Embodied Computation – An Actuated Active Bending Tower

Using Simulation-Model-Free Sensor Guided Search To Reach Posture Goals

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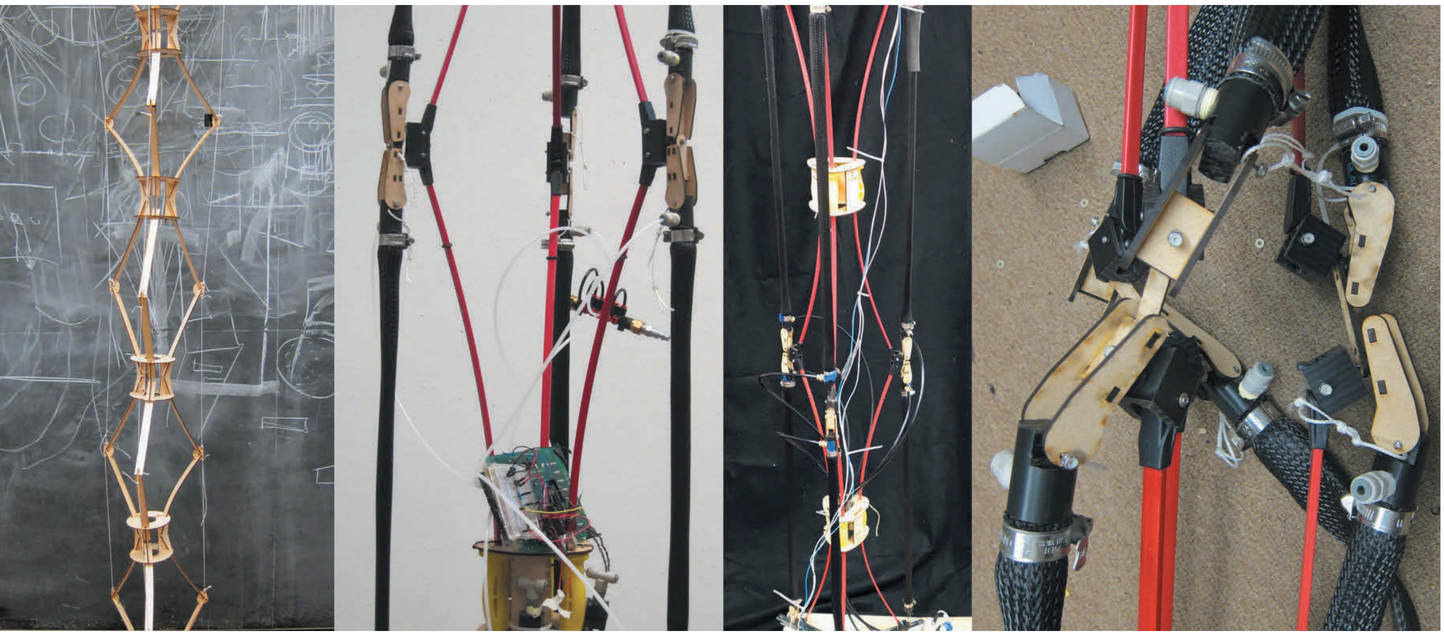

