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Publication date

2018

Document Version

Final published version

Published in

Proceedings of the 36th eCAADe Conference

Citation (APA)

Aut, S., Eigenraam, P., & Christidi, N. (2018). Re-flex: Responsive Flexible Mold for Computer Aided Intuitive Design and Materialization. In A. Kepczynska-Walczak, & S. Bialkowski (Eds.), *Proceedings of the 36th eCAADe Conference: Computing for a Better Tomorrow* (Vol. 1, pp. 717-726). Lodz University of Technology. http://papers.cumincad.org/cgi-bin/works/paper/ecaade2018_309

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re-flex: Responsive Flexible Mold for Computer Aided Intuitive Design and Materialization

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The paper presents an ongoing research about the design and a possible use of a responsive flexible mold. The mold is developed by integrating its precedents with automation and Human-Computer Interaction (HCI). The objective of the design is to provide an immersive design tool which has direct link to fabrication. It allows intuitive interaction to its user in order to help with the design and production of complex forms by supporting the designer's implicit skills with computer. The paper presents the design by illustrating the use of the hardware such as the actuators, the sensor and the projector; and by defining the workflow within the software. The paper concludes with the description of a possible use case in which the system is used to design and materialize an object in different scales.

Keywords: *Design tools development, Digital fabrication and robotics, Human-computer interaction in design, Shape, form and geometry, Inventive Making*

INTRODUCTION

The aim of this paper is to present our ongoing research project which focuses on a Human-Computer Interaction (HCI) add-on to a flexible mold system towards developing an immersive design tool with direct link to fabrication. We have been working with flexible mold systems for research and teaching purposes since 2013. These practices have utilized a series of custom-designed and self-built flexible molds which are based on the concept of a flexible surface placed on a pin-table on which the heights of each pin can be adjusted manually. Our experiences with these tools, as well as the relevant studies by others, have shown that this concept is efficient to be used both as a fabrication tool for producing double-curved panels (Eigenraam 2015) and as a set-up for

active learning of the fundamental notions of computer aided fabrication (Aşut and Meijer 2016).

Our goal in this project is to upgrade this concept with computer support within two associated levels. The first level is the automation of the system which does not necessarily change the way it is principally used. It rather reduces the time needed to adjust the pins and increases the precision due to computer control instead of manual adjustments. On the other hand, automation and computer control enables other versatile functionalities such as the possibility of an immersive tool with the help of HCI support, which addresses the second level of upgrade in this project. With the HCI support, the mold can also be used as an immersive tool with which the designer can interact bodily in order to design and materialize

complex forms in different scales or in actual size. By this means, the conception and the fabrication of the design becomes integrated and reciprocal, allowing the designer to use his/her intuitive skills while utilizing the computational media to the full extent for better designs. A possible use case scenario for the use of such an immersive tool is described in the following chapters.

In this paper, we present our design concept of the aforementioned tool by describing the technical upgrades within automation and HCI, and by illustrating a possible use case as a design instrument.

PROBLEM STATEMENT: IMMERSIVE INTERACTION FOR MAKING FREE-FORM OBJECTS

Piano (1969) claims that production by means of industrial instruments and processes is rather conditioned by the complexity and versatility of which the machines are capable, and by the processes and material of production. Producing building elements which consist of free-form surfaces is still a challenging task for technical and economic reasons. Particularly, when the design consists of several elements each of which has a different form, it is necessary to produce a unique mold for each element. This situation increases the building costs significantly by maximizing the cost required for producing the molds. Also, using a unique mold for each panel results in high waste, which is an unsustainable operation. Moreover, subtractive manufacturing techniques, which are commonly used to produce molds with complex forms, increase the waste even further. Therefore, it is necessary to develop systems which enable the fabrication of objects with complex forms efficiently while reducing the waste and the building costs. This project aims at tackling this problem by proposing an inventive way of using the existing flexible mold systems by improving them as immersive design tools with direct link to fabrication.

