Learning from the Trenches of Embodiment Design: The Designing, Prototyping, and Fabricating a Large Interactive Display

Jouke Verlinden[1], Daniel Saakes[2], Rob Luxen[1]

[1] Department of Industrial Design, Delft University of Technology, Delft, The Netherlands
[2] Department of Industrial Design, KAIST, Daejeon, Republic of Korea

Abstract

Background The advent of ubiquitous computing requires us to reconsider all aspects of industrial design engineering – to invent, package and optimize such products, services and experiences to society. This project was devised to bridge these in a compelling and magical prototype, called the Kinetic Mirror, a mirror that can not only mimic color but also shape in front of it. It builds upon the efforts performed in the field of projector-based augmented reality and natural design interfaces, and it showcases our ideas of future prototyping of design concepts.

Methods This article describes the complexity of engineering when embodying and producing such interactive systems to disseminate design knowledge. Specifically, we reflect on the conceptualization and development of the Kinetic Mirror: a three-dimensional display that mirrors depth and color in 400 “pixels”. Enabled by the introduction of low-cost structured light sensors, we envisioned an instantaneous physical manifestation of the captured scan.

Results Challenges included: selecting electronic parts, software architecture, hardware and networking performance, outsourcing of production, power consumption, and overall assembly and construction

The final system was put to show on five exhibits to test audience engagement and robustness of the result. This work has implications towards design curricula and provides new focal points of attention for design research and prototyping.

Conclusions Demonstration and prototypes are an increasingly important medium to disseminate design knowledge, because experience can only partly conveyed in written text or even in video. However, if products become dynamic, articulated and with behavior, the technology requirements for prototypes become more complex, and as a result harder to maintain. In this paper we shared our lessons learned.

Keywords Prototyping, Shape Changing Display, Design Process

*Corresponding author: Jouke Verlinden (j.c.verlinden@tudelft.nl)

The project was funded by a Research Initiatives grant by Industrial Design Engineering in Delft.

Citation: Verlinden, J., Saakes, D., & Luxen, R. (2015). Learning from the Trenches of Embodiment Design: The Designing, Prototyping, and Fabricating a Large Interactive Display. *Archives of Design Research, 28*(3), 5-19.

http://dx.doi.org/10.15187/adr.2015.08.28.3.5

Received : Jun. 01. 2015 **; reviewed :** Jun. 16. 2015 **; Accepted :** Jul. 16. 2015
pISSN 1226-8046 **eISSN** 2288-2987

1. Introduction

Information and communication technologies are swiftly penetrating our domestic environments. One of the best examples is home entertainment. Present gaming consoles such as the Nintendo Wii and Microsoft XBox allow natural interaction with the computer, by gestures and bodily movement. Advances in hardware present a future generation of consoles including virtual and augmented reality for 3D experiences. The advent of ubiquitous computing requires us to reconsider all aspects of industrial design engineering – to invent, package and optimize such products, services and experiences to society.

This project was devised to bridge these in a compelling and magical prototype, called the Kinetic Mirror, a mirror that can not only mimic color but also shape in front of it. It builds upon the efforts performed in the field of projector-based augmented reality and natural design interfaces, and it showcases our ideas of future prototyping of design concepts. In comparison to manual prototyping or digital fabrication methods, deformative or shape changing solutions have the potential to reduce the time of physical prototyping to minutes or even seconds and inherently could open new avenues for developing shape changing products.

The mirror was intended as an interactive installation for inspiration that mimics and plays with the audience or object held in front of it, in dynamic shape changes and vivid colors. In the course of two years, we developed the mirror from concept to exhibition with the help of students in the Minor on advanced prototyping at Delft University of Technology. Here, we report of the development process consisting of prototyping and implementation and share our lessons learned and reflect on the implications for the various roles prototypes play in design research.

2. Related Work

Most of Today’s digital media is experience through 2D displays, which provide only a limited fidelity of the 3D virtual or remote environment that is portrait. A large body of work is involved in the design of display technologies that go beyond 2D depiction, such as 3D televisions and Head Mounted Displays with stereovision. In this paper we are interested in a specific type of such displays, those that provide rich 3D content that is part of the physical environment and so allow viewers to experience the virtual content in relation to their physical environment.

The related work is spans multiple disciplines and is categorized in four subsections: Spatial Augmented Reality (2.1), Shape changing objects (2.2), shape changing materials (2.3) and actuated mirrors (2.4).

