Prototypes as Embodied Computation

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Abstract The development of computational constructs that span the physical and digital realm opens up a new domain referred to here as embodied computation, a term introduced in my research at Princeton University. The role of prototyping is shifting from that of the confirmation of design assumptions in the early design stages to that of the embodiment of a design idea deployed into the world at large and continuously tested and updated digitally and if necessary physically throughout its lifetime. Feedback and control based on sensors and network-based information is enabling relatively simple mechanical structures to perform a wider range of tasks. There is a shift from mechanical complexity towards algorithmic complexity resultant from this change in many areas. In this article a number of prototypes are discussed in developing the concept of embodied computation through material and actuated constructs.

1 Introduction

The development of computational constructs that span the physical and digital realm opens up a new domain referred to here as embodied computation, a term introduced in my research at Princeton University (Johns et al. 2014). The role of prototyping is shifting from that of the confirmation of design assumptions in the early design stages to that of the embodiment of a design idea deployed into the world at large and continuously tested and updated digitally and if necessary physically throughout its lifetime. Feedback and control systems based on sensors and network information are enabling relatively simple mechanical structures to adapt to a wide range of situations (Mueller and D'Andrea 2012). Underlying this change is a shift from mechanical complexity towards algorithmic complexity that is observable in many areas from the long established fly by wire concept in aircraft

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design to more recent consumer products, such as smartphones. Yet the implication of these possibilities for more varied programs and forms such as architecture and engineering structures are less clear (Kilian 2006a). This article focuses on a range of computational factors in the exploration of design in small to medium design artifacts—in design, architecture, and engineering—and how the notion of the prototype is evolving and assuming different forms depending on the design challenge (Kilian 2006a). In this article, a number of prototypes are discussed with respect to developing the concept of embodied computation through material and actuated constructs.

Prototyping can be found throughout the design process; here I would like to focus on its role in different types of design exploration. Three different types of design exploration will be discussed: (1) the fine tuning of a design construct that incorporates known design parameters, (2) the creation of a new design definition in experimental prototype iterations and (3) the discovery of novel design constellations in a constraint solver based software (Kilian 2006a).

In a design process, every new design state is prototypical; it tests the further specification of a design idea in a new rendition, in a new medium and in greater detail. Also with increasing fidelity of design tools such as CAD software and rapid prototyping, the meaning of prototyping increasingly shifts to the further specification of the design and less so its traditional physically based role of design testing.

The design development as the formation of an idea in stages, through the translations from one implementation to the next, translating an idea into a different medium such as a sketch, then a text, then into geometry, then a physical construct and finally into a functional evaluation. Each translation opens up apparent gaps in the process and requires some of these gaps to be filled in order to accomplish the translation. Prototypes play a crucial role in this process, both as physical and algorithmic constructs and any combination thereof. Next, in greater detail, we discuss a number of these design explorations through prototypes.

2 Case Studies

Assembly Based Form, Prototyping as a Fine Tuning Exercise—The Plywood Chair The chair experiment (Kilian 2006a, b) was developed to demonstrate the possibility to create a plywood assembly from flat sheet, laser cut parts that achieve their curved state through cold bent spring loading during assembly, without glue or fasteners. To achieve this completion of the form through material based computation, the material response was tested through a series of fine tuning prototypes and the translation of the design intent into parametric proportionally flexible geometric models that represent and implement the desired curvature in a relational computational constructs. Those geometric constructs specified the laser cutting geometry, which then through spring loaded assembly of the parts induces the cold deformed curvature of the parts in the final chair. The creation of the chair is only possible

