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Robotic Building as Integration of Design-to-Robotic-Production & Operation

Henriette Bier

TU Delft
Faculty of Architecture and the Built Environment
Delft, Netherlands

Abstract

Robotic Building (RB) implies both physically built robotic environments and robotically supported building processes. Physically built robotic environments consist of reconfigurable, adaptive systems incorporating sensor-actuator mechanisms that enable buildings to interact with their users and surroundings in real-time. These require design-to-production and operation chains that may be (partially or completely) robotically driven.

Keywords

Robotic environments; Robotic Building; Design-to-Robotic-Production; Design-to-Robotic-Operation.

 Bier, H. (2017). Robotic Building as Integration of Design-to-Robotic-Production & Operation. SPOOL, 4 (1). doi:10.7480/spool.2017.1.1908

1 Introduction

While architecture and architectural production are increasingly incorporating aspects of non-human agency employing data, information, and knowledge contained within the (worldwide) network connecting electronic devices, the relevant question for the future is not whether robotic building will be implemented, but **how robotic systems will be incorporated into building processes and physically built environments**[1] in order to serve and improve everyday life.

This 1st issue of SPOOL in 2007 aims to answer this question by critically reflecting on the achievements of the last decades in applications of robotics in architecture and furthermore outlining potential future developments and their societal implications. The focus is on robotic systems embedded in buildings and building processes implying that architecture is enabled to interact with its users and surroundings in real-time and corresponding design-to-production and -operation (D2P&O) chains are (in part or as whole) robotically driven. Such modes of production and operation involve agency of both humans and non-humans. Thus agency is not located in one or another but in the heterogeneous associations between them[2] and authorship is neither human or non-human but collective, hybrid, and diffuse.

2 Robotic Building

Robotic Building (RB) relies on interactions between human and non-human agents not only at design and production level but also at building operation level, wherein users and environmental conditions contribute to the emergence of multiple architectural configurations. RB implies both physically built robotic environments (fig.1) and robotically supported building processes (fig.2&3). Physically built robotic environments consist of reconfigurable, adaptive systems incorporating sensor-actuator mechanisms that enable buildings to interact with their users and surroundings in real-time. These require **design-to-production (D2P) and operation chains that may be (partially or completely) robotically driven**.

In this context, design becomes process- instead of object-oriented, use of space becomes time- instead of program- or function-based, which implies that architects design increasingly processes, while users operate multiple time-based architectural configurations[3] emerging from the same physical space that may physically or sensorially reconfigure in accordance to environmental and user specific needs.

1 Bier, H. (2013) 'Robotic(s in) Architecture', Interactive Architecture #5 (Heijningen: Jap Sam Books), pp. 6-8

2 Latour, B. (2014) Reassembling the Social: An Introduction to Actor-Network-Theory (Oxford: Oxford University Press), pp. 63-86

3 Bier, H. and Knight, T. (2010) 'Digitally-driven Architecture', Footprint #6 (Delft: Stichting Footprint), pp. 1-4

FIGURE 1 Design-to-Robotic-Operation framework developed at TUD (2013-16)

In this context, spatial reconfiguration may be facilitating multiple, changing uses of physically built space within reduced timeframes. Furthermore, interactive energy and climate control systems embedded in building components and employing renewable energy sources, such as solar and wind power, may reduce architecture's ecological footprint while enabling a time-based, demand-driven use of space[4]. Both rely on virtual modelling and simulation that interface the production and real-time operation of physically built space[5] establishing thereby an unprecedented design-to-robotic-production and -operation (D2RP&O) feedback loop, which is focus of this issue.

NGB #3 presents extended abstracts from the RB session hold 2016 at the GSM#3 symposium. Most abstracts discuss D2RP&O as separate and quite different processes, while RB aims at the integration of two.

4 Liu Cheng, A. and Bier, H. (2016) 'An Extended Ambient Intelligence Implementation for Enhanced Human-Space Interaction', Proceedings of the 33rd International Symposium on Automation and Robotics in Construction, pp. 778-786

5 Bier, H. and Knight, T. (2014) 'Data-driven design to production and operation', Footprint #15 (Delft: Stichting Footprint), pp.1-5

3 D2RP

D2RP is discussed by Kathrin Dörfler in terms of robotic fabrication implemented directly on construction sites. She brings robots directly to the construction site (video 1) in order to autonomously fabricate structures outside factories. Jelle Feringa explores the industrial ramifications of architectural robotics (video 2), while Justin Dirrenberger implements with XtreeE robotic 3D printing with concrete on and off site. He also introduces architectured materials bridging across the micro-scale of materials and the macro-scale of engineering structures. He identifies this as a paradigm shift. According to him, materials cannot be considered monolithic anymore as any set of materials functions, even antagonistic ones, can be envisaged in the future.