Our proposal is based on the idea that designing free-form objects is a challenging task especially when considering manufacturability. Computational

methods with the help of advanced software applications provide us with solutions for design development, optimization and simulation for complex forms. They even allow us to integrate certain material aspects in order to predict the fabrication process during design development. However, as claimed by Aish (1979), it is often difficult for the user of conventional graphic computer aided architectural design (CAAD) systems to conceptualize the building being designed by only inspecting and manipulating drawings displayed on the screen. Accordingly, it is necessary to integrate immersive HCI applications into CAAD systems in order to allow reciprocal, direct and organic interactions between the physical and digital environments; or, in the words of Negroponte (1975), between the real and the model worlds. In this sense, it is possible to consider the fabrication machines also as instruments for design thinking which can better integrate the material aspects into the processes of design development.

Schmidt (2000) defines the concept of Implicit Human-Computer Interaction (iHCI) as an action performed by the user that is not primarily aimed to interact with a computerized system but which such a system understands as input. This implicit dimension of HCI is key to develop better design tools which enable intuitive interaction. And during the design of three-dimensional objects, intuitiveness can be achieved by immersive interaction. This requires the use of design media which enable the designer to develop, test and modify his/her ideas on a physical three-dimensional interface through bodily movements instead of on-screen representations which are merely two-dimensional. The responsive flexible mold system (re-flex) which is presented in this paper is developed as a medium of HCI which allows intuitive interaction that allows the use of implicit and bodily skills in the design and materialization of free-form objects.

RELATED RESEARCH ON FLEXIBLE MOLDS

Several concepts of reusable flexible molds already exist. One of the early examples was developed by

Figure 1
The former
FlexiMold.

Piano (1969) when aiming to construct shell structures using a flexible mold system. Designs of flexible molds which are closely related to our project are developed by Kosche (1999) and later by Rietbergen and Vollers (2008). Except these ones, there are a number of related patents of which an extensive overview is given by Schipper (2015), whose works focus on the use of flexible molds for producing concrete elements. A limited selection of other developments which worth mentioning but are too extensive to elaborate on in this paper are the ones by Spuybroek (2004) and Oesterle et al. (2012).

There exist three similar flexible molds which are used for large scale production in industrial applications. The first one is the one which is developed by Adapa (see Url[1]). Another similar system is used by Curve Works (see Url[2]). Also, the concrete factory mbX (see Url[3]) has developed its own system which is used to produce the double curved roof panels of Arnhem Central station.

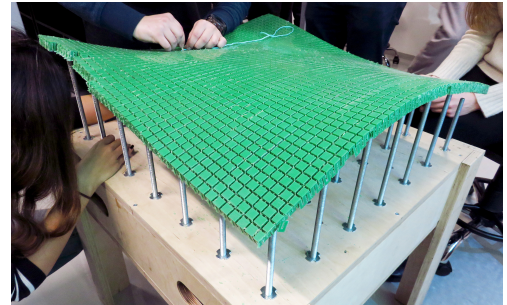
THE DESIGN

The Former FlexiMold

The design of the former flexible mold, which we have been using for research and teaching and named as FlexiMold, is based on the concept of a flexible surface supported by adjustable pins in vertical direction. The flexible surface is made of high-density polyethylene (HDPE). The HDPE plate is able to bend and perform double-curved surfaces due to the pattern which is milled on the two opposite sides of the plate. Therefore, the surface of the mold is both flexible enough to perform complex curved forms and rigid enough to cast the material on (see Figure 1).

The form of the flexible surface is determined by the position of the pins which are located on a regular grid. The height of each pin is adjusted manually by following an algorithm which is developed in Grasshopper (see Url[4]). The algorithm analyses the form of the designed surface and calculates the height of each pin needed for adjusting the mold. After all of the pins are adjusted, the flexible surface is placed on top so that it is identical to the designed

surface and the mold is prepared to cast the material on. This set of operations is repeated for each unique surface design. A more detailed description of how it is used was previously presented by Aşut and Meijer (2016).



