Magnetform: a Shape-change Display Toolkit for Material-oriented Designers

Iddo Yehoshua Wald
Media Innovation Lab (IDC milab)
School of Communications
Interdisciplinary Center
Herzliya, Israel
iddo.wald@milab.idc.ac.il

Oren Zuckerman
Media Innovation Lab (IDC milab)
School of Communications
Interdisciplinary Center
Herzliya, Israel
orenz@idc.ac.il

ABSTRACT
This work presents Magnetform, a shape-change display toolkit designed to enable exploration of movement in soft materials. The toolkit allows designers with no technical knowledge to leverage their material expertise to experiment with shape-change. We present the toolkit design, and case studies with two design studios who used the toolkit for 15-days each. Through the presentation of their process, we reflect on two main themes: empowering designers to participate in shape-change exploration; and the developing practice of designing objects which integrate motion. We situate this work as part of the growing efforts in the TEI community to involve designers in the evolution of shape-changing interfaces, and demonstrate how material-oriented designers could contribute to this field in which materiality plays a major role in.

[A] The Magnetform platform with a sample material. Two layers of textile with embedded magnets and acrylic circles.

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CSS Concepts
- Human-centered computing

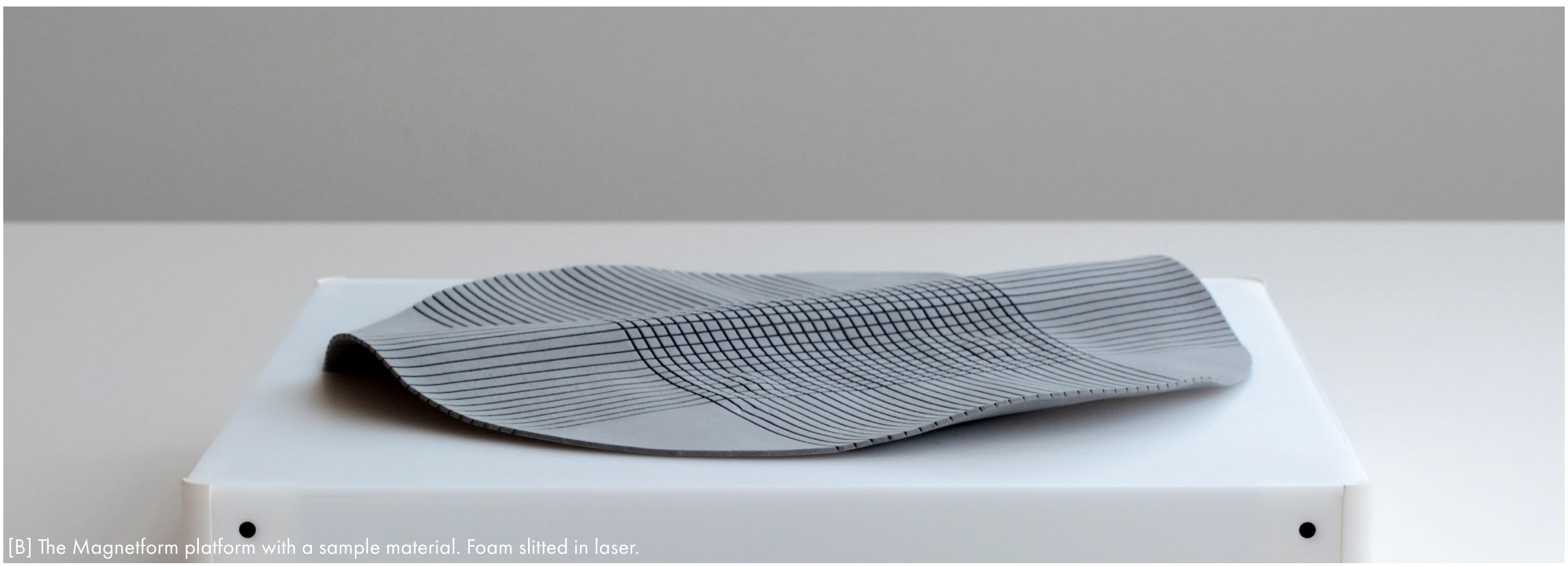
INTRODUCTION

The relatively young field of Shape-Change brings with it exciting new design challenges. As a discipline engaged with tangible objects, factors as materiality and form-finding take a major role in the design of such interfaces. Also, shape-change technologies have the potential to affect how designers currently develop everyday objects. As such, the involvement of designers in the exploration of the field is acute. Designers of more traditional fields than Interaction Design such as textiles, ceramics, fashion and other disciplines, could potentially contribute greatly to the development of the field, and should partake in designing what could potentially influence their future practice.

Previous work emphasized the importance of bringing designers on board to test their application potential [25] and prompt collaborative work among disciplines in the field. The need of developing tools for designers in order to address the challenges in the field was captured in a recent work based on a workshop with twenty five experts, laying out the Grand Challenges in Shape-Changing Interface Research [1]. The design challenges they discussed were: The challenge of designing for temporality, and to address it the writers suggested developing techniques and methodologies that allow the design, construction, and direct comparison of temporal forms; The challenge of integrating artefact and interaction, which required for the development of tools to support the design process and develop designers understanding of dynamic affordances, expanding their competences; And addressing the challenges of application and content design, which also requires the involvement of informed designers to contribute to the discussion of when, what and how to apply shape-change in various applications.

Parkes, Poupyrev and Ishii [20] discussed the need to provide interaction designers with tools to produce kinetic interactions. In 2012, Ishii et al. overviewed pioneering shape-change technologies [11], however most of these prototypes were technically complicated and were not aimed for non-technical interaction designers. Hardy et al. [10] argues shape-change systems are still too difficult to construct and deploy, preventing non-technical designers from taking part in the field. They define the following barriers: cost, complexity, and skill required to create a shape-change experience.

Toolkits have always been an instrumental aspect in HCI, and researchers have defined design guidelines for toolkits, including: rapid generation and testing of new ideas (iterations), replicate and refine ideas, and create demonstrations for others to try [9]. They emphasized that removing burdens and giving people a 'language' to work



[B] The Magnetform platform with a sample material. Foam slitted in laser.

with, promotes creative exploration.

Therefore, our goal was to create a shape-change display toolkit that allows non-technical designers to animate material using shape-change technology. Based on prior work, we have defined the following design principles: accessibility to non-technical designers; generate movement in a wide range of soft materials; encourage creative exploration.

