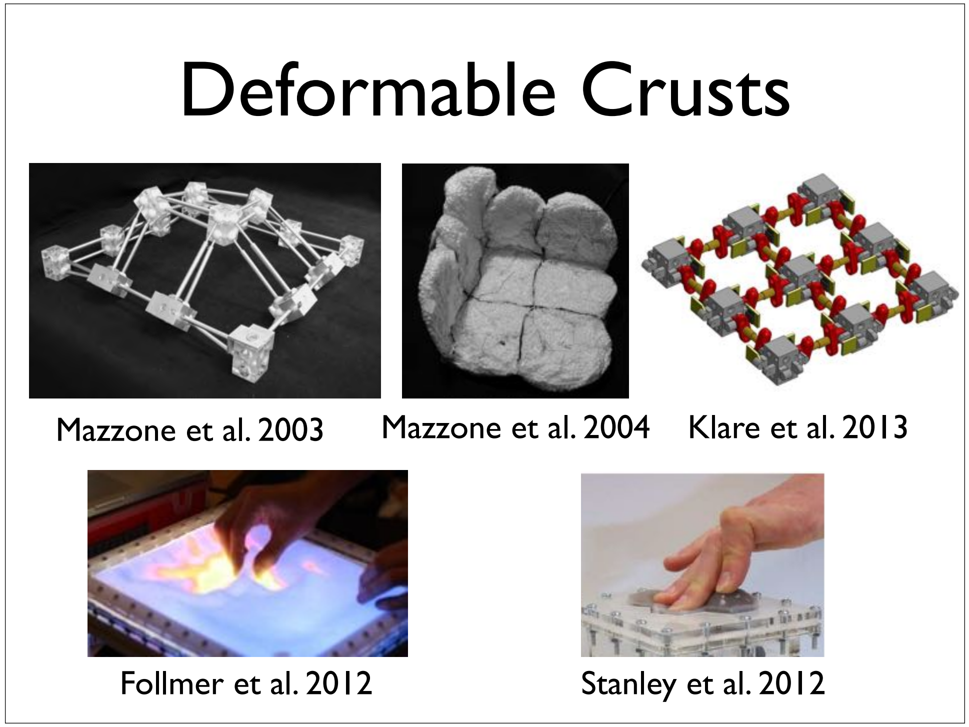
On contrast, tactile displays stimulate the skin locally. They can change shape or stiffness very locally. In addition, new surface haptic displays are now used to modulate friction between the finger and the surface in order to generate textures, virtual “walls”, etc.

Types of Active Surfaces

Active surfaces are, in a sense, a brute-force approach to haptic display. Rather than trying to re-create the illusion of a surface through minimal feedback (e.g., at the point of a tool, or only on the fingertip), an active surface tries to literally re-create the object that is being touched. This creates numerous challenges in design, construction, modeling, and control. Yet, active surfaces are a powerful concept that continue to be explored as we seek more immersive and realistic virtual environments.



Pin arrays render 3D models physically, allowing for many points of contact and un-tethered interaction. Shape displays render physical shapes through an array of actuators. This rendering is often limited to 2.5D shapes due to linear actuators, although other topologies have been proposed – such as digital clay. For the bed of pins, each pixel is a physical pin attached to a linear actuator that can move up and down to render 2.5D shapes. A variety of different technological approaches have been applied for actuation: DC motors with lead screws, rotational servos, pneumatic actuators, and shape memory alloys. For a bed-of-pins display consisting of hydraulic actuators arranged along the rows and columns of an array, the resolution of the interface can feasibly be increased because the number of actuators scales linearly rather than polynomially with the size of the array. These types of shape displays remain limited by their 2.5D nature and the fact that they are often large table scale devices due to the size of actuators.



Another approach is formable crust topologies. Examples shown here use a variety of actuation technologies. In this presentation we will focusing on particle jamming (last two examples) because they enable continuous surface control with much better resolution than approaches using rigid linkages.

Haptic Jamming: Four-Cell Surface

Stanley, et al. 2013

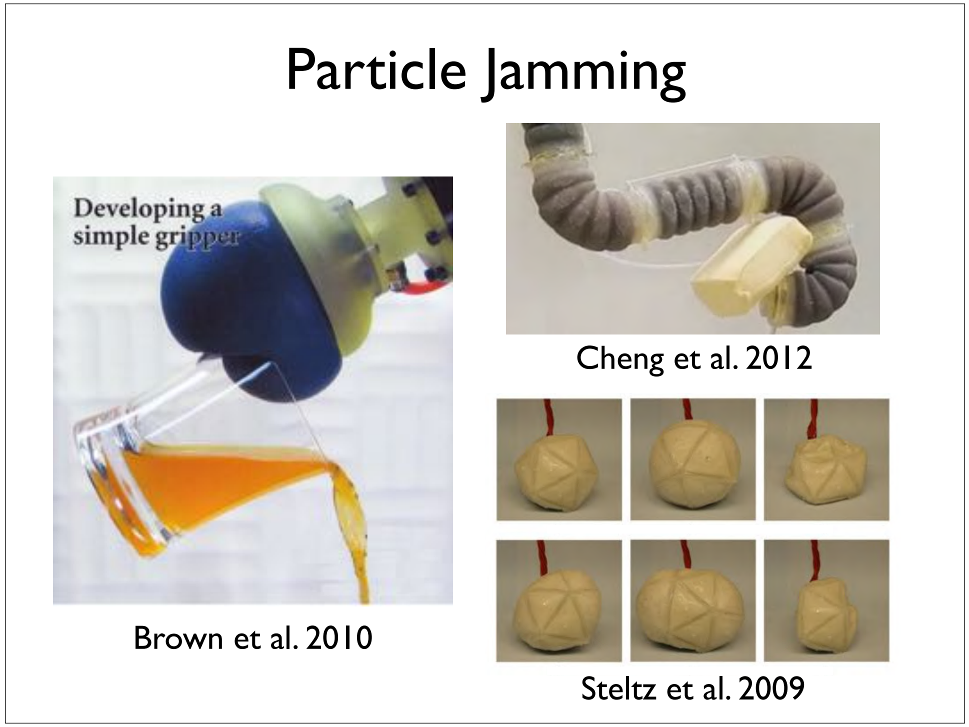
Video is real time

This video demonstrates an active surface using the particle jamming approach. Air pressure from below generates the shape, and particle jamming in individual cells is used to control local stiffness. It is important to note that the particle jamming can also play a role in the shape control, as will be shown later.

Making
Active Surfaces

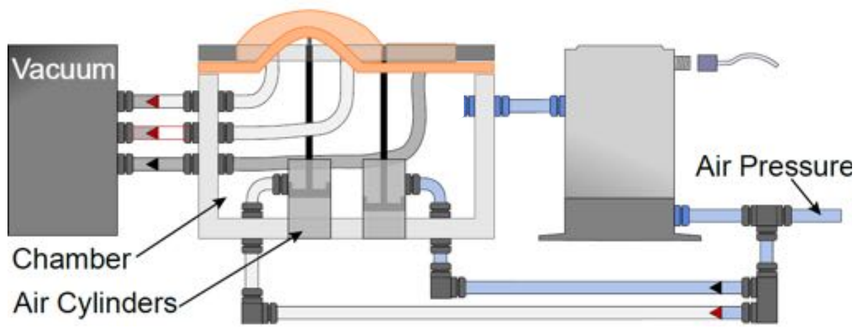
Example:
Particle Jamming Arrays

Every type of active surface is unique in its use of sensors, actuators, and other components. Because this field of haptics is so new, we have yet to develop generalized principles for active surface design. Thus, we explain the various aspects of active surface design and construction by example: Namely, through the making of a particle jamming array.



In contrast to the rigid actuation techniques used traditionally in robotics, Soft Robotics is an emerging domain that focuses on soft, flexible, and compliant actuation and sensing techniques. These systems have many advantages over traditional robotics – especially in the amount of strain and overall shape change, as well as the fact that they are deformable and compliant, which can be ideal for interaction. Pneumatic soft composite actuators can have complex shape change with a single degree of freedom. Particle jamming can be used for controlling the stiffness of segments of a robot to lock segments, allowing for locomotion or shape change. In particle jamming, vacuum is applied to change effective hardness/stiffness. Here, we use the particle jamming principle to construct active surfaces.

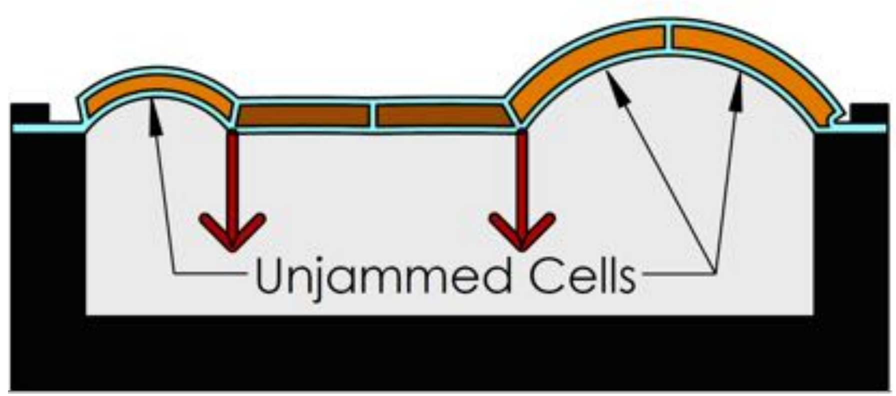
Haptic Jamming Actuation



Stanley, et al. 2013

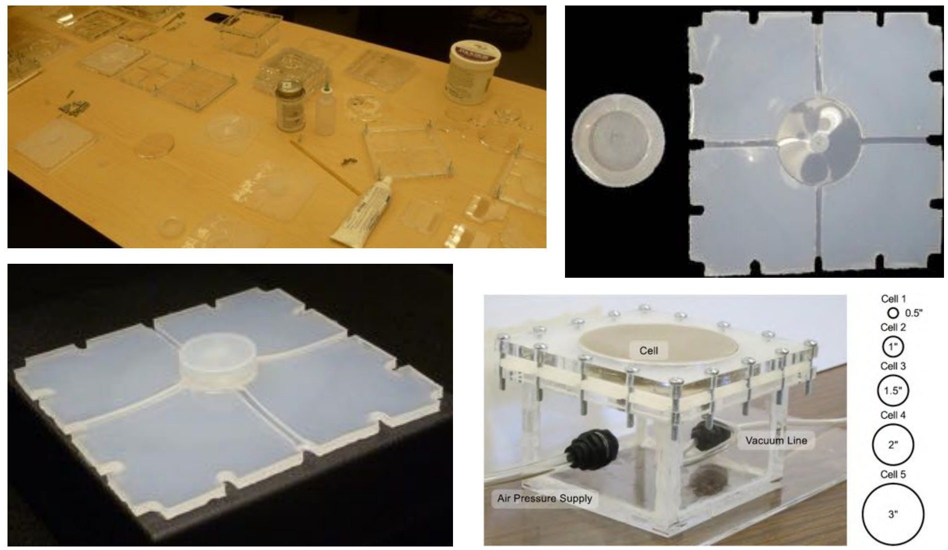
Haptic jamming actuation has two main components: controlling the overall shape, and controlling the mechanical property (stiffness). Here we consider a single cell. Positive air pressure under the cell is regulated to determine the amount of cell “ballooning”. Negative air pressure (vacuum) is used to regulate the stiffness of the cell itself.

Haptic Jamming Actuation



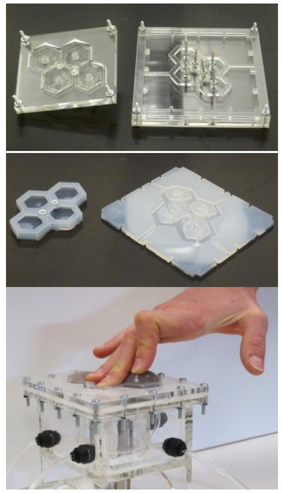
When multiple cells are present, we need a way to have more control over shape. Here, we see that we can pin two nodes between cells. If two cells are jammed and the shown nodes are pinned by a downward force, application of positive air pressure results in the other cells ballooning outward while the two jammed cells remain in the shape they were originally. Thus, node pinning becomes a third type of actuation (which is termed “activation” because it is not a continuous form of actuation) used by a multi-cell particle jamming shape display.

Making Particle Jamming Cells

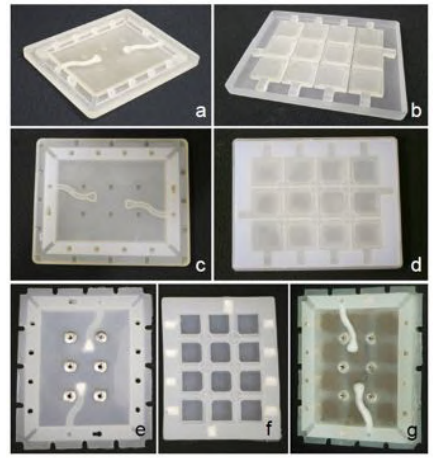


To make a single particle jamming cell requires the development of a mold for high-strain silicone rubber. The inside of a cell must be left empty, requiring a multi-step molding and gluing technique. After he cell is created, it is filled with a granular material. We use coffee ground because the asymmetric shapes of the ground results in a “locking” between granules that enables relatively high stiffness for a given vacuum level in the cell. A vacuum line is attached to access the interior of the cell with silicone glue. Then the surface/cell is clamped over a chamber through which positive pressure is applied.

Multi-Cell Arrays



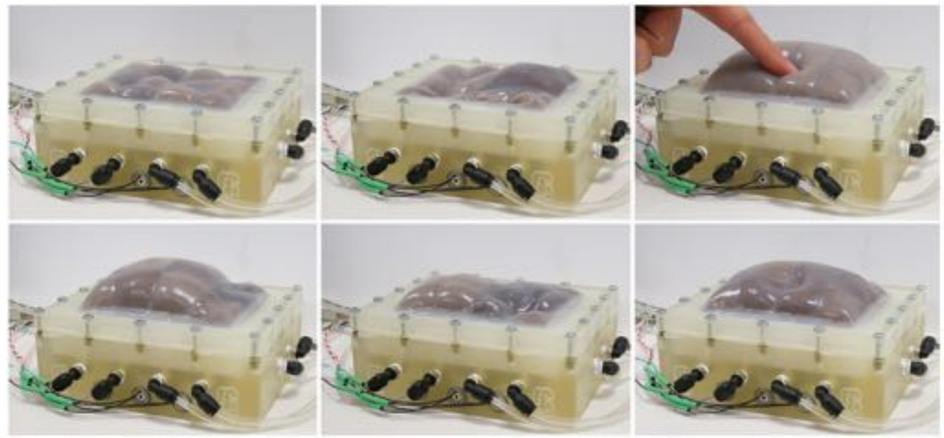
4 cells



12 cells

Expanding this concept to multiple cells requires more molds. For arrays with larger numbers of cells, the vacuum lines can be embedded in the silicone surface to minimize the number of tubes in the device and thus the overall size. However, the mechanical construction is not perfect and such embedded lines can be very difficult to mechanically "debug" if there is a leak!

