The Flexing Room Architectural Robot

Axel Kilian
School of Architecture
Princeton University

An Actuated Active Bending Robotic Structure using Human Feedback

1

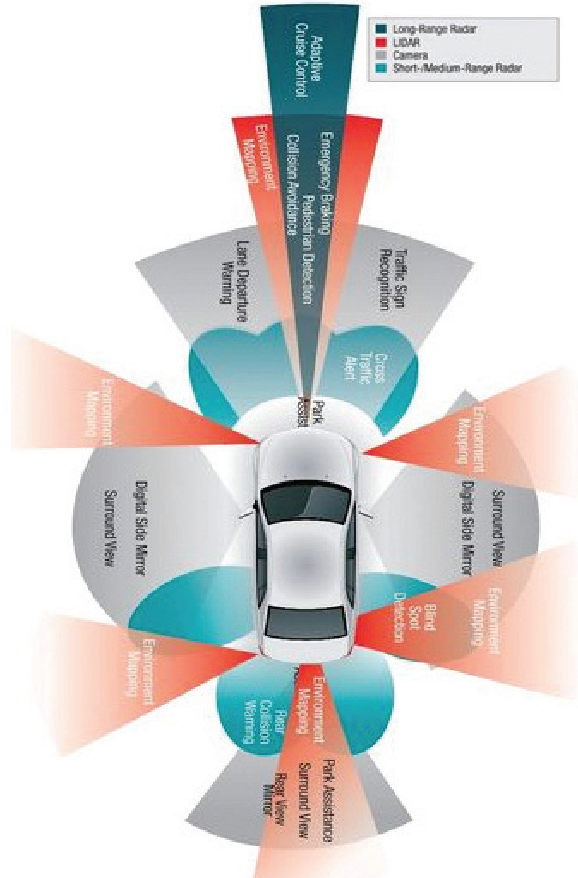
1 The Flexing Room installation

ABSTRACT

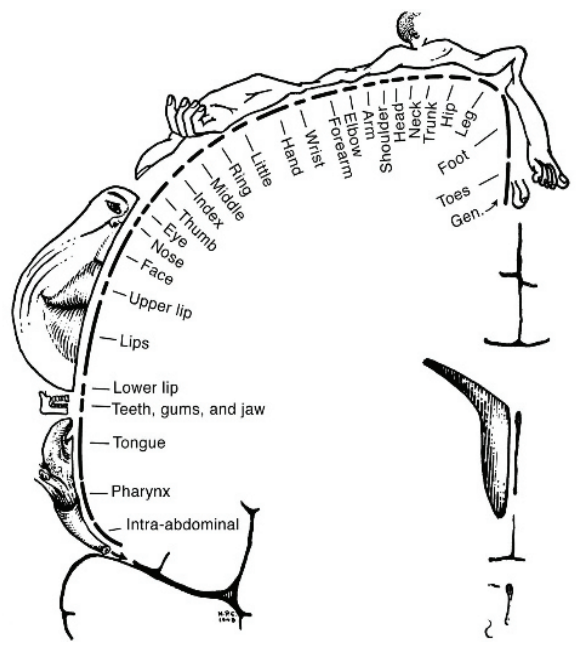
Advances in autonomous control of object-scale robots both anthropomorphic and vehicular are posing new human-machine interface challenges. In architecture, very few examples of autonomous inhabitable robotic architecture exist. A number of factors likely contribute to this condition, among them the scale and cost of architectural adaptive systems, but on a more fundamental conceptual level also the questions how architectural robots would communicate with their human inhabitants. The Flexing Room installation is a room sized actuated active-bending skeleton structure. It uses rudimentary social feedback by counting people to inform its behavior in the form of actuated poses of the room enclosure. An operational full-scale prototype was constructed and tested. To operate it no geometric based simulation was used; the only communication between computer and structure was sending values for the air pressure settings and gathering sensor feedback. The structure's physical state was resolved through the embodied computation of its interconnected parts and the people counting sensor feedback influences its next action. Future work will explore the development of learning processes to improve the human-machine coexistence in space.