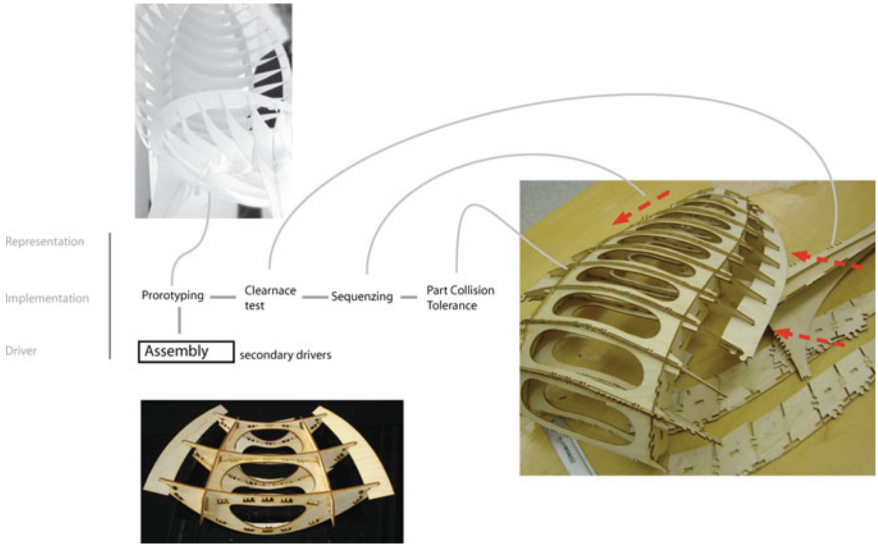

Fig. 1 Prototype series bent plywood assembly. © "Collection FRAC Centre, Orléans", (Kilian 2006a)

through the combination of geometric instruction sets generating the fabrication paths and the physical interaction and deformation of the material pieces to induce the final shape during assembly. Although the deformation is represented geometrically and implemented through NURBS surfaces, the final form is determined by the material interaction and the interaction of the assembly parts (Figs. 1 and 2).

The material behavior and tolerance parameter were explored through a number of prototypes of increasing complexity up to the full implementation, all based on an evolving CATIA parametric model. The translation of the intention into an assembly-based model occurred through a number of implementation and representation steps that were fine-tuned through physical prototypes. The resulting parametric model allows for the proportion and relational variation of all parts and through visual feedback the confirmation of the state of the model.

The adjustment of the parametric model allows for the regeneration of all joints and assemblies to create another chair geometry with different proportions. Successful outcomes are not guaranteed for all settings in this stage of the development and the two full prototypes created still exhibited detail flaws and are not reliable structurally overall, which would limit actual use. Here, however, the focus of the exploration was on the material formal interaction for an assembly test in a chair dimension. More development iterations would be necessary to achieve an everyday, usable chair.

Sequential Prototyping for Design Definition—Concept Car Exploration In this design exploration, the prototype played the role of defining the design space itself iteratively through the expansion of the design criteria with each successive

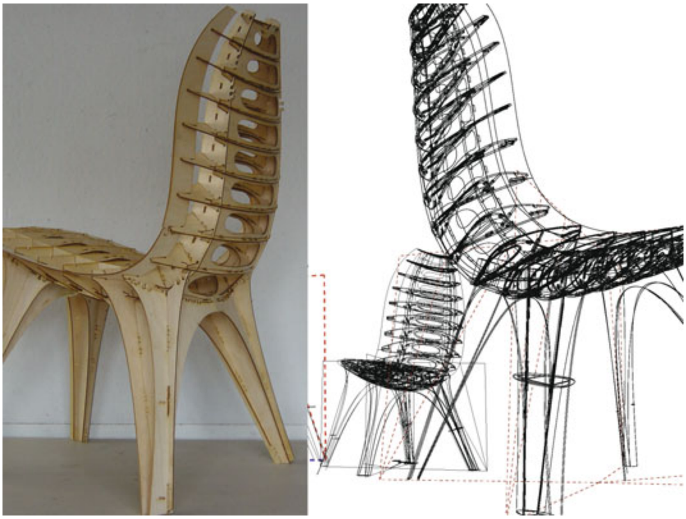

Fig. 2 Physical material based spring-loaded state versus geometric construct. © "Collection FRAC Centre, Orléans", (Kilian 2006a)

prototype. The evolution of the understanding of the design task is reflected in the prototype series. The embodiment of the design idea is also developed in the integration of actuation mechanisms that expand the design space, from the formal criteria to that of movement and flexible enclosures. Ultimately, the design cumulates in an exoskeleton-like extension of the body and was tested in a selective physical prototype that was an implementation of a selection of key components in a testable test rig with a meaningful interplay of features (Kilian 2006b).