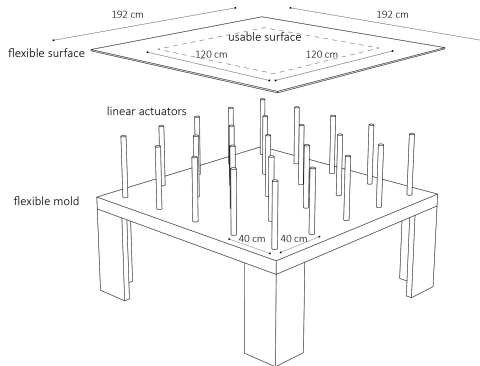
The Responsive Flexible Mold, which we name as re-flex, is based on the same principals with two important upgrades. The first upgrade is aimed at automating the pin adjustment step towards a faster and more precise process. The second upgrade is aimed at integrating the system with HCI support.

First Level of Upgrade: Automation

The automation of the mold is not the actual inventive aspect of this project. It is rather a technical improvement which brings about higher speed and precision for adjusting the mold. However, it enables a more profound upgrade in the next level.

The automation of re-flex is achieved by replacing the regular adjustable pins of the former FlexiMold with 12V DC linear actuators with built-in potentiometers. The first query at this stage is to determine the number of actuators needed for an efficient system. A greater number would enable higher control on surface curvatures. However, the number is limited to the number of available Input/Output (I/O) pins on the microcontroller board which will communicate information between the digital model and the mold. Also, increasing the number of the actuators will increase the cost of the system. Eventually, the design is developed by using 25 actuators

which are positioned on a grid of 40*40 cm on a layout of 160*160 cm with an actual usable surface area of 124*124 cm on XY plane (see Figure 2).



The actuators are controlled by an Arduino Mega (see [Url\[8\]](#)), which is a microcontroller board with 54 digital I/O pins. Each actuator is connected to one output and one input pin. The output is used to position the actuator at correct height. And the input is used to read the current position of the actuator. Both the input and the output are communicated through the Arduino board between the actuator and the digital model in Grasshopper with the help of Firefly (see [Url\[6\]](#)) plug-in (see Figure 3).

The automation through actuators with direct link to the digital model enables fast and precise positioning of the pins, therefore allows the accurate and rapid forming of the flexible surface without the need for manual adjustments. By this means, the mold is prepared for casting the material on with one click right after the design is defined in the digital environment. Furthermore, it is possible to keep the actuators operating while the design is being modified by the designer in the digital environment. Thus, it becomes possible for the designer to receive real time feedback through the physical surface during design development with the help of an automated mold and to materialize the different designs which emerge during the process.

Second Level of Upgrade: HCI Support

The upgrade of the system with HCI support is based on the idea that the mold can serve as an immersive design tool which does not only output the design in the physical environment but also receives physical inputs from the designer and communicates them to the digital model. By this means, it enables the designer to design a free-form surface in real 3D environment by using his/her bodily and intuitive skills while simultaneously developing a digital model of the design. Also, the digital model can be used to further improve and optimize the design decisions which can then be outputted on the physical mold. Thus, design process becomes a reciprocal activity that occurs between the physical and the digital media and the variations of the design can be materialized anytime during the process.

The HCI support is achieved by integrating the system with a sensor device and a projector. The sensor we use is the Leap Motion (see [Url\[7\]](#)), which tracks hand and finger motions and gestures without any physical touch. In our application it tracks the hands of the designer while he/she shapes the flexible surface by moving his/her hands and performing certain gestures in real 3D space over the mold. The sensor uses them as input to the parametric model by communicating with it through the Firefly plug-in and the input is used to position the actuators in real-time (see Figure 4).

The function of the projector is to provide the designer with real-time visual guidance on the flexible surface. It projects several types of information related with the design which are integrated into the computational model. By this means, the model performs analyses on several design aspects and projects the related information on the flexible surface. Therefore, it enables a real-time communication between the designer and the digital model in real 3D space.

Visual Guidance

The visual guidance which is enabled by the projector is a part of the HCI support and it provides the de-

Figure 2
The actuators and the flexible surface of re-flex.