INTRODUCTION

The public perception of robotic development has been dominated by anthropomorphic and vehicular robotics. But most machines, whether acting on commands or autonomous, could be considered robotic even if their configuration has no resemblance with living beings. Architecture as a built construct has a long history of incorporating physical adjustment such as doors or windows and other kinetic features. Predominantly such controls are human operated and not connected with each other and no overall awareness of the state of the building exists. Building automation is gradually changing this but architectural qualities are still conspicuously absent from leading home automation initiatives. Spatial modulation or programmatic changes remain largely untouched, limiting the changes to accessorization driven integration of technology into architecture. What is missing is a discussion of buildings as overall autonomous robots that, though stationary, can be designed to have short and long term plans, open-ended plans for higher level objectives, and, most importantly, a form of intelligence that lets them interact with their inhabitants. But the type of exchange between building and user is different from the established paradigm of human-machine interaction present in object-scale computer devices. Screen and touch-based interfaces in mobile devices dominate, and voice control has been established for interaction in architecture across rooms. But those interaction paradigms do not consider any architectural qualities or include architectural features but anthropomorphize architecture by reducing it to a disembodied voice. In the most active areas of sensory controlled robotics, autonomous driving, sensors are oriented outward to address the challenge of an object moving in space, while ignoring the human occupied interior for the most part. Posture and gesture sensing have been established in the main stream through gaming. But a key difference between an architectural robot and its object-scale predecessors is the fact that architecture is inhabited, meaning the human is within the machine. The exchange is thus not only defined in an object-to-object relationship, but by the space the architectural construct defines and it can potentially also manipulate the position and posture of the human inhabitant [Eng et al 2005]. Even in our own body it is interesting to observe the understandable strong bias of our consciously perceivable sensory perception on the exterior of our body, where most interactions we consciously respond to take place. The discovery and first mapping of the now outdated yet iconic understanding of the somatosensory cortex of the brain by Penfield ([Penfield and Boldfrey 1937] shows the majority of sensory stimuli being focused on the external skin and only a small fraction on internal organs. In a way dealing



2



3

2 Autonomous vehicle sensor fusion coverage surrounding the car (Image Texas Instruments), reinforcing the object centric sensing paradigm in autonomous robotics.

3 First discovery of distribution of sensory map in the brain (image Penfield Rasmussen 1950), exterior sensing dominates reflecting the object centric interactions with the world.

4

with the sensory response of the inside of architecture is like a human being swallowed by a whale. But just as we are only slowly beginning to understand the complexities of our own bodies and brains, we are also developing a notion of a more differentiated sense of architectural autonomy. Developing more experiments in architectural robotics is therefore crucial to push the discourse into a more architecture aware realm and form a design sensibility for those challenges in research and education. The closest robotic precedent is probably that of wearable exoskeletons while in a much more directly linked relationship, the actions of the body directly affect the worn robot. If the gap between human and machine is increased so are the possibilities of design expressions and interpretations of human and machine intent. The Flexing Room experiment is a simplified implementation of an architectural robot in response to the above questions. The structural skeleton of a room-sized enclosure is tested for its expressive potential and allows humans to occupy the central enclosed space while using sensors to capture their presence and feed it back to the robot. The current iteration does not differentiate human orientation in space, or time spent hence the sensory feedback is much too crude to capture human response to architectural expression but would need further development to integrate.

BACKGROUND

Architectural robotics is an evolving field with overlapping domains [Green and Gross 2012;Kapadia 2010]. Most precedents are situated in an interactive architecture paradigm shaped likely by the then contemporary discourse focusing on interaction in human technology interfaces. With the shift towards autonomy in robotics the definition of architectural robotics needs to be revisited. The ADA intelligent room was an early autonomous architectural robotic installation for the EXPO 2002 in Switzerland that benefited from a large collaborative group of different computer and cognitive scientist groups and is an example of engaging people in space in a social form of interaction between architectural enclosure and visitors. Communication happened through screen covered walls and lighting up floor tiles as well as voice[Eng et al 2003]. More recent work on tracking groups of humans in confined indoor spaces succeeded in detecting social cues from minute variations in human's body positions relative to each other and within space using a very large number of cameras installed on the perimeter of a space enclosing shell [Joo et al 2015]. Responsive and interactive architecture has long been explored as a way to have technology and kinetics integrated into architecture. Sterk developed tensegrity responsive roof and tower structures[Sterk 2003] that established a holistic approach combining actuation and structure. Michael Fox's work in the kinetic design group and later robotic architecture and publication interactive architecture explored environmental responsive kinetic structures and architectural programs[Fox and Kemp 2010]. The Hyperbody group under Kas Oosterhuis at the Delft University of Technology has explored interactive and kinetic architectural structures such as Muscle, not inhabitable, and Musclebody, inhabitable, and Muscle Towers I and II. Bier published a number of papers combining architectural robotics for fabrication with architectural robotics as interactive inhabitable architectural structures. [Oosterhuis 2012; Bier 2011; Bier 2014]. In biology and neuroscience research provides new insights into the control of high degrees of freedom articulated limbs some of which may be applicable for learned architectural responses [Richter 2015; Cheney et al 2013].

