Bosu
A Physical Programmable Design Tool for Transformability with Soft Mechanics

Amanda Parkes and Hiroshi Ishii
Tangible Media Group
MIT Media Lab
20 Ames St E15-350
Cambridge, MA 02139
{amanda, ishii}@media.mit.edu

ABSTRACT
Physical transformability is emerging as an important element of interaction design as advances in material science and computational control give rise to new possibilities in actuated products and kinetic environments. However, this transition also produces a new range of design problems- how do we visualize, imagine, and design the physical processes of transformation? This paper presents Bosu, a design tool offering kinetic memory—the ability to record and play back motion in 3-D space—for soft materials. It is used for motion prototyping and digitally augmented form finding, combining dynamic modeling with coincident sensing and actuation to create transformable structures. Evaluation from a workshop with architects and interaction, product, and fashion designers is presented discussing the ramifications of physically programming motion with a new soft materiality, moving toward new ideas in body mimesis and material construction for kinetic design.

Author Keywords:
Tangible User Interface, Kinetic Interface, Transformability, Case Studies, Product Design, Interaction Design

ACM Classification Keywords:
H.5.2 Information interfaces and presentation: Prototyping

INTRODUCTION
At its core, the concept of Tangible Interfaces [8] leverages the idea of using the movement of the body as an inherent part of the human side of a human-computer interaction, assuming that bodily engagement and tactile manipulation can facilitate deeper understanding and more intuitive experiences. However, as an interaction principle in our era of digital design, motion construction and control has been underutilized and little examined as a design tool, leaving open the possibilities of motion's natural ability to draw our attention, provide physical feedback, and convey information through physical change. The ability to experiment, prototype, and model with programmable kinetic forms is becoming increasingly important as digital technology becomes more readily embedded in our objects and environments. The need for tools and systems with which to create, manipulate and finesse motion in response to computational and material input remains an under-developed design area.

DIS 2010, August 16-20, 2010, Aarhus Denmark

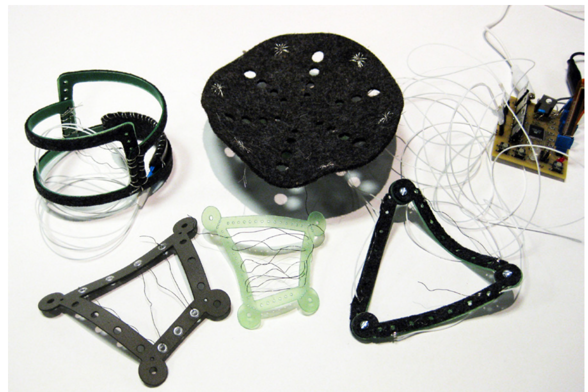


Figure 1. A Mixture of Bosu Modules

This paper presents Bosu, a design tool which combines physical record and playback functionality with the organic qualities bringing kinetic memory to soft materials and marking a new arena of actuation in soft mechanics. Bosu is used for motion prototyping and digitally augmented form finding, combining dynamic modeling with coincident sensing and actuation to create transformable structures. The system consists of varying modular units of bend sensors paired with shape memory alloy (nitinol) actuators woven into a bendable plastic frame and embedded in fabric [fig. 1]. Each module can actuate between two positions and when combined form three dimensional motion pixels.

MATERIALITY & KINETIC DESIGN
Materiality has emerged as an important design parameter to open up a greater range of aesthetic, tactile and perceptual qualities in interaction design. In interface design, we generally rely on the visual affordances of an object to

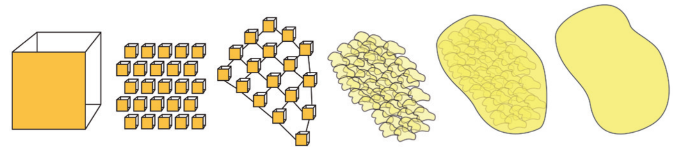
determine behavior and functionality. However, material affordances can connote a variety of qualities that are the source of rich sensory experiences and occasion for numerous action modalities. From a tactile perspective, the static quality of rigid objects affords unary or binary controls. Hard objects are simply touched or pressed in a singular fashion, while malleable objects have a compliant material quality that invites users to multiple levels of tactile exploration and control. The physical act of deforming a malleable tangible interface can be mapped to a continuum of meanings. For objects in motion, a very significant perceptual shift can occur with a change in material – a jerky disjointed motion of a series of mechanical motors can be embedded in a soft padded exterior and the quality of motion can be inverted to a smooth oscillation. Materials also play an important role in kinetic behavior when considering how objects are subject to the natural environmental forces of gravity and friction.

All materials are in essence created of discrete components which combine to create continuous systems. The importance of modularity in creating a material language is evident in our environment from the microscopic level, such as building blocks of biological systems (cells) or chemistry (atoms) to the architectural level, such as prefabricated panels. Modularity leads to systems of physical primitives, grammars forming the basis of constructive assembly systems. Our experience with the tactile qualities of a material, are related to the scale of modularity at which we experience it. For example, fine particles of sand, while rigid in nature individually, feel soft to the touch when combined into a large pile and sift through our fingertips. Figure 2a demonstrates the shifting scale of material perception, from rigid and discrete to amorphous and continuous.

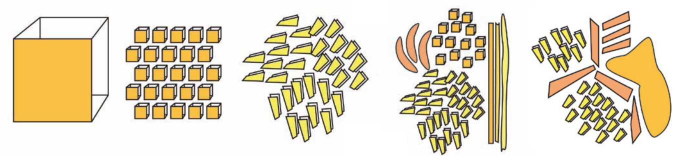
As a kinetic prototyping interface, Bosu attempts to shift motion design away from discrete rigid mechancal structures of motors or pistons toward the organicism of the body. Our bodies offer a unique structural framework on which to base a kinetic construction - a rigid skeleton of bones with an expected range of motion from our joints, surrounded by muscle, tissue, and skin, each of varying densities offering infinite variability in form from one individual to another. The motion of our bodies is interpreted through the surrounding soft tissues, appearing organic in nature, where repeated motions are never exactly the same, a seeming complexity imbued with the familiarity of experience.

