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PROTOTYPING SHAPE-CHANGING INTERFACES - AN EVALUATION OF LIVING HINGES' ABILITIES TO RESEMBLE ORGANIC, SHAPE-CHANGING INTERFACES

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Abstract

This paper presents an evaluation of nine laser cut living hinges in terms of their ability to resemble earlier defined properties of mechanical shape-changing interfaces. Such interfaces are expected to become more prominent in future human-machine-interactions. However, there is a lack of empirical research regarding how users respond to such interactions since the actual interface can be difficult to build. The project therefore aims to prototype the user experience of a shape-changing interface through more simple methods yet with convincing, robust and organic appearance. Based on previous research we define nine criteria to evaluate the patterns ability to imitate a shape-changing interface. Grounded on those criteria we select the pattern with flexibilities resembling organic behaviour the most. This pattern is used to build the Breathing Box, utilizing a computer-controlled actuator that is able to alter the shape of the surface. Hence, we illustrate how designers can move from low-fidelity prototypes to functional prototypes allowing repeatable experiments. Such controllable experiments in turn allow a quantitative evaluation of user experience of shape-changing interfaces.

Keywords: Evaluation, User centred design, Design practice, Multisensory product experience

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1 INTRODUCTION

This paper presents an evaluation of nine different types of shape-changing interfaces in form of laser cut living hinges. Their physical characteristics related to mechanical properties and user-experience are measured and compared, as well as simulated through finite element analysis. The purpose is to provide the above-mentioned information to designers who wish to prototype shape-changing interfaces in the early stages of human-machine-interaction in a controlled and repeatable manner.
We place ourselves in the field of human-machine-interaction (HMI) with a focus on intelligent machines/robots that soon will be dominant in everyday use cases (Alonso et al., 2013, 2014; Dawid et al., 2016). Earlier robots and intelligent machines were primary artefacts in an industrial context. However, due to circumstances such as cheaper sensors, customization trends, a growing elderly population, autonomous vehicles, future interactions between smart machines and humans will take over the private consumer market as well (Kemp et al., 2007). This calls for a revisit on how machines interact with their surrounding users (Hallnäs and Redström, 2002; Parkes et al., 2008). Along this line new types of interactions are being developed through other media than screens and software e.g. shape-changing interfaces (Ende et al., 2011; Hallnäs and Redström, 2002; Jensen et al., 2016). (Kwak et al., 2014; Rasmussen et al., 2012) call for more structured evaluations of the users experience of shape-changing interfaces. This study explores whether such interactions can be prototyped in a controlled and efficient manner by utilizing different types of living hinges to simulate a shape-changing interface. Defining a suitable living hinge pattern will support the building of convincing experimental setups for systematic and repeatable user-experience testing. Hence, the research question of this work has been:

> R1: How does laser cut MDF plates support exploration and test of previously defined dimensions of shape-changing interfaces?

The main contribution is two-fold. First, we provide an overview of nine different laser cut patterns leading to different properties of the plate in which the pattern is cut. Second, we present an early prototype in form of the Breathing Box that by utilizing one of the evaluated patterns creates a shape-changing and breathing feeling. The box is therefore a concrete example of how designers easily and cheap can build repeatable experimental set-ups for HMI-design.
Section 2 presents how previous researchers have approached the field of shape-changing interfaces and the prototyping of such. Further, we define nine criteria used as starting point for the evaluation of the nine patterns. Section 3 describes the patterns chosen for the investigation and the methods when evaluation the patterns. Section 4 schematically presents the results of the evaluation and holds the properties of the patterns up against the categories of shape-changing interfaces defined by (Rasmussen et al., 2012). Section 4 describes the building of the Breathing Box, utilizing the pattern resembling organic behaviour the most. Finally, the limitations of the work are discussed as well as the trade-off the designer needs to make when prototyping physically shape-changing interfaces.