The Prototype as an Idea-Defining Iteration Another use of prototyping is the establishment of a new design approach and test the effect of the partial implementation in a deployed scenario. The prototyping cycles then can lead to a successively more refined definition of the design task informed by the insights gained from the partial prototypes along the way. This process is well established but here the emphasis is explicitly on the exploration of a design idea through partial prototypes (Fig. 3).

The question of how to generate novel instances for an established design space could be approached through the development of a design language. In this case, the starting set was a set of writing devices that are analyzed for shared traits, such as the material used to leave a trace, how the handling is done and how the material is transported to leave a trace. A series of questions were developed as a starting point for the creation of a new instance from the common features identified in the analysis. This is an example of a very simplistic design and not representative of the open-endedness and complexity of larger architectural projects, but the study is a reminder that little progress has been made in the development of computational support in the concept forming stages of design. Most advances are situated in the

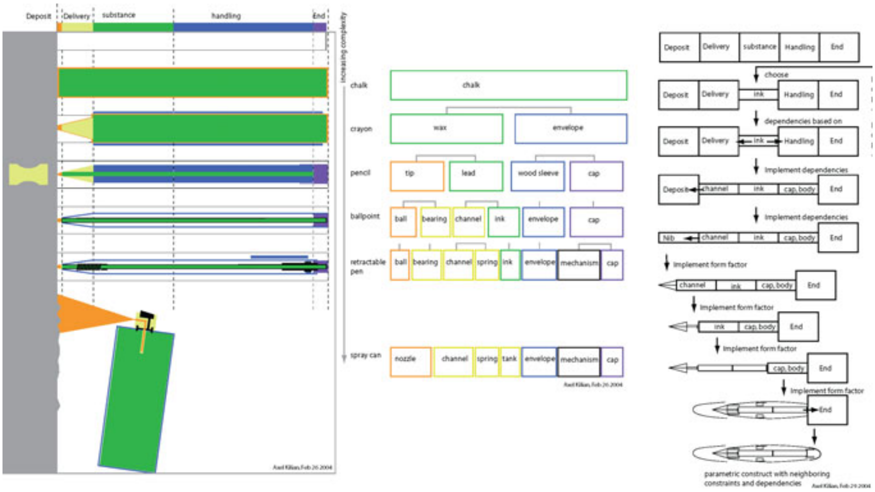

Fig. 3 Prototyping an idea process (Kilian 2006a)

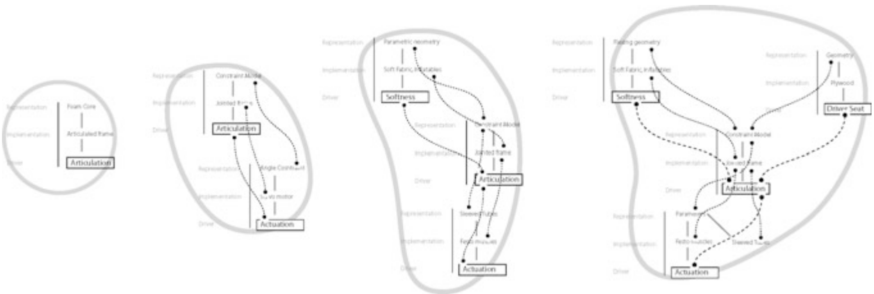

Fig. 4 Expanding design definition through prototypes (Kilian 2006a)

geometry management portion and the fabrication part of the design process. The following example of a concept car study conducted by the author with the William J. Mitchell smart cities group at the MIT Media lab (Kilian 2006a).

The design scope expands with each prototyping iteration and the definition of the design is becoming more detailed (Fig. 4). Here, prototyping is the successive definition of the design idea, not just its confirmation. The series of design studies are used to identify additional design features that are then added in the next iteration, beginning with an articulated chassis, as illustrated in Fig. 5. The degrees of chassis freedom demonstrate the obvious need for actuation, which comprises the first addition (Fig. 5).