RELATED WORK

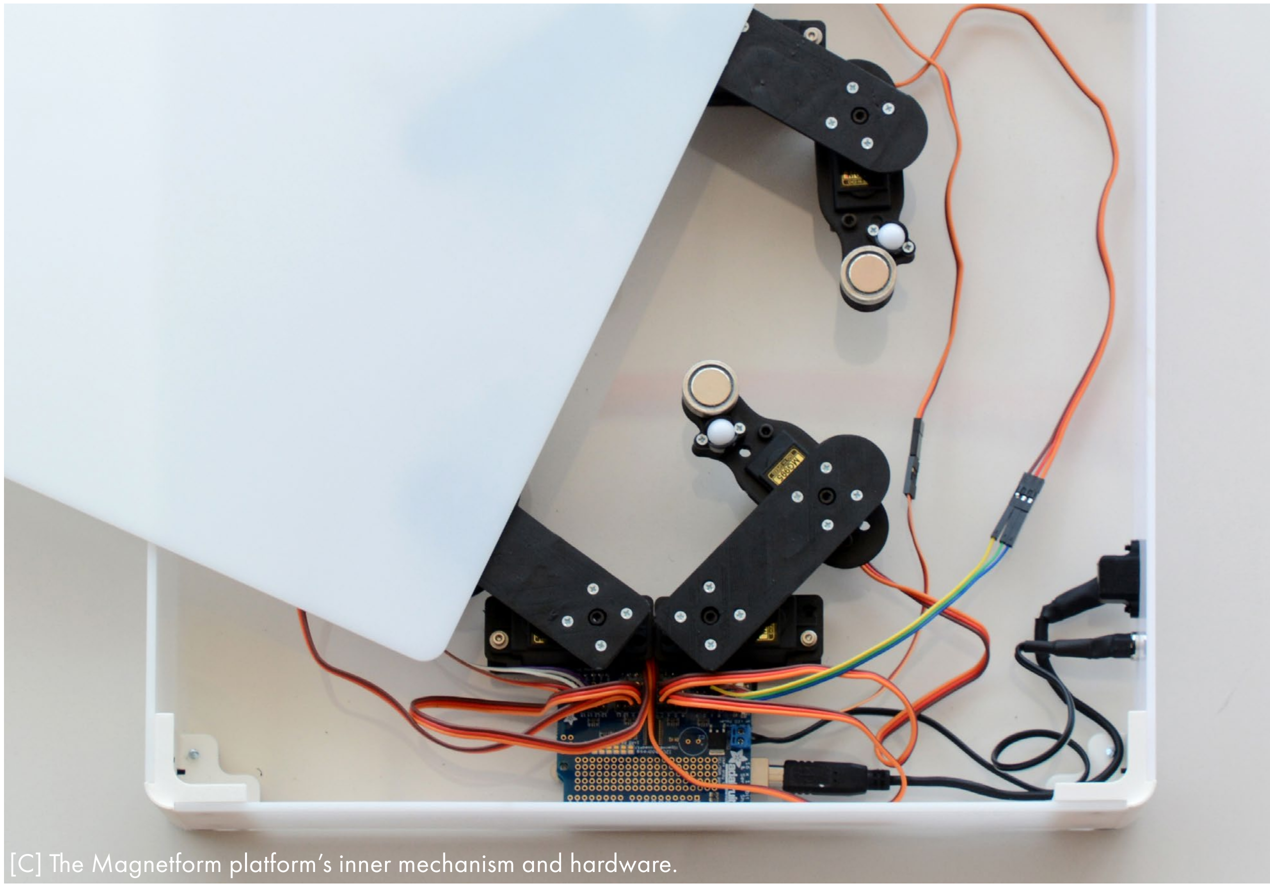
A variety of shape-change technologies have been introduced to actuate soft materials, including shape memory alloy for actuating foam (*Surflex* [4]) and hair (*HäirIÖ* [5]), pneumatic actuation (*PneUI [29], AearoMorh [17]*), and more [25]. However, most are designed for actuating a single or small set of materials.

Magnetic force in tangible interfaces technologies was introduced in the 2002 Actuated Workbench [18], which used an array of electromagnets to control a puck's movement on a surface. ForceForm [26] also uses a magnetic grid, adding a stretched silicon surface with an embedded grid of small magnets that can move along the Z axis, causing subtle pattern changes to be formed. *ZeroN* [14] used magnetic force to create a digitally-controlled levitating ball, and *BubbleWrap* [3] leverages the same technique to create a shape-changing haptic display. Our work also utilizes magnetic force, building on the preliminary magnetic actuation system demonstrated by Wald et al. [27]. Another approach was introduced by *TableHop* [23], leveraging electrostatic force to manipulate soft fabric, yet cannot vary in materials and has similar size and cost limitations as the previous system mentioned.

Motor-based shape-change actuators have also been used to perform vertical movement that forms 3D discrete topologies. These works include *FEELEX* [13] and in recent years *inFORM* [8], *Recompose [15]*, *Transform [12]* and *shapeShift [24]*. These systems create a very powerful shape change experience for end users. However, they are typically expensive, and consist of large mechanisms that are difficult to embed. In addition, the discrete vertical movement sets a limitation on the style and nature of the material movement. Some have achieved more organic movement by programming [16], or by overlaying materials above the pins [6]. In our system we tried to avoid the limitation vertical movement poses, and aimed for organic material movement generated by magnetic force.

Several toolkits aimed to make shape-change displays more accessible to non-technical designers. Bosu [19] was created as a design tool offering kinetic memory, using plastic, fabric and memory shape alloy modules. Bosu enabled experimentation, but was limited by the pre-made modules and the control and movement features of memory shape alloy. *ShapeClip* [10] created independent low-cost z-actuating units that can be controlled by intensity of light from an LCD screen.

Our system builds on prior work and extends it by using low cost mechanical components, a two-layer system architecture that generates organic movement in soft materials using magnetic force, and an intuitive Animation Interface allowing continuous motion control. In addition, the system is small, portable and can be placed on any design studio desk.



[C] The Magnetform platform's inner mechanism and hardware.

THE MAGNETFORM SYSTEM

We present a two layered system: (1) an actuation layer with four robotic arms, each holding a magnet [C]; and (2) a soft material layer, enabling designers to embed magnets in any soft material they wish to explore [A][B]. A plastic surface is placed on top of the actuation layer, so a soft material can be placed over it, with magnets embedded in or attached to the soft material. Due to magnetic force applied through the thin plastic surface, the 2D movement of the magnets placed on the robotic arms creates a 3D movement in the soft material. The soft material properties, such as thickness, flexibility and structure, contribute to the nature of the 3D movement.

Hardware

The system is constructed from a 35x35x5.8cm acrylic box containing four robotic arms, each comprised of two servo motors, operated by a microcontroller. Each of the four robotic arms has a neodymium magnet mounted at its end, designed to hold the magnet close to the top surface [C].