2 THEORETICAL BACKGROUND

2.1 Rapidly prototyping Shape-Changing Interfaces

Prototypes can be used for various purposes in the engineering design process (Ulrich and Eppinger, 2008). This work focuses on the context of aiming at building prototypes simulating users interacting with machines through haptic interfaces rather than traditional screen interactions. Hence, it should be stressed that the goal of this work is to explore new interactions and their corresponding user feedback rather than designing the final haptic interface. This is with the aim to answer the research question whether HMI could benefit from providing a machine with a more holistic interaction system. Such user tests has previously been done through Wizard-of-Oz prototypes or more low-functional prototypes (Avrahami and Hudson, 2002; Blackler, 2009). More advanced systems have also been built for instance by (Nørgaard et al., 2013) who, inspired by animal body language, prototyped the w-O-r-m. This is a combined furniture and toy that contracts or expand according to how the user interacts with it. Another example of shape-changing interfaces are the several projects conducted at MIT Media Lab such as the LineForm, Materiable or the Exoskin (Nakagaki et al., 2015, 2016; Tome, 2015). These projects are very inspiring as new products, but are not used to systematically explore users interpretation of such shape-changing interfaces (Kwak et al., 2014). In fact only 10 out of a literature review of 44 papers on shape-changing interfaces approach the context from a user-experience point of view ((Rasmussen et al., 2012). One example is of the (Vallgarda et al., 2015). They build two interfaces by a combination of textile and servos. The interfaces initiate different movements when approached by a user. By letting seven expert designers reflect upon a set of 11 simple temporal forms, varying in synchronous/asynchronous form and direct/indirect control their work reflect and explore the experiential qualities of temporal aspects of interaction design (Vallgarda et al., 2015). Their study proves strong emotional interpretations of the different movements spanning from relaxation and meditation to sexual interpretations leading to embarrassment. Hence (Vallgarda et al., 2015) supports the argument that shape-changing interfaces will create powerful user experiences and further proves the need for understanding how we humans understand movements in more detail.

2.2 Defining the Evaluation Criteria for the Shape-Changing Prototype

The work of this paper focuses exactly on the evaluation processes of these new user experiences. The aim is to create repeatable and hypothesis testing experiments, while moving away from soft low-fidelity prototypes. For this purpose, robust test-systems yet easy-built and low-cost are needed. The flexibility yet robustness of laser cut living hinges might provide researchers with such setup. (Rasmussen et al., 2012) define eight different ways for a shape-changing interface to change form: Orientation, Form, Volume, Texture, Viscosity and Spatiality. Further the type of Transformation is divided into the categories; Velocity, Path, Direction and Shape. When proposing living hinges as a method for prototyping shape-changing interfaces it is meaningful to compare their flexibilities with these categories.

For systematically testing the flexibilities of the plates used in this study they were seen as plane structural elements. This is valid since they have a thickness of 3mm compared to the planar dimensions of 150x150mm, and they can be considered as plane structural elements with a thickness much smaller than the planar surface (thickness/width ratio < 0.1)(Reddy, 2007). A plate can be affected by forces and moments, inducing stresses and strains, depending on the elastic properties of the material. By providing the plate with a laser cut through pattern, the bending properties of this plate changes (Reddy, 2007). By evaluating the plates in terms of these quantitative criteria it would be possible to conclude which pattern would be suitable for the categories of shape-change and Transformation defined by (Rasmussen et al., 2012).

The focus of this work has been looking for movement that could imitate organic behavior. For future reference this appearance will be covered by the term *organic*. This was with the assumption that such behavior would provide a more convincing anthropomorphic or zoomorphic analogy, which has been favored by previous researchers (Alexander and Holman, 2013; Parkes et al., 2008; Rasmussen et al., 2012). For achieving such experience, one criterion is that the user should not be able to see the solutions making the system move. This would remove the impression of an intelligent organic moving surface. Further (Togler et al., 2009) emphasize how continual, small movements “enriched the impression of a living object”. Such movement would demand a smooth continuous feeling of the laser cut plate and therefore lead to criteria 7 and 8 dealing with whether the bending curve of the plate was continuous, and if the plate was bendable in several directions at the same time. The appearance was also considered in passive mode since this would be the first impression for the user when visually encountering the interface. Finally, in the context of early stage prototyping the amount of time it takes to build the prototype becomes an evaluation parameter (Jensen et al., 2017; Leifer and Steinert, 2012). In these phases, rapid learning is critical and hence shorter prototyping times are favorable. With these considerations nine evaluation criteria were defined for the nine different patterns in the search for the most organic flexibility and behavior. For further clarification, Table 1 presents the evaluation criteria as well as the applied testing method and the justification of the certain criterion.

