jamSheets: Thin Interfaces with Tunable Stiffness Enabled by Layer Jamming

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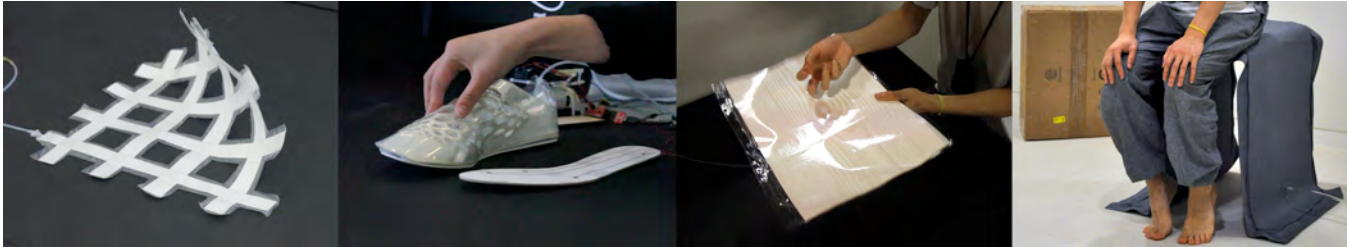Saarbrücken, Germany

Figure 1. (a) Weaving structure in layer jamming; (b) Jamming Shoes; (c) Stiffness-Changing Display (d) Deformable Furniture.

ABSTRACT

This works introduces layer jamming as an enabling technology for designing deformable, stiffness-tunable, thin sheet interfaces. Interfaces that exhibit tunable stiffness properties can yield dynamic haptic feedback and shape deformation capabilities. In comparison to the particle jamming, layer jamming allows for constructing thin and lightweight form factors of an interface. We propose five layer structure designs and an approach which composites multiple materials to control the deformability of the interfaces. We also present methods to embed different types of sensing and pneumatic actuation layers on the layer-jamming unit. Through three application prototypes we demonstrate the benefits of using layer jamming in interface design. Finally, we provide a survey of materials that have proven successful for layer jamming.

Author Keywords

Jamming, Variable Stiffness, Organic User Interfaces, Flexible Interfaces, Haptic Feedback.

ACM Classification Keywords

H.5.2. Information interfaces and Presentation: User interfaces and Evaluation; User Interfaces; Haptic I/O.

General Terms

Human Factors; Design.

INTRODUCTION

Recent research in Human-Computer Interaction (HCI) looks beyond static, rigid physical interfaces, and explores the rich materiality of input/output devices [12]. Organic User Interfaces (OUI) leverage the advantages of soft materials, which allow interfaces to be deformed and adapted to any non-planar surface [29]. Recently, researchers have explored advanced technology to dynamically control material properties like shape and stiffness [3, 6]. Shape-changing interfaces investigate dynamic interaction that derives from actively changing forms [2, 15], to build more responsive physical interfaces. Previous work provided a material perspective and approach of designing interfaces. In this paper, we look into sheet shaped material. By deploying layer jamming [27, 16] as a simple, low-cost way of switching between rigid and soft, we developed a range of techniques to give more control of stiffness for thin layer interfaces. This research is driven by the vision of Radical Atoms [12], which proposes a group of physical materials as a dynamic manifestation of digital information.

In everyday life we frequently encounter sheet shaped material, since various raw materials, such as metal, wood, and plastic, are vastly available in sheet. In the creation process of design and architecture, sheet materials, such as paper, have been frequently used for transforming flat surfaces into three-dimensional objects by cuts and folds. Drawing inspiration from prior work in the field of robotics [16], we propose a design space and promising application domains of the layer jamming mechanism for Organic User Interfaces. The ability to reconfigure the stiffness enables novel interactions for sheet shaped material. As devices and electronic gadgets have become increasingly thin, research

on thin stiffness-changing sheets contributes to the future of interaction with displays, tablets and cellphones.

In this paper, layer jamming has been explored from two aspects: (1) structural designs for layer jamming, such as weaving or crease patterns, to adjust the deformability of interfaces; (2) composite active layers for sensing and actuation on the layer jamming interface, to close the interaction loop. Our contribution includes:

- Introducing layer jamming as an enabling technology for HCI and design, to realize deformable thin sheet interfaces with tunable stiffness.

- Five novel structural designs of layer jamming to control the deformability of sheet material, e.g. directional or locational.

- Prototypes of applications that demonstrate the benefits of layer jamming in HCI, design and wearable products.

- A survey of performance of materials for layer jamming.

RELATED WORKS

Tunable Stiffness in Mechanical Engineering
Variable-stiffness materials and mechanisms have been explored in mechanical engineering to construct novel robotic systems [1]. One approach for achieving tunable stiffness is to utilize field-actived materials, such as magnetorheological (MR) or electrorheological (ER) fluids. Although the control is precise, the change of stiffness is not drastic. Particle jamming has been widely adopted recently. Such systems can switch from fluid-like states to solid-like states simply by controlling the differential air pressure in the system.