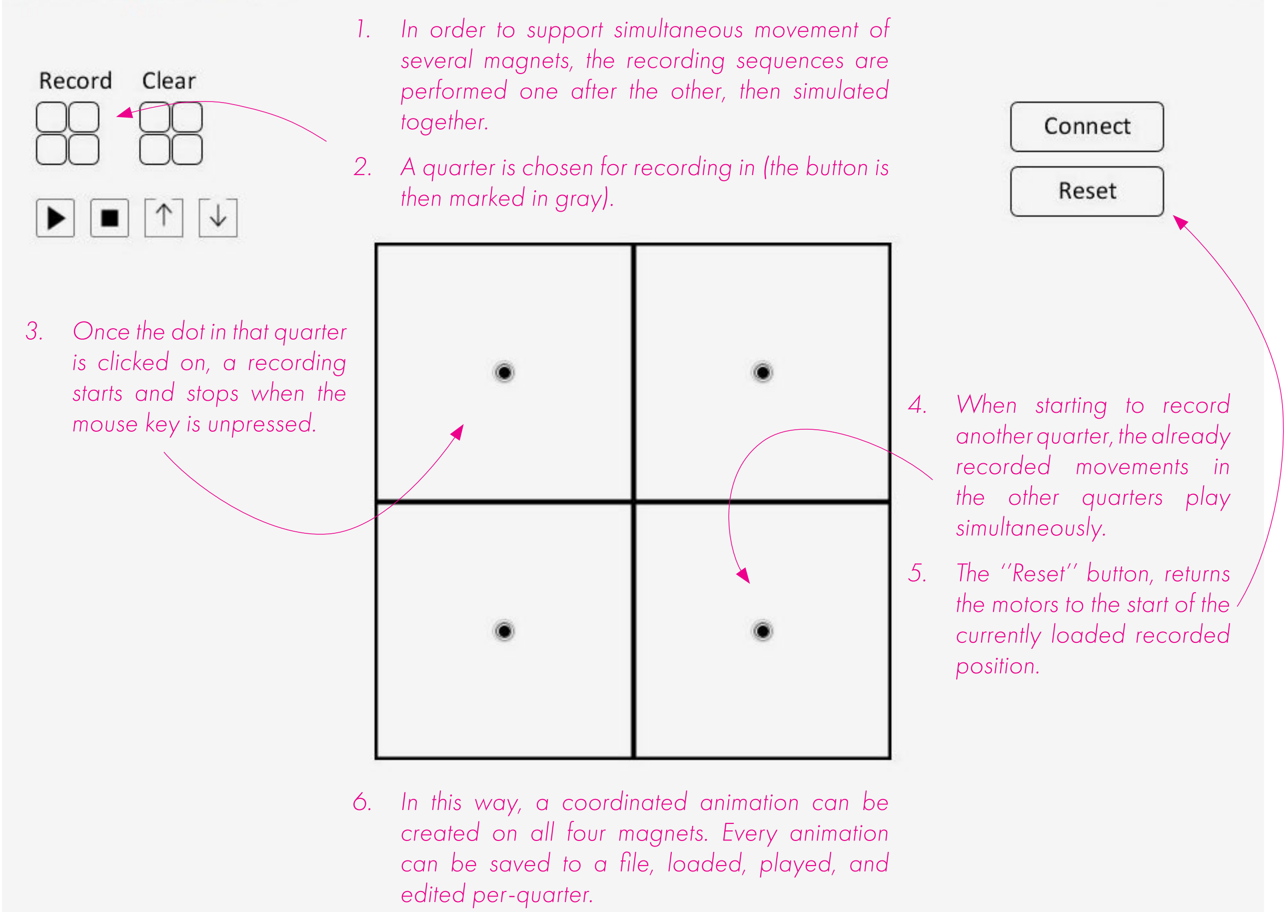
Next to the magnet, we fitted a ball caster, about 1mm higher than the magnet top in order to reduce friction and noise caused by the magnet running against the top surface. Every arm is designed to cover an 88cm square surface in the center of the platform, but can potentially overlap into its neighboring areas and to other parts of the platform, giving more freedom of movement. We chose to limit the active area of the platform to 16X16cm to simplify the control over it. The thin yet durable acrylic top surface can be removed to explore the underlying mechanism.

We used an off-the-shelf Arduino control board, a motor control shield (PWM/servo shield, based on a PCA9685), and a standard 5V DC power supply. Each arm is constructed of two MG666R metal-geared servo motors that were chosen for simplicity of use and affordable cost. These were tested to have sufficient torque and speed to generate a controlled and fairly smooth movement. In addition, these motors provide convenient power requirements of 5V that allowed the use of a standard portable power supply.

The Arduino code was designed to receive a simple command format of ARM#,X,Y, enabling easy control using any digital input and potentially connecting it to a variety of interfaces, sensor controls or other. The firmware includes the reverse kinematics equations needed for translating an x,y point into two angles for each motor, and the mapping of each motor angle to a motor command.

Interface

The Animation Interface [D] was designed to enable real-time experimentations and iterations. We implemented it using Processing making it cross platform. The movement in the interface is recorded frame by frame (position by position) at a constant 24fps rate, and then the commands are sent to each motor. The result is a smooth motion, experienced as identical to the one on-screen. The four quarters represent the range of movement for each of the magnets. Designers can experiment by dragging and moving the magnets in real time, and can also record movements. In order to support simultaneous movement of several magnets, the recording sequences are performed one after the other, then simulated together [D].



[D] The platform control interface (annotation on synced recording process is overlaid over the figure).

We avoided keyframing and easing in and out in order to make the design process direct and intuitive. We considered using a multi-touch interface, but decided that accurate individual control over each motor separately will give designers a more systematic control over a multi-touch interface that can bias designers towards synchronized movement with both hands or fingers.

MAGNETFORM IN THE WILD

The system was given to two design studios for a 15 days evaluation period without our presence (beyond the short Installation stage and interviews). One studio was of two industrial designers who work together (Studio A), another studio was of an interdisciplinary material designer/ wearable artist (Studio B).

The evaluation protocol was designed to be open-ended so designers will have the freedom to explore the system's capabilities in their own way and with their favorite materials, and hopefully accept it as a new creative tool in their studio.

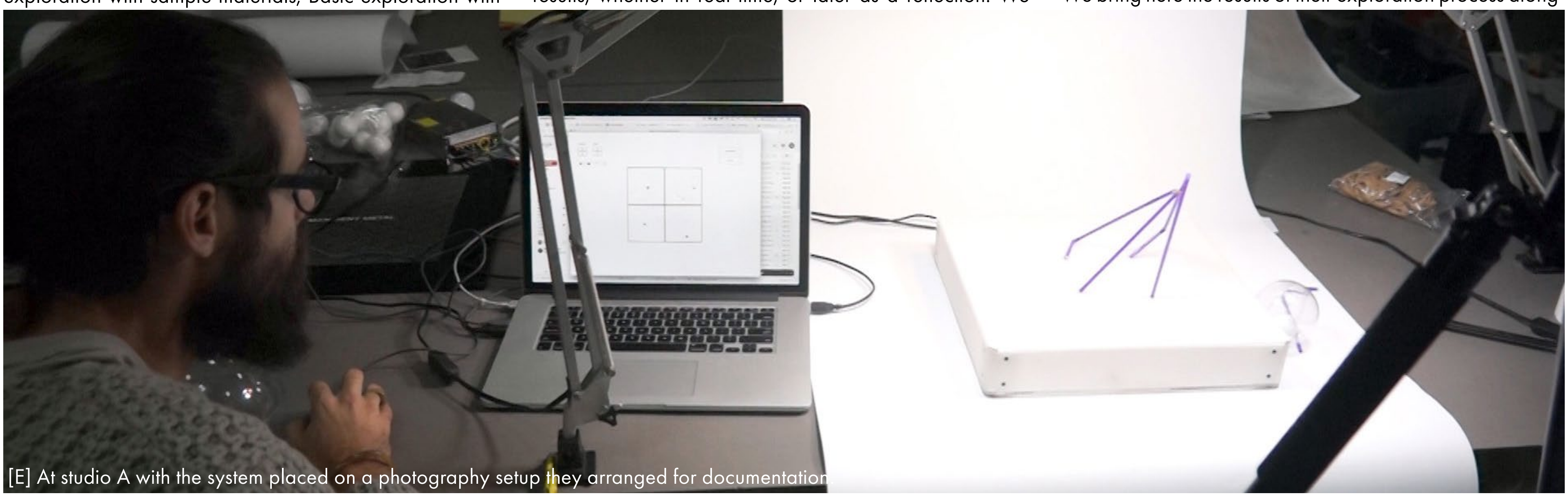
We divided the process into four stages: Installation; Initial exploration with sample materials; Basic exploration with custom materials; and Advanced exploration with custom materials, and conducted semi-structured interviews at the beginning, middle, and end of each stage.