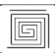
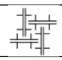
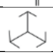
Table 1 Description of the criteria used in the evaluation and comparison of the laser cut plates (x and y axis are defined as shown in Appendix 1)

Criterion no.	Requirement Description	Applied Test	Justification
1	Bending around x axis	2N applied, while deformation measured	Investigating flexibility of the laser cut plate
2	Bending around y axis	2N applied, while deformation measured	Investigating flexibility of the laser cut plate
3	Compression in x- or y-direction	4N applied, while compression measured	Investigating flexibility of the laser cut plate
4	Elongation in x- or y-direction	2N applied, while elongation measured	Investigating flexibility of the laser cut plate
5	Transparency	Percentage of removed material in the pattern	Testing how well the pattern hides underlying technical solutions
6	Solid-like feeling	Measurement of Deformation in Neutral mode	Indicates the visual first impression of the interface
7	Organic feeling	Rating how continuous the bending curve of the pattern was	To explore how the pattern could create a continuous vs. abrupt surface
8	Organic feeling	Testing whether the pattern allow for bending in multiple directions at the same time	Bending in multiple direction would create a continuous movement
9	Rapidly Prototyped	Length of Cutting time	Important parameter in early stage product development

3 METHOD

The strategy of this work has been to explore the bending properties in relation to different patterns laser cut into a 3mm thick, 150x150x3mm, MDF plate and further hold the properties up against the categories and dimensions of shape changing interfaces defined by (Rasmussen et al., 2012). Further, the aim was to identify the most organic behaving pattern. Five patterns were found from online sources specifically recommended for laser cutting (Obrary, 2016). Four patterns were found in the book Politikens Ornament Atlas, which is a presentation of historical patterns from around the world (Smidt, 1971). Table 2 explains which patterns were chosen, and the reason behind this choice. In further mentioning, the patterns will be referred to as P1, P2 etc. as introduced in Table 2.

Table 2. Presentation of the nine evaluated patterns. In further mentioning, the patterns will be named as P1, P2 etc.

	Pattern	Explanation	Source
P1: Living Hinge		The classical living hinge seen in several design projects online.	(Obrary, 2016)
P2: Cross		Picked because of the low amount of cut and as an add-on to the classic living hinge.	(Obrary, 2016)
P3: Cut-out Cross		Picked to explore the effects of cutting out more material compared to the Cross (P2).	(Obrary, 2016)
P4: Diamond		Picked to test effects of thin grid structures	(Obrary, 2016)
P5: Triangle		Picked to test mobility in many directions	(Obrary, 2016)
P6: Egypt Sun		Picked to test “point centered” moving in the z-direction	(Smidt, 1971)
P7: Uneven Lines		Picked to test rules on expected continuous bending behaviour	(Smidt, 1971)
P8: Straight Lines		Picked to test rules on expected continuous bending behaviour	(Smidt, 1971)
P9: Arabic Pattern		Picked to test rules on expected continuous bending behaviour	(Smidt, 1971)

Each pattern was cut with a Gravograph LS1000 100W laser cutter. Each repeated pattern-cell had a maximum height of 15mm (See Appendix 1). Each pattern was investigated and compared to the evaluation criteria described in the previous section in order to identify the pattern having the most organic appearance. The evaluation was done purely internally since the criteria were quantitative and the whole project should be seen as a Proof of Concept for further experiments. This procedure is for further reference called Evaluation Round 1.

The plates were fixed as a cantilever with length 70 mm. Now the end deflection was measured when a force of 2 N was applied on the free end (Figure 1). Deflection dx and dy around either x or y direction was measured independently.