However, particle jamming can only work in large-volume systems. It cannot be used to construct thin and light surfaces/walls with tunable stiffness. To solve this issue, layer jamming was developed very recently by Kim Y, et al. in MIT [16]. Layer-jamming systems can be composed of an airtight envelope with multiple thin layers of "flaps" (e.g., paper) inside. As with particle jamming, the system utilizes negative air pressure to vacuum-pack the thin layers of material to amplify the friction between each layer. As illustrated in Figure 2, where S, P, n and μ represent the overlapped surface area, the pressure applied on the surface, the number of layers present, and friction coefficient of the thin layers respectively, the maximum resisting tensile force (F) can be calculated as follows: $F = \mu n P S$.

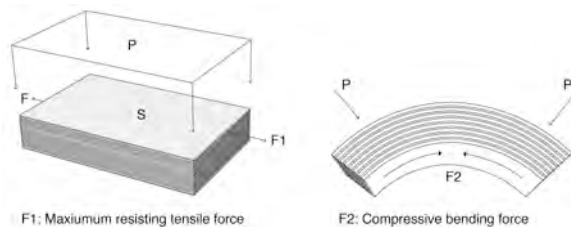F1: Maximum resisting tensile force   F2: Compressive bending force

Figure 2. Layer jamming effects are dependent on both maximum resisting tensile force and compressive bending force

Depending on the direction of applied external loads, the flexural stiffness of the jamming layers can also be important. If the direction of an applied external force is not parallel with all the flaps, then the layered flaps can be subjected to bending forces. That is the reason why even sheet materials with high friction coefficients do not necessarily result in a layer-jamming system with significant bending stiffness.

In addition to robotic manipulator, layer jamming has been used for orthosis and protective equipment that can be shaped and fitted to the body in an optimal way have also been developed [27].

Previous Uses of Jamming in HCI
Jamming user interfaces based on particle jamming principles have been introduced to HCI by Follmer S. et al. [6]. In this research, both hydraulic and pneumatic systems are implemented for use cases such as tunable clay, a transparent haptic lens and ShapePhones. This work demonstrates the large potential of utilizing jamming techniques to construct flexible, free-formed and tunable-stiffness displays and shapes. Similarly, HoverMesh applies a jamming technology with polystyrene beads to form a tangible tabletop interface [18]. Jamming can enable dynamic deformation and "solidification" of the tangible medium. ClaytricSurface is another example of a pneumatic jamming tabletop interface, which enables optical shape sensing through a ceiling-mounted depth-sensing camera [17]. By building on top of such existing jamming-interface research, we introduce a new technique, layer jamming, to design thin surface interfaces with tunable stiffness.

Thin Sheets as Organic Interfaces
Research on flexible interfaces composed of thin sheets is a growing field [29] in HCI. It spans from flexible displays, analog sensing, and "claytronic" output.

Considerable research has been conducted to explore devices that can be bent [10, 24], actuated [9, 23], and flexibly deformed [21, 25]. The role of stiffness on flexible displays has been investigated by Kildal and Wilson, who stated that increasing stiffness will have a negative influence on the performance when a user deforms a flexible interface [14].

A range of sensing techniques on organic and flexible interfaces has been explored in HCI: depth sensing [25], marker tracking [7], and embedded capacitive sensor networks [6, 19] are among common approaches.

Either external actuators or changes in material properties can achieve the deformation of flexible interfaces. For thin sheets, shape memory alloys [22, 23, 9], Electroactive Polymers (EAP) [20], electromagnets [8] and air bladders [24, 30] are among widely used external actuators. Particle jamming and air bladders have been combined to achieve rotating and bending structures [26].
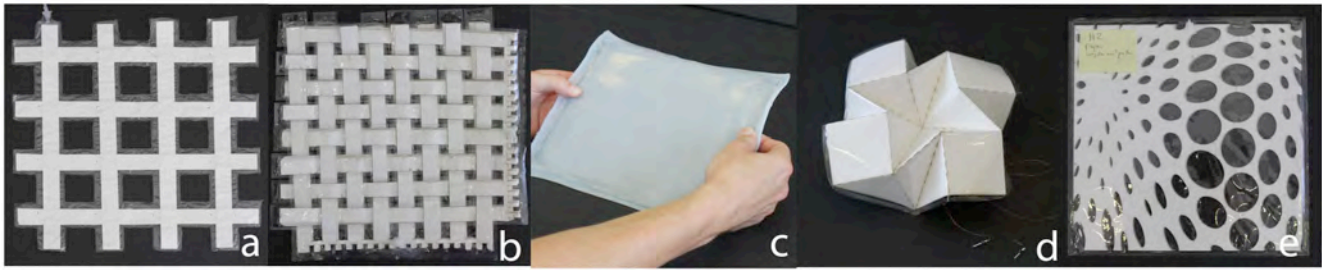
Figure 3. (a) Woven structure inside jamming envelope; (b) Multiple woven jamming units; (c) Interleave flaps enveloped in a elastic air bladder; (d) Crease pattern on jamming flaps; (e) Geometrical pattern cut on jamming flaps.