METHODS

The Flexing Room Experiment Of A People Enclosing Architectural Robot

Many example of interactive architecture developed façade like structures or architectural objects that humans can interact with. Fewer examples exist that address the architectural robotic potential of an inhabited robotic space that go beyond a static room accessorized with screens or interactive elements and focus on influencing human behavior (Eng et al. 2005). There is a fundamental shift when the robotic is not an object but an enclosure, if the interaction shifts from screen-to-person to space-to-person. The Flexing Room was developed as a minimal version of this, using a kinetic, actively bending actuated skeletal framework to define a volume and to give the room entity some architectural expression in the form of framing postures.

The development process

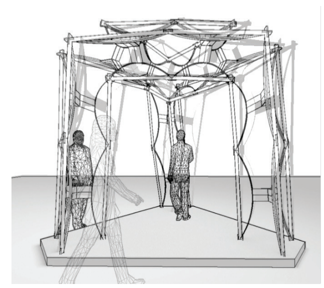
The actuated basic building unit of the Flexing Room is a scaled up and reengineered version of the units in the Bowtower experiment (Kilian and Sabourin 2017). In the following sections the different aspects of the development are discussed in detail. The prototype development and fabrication was done by the author alone using an ultimate 2+ 3d Printer and basic hand power tools and electronics over a period of about 3-4 months in preparation for the installation at the 2017 Seoul Biennale for Architecture and Urbanism [Zaero-Polo and Anderson 2017].

Actuation

The fluidic actuators are based on the cross fiber sleeve pneumatic tube McKibben actuator design from 1956 [Klute et al 1999]. Since the actuator can only contract, it either requires a paired alternate actuator or spring action to reset it. For the Flexing Room, similarly to the Bowtower test column, pretensioning of the actuator is achieved through a fiberglass recurve bow which is tensioned with an actuator in place of the bowstring. This pretensioning allows the actuator to resist a set amount of compression force depending on the bow tension. In the case of the Flexing Room a larger recurve bow with a complex varying cross section was used that produces a more linear pull force curve of around 30-35 lbs. This equates to the structure being able to carry larger vertical loads to deal with the combined self-weight of the horizontal beams and columns. The fluidic actuator in itself is a compliant actuator. Due to the air pressure and its stretching membrane it does have some compliance when loaded. The combination with the fiberglass bow pretensioning makes for an overall compliant unit. The compliant behavior is useful for human inhabitable space and helps with the less predictable forces at architectural scale to prevent breakage. But it also brings with it a level of uncertainty in the state of the overall linked system given a specific air pressure as all changes affect the entire structure. McKibben actuator behavior has been modeled [Klute et al 1998] but the modeling of the overall structure in its flexing looseness in a synchronized fashion with its physical equivalent is not reasonable for the precision that is needed would require extensive sensor feedback. Conceptually this led to a rejection of the simulation approach. In the previous Bowtower experiment [Kilian and Sabourin 2017] a simulation based approach was also rejected and a feedback based approach using an accelerometer added to the tower top was taken and used to coordinate all actuators towards a posture goal, in this case a level tower top. In the Flexing Room, the feedback is