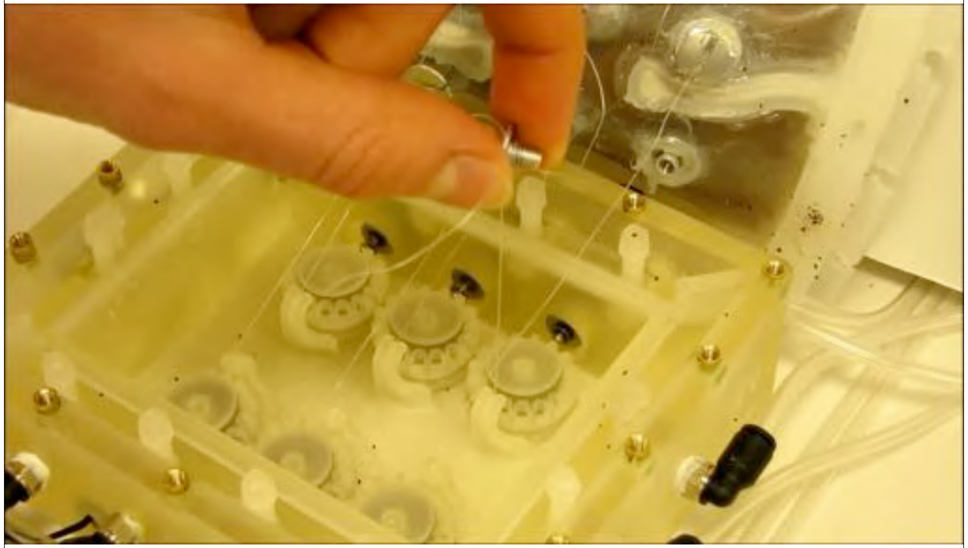
Multi-Cell Arrays



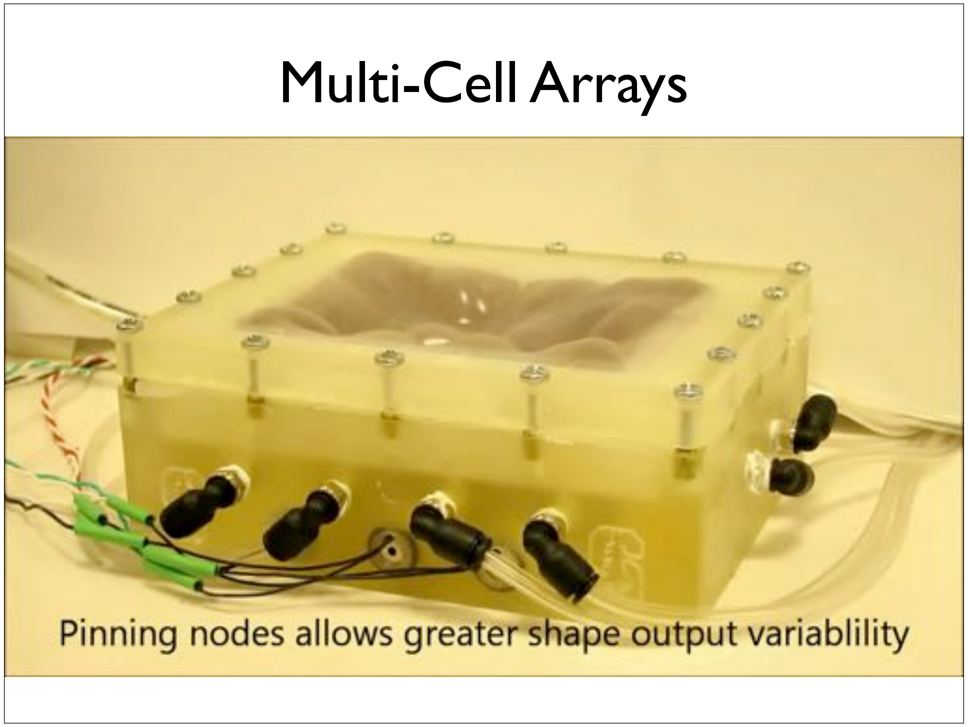
Stanley and Okamura, 2015

Demonstration of shape control on a 12-cell array.

Multi-Cell Arrays

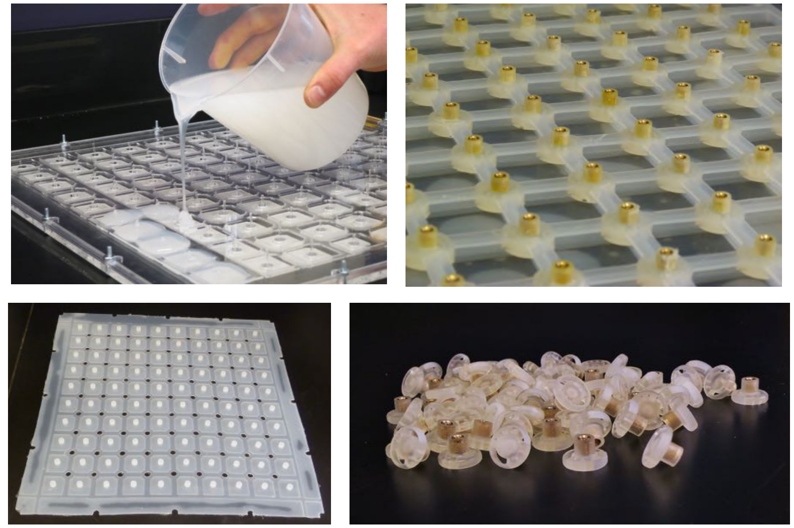


Demonstration of node pinning on a 12-cell array.



Demonstration of node pinning on a 12-cell array.

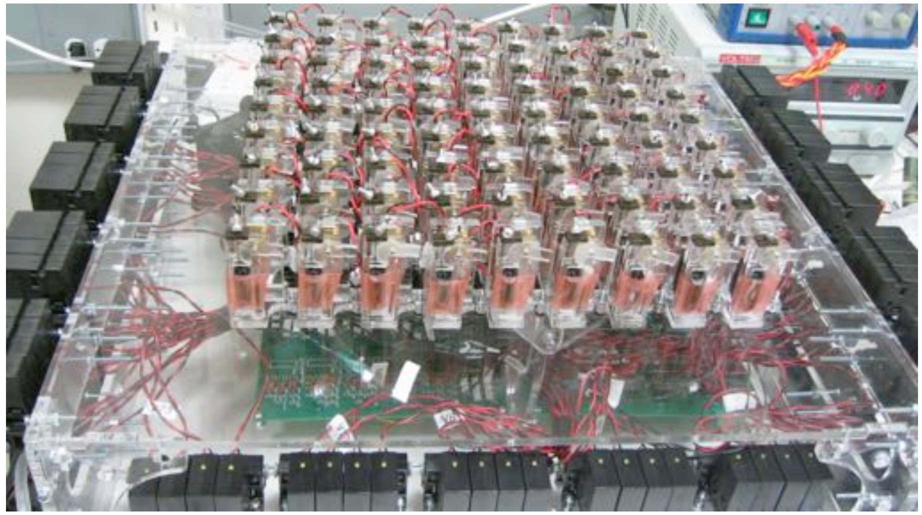
100-Cell Array



100 cells

Construction of a 100-cell array highlights the challenge of scaling up.

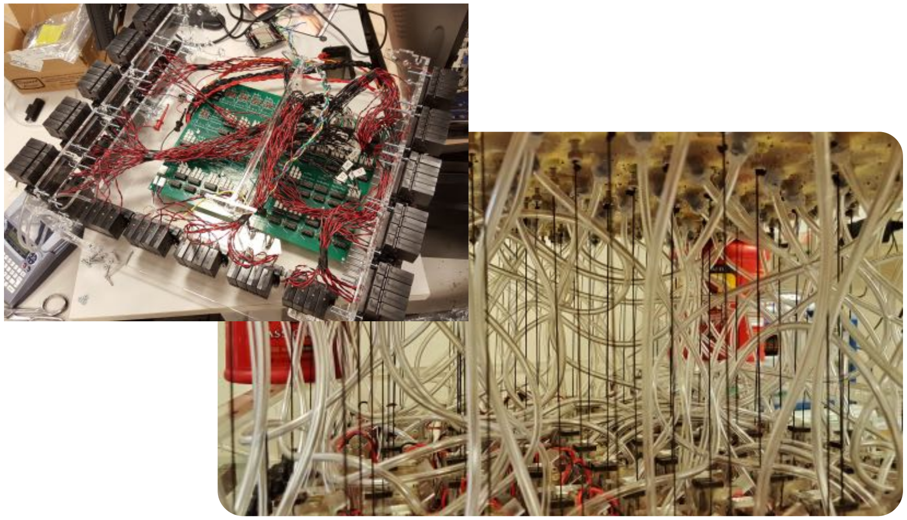
100-Cell Array



100 cells

Construction of a 100-cell array highlights the challenge of scaling up.

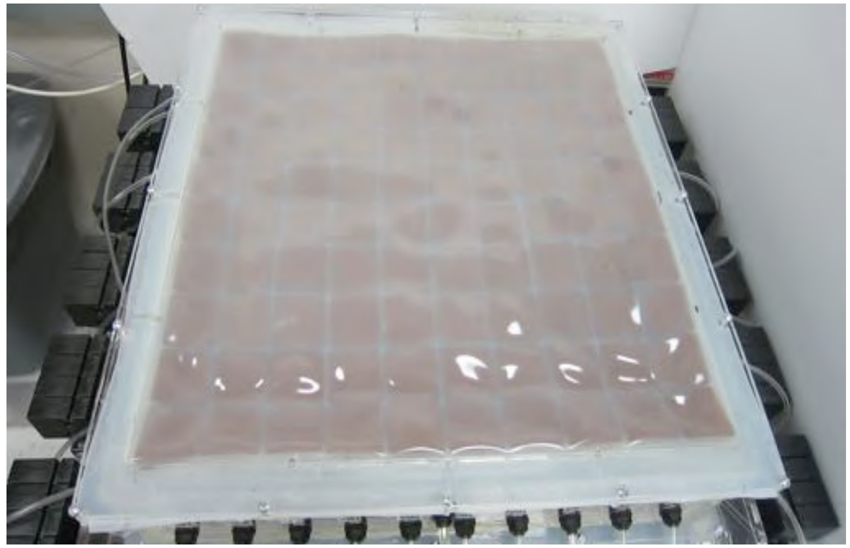
100-Cell Array



100 cells

Construction of a 100-cell array highlights the challenge of scaling up.

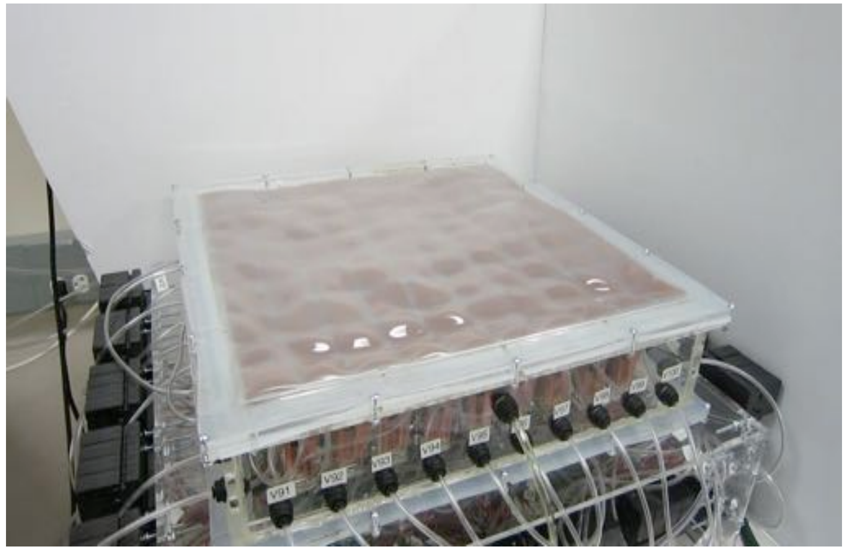
100-Cell Array



Video is real time

Demonstration of cell jamming (stiffness control) on a 100-cell array.

100-Cell Array



Video is real time

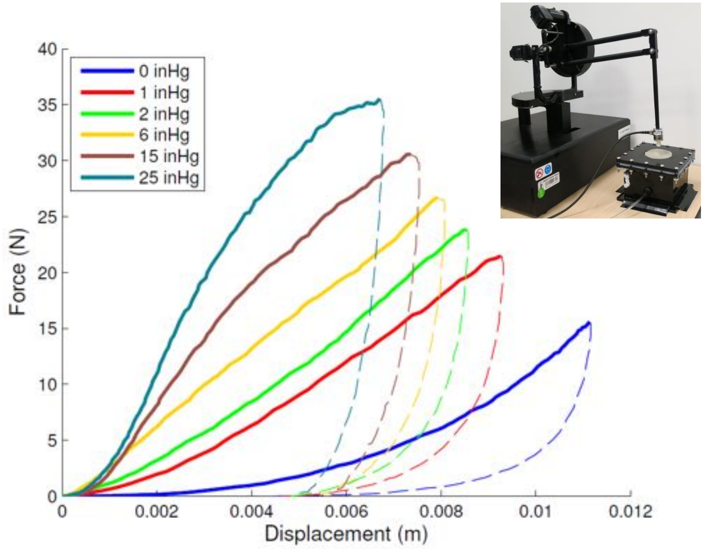
Demonstration of pressurization (global shape control) on a 100-cell array.

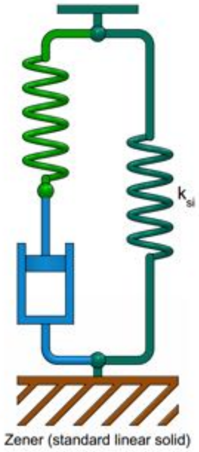
Modeling and Control of Active Surfaces

Example:
Particle Jamming Arrays

Once the particle jamming device is made, the actuators must be locally controlled based on an overall control objective in order to achieve a desired shape (and possibly stiffness). The control requires a plan that in turn requires a model of the device. While pin array control is relatively straight forward, the interaction of surface elements (cells) in a deformable crust device creates significant challenges for modeling and control.

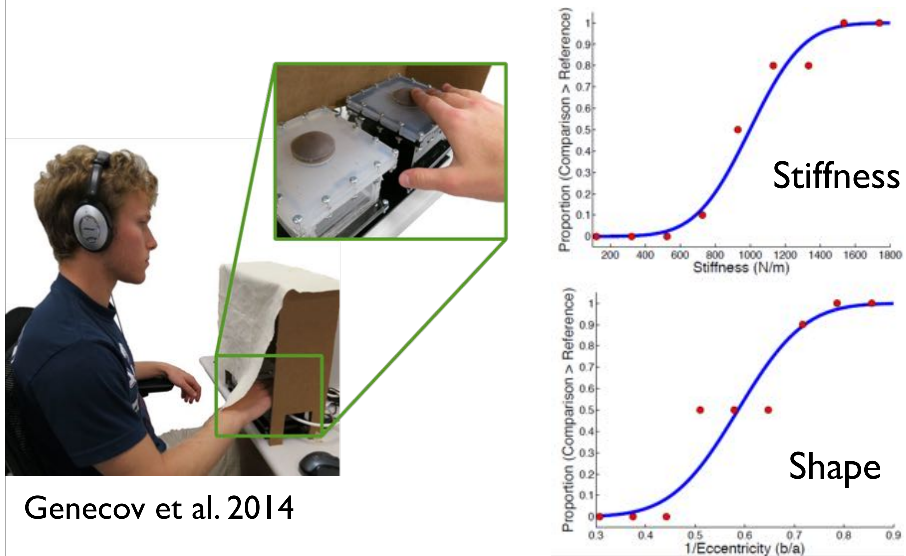
Mechanical Properties





Hysteresis in curves with plastic deformation “Stress relaxation”
Nonlinear stiffness due to “force chains” shortening as granules rearrange

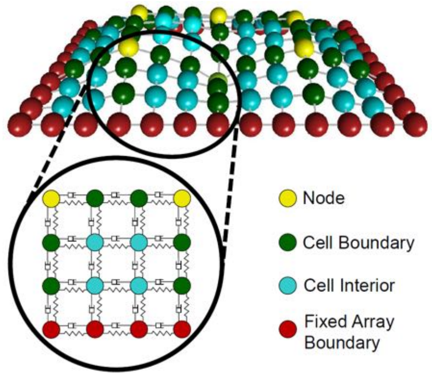
Perception (Psychophysics)



Genecov et al. 2014

Perception of active surface should be taken into account in the modeling and control process (and indeed, in the design). Here I show an example of a perceptual experiment in which we look for the just-noticeable difference in stiffness and shape of a particle jamming device. The user feels each of two devices controlled to have different shapes or stiffnesses, and specifies which one is larger (more ballooned or more stiff). The responses are used to generate psychometric curves from which we can determine the human sensitivity to difference in shape and stiffness. This can be used to drive the required resolution of the device.