2. 1. Spatial Augmented Reality

A number of related systems use projectors to augment physical objects with colored light. This technique, called "spatial augmented reality" or projection mapping is exemplified by the shader lamp system by Raskar [Raskar et al., 2001]. In shader lamp systems a virtual camera matches the properties of the physical projector. The system tracks the position and orientation of the physical objects and the projector projects a shaded virtual 3D copy on the objects. Vice versa, using a tracked physical brush, the objects can be colored and annotated with virtual paint. The underlying principles encompass projection, 3d tracking, and model manufacturing [Verlinden et al., 2006]. Various systems are presented for objects, rooms [Jones et al., 2013] but also for environments [Low and Raskar, 2001]. Saakes et al. [2012] introduced the concept of persistent augmented reality to bridge between visualization and fabrication. Using a laser projector they active bi-stable color changing material so that the object maintain color without the need for active projection. Despite the projection of dynamic digital media and visual trickery, augmented objects remain static and not malleable.

2. 2. Shape Changing Objects

Another body of work is in shape changing objects and is increasingly used in physical user interfaces both as input and output. [Rasmussen et al., 2012], such as the inflatable mouse by Kim et al. [2008] or the shape changing mobile phone [Hemmert et al., 2010] that alerts the users by changing shape and through active shape change allows for novel tangible interaction. These shape changing systems are rapidly developing in the field of soft robotics, using 3D printing in combination with pneumatics [Vázquez et al., 2015] or other types as actuation [Tibbits, 2014]. However, current abilities of these principles only allow limited degrees of freedom.

2. 3. Shape Changing Materials

A third body of work is into shape changing materials that can mimic shapes. For example, Jamsheets were sheets that can switch from mallaeble to stiff and can shape change to form furniture [Ou et al., 2014]. Several projector-based AR solutions have been presented that use deformative materials such as clay [Piper 2002], beads [Ratty, 2005], and thereby extend the natural interface to physical malleability by adding digital content.

For over a decade, automatic deformation tools have been explored, often labeled as actuated surfaces; through some kinematical structure, a surface is distorted in 3D. Within certain boundaries, this technique offers a direct coupling between physical and virtual geometry. One example is the Feelex apparatus [Iwata et al., 2001], which consists of a grid of small linear pneumatic actuators and sensors which establishes a 50 × 50 × 18 mm surface that serves as input and output. Leitinger et al. [2013] demonstrated a spatial display (2.5D) that used off-the-shelf motor faders as inexpensive linear actuators . In this setup, a color image was projected on top of the display.

2. 4. Actuated Mirrors

Daniel Rozin's work on mechanical mirrors encompasses several interactive installations of actuated elements that mimic color in front of the mirror. In his wooden mirror, servo motors were changing the orientation of wooden blocks, and alter the reflected light so a mirror image appears [Bodow, 1999]. Shape changing mirrors are found in low-tech pin screens consisting of an array of pins that slide in and out independently in a screen to create a three-dimensional relief [Flemming, 1987]. These displays have two sides: a negative and a positive. Our mirror was inspired on these pin screens and our design effort was driven to create an equally slim form-factor with a positive and negative.

3. Design

Our basic concept consisted of a mirror inspired by slim form factor of the pin screens with a positive and negative side. Each pixel was actuated to slide in and out of the mirror surface to form a 2.5D depth image colored by RGB LEDs. We aimed at sufficient resolution to make recognizable portrait in color and depth of people in front of it. The key challenge in designing the mirror was in finding a balance between cost, resolution, maintainability and complexity.

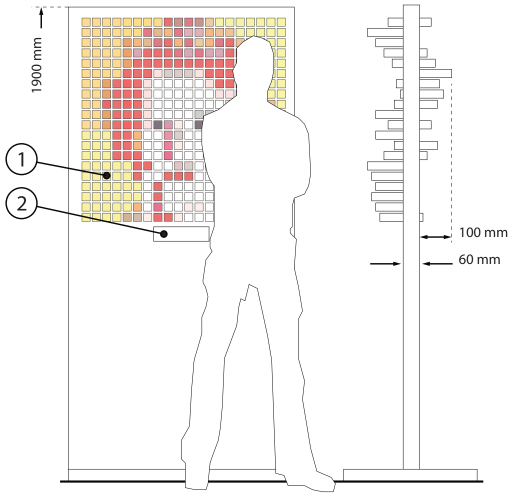

Figure 1 The basic design of the Kinetic Mirror. A grid of actuated pixels (1) mimics color and depth of objects and people in front of the mirror, using a time of flight depth camera (2).

Several electromechanical solutions were evaluated, and several ideas of actuating pixels were devised before settling on the use of commercially available motor faders as used in professional mixing tables. We found that the use of motor faders as an off-the-shelf component was the only way to achieve decent resolution within reasonable complexity that was feasible to be finished within our time frame.