LAYER JAMMING DESIGN

While related works of layer jamming mechanisms focus mainly on controlling the degree of deformability (between soft and hard), we introduce the structural design of jammable materials to reconfigure other aspects of deformability, such as directional and locational anisotropy. In this section, five structure design principles are explained. We then introduce a method for integrating multiple materials into one jamming unit as an alternative approach for varying the degree of deformability.

Jamming Material Structure

We investigated how the geometric structure of the jammable material can expand the unique interaction capabilities that are afforded by layer jamming. We have explored this in five ways. Figure 3 presents an overview:

- Woven structure inside the jamming envelope: By interweaving strips of material in the jamming envelope, which snugly encompasses the strips, the form of the unit can be "solidified" by vacuum-packing the system. Furthermore, the bulk jamming unit can be relatively flexible while not jammed due to its porous, sparse structure.

- Multiple woven jamming units: In addition to the weaving in one jamming unit, we can also weave multiple jamming units to modify the stiffness of layer jamming. In our test, we design a jamming unit, which has twelve layers of eight strips. By cross-weaving the two and applying different air pressures on each, we can define the directional bending behavior. When only vacuuming the horizontal jamming unit, the whole piece can be only bent up and down; when only vacuuming the vertical one, the whole piece can be only bent left and right.

- Interleaving flaps enveloped in an elastic air bladder: In this design, we bind one edge of eight layers of flaps together like a book and duplicate another one. We then slide each flap into the layer gaps of the other one and seal them in an elastic airbag (silicone, EcoFlex 30, in this case). This allows user to pull the airbag from one direction to change the size of the layer-jamming interface. When jammed, the piece can be consolidated in its new size.

- Crease patterns in jamming flaps: An identical crease pattern can be applied on each flap before they are sealed in the jamming envelope. This technique can be useful for free-form paper origami. Traditionally, locking structures are required for maintaining a solid shape in origami. Layer-jamming with crease patterns can help to solidify the shape without additional locking structures. This can also be applied in the area of self-folding robotics.

- Geometrical patterns cut into jamming flaps: Since the jamming stiffness depends on the contact surfaces of the flaps, we can vary the stiffness locally by cutting out the material based on a designed pattern. In our sample, an area with less material is more flexible than areas with more material.

Composite Jamming Material

In order to leverage the advantages of combining different materials together, we also constructed layer-jamming samples that combine two types of materials. Combining jamming materials can not only vary the jamming stiffness within a certain thickness or weight limitation, but it can also maintain surface softness when jammed. For example, by adding a layer of soft felt to a stack of paper, a high resistive bending force can be achieved by the stack of paper, while softness of the felt remains on the surface of the composite. This composite principle has been deployed for one of our jamming shoe designs.

COMPOSITE ACTIVE LAYER

Composite Sensing Layer

Sensing layers can be embedded in layered jamming materials. The way to construct thin pressure and bending sensors with off-the-shelf materials has been introduced [19, 23]. We construct our pressure sensor and bending sensor with one layer of copper tape, one layer of 3M velostat [28], and another layer of copper tape. As the sensor are pressed or bent, the copper tapes will make more contact with the velostat. Thereby the electrical resistance between the three layers will be reduced. This behavior allows us to detect the amount of force applied on the sensor. In our material samples, pressure sensors are constructed as round shapes and can be attached to any area that need pressure detection (Figure 4a-c). Bending sensors

are constructed in rectangular shapes and can be attached to the hinges at which bending needs to be detected (Figure 4d-f). As a preliminary exploration, our current sensors have discrete sensing points. In the future, a more generic sensor network can be constructed as well. For example, instead of four pressure sensor points, the entire layer can sense pressure at any given point. Mutual capacitive sensing is also explored as an approach to detect proximity between two folding surfaces (Figure 4g-i). The method for designing the capacitive sensor is similar to the Jamming UI [6].
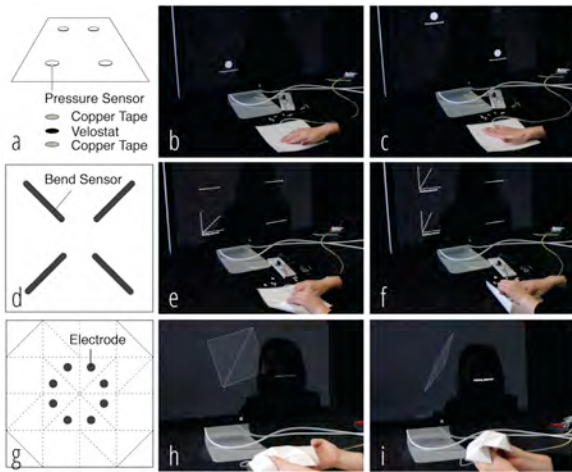