The structure of the Bosu elements look toward an alternative idea in material transformation where the continuum is no longer a simple repetition of elements descending in scale. Instead, discrete elements move toward smaller repeated elements, dividing into 'tissues' of varying densities and eventually through combined elements, structures to prescribe specific behaviors in a separate parts of the whole [fig.2b]. Designers can start to think of transformable devices in terms of their material composition.

Figure 2. Material Transformation



a) from discrete to continuous



b) from discrete to skeletal, with one example of different compositions of distinct material qualities

BACKGROUND AND RELATED WORK

Bosu find inspiration from a variety of sources, including contemporary robotics and research into new soft materiality in physical computing. In the field of contemporary robotics, the project Keepon [11] and the Blanket project [17] provides an example of how incorporating a soft material exterior can be used to manipulate the perceptual qualities of a simple combination of mechanical movements, the former through anthropomorphizing with a soft silicone form of a cartooned face and body, and the latter with an abstracted form of a mechanical grid of motors wrapped in foam and sheets creating an interactive blanket.

Soft computing concepts, specifically with the inclusion of nitinol as a soft actuator include Shutters [5] a permeable felt surface for environmental control and communication, Surflex [4] a programmable surface combining shape-memory alloy and foam that can be electronically controlled to deform and gain new shapes, and Kukkia and Vilkas [2] two dresses employing soft actuation as a form of personal expression in fashion design. While static in nature, the project Senspectra [10] provides a basis by which to consider incorporating material affordances and feedback into the tangible interaction loop.

Larger concepts in the future of transformable design in interaction design include Lumen [14] an interactive visual and shape display for calm computing with haptic

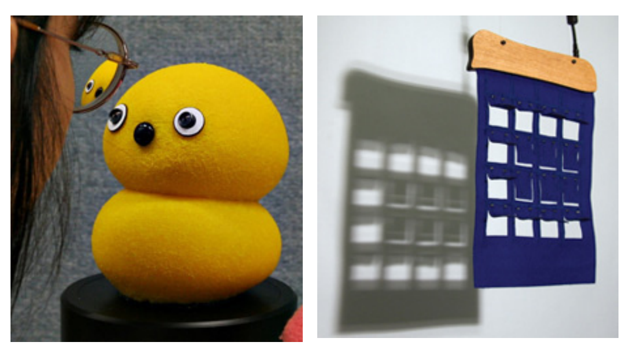


Figure 3. a) Keepon, Michalowski, 2007 b) Shutters, Coelho, 2008

Fig. 4 a)Robotic Dress, Chalayan, 2007, b) Emergent Surface, Hoberman, 2008

interaction, in architecture, the adaptive building skin of Hoberman's Emergent Surface [7] [fig. 4b] a wall that continuously reconfigures itself–portions selectively disappearing and reappearing, and as a form of aesthetic and conceptual expression in fashion, the Robotic Dresses of Hussein Chalayan [6] [fig 4a] which transform through a century of fashion forms.

SYSTEM DESIGN

Bosu is intended to incorporate new concepts in materiality into the interaction loop for TUIs. We determined two design principles to help guide the design of Bosu, as well as to more generally apply to incorporating soft materiality in TUI systems:

> Use texture, plasticity and elasticity to inform the user about functionality and interaction usage of a physical interface
>
> Map the material affordances of a tangible interface to inform and manipulate its control structure

MODULES

The system consists of a series of modular units of differing geometries designed to embody varying mechanical structures common in kinetic systems (linear, rotational, radial) as deconstructed in the analogous rigid mechanical structures created in the Kinetic Sketchup system [12]. Each module pairs a bend sensor with a shape memory alloy (nitinol) actuator segment woven into a bendable plastic frame and embedded in fabric [fig. 1]. The nitinol segments have been shape set by high temperature annealing into spring shapes to maximize contraction. Up to four modules connect to a single PCB featuring a ATMega32 and pulse width modulating current to the nitinol strands through TIP120 transistors. Each module can actuate between two positions and together form three dimensional motion pixels.

The modules offer a simple point of entry for the user, however, the strength and benefits of the Bosu system lie most directly in its functionality as a type of 'raw material,' allowing for its flexibility to be easily embedded and incorporated into customized soft structures. In this way, these modules serve as examples and points of departure for potential behaviors and mechanical structures but are in no

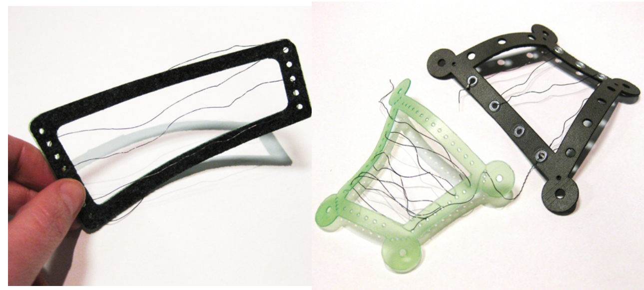


Figure 5. Bosu Hinges

way intended to encapsulate the variability of the system. The ways in which designers flexibly applied Bosu in custom structures is exemplified in the workshop case studies.

The material properties of nitinol as an actuator also determine a particular quality of the Bosu system. As an actuator, shape memory alloy does not offer a continuous variability in position, like a servo motor. By applying heat, via a control circuit, it moves between two states - original length and a contracted length where a cool down time is necessary for it to return to its original length. Thus constructions created in Bosu do not lend themselves to a continuously dynamic interaction, instead the system favors the creation stato-dynamic objects (objects that move between states but are functional as static), or object gradually shifting in form. As a design tool, Bosu provides a temporal shift to focusing on stato-dynamicism as a new direction of interaction design.