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ABSTRACT

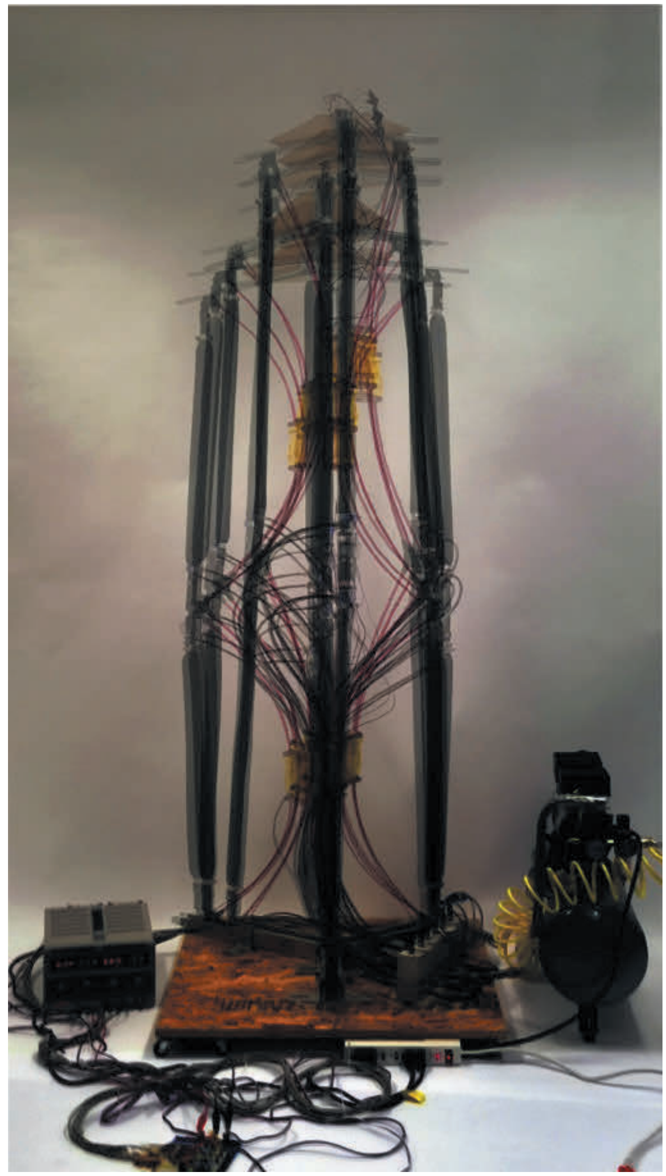
The concept of Embodied Computation is to leverage the combination of abstract computational and material artifact as a method for exploration in the design process. A common approach for the integration of the two realms is to use computational simulation based on the geometric form of the artifact for the prediction of material behavior. This leads to the integration of a geometric model abstraction of the physical artifact into the control software of the actuated device and can produce deviations between the state of the physical construct and the computational state. Here an alternative approach of a soft, actuated, active bending structure is explored. Six fluidic actuators are combined with a six degree of freedom (DOF) sensor for posture feedback. Instead of relying on simulated kinematics to reach a particular posture, the sensor-enabled posture feedback guides a simplex search algorithm to find combinations of pressures in the six actuators that minimize the combined tilting angles for the goal of a level tower top. Rather than simulating the structure computationally, the model is shifted to one of feedback and control, and the structure operates as a physical equation solver returning an x-y-z tilting angle for every set of actuation pressures. Therefore the computational model of the search process is independent of the physical configuration of the structure itself and robust to changes in the environment or the structure itself. This has the future potential for more robust control of non-determined structures and constructs with heterogeneous DOF common in architecture where modeling behavior is difficult.

1 a) First active bending prototype testing overall stacking stability b) miniature valve experiments for integration into the structure proved relatively slow c) switch to 8mm diameter pressure tubes and commercial proportional pressure valves d) frequent complete structural collapse of the early prototype structure due to multiple component failures. Resolved through rebuilding all joints in delrin plastic.