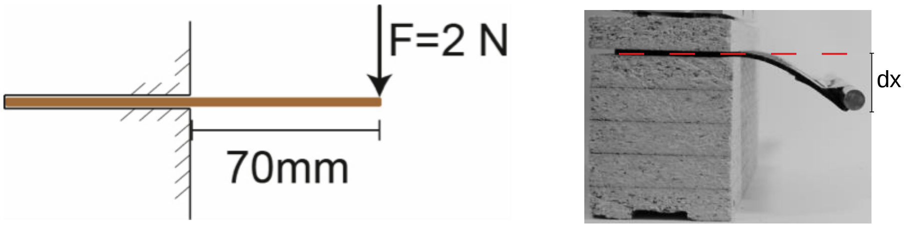


Figure 1. Evaluation-setup when investigating bending around x and y axis. Dx was measured (x and y axis are defined as shown in Appendix 1)

The elongation of the plates was investigated by applying a tensile force of 2N in one end of the laser cut pattern. For the investigation of compression, a small frame was built to keep the plate flat (Figure 2). A compressive force of 4N in axial direction was applied and the deformation was measured.

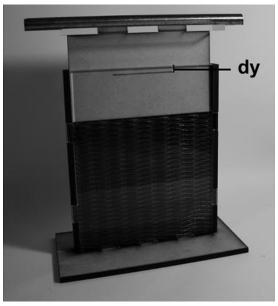


Figure 2 Setup for measuring compression along the y-axis of P4. The movement of the horizontal line indicated the deformation dy.

The final identified pattern was then simulated in Siemens NX and analysed through the finite element method. This was done to explore how the pattern behaved in more detail especially when subjected to multiple transverse point loads. The finite element method is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. It subdivides a larger problem into smaller parts that are called finite elements and can be utilized as a computational tool for performing engineering analysis as bending behaviour of plates of beams (Reddy, 2006). In this study, a 10-node tetrahedral mesh with 1mm element size was used. All four sides of the plate were fixed and point loads of 50 N were applied to three point on the plate. Further the Young Modulus of 3000 N/mm² (Spanolox, 2011) and Poisson Ratio of 0.25 (MakeItFrom, 2016) for the MDF material was used. Finally, as a case scenario a 300x300mm Breathing Box was built, utilizing the identified pattern.

4 RESULTS OF THE EVALUATION OF THE LASER CUT PLATES

In this section, the results from the evaluation of the nine patterns are described. This is followed by the results from the finite element analysis of the plate with the most organic behaviour.

Table 3. Presentation of the results from the evaluation related to user-experience and mechanical properties aspects (x and y axis are defined as shown in Appendix 1)

Pattern No.	Test 1: Deformation in x-direction when applied 2N [mm]	Test 2: Deformation in y-direction when applied 2N [mm]	Test 3: Expansion when applied to 2N [mm]	Test 4: Compression when applied to 4N [mm]	Test 5: Deformation in "non-activated" mode [mm]	Test 6: Ratio of removed material in the pattern [%]	Test 7: Continuous or Abrupt (Scale 1-5 where 1 is very smooth)	Test 8: Bendable in multiple direction [Y/N]	Test 9: Laser Cutting time [min]	Fitting Dimensions of Rasmussen et al. (2012)
P1	88.7	1	56	1	38.6	26	1	N	9	Orientation, Form, Volume
P2	34.5	1	0	0	5.6	27	1	N	16	Orientation, Form
P3	35.6	1	0	0	0	65	2	N	22	Orientation, Form
P4	68.0	0.7	4	8	8.6	49	2	N	15	Orientation, Form, Volume
P5	50.6	20.4	0	0	5.3	48	3	Y	19	Orientation, Form
P6	31.4	4.4	0	0	4.7	34	5	N	21	Orientation, Form, Texture
P7	23.3	4.3	0	0	2.3	28	3	N	14	Orientation, Form
P8	2.5	2.5	0	0	0	38	1	N	13	Orientation, Form
P9	18.2	17.5	0	0	2.1	21	2	Y	11	Orientation, Form

Table 3 presents the results from Evaluation Round I. As expected, the properties of each pattern are very different. Yet, when comparing them to (Rasmussen et al., 2012) categories they all fall under the categories Orientation and Form. Overall, four types of patterns were identified. First the patterns that only allow deformation in one of the x,y directions (P1, P2, P3 and P4); second comes the patterns that allow bending in both directions, yet not at the same time (P6 and P7); Third, the patterns allowing bending in multiple directions at the same time (P5 and P9). Last, P8 showed a case where no bending in each direction was really observed. P1 and P4 showed possibilities of creating compression and elongation respectively, changing the actual volume they take up. In this way they can fit in the category of Volume of (Rasmussen et al., 2012). Further P6 is an example of how a designer can create "point-based" movement in one direction almost resembling a button or keyboard like feeling (Figure 3). With this movement P6 besides orientation and form also falls into the category of Texture (Rasmussen et al., 2012).