5

6



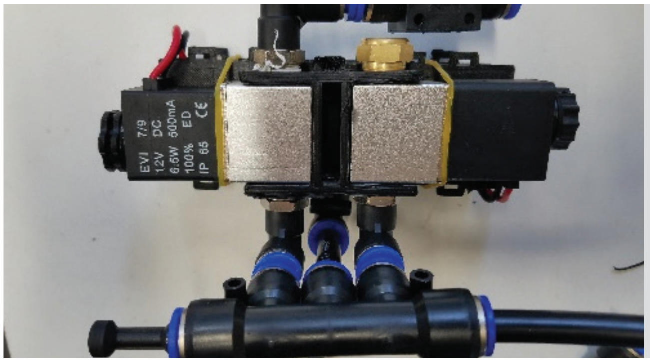
7

4 Comparison a) Ekso exoskeleton wearable robotics (https://eksobionics.com)– b) Flexing room inhabitable robot

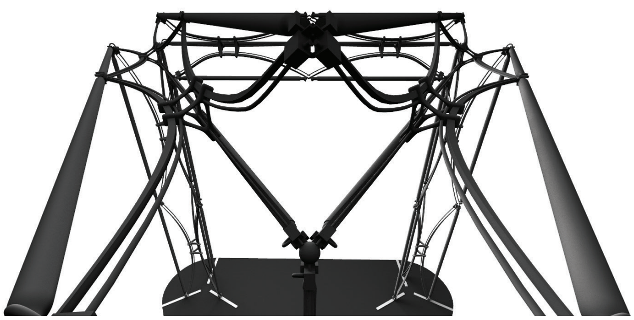
5 Different assembly stages of a bow-actuator unit assembled with a 3D printed connector into a star shaped level with neoprene connector joints

6 Partial test setup and fabrication of actuated active bending frame units and pressure control valve units and power distribution details.

7 Initial particle spring based simulation to test overall stability – but the simulation is not usable for exact behavior prediction of the specific physical structure.



8



9

8 Custom pressure valve development with dual pressure control valves

9 Original double height column design modeled

shifted to an architectural metric of human occupation. The more complex interconnected structure makes isolated measurements less meaningful for positional feedback. Instead the focus is on providing the structure with a simple measure of human evaluation in spatial terms.

1.4 Valve development

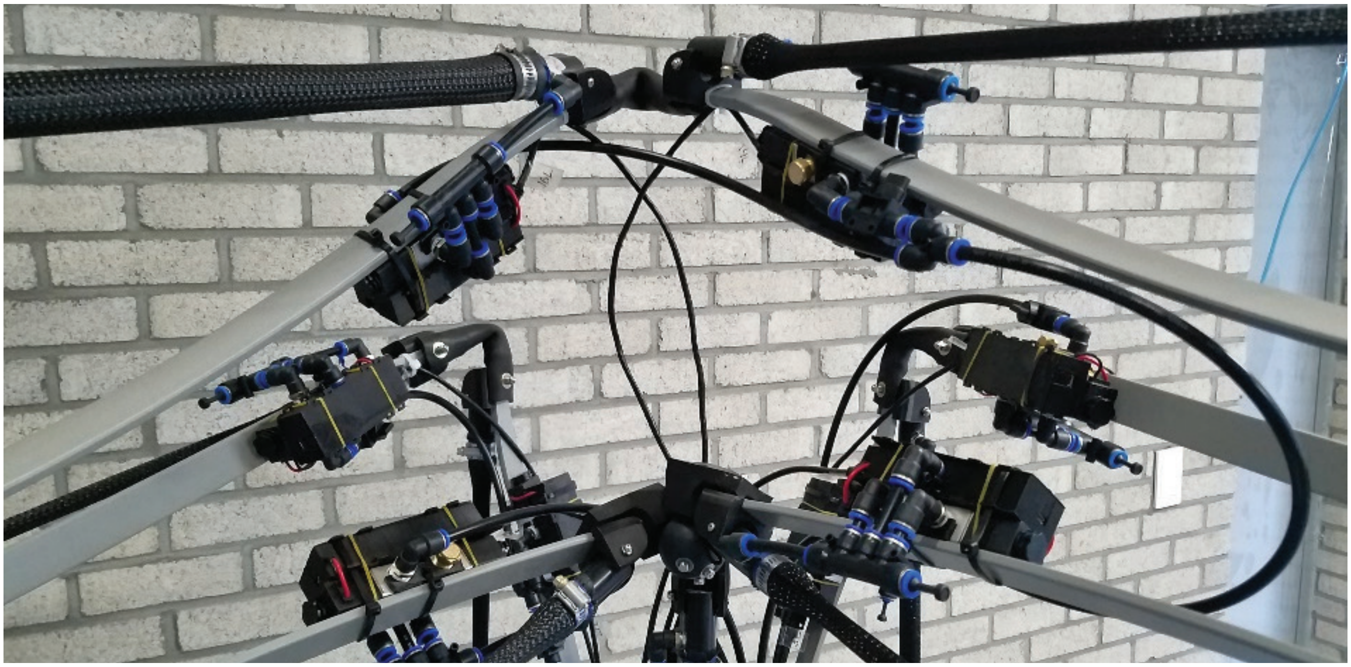
Each actuator has a custom made pressure control unit with two simple open-close solenoid valves controlled by a Arduino metro, a pressure sensor and some power transistors packaged in a custom 3d printed housing. This choice was made based on the prohibitive high cost of the previously used Festo differential pressure valve units that are priced around $400-500 per unit. The pressure stability proved to be a problem though in the larger interconnected structure where feedback cycles between the different actuator units led to uncontrolled feedback cycles in the overall structure and situations in which the valves never settled down leading to a convulsion like overall behavior. This is a combination of simple bang-bang control and the lack of proportional pressure valves allowing for progressive adjustment of air pressure for a more smooth and continuous control of air pressure.