4 D2RO

D2RO is discussed by Sebastian Vehlken by critically examining the techno-history of robotics, which intertwines engineering and biological knowledge and whose applications deal with questions about self-organization in changing environments – on the ground, in the air, and under water. Keith Evan Green investigates interactive, intelligent, and adaptable environments (video 3) by way of embedded robotics. He examines how architectural robotic systems support and augment everyday life at work, school, and home, while Holger Schnädelbach is concerned with buildings that are specifically designed to adapt to their environment and to their inhabitants. His focus is on how architects and inhabitants co-create Adaptive Architecture, how the emerging feedback loops shape people's behaviours and how inhabitants and environment become interaction partners.

5 D2RP&O

The integration of D2RP with D2RO implies understanding both approaches as requiring safe human-robot interaction and collaboration in the production and operation of buildings. Since production and operation of buildings takes place in more or less unstructured environments both imply similar challenges and opportunities.

Integrated D2RP&O as explored at TUD, addresses the notion of hybrid componentiality, where the components of a system are designed to embody a *hybrid* whole. In this context, the D2RP is informed by structural, functional, environmental, and assembly considerations[6]. At the micro-scale, the material is conceived as a porous system, where the degree and distribution of porosity i.e. density are informed by functional, structural and environmental requirements, while taking into consideration both passive (structural strength, thermal insulation, etc.) and active behaviours (adaptive, reconfigurable, etc.). At the meso-scale, the component is informed mainly by the assembly logic, while at the macro scale, the assembly is informed by architectural considerations[6].

6 Mostafavi, S. and Bier, H. (2016) 'Materially Informed Design to Robotic Production: A Robotic 3D Printing System for Informed Material Deposition', Robotic Fabrication in Architecture, Art and Design 2016 (International: Springer), pp. 338-349

By integrating sensor-actuators such as light dependent resistors, infrared distance sensors, pressure and accelerometer sensors, etc. that are informing lights, speakers, heaters, ventilators, and/or reconfigurable building components, users implicitly and explicitly customize the use of the physically built space.
For D2RO, a distributed and decentralized system architecture is employed to identify activities4 in order to engage users proactively and to enhance their experience.

The ambition is to advance D2RP&O methods in order to increase process- and material-efficiency and improve interactive use of physically built space. RB is unique in its aim to link design and production with smart operation of the built environment and advances applications in performance optimization, robotic manufacturing, and user-driven operation in architecture.

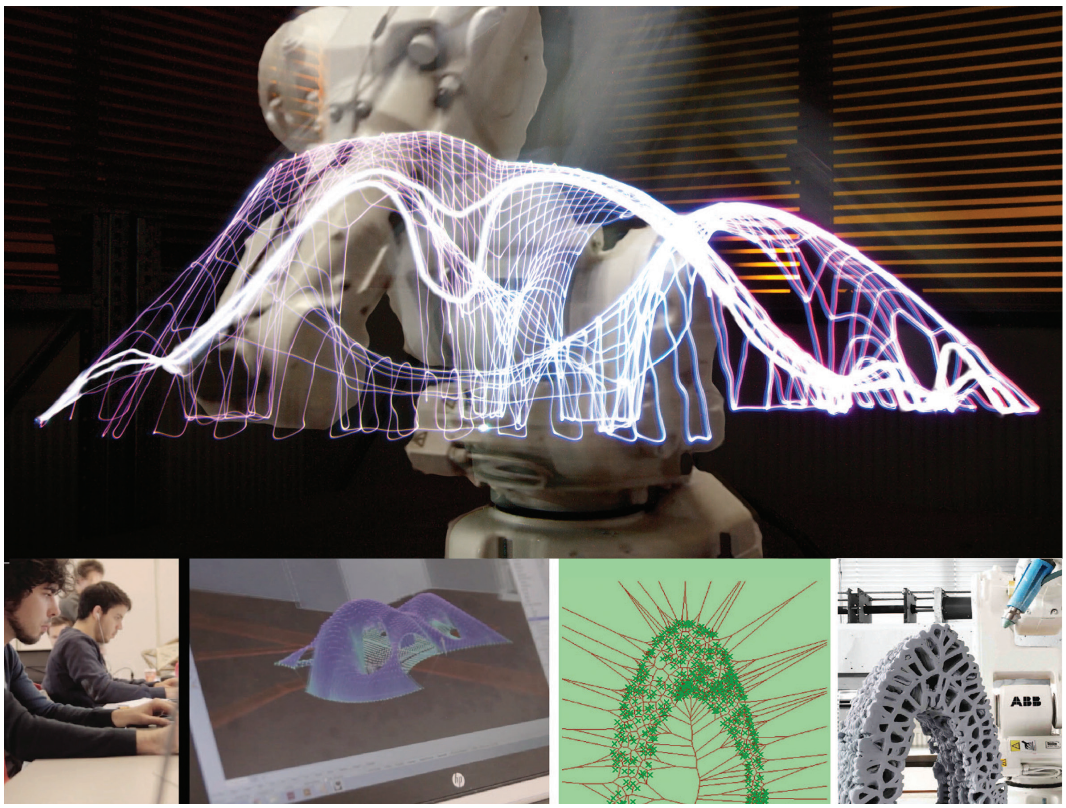

FIGURE 2 Design-to-Robotic-Production developed at TUD (2014-16)

Acknowledgements

This paper has profited from the contribution of Hyperbody and in particular Robotic Building researchers and MSc students involved in the presented projects. It furthermore, profited from the presentations and discussions during the Robotic Building session at the Game Set Match #3 symposium organised at TUD, 2016.