Figure 4. Embedding sensors in the jamming units: (a-c) pressure; (d-f) Bending; (g-i) Mutual capacitance

Composite Actuation Layer

We chose air bladders as the actuation approach, as it shares the same main control system including the pumps and valves. We use vinyl material for constructing the air bladders, which can be fabricated with plastic welding and can be glued to the jamming layer. When inflated, the air bladder compresses and curls the attached jamming layer (Figure 5) [30]. While jamming requires negative pressure, air actuators require positive pressure. Air actuation has been introduced in mechanical engineering for soft robot control [24]. By introducing air actuation, layer-jamming surfaces can be self-actuated and deformed when flexible (Figure 5a), and jammed into a rigid configuration once it reaches the desired state (Figure 5b). Air bladders can be deflated once the system is jammed into place (Figure 5c).
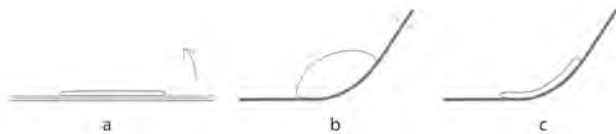

Figure 5. Compositing pneumatic actuation to jamming unit

LAYER JAMMING CONTROL SYSTEM

In a layer-jamming control system, air can be either vacuumed out of or pumped into the jamming envelope. A layer-jamming control circuit can be composed of two 3-port solenoid valves and one air pump for a single jamming envelope. For most of our tests and applications, we built a portable control system composed of an Arduino mini Pro, mini Arduino FET shield, SMC s070c-sdg-32 solenoid valves and AIRPO mini D2028 air pump (Figure 6b).

There are three modes to control the airflow in and out of the layer-jamming envelope: exhaust, supply, and close. The exhaust/supply is the mode to deflate/inflate an air bag, respectively. The close mode stops the airflow to maintain the system at a certain air pressure and therefore a degree of stiffness (Figure 6a).

For the deformable furniture application, we use a large stationary vacuum pump instead of a small portable air pump, due to the large volume of air that needs to be removed for the application. The stationary version of the layer-jamming control system can achieve greater jamming and inflation speeds, as well as larger negative pressures when jamming. This is crucial since a higher jamming stiffness is desired for the furniture application.
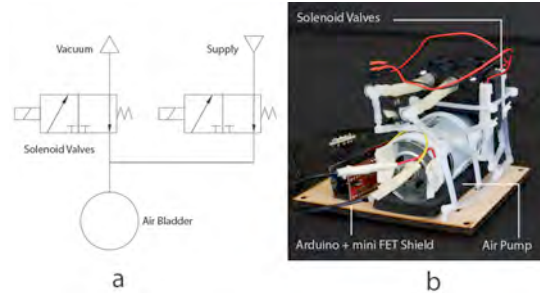

Figure 6. Layer-jamming control system: (a) Basic pneumatic circuit for single air bag; (b) Portable pneumatic system

APPLICATIONS

We built three applications to evaluate three main features of using layer-jamming mechanism in interfaces: stiffness tunability, large material strength, and their ability to be lightweight. Through these applications, we demonstrate that an interface can tune its stiffness to match projected material texture; it can support body weight when it becomes stiff; and it is light enough for wearable product.

Stiffness-Changing Display

In this application, we introduce tunable stiffness as a physical parameter in displaying digital contents. The first scenario demonstrates that the display can simulate stiffness of different projected material textures (Figure 7a-c). We sequentially project three material textures (wood, foam and leather) on a layer-jamming unit, which is shaped like a tablet. When the visually projected texture changes, the layer-jamming control system provides negative or positive air pressure to adjust the display's stiffness; the wood is the stiffest material and leather is the most flexible one.

In the second scenario, the surface can transform from a shared display into a private working station (Figure 7d-f). In one state, shared contents are displayed on a flat surface;

when a certain user needs to read a private email, he or she can fold half of the display to make it perpendicular to the table, such that the displayed contents can only be seen from one side. The system will freeze the deformed shape. The last use case demonstrates how the stiffness changing of the display can be mapped to the movie contents. In "Ice Age: The Meltdown" [the movie homepage], the display turns stiffer when it plays the ice scene, and softer when the water scene appears (Figure 7g-i).
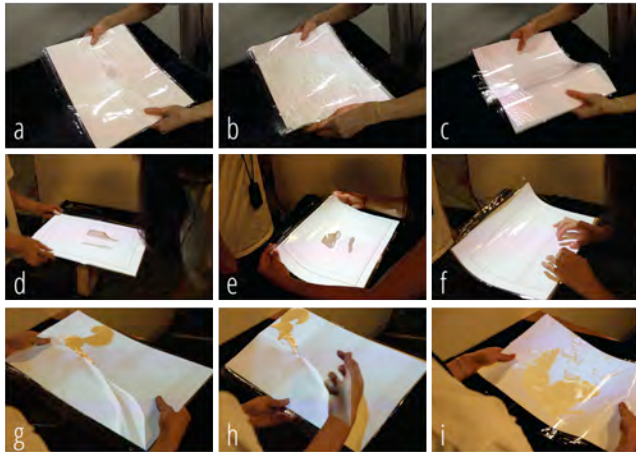

Figure 7. Flexible display with controllable stiffness: (a-c) Rendering stiffness of textures (wood, foam and leather); (d-f) Deforming the display for switching between public and private views; (g-i) Stiffness changes mapped to movie contents.