3.5 Overall structure assembly

A three bow-actuator unit is connected by a 3D printed connector at 120 degree angles into a level forming unit. These units were connected at the fiberglass bow ends with neoprene tubing to allow for a flexible ball joint-like connection and easy assembly and disassembly. For the three vertical column sections the lowest ends were attached to a base via a separate aluminum sliding track each to ensure a compression and tension load transfer as well as the expansion and contraction of the fiberglass bow unit stance as the actuators adjust. The top column unit has a shortened inner bow unit to enable the tetrahedral joint geometry with the two incoming horizontal crossbeams. The lowered inner connection rotates the horizontal beam such that the lower one connects with the respective lower bow ends and the upper ones join with each other to form the overall corner joint. This configuration proved to be structurally stable and strong and allow for some flexibility for actuation. But the lower triple connecting joint proved too constraining for the overall skeleton to reach its full motion potential as the inner triangle created a locked ring that also fixed the column's top vertical inner tips in position. Due to a mezzanine level in the exhibition space that protruded further into the space than expected it was not possible to install the second column unit level which further limited the flexibility of the overall structure. The three double columns were joined by horizontal crossbeams of the same configuration. It was a challenge to develop the joint to allow for flexibility and motion in the system while also providing a stable structure in all states and a way to safely and quickly assemble and disassemble the structure. In the corners four joints form an expanding tetrahedron geometry that provides the flexibility required for the motion of the interconnected units. This is an interesting conflict between compliant behavior and structural stability that increases with scale and the mass of a structure and contributes to the difficulty of kinetic structures at architectural scales. In a future installation this triple connection point would be altered to include a sliding bar between upper ring and vertical support to free up the motion of the top unit, which proved problematic as the triangulation of the upper ring locked the inner bows motion.

1.6 Robot Base

All three column units connect to the same grey base plinth that provides a level walking surface between the columns for humans to occupy the central space of the Flexing Room in view of the Kinect sensor. The base also houses the pressure, power and control voltage lines in form of Ethernet cables and 8mm pressure lines all being fed back under the base floor into the control unit in the middle of one of the triangular sides of the base. The base also delineates the



10

Tetrahedron corner joint detail allowing the individual bow units to flex yet provide a stable connection of the overall frame.

boundary of the room when people step onto the base and into the skeleton frame.

1.7 Electronic and power control unit

The control unit is an integral part of the base and extrudes out from the base and has the same grey color and materiality as the base to emphasize the complimentary nature of the flexing skeleton and solid sensing base. The tower contains all electronic controls in the form of three Arduino mega boards to control the up to 36 pressure valves in the actuators and to distribute power to the valve controllers and valves. To simplify connectivity and use standard parts as well as shield signals from noise, CAT 5 Ethernet cables were used for all connections. In addition, the tower carries a Surface 4 Pro computer facing away from the room center and a Kinect sensor on top to oversee the space.

1.8 Sensing

Each of the actuators has a pressure sensor connected to its air volume to maintain the set pressure and correlated contraction length. This sensor also tracks small changes in pressure due to force being applied to the actuator from the outside. It was not actively used in this iteration but led to some interesting yet undesirable feedback cycles between actuators throughout the structure triggering each other through the motion they caused. Overlooking the central enclosed space a Kinect sensor is used to register the presence of a person. Each pose of the Flexing Room has a score of how many times a person was present that is updated based on the sensor feedback. This sensing enabled a rudimentary social feedback for the different actuation configurations to be used over time to influence which poses are more popular than others and influence kinetic changes over time. In the test setup, the one unit high columns caused problems with the Kinect sensor which was now located at the same level as the cross beam which frequently interfered with the skeleton detection of people. In a future complete double high column installation this would be avoided.