Shape Simulation



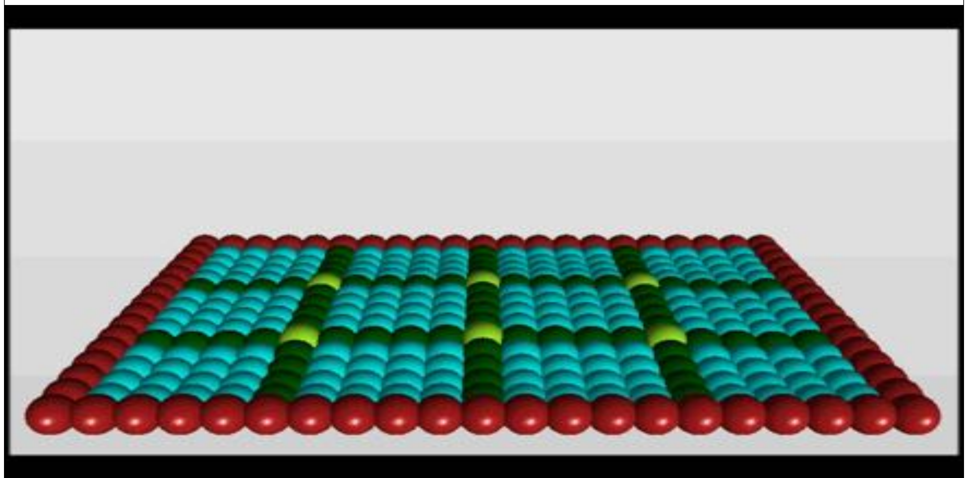
$$\vec{\mathbf{F}}_{\mathrm{s}}^{B/A} = -k\left(\left\|\vec{\mathbf{r}}^{B/A}\right\| - l_{\mathrm{eq}}\right)\hat{\mathbf{r}}^{B/A}$$

$$\vec{\mathbf{F}}_{\mathrm{d}}^{B/A} = -b\left(\vec{\mathbf{v}}^{B/A} \cdot \hat{\mathbf{r}}^{B/A}\right)\hat{\mathbf{r}}^{B/A}$$

$$\mathbf{a}^{i} = \mathbf{g} + \sum_{j \in p_{\mathrm{n}}^{i}} \frac{\vec{\mathbf{F}}_{\mathrm{s}}^{i/j} + \vec{\mathbf{F}}_{\mathrm{d}}^{i/j}}{m^{i}}$$

A dynamic simulation is used to model the effect of pressure, vacuum, and node pinning on the shape and stiffness of the device. Dynamic equations shown here describe the dynamics. We we numerically integrate twice per time step to get position. To pin a node, we “fix” it by not updating its position each time step.

Shape Simulation

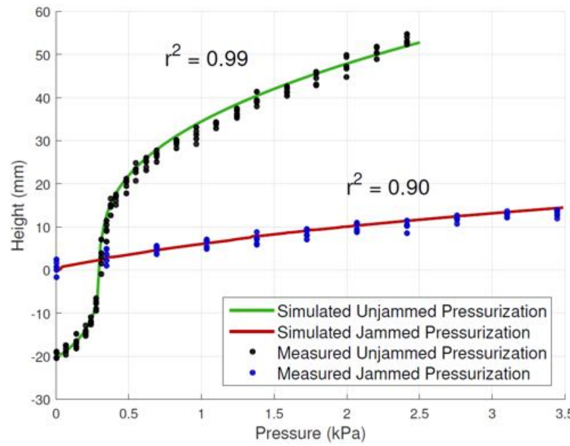


Stanley and Okamura, 2016

Results of dynamic simulation.

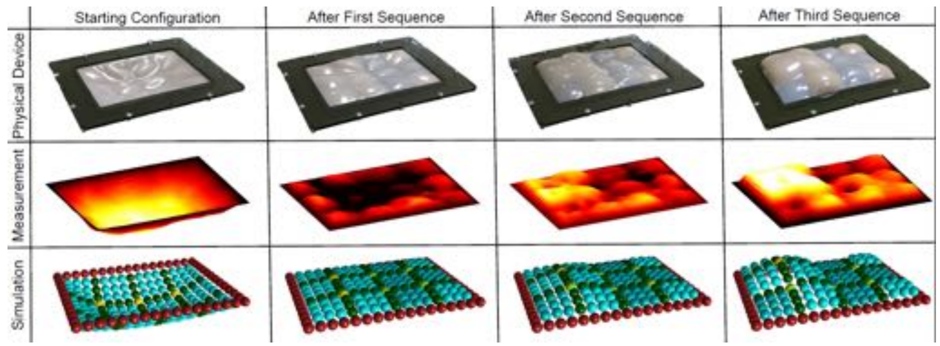
Shape Simulation

Parameter fitting using surface height data from Kinect depth sensor

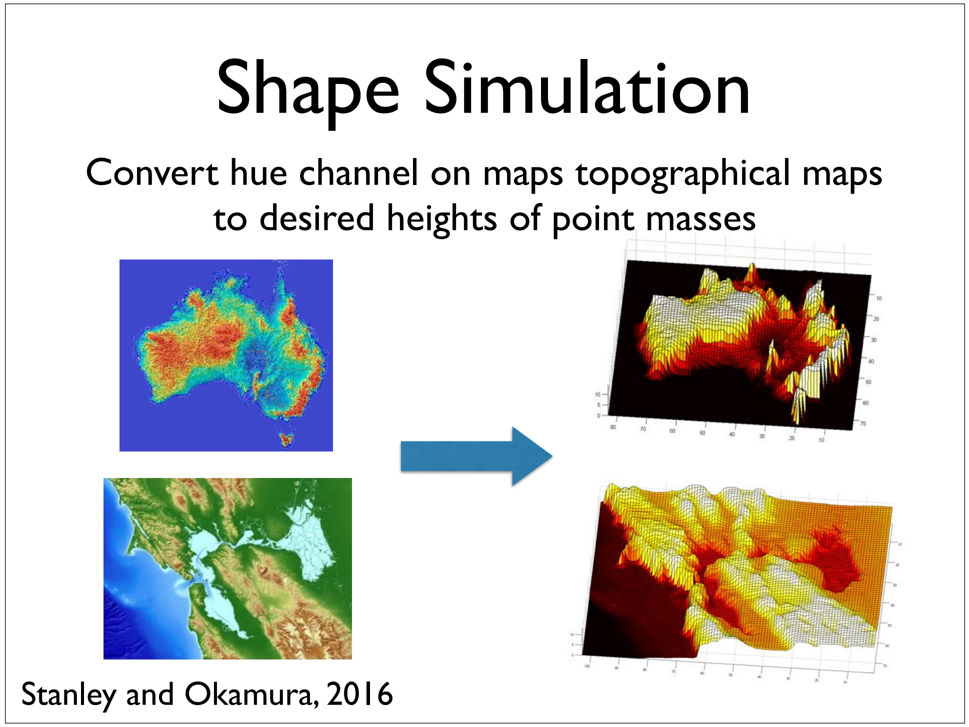


Since the dynamic simulation is used in planning, it is important that the simulation be verified with sensed shape. Here we show that data from a Kinect verifies that the predicted shape matches the actual shape.

Shape Simulation



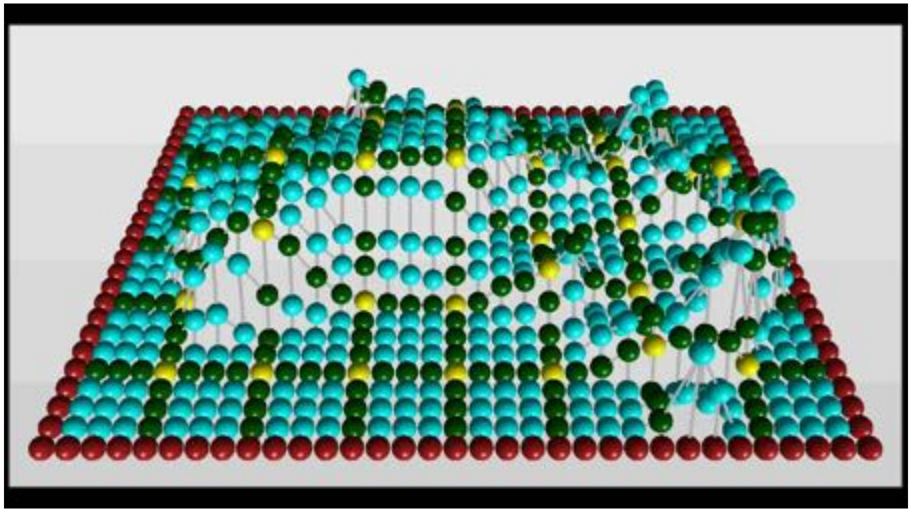
Details of comparing actual shape to simulated shape for a sequence of actuations.



One possible application of a Haptic Jamming surface display is a refreshable tactile topographic map. Visual two-dimensional topographic maps typically use constant elevation lines or coded colors overlaid onto regions to show elevation changes from features like mountains and valleys. A tactile display that physically changes its geometry to match the slopes within a region could provide an additional, intuitive information channel, or even an alternative method to convey maps and topography to the visually impaired. Many three-dimensional globes use textured surfaces to present topographic information in exactly this manner, but a refreshable display like Haptic Jamming could essentially zoom in on any region of interest to create its surface features on a larger scale before reconfiguring for a different region of interest.

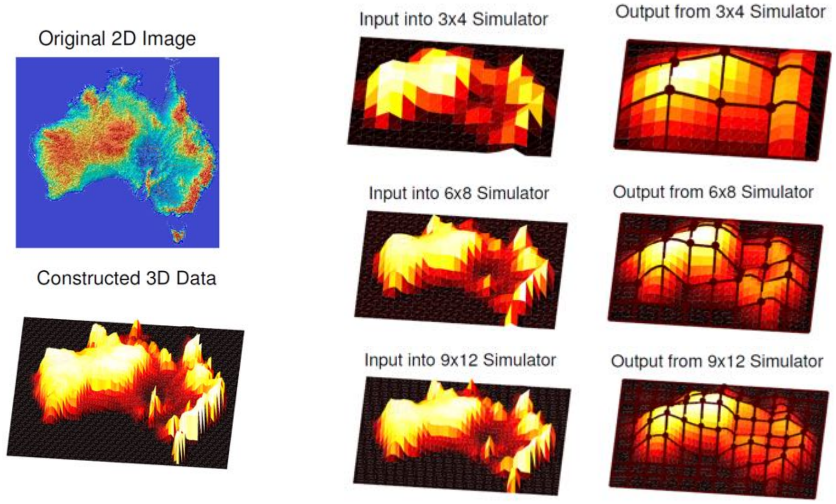
The dynamic simulator provides an efficient means to test the potential effectiveness of an active surface to display topographical maps, evaluate the capability of the shape construction algorithm to recreate desired shapes, and quantify the relation between the number of cells in an array and the resulting detail of the shapes it can create. Creating a goal configuration from a topographical map for input into the algorithm requires a desired height for each point mass in the simulator, so we selected maps with pixel values easily converted to heights.

Shape Simulation



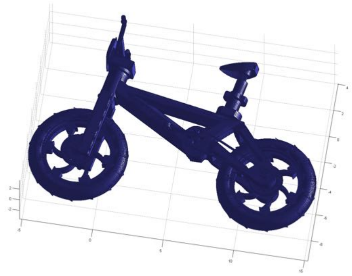
Results of dynamic simulation.

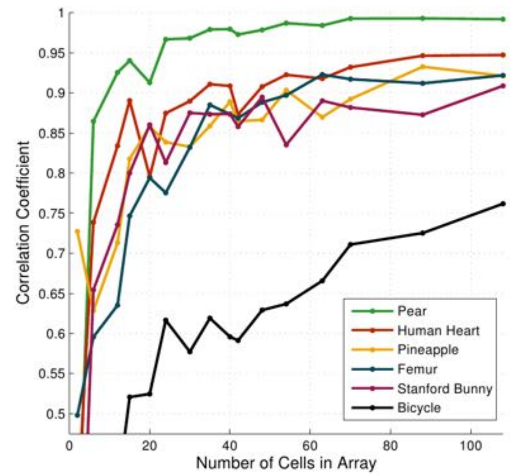
Shape Simulation



Results of simulation, and what can be achieved with different cell resolutions.

Shape Simulation

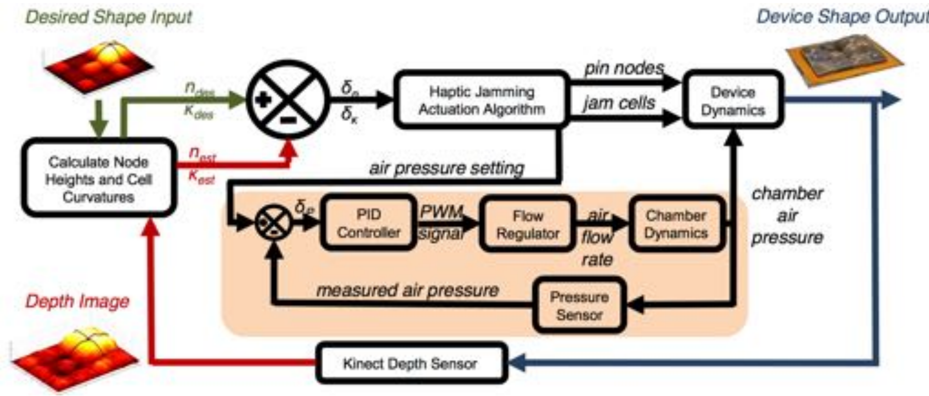




Which shapes will render well and which will not? We can determine this using the simulator.