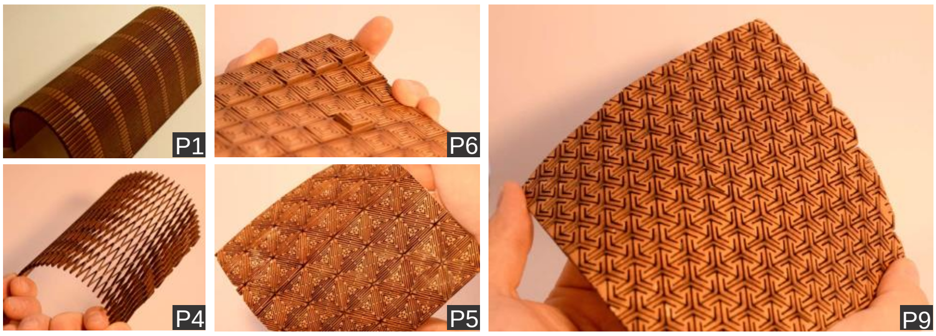


Figure 3 Examples of some of the patterns. Notice P9 to the right, which was chosen for further usage.

In the search for a pattern that overall created the most organic and continuous appearance P9 was chosen since it allowed for bending in multiple directions at the same time, had low transparency, had a continuous bending curve and a relatively low cutting time compared to the results.

P5 was also considered since this pattern showed very flexible properties in multiple directions. However, the cutting time was almost double the time compared to P9 and the bending curve more edgy and abrupt than P9. P9 was hence simulated in Siemens NX and analysed through the finite element method.

The finite element analysis allowed exploration of the laser cut pattern when applying multiple transverse forces at the same time. Figure 4 presents the simulations of P9 conducted in Evaluation Round II. The colours illustrate the plate deformation and the bending is observed to be continuous and smooth even when load is applied at three points. The profile illustration allows the viewer to see the bending curve being smooth and continuous.

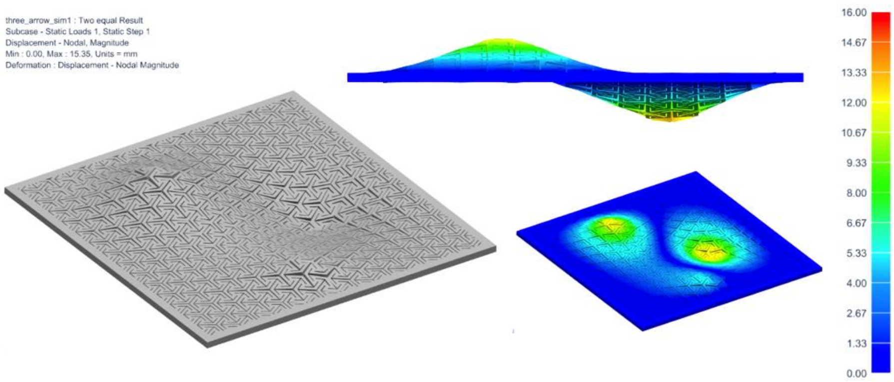


Figure 4. Example of Finite Element Analysis of P9

5 THE BUILDING OF THE BREATHING BOX

When convinced about P9s ability to work as an organic surface, a box was built that allowed for sliding a laser cut plate under a wooden frame. The pattern of P9 was repeated to fit a size of 300x300mm, which allowed an average size hand to rest upon the surface. The size of the pattern unit cell was kept at 15mm.