The manual movement of the articulated chassis allowed the testing of the range of motions and the next iteration added several degrees of freedom, which no longer made it possible to control all six degrees of freedom simultaneously. The need for

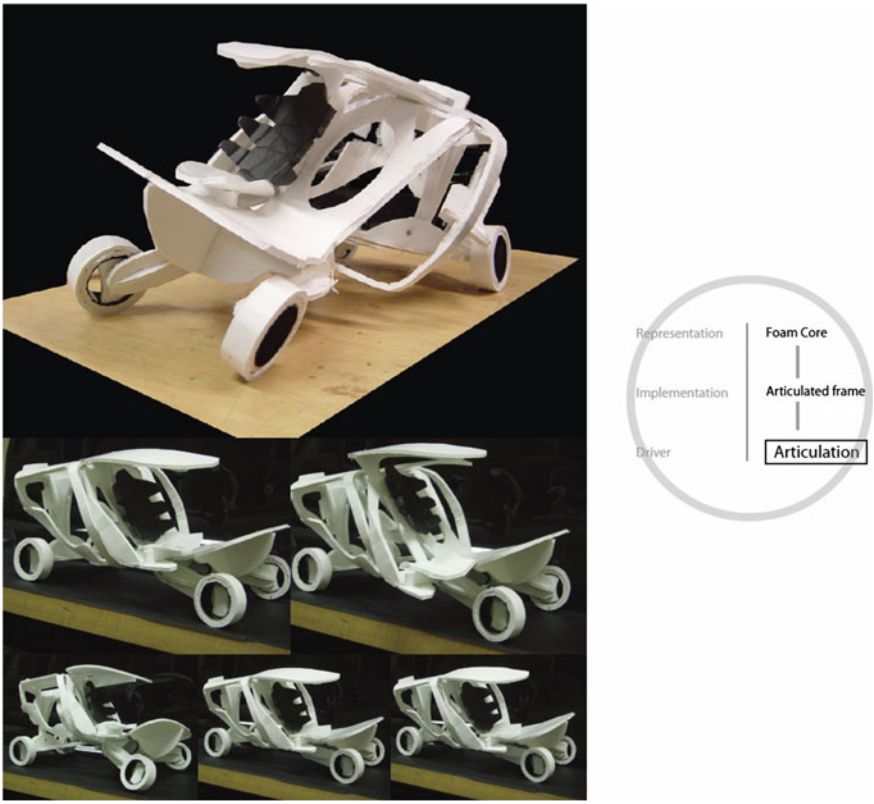

Fig. 5 An articulated frame as the starting point of a concept car exploration (Kilian 2006a)

simultaneous control triggered the introduction of servos and a micro controller to coordinate the range of motion and allow for design iterations through programming the controller and exercising the physical impact (Fig. 6).

Adding actuation to the chassis expands the design space with the movement choreography of an articulated body. Programming movement patterns allow for the exploration of the design space of motion as design expression. The insights gained from the six degrees of freedom test lead to the addition of two more degrees of freedom and a stiffer chassis in the form of an aluminum waterjet cut assembly (Kilian 2006a) (Fig. 7).

The next iteration included the development of the human machine interface in the form of an exoskeleton seat that snaps on the human body and maps the human motion onto the car chassis. The construct becomes a wearable extension of the body, covered in a soft adjustable skin and held together by a skeleton-like chassis with pneumatic actuators. A full-scale selective prototype was developed in order to make it possible to experience the concept physically and develop the interplay of parts. The idea of a selective prototype is to include all crucial elements in a