Figure 3
Automation of the
actuators

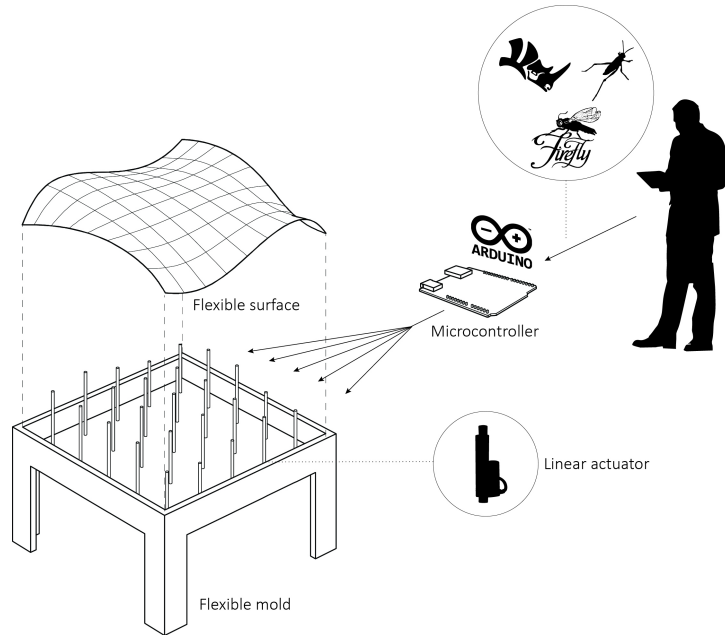
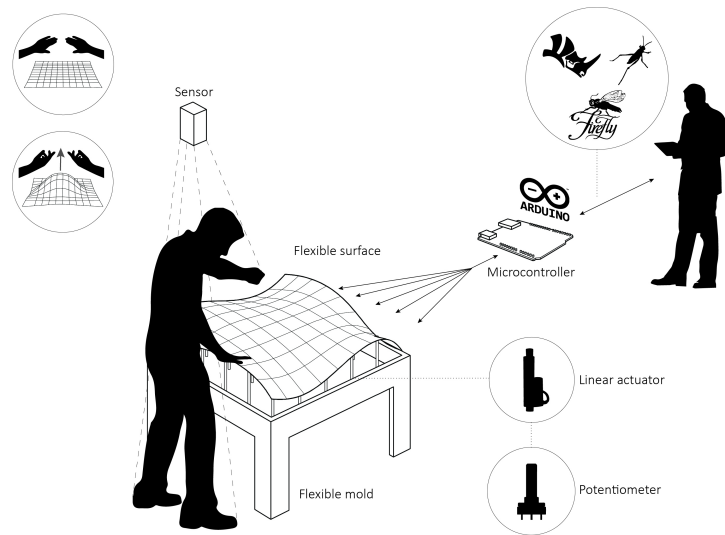


Figure 4
HCI integration on
re-flex.



signer with real-time information which he/she can use to develop better designs. The information is derived from the computational model and its content can vary according to design objectives. In our application, the visual guidance communicates information on the structural performance in relation with the form of the surface. As the design evolves, certain geometric and structural conditions continuously change. The model keeps real-time track on these aspects and communicates them to the designer through the projection. To this end, the computational model is integrated with analysis and optimization algorithms.

The structural performance analysis is performed by Karamba (see [Url\[5\]](#)) plug-in in Grasshopper. It calculates the results of the user's preferences of analy-

ses such as, in-plane or out-of-plane forces and visualizes the output using contour plots on the flexible surface through the projection. By this means, the designer is able to receive real time feedback on the structural performance on the design and thereby to quickly gain insight on the consequences of his/her design modifications or have feedback towards how to improve the performance (see Figure 5). This feature is particularly interesting as it is able to provide an opportunity to the designer towards investigating a good balance between the formal exploration and a reasonable structural behavior instead of a search which is focused on the most optimal form.