INTRODUCTION

The abstraction of scientific modeling has produced some of the greatest breakthroughs of the 20th century by enabling researchers to leverage a deeper understanding of the world to produce complex interventions in the world that worked as predicted. While immensely powerful, this approach also has an inherent side effect which is the potential separation between abstract model and physical matter. The power of models is that they are reductive and thereby cannot holistically capture the world; this is at the same time also their greatest shortcoming when unexpected changes occur that no longer register within the predetermined abstraction mode. New approaches center on machine learning but they tend to be image and data centric, and the physical body or structure tends to be underrepresented. What we propose here is an alternative approach which we refer to as embodied computation, a hybrid between computational abstraction and reliance on the physical world for computing outcomes. In this simple example the link between the two is in one direction algorithmic-controlled actuation and in the reverse direction sensing. This bidirectional link is still not standard in everyday designed artifacts but instead internal models are used for directing the physical construct, relying on mechanically determined structures to ensure synchronicity between internal model and the physical state. Physical constructs tend to be stiffened to maintain precision such as in industrial robotic arms. Linking the algorithmic control directly with the physical artifact, ignoring how it is exactly configured and instead directing things via sensing feedback may be a path forward in overcoming model simulation and allowing for the discovery of new combinations of actions for a desired result. Rather than developing a complex model of the active bending structure with all its degrees of freedom and six degrees of actuation, the experimental approach taken here is to treat the physical structure as a function solver with six parameters in the form of the actuation pressures and a return value in the form of the accelerometer returning the x-y-z tilting angle of the tower top. Studies of extremely high DOF biological structures such as octopus arms suggest the existence of similar models of control that work closely with the physical sensory construct of the arm in contact with the environment triggering different behavioral models (Richter et al. 2015).

In a larger conceptual framework, embodied computation also implies the continued design development in the deployed artifact past design and construction. In future work machine learning could be applied to let the control model emerge from many training iterations of the artifact in its environment and in interactions with human occupants for an open-ended approach where design shifts from describing the artifact to models of exploring the potential of new physical-sensory control-mapping-based sensory feedback.



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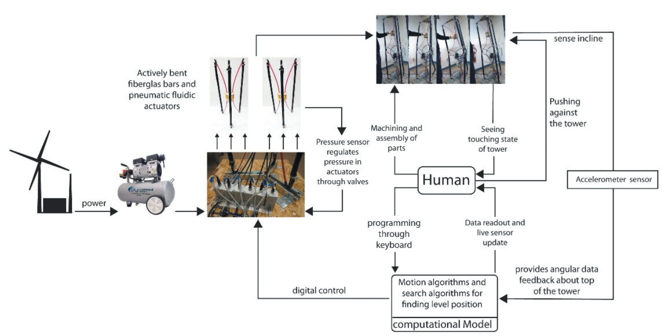

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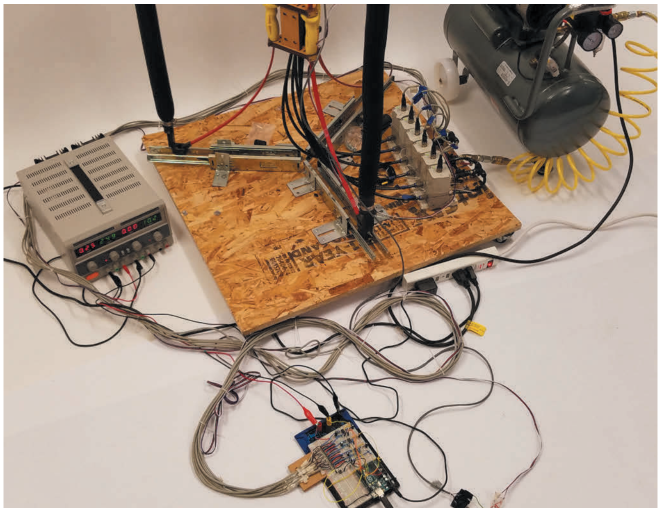
2 Image super imposition showing simultaneous contraction of all actuators affecting tower height and resulting height and foundation changes