1.9 Addressing actuators – coordinating actuation for a particular result

Similar as in the previous Bowtower experiment none of the actuators was assigned a specific control number but the connection between control ports and actuators was done randomly on the physical hardware side. The goal was to rely not on knowledge of the physical configuration of the Flexing Room structure, but to use feedback to influence knowledge of the structure and its behavior over time. This intentionally prevents that coordinated designed motion could be directly programmed by the designer. Instead every restart created twenty new randomized poses that exposed different pose possibilities of the structure .

1.10 Striking poses

The control was setup in a processing program to generate 29 random actuation pressure values for each of the 20 poses to initialize the posture sequence of the Flexing Room structure. Each pose was held for a set time period anywhere between a few seconds and half a minute. During the holding time, the Kinect would test whether a person was present in the room or not. If a person was present, 1

11

12

was added to the social counter of that posture. The selection of the next pose was influenced by an increased biases towards poses with a high people count when the structure was in a high mood, and to unpopular poses when in a low mood. The 29 random pressure values result in a physical pose through the physical connectivity of the actively bent actuated structure and would not be known beforehand but rather resolved in the physical structure itself following the embodied computation principle. Runtimes of around an hour or two were too short to develop a meaningful feedback and possible evolution of the poses based on human feedback in the experimental feedback. The vision is that over time more distinct poses such as for instance an arching cross beam would feature more prominent as more people visit the room in that pose. For a more complex learned association between nuanced poses and human responses within the space machine learning would likely be the only feasible option. To achieve enough data much longer runtimes would be necessary. For prolonged unmonitored runtime the structure would need to be more robustly designed and made more redundant if individual elements failed.

RESULTS

The Flexing Room experiment did not reach a more complex development stage on the behavior side and only had a limited number of operational hours for testing with frequent hardware issues and sensor noise and feedback cycles that only became apparent in the full scale structure. One surprising problem arose from the structure inferring with its own sensors due a last minute lowering of the structure's height to a one level high ring due to collisions with a mezzanine level in the space. The horizontal truss ended up directly in front of the Kinect sensor interfering with the skeleton perception of the Kinect sensor and leading to physical trashing of the sensor and at times endangering the integrity of the sensor unit itself. Due to the short testing period only anecdotal evidence exists of the human-machine responses. Visitors generally were hesitant to step onto the platform inside the room structure. This was likely in part due to the low height of the horizontal ring and platform nature of the Flexing room base in combination with the possibly intimidating movement and sounds of the actuated frame. As poses were generated randomly per set of twenty the poses rarely had a coordinated expression. This was chose intentionally to not fall into animating the structure but to be effective would have needed gradual adjustment over time based on perceived human behavior evaluating the effect of the poses. This was not possible in the testing period. Upon entering most visitors looked around the structure for some reference to interact with or look at, many oriented themselves towards the sensor pole with the Kinect being likely familiar with its function from games or research.

REFLECTION AND IMPLICATIONS FOR ARCHITECTURAL DESIGN

The added active expressive abilities to architectural enclosures poses interesting questions for design. The temptation is to hardcode designed behaviors into a structure like this. But architecture is rarely reducible to a few isolated degrees of freedom and frequently situations develop for which the architecture has no directly built in response. This is where a more generalized approach

7

11 Robot base assembly showing data and power connection and step up threshold of the room.

12 Control tower at base edge with integrated power and Kinect sensor at top facing inward and Surface 4 Pro tablet PC control screen facing outward (door shown open here) away from the inhabitant.

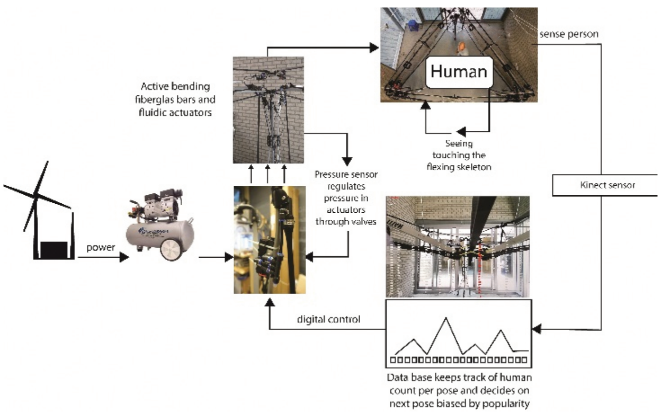
13 Human occupation of the space and a few superimposed poses and person response.