The computational model is also integrated with an optimization algorithm which is developed in Kangaroo (see [Url\[9\]](#)) plug-in. Its objective is form-

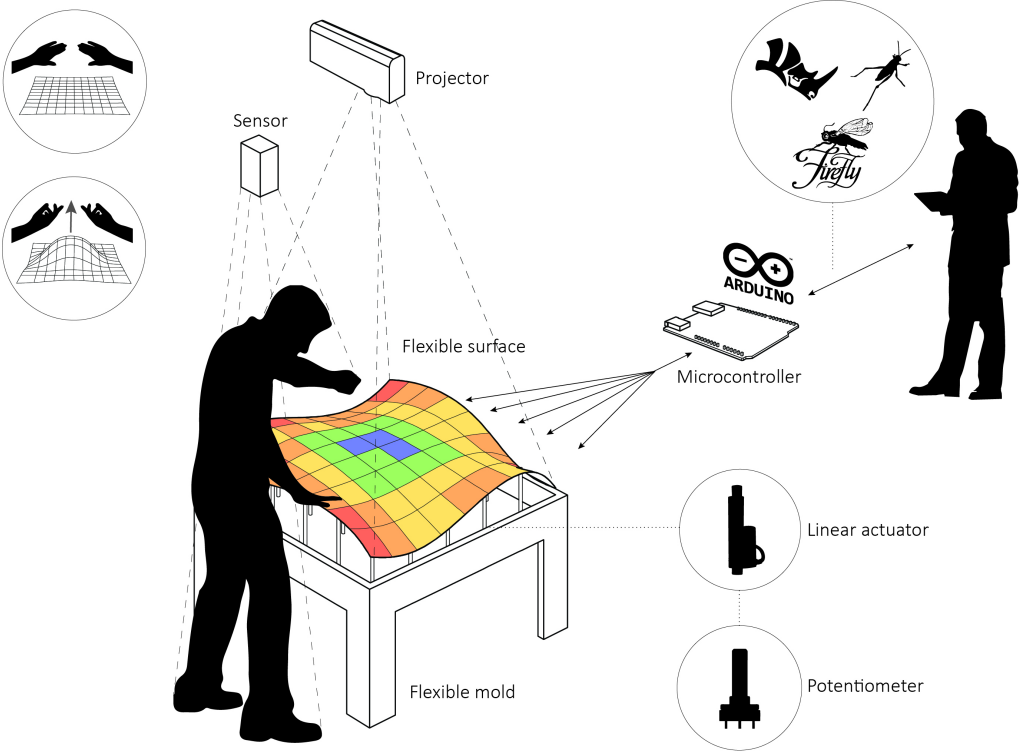


Figure 5
Real-time feedback
on the structural
performance of the
design through the
visual guidance.

Table 1
Pre-defined
gestures.

id	Gesture	Function
01	Pick Point	Pick a control point on a curve to pull upwards or push downwards.
02	Rotate 2D	Rotate the surface on XY plane.
03	Rotate 3D	Rotate the surface in 3D around the given rotation axis.
04	Translate	Move the surface on XY plane inside the flexible surface area.
05	Reflect	Mirror the surface on XY plane.
06	Make Hole	Subtract a custom hole on the surface.
07	Trim	Trim an edge of the surface.
08	Zoom-in	Shift to a larger scale.
09	Zoom-out	Shift to a smaller scale.
10	Undo	Go back one step.

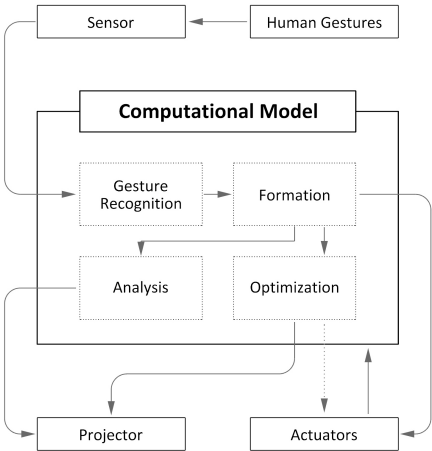
Figure 6
The workflow.

finding towards the most optimal structural performance. It takes the current state of the form and optimizes it which results in a new form depending on the pre-defined loading and support conditions. The new form is different but geometrically similar to the one which is formed by the designer on the mold and it is visualized on the flexible surface through the projection. So that it guides the designer towards the optimum structural performance but the use of it is optional and not deterministic. Alternatively, the designer has the option to transfer the optimized form directly from the computational model to the mold. This allows him/her to form the surface intuitively until a good balance between the form and the structural performance is achieved and then end up with a final product which is optimized by the computer.