3 Bowtower diagram showing the dependencies of the different components



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BACKGROUND

This project explores the influence of geometry-based simulation models in design and the consequences of their introduction on design in architecture and engineering. With the increasing reliance on predictive models, the physical constructs begin to conform to the abstractions that are representable in the models (Kilian 2007). This approach to modeling formed in parallel to careful measurements and calibration of the abstract models with the observed behavior in the physical world. But the density of measurement and time delay between measurements was large in a pre-digital world and still expensive and difficult to implement today. Results achieved through predictive modeling are not necessarily verified through measurements in the structure once built. This requires conservative margins of error and approximations that all contribute to a potentially widening gap between modeled and built construct. It also requires that the built artifact cannot change outside its predicted behavior as otherwise the assumed abstraction and the physical state of the model would no longer match. Such changes could be the failure of a component or the unexpected influence of an external force from the environment or from humans. It also draws conceptually on the embodied intelligence concept by Rodney Brooks (Brooks 1991), in being an actuated structure using only sensors as feedback for the control system, without building in any representation of the physical structure into the algorithm. The Bowtower builds on the precedent of other actuated tower prototypes such as TU Delft Hyperbody's Muscletower I and II (Bier 2011) and the WhoWhatWhenAir tower (Kilian et al 2006) but does so by shifting the structural principle to active bending with sliding foundations for a much wider posture range and integrating feedback through sensing. Overall the work is situated in the context of responsive buildings (Sterk 2003) and adaptive structures (Senatore 2016) and architectural robotics (Green and Gross 2012; Bier 2011; Bier 2014), an approach where the building becomes a robot itself.

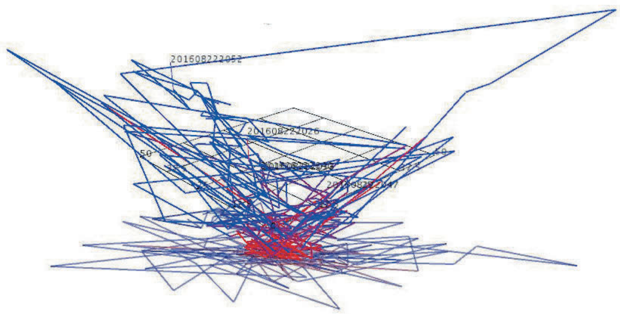
METHODS

The experimental room height structure was constructed through a series pf physical prototypes (Figure 1) to provide a robust but not fully determined structure that would not constrain its adaptability in its anchoring and connection details. It is built around six fiberglass struts that are kept in active bending by six pneumatic actuators, which are in turn pre-stressed by the fiberglass bow. The structure tips are connected to sliding foundations at the base that allow the base to widen and contract during actuation leading to wide variety in height and width (Figure 2).

In parallel to the physical structure, an electronic control for regulating the pressure level in the actuators was developed using an Arduino board connected to a six degrees of freedom accelerometer that was attached to the tower top for sensing its tilting angle in space (Figure 3).

Increasing the pressure in the actuators leads them to contract, decreasing pressure elongates them based on the pretension of the paired bows connected to each actuator end. The proportional pressure valves are fed air pressure by a compressor and are controlled by a set voltage that is provided by an Arduino board. A second Arduino board is connected to a combined accelerometer, magnetic compass, and gyroscope at the top of the tower that reports the pitch and roll angles of the tower top (Figure 4).

As a first test case of achieving a physical goal with the un-modelled structure, a search algorithm was used to minimize the pitch and roll angle at the top, searching essentially for positions that keep the top level. Specifically, the search algorithm used is a downhill simplex search algorithm (Nelder and Mead 1965) implemented based on the description in Gershenfeld (2011). It works by searching for a global minimum using a simplex, a construct with one more vertex than the dimension of the search space. In the case of the Bowtower the search space is six dimensional because of the six actuator pressures. In order to receive a return value for the function, the six function parameters are sent as pressures to the physical tower and the combined absolute pitch and roll angle of the sensor is the function return value to be minimized. There is no explicit analytic function describing the behavior mathematically, there is only the physical construct acting as the embodied computation of the "tower function" using its sensor to generate the return value. This arrangement makes the search process, in this case a downhill simplex algorithm, independent from the tower hardware. The overall conceptual model is the combination of the two approaches to achieve a level posture. Any physical inaccuracies, changes or defects in the tower over time simply change the nature of the function that is being searched but it does not