Related works employing linear actuators make use of a transmission system from the linear actuator to a secondary sliding mechanism, to minimize spacing between "pixels" and minimizing "pixel size". For instance, Iwata et al. [2001] employed a linkage between a (rotational) servo motor and a sliding mechanism, to provide sufficient resolution for an actuated touch display. For a horizontal and small display this is possible, However in our case, vertical with a slim form factor, it is less feasible. We found an optimal trade-off by mounting the motor fader on the handle, thereby moving the fader instead of the handle, so that the fader itself would become the actual pixel. In this way, a pixel spacing of 40x40 millimeters could be achieved and 400 pixels fit in a mirror frame of 800x800mm as depicted in Figure 1. The thickness of the mirror could be less than 60mm and each pixel could move 150mm.

Using the considerations of a sufficient resolution and a slim form factor, tradeoffs for basic design was made and budgeted, and funding was acquired. We decided to embed the RGB LEDs only on one side to reduce costs.

4. Prototyping

Throughout the process we have build three intermediate prototypes to identify and address potential problems in performance and reliability, depicted in Figure 2. The first electromechanical prototype consisted a single actuated pixel (4.1), from there we went on with a column of pixels (4.2) towards a matrix of four by four pixels (4.3). These prototypes allowed us to focus the design and development effort. Parallel to developing the hardware prototypes we devised a modular software architecture that allowed content developers to work with a simulated display (4.4.1), and allowed the electrical engineers to test and drive the pixel display without the complexity of depth sensor (4.4.5).

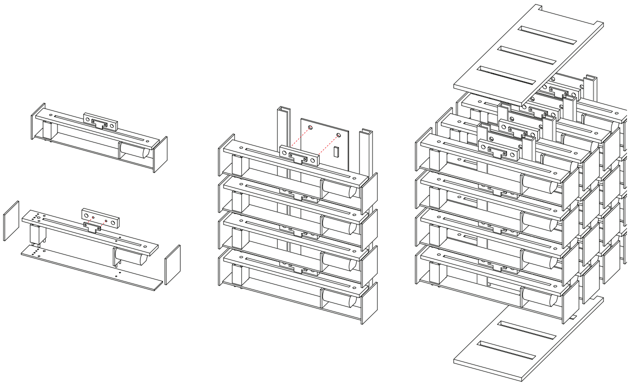

Figure 2 The prototyping process depicted. From left to right, the single pixel prototype, a column of four pixels, and 16 pixels securely mounted in a T–Slot frame.

4. 1. First Prototype: single pixel

The first prototype consisted of a single actuated pixel. This was necessary to test the intended mounting system of the pixels. Our design goals were to minimize the spacing between pixels and minimize the size of the construction, while keeping the design affordable and manageable. Similar to the prior art, we selected motor faders as a base component.

Each fader consists of a motor that drives a belt and a linear potentiometer that reports of the absolute position of the handle. As stated in Section 3, we "hang" pixels on the handle, so that the slider moves back and forth and not the handle. This mounting re-appropriates the use of the fader: reliability and wear had to be tested .

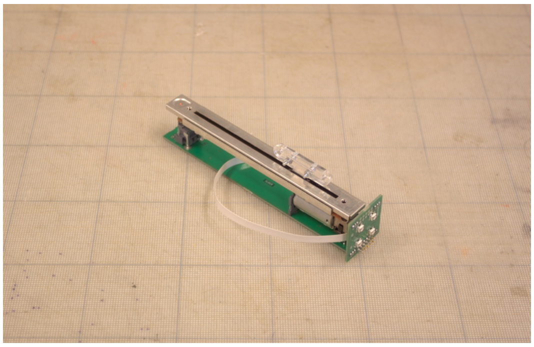

Figure 3 Single pixel prototype. The pixel is mounted on the slider with a transparent piece laser cut acrylic. A circuit board doubles as the structural component. A flexible ribbon cable connects the motor, potentiometer and LEDs to the structure.

Depicted in Figure 3, the single pixel prototype also allowed us to debug the electronics that drive the motor. We designed an analog control circuit to move the pixel to a specific depth. Since the objective was to drive 400 pixels, costs was a driving factor, we devised a simple analog control loop using op-amps driven by a low-cost microcontroller. The microcontroller's pulse width modulation output is compared to the slider value and motor is actuated accordingly. Using this analog approach, a single ATMEGA168PA-AU microcontroller with 4 analog input and 4 PWM outputs was able to control four pixels, and 100 nodes would comprise the complete mirror.