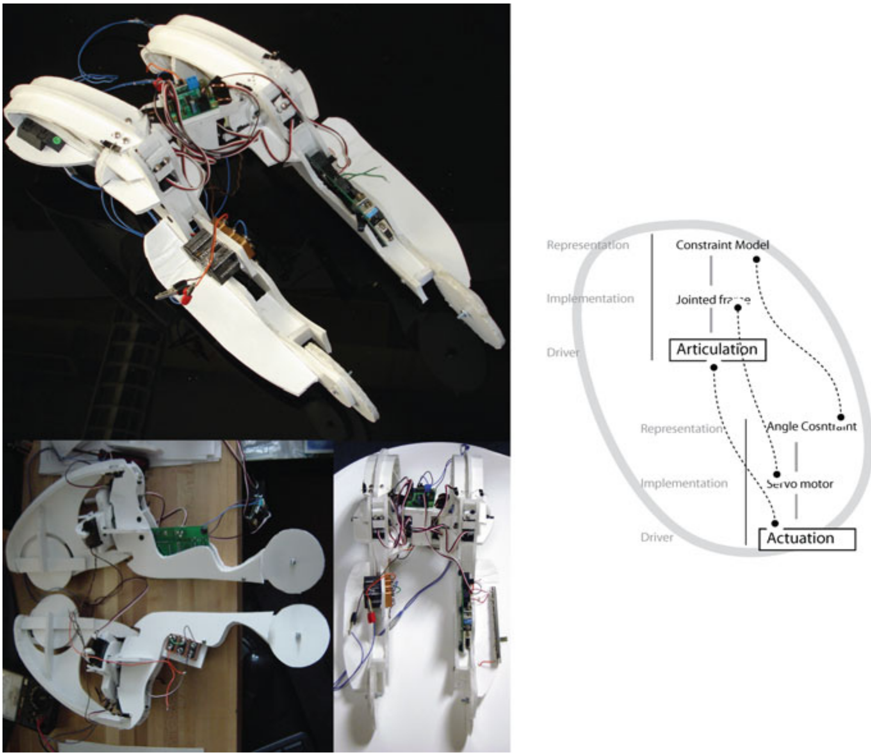

Fig. 6 A microcontroller servo actuated frame for movement prototyping (Kilian 2006a)

meaningful constellation, but at reduced complexity, in order to manage the cost and scope of construction while still allowing for the experience of the effect. Figure 8 shows the design iterations through progressively more detailed and designed physical iterations, from cardboard to milled foam to carbon fiber construct.

The full scale selective prototype shows the final design by the author with bent plywood seat as implemented by Patrik Künzler and Enrique Garcia, along with the carbon fiber integrated suspension wheel by Peter Schmitt and chassis by the author and Peter Schmitt (Fig. 9).

Prototyping Interdependencies—Form-Finding Application for Design Discovery When the prototype becomes a programmed construct, it can function as a dependency prototype that allows for the exploration and discovery of novel design solutions within a defined set of constraints. In this case, the example is that of a form-finding hanging chain modeler that enables the user to set up the connection topology and the rest length of the geometry as well as material resistance in form of the spring constant. Simulated gravity then acts on the particle mass to move the geometry incrementally towards an equilibrium state. With respect to the form-finding application, these are states of equilibrium (Kilian and Ochsendorf 2005). Part of

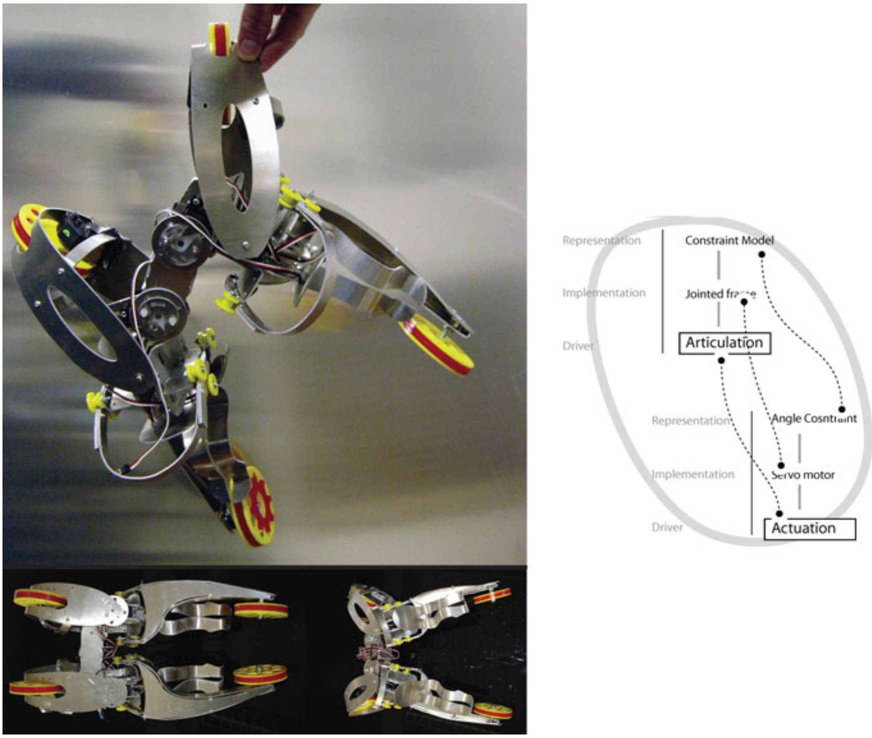

Fig. 7 Further development of the actuated frame with eight degrees of freedom (Kilian 2006a)