beyond movement of the structure including more architectural qualities such as light, temperature, and program with the ability for feedback based learning is promising. At the core is the assumption that in some cases it may be beneficial to not predetermine the behavior of an architectural structure but rather allow the structure to learn from how its changes are perceived by its inhabitants. This requires to move beyond screen based interfaces and fully embrace space as the mode of exchange within architecture. Architecture has the unique quality of having comparatively large volumes and therefore a high potential spatial resolution of social scenarios playing out within. The motivation for this work is to not mimic other forms of intelligence and their body plans, but to develop a genuinely architectural version of robotics giving form to physical autonomy and to strengthen the potential of space to act as an architectural scale communication device between human occupants and the architectural entity. The Flexing Room installation was a short-term experiment of a full-scale installation to test the physical entity and people's reactions. A challenge in this endeavor is how to design the behavior of robots. In locomotion-based robotics, movement is primarily focused on coordination for the sake of balance and propulsion. Movement as expressive form has a long history in architecture with work by Lynn, Oosterhuis, Spuybroek and others. In the Flexing Room motion is used as low level form of exchange between a potentially autonomous architecture and its human inhabitant. Also, legged or arm-based robotics tend to rely on kinematic chains where the different degrees of freedom are highly interdependent mechanically. Architectural degrees of freedom are much more heterogeneous and interdependencies are more environmentally than mechanically based. Moreover, humans play a larger role as co-inhabitants, increasing the social complexity of the overall human-machine system. Another open question is how to combine different degrees of freedom to achieve a particular result. In a heterogeneous and not necessarily purpose-built architecture there may be many unintended and unknown ways of using the physical artifact to interact with the world and affect change. How can we overcome the perception of programming a set of behaviors triggered by control inputs and develop more emergent behaviors that through the lifetime of the structure can gain deeper insights about what its physical body is capable of? The result would be that the architectural robot could learn possible combinations of actions in response to human feedback; this is very different than having a human designing the robot's actions before it is built and then simply mapping them onto the structure without future change.

CONCLUSION

The development of architectural robots as autonomous entities will be a longer process than any one experiment or any one discipline can deliver. The potential for differentiating architectural robotics from object-based robotics is promising and the active inclusion of space and human interaction in it is a crucial to making progress in this direction. Kinetics seem to promise answers in giving architecture more physical variability and expression, but most likely mechanically based motion is not the answer due to the issues of scale and cost and robustness. Rather,

8



8

14 Kinect camera view of the space with 20 actuation state groups and human presence history curve superimposed

15 Control flow diagram of the different parts

adaptability on a finer grained material level, addressing multiple architecturally relevant qualities at once, will lead to a more distributed and robust behavior. The Flexing Room's actuated active bending structure is a simplified attempt in that direction. The experiment acknowledges the need to depart from animated, previously designed and simulated structures in order to include unpredictable environmental and human factors directly into the architectural response. Learning open ended combinations of architectural degrees of freedom in parallel to evolving human use requires more robust and large scale techniques such as machine learning processes to develop architectural expression based in the behavioral and in spatial interfaces. Design has always included a certain amount of open-endedness in its programmatic and social approach. What is new is that design intent is not only captured in material form of the built artifact and in information conveyed to its human occupants, but can also evolve based on feedback in the programmed autonomous behavioral side of architectural design.

ACKNOWLEDGEMENTS

The flexing room installation was made possible by a commission for its installation for the 2017 Seoul Biennale of Architecture and Urbanism in the "Iminent Commons" exhibit curated by Alejandro Zaera–Polo and Jeffrey Anderson [Zaero-Polo and Anderson 2017]. Furthermore its development was supported with research funds from Princeton University based on findings developed from the Bowtower project.

REFERENCES

Bier, Henriette., 2014, “Robotic Building(s)”, Next Generation Building 1 (2014) 83–92 83, DOI: 10.7564/14-NGBJ8

Bier, Henriette, 2011. “Robotic environments”, In Proceedings of the 28th international symposium on automation and robotics in construction, 863–868

Brooks, Rodney. A., “Intelligence without representation”, Artificial Intelligence 47 (1991), 139–159

Cheney, Nick, MacCurdy, Robert, Clune, Jeff , Lipson, Hod, 2013, “Unshackling evolution: evolving soft robots with multiple materials and a powerful generative encoding”, In Proceedings of the 15th annual conference on Genetic and evolutionary computation (GECCO '13), Christian Blum (Ed.). ACM, New York, NY, USA, 167-174

Eng, K., Mintz, M., Verschure, P. F M J, 2005, "Collective Human Behavior in Interactive Spaces", International Conference on Robotics and Automation.