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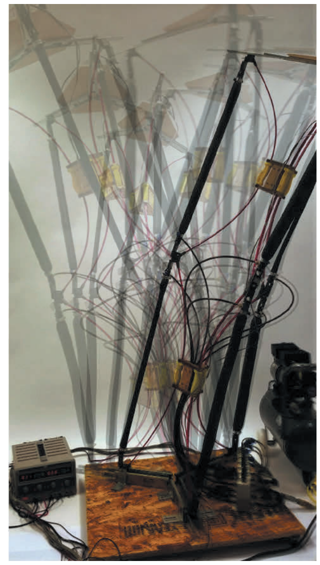

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4 Component setup and sliding foundation tower base,

5 a) Graphing a part of the complete movement set of all possible pressure combinations with two of six pressure levels visualized, one in x and one in y direction, and the corresponding tilting angle in the z axis. Lower pressure values are drawn more red. b) Resulting tower positions in image super imposition,

require a reformulation of the search function itself or changes on the algorithmic side of things. The very slow update rate of the physical structure and the relatively low sampling rate of the physical actuators does cause noise problems occasionally, which will throw off any convergence as for instance if a stuck foundation slide starts abruptly sliding again. The search for a posture with a particular quality, in this simple case levelness at the top, is informed by the response of the physical configuration, the embodiment of the structure in combination with a sensor that is physically located on the structure without any built in assumptions about the configuration or dependencies of the actuators and structure.

RESULTS

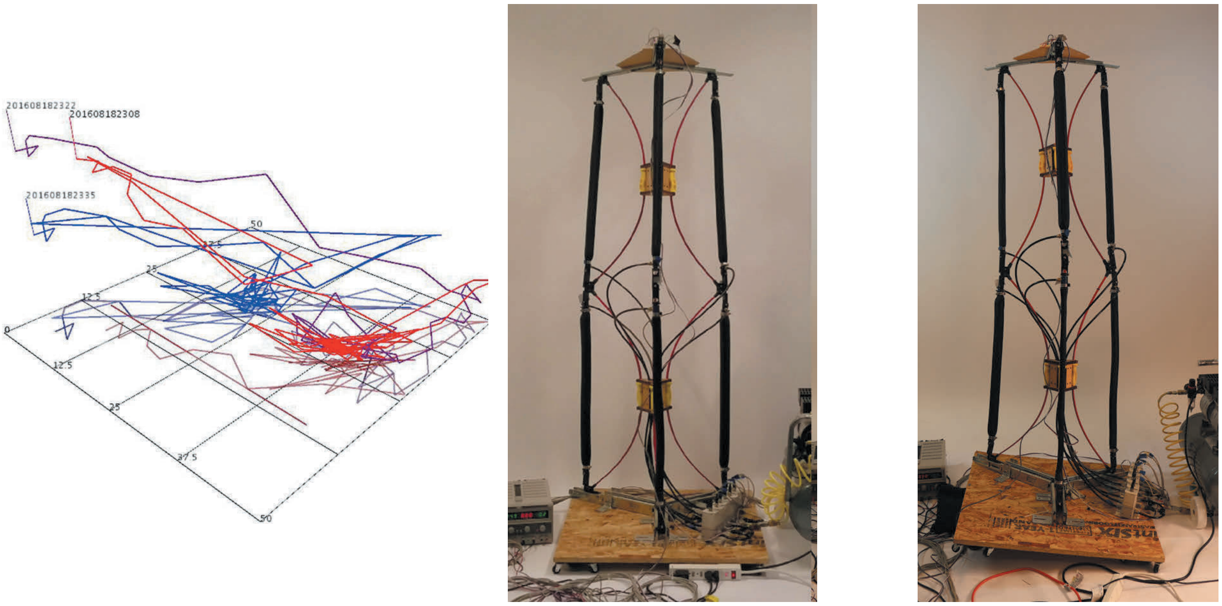
Graphs were produced from different runs visualizing only two of the six pressures for visualization purposes in the x and y axis and mapping the combined x-y-z tilt angle in the z axis.