Fig. 8 Prototype iteration through increased fabrication precision and parallel design refinement (Kilian 2006a)

design shifts from a descriptive and generative operation of the intent into the playing of the relational construct more like an instrument in order to discover novel design constellations. In its extension, the form-finding becomes the steering of form, an

Fig. 9 Final selective prototype in carbon fiber, Axel Kilian, Peter Schmitt, Patrik Künzler, Enrique Garcia (Kilian 2006a)

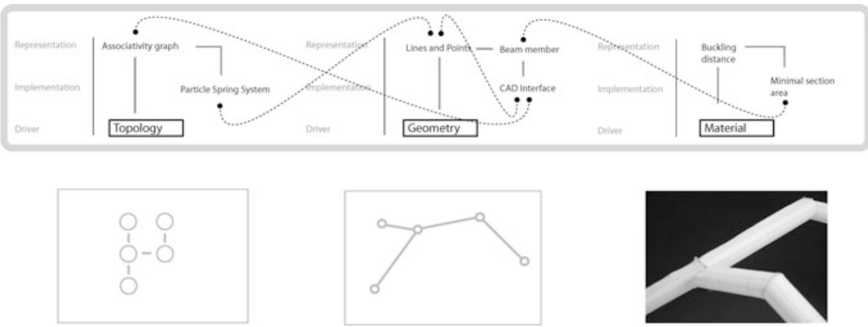

Fig. 10 Dependencies diagram of constraint prototype by programming (Kilian 2006a)

approach that embraces the open-ended nature of the definition of the dependencies as the design exploration unfolds, encouraging potentially competing factors to be leveraged against each other within the same set of constraints. For instance, in the force equilibrium example, this can mean extending the freely linked chain model that is purely in tension with moment-actuated joints to enable moment resistant sections as well. And more generally speaking, the design approach is the interplay between creating design constraints and exercising those constraints for exploring the design possibilities within the remaining degrees of freedom that still fulfill the desired dependencies (Fig. 10).

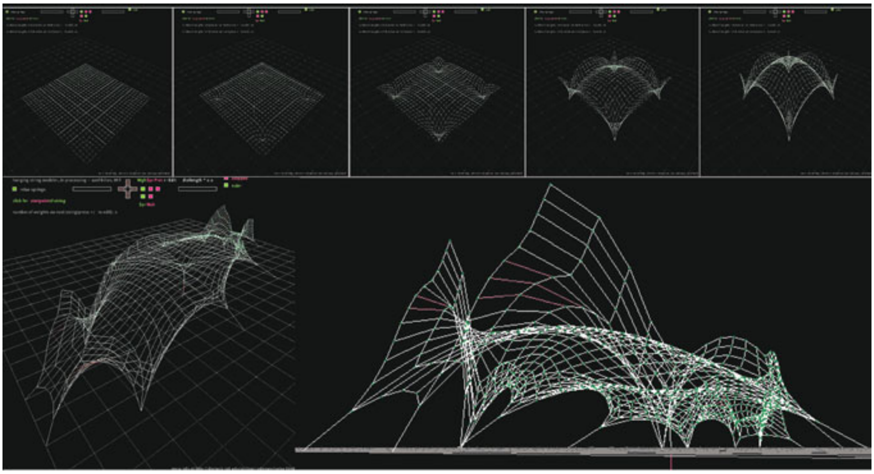

Fig. 11 Design process sketch in an equilibrium based form-finding tool (Kilian 2006a)

Design extends from descriptive geometry modeling to system modeling and the exercising of that constraint system. This challenges the notion of the design process because the interplay of design factors changes the setup and evaluation criteria of the process with different criteria, such as a state of equilibrium, compete with more established selection criteria, such as aesthetics (Fig. 11).