Hinge

Figure 5 shows examples of the hinge module which actuates between two states, flat and curled up into a bend. The hinge is made from laminating fabric (felt or polyester) and flexible polypropylene sheets, which gives it a soft feel with a spring-back capability. It works like a simple elbow joint, by which many more complex structures can be created. For example, multiple hinges can be strung together to end to end to turn a linear chain into circle.

Circular Cinch

Figure 6 shows an example of the circular cinch, in which multiple strands of nitinol are sewn in a star pattern across the surface of a fabric circle, with a propropylene start structure sewn on the reverse, as a return mechanism. The nitinol provides multiple points of linear actuation which together produce a radial motion, like that of opening and closing an umbrella.

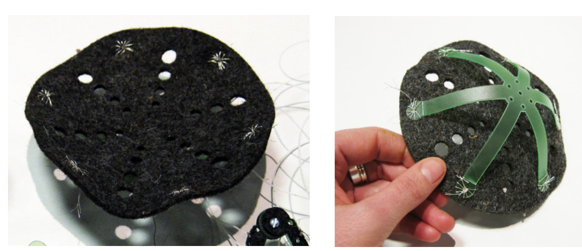


Figure 6. Bosu Circular Cinch

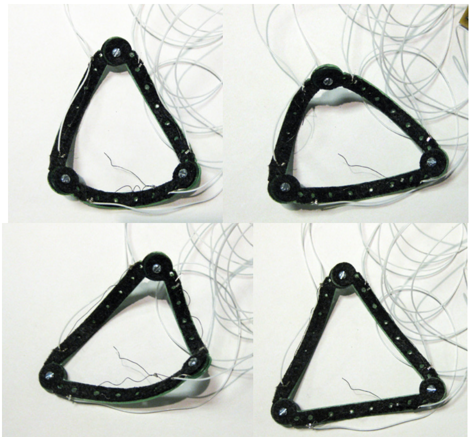


Figure 7. Bosu Triangle module

Triangle

The triangle module contains nitinol embedded linearly along its three sides, allowing each side to actuate linearly between two lengths, causing the triangle to change from equilateral to varying isosceles states [fig. 7]. Like the hinge, the triangle modules works as a base unit by which many more complex structures can be created. Using triangles to create a surface of repeated patterning, arises as a natural choice because interconnected triangles can describe any freeform shape in physical space, as well as triangulation is employed in the algorithmic process of creating surfaces in 3D modeling software, thus creating a physical surface which could directly mimic a digital model.

MODES OF OPERATION

The Bosu PCB features a two button control interface. Bosu can be manipulated via direct manipulation or via remote control and also features a mode called 'direct control' activated via a second button.

Direct Manipulation

To record a motion or 'state' into Bosu, the first button is utilized – a single press of the button sets the system into record, a second press into playback and third press to pause – the system toggles between these states. For direct manipulation, the bend sensors of the system (up to 4 per PCB, more if multiple PCBs are connected together) are embedded into the structure in positions corresponding to nitinol springs, creating coincident input and output space for motion recording. During the recording state, a user manipulates the entire structure through a series of positions, which are recorded by the physical bending of the bend sensors [Fig 8a]. In playback the system sequences through these positions by actuation of the nitinol activated by heat from modulated current in the circuit. A double click on the button plays back the system's last recorded sequence.

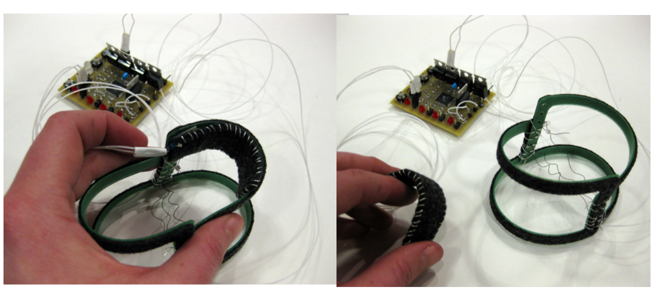


Figure 8. a) Utilizing Bosu in direct manipulation b) Bosu used in remote control mode

Remote control

In remote control mode, interaction with the system is similar to direct manipulation except instead of the bend sensors being embedded in the structure, they are manipulated away from the structure, attached only to the PCB by thin wires [Fig 8b]. This mode allows users is record and playback motions without the interference of their hands on the structure itself. This need arose in response to the soft and delicate material nature of many Bosu constructions, making it much easier to control and observe subtle changes in shape.

Direct control

A double click on a second button puts the system into direct control mode in which the moving of a bend sensor directly actuates its corresponding nitinol spring. This mode was designed as an entry point for users to become familiar with the behavior of nitinol as an actuator, allowing for exploration of responsiveness to the sensor controllers and experimentation in timing for actuation and cool down (retraction).

Surface for Organic Form Finding

The Bosu system was intended to contain one module which would intentionally function as a primitive by which to create a repeated mesh structure. By their nature, meshes take advantage of the structural relationship between the solid and the void, and reference biological paradigms for strength and lightness through spacial looping, such as the bone structure of a bird's wing. The meshed surface is intended to transcend Bosu's functionality as an open ended toolkit, creating a kinetically transformable meshed textile interface which can be used for form finding and capturing organic surfaces. After initial experimentation with repeated triangles, a solution of repeated trapezoids (functioning like two connected triangles) was realized [fig. 9a]. Repeated trapezoids can deform in three dimensions to form overall shapes similar to those created with triangles, but allow a simpler infrastructure where each module utilizes only one embedded strand of nitinol to actuate between two positions, flat and curved.