A sub sample of a complete posture scan of all possible positions (Figure 5ab) at ten different pressure levels for all six actuators was performed and the corresponding combined pitch and role angle recorded. When the pressure/angle relations are graphed, a visual spatial distribution pattern emerges that shows clusters of levelness and could be further explored as a form of muscle memory of the Bowtower that accumulates and is constantly refreshed with any movement it makes to serve an increasingly detailed context to operate in and accelerate the achievement of, in this simple case, a level top from any position in space. There are a large number of level top positions within the reach envelope of the structure, but many are in neighborhoods of large inclination angles and therefore less likely to be reached by the simplex search, as they appear similar to noise, or are simply stepped over in the search iterations.

The graphing of the pressure data over time shows traces of the changes to the environment such as when the tower base is initially placed flat on the ground (Figure 6b) and then unevenly (Figure 6c) using a sand bag the found function minimum shifts accordingly in the graph without any changes to the algorithm. Equally when one of the actuators developed a progressively larger leak during testing it did not affect the search algorithm as the changing hardware was simply part of the changed function behavior and absorbed by the simplex search. This potentially also enables the reuse of the n dimensional implementation for higher degrees of freedom actuated structures, for instance, a higher multi-level tower or different hardware configurations.

For further development the concept of muscle memory will be expanded and also applied to more complex posture configurations. Currently a room sized version with 36 actuators is being implemented for an exhibition at the Seoul Biennial starting in Sept 2017.

Another concept that has been explored in a preliminary fashion is the interaction with outside actors such as a person stepping up to the tower and pushing it, or wind forces acting on the tower. In an earlier version of a different even simpler search algorithm the Bowtower would compensate for the displacement from levelness when pushed by a human by slowly pushing against the displacing force. This is similar to the changes in the physical structure of the tower, but it happens unpredictably and may change continuously exceeding the relatively slow response of the implementation of the search, which also relies on the tower's movement to evaluate its next step. If the holding force is substantially larger than the actuation forces this would not be possible.



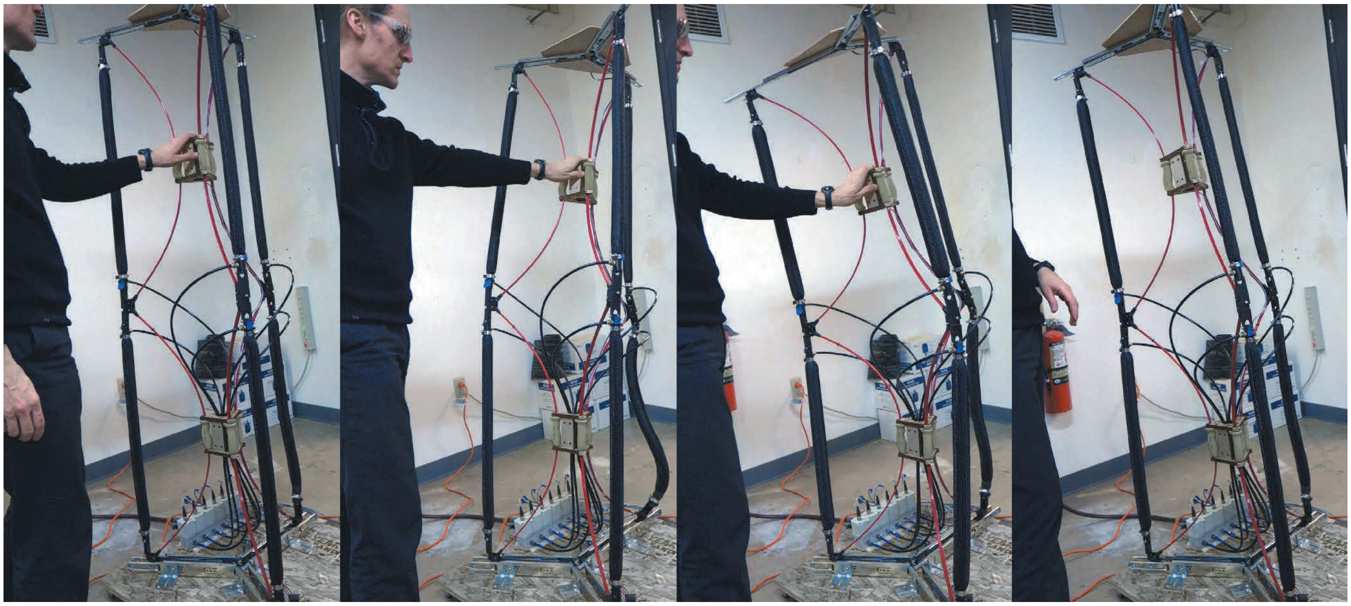
6 a) Graph showing the in-pressure settings of a sub sample of two actuators pressures, one mapped in the x and one in y direction searching for minimal combined tilting angle for a level top mapped in the z axis, with zero at the grid level. The structure on b) level ground (blue path and left image) and on c) tilted ground (red path and right image.)