Embodied Computation Prototype—Active Bending Bow Tower Example A sensor-equipped and actuated structure serves as a small-scale test platform for exploring the range of posture changes that an active bending-based actuated tower can take. The goal is to develop a vocabulary of actuations to resist external forces and also use movement and shape change for design expression. Ultimately, this approach enables extending the prototype phase into the deployed design as it is possible to continuously update programmed behavior and, more importantly, to learn from the structure's environment (Fig. 12).

In smart phones and computers, the continued software update of devices is already part of the everyday cycle of product use and development. In the automotive sector, Tesla has repeatedly remotely updated the features and capabilities of their customer-owned cars by means of software updates. Due to their relative longevity, individual buildings and cities are promising candidates for retrofits of feedback and control systems to enable a more flexible response both to local and global changes. This is currently occurring already on a small-scale in networked climate-control systems, but it is certainly possible to imagine this approach extending into changing architectural programs and flexible, short-term use of existing structures. As the majority of the built environment will remain, retrofitting buildings and infrastructure (wherever possible) with feedback and control abilities

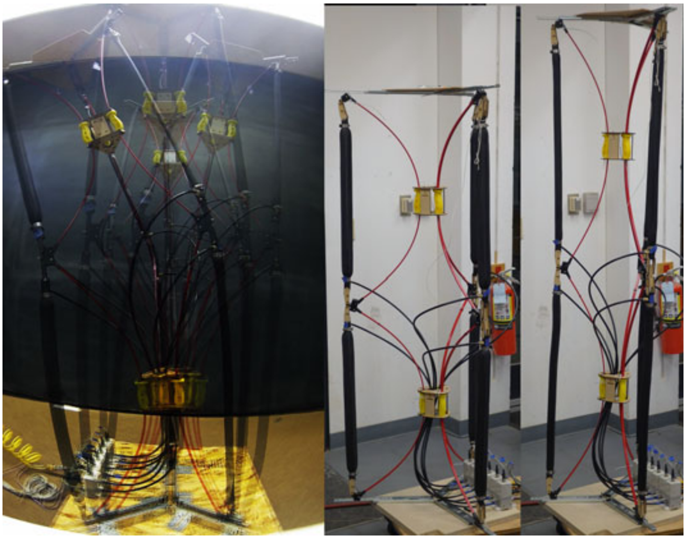

Fig. 12 Active bending combined with Arduino controlled actuation and sensor based feedback as embodied computation

may enable the existing structures to behave in ways that have positive effects on resource consumption and enable more flexible programmatic use, both collectively and individually.

Prototyping Material Organization—3D Printed Material States The printing of a material effects, i.e. printing with a material that is not different based on its chemical composition and that is not an assembly of parts, but rather exhibits different properties based on the specific, physical organization of the material require a different approach for realization. For example, in an instance where the shared cellular focal point creates a transparency effect that moves with the viewer as he or she circles the object and simultaneously conforms to the superimposed boundary effects of an inner compression dome and an outer moment frame to counteract the horizontal dome forces (and also provide a level seating surface) due to the material organization details, 3D printing is the only feasible production technique. The design construct relies on the printing process to become a physical object due to geometric properties. The material embodiment through 3D printing is the only form of materialization and testing of the object. The process has its own constraints, such as limits in the maximum overhang distances and angles of the pieces while being printed upside down. Additionally, production time is a big problem, requiring over 400 h of printing, as well as printing in nine parts due to the limited print volume of the simple desktop machine 3D printer.

3 Conclusion

Understanding of prototyping is evolving rapidly, particularly in its relationship to the design process. As discussed in this paper, due to the increased possibilities of linking design intentions into the built object, the separation between the design process and the finished artifact is disappearing on all scales. This presents unique opportunities for the continuation of the design process and the delivery of feedback from existing objects to the design teams developing them. Architecture presents a special case due to the relative longevity of its build constructs and the higher likelihood of reuse of existing structures. The prototypical experiments discussed here span a range of research interests under the general umbrella of embodied computation and represent ongoing research into the relationship of design, machines and the physical artifacts as created by the author.

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