The Bosu trapezoids are created by laminating bendable polypropylene sheet between polyester fabric, the nitinol is threaded through aluminum eyelets, used to insulate the heat in the nitinol to prevent melting in the polypropylene or burning in the fabric. Together the trapezoids form a 'pixelized' surface which can be deformed in three dimensions surface when draped over an object. The interaction with the

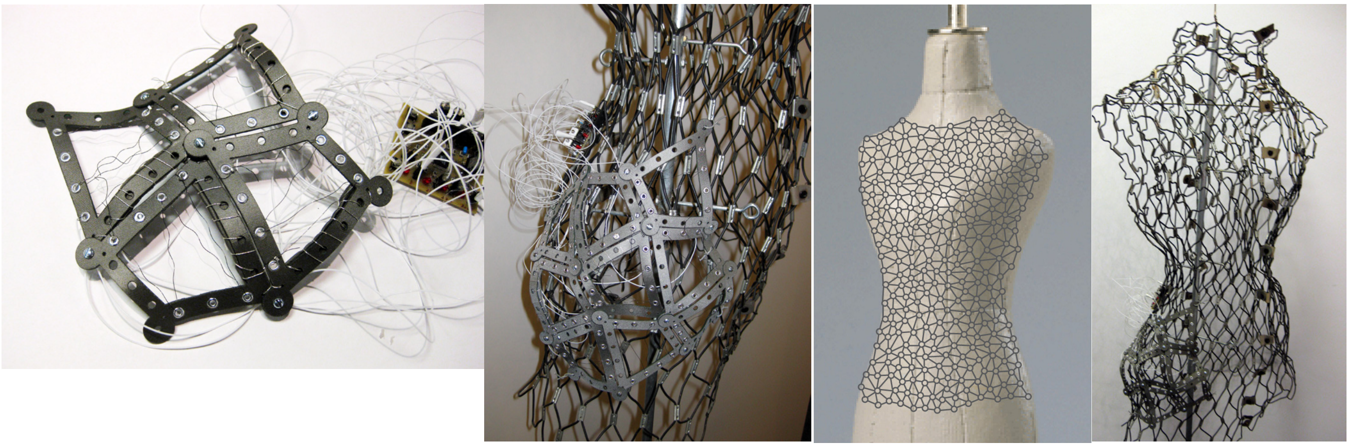


Figure 9. a) Bosu Surface as 4 connected trapezoids b) Bosu surface inspired by shape change mannequins

surface is similar to working with individual modules with the Bosu hardware in direct manipulation mode. A single button press sets the surface into record mode, and a second into playback. The modules record and playback their state independently but function like a distributed network with a global behavior to produce an overall form.

The Bosu surface is intended to be used as an interface for recording a three dimensional snapshot of curved surfaces, a sort of object surface recorder. Inspiration for the surface was taken from the idea of personalized mannequins which when wrapped around the body, record the body form by deforming the metal mesh [fig. 9b]. The Bosu surface could potentially replaces the need for a 'fit model,' (a person representing a specific size) an idea that emerged while consulting faculty at the Boston School of Fashion Design as to the state of the art in digital tools for fashion design. While technologies currently exist for scanning bodies into a digital model, the nature of fashion design favors working purely in the physical realm. Currently, the body is physically defined as a series of linear measurements, inadequately representing the uniqueness and individual nature of each body. While lower in resolution, the Bosu surface seeks to present an active physical measure of the body surface in three dimensions, the first step to being able to record and transform between multiple physical body forms.

WORKSHOP EVALUATION

The evaluation of Bosu took place as a four day workshop entitled 'Prototyping Motion: Transformable Design and Kinetic Behavior in Architecture and Product Design' during January 2009 at the MIT Media Lab. The workshop focused on stimulating issues and directions for the future of transformable design, addressing questions such as:

- How does transformability lead to new ideas in interactivity and interaction design? What is its role in ergonomics or universal design?
- What is the role of kinetic architecture or structures in solving urban infrastructure issues (in energy, for example)?
- What are new ways to think about motion design using new/smart materials which allow for new motion qualities perceptually and functionally?

In evaluating Bosu in a workshop environment for designers of ranging interests, the Bosu modules were used as part of the design process, while the participants could reference their own bodies, physical intuition, and material assumptions as tacit knowledge. This would in turn ease and expand the process of designing transformation. The evaluation focused on how the design process is altered by use of a new physically programmable tool, in terms of functional characteristics, affordances, collaboration, and the capacity for supporting a creative, expressive and inspirational user experience.

Participants in the workshop were self-selecting, recruited through campus-wide emails and posters throughout MIT, Harvard and surrounding Boston areas . The final workshop totaled 11 participants- 6 male, 5 female -who were professionals or students in the areas of architecture, fashion design, interaction design and mechanical engineering. Participants were minimally familiar with concepts of transformable design, showing an interest in the subject matter, and some came to the workshop with existing ideas which they planned to explore further. Data was collected both in video and personal observations during the workshop as well as written and oral interviews at the end of the workshop. The results are presented as overall findings on the use of the tool and the design process and as case studies of individual projects which emerged from the workshop.

On Day 1, the workshop began with a brief lecture on the state-of-the-art in transformable design including theory and examples from architecture, product design and robotics. After the lecture, participants were given the challenge to, over the next 3 days, design and prototype a concept that employs physical motion as a design parameter. They were

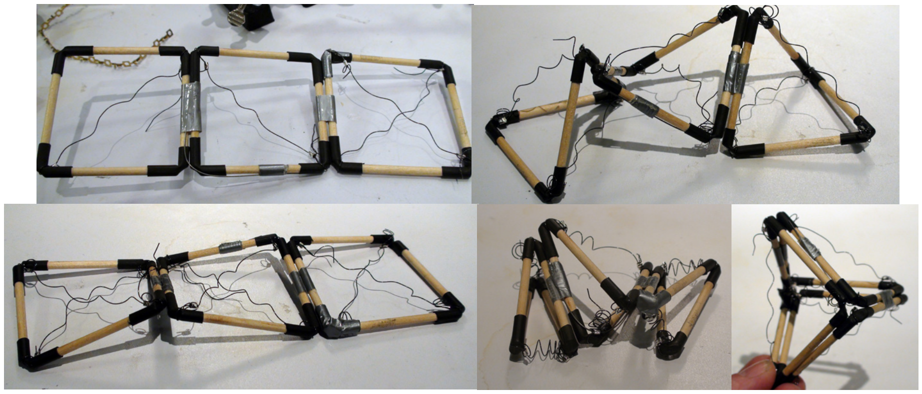


Figure 10. Abstract transformable construction by a workshop participant with Bosu - conversion from three flat squares to a tetrahedron using malleable joints and six nitinol segments

then given an hour of free time to brainstorm and discuss ideas and identify overlap or similarities of interest which could result in collaboration on projects. The Bosu system was then introduced as a prototyping material to explore motion concepts as part of their prototyping process and in their final models and diagrams, as they so chose. Participants also had The participants were also provided with stripped down versions of the Topobo system [15], raw servo motors with record-and-play functionality allowing them to reference and incorporate conventional mechanical motion if so chosen.