Installation included setup at the designers studio and installing the software. Initial exploration was done with sample materials that were included with the system in order to reduce barriers and promote immediate exploration of material animation and shape-change (one square textile made of two layers with magnets between them , as well as materials [A] and [B]). The following exploration stages were conducted without our presence, and we generally marked the shift from Basic exploration to Advanced exploration, when the designers started to shift into a systematic and focused process, developing concepts from their Basic exploration. Designers were given a variety of magnets, and were asked to use the system as they wish, every day for 1-2 hours alongside their everyday work. For documentation, we shared with them an online folder and instructed them to document their process on a daily basis, informally, using pictures, videos, and text. We instructed them to share both challenges and successes, process and results, whether in real-time, or later as a reflection. We also told them that anything they share is valuable for us, yet noted they should not bother with documentation when they feel it interferes with their work.

Except for a long weekend break in studio A, the self-reports indicate the designers generally used the platform for the requested 1-2 daily hours, and in some cases for much longer sessions. Studio A generated 24 images, 40 videos, 9 motion design files and 7 pages of written text. Studio B generated 58 images, 7 videos, 24 animated GIFs, 39 motion design files and 17 pages of written text.

The transcripted interviews, together with the designers' notes, were analyzed by two researchers who identified initial three themes: materiality; process and interface with the system; reflection on the results and future thinking. After initial themes definition, both researchers separately analyzed all data, including the visual documentation, and selected the most representative quotes and visuals along the exploration stages of each studio. This condensed version of the data was then reviewed again to identify similarities and differences in each studios' work.

We bring here the results of their exploration process along



[E] At studio A with the system placed on a photography setup they arranged for documentation with chosen quotes of their own words which we found to be reflecting on two overarching themes: empowering designers to participate in shape-change exploration; and the developing practice of designing objects and material that include motion.

STUDIO A EXPERIMENTATION PROCESS

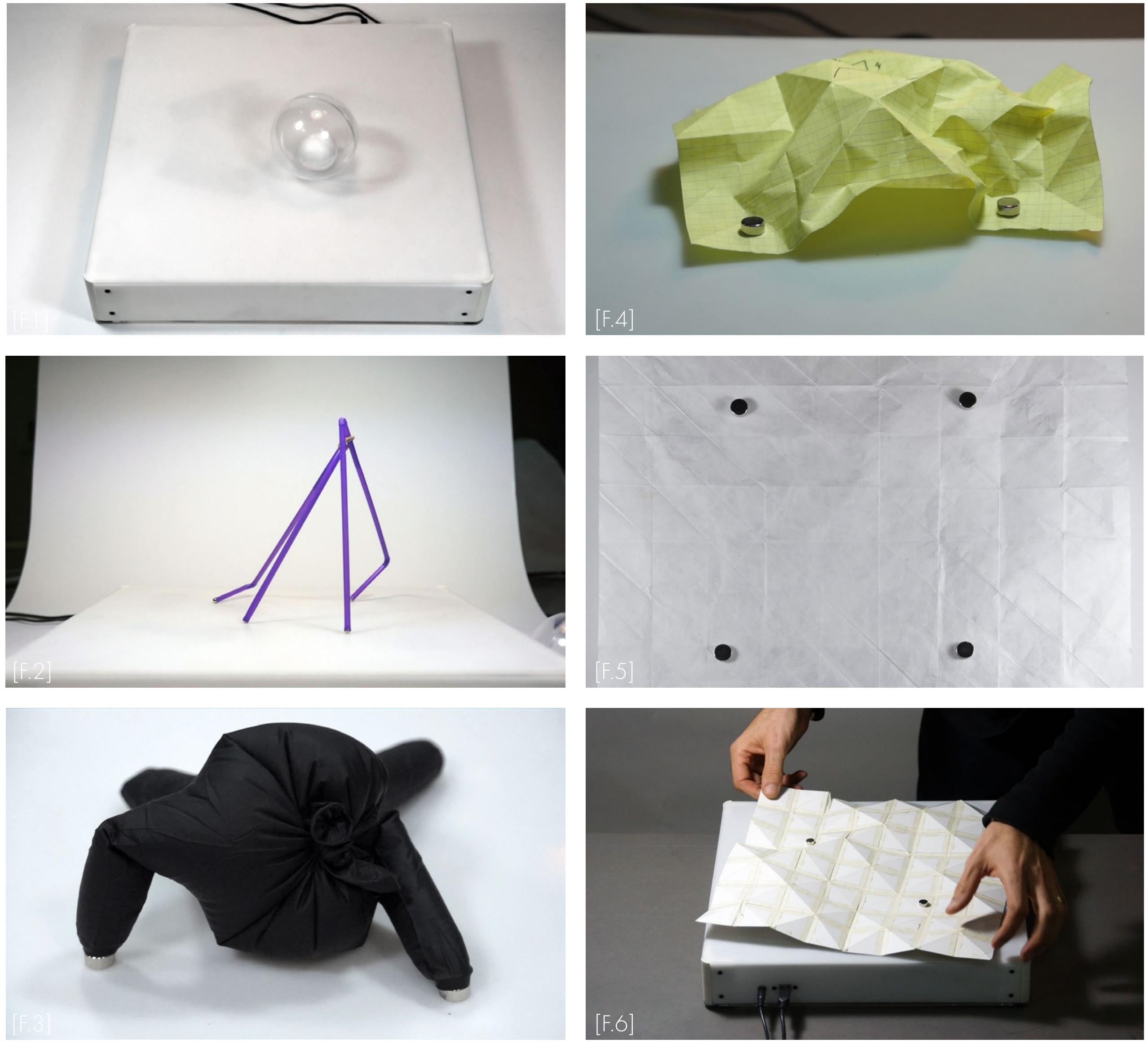
The designers in studio A studied industrial design together and now work as a team in the same studio. Their work involves physical product design with wood, various metals, and specifically brass. The products they design include furniture, lighting objects, and luxury items such as handmade jewelry, mostly brass bracelets made of a single bent extruded rod. Beyond their traditional training in product design, one of them performs street statue restoration working with metal and bronze, and the other specializes in model building for architects.

We found that the design enables quick and effortless deployment with about a three minute setup and installation, and the designers naturally locating it in the space on their working table [E]. Within fifteen minutes they felt they concluded their initial exploration of understanding the system, were able to control it, and moved on to basic exploration with different materials.

The designers started by exploring the different aspects of the system, beginning with removing the lid. Being more technically oriented in their training as Industrial designers, they studied the way the robotic arms are configured and how the supporting mechanisms are implemented. They could also imagine how they might reconfigure and change it. They then continued exploring the interface, concluding *"The more control I have over them and ways to sync, that's when the real action happens"*.

The Basic exploration was of a very intuitive, free exploration nature, initiating their work with the various materials available in their immediate environment (*"We just saw the thing and tried to understand who it is, what it is. Just threw things at it with no real esthetic or mechanical intent. We wanted to see what it does when it moves"*).

They made very quick experiments, started with a plastic glove made of latex [F.3], continued with balloons (filled with air, and then with water), paper folded in various patterns [F.4], Tyvek [F.5], styrofoam balls [F.1] (first just the balls, then within plastic balls for generating secondary motion), straws and rubber bands creating semi-rigid structures with soft joints [F.2], and mixed-material designs based on a soft paper sheet with polygons of harder materials on top of it [F.6].