Eng, K., Klein, D., Baebler, A., Bernardet, U., Blanchard, M., Costa, M., Delbrueck T., Douglas R., J., Hepp, K., Manzolli, J., Mintz M., Roth, F., Rutishauser, U., Wassermann, K., Whatley, A.M., Wittmann, A., Wyss, R., Verschure, P., F.M.J., 2003, “Design for a brain revisited: The Neuromorphic Design and Functionality of the interactive space 'Ada'”, Reviews in the Neurosciences, 14, 145-180.

Fox, Michael, Kemp, Miles, “Interactive Architecture”, 2010, Princeton Architectural Press

Green, Keith Evan and Gross, Mark 2012, “Architectural Robotics, Inevitably”, Interactions Magazine xix,1 January February.

Joo ,H., Simon, T., Li, X., Liu, H., Tan, L., Gui, L., Banerjee, S., Godisart, T., Nabbe, B., Matthew, I., Kanade, T., Nobuhara, S., and Sheikh, Y., (2015), “Panoptic Studio: A Massively Multiview System for Social Interaction Capture”, 2015 ICCV.

Hyperbody Group TU Delft, accessed 2017, http://www.hyperbody.nl/research/projects/robotic-architecture

Superimposed images of different poses, showing the sensor view on screen 11

Kapadia, A., Walker, I., Green, K. E., Manganelli, J., Houayek, H.,James, A. M., Kanuri, V., Mokhtar, T., Siles, I., Yanik, P., "“Architectural Robotics": An Interdisciplinary Course Rethinking the Machines We Live In", 2010 IEEE International Conference on Robotics and Automation Anchorage Convention District.

Kilian, A., Sabourin, F. “Embodied Computation – An Actuated Active Bending Tower: Using Simulation-Model-Free Sensor Guided Search To Reach Posture Goals” ACADIA 2017: DISCIPLINES & DISRUPTION 2017.

Klute, G.K., B. Hannaford, “Modeling Pneumatic McKibben Artificial Muscle Actuators: Approaches and Experimental Results,” Submitted to the ASME Journal of Dynamic Systems, Measurements, and Control, November 1998, revised March 1999.

Oosterhuis, Kas, et al., 2012, “Hyperbody First Decade of Interactive Architecture”.

Penfield, Wilder.; Boldfrey, E. (1937). "Somatic Motor And Sensory Representation In The Cerebral Cortex Of Man As Studied By Electrical Stimulation". Brain 60

Penfield, Wilder, Rasmussen, Theodore, 1950, "The cerebral cortex of man", The Macmillan Company, New York, N.Y. 1950. 248 pp.

Richter, J. N., Hochner, B., Kuba, M. J., 2015, “Octopus arm movements under constrained conditions: adaptation, modification and plasticity of motor primitives”, The Company of Biologists Ltd, The Journal of Experimental Biology (2015) 218, 1069-1076 doi:10.1242/jeb.115915

Sterk, T. d'Estrée, 2003, “Using Actuated Tensegrity Structures to Produce a Responsive Architecture”, ACADIA 2003 Indianapolis.

Zaero-Polo, Alejandro, Anderson, Jeffrey, (Editors) "Imminent Commons: The Expanded City: Seoul Biennale of Architecture and Urbanism 2017", Actar 2017.

IMAGE CREDITS

Figure 2: ©Texas Instruments
Figure 3: © Original diagram from (Penfield and Rasmussen 1950)
Figure 4 @Ekso exoskeleton https://eksobionics.com
All other drawings and images by the author.

Axel Kilian has taught and researched as an Assistant Professor at Princeton University and Delft University of Technology and a Postdoctoral Associate at MIT. He holds a PhD in Design and Computation and a Master of Science in Architectural Studies from MIT as well as a professional degree in architecture from the University of the Arts Berlin. He came to MIT on a German-American Fulbright scholarship. His most recent research work in architectural robotics has been exhibited in the 2016 Istanbul Design Biennale and the 2017 Seoul Biennale of Architecture and Urbanism. His current research is on embodied computation.