Day 2 through the morning of day 4 were spent working open-endedly on the design and creation of project ideas. Participants has a wide variety of materials available including plastics, foams, fabrics, wood, paper and wire as well as use of the lasercutter, sewing machine, and varying construction tools. Informal individual check-ins sessions were conducted by workshop leaders with each participant during these days for conceptual and construction advice. The afternoon of day 4, the participants presented their projects to the group and we conducted oral interviews followed by a written questionnaire.

OVERALL FINDINGS

All the participants of the workshop were able to successfully utilize the Bosu systems and appreciated the consistency of the record-and-playback interaction style of both the systems. The final creations from the workshop included ideas in architecture, furniture, fashion and product, both functional and conceptually abstract [fig.10] with the participants working with materials of mixed properties, hard and soft, in all cases. Participants were generally surprised by the unexpected behavior of soft materials and fabrics when interacting with actuators, highlighting to many the importance of working in the physical realm when first experimenting with kinetic design and unfamiliar materials.

Inspirational vs. Construction Tools

Throughout the workshop, the participants' design process evolve through a series of phases when using the modules. They began in an 'observational' phase in which users experimented with very simple motion constructions of one or two modules and an isolated behavior pattern. During the observational phase, the physicality and aesthetic of the modules was very important in conjuring familiar motion qualities of recognizable objects in motion – butterfly wings, swimming fish, blooming flowers, etc. Because motion construction is a relatively unfamiliar form of design, working with a physical medium in the observational phase was essential to understand spatial translation and real world forces surrounding objects in motion and highly influenced the designers' perspectives as they moved forward with their ideas.

Following the observational phase, participants moved onto a 'constructive' phase, in which they designed their own creations from scratch. The most successful design strategy emerged as an iterative prototyping style where form and motion were developed in tandem based on materiality. As participants moved through the project working on more customized constructions, the modules themselves became less useful as tools. Designers began working directly with the nitinol strands, embedding them into their structures. This raises the question of what is the appropriate level of 'tool' for physical motion prototyping. The designers' ability to rapidly move toward raw actuators potentially negates the purpose of the modules themselves. However, the ability to conceptualize and construct kinetic systems so quickly and intuitively reveals a level of understanding which was derived from the observational phase of the process, a direct result of the mechanical and behavioral experimentation with the modules, the inspirational source for conceptual and functional ideas.

Temporal Design

Perhaps the most salient and observable shift in the design process occurred around the process of design for physical change through time. Designer's are typically concerned with an object's static presence, functionally and aesthetically, but the introduction of transformation opened up new channels of thinking, both in designing the process of change, and an object's multiple states. One participant observed, "I was thinking in the 4th dimension…with how the object I would create would change over time. So I was not stuck on designing a specific static object. It influenced the materials I chose and used as well as pushed my conceptualization abilities to think of the object as just one state among many. I had no idea how it would really turn out. I'd never had this kind of process….It felt like I was conceptualizing in video,…but I could touch it and interact with it." This idea marks a conceptual shift in the design process, where designer's are able to concurrently think and improvise both physically and temporally, bringing to light the emergence of stato-dynamicism as a potential design strategy.

Materiality and Organicism

Outside of the temporal shift, what was most unique to the designers' experience came from the nature of soft materials and the novelty and unexpected behavior of nitinol as a smart material. When presented with a range of material qualities from hard, layered, hybrid to malleable, the shifting nature of materiality became a design inspiration in itself. This stressed the importance of working in a physical medium to challenge assumptions about kinetic behavior and leverage our intuitive understanding of the physical world, "(I learned) how important the possibility to experiment with a lot of different materials is for this kind of design, how important material properties are, even with powerful actuators." By initially juxtaposing the mechanical motion of servo motors with the organic motion of Bosu, participants were confronted with a comparison of motion attributes, revealing a relationship between what can be viewed as 'machine' motion versus the organic motion of our bodies and the natural world. With tools available to experiment with a range of motion qualities, participants were offered insight into the nature of how to create diversity within motion design. One designer stated, "I began to understand the pure subtleties involved in the process of capturing movement. Particularly how one might attempt to capture human or animal movement over mechanical."

Intuitive Technology

While physical temporality and organicism added a shift in design thinking, Bosu attempted to ease designers' explorations into transformable concepts which they were previously hesitant to tackle due to limited technical