[F] Representative milestones from Studio A's Basic exploration process.

The need for creating synchronized movement was one of the first to arise, and the designers suggested the interface could benefit features for "mirroring" and copying gestures between quarters.

Moving beyond the very first experimentation was difficult for them, but in the same way other open-ended processes are (*"At first we had a bit of frustration... that we stand in front of something we don't know and don't understand and we need to give it an identity. That frustration was familiar from other open-ended processes. When there is no clear path it's more threatening."*), implying the system did not fixate them or interrupt their exploration.

After the Basic exploration, the designers were captured by the potential of the paper folding prototype [F.4] and chose to focus on developing it [F.6][G]. In describing their choice, it is apparent how the design of form and movement were weaved together in their process (*"The folded paper changes all it's 3D structure while moving. If the movement is random it just looks like a wrinkling paper, I believe once we are able to soften it a bit, control the movements and know what kind of wrinkling I'm going to make, I could create wrinkling that is communicative and has more character."*).

They wrote more about "movement with character" and "communication medium". And tried achieving subtle and deliberate material movement to communicate a message.

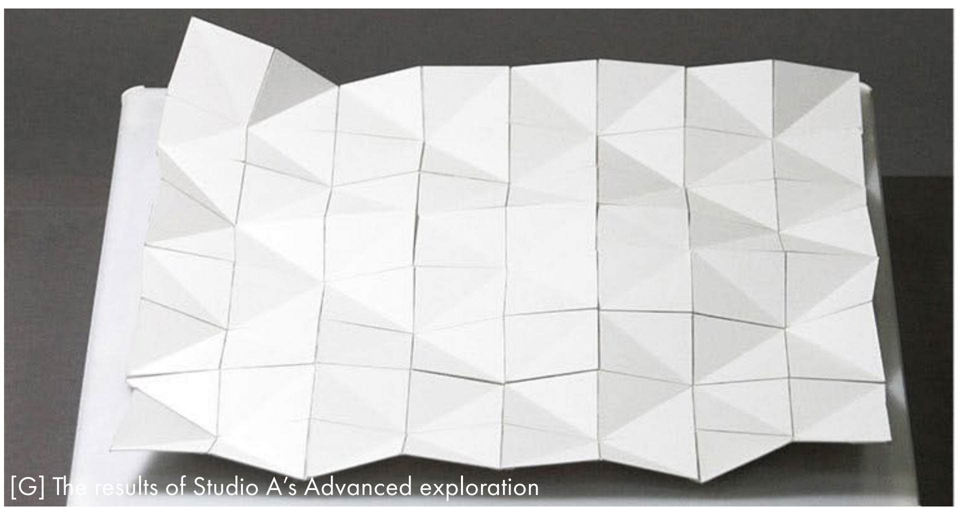
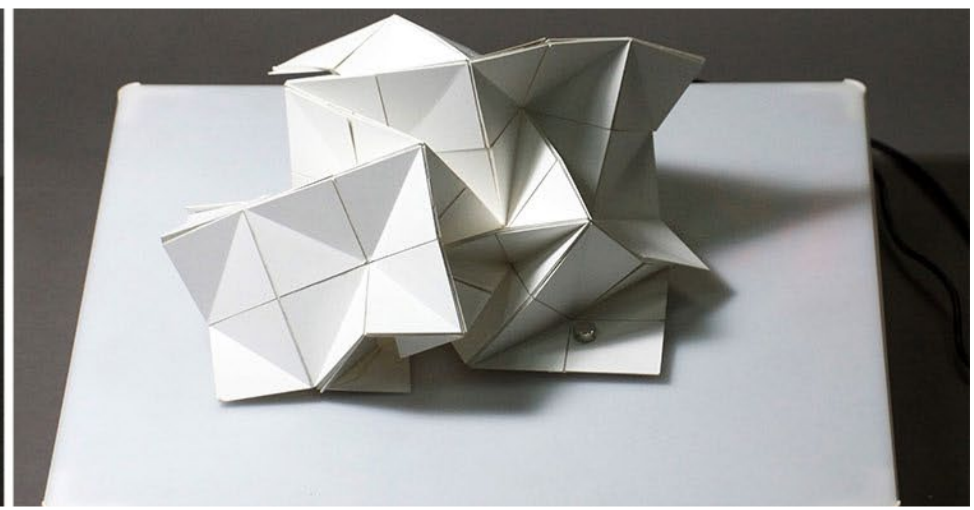
The designers used the Animation Interface for finesse motion control, and were excited to discover how rich and surprising the movement can be. The ability to use fine motion control to create a rich and surprising movement was an early meaningful discovery (*"I must say it really surprised me. My instinct was that the things I would move with these four arms, they won't really bring something new, and it does bring it. The arm has a behavior, and it has character. And the movement it makes has a character. Especially how you move several together, it suddenly creates another level of movement"*). The ability to create character or express emotion through movement was a powerful idea that guided the rest of their process.

While control of finesse movement was crucial, the nature of the soft materials and the expressiveness of the movement, drew the designers to strive for an organic feeling by trying to damper the movement (*"The lack of accuracy made it feel more independent and alive... the esthetics comes from the nature of the movement. When the movement has an element of randomness it is much more fascinating"*). To damper they used mixed materials such as putting water into the plastic glove, or placing a surface of Lycra over styrofoam balls, converting one movement to another movement that is less mechanical.

In general we characterized the use of either mixed materials with different properties for achieving joints and characterization of movement (e.g., plastic and rubber bands [F.2], styrofoam and plastic [F.1], water and latex, plastic and tape [G]) verses the use of geometry and processing in a single material for those purposes (e.g., straw bend [F.2] and paper folding [F.4][F.5]).

The designers could envision future applications of the technology in different domains such as architecture (*"In an architectural scale it could be amazing. We've seen the change that four points movement can do. An architecture office could take the idea of multiplying it and have sixty of these doing something. They can take it to an unexpected direction"*). It also arose inspiration for ideas such as a robotic object for language teaching.

By the end of the 15 days, they said that the new tool found its place aside the other design tools in the studio (*"It found its place, just like other objects in the studio, always there, always on your mind. Sometimes you suddenly get an idea and feel like trying it..."*)