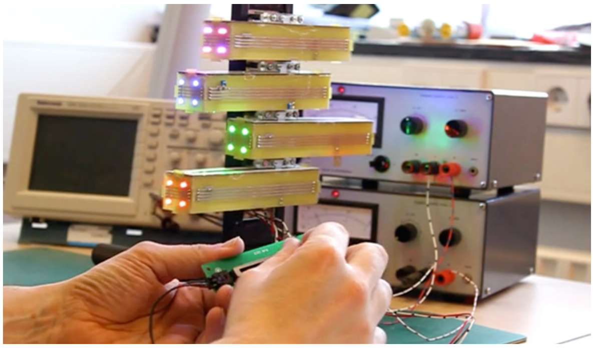

Figure 4 The four pixel prototype. The pixels are mounted on a circuit board and driven by a single Arduino. A slider connected to a PC is used to manually evaluate the responsiveness of the setup. This prototype was exposed to 96 hours of continuous operation to test durability.

4. 2. Second Prototype: four pixels

A second prototype was build to test a unit of 4 pixels. This prototype, shown in Figure 4, includes a PCB with the electronics that doubles as a mounting structure. This allowed us to determine the minimal spacing between the pixels and also the control system, as the unit of four was a single node of the network.

Here, we learned that the mounting of the handle to the PCB requires precision to make the pixels move parallel, and a laser-cut custom mounting part was devised. This second prototype was tested for several days to find potential problems in the mechanical construction.

At this stage we iterated through several methods to diffuse the led light to make an area of 40x40mm light up evenly. We discovered that a volumetric diffuser of the LED provides a very nice visuals when looking at the mirror from an angle. Iterations when designing complex systems allows to explore details that emerge during building. These details cannot be fully anticipated or understood without a working prototype, and allowing these design changes is an key aspect of the art and craft of prototyping.

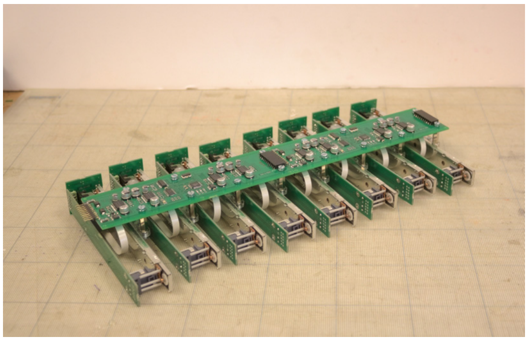

Figure 5 Two 4 pixel boards connected to form a column. The column of circuit boards would be sandwiched between two aluminum profiles for structural rigidity.

4. 3. Third Prototype: four by four pixels

Based on the second prototype we finalized the design, shown in Figure 5, by connecting PCB's with connectors and clamping the sides in a aluminum profile to dampen the kinematic forces. A third prototype included four nodes in a network, a sixteen pixel mirror arranged in a four by four grid as shown in Figure 6. This allowed us to check how to mount columns of pixels and optimize the system for assembly per column. We made laser cut holders for the aluminum profile, completed with a cube structure made with a T Slot aluminum and firmly mounted on a stone base. This complete system, allowed us to implement the cabling of power and data, entailing a bus system to communicate with the microcontrollers

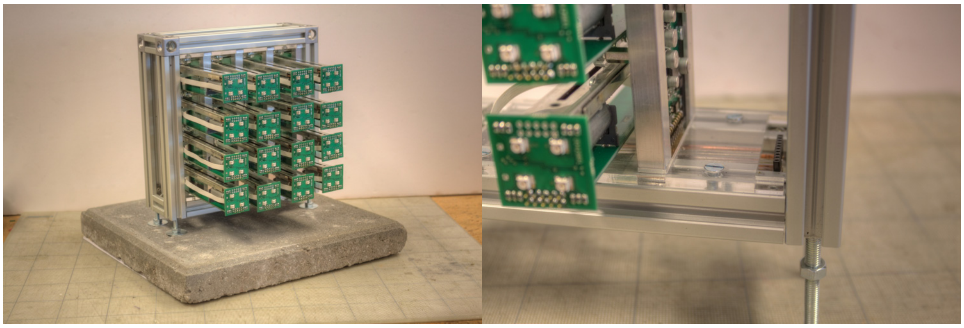

Figure 6 The sixteen pixel prototype. Four columns of pixels are mounted in a t-slot frame and firmly grounded on a block of concrete for aesthetic purposes. On the right, a detail view that shows the mounting of the columns. Each circuit board is sandwiched between two aluminum profiles and clamped into a acrylic support structure (transparent).

This prototype provided valuable insights in the power consumption of the system and also the forces that the system generates when protruding all pixels at once. Staggering approaches were considered to lower the power and stability requirements. Although having less pixels, the complete system was implemented from capturing the 3D environment to actuating the pixels accordingly. A bus system was devised to drive the pixels, and a simple protocol send the RGB color information as well as the depth. This prototype provided sufficient information to split the further development in a content generation with on-screen visualization and a hardware development, making the design ready for scaling up manufacturing.