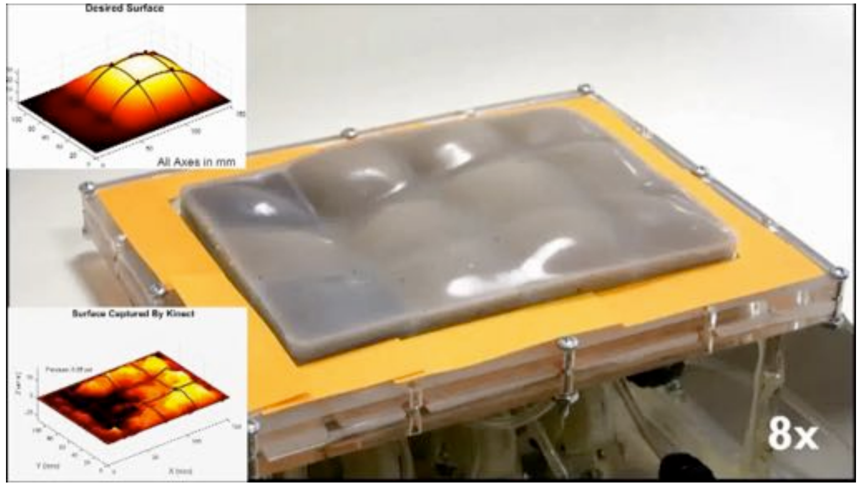
A correlation coefficient can be used to describe what can be achieved with different cell resolutions.

Closed-Loop Control



In order to more accurately control the device to achieve a desired outcome (planned/predicted in simulation), feedback control is required. Ideally, the device would have embedded sensing for high accuracy and so that occlusions are not a problem. But here we demonstrate what can be done with the ubiquitous Kinect RGB-D sensor. We will walk carefully though this block diagram to demonstrate the different components of the closed-loop control.

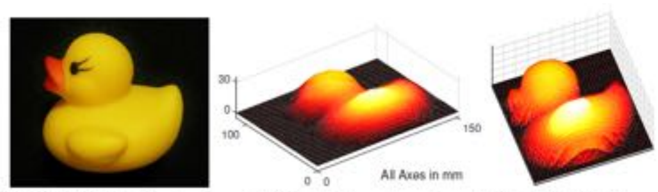
Closed-Loop Control



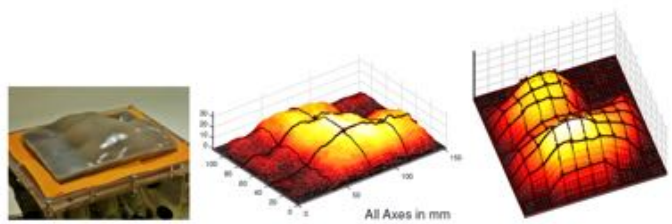
Stanley et al. 2016

Closed-loop control results.

Closed-Loop Control

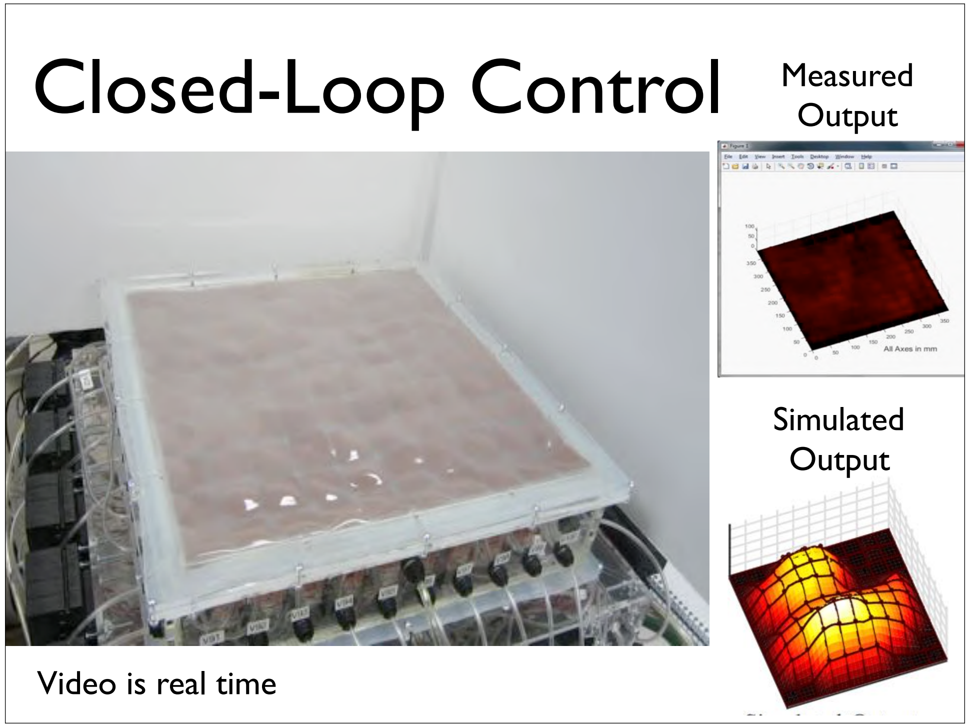


(a) 3D Object Desired Shape (b) 3×4 Array Input (c) 10×10 Array Input



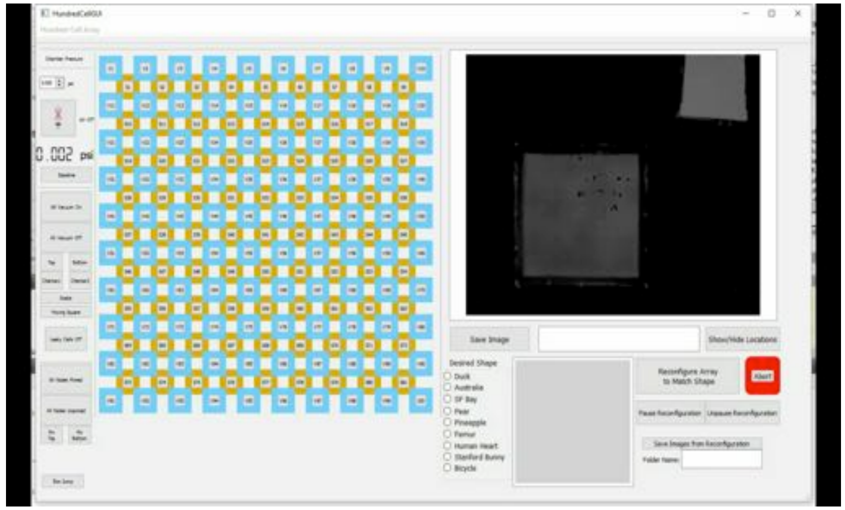
(d) Device Output (e) Measured Output (f) Simulated Output

Closed-loop control results.



Closed-loop control results on actual 100-cell array.

GUI for 100-Cell Array



Video is real time

Manual control of an active surface can also be achieved through a GUI.

Applications of Active Surfaces

To consider various applications of active surfaces, here are a set of scenarios for use. These range from applications feasible by the end of this project, to the “holy grail” of customizable, personalized devices that can be considered in the future:

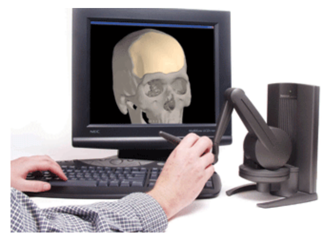
Design: A designer has a rough CAD model of a new water bottle. She “prints” her model on the soft interface and carefully tries various grasps at different orientations. She decides that one edge is too sharp, so she pushes on it with her fingers – it flattens under her hand. The CAD model is updated in real-time based on this change, and she sends it to her colleague across the country.

Consumer: A teenager sees an cool pair of sneakers on Amazon, but he has trouble visualizing the shape and size from the images on the website. He clicks a button that downloads the vendor’s shoe model onto his soft interface. He holds it in his hand, feeling the contours, and then presses the “sole” against his own foot to check the size. He bends the device to feel its stiffness. He prods the toebox into a shape he likes better – the system then searches for similar shoes.

Medical: A doctor asks her hand rehabilitation patient to lightly squeeze a very compliant, unformed soft interface, which molds to the shape of the patient’s hand. Then the device stiffens, and she asks the patient to squeeze as hard as possible. The patient then goes home for two weeks with a device that perfectly fits in his hand, and is prescribed an adaptive regimen of squeezing
exercises at different levels of force and varying repetition.

Application: Medical Simulation

Laerdal's SimMan



Phantom Desktop

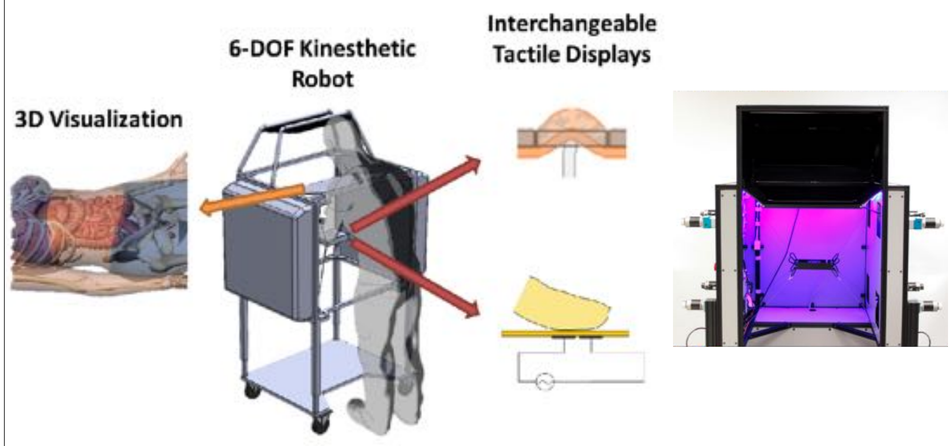
Mannequins: passive, tactile, multi-contact

Tool-based interaction: active, programmable forces

Can we have the best of both worlds?

Here we focus on an immediate, work-in-progress application for active surfaces: medical simulation. Current medical simulation approaches with haptic feedback range from passive mannequins to virtual environments for surgery with single-point interactions. Active surfaces would provide an ideal scenario that provides the best of both worlds.

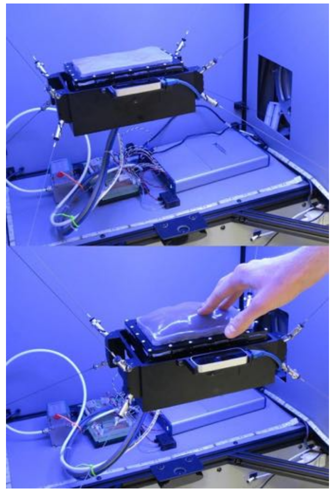
Encountered-Type Medical Simulator

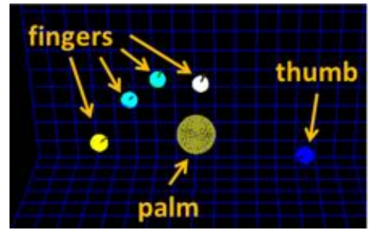


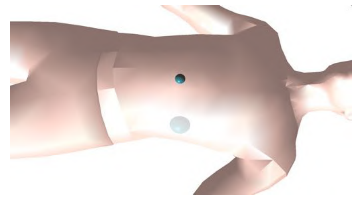
Intelligent Automation, Inc. and Tangible Haptics

To further enhance haptic interaction, a surface haptic device can be integrated with a kinesthetic force-feedback device (i.e., a robot) to allow encountered-type haptic interactions.

Encountered-Type Medical Simulator





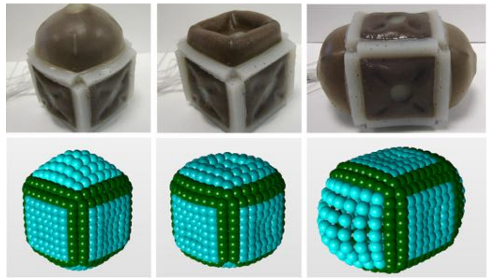


Stanley et al. 2014

Haptic feedback serves as an important element of a clinician’s diagnoses and decision regarding many procedures. Palpation is often necessary to identify subcutaneous anatomical landmarks or to differentiate between similarly shaped objects.

Future Work

Truly 3D shapes



Human-Computer Interaction

Self-sensing of shape and contact with human

Mid-air Haptics

Prof. Sriram Subramanian
School of Engineering and Informatics
University of Sussex

@sssram
@LabInteract

Outline

- Motivation
- Mid-air haptic Systems
- Designing interactions

Motivation

Ian Waterman had a bout of severe gastric flu that led to infection and permanent loss of touch and sense of movement and position sense below the neck. He lost his ‘proprioception’ and could not move in a controlled way at all, and was effectively paralysed not by weakness but by an absence of any ability to make an ordered movement. Although Ian has since learnt to cope with life without proprioception, his journey highlights the importance of proprioception and haptics.

While VR, AR and many automotive dashboards talk about touches control or full visual immersion, they lack tactile feedback. In this course we talk about various systems that can augment visual immersion and touchless interactions with tactile feedback.

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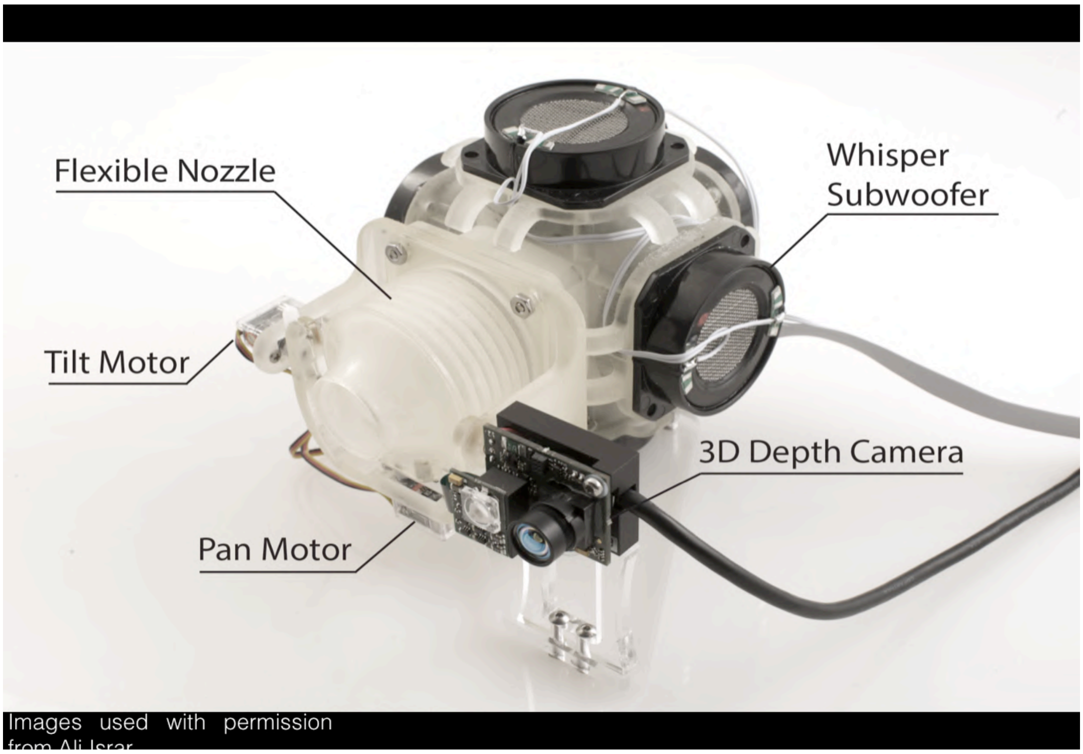
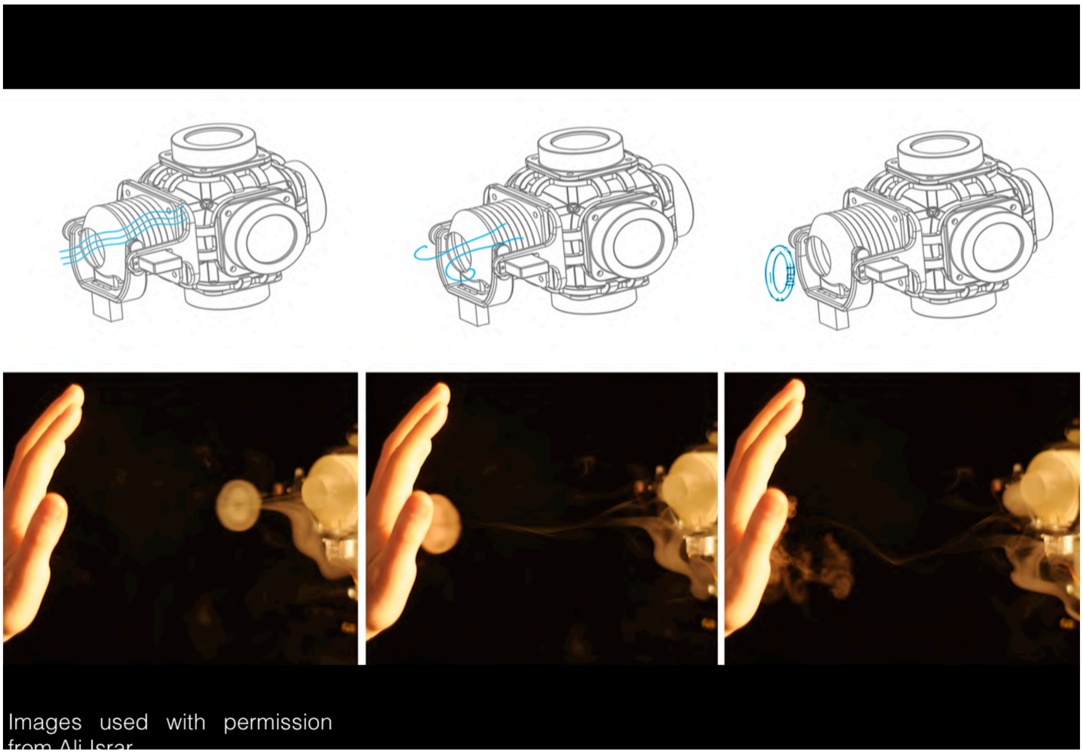
Mid-air haptic Systems