To detect the shape and orientation of the display, and also to avoid the noise from users' hand occlusion, we utilized depth sensing with a depth camera mounted on top of the display. The tracking setup and technical solution are similar to the FlexPad system [25], with optical material analysis differentiating hands from the display, and the 15-dimensional vector deformation model to reconstruct the display in a digital environment. Compared to our existing composite sensing techniques, optic tracking can detect the 3D spatial change of the jamming surface. This feature is useful for projection mapping to simulate flexible displays of future tablet devices.

Figure 8. Deformable Furniture: (a) Unwrapping a flexible carpet. (b) Vacuuming the carpet. (c) Carpet becoming stiff. (d) Carpet becoming soft again and conformed to the shape of the box. (e) Carpet turning into a chair. (f) The chair holds weight up to 55kg.

Deformable Furniture

We design a portable chair that resembles a flat, flexible carpet in its unjammed state, such that it can be folded and carried easily (Figure 8). When users transform the flat sheet into the shape of a chair by creating two folds where the sensors are embedded, the system will automatically start the jamming process after three seconds. Once jammed, the carpet will become stiff enough to maintain the chair shape and support up to a load of up to 55 kilograms. The carpet can be formed into other 3D shapes as well, such as a table board, or a free-formed lounge.

We use 45 layers of 120-gram sketch paper as jamming flaps to build the entire jamming unit. Each flap has a dimension of 45 × 152 cm. The total thickness of the unit is 8.5 mm. For the jamming envelop, we laminate two pieces of PVC sheets to create an airtight seal and outer layers of woolen fabric for aesthetics and tactile sensation.

Figure 9. Self-Deforming Furniture: (a) Flexible surface. (b) Self actuated and deformed. (c) Table becomes stiff by Jamming.

The second example is a self-actuated coffee table (Figure 9). We attach two air bladders at the hinge of a bendable surface, which is a jamming bag by itself. The two air bladders function as actuators, which can compress and therefore bend the surface when it is flexible. Jamming the surface will maintain the actuated shapes. Afterwards, the inflated bladders can be deflated while the table shape is maintained.

The actuated coffee table has the identical dimension of the chair. Two air bladders are measured as 50 × 38 cm. They are bonded to the jamming unit by heat welding.
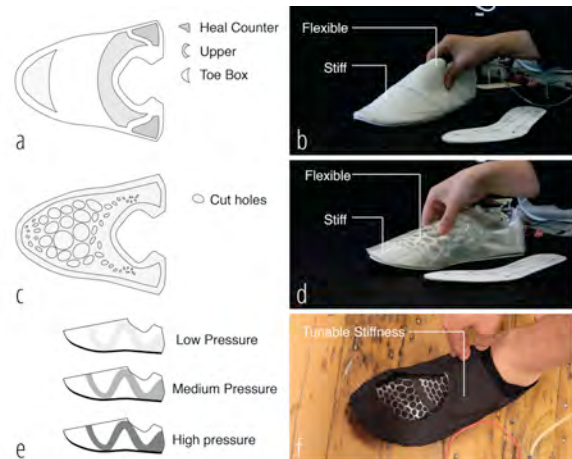

Figure 10. Jamming Shoe: (a, b) A shoe with reconfigurable jamming parts. (c, d) A shoe with different stiffness distributions. (e, f) A shoe with tunable stiffness on the outline frame.

Jamming Shoe

Three jamming shoe prototypes were built to demonstrate how a single system could be used to explore different designs and their impact on footwear products. Compared to other stiffness-changing approaches, layer jamming is ideal for tuning the stiffness of shoes, as their thin and lightweight characteristics are desirable.