A small RC-type servo controlled by an Arduino was placed under the pattern cut plate (Figure 5). The servo was placed in a distance that allowed the lever to lift the pattern-cut plate up and down. The Arduino was programmed to rotate the servo with a sinus-inspired acceleration to resemble a breathing behaviour. The Breathing Box serves as an illustration of how designers in the future can create simple yet repeatable experiments to test aspects of (Rasmussen et al., 2012) category Transformation. Since the cut plates are durable and the small RC-type servomotor through Arduino code can be programmed to move in many different rhythms researchers could gain feedback on different Velocities and Rythms (Rasmussen et al., 2012). Adding more advanced control systems under the plate such as an x, y and z movement one could further design different Paths and Directions (Rasmussen et al., 2012). Figure 5 shows the Breathing Box and the motor below the laser cut plate. A video showing the box in action can be found through the following link: https://vimeo.com/195786200 (Password: ICED2017)

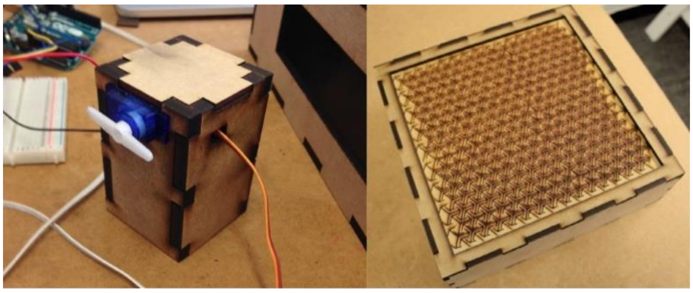


Figure 5 The Breathing Box - A video can be found through the following link: https://vimeo.com/195786200 (Password: ICED2017)

The Breathing Box allows exploring what kind of information can be transferred through different kind of transformations. The controlled setup opens up for evaluating interaction “samples” through multifactor analysis, which is a multivariate data analytical technique that seeks the common structure between several blocks of variables describing the same observations. By controlling construct-vocabularies assigned to the different transformations, the researcher could further explore whether a true organic interpretation has been created and what characteristics distinguish e.g. *mechanical* from *organic*. If the researcher designed boxes with different movements A Repertory Grid Study could be utilized. This method has been used previously when exploring which constructs user assign certain shape changing interfaces (Kwak et al., 2014). Also, one could investigate whether there would be some interactions that would be interpreted differently when experienced haptic or visually respectively. In one experiment the participants could be able to watch the interaction whereas in the other experiment they could be limited to only feel the interaction with the hands.

6 DISCUSSION AND FUTURE WORK

6.1 To use or NOT to use Living Hinges for Prototyping Advanced HMI

Through our work, a proof-of-concept project was built, suggesting future researchers to explore the user-experience of Shape-Changing Interfaces under controlled setups. In this context, the Breathing Box and the application of living hinges allow for more continuous and repeatable studies of human factors when interacting with shape changing machines compared to other prototyping methods such as Wizard of Oz prototypes.

On the other hand, the danger of such higher-functional prototypes and interactions in the early design phases are that they become too advanced for final production. When having evaluated and concluded which movements could be interesting to use in final products, the question of actual implementation will rise. How can these movements be implemented in final products in a resource efficient manner? Yet, the increased focus on robots and developments in the world of virtual reality are strong drivers for engineers to solve the challenge of making objects or surfaces move in resource efficient ways. In this field researchers are exploring how to add haptic feedback to the virtual scenarios, while having energy as well as material consumption in mind.

6.2 Styles and Contexts of Shape-Changing Interfaces

In this work, we have had the intention of prototyping an organic moving shape-changing interface since previous researchers have focused on such movements. However, when it comes to developing organic feeling we have not evaluated the Breathing Box systematically and hence cannot argue that the movement is actually interpreted as organic.

Moreover, the importance and usage of organic behaviour in previous work have been of no proved value. Rather it has been an unplanned interpretation from users. That is - it has yet to be proven whether organic moving interfaces are more lucrative than e.g. mechanical interfaces. In the field of robots and humanoid design the Uncanny Valley describes the emotional human responses to robots trying to imitate humans regarding look and interactions. There seems to be a fine line between impressive and convincing vs. creepy and uncomfortable user experiences (Burleigh and Schoenherr, 2015; MacDorman and Ishiguro, 2006). Will this interesting design challenge also appear when designing Shape-Changing Interfaces? To address this lack in research it would be interesting to create comparative studies between movements and interpretations from users.