[G] The results of Studio A's Advanced exploration

STUDIO B EXPERIMENTATION PROCESS

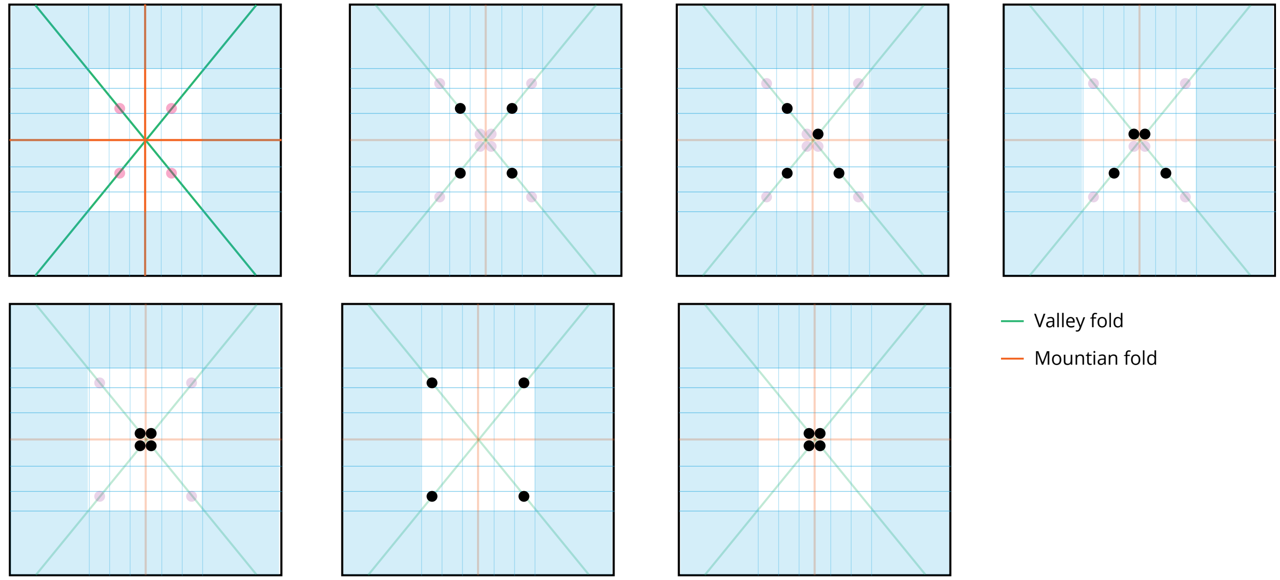
The designer in studio B is an interdisciplinary material designer. She holds a BA in visual communication, a M.Des. (with a specialty in wearables and motion research studied), and also studied for a MA in integrated design. Her studio work involves mostly dance costume design, performance design and information design. In addition, she is a material researcher in a textile design center, where she explores applications for new textile technologies.

The designer found the system intuitive and treated it as a design tool. *"My initial impression from exploring the fabric samples was that the interface was quite intuitive to operate... I wanted to understand the range of movement enabled by the robotic arms, so I opened the top cover and used the Animation Interface to move the arms around to see their range and the movement patterns."* [J.3]

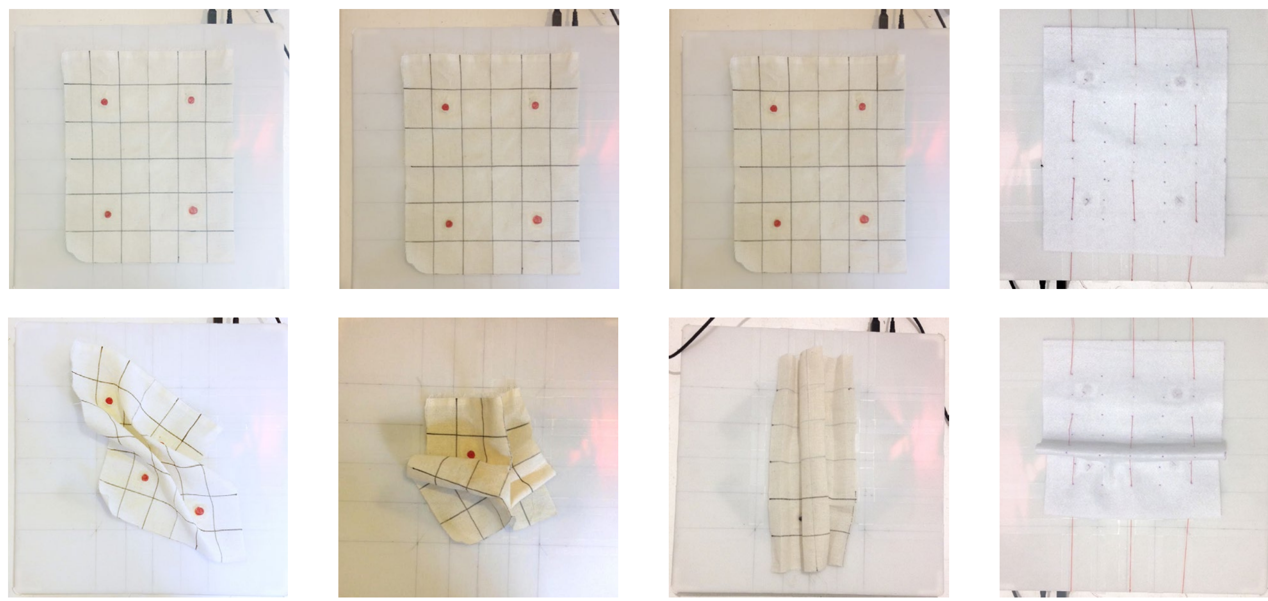
Following the Initial exploration stage, she started to explore movement with a range of fabrics she commonly uses in her studio including: Lycra, wool, cotton, polyamide, fly-net, and polyester. She was interested in the different movement characteristics of each, and how they influence each other. For example: light fabrics with heavy ones on top of them, and soft fabrics with rigid ones on top. *"I used mainly fabrics and sponge cloth, and thought what might happen when I pile them up one on the other, how they influence each other's movement. For example, I discovered that the Lycra is doing what the material above 'told it to do', but with the fly-net material it was different, each material 'had its own will'." "Different fabrics have different weights and different material characteristics and they 'fall' differently. Each of them behave differently with the magnet pull."*

Around day 5 she embarked on a systematic exploration of material movement [H]. Her years of experience working with choreographers and dancers led her to fully utilize the Animation Interface by designing various sets of movements, then saving them to custom-created libraries [H.1] [J.4]. She tried it with sample materials and leveraged this technique to create a vocabulary [H.2][J.5][J.6]. She was intrigued by the tension between the accurate

Timeline 1 - X Shape movement folding pattern



[H.1]



[H.2]