CONCLUSION

The Bowtower experiments provided an interesting insight in a simulation-free control approach to a complex physical structure. The insight of using the physical structure as the function generator helped in rethinking the relation between algorithmic control and physical artifact and what agency is given to which part. Similar approaches exist in other fields with tight feedback loop integration in control loops such as the control of drones or other flying constructs that are inherently unstable and rely on constant sensor feedback to stabilize their position in space. Other mechatronic research platforms such as the “Cubli” project by Raffaello D’Andrea’s research group at the ETHZ explores interesting new combinations between sensory feedback and state estimates for control (Gajamohan 2012). Recent progress in machine learning has led to compelling experiments in learning-based approaches to robotic control around hand–eye coordination for grasping where the fluctuations of real world variations are continuously integrated based on network data collection and sharing between robotic entities and using sensory feedback, replacing the established analytics based path planning approach (Levine et al. 2016).

Architecture is unique in that it tends to have much less homogenous degrees of freedom that may involve large time spans and many humans and large environments with much complexity that become very hard to model in a finite closed model that is integrated into the structure at the end of design. This work is meant as a provocation to rethink how we can use the physical constructs we design as vehicles for adjusting the design continuously from within the environment they are positioned in.

While the presented example is simplistic in its search approach and in its basic posture goal, without additional constraints it does point towards a possible more open-ended shared approach in the future control of architectural constructs and the possibility of integrating learning from their behavior once deployed over time. There are plenty of safety challenges and unpredictable outcomes which make the approach difficult at architectural scale. It is an attempt to reshape control in complex structures especially architectural ones towards a more open ended and ultimately more robust part of the built environment. Closed systems that cannot adapt to environmental or use changes are less adaptable and with the unique scale, cost and resource requirements of architecture and engineering structures there may be a niche in which such an embodied computation approach may work. The current experiment hopefully can serve as an inspiration to further investigate the potential of using the physical world as a computational component in life long computational design processes. It also points to the need for the development of more sophisticated links between a denser sensory set and less constrained model of control to enable physical-based machine learning in the emerging area of architectural robotics. It is fascinating to imagine the possibilities of machine learning based discoveries of new behaviors in the mapping of sensory feedback to the degrees of freedom of buildings, whether those may be doors and windows of existing structures catching a breeze for ventilation, or novel architectural robotic developments actively shaping the social dynamics of their inhabitants



7 Sequence showing human intervention pushing against the tower pushing it out of levelness and deforming its soft structure. The sensor registers this and the search for a pressure set continues, eventually resulting in a push back against the external force.

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IMAGE CREDITS

All drawings and images by the authors.

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