One shoe integrates four independently jammable components: the toe box, the heel counter (the part between heel top and sole) and the upper (Figure 10a, 11b). For different situations, we can achieve different combinations of jamming. For walking, the toe box is jammed to enable users to roll off their toes rather than bend through them, as they will do for running. For hiking, the upper and heel counter can be jammed to give extra support and protection. Moreover, jamming effects can vary temporally. For marathon runners, feet might swell as time passes. In this case, the upper and toe box can become looser and softer to adapt to the size of feet. In Figure 11d, the entire shoe is one jammable component. However, by designing the cut pattern on each jamming flap, different levels of flexibility can be achieved across the shoe. In the case of Figure 10f, jamming layers for the ramp part have larger and more holes, which enables the ramp to be more flexible than the other parts of the shoe in the jammed state. The last shoe system demonstrates programmable jamming levels. By controlling air pressure via a microcontroller, we can achieve tunable stiffness for different use cases.
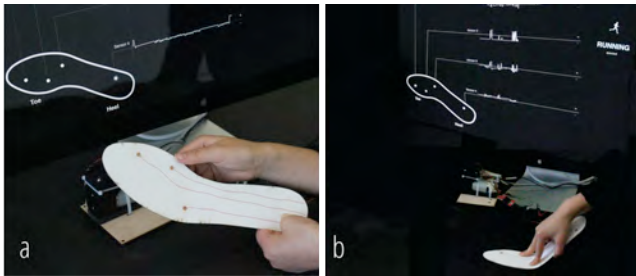

Figure 11. Jamming Shoe: (a) Sensor distribution on the sole. (b) Running mode detected.

For each shoe, the insole is jammable as well to provide various levels of cushion and stability. For example, when people play basketball and run on the court, the insole turns stiffer to provide extra stability. And the insole can become softer to provide more cushion impact for jogging.

Figure 12. Fabrication process of Jamming Shoes

Four pressure sensors are integrated into the insole to detect predefined motion patterns: three in the front sole and one in the back (Figure11). For example, when users switch from walking to running, larger forces will be applied to the front sole, thus the running state can be detected. As the pressure applied on insoles changes when users lift their feet up every time, the frequency of such changes can be utilized to determine the speed at which feet are moving.

The fabrication process of the shoes includes cutting and sealing jamming bladders, designing and gluing 2D patterns for top parts, and assembling top and bottom parts into 3D shoes (Figure 12).

SELECTION AND TEST OF JAMMING MATERIALS

Based on the aforementioned calculation of layer jamming's maximum resistance to tensile loads, stacking layer materials with high friction coefficients can achieve a higher stiffness while the system is jammed. However, some materials, which have high friction coefficients, cannot achieve a considerable stiffness when jammed due to their own softness. Therefore the material selection is not trivial anymore. For this paper, we have surveyed 32 types of thin sheet materials (Figure 13) that are that are relatively inexpensive, commercially available materials, and conducted bending torque comparison tests between normal and jammed states to quantify a material's stiffness change. The purpose of this test is to provide designers and researchers with an overview of what materials are suitable for layer jamming and to compare and extrapolate relevant and desirable properties (thickness and weight) for different applications.
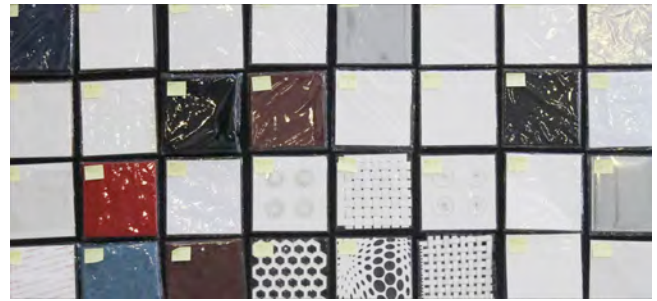

Figure 13. Samples of materials tested for layer jamming

Figure 14 shows the test setup. A standard layer-jamming test sample is 12 flaps of targeted materials (20cm by 20cm) sealed in Vinyl-Pane clear plastic (Warp Bros). In the test, we bend a test sample from 0° to 30°. The lever arm is 15.2 cm. Based on the measured bending force, the bending stiffness (jammed or unjammed state) of a sample can be roughly calculated as: torque = $0.152 \times F \times \sin30º$, where F is the measured bending force.
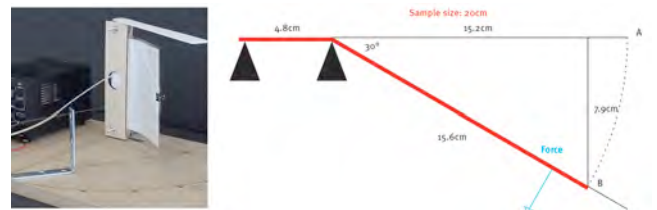

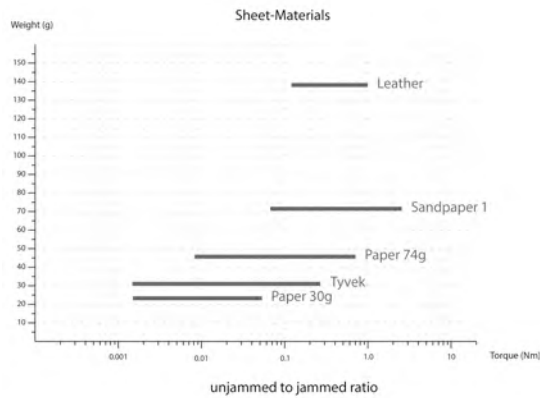**Figure 14. Test setup of jamming samples' torque**