AIREAL is designed to use a vortex, a ring of air that can travel large distances while keeping its shape and speed. When the vortex hits a user's skin, the low pressure system inside a vortex collapses and imparts a force the user can feel.



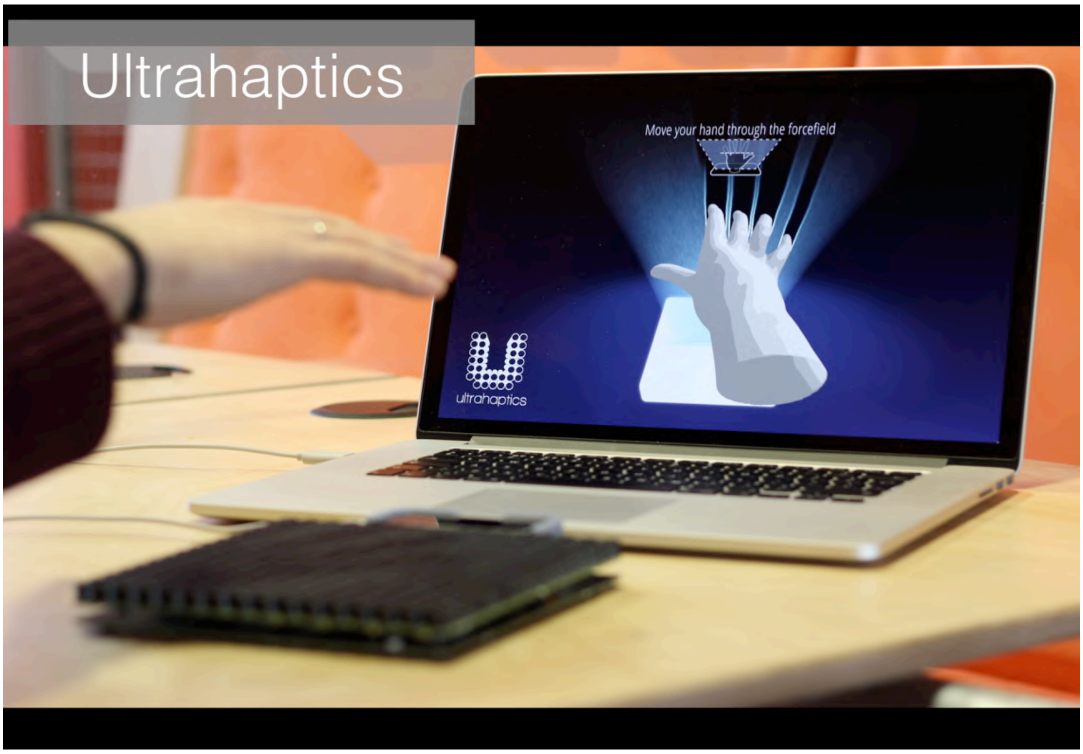
Images used with permission

The AIREAL technology is almost entirely 3D printed using a 3D printed enclosure, flexible nozzle and a pan and tilt gimbal structure capable of a 75-degree targeting field. Five actuators are mounted around the enclosure which displaces air from the enclosed volume, through the flexible nozzle and into the physical environment. The actuated flexible nozzle allows a vortex to be precisely delivered to any location in 3D space.

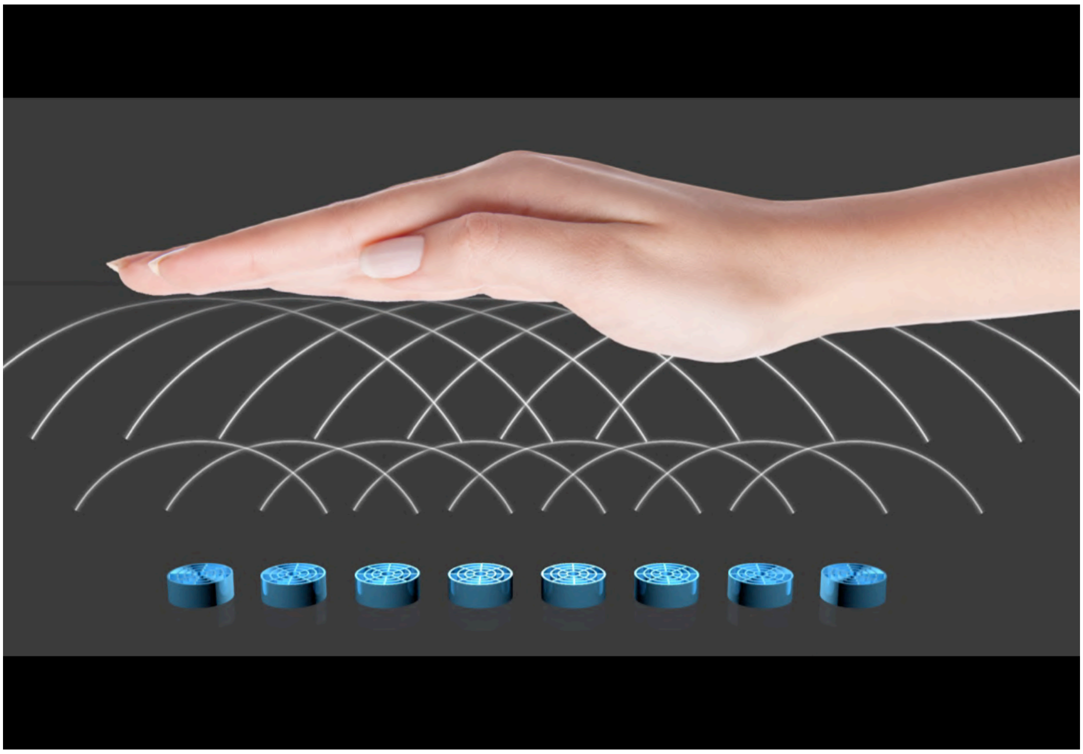


Images used with permission from Ali Israr

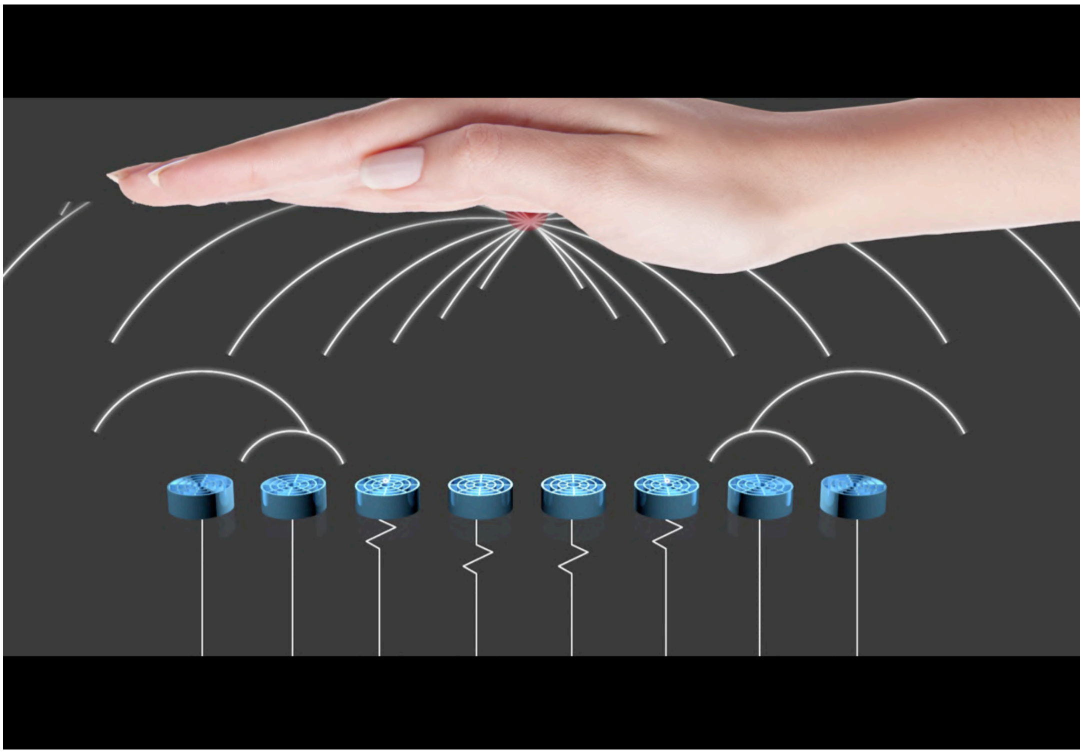
A volume of air is pushed out of the enclosure and pinches off from the aperture of the nozzle, resulting in a ring of air directed at an object in 3D space.



Ultrahaptics is another system to deliver mid-air tactile feedback using ultrasound speakers. They use multiple ultrasound speakers to make changes in the air pressure around the user. This provides the ability to feel the pockets of air pressure focused in the environment. This gives the user tactile cues for gestures, invisible interfaces, textures, and virtual objects.

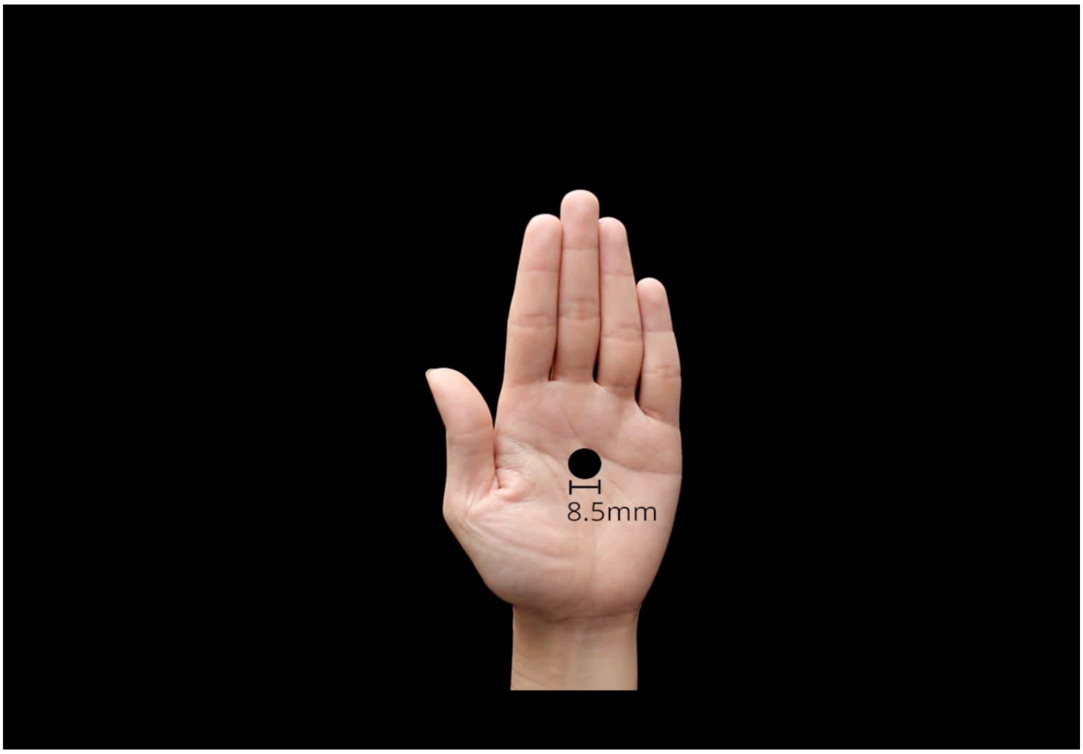


Here is an illustration of how sound waves propagate when we turn the speakers ON. Here we are turning the speakers ON at the same time. The waves then disperse equally everywhere and we feel nothing. BUT

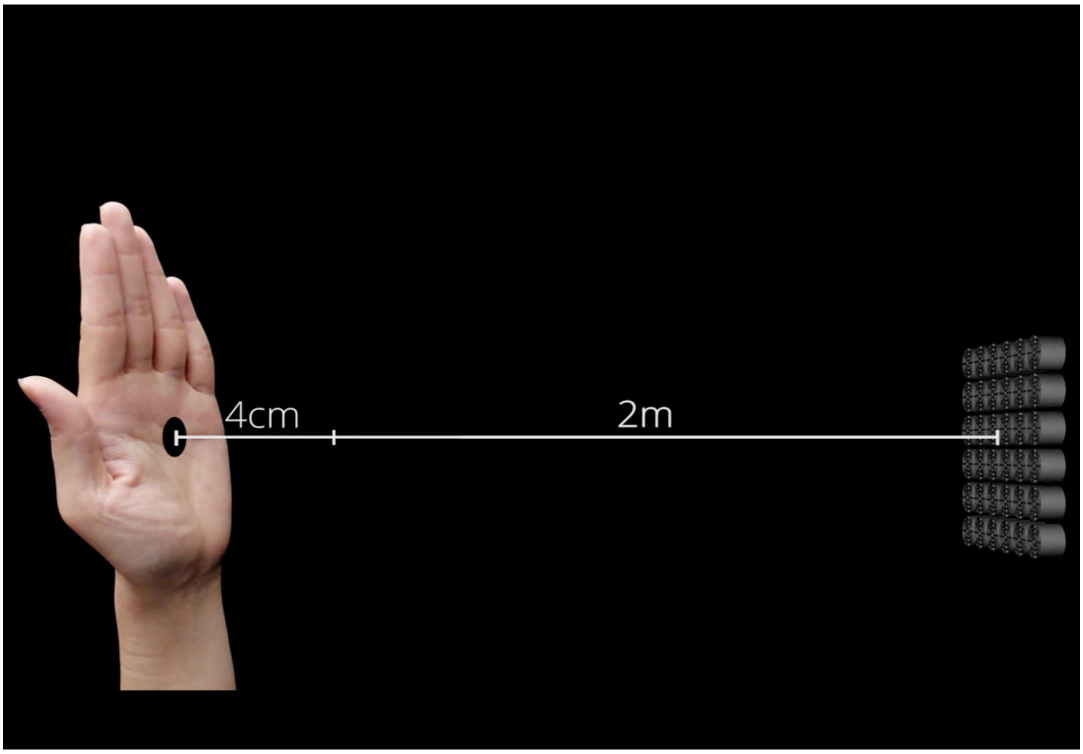


If we turn the speakers ON and OFF at very specific times, then the waves will collide to construct a strong “red” focal point at the hand.