[H] Studio B's Basic exploration

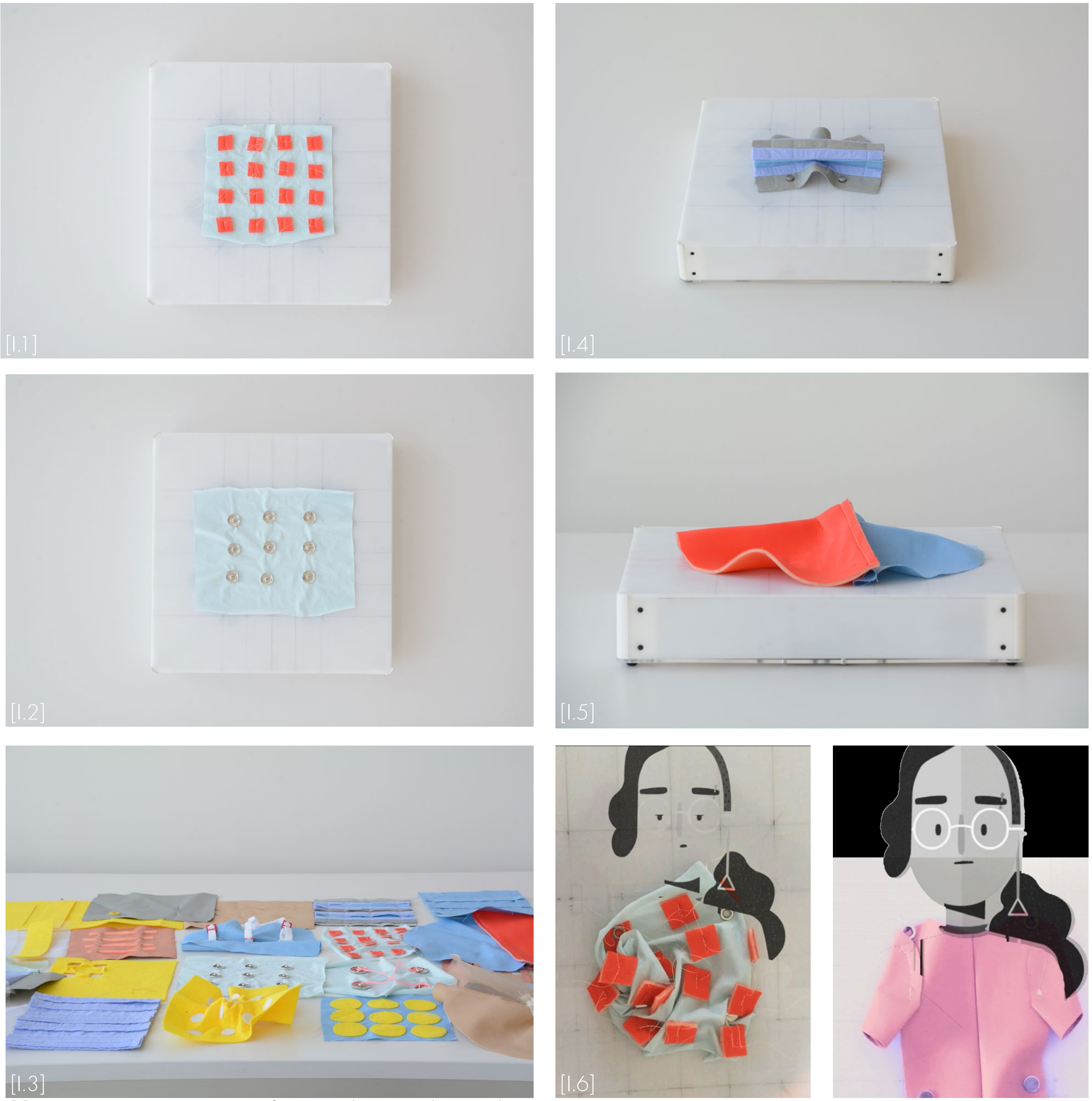
movement design on the computer and the different result each of her chosen materials generates [J.7].

"I recorded many different movement patterns, like straight line, diagonal line, quarter circle, and created a movement dictionary for myself... movement patterns is a known term in dance theory, it's the idea of repetitions... and my idea was to test each of the movements on each of the materials, to better understand each material quality and to learn what I can get from it in the feeling and character of the movement... I tried to see what works and what doesn't, for example it was very disappointing to see that the Lycra did not have a 'volume' to its movement, it stayed flat, but it was interesting to see the relationship between what the magnet 'tells the material to do' vs. what the material 'wants to do'".

"It brought up the concept of animation and movement of water, how can I create a feeling of waves, if I had a library with more complex movements I could 'place a movement on a material'. For example I would like to test a 'stormy sea' movement on various materials. In general it will be really interesting to work with patterns of movement from nature." "Now I finally feel I do not plan the movement but I touch the materials and feel them while they move and it inspired me to think what combinations I want to make, and right now I have too many things I want to create and I do not know if I'll have enough time to try them all."

After gaining some familiarity with the materials behavior, and controlling movement by gesture design and physical manipulations such as building a guiding wire grid [H.2] [J.6], she continued to explore several more advanced directions [I]. To state a few, using mixed materials [I.3] for more characterized movement [I.1][I.5][J.9][J.11][J.13] or functional elements (buttons) [I.2][I.4][J.9][J.12]; forming narratives[J.8][J.10]; and combining these with projections as a storytelling medium [I.6][J.14].

Starting form the Initial exploration stage, working with the platform sparked many thoughts about her current practices and how the work with the platform could contribute to it. *"In fashion design there is a real disconnection in the process between the computer-based design stage and*

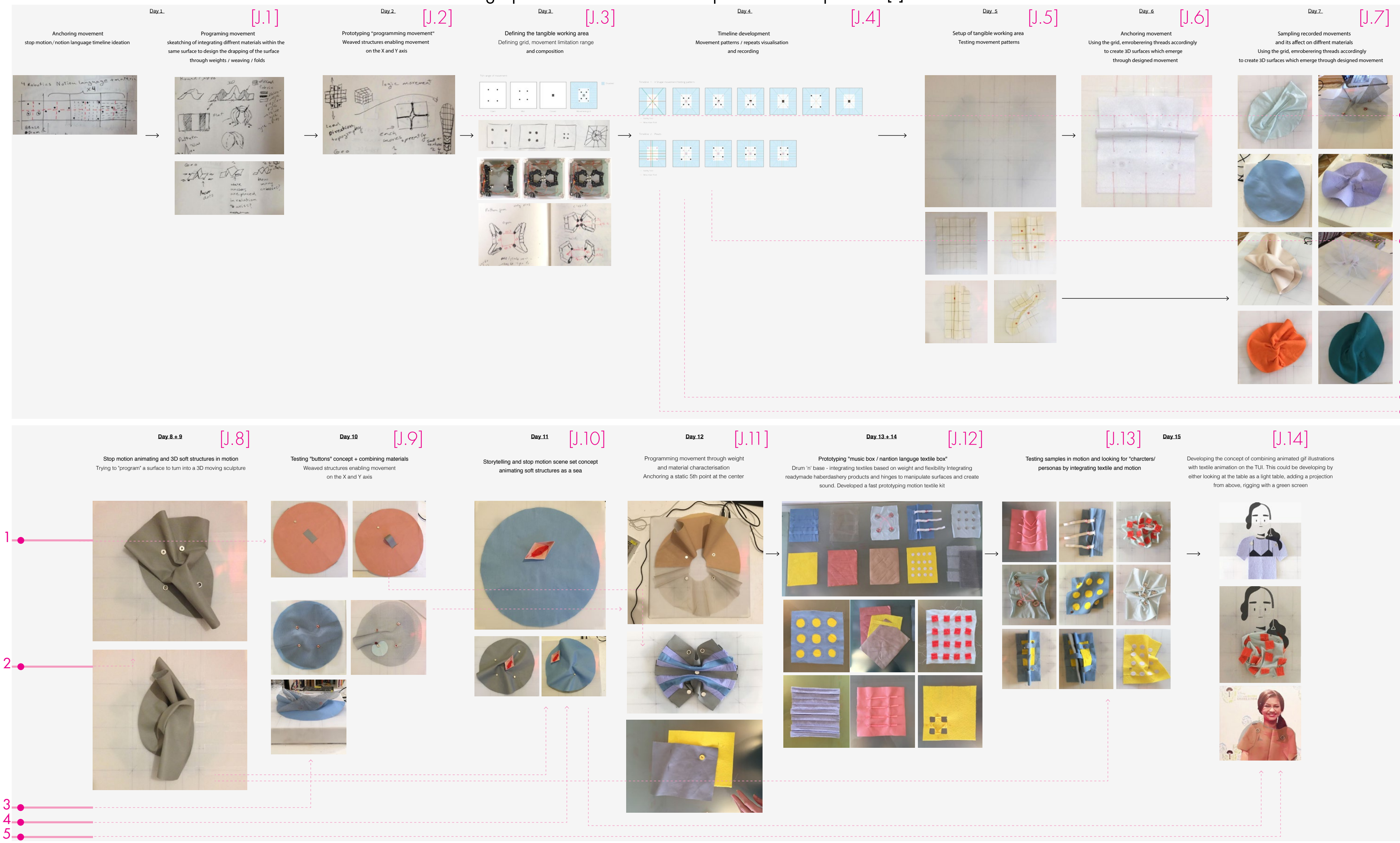


[I] Representative milestones from Studio B's Advanced exploration process.

the material design stage. With this tool I think I'll be able to connect the two stages and design also with the material... I can feel the behavior of the material while I'm designing." "I feel I got a new tool to work with, it opened new opportunities to things I wasn't able to produce before. I can model and think while creating, I don't need to stop."