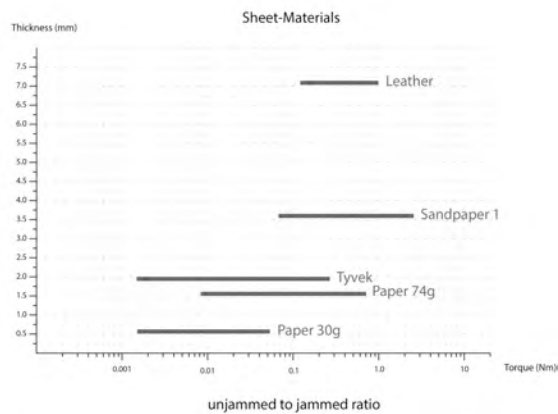**Figure 15. Materials' distribution in weight and torque**

Figure 16. Materials' distribution in thickness and torque

Figure 15 and 16 present examples of the normal and jammed bending torque ratios of five types of materials as a function of weight and thickness, respectively. As indicated in figure 17, we have also tested the bending stiffness changes based on the change in air pressure in the jamming envelope in order to understand how the negative air pressure influences the jamming performance. These graphs can be useful for designers to select jamming materials based on thickness and weight criteria.
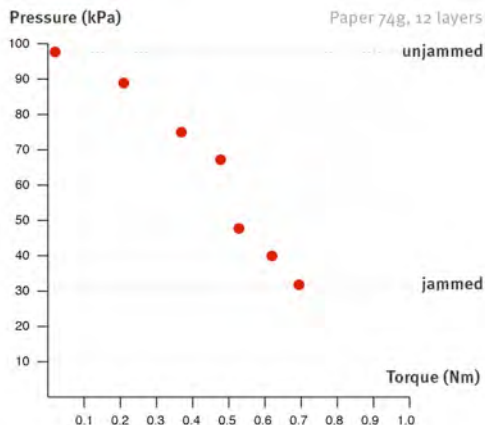

Figure 17. Torque change in relation to air pressure.

LIMITATIONS AND FUTURE WORK

Malleability

In previous work on particle-jamming user interfaces [6], malleability has been described as one advantage of deformable 2.5D surfaces or objects. With layer jamming, it is more challenging to achieve malleability. In future work we plan to explore techniques of origami-pleating or pattern-creasing, which will add relative malleability to the thin sheets of jamming layers.

Reconfigurable Actuation

We consider the combination of air actuation and layer jamming as an efficient approach for self-actuated and deformed interfaces, as both techniques can share the same control system consisting of pumps and valves. While air bladders need to be inflated for actuation, layer-jamming sheets need to be vacuumed to achieve variable stiffness. Although we added two simple air bladders in one of our applications, the exploration is very limited.

In the future, there are two ways to design jamming surfaces that can be self-deformed and jammed in various ways. First, by placing multiple air actuators and inflating different combinations of them, the same surface can be deformed in different ways. Second, by placing a single air actuator but multiple jamming bladders, we can tune the stiffness at different locations, so that the surface can be deformed differently.

Multimodal Interaction with Jamming Materials

By embedding further computational capabilities into the jamming system, we can explore multimodal interaction with the material, and enable "memory" of its own shape to the material. If combined with voice, gesture or external switch controls, the self-actuated surfaces can respond to multimodal inputs and transform accordingly. One example scenario: users manually deform a flat, jammable sheet into a chair and verbally say "save," and the configuration is saved automatically. After the chair is unjammed and returns flat, users can say, "replay," to recall the saved shape via the structure's self-actuation capabilities.

CONCLUSION

This paper introduces layer jamming as an enabling technology for designing deformable, stiffness-tunable thin sheet interfaces. We contribute several structural design principles of materials. We also demonstrate how to embed sensing and pneumatic actuation. To guide the reader in selecting materials for layer jamming, we give a survey of materials. We see layer jamming as a highly useful technique for shape-changing user interfaces and products. It is one step further towards the vision of Radical Atoms [12].

REFERENCES

1. Cheng, N.G., Lobovsky, M.B., Keating, S.J., Setapen, A.M., Gero, K.I., Hosoi, A.E., and Iagnemma, K.D. Manipulator Enabled by Jamming of Granular Media. ICRA (2012), 4328–4333.

2. Coelho, M. and Maes, P. Sprout I / O : A Texturally Rich Interface. TEI '08, ACM Press (2008), 221–222.

3. Coelho, M. and Zigelbaum, J. Shape-changing interfaces. Personal and Ubiquitous Computing Vol.15, Issue 2, Springer-Verlag London (2010), 161–173.