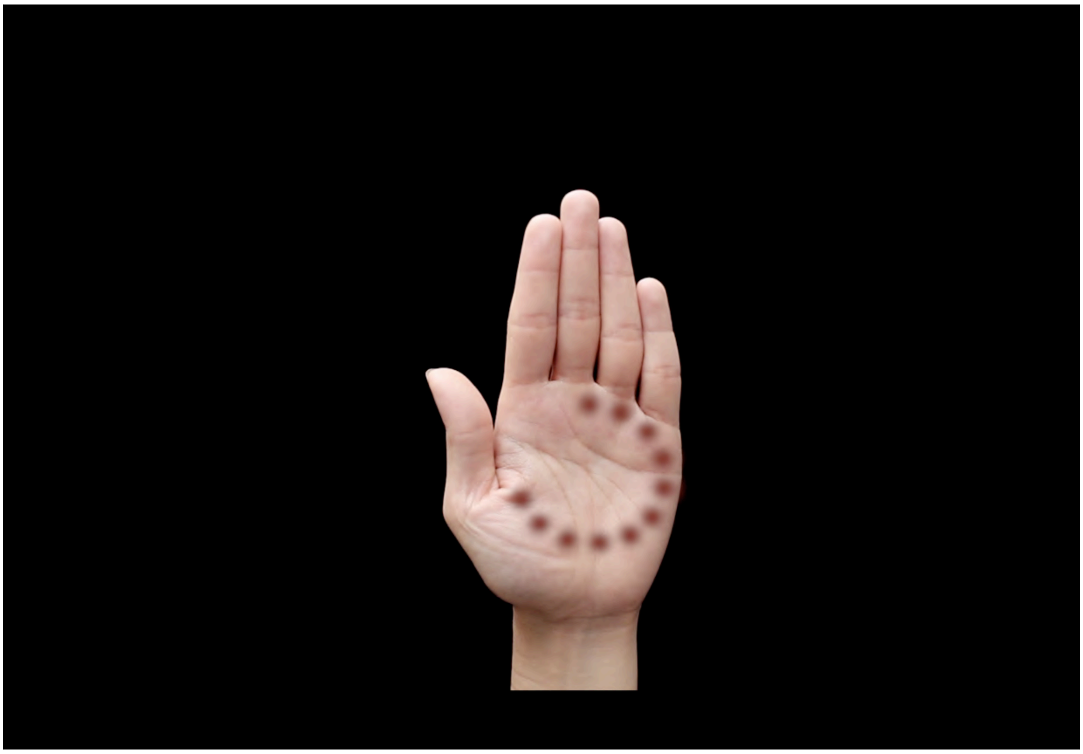
This focal point can be felt by the hand. This is how we create our haptic sensation!



The diameter of the focal point is approximately 8.5mm (the wavelength of 40KHz sound wave in air).



In the implementations of the system, the authors claim that the tactile sensation can be felt on the palm when it is between 4cm and up-to 2m away from the source of the ultrasound wave.



Through a computational approach they can render multiple tactile focal points at the same time. The details of the approach are given later.

This allows them to create not only focal points but also surfaces that can be felt by the palm.

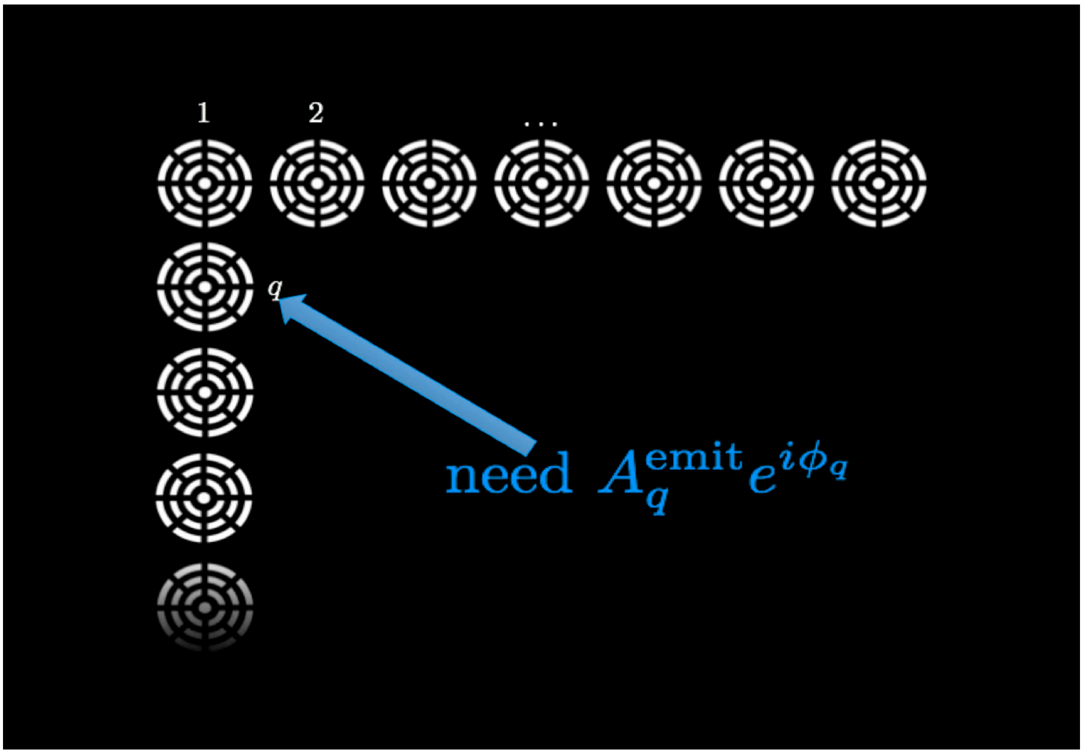
Algorithmic Details

Benjamin Long, Sue Ann Seah, Tom Carter, and Sriram Subramanian. 2014. Rendering volumetric haptic shapes in mid-air using ultrasound. ACM Trans. Graph. 33, 6, Article 181 (November 2014), 10 pages.

$$\Psi(x,t) = A(x,t)e^{i\theta(x,t)}$$

$$\Psi(\mathbf{x},t) = A(\mathbf{x})e^{i(\phi + k(\mathbf{x}) - \omega t)}$$

$$\Psi(\mathbf{x},t) = \underbrace{A^{\mathrm{emit}}e^{i\phi}}_{\textbf{Initial}}\underbrace{A^{\mathrm{attn}}(\mathbf{x})e^{ik(\mathbf{x})}}_{\textbf{Spatial}}\underbrace{e^{-i\omega t}}_{\textbf{Temporal}}$$



1
2
...
q
need $A_q^{\mathrm{emit}} e^{i\phi_q}$

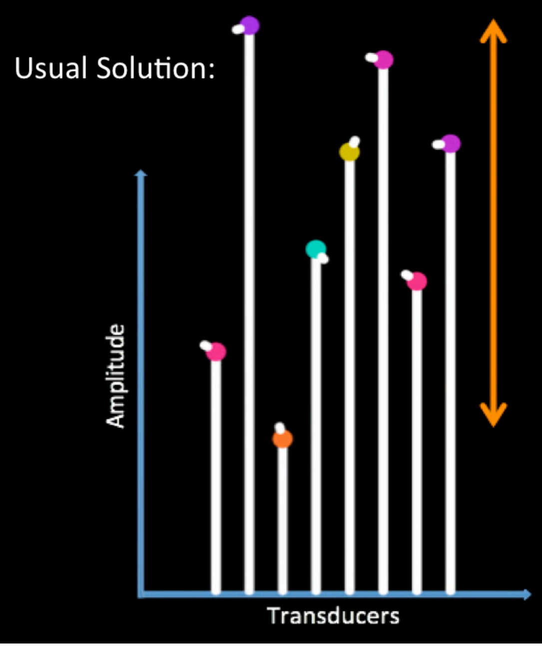
Usual solution method for multiple points

$$\begin{bmatrix} \Psi_1(\chi_1) & \cdots & \Psi_n(\chi_1) \\ \vdots & \ddots & \vdots \\ \Psi_1(\chi_m) & \cdots & \Psi_n(\chi_m) \end{bmatrix} \begin{bmatrix} A_1^{\text{emit}} e^{i\phi_1} \\ \vdots \\ A_n^{\text{emit}} e^{i\phi_n} \end{bmatrix} = \begin{bmatrix} \Psi'_\Omega(\chi_1) \\ \vdots \\ \Psi'_\Omega(\chi_m) \end{bmatrix}$$

No representation for transducer power limitations.

- Far away transducers – amplitude too high
- Near by transducers – amplitude too low

Example Solution

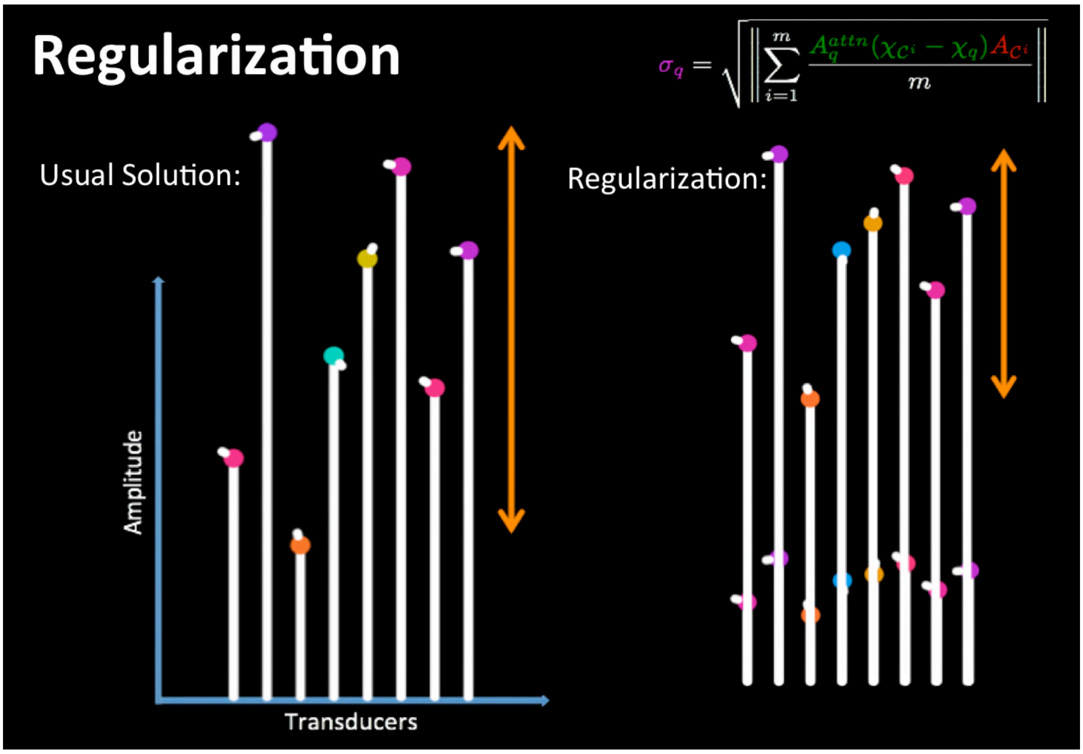


Adding regularization

$$\begin{bmatrix} \Psi_1(\chi_1) & \cdots & \Psi_n(\chi_1) \\ \vdots & \ddots & \vdots \\ \Psi_1(\chi_m) & \cdots & \Psi_n(\chi_m) \\ \sigma_1^{\gamma} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_n^{\gamma} \end{bmatrix} \begin{bmatrix} A_1^{\text{emit}} e^{i\phi_1} \\ \vdots \\ A_n^{\text{emit}} e^{i\phi_n} \end{bmatrix} = \begin{bmatrix} \Psi'_{\Omega}(\chi_1) \\ \vdots \\ \Psi'_{\Omega}(\chi_m) \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

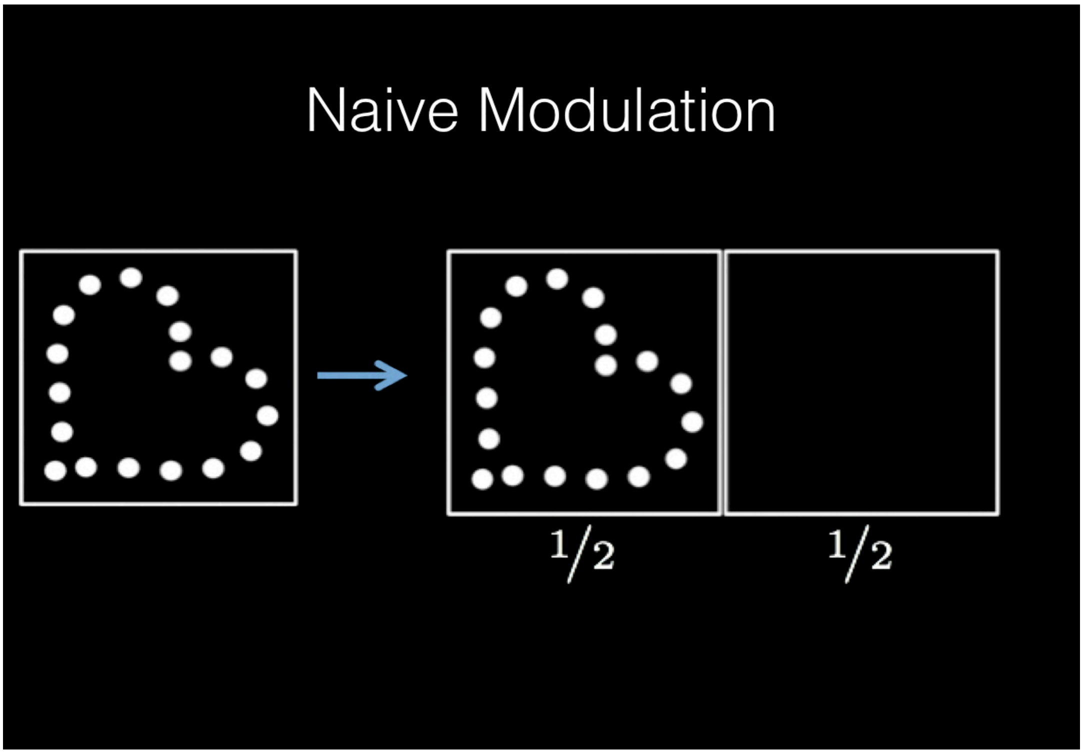
where with this augmented matrix:

$$\underset{A_q^{\text{emit}} e^{i\phi_q}, q \in \{1,\ldots,n\}}{\arg\min} \begin{bmatrix} \|\Psi_1(\chi_1) A_1^{\text{emit}} e^{i\phi_1} + \ldots + \Psi_n(\chi_1) A_n^{\text{emit}} e^{i\phi_n} - \Psi'_{\Omega}(\chi_1)\|^2 \\ \vdots \\ \|\Psi_1(\chi_m) A_1^{\text{emit}} e^{i\phi_1} + \ldots + \Psi_n(\chi_m) A_n^{\text{emit}} e^{i\phi_n} - \Psi'_{\Omega}(\chi_m)\|^2 \\ \|\sigma_1^{\gamma} A_1^{\text{emit}} e^{i\phi_1}\|^2 \\ \vdots \\ \|\sigma_n^{\gamma} A_n^{\text{emit}} e^{i\phi_n}\|^2 \end{bmatrix}$$