The Gestures

The designer interacts with the system through hand movements and gestures. These gestures are defined in Grasshopper by using the the data which is derived from Firefly that communicates with the Leap Motion sensor. There are ten pre-defined hand gestures which are needed to perform the different functions integrated in the system. These gestures are used mainly for geometric modifications and to

change the scale. It is possible to introduce more gestures if needed in the later phases of the project. These gestures are presented in Table 1.



The Workflow

All of the hardware and the functions which are defined in the previous chapters are integrated within an algorithm which is developed in Grasshopper by using different plug-ins. The workflow (see Figure 6)

starts with the hand gestures of the designer. They are tracked by the Leap Motion sensor and transferred to the algorithm through Firefly plug-in. The transferred data is used to form the surface of the design in the digital model. Simultaneously, the model actuates the mold by communicating with the linear actuators through the Arduino microcontroller which receives data from the Firefly component. Eventually, the flexible surface of the mold is formed. Also, the computational model receives data from the built-in potentiometers inside the linear actuators so that it can keep a track on the actual position of each linear actuator. The structural performance of the formed surface is analyzed by using Karamba plug-in and the output is visualized on the mold through the projector. It is also optimized structurally by using Kangaroo plug-in and the output is visualized on the mold through the projector as well. Also, there is an option to send information from the output of the optimization directly to the actuators in order to shape the mold for the most optimal design.

THE USE CASE

The re-flex is an instrument which can be used in different cases towards different objectives which are defined by its user per se. The use case which is defined here illustrates a use of it in which the user develops a design by working in different scales. In this case, the flexible surface of the mold is considered as both a medium which represents the design and a device which is used to materialize it in different scales. The change between these two states is possible at any required phase during the design process and it is determined and controlled by the designer.

Currently, we do not have a distinct decision on the material of production which will be used in this use case. The possible options include fiberglass, concrete, clay, resins, plaster and paper pulp, which are suitable to use as we know by experience. The elaboration which is presented here excludes the aspect of production material and focuses on the form development. The aspect of material and the issues which are brought with it will be investigated at a

later phase.

The main challenge of this use case is to utilize the mold for designing and fabricating objects not only in actual size but also in different scales. This is achieved by using the flexible surface as a medium which is able to represent the design in different scales such as 1:1, 1:2, 1:5, 1:10, 1:20, 1:50 and 1:100. By this means, the 1,44 m² (120*120 cm) actual usable area of the flexible surface is able to represent a maximum of 14.400 m² (120*120 m) depending on the used scale. Therefore, the surface can be used to design objects of different sizes from a single facade panel to an entire roof of a large building. Furthermore, it can be used to materialize actual objects such as a facade panel and the scaled models of larger buildings or building components. The most critical point is that the alterations between the different scales are possible whenever it is needed during design development. So, the designer is able to work in different scales, from 1:1 to 1:100, to focus on the different aspects of the design problem, just like in a typical CAD application but in a physical, tangible and immersive environment (see Figure 7).

The shift between scales is performed through simple hand gestures which are pre-defined; such as the gesture 08 and 09 for zooming-in and zooming-out as seen in Table 1. Each time the designer performs one of these gestures, the model recognizes it as input, calculates the position of each actuator needed for reshaping the surface, and actuates them to shape the surface simultaneously. For example, the designer works in 1:50 scale, so the surface represents an actual area of 3.600 m² (60*60 m). This area refers to a shell which will be constructed by assembling panels each of which is 120 cm in width and length. The paneling of the shell is being performed by the model and the borders and id tags of the panels are projected onto the surface. So, the designer is able to see how the shell is panelized and how the panels are changing as he/she keeps modifying the design. When he/she needs to see or modify the design in larger scale, he/she performs the zoom-in gesture on the specific panel that he/she wants to