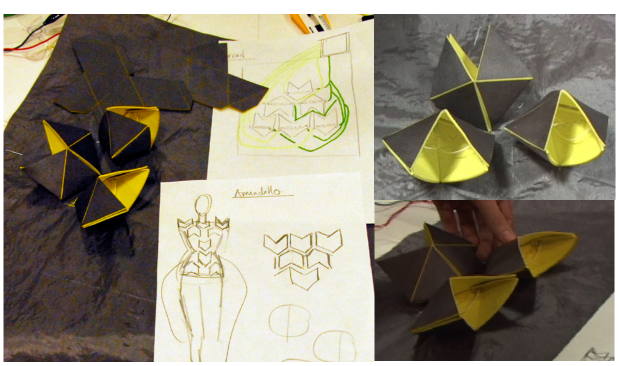


Figure 11. Body as Pop-up book by a fashion designer

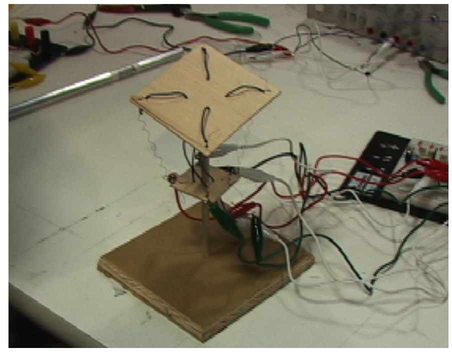


Figure 12 Context aware screen/pen by an interaction designer

knowledge. The system lowered the point of entry on mechanical design, providing an infrastructure on which to build and models to emulate. The intuitive nature of record and play offered a simplicity and accessibility to the technology of programming motion, as participants noted, "Gestural recording was useful for experimenting with the nitinol, I could easily observe how long it takes to move the object when actuating the nitinol, what properties we want to design – change in speed, time of different stages." and "The bend switch is a fantastic aide, very efficient way to test ride an idea and also to create a kind of choreography on the fly."

FOUR SELECTED CASE STUDIES

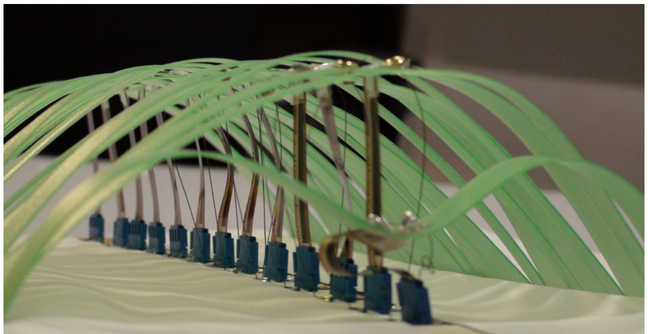
The following four projects offer a sampling of the ideas which emerged from the workshop.

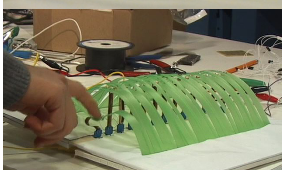
Body as Pop-up Book

A fashion designer came to the workshop looking to investigate the concept of a transformative garment which used the natural motion of the body's limbs to actuate a structure, like a pop-up book construction or a 'three dimensional suit of armor' [fig. 11]. The garment would take the contours of the body, being made of multiple repeated units. She created cubes that moved from 2D to 3D by embedding nitinol in foam laminated with polyester fabric to create a hybrid material that would form malleably to the body while also provide structure to counteract the actuation. She used the Bosu hardware to program the motion using bend sensors by remote control. Although she intended to use the body as the actuator for the final garment, she experimented with designing the kinetic behavior of the units off the body. In different mechanical designs, she was able to isolate variations of motion, and observe and tweak the behavior until arriving at a desired motion effect before adding the variability of the body in motion.

Context Aware Screen/Pen

This concept by two interaction designers combines a tablet pen with a mini-monitor for spatial co-location when interacting with digital data, illustrating an idea of employing actuation for creating context awareness in a interface. As a user writes with the pen (on a digital tablet), the screen atop the pen stays facing the user by continuously adjusting its





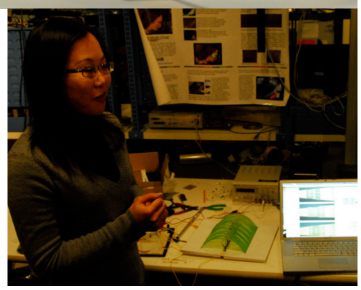


Figure 13 An architect showing her programmable facade

angle in relationship to the pen [fig. 12]. To illustrate the concept, designers used four nitinol springs attached from the pen to the four corners of a square screen. Using the Bosu bend sensors as direct controllers of the nitnol (off the structure), they were able to improvisationally demo how the screen would stay facing the user. The designers originally conceived of using four motors to rotate the screen but because of spatial constraints decided on the four stranded nitinol actuation. This construction resulted in the unexpected effect of creating an extremely smooth ball and socket joint (3DOF), with a very organic motion, like a snake following the movement of a charmer.

Programmable Facade

Designed by an architect, the programmable facade uses the metaphor of record and play in the Bosu system as an interaction scenario scaled up for a kinetic facade [fig. 13]. The permeable membrane can be programmed by pushing and pulling on the malleable structure of the wall to record stato-dynamic states or kinetic patterns played back in the surface. In her model, bend sensors are embedded in the structure coincident with nitinol spring actuators in a linear formation. While she originally envisioned the interaction at a 1-to-1 scale of the body to the wall, while working on the prototype, she also conceived of a scaled hand held remote controller, like a musical instrument that could be strummed with the fingers and translated into the architectural surface, changing in materiality as well as scale.

Reconstructing Vase

A highly conceptual idea developed by an interaction designer, the reconstructing vase addresses issues mapping functionality or uniqueness to the destroyed or regenerated state of an object. He was addressing the possibility of using the way things transform (for eg. the violence of smashing) to convey information or emotion as well as the functionality

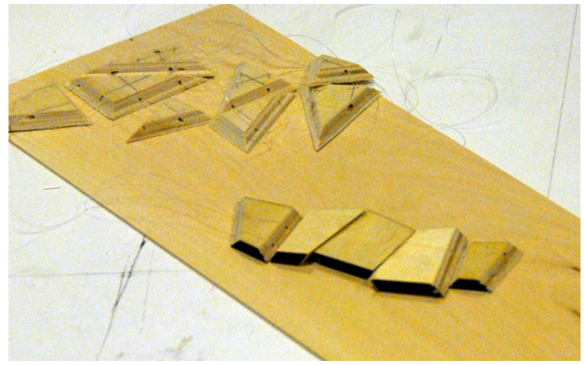


Figure 14. Reconstructing vase concept by an interaction designer

of different intermediary stato-dynamic states (for eg. a lamp shade changing shape to cast light in different ways). To illustrate the idea, the designer used simple wooden elements, with edges cut to specific angles, strung together [fig. 14]. A single servo motor was used for a large scale motion of coiling the string to contract the object, with subtle small motions of nitinol segments installed between the pieces to pull them into formation. While extremely low resolution and barely functional in its prototyped state, this project makes an important shift in the development of forward thinking ideas in transformability like programmable matter. By using tools and technologies that are available now he was able to create a comprehensible interaction scenario to shed light on how we develop interaction techniques for materials that are presently out of our physical familiarity.