4. 4. Software Prototype

The software is split into two parts connect through a TCP data stream, as depicted in Figure 7. A front-end application manages the content generation while a back-end drives the actual pixels. Separating these two has several advantages. First, it allows design students to use several interactive environments to generate content; a dummy back-end was developed that visualized the output on screen to test and debug content generation. Second, it allows concurrent development across multiple teams.

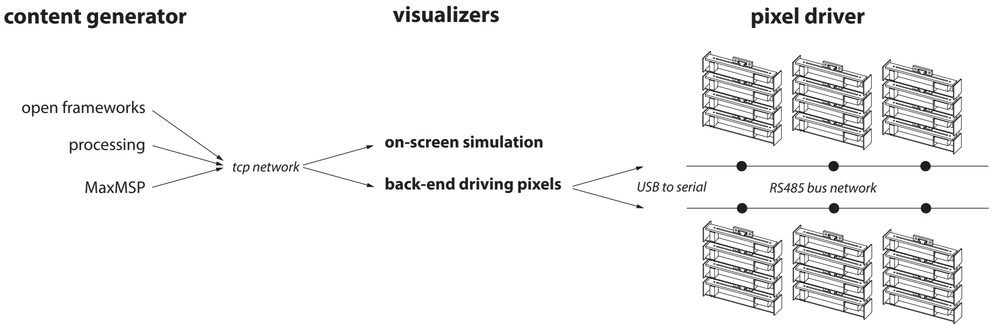

Figure 7 The modular software setup. Content generation is separated from the back–end that drives the pixels in the mirror and can be developed prior to and concurrend with the development of the back–end

4. 4. 1. Front–end Application

A “mirror” front-end was developed in Open Frameworks using Microsoft Kinect version 1, which captures both color and depth information; it employs structured light through an infrared projector that projects a pattern in front of an infrared camera and by means of image-based 3D reconstruction the depth of each pixel is established [Zhang, 2012]. A second camera captures color, if both depth and color camera feeds are aligned and combined, they produce a colored point cloud, also known as a RGBD stream. A simple mapping was implemented through partitioning the point cloud in a grid according to the physical dimensions of the mirror in order to estimate color and protrusion of each pixel. In that way the mirror mimics the color and depth of objects in front of it, as shown in Figure 8.

Several mappings and visualizations are imaginable. For instance motion filters with a slow decay could show artificial motion blur, other programs could implement set and release mechanism to support painting with depth and color. We also considered abstract representations of the space in front of the mirror such as histograms.

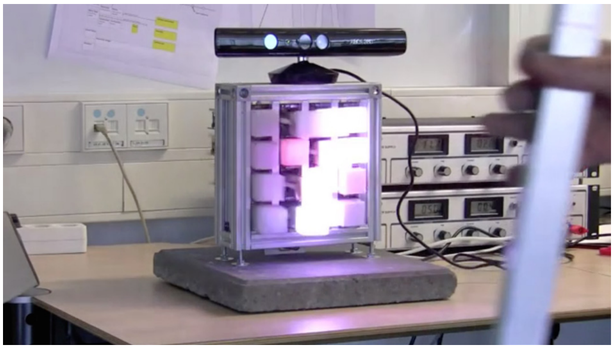

Figure 8 The software in action with the sixteen pixel prototype. A vertical metal bar is moved in front of the mirror, and the mirror takes the shape and color.

The pixel data was packaged into a dense format and send over TCP to the backend that reduced the complexity of streaming content to the mirror. Since TCP communication is a common denominator in networks, content could be written in several design and artist content creation tools such as openframeworks, processing and MAX/MSP.

4. 4. 2. Backend

The task of the back-end software is to visualize the RGBD data received from the TCP socket. We prototyped two back-ends: i) for on-screen visualization to simulate the mirror before the final embodiment was realized, and ii) a back-end to drive the actual mirror and to route the position and color to one or multiple UART networks with the microcontrollers.

We selected the RS 485 bus network to connect all the pixel boards, based on a workstation with a USB to UART ftdi connector. Each boards was assigned a unique address stored in the permanent memory (EEPROM) on the microcontroller. A packet protocol was implemented to address a single board and set the position and color or to update the firmware. Because of the modular setup, in case of low framerate, we could split the network using multiple USB to UART drivers.

When implementing the sixteen prototype, it became clear that the mapping of the unique id to the position XY in the frame would cause a logistic problem when assembling the mirror or replacing boards when maintaining the mirror. Therefore we devised a interactive solution for mapping pixel board ID to a position on the mirror.

4. 5. Key Insights From the Prototypes

Whereas in prototyping and implementing a single object, a prototype electronics on a matrix board would be feasible, when dealing with 100 boards with microcontrollers and 2x400 boards for the pixel and LED it becomes an impossible task and outsourcing is required. The extensive prototyping proved necessary strategy to make sure that the implementation would be successful.