work on. Then, the actuators are re-positioned and the surface is reshaped so that it represents an area of 576 m² (24*24 m) in 1:20 scale in which the specific panel is centered and projected onto the flexible surface with its neighboring panels inside the given area. The designer is then able to work more precisely on this area. Likewise, he/she can gradually zoom-in or zoom-out to shift between the scales in order to gain more precise control on certain parts of the shell or an overall perception of the whole design. He/she can move around the mold and perceive the design from different perspectives and gain a profound spatial understanding of the design object. He/she can touch the surface to not only see but also feel the form and perceive the curvature continuities. So, he/she develops the complex form of the design through bodily interactions in an immersive environment by using his/her intuitive skills while making use of the feedback which are received from the computational operations. Furthermore, he/she can materialize the design in different scales at any

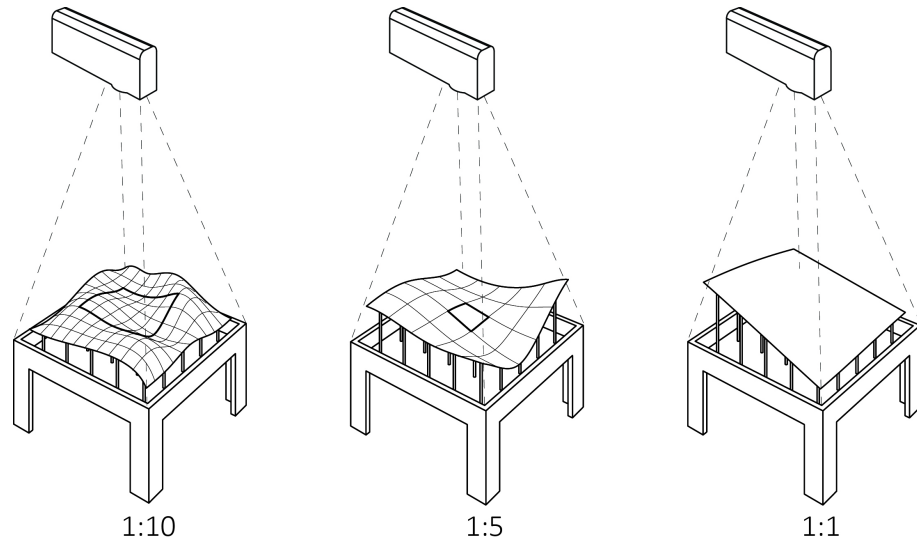
phase of the design development and can evaluate his/her design decisions through a material interface as well.

CONCLUSIONS

In this paper we have presented the concept design of re-flex, a responsive flexible mold system which is developed by upgrading the former flexible mold systems with HCI support. The project is ongoing and we are currently building the mold to be used in experimental case studies. Even though there exist certain technical challenges in building the system, the paper is able to provide a thorough overview on the main principles in terms of both hardware and software aspects.

One of the problems to be solved while building the mold is the connection details between the actuators and the flexible surface. The connection needs to be able to both push the surface upwards and pull it downwards without losing precision on the curvatures. On the other hand it needs to be rigid enough

Figure 7
The change of scale
on re-flex.



to bear the load of the flexible sheet and the material of production while allowing movement in all three rotation axes. We are developing this detail by using built-in universal joints which are integrated into the flexible surface and are connected to the actuators.

Another important aspect is the material of production. As mentioned earlier, we have experience in using a range of materials on the former flexible molds. This aspect needs to be investigated further with the use case experiments in the following phases of the project. Furthermore, the design and application of the connection details between the produced curved panels is another aspect which needs to be considered together with the material of production.

The main objective of this project is to expand the capabilities of the tools towards more complex and versatile instruments so that they can better answer the particular needs of the designer per se. To this end, this project presents the possibility of an immersive design tool which has direct link to fabrication and allows intuitive interaction to its user. It suggests a consideration of the fabrication machines also as instruments for design thinking so that the integration of the material aspects into the design process becomes easier. It provides a framework for connecting the model and the real worlds so that the designer can inspect and manipulate the design not only on the screen but also in his/her physical immersive environment.

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