Issues and Limitations

While Bosu added to the kinetic design process in many ways, it also possessed several issues and limitations for working with motion design. The most significant proved to be the number of components available and the level of independent control offered in choreographing motion. Designers naturally desired the multiplicity so inherent in digital systems, where ideas could be generated with complex motions systems involving hundreds of actuators, a limitation commonly noted in tangible systems. Many of the projects developed in the workshop were conceived as distributed systems with simple repeated elements designed to give an emergent global effect. By physically engaging with Bosu components, designers were confronted with the reality of designing mechanical systems in physical space and they quickly came to realize the complexity they faced in a real world system. Designers also reached limitations of coordinating motions into more choreographed structures, citing the need for additional sensing and feedback systems to further develop their interaction concepts. While Bosu provide a simple point of entry exploiting physical intuition for motion control systems, the next challenge is to balance this with the variability and complex control structures of digital systems, with potential inspiration emerging from applying and appropriating procedural animation or motion authoring techniques for virtual characters [3.16] .

As with all prototype physical systems, Bosu suffered from issues of mechanical reliability and shear number of each different modules available to the participants. While these issues can be directly addressed with further development and production, it emphasizes the mechanically demanding nature of physical systems and the difficulties of deploying tangibles in large scale as a research platform.

The Threshold of Controlability

In the workshop, the majority of the designers used Bosu exclusively in their constructions, citing the novelty of interacting with nitinol as a smart material and the excitement for a system which allowed them to control it without technological overhead. However, for the few who did choose to use motors, they all used mechanical actuation in combination with nitinol or with some kind of soft static material (fabric or silicone). Systems that were conceived to have an organic fluid kinetic behavior through combining a multiplicity of mechanical actuators, could instead be simulated through a shift in materiality, wrapping a few mechanical actuator in fabric to smooth the effect.

In many ways, the workshop participants were seeking to operate in an idealized physicality, existing at the border between the practical concerns of mechanical actuators (space constraints, torque) and the fluid nature of organic form. Bosu as a raw material allowed participants a fluid motion at a smaller scale. However, the nature of Bosu as a relatively unpredictable material, with quirks in behavior unplanned by the designer, brought an unexpected expressive quality to the interaction. Designers stayed most engaged in facilitating an experience that they comprehended as a result of their conceived design but operating in an expressive realm just outside of their plan.

Programmability with Bosu has touched on the very nature of the human fascination with motion as a communication medium, where even in a non-anthropomorphized form, we can identify a quality of being alive. Striving toward organic forms of motion shows a common thread running through the projects, where the most engaging for both for the designers and the viewers were operating at the threshold of controlability. A shift in materiality toward pure malleability can derive an organic feeling in an interaction but the level of controlability falls proportionally. The use of hybrid material structures where we can identify an underlying skeletal structure combined with organic elements, expands the threshold of controlability, pushing both the natural-like nature of an interaction with the designer's ability to control and designate the interaction. It is within this realm that the future of interaction for kinetic and transformable structures lie.

THE EVOLVING TANGIBLE INTERACTION LOOP

In the tangible interfaces vision of interaction, a physical object combined with computation gives both tactile and visual feedback to the user as illustrated by the Tangible Interaction Loop [fig 15a]. The addition of kinetic behavior through an actuated object or interface creates a second interaction loop, where the user receives tactile and kinetic feedback via motion of the object, as well as visual feedback [fig 15b]. As a kinetic memory object, Topobo [15] provides feedback as a reflection of the user's gesture, while in an interface like Pico [13] the computer becomes a physically active participant in the process of problem solving. Both systems benefit from the physical nature of their kinetic feedback, with the interface responding to the physical forces of the surrounding environment, such as friction and gravity.