Making use of standard and well-proven protocols while understanding the limitations was essential to avoid reinventing the wheel. A few months prior to developing the mirror, colleagues that build an interactive floor of 100 tiles with microcontrollers, misunderstood a network protocol. Although their prototypes were working fine on their desktop, they didn't take into account that the distances between floor tiles and the length of the cables were not supported by technologies intended for on motherboard communication. Having a multidisciplinary team and that one of the authors has a background in analog electronics was key to a success implementation.

Using PCB both for electrical and structural purposes proved to be a good approach to minimize assembly time and to avoid additional components such as connectors and fasteners.

We did not foresee the power consumption that 400 motors and 1600 LED would require, and a staggered actuation was devised. Also the impact force of 400 pixels moving forward could potentially tip over the mirror.

5. Final Embodiment

We devised the final 400 pixel version based on the same construction principles as the sixteen pixel prototype: an extrusion frame with laser cut acrylic planes to clamp the pixel subassemblies as specified in Section 4.3, resulting in a structure of 25 columns consisting of 16 pixels each. The challenges to overcome were the PCB production process, assembly, and software tuning.

5. 1. PCB Production Process

We outsourced manufacturing of the PCBs - including components and firmware- to a known electronic partner in China. Although this significantly deceased production cost, the procurement and quality testing phases suffered from delays in subcontracting: the communication trail spanned exactly 10 months from initial contact to final payment, a complete overview is provided in the Table below.

Table 1 PCB outsourcing

Activity	Duration (months)	Communication mode	Challenges
Quotation	1	Email	
Design specification & production planning	2	Skype & email	Initial payment Delay in component delivery (LEDs)
First prototype	1	Email + courier	Wrong component (resonator) & fuses
Revised prototype	2	Phone, Email + courier	pass
Production	2	Email	Chinese newyear
Delivery	1	Email + courier	Loose components
Replacement delivery	1	Email + courier	
Total	10 months		

Of the challenges that we faced, the initial payment merely entailed internal bookkeeping for intercontinental money transfers. The production planning was held up due to limited availability of the RGB LEDS, while the first prototype seemed to work out of the box: it passed the internal test procedure that we built into the firmware when powered on. However, the systems could not communicate with the PC through the RS 485 bus, which was due to the fact that the manufacturer had selected a different resonator – the component that generates clock pulses. Together with the electronic partner, we decided that to first demand a functional prototype before ramping up production. Although this added significant delay to the process (including seasonal holidays), this proved to be the right decision and 8 months after the initial contact we received the large collection of motherboards and pixels.

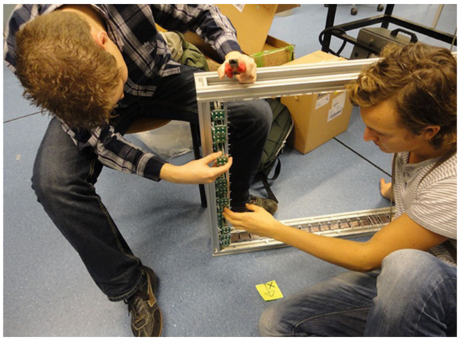

Figure 9 Assembling a row of pixels in the frame.

5. 2. Assembly

Assembly of the PCBs encompassed the soldering of the individual PCBs to pixel constructions, connecting these to the motherboard PCBs and assembling the complete display. The volume of this task called for working in parallel, supported by molds to ensure angle of the PCBs during soldering and by intermediate mechanical and electrical tests to validate the subassemblies. The student teams involved in this endeavor designed the extrusion frame based on the 16-pixel prototype, with enlarged extrusion profiles (4 cm instead of 2 cm of the prototype), shown in Figure 9. However, due to the delay in the delivery of the PCB's, one of the student groups were stranded and could only work on the structural engineering – by creating finite element simulations to determine static and dynamic forces (moment and impulse). The second team started when all parts were just delivered and had a articulated hands-on approach towards the embodiment design, selecting materials and components that were at hand at the workshop; this worked successfully and this particular multidisciplinary team (including electrical engineer, aerospace design, industrial design) could balance the work between optimization of the assembly process (e.g. creating molds for soldering, part testing procedures), improvement to the final prototype (part consolidation) and manual labor.

During the course of the assembly, we measured the overall power consumption for per column of 16 pixels – per pixel 5 Volts: 0.15 Ampere (mainly for the RGB LED) and 12 Volt: 0.17 Ampere (the motor). To power the total structure, we split the electric supply in half: 30 amperes for both 5 and 12 volt for 200 pixels. In terms of part consolidation, the students simplified the light diffuser design: originally part thermoformed plastic screwed to a metal clip to a planar cut plastic foam, mounted on the pixel PCB with double-sticking tape. The other significant improvement was the fixture of the motor fader to the motherboard PCB: by devising a sandwich structure, only 2 screw mounts per pixel remained (instead of 4 smaller ones, requiring drilling and deburring of the motor fader and related plastic structure).