Following her experimentation process, she created a graphic reflection of how she perceived her process [J].

Following the experiment, she was interested in developing a method that will allow her to design the material in relation to the movement. Leading her to create a form of metamaterial textile [K].



[J] Studio B's graphic reflection of her process.

DISCUSSION

Based on the experiences brought in the previous sections, we offer our reflection on the two overarching themes of: Empowering designers to participate in shape-change exploration, and the developing practice of designing objects which include motion.

Empowering designers to participate in shape-change exploration

First, from an overview of the different deliverables, we can see a very diverse range of materials used in various ways. Some of which, as far as we know, were not used in shape-change before, from some of the uses of everyday objects, to the ways some mixed materials were used to create expression or movement for function. It was also apparent how the designers leveraged their own professional worlds of materiality and skills in their designs.

While these are very initial ideas and experiments, and are limited in their exploration by our fairly simple system, we feel these results indicate that the platform can enable designers to create unique deliverables. Such that could be inspiring for the shape-change community, and as such demonstrates the potential of developing similar systems and involving material-oriented designers in the exploration of shape-change.

Also from viewing the sum of the deliverables, we can see that while there are some resemblances in the products the two studios created, they greatly defer in material choices, applications and style. As such we believe it can be said that the platform enables creative exploration with personal expression for a diverse group of designers.

Looking at the resemblances in the products, we can see many patterned sheet materials (mostly in studio A's paper prototypes [F.4][F.5][F.6][G] and many of Studio B's prototypes [I.1][I.2][I.3]). We believe this is a product of the system's most natural affordances as a flat symmetrical platform. Such directing affordances would exist in any system. And so, we noted that the balance of such affordances as limiting or enabling is a fine one which should be considered when designing similar systems, and can be leveraged for encouraging focused prototyping around a specific need or technology.

This balance of constraints and flexibility raises the question of the longevity of such systems. Our belief is that the enabling of creative exploration and diversity, as reflected in our design principles, are key for building a system that will remain relevant for the designers beyond a short exploration. This corresponds with the feedback from the designers, who were all eager to continue working with the system, and could see a potential in integrating it into their work. With that said, they were also conscious of it's limitations, and without a longer study it is hard to predict how long it will maintain it's relevance for them and in what way.

In regards to validating our design principles of accessibility to non-technical designers; generating movement in a wide range of soft materials; and encouraging creative exploration. We observed that the two layer system proved itself for encouraging creative exploration with it's flexibility to generate movement in a wide range of materials. Our takeaway is that other systems could utilize the principle of separating the actuator from the actuated material as a method for making flexible systems which require minimum mechanical adjustments. While magnetic actuation is one option, we can imagine other methods as air pressure, pin systems or others which could be used.

The designers were able to easily integrate the system into their practice and routine workflow, from finding a place for it, to learning how to use it and leverage it. From this we concluded that accessible prototyping systems have the potential of finding their place in designers studios, be used as design tools and influence designers' everyday practice. We defined our guidelines for accessibility to be: low cost, durability, small footprint, standard connections, cross platform software, easy installation and intuitive interfaces.

We found it interesting to see the need both studios had to explore the inside of the platform for understanding it and feeling in control of the system. This sort of transparency could be of importance for the design of similar systems.

The designers were able to gain control and create subtle and expressive motion in their design. We find that the direct and immediate movement design enabled the designers to work "close to the material" and refine movements in an intuitive way. To expand their ability of controlling the movement, studio B requested on one hand even more direct control which would allow her to keep her eyes on the object while designing the movement. On the other hand, both studios wished for more "programmable", editing control (e.g., syncing or copying movements). For the direct control, studio B suggested a tablet multi-touch interface, with physical limiters laid on it to keep the user within the movement limits. Such an interface, along with the current quarter recording features and some expanded editing capabilities could be a good balance for our system. We believe the mix of very intuitive, close to the material and perhaps tangible methods for designing shape-change movement, together with some editing capabilities, could be fitting for designers to use when designing for shape-change.

The developing practice of designing objects which include motion.

Similarly to the case with the deliverables of the different studios, the processes had some similarities and differences which we found of interest.

Both studios were strongly drawn to the exploration of expressiveness in motion, expressing emotion or building a character. This could be due to the nature of soft materials, that allowed for movement with organic qualities, which both studios were interested in for many of their designs. But the interest in expression might also be a response to the strong expressive effects autonomous movement have been shown to have even in abstract objects [2][7]. In either case, it seems likely that the expressiveness and character of shape-changing objects would play a big role in their design, and it is important to build the design tools to support expressive gesture design.

We found it interesting to see how the designers regular work manifested in their work methods (e.g., studio A forming structures and using simple mechanisms [F.1][F.2]

[F.6], and studio B using mixed textiles, haberdashery [I.2], knitting and binding techniques [I.3]). It also manifested in the objects they decided to make, and how they could see the platform relate to, or be used in their work, be it architecture or dance performance. In that aspect, we feel it would be of value to enable a longer experimentation process with the platform and see if and how it is integrated into the designers every day practice, or influences and inspires it. As one of the designers in studio A suggested - *"it could be that I would never look at it, but it could be that it would be like I need the drill, I suddenly need it"*.

Similar to how the deliverables diversed in style, so did the work processes. While studio A's process started off as a very intuitive exploration [F], studio B's process was much more methodological [J]. In regards for working with materials and movement, Studio A intertwined the two in their process, while Studio B started by separating the movement from the material and processing it by building the movement vocabulary [H.1] which she explored first with "generic" materials [H.2] and gradually expanded to other materials [J.7]. As she progressed, the relationship between the elements of structure, materiality and movement became more dependent. From finding form and characters within a material [J.8], to designing materials to form specific shapes when moved in a certain ways [J.9][J.11], to serve a function [I.4][J.9][J.12] or tell a story [I.6] (e.g., a marital is chosen and cut to act as a light shirt [J.14], or as a sea [J.10], fitted with specific gestures).

In both approaches, we feel it is apparent that designing with motion both in mind and in hand, being able to physically experience and prototype with movement in early stages of the design process, is a fertile ground for creating work where the relations between material, motion and expression are tightly bound. In recent years, designers have been learning to work with new digital materials for designing interactions [28]. Following the results shown in this work, we believe designing tools for material-oriented designers which follow principles and guidelines such as the ones we presented, could allow designers to use movement, and potentially other elements in shape-change interactions, as another material in their design work. This expansion of designers competences can allow for building on their skills, experience, formal and tacit knowledge, for making meaningful contributions towards developing the field of shape-change.

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