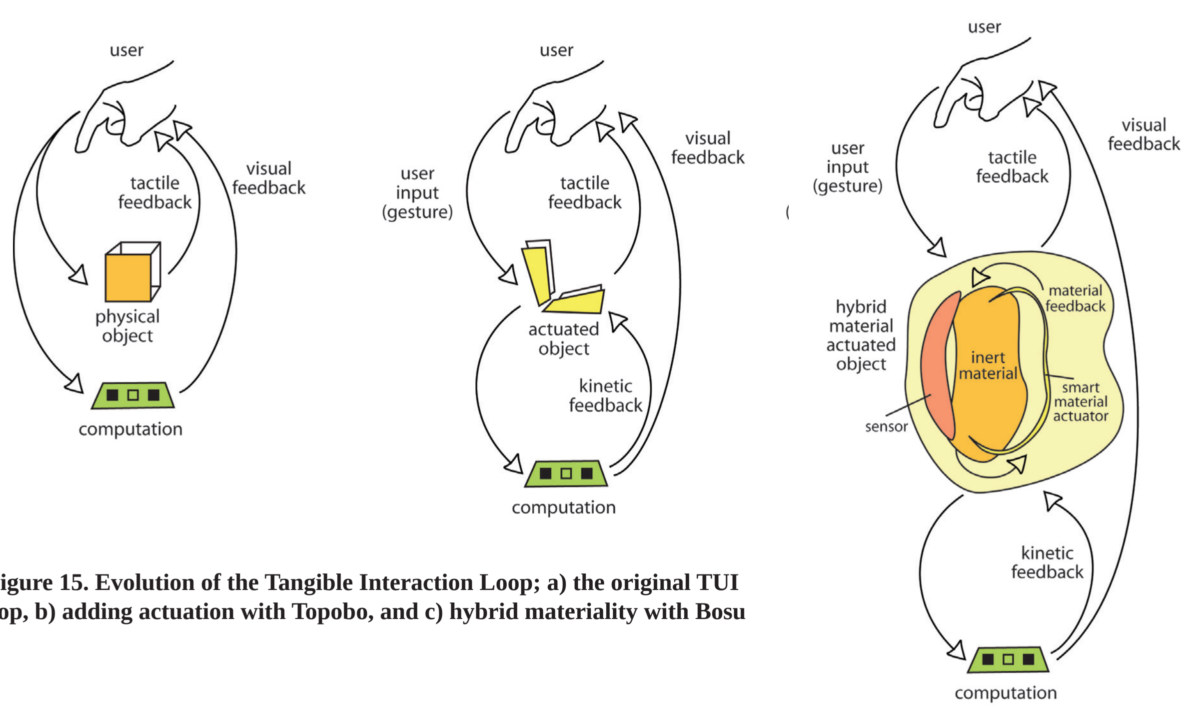


Figure 15. Evolution of the Tangible Interaction Loop; a) the original TUI loop, b) adding actuation with Topobo, and c) hybrid materiality with Bosu

The hybrid material structure of Bosu introduces a new element into the Tangible Interaction Loop [fig 15c] where the material itself creates its own internal loop. A hybrid material actuated object receives user input via gesture which is translated both into computational input and material input via the sensor. Once in motion from a user's gestures, the smart material actuator in turn creates material feedback back onto the sensor, resulting in new computational input to the actuator. Designing how this internal material loop affects the tactile and kinetic feedback to the user is an area as yet unexplored and offers interesting possibilities for new perceptual qualities in interactions. This material loop is just outside of the control of the user and yet is affected by the user's actions, it is in this realm in which we can learn to design how an interface to be kept at the threshold of controlability. The user must easily comprehend the resulting cause and effect of their actions and the logical outcome of the computational feedback but it can also offer an element of surprise, relaxing the rigidity of expectations from computational systems. What can emerge is an intuitive yet slightly unexpected scenario often associated with phenomena of the natural world.

CONCLUSION

Bosu presents a system providing designers the ability to experiment, prototype, and model with programmable kinetic forms. Moreover, the design of Bosu considers how the changing concept of the body alters how and what we strive to design for ourselves and the nature of digital products made to be used by the body. Transformability can begin to play a bigger role in this design process with a means to physically translate the structural organicism of the body more fluidly and conceptually, blurring the line between design tool and design material. Bosu brings kinetic memory and physical programming into the realm of soft materials, inspiring novel dimensions of design thinking for kinetic behavior, and engaging new sensibilities for the future of functional and behavioral transformability.

ACKNOWLEDGEMENTS

We would like to thank John Pugh, Julie Henion, Andy Goessling, members of the Tangible Media Group and the workshop participants.

REFERENCES

1. Addington, M. and Schodek, D. Smart Materials and Technologies for the Architecture and Design Professions. Oxford: Architectural Press, 2005.
2. Berzowska, J., Coelho, M., Kukkia and Vilkas: Kinetic Electronic Garments, Proceedings of the Ninth IEEE International Symposium on Wearable Computers, p.82-85, October 18-21, 2005
3. Blumberg, B., Downie, M., Ivanov, Y., Berlin, M. , Johnson, M., Tomlinson, B.: Integrated learning for interactive synthetic characters. In ACM Trans. on Graphics (2002).
4. Coelho, M., Ishii, H., Maes, P., Surflex: a programmable surface for the design of tangible interfaces, CHI '08 extended abstracts on Human factors in computing systems, April 05-10, 2008, Florence, Italy
5. Coelho, M., Maes, P., Shutters: a permeable surface for environmental control and communication, Proceedings of TEI, 2009, Cambridge, UK
6. Chalayan, H. Robotic Dresses. http://www.technovelgy.com/ct/Science-Fiction-News.asp?NewsNum=925
7. Hoberman, Chuck. Emergent Surface, 2008. http://www.hoberman.com
8. Ishii, H. and Ullmer, B. Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms. Proceedings of CHI'97, ACM Press, (1997), 234-241.
9. Hayward Gallery, <u>Force Fields: Phases of the Kinetic</u>. Manchester: Cornerhouse, 2000.
10. LeClerc, V., Parkes, A. Ishii, H. Senspectra: A Computationally Augmented Physical Modeling Toolkit for Sensing and Visualization of Structural Strain. Proceedings of CHI '07 San Jose, April 2007.
11. Michalowski, M., Sabanovic, S., Kozima, H. A dancing robot for rhythmic social interaction. Proceedings of HRI 2007, March, 2007.
12. Parkes, A., Ishii, I., Kinetic Sketchup: Motion Prototyping in the Tangible Design Process. Proceedings of Conference on Tangible and Embedded Interaction (TEI), Cambridge, UK. February 2009..
13. Patten, J. Ishii, H. Mechanical Constraints as Computational Constrants. Proceedings of CHI 2007. ACM Press (2007).
14. Poupyrev, I., Nashida, T., Maruyama, S., Rekimoto, J., Yamaji, Y. Lumen: Interactive Visual and Shape Display for Calm Computing. SIGGRAPH 2004 Emerging Technnologies, ACM Press (2004).
15. Raffle, H. Parkes, A. Ishii, H. Topobo: A Constructive Assembly System with Kinetic Memory. Proceedings of CHI 04. ACM Press, (2004), 869-877.
16. Rose, C., Bodenheimer, B. Cohen, M.: 'Verbs and Adverbs: Multidimensional Motion Interpolation Using Radial Basis Functions. IEEE Computer Graphics and Applications 18, 5 (1998), 32–40.
17. Stedman, N. The Blanket Project. http://nickstedman.banff.org/blanket.html
18. Vertegaal, R. Organic User Interfaces (Oui!): Designing Computers in Any Way Shape or Form from Unconventional Computation. Heidelberg: Springer Berlin, 2007.