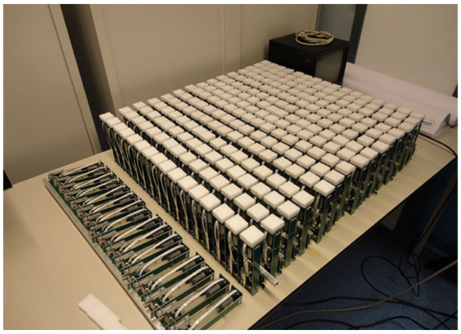

Figure 10 All 400 pixels assembled and equipped with diffuser.

Both student teams expressed that they learned a lot, yet the second team was much happier and motivated during the hands-on challenge they faced – which resulted in a complete and working prototype. For academic students, they had the rare opportunity to construct and improve a large mechatronic system, which required scrupulous and teamwork.

5. 3. Software Tuning

It took approximately 1 man month to tune the prototype after the electro-mechanical system was ready, shown in Figure 11. This initially encompassed programming and mapping the addresses of the pixels, and later on focused on communication bandwidth of the RS 485 serial bus. Finally, the mapping of the Kinect field of view and resolution depth and color images to the pixels was tuned to create a 1:1 size mirror; the depth image was enlarged to 1:2 to improve the perceived spatial effect.

6. Evaluation during Exhibits

We pursued exhibiting the system: enabling a confrontation beyond a short demonstration to the academic community. Situations with unbiased audiences provide a better reasoning platform to consider the envisioned experience of the design (Koskinen et al., 2011). Apart from verifying the robustness of the software, power consumption, and electro-mechanical behavior this allowed optimization of the mirror effect. For example, when no one was in front of the Kinect camera, it would not attract audiences, as the display was not moving. We countered this by including a screen saver mode, which would play back the last minute of the depth image when inactivity was detected.

The system has been on exhibit in five different locations, each ranging between 2 days to 2 weeks of opening time. In general, the user responses were positive. We observed two different types of audience responses: i) fully engaged with the embodied system, in which the system is perceived a kinesthetic mirror of the user (Figure 12, dancing, juming, moving back and forth), ii) conversing with others on making sense of the system and its implications.

Figure 12 400 pixels assembled and with diffuser.

The robustness of the system was suboptimal, in particular the tolerance of the aluminum U-profiles for clamping the PCBs was 2 millimeters off, which didn't prove to be an issue in local transportation but in one occasion the pixel assembly collapsed during transport by car. This required re-assembly and re-programming of the module addresses (2 additional man days). Furthermore, after 4 days of continuous operation, one of the pixels loosened. The exhibit operator did shut the system down as a precaution, whilst this was unnecessary as the remainder of the system worked appropriately.

7. Conclusions and Reflections

Demonstration and prototypes are an increasingly important medium to disseminate design knowledge, because experience can only partly conveyed in written text or even in video. However, if products become dynamic, articulated and with behavior, the technological requirements of prototypes become more complex,.Today's prototypes are often combinations of software and hardware with embedded systems communicating with PC based software and might interact over the internet. As a result, prototypes harder to maintain

The emergence of digital fabrication and software toolkits targeted at designers empower future designers tand engage them in the manufacturing and prototyping of complicated cyber-physical systems. However, a common platform for documenting prototypes does not exist yet. Several online systems exist for sharing and collaborating on specific parts that make up a prototype. For designing physical objects, thingiverse or youimagine are repositories for sharing 3D model data. For software codevelopment, platforms such as github, or Scratch aimed at young designers, and general techniques are shared on instructables. To make design curricula fit for the future, these platforms and mechanics need to be addressed while prototyping.

As prototypes are frequently the result of exploration, the cumulative results of ad-hoc decisions and hacking to simply make it work within a tight deadline, it can be seen as craft, where the form of the product is determined by the creator at the time of creation. As often manifested in agile development processes, there is little need to fully document the workings and document decisions in order to produce repeatable design, because the demonstration typically has a short live span, only during a video, and only during a presentation [Mulder et al., 2014]. When designing for durable installations, that need to run for months, maintenance becomes an issue and requires a design approach in which parts are fully documented and tested before creation. Maintaining the environment and dealing with new versions of software, complicated setup procedures, makes it unlikely to survive without continued care of the creator. When working in an academic environment with makers only present for a short period of time, this issue of keeping demos alive becomes more apparent. In this project we set out with a clearly defined vision and here we attempted to provide a comprehensive report on decision making processes.