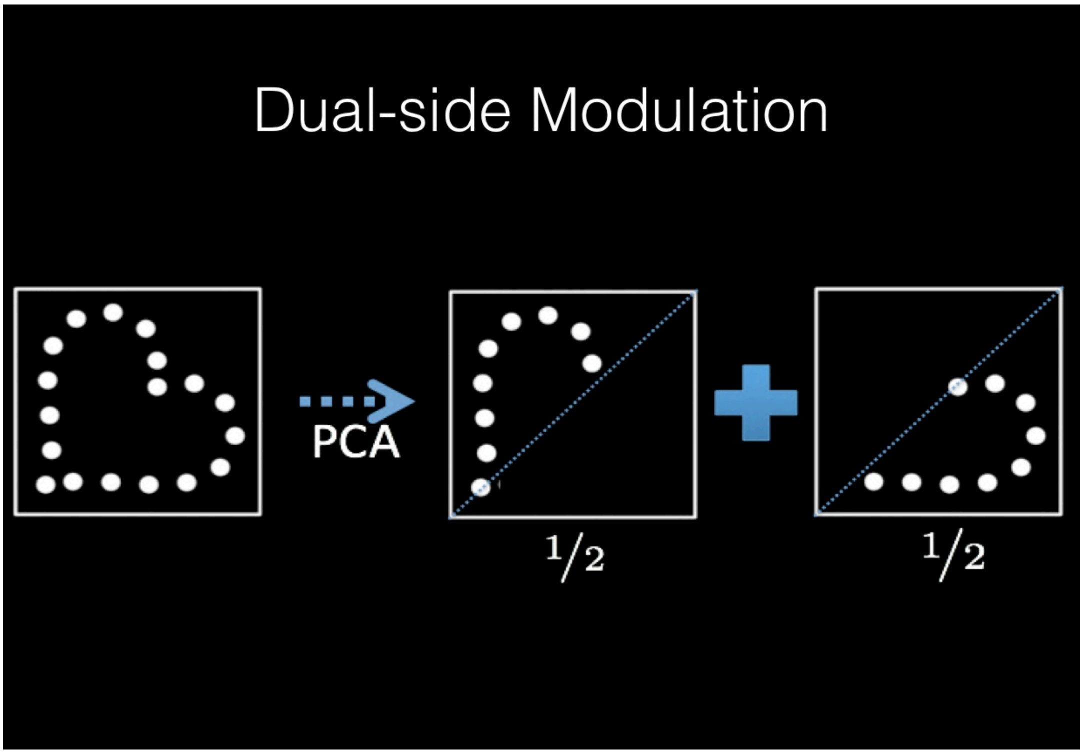


Regularization
$\sigma_q = \sqrt{\left\| \sum_{i=1}^{m} \frac{A_q^{attn}(\chi_{C^i} - \chi_q) A_{C^i}}{m} \right\|}$
Usual Solution:
Regularization:
Amplitude
Transducers

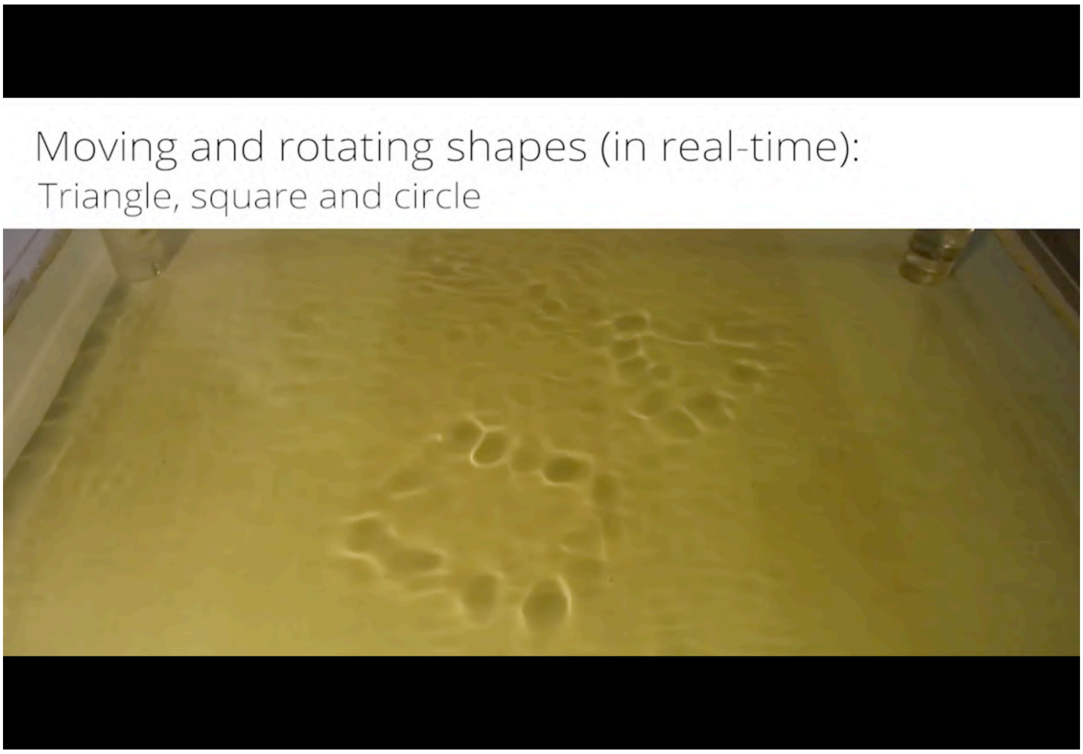
To perceive a tactile sensation, the 40KHz wave is modulated to between 10 and 250Hz so the user can feel the sensation.



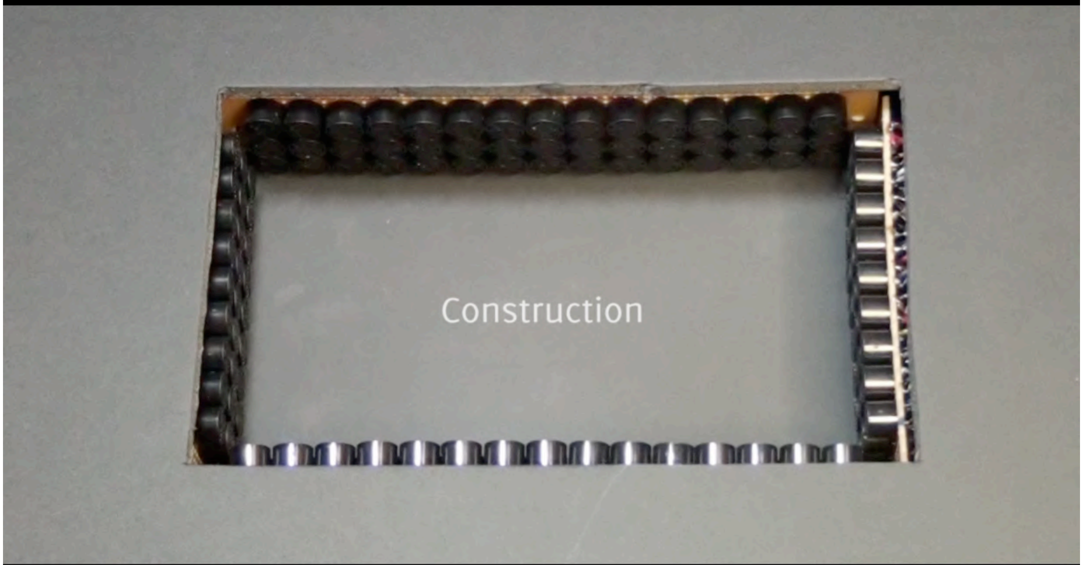
A naive approach to this modulation is to turn the entire array ON or OFF at the specified modulation frequency.



However a better approach would be to do a PCA to identify 2 sets of focal points that are turned ON in alternate cycles. This increases the strength of each focal point and improves quality of perceptible signal.

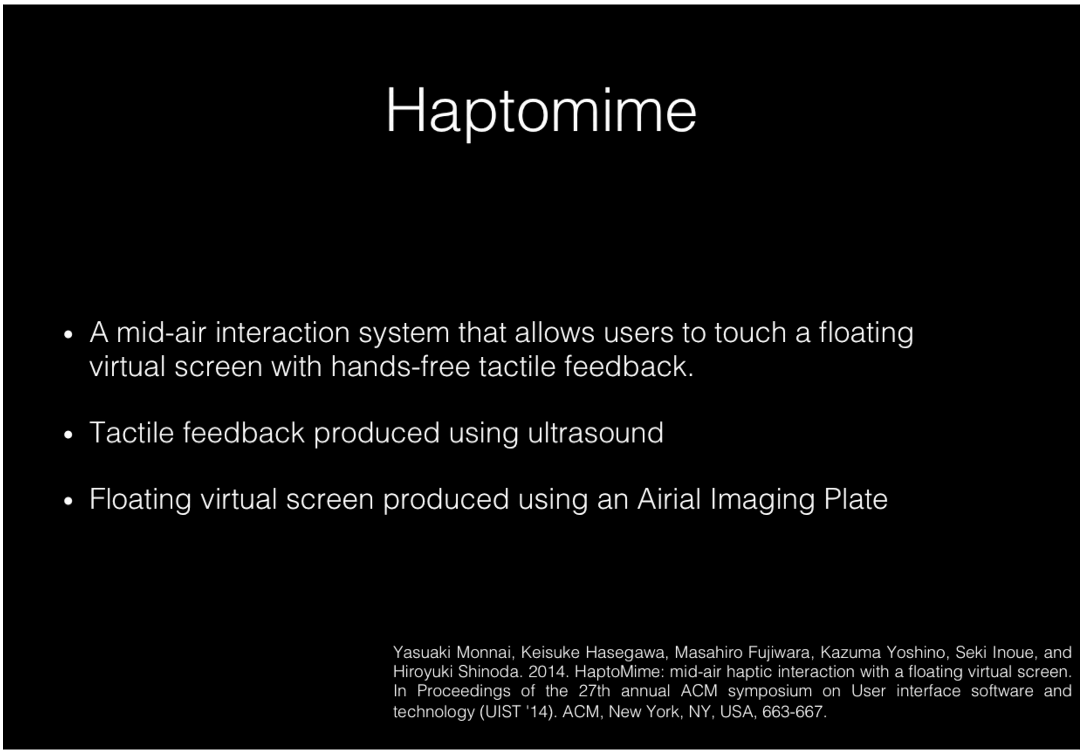


This video illustrates how the focal points look when we turn the ultrasound array on a petri-dish filled with oil.



Tom Carter, Sue Ann Seah, Benjamin Long, Bruce Drinkwater, and Sriram Subramanian. 2013. UltraHaptics: multi-point mid-air haptic feedback for touch surfaces. In Proceedings of the 26th annual ACM symposium on User interface software and technology (UIST '13). ACM, New York, NY, USA, 505-514.


Move your hand through the forcefield
ultrahaptics



Haptomime combines the tactile feedback system presented before with a floating display to create a system that allows users to touch a floating virtual screen with hands-free tactile feedback.

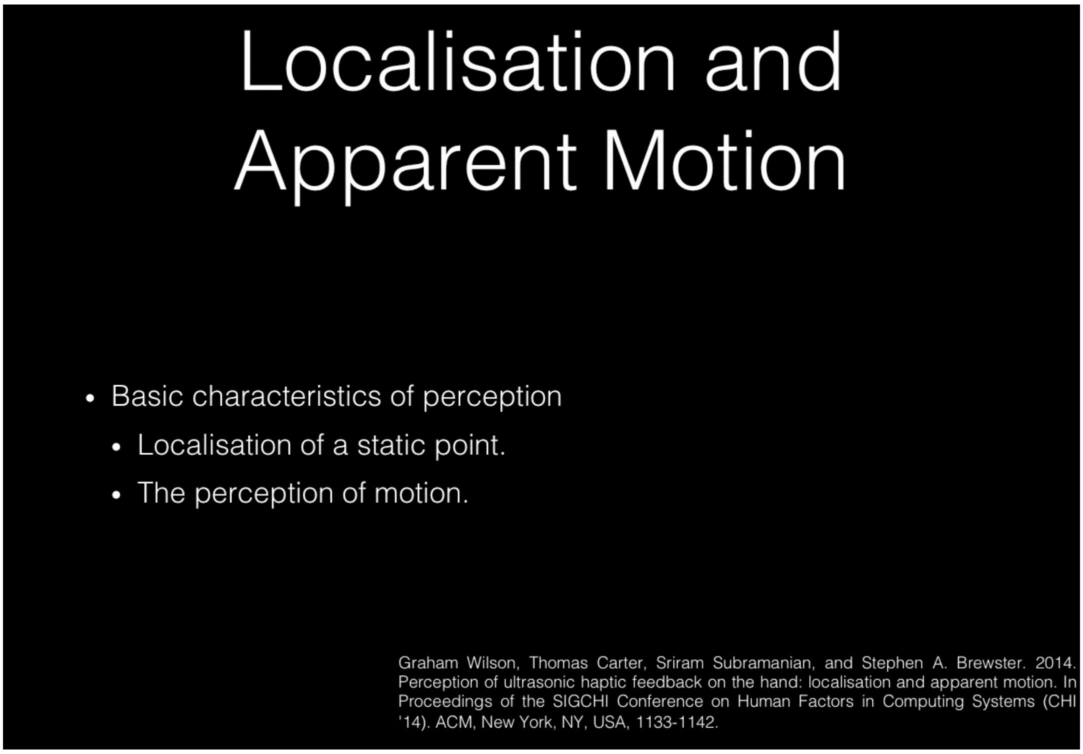
Laser Induced tactile sensations

- Use Lasers to induce tactile sensations
- Uses infrared light source with optical filters to control spot size.
- High patio-temporal resolution.