Second, there is a need to investigate which kind of information that is suitable for shape-changing interfaces. Our work has been with exploration and building in mind, rather than being context driven. With this, we wish to encourage other researchers not only to focus on how users interpret certain transformation of shape-changing interfaces in terms of emotions recreated, but instead to approach the topic from a context perspective. This could be done by putting the Breathing Box in a context of certain products expected to have smarter dimensions in the future. This covers autonomous car, refrigerators in the future smart home, personal assistance, health care robotics and more.

7 CONCLUSION

This paper presents an evaluation of nine different types of patterns laser cut in 3mm MDF in terms of their ability to prototype organic shape-changing interfaces. This is to address the lack of research in user-interpretations of shape-changing interfaces.

By providing the plates with these patterns the plate changes bending properties, and turn into a flexible surface also called a living hinge or a living lattice. Our aim was to identify the pattern that provides the plate with the most organic properties in terms of flexibility. Such plate would further allow for prototyping physical shape-changing interfaces for designing new human-machine-interaction. A very organic movement was prioritised since such movements have been prioritised in earlier work seeking to bring traditionally static objects to life (Alexander and Holman, 2013; Parkes et al., 2008; Rasmussen et al., 2012; Togler et al., 2009).

Nine criteria were defined, evaluating both mechanical properties as bending and elongation, as well as organic-like requirements as continuity of bending curve and multiple bending possibilities. This evaluation proved that the laser cut patterns allowed prototyping interfaces varying in the shape-changing categories; Orientation, Form, Volume and Texture defined by (Rasmussen et al., 2012). The evaluation as well as a finite element analysis further led to the selection of P9 as the pattern most suitable for creating organic physical shape changing interfaces. With this knowledge a so-called Breathing Box was built utilizing a hidden RC-type servomotor to move the plate up and down in a sinus-like breathing manner.

This work provides future interaction designers and researchers with a schematic presentation of different kinds of living hinges, allowing for different types of shape-changing properties. Moreover, for researchers with similar focus, we provide a concrete example on how to easily build a starting point for repeatable experiments, testing different types of Transformation types as Velocity, Path and Direction ((Rasmussen et al., 2012). Hence, we hope our work will inspire others to start conducting experiments investigating whether such interactions indeed can improve the overall user experience and interactions of smarter everyday products.

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APPENDIX I: THE LASER CUT PLATES

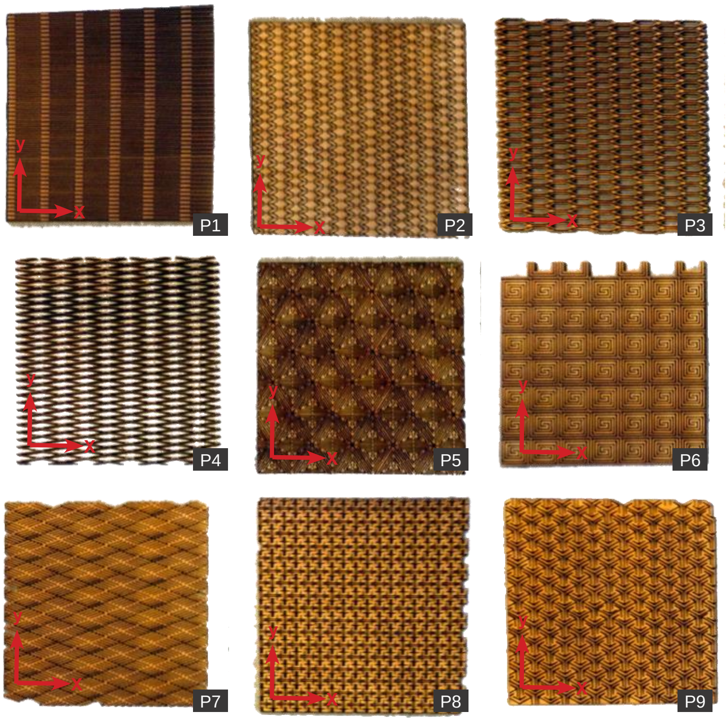

Figure 6. Laser cut plates used in the study