Acknowledgements
The project was funded by a Research Initiatives grant by Industrial Design Engineering in Delft.
The following students have contributed to the calculation, consolidation and assembly of the final prototype: Nick Noordam, Bas Linssen, Jitender Pritipalsingh, Mauricio Sandoval Martinez, Bjorn Luik, Simon Gamme, Christiaan Karsen, Jaap Sybenga and ManWai Shing.

References

1 Bodow, S. (1999). *Wooden expression.* Wired Magazine.

2 Fleming, W. (1987). *U.S. Patent No. 4,654,989.* Washington, DC: U.S. Patent and Trademark Office.

3 Hemmert, F., Hamann, S., Löwe, M., Wohlauf, A., & Joost, G. (2010, January). Shape-changing mobiles: tapering in one-dimensional deformational displays in mobile phones . In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction* (pp. 249-252). ACM.

4 Iwata, H., Yano, H., Nakaizumi, F., & Kawamura, R. (2001, August). Project FEELEX: adding haptic surface to graphics. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques* (pp. 469-476). ACM.

5 Jones, B. R., Benko, H., Ofek, E., & Wilson, A. D. (2013, April). IllumiRoom: peripheral projected illusions for interactive experiences. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 869-878). ACM.

6 Kelly, T., & Littman, J. (2002). The art of innovation: lessons in creativity from IDEO. *NEW. ARCHITECT, 7*(6), 52-53.

7 Kim, S., Kim, H., Lee, B., Nam, T. J., & Lee, W. (2008, April). Inflatable mouse: volume-adjustable mouse with air-pressure-sensitive input and haptic feedback. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 211-224). ACM.

8 Koskinen, I., Zimmerman, J., Binder, T., Redstrom, J., & Wensveen, S. (2011). *Design research through practice: From the lab, field, and showroom.* Elsevier.

9 Leithinger, D., Follmer, S., Olwal, A., Luescher, S., Hogge, A., Lee, J., & Ishii, H. (2013, April). Sublimate: state-changing virtual and physical rendering to augment interaction with shape displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 1441-1450). ACM.

10 Mulder, F. A., Verlinden, J. C., & Maruyama, T. (2014, May). Adapting scrum development method for the development of cyber-physical systems. In *Proceedings of the 10th international symposium on tools and methods of competitive engineering TMCE 2014,* Budapest, Hungary, May 19-23, 2014.. TMCE.

11 Ou, J., Yao, L., Tauber, D., Steimle, J., Niiyama, R., & Ishii, H. (2014, February). jamSheets: thin interfaces with tunable stiffness enabled by layer jamming. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction* (pp. 65-72). ACM.

12 Piper, B., Ratti, C., & Ishii, H. (2002, April). Illuminating clay: a 3-D tangible interface for landscape

analysis. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 355–362). ACM.

13 Raskar, R., & Low, K. L. (2001, November). Interacting with spatially augmented reality. In *Proceedings of the 1st international conference on Computer graphics, virtual reality and visualisation* (pp. 101–108). ACM.

14 Raskar, R., Welch, G., Low, K. L., & Bandyopadhyay, D. (2001). *Shader lamps: Animating real objects with image-based illumination* (pp. 89–102). Springer Vienna.

15 Rasmussen, M. K., Pedersen, E. W., Petersen, M. G., & Hornbæk, K. (2012, May). Shape-changing interfaces: a review of the design space and open research questions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 735–744). ACM.

16 Ratti, C., Wang, Y., Piper, B., Ishii, H., & Biderman, A. (2004, August). PHOXEL-SPACE: an interface for exploring volumetric data with physical voxels. In *Proceedings of the 5th conference on Designing interactive systems: processes, practices, methods, and techniques* (pp. 289–296). ACM.

17 Saakes, D., Inami, M., Igarashi, T., Koizumi, N., & Raskar, R. (2012, August). Shader printer. In *ACM SIGGRAPH 2012 Emerging Technologies* (p. 18). ACM.

18 Tibbits, S. (2014). 4D Printing: Multi-Material Shape Change. *Architectural Design, 84*(1), 116–121.

19 Vázquez, M., Brockmeyer, E., Desai, R., Harrison, C., & Hudson, S. E. (2015, April). 3D Printing Pneumatic Device Controls with Variable Activation Force Capabilities. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (pp. 1295–1304). ACM.

20 Verlinden, J., Horváth, I., & Edelenbos, E. (2006). Treatise of technologies for interactive augmented prototyping. *Proceedings of Tools and Methods of Competitive Engineering* (TMCE), 523–536.

21 Zhang, Z. (2012). Microsoft kinect sensor and its effect. *MultiMedia, IEEE, 19*(2), 4–10.