4. Delle Monache, S., Rocchesso, D., Qi, J., Buechley, L., De Götzen, A., and Cestaro, D. Paper mechanisms for sonic interaction. TEI '12, ACM Press (2012), 61-68.

5. Van Donselaar, R. and Chen, W. Design of a smart textile mat to study pressure distribution on multiple foam material configurations. ISABEL '11, ACM Press (2011), 1–5.

6. Follmer, S., Leithinger, D., Olwal, A., Cheng, N., and Ishii, H. Jamming user interfaces: programmable particle stiffness and sensing for malleable and shape-changing devices. UIST '12, ACM Press (2012), 519–528.

7. Gallant, D.T., Seniuk, A.G., and Vertegaal, R. Towards More Paper-like Input: Flexible Input Devices for Foldable Interaction Styles. UIST '08 ACM (2008) 283–286.

8. Goldstein, S.C., Campbell, J.D., and Mowry, T.C. Programmable matter. IEEE Computer Vol. 38, Issue 6 (2005), 99–101.

9. Gomes, A., Nesbitt, A., and Vertegaal Roel. MorePhone: A Study of Actuated Shape Deformations for Flexible Thin-Film Smartphone Notifications. CHI '13 ACM Press (2013), 583–592.

10. Herkenrath, G., Karrer T., and Borchers J. TWEND : Twisting and Bending as new Interaction Gesture in Mobile Devices. CHI EA'08 ACM Press (2008), 3819–3824.

11. Huang, Y. and Eisenberg, M. Easigami : Virtual Creation by Physical Folding. TEI '12, ACM Press (2012), 41–48.

12. Ishii, H., Lakatos, D., Bonanni, L., and Labrune, J. Radical atoms: beyond tangible bits, toward transformable materials. Interactions, Interation Vol. 19, Issue 1, ACM Press (2012), 38–51.

13. Jung, J.H. and Keller, T. (19) United States (12) Patent Application Publication (10) Pub . No .: US 2012 / 0310126 A1. 1, 2012.

14. Kildal, J. and Wilson, G. Feeling It : The Roles of Stiffness, Deformation Range and Feedback in the Control of Deformable UI. ICMI '12, ACM Press(2012), 393-400.

15. Kim, S., Kim, H., Lee, B., Nam, T.-J., and Lee, W. Inflatable Mouse: Volume-adjustable Mouse with Air-pressure-sensitive Input and Haptic Feedback. CHI '08, ACM Press (2008), 211–214.

16. Kim, Y., Cheng, S., Kim, S., and Iagnemma, K. Capability by Layer Jamming. IROS '12, IEEE/RSJ (2012), 4251–4256.

17. Matoba, Y., Sato, T., Takahashi, N., and Koike, H. ClaytricSurface: an interactive surface with dynamic softness control capability. SIGGRAPH '12 Emerging Technologies, ACM Press (2012), Article 6.

18. Mazzone, A., Spagno, C., and Kunz, A. The HoverMesh: a deformable structure based on vacuum cells: new advances in the research of tangible user interfaces. ACE '04, ACM Press (2004), 187–193.

19. Mazzone A., Zhang, R., and Kunz A.; Novel Actuators for Haptic Displays based on Electroactive Polymers. VRST '03, ACM Press (2003), 196-204.

20. Perner-Wilson, H., and Buechley, L., Making textile sensors from scratch. TEI '10, ACM Press (2010), 349-352.

21. Schwesig, C., Poupyrev, I., and Mori, E. Gummi : A Bendable Computer. CHI '04, ACM Press (2004), 263-270.

22. Qi, J. and Buechley, L., Animating paper using shape memory alloys. CHI '12, ACM Press(2012), 749-752.

23. Roudaut, A., Karnik, A., Löchtefeld, M., and Subramanian, S. Morphees : Toward High " Shape Resolution " in Self-Actuated Flexible Mobile Devices. CHI '13 ACM Press (2013), 593–602.

24. Shepherd, R.F., Ilievski, F., Choi, W., et al. Multigait soft robot. PNAS Vol. 108, No. 51 (2011), 20400–3.

25. Steimle, J., Jordt, A., and Maes, P. Flexpad : Highly Flexible Bending Interactions for Projected Handheld Displays. CHI '13 ACM Press (2013), 237–246.

26. E. Steltz, A. Mozeika, J. Rembisz, N. Corson and H.M. Jaeger, "Jamming as an Enabling Technology for Soft Robotics," EAPAD '10, San Diego, CA, 2010.

27. Varstiff. www.tecnalia.com/es/salud/index.htm

28. Velostat. www3.3m.com

29. Vertegaal, B.Y.R., Poupyrev, I., and Editors, G. Organic user interfaces. Communications of the ACM, ACM Press (2008), 26-30.

30. Yao L., Niiyama., Ou J., Follmer S., Silva C., Ishii H., PneUI: Pneumatically Actuated Soft Composite Materials for Shape Changing Interfaces. UIST'13, ACM Press (2012), 13-22.