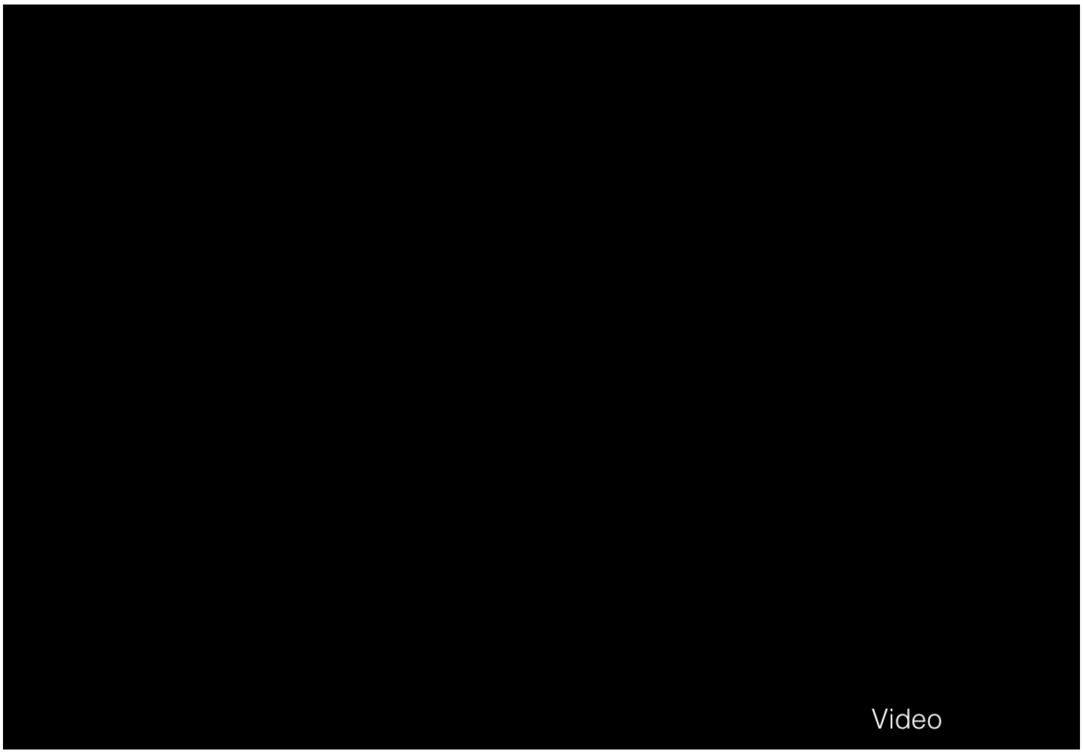
Jae-Hoon Jun, Jong-Rak Park, Sung-Phil Kim, Young Min Bae, Jang-Yeon Park, Hyung-Sik Kim, Seungmoon Choi, Sung Jun Jung, Seung Hwa Park, Dong-Il Yeom, Gu-In Jung, Ji-Sun Kim, and Soon-Cheol Chung, "Laser-induced Thermoelastic Effects can Evoke Tactile Sensations," Scientific Reports, Vol. 5, No. 11016, pp. 1-16, 2015.

Yoichi Ochiai, Kota Kumagai, Takayuki Hoshi, Jun Rekimoto, Satoshi Hasegawa, and Yoshio Hayasaki: Fairy Lights in Femtoseconds: Aerial and Volumetric Graphics Rendered by Focused Femtosecond Laser Combined with Computational Holographic Fields, Proc. ACM SIGGRAPH 2015, Talks, accepted, Los Angeles, California (USA), 9-13 Aug., 2015.

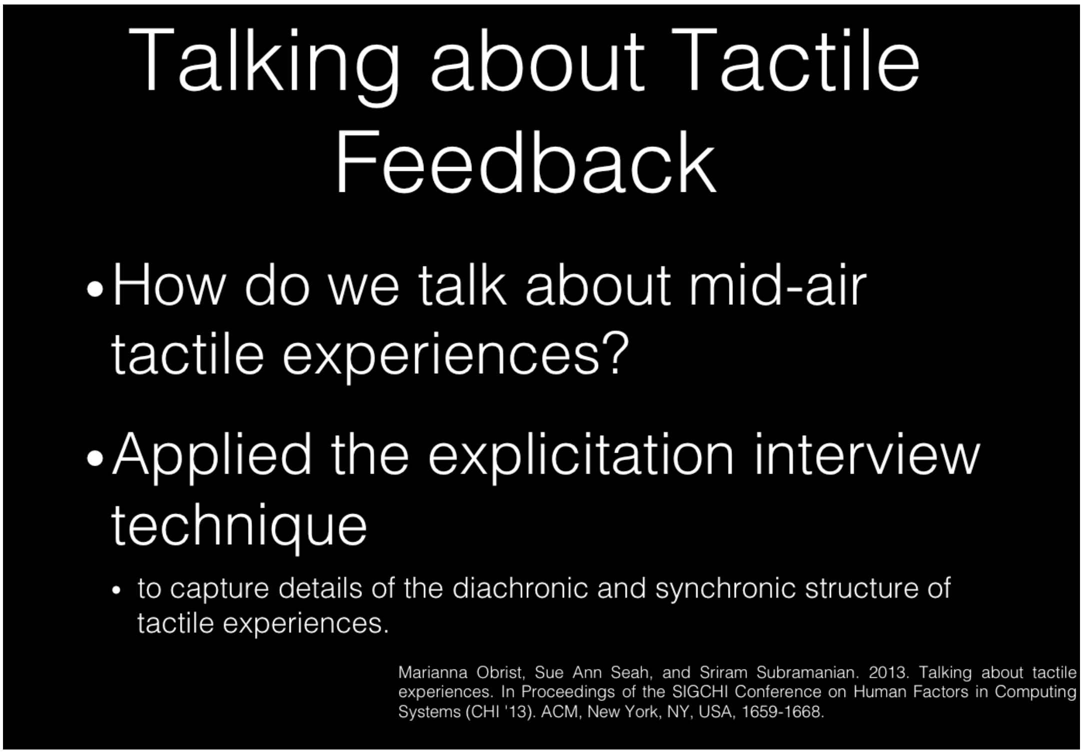
Designing interactions



While mid-air tactile systems have been proposed there is still a need to understand the basic characteristics of perception of this new feedback medium. In this paper the authors describe two experiments to look at a) localisation of a static point and d) the perception of motion.

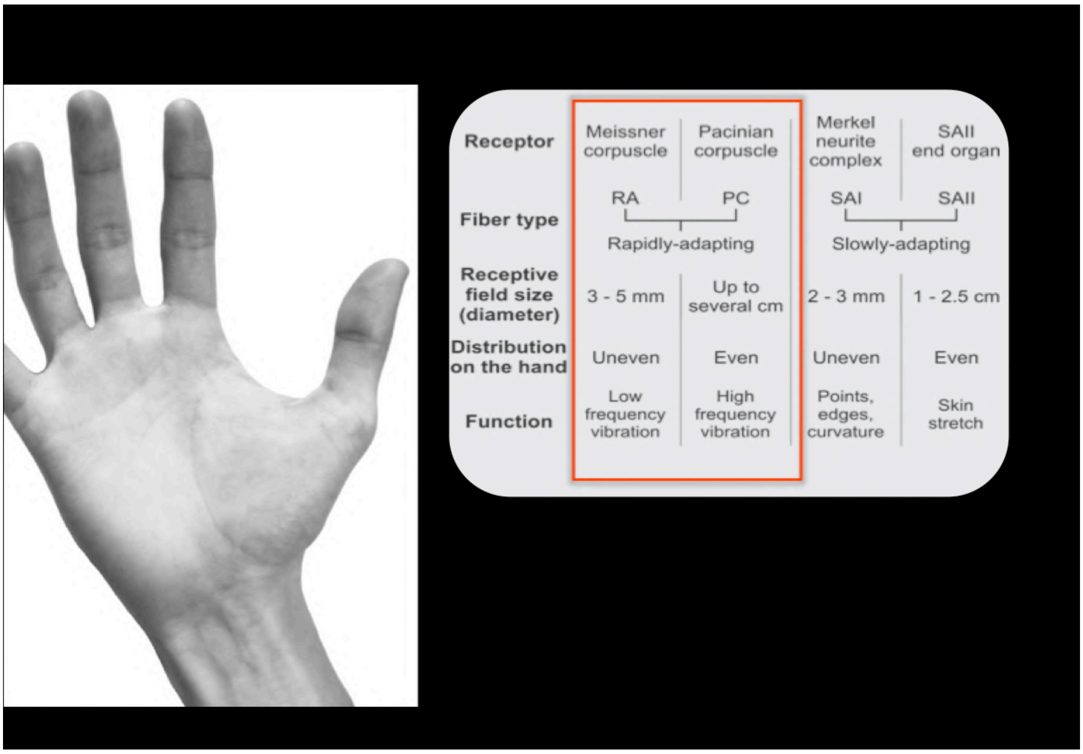


Results show an average localisation error of 8.5mm, with higher error along the longitudinal axis. Convincing sensations of motion were produced when travelling longer distances, using longer stimulus durations and stimulating multiple points along the trajectory.



A common problem with designing and developing applications with tactile interfaces is the lack of a vocabulary that allows one to describe or communicate about haptics.

In one study on how participants verbalise their tactile experiences the authors used an explicitation interview technique to capture detailed descriptions of the diachronic and synchronic structure of tactile experiences.

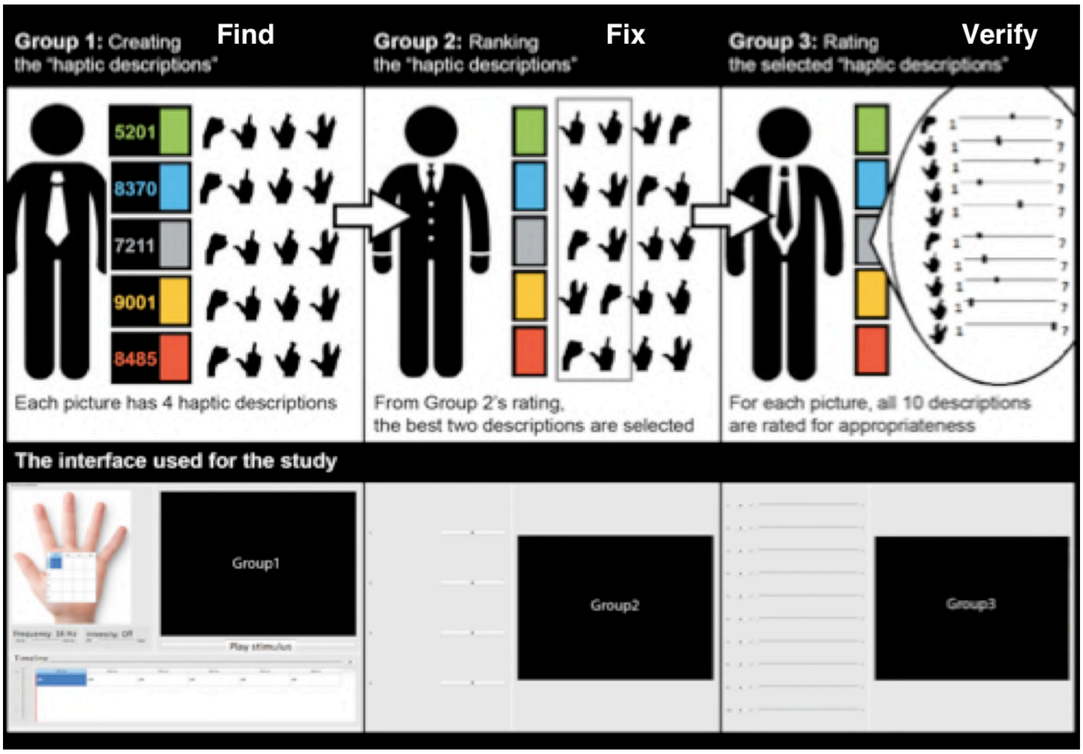


Verbalizations focused on tactile experiences across two modulated stimuli (16Hz and 250Hz) relating to two important mechanoreceptors in the human hand (Meissner Corpuscle and Pacinian Corpuscle).

Their results could highlight 14 categories for a human-experiential vocabulary based on the categorization of the findings and tie them back to neurophysiological and psychophysical data on the human hand.

Here the authors combined self expressivness with objective tactile parameters, to make suggestions on how to design haptic stimuli to create specific emotions (Bradley and Lang)

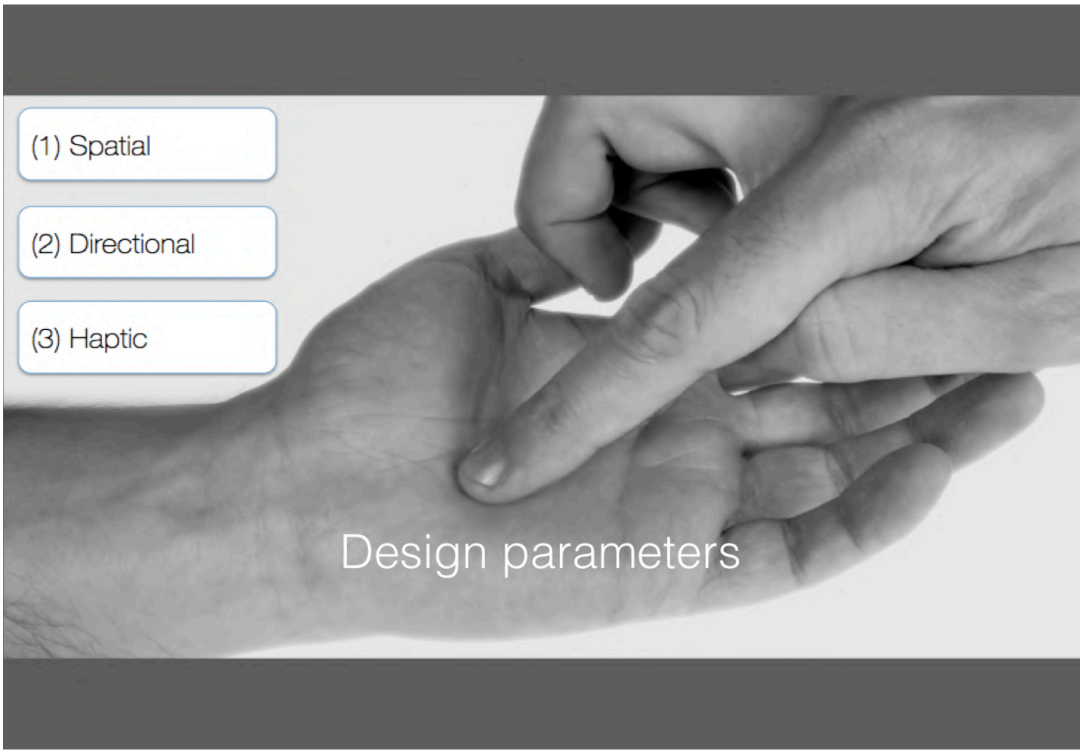
They used 5 standardised emotional stimuli, pictures from the International Affective Picture system database to represent positive and negative emotions, low and high arousal as well as a neutral stimulus



Group 1- Create haptic descriptions for each picture. So each picture has 4 haptic descriptions

Group 2 - Select the best 2 haptic descriptions for each picture

Group 3 - Rate all haptic descriptions against each picture



To better investigate the relations between the ratings related to each class of haptic descriptions (that is: haptic descriptions intended to describe each specific emotional picture), a metric multidimensional scaling (MDS) on two dimensions was applied (pooled together from each participant). The correlation plot was transformed into a similarity matrix representing the distance among the different haptic descriptions in a two dimensional space. The number of spatial dimensions was set at two based on a scree-plot evaluation; a scree-plot displays the proportion of the total variation in a dataset that is explained by each of the components from the principal component analysis.

The results from the MDS show that two dimensions were enough to represent the data. Interestingly, the


Emotions Mediated Through Mid-Air Haptics
Marianna Obrist, Sriram Subramanian, Elia Gatti, Benjamin Long, Thomas Carter
Video

Questions

@sssram
@Labinteract
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