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Bier, H. and Knight, T. (2014) 'Data-driven design to production and operation', Footprint #15 (Delft: Stichting Footprint), pp.1-5

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Latour, B. (2014) Reassembling the Social: An Introduction to Actor-Network-Theory (Oxford: Oxford University Press), pp. 63-86

Liu Cheng, A. and Bier, H. (2016) 'An Extended Ambient Intelligence Implementation for Enhanced Human-Space Interaction', Proceedings of the 33rd International Symposium on Automation and Robotics in Construction, pp. 778-786

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Design to Robotic Production for Informed Materialization Processes

Sina Mostafavi, Ana Anton, Serban Bodea

TU Delft
Faculty of Architecture and the Built Environment
Delft, the Netherlands

Abstract

Design to Robotic Production (D2RP) establishes links between digital design and production in order to achieve informed materialization at architectural scale. D2RP research is being discussed under the computation, automation and materialization themes, by reference to customizable digital design means, robotic fabrication setups and informed materialization strategies implemented by the Robotic Building group at Hyperbody, TU Delft.

Keywords

Robotic Production; automation; Scalable Porosity; informed materialization

 Mostafavi, S., Anton, A, Serban, B. (2017). Design to Robotic Production for Informed Materialization Processes.
SPOOL, 4 (1). doi:10.7480/spool.2017.1.1914

FIGURE 1 Recursive milling method: left - with homogenous resolution; middle - tool path with informed resolution based on material removal; right - prototyping.

1 Computation and design

Computation in architecture generates and processes large amounts of data resulting from algorithmic models involving multiple levels of resolution and scale. Inherently, computational design methodologies use analytical and generative routines that inform 3D models, often resulting in multidimensional arrays of associative spatial-material data. These require building logical relations between *information* and *matter* for the creation of inhabitable and efficient environments, with distinct materialization and aesthetics.

Specifically, the role of computation in robotic production systems is extended firstly, by the way machines are programmed and secondly, by the way material is distributed and behaviors are processed. The computation of the production logic applies procedural design that leads to synthetic forms of representation. For instance, *recursive milling* (figure 1) consists of continuous robotic paths with embedded information about form, material texture and fabrication constraints. Optimization of the path is embodied into a self-avoiding curve[1] that translates into a minimum length tool-path, featuring low and high resolution, for fast and slow material removal.

Another application of computation in robotic production has been explored through *porosity*. This implies quantifiable relations between matter and void that construct a computable binary system, in order to improve efficiency of building systems. Robotic path constraints are embedded as design drivers to create informed volumetric tectonics and surface textures (figure 2). Computation of porosity involves material optimization in order to facilitate optimal structural and environmental performance with minimal material use.

In this context, computation becomes more than series of logical steps for rationalization or performance optimization, but rather a part of design to production. This enhanced multi-dimensional computation model processes data related to material properties and robotic fabrication routines in order to address scalability of robotic fabrication.

1 Hilbert space-filling curve, first described by mathematician David Hilbert in 1891.

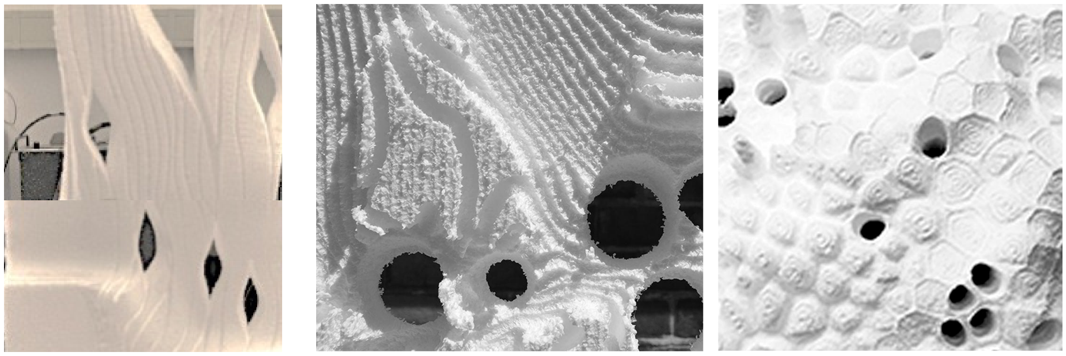

FIGURE 2 Materialization of informed porosity computed for volumetric tectonics and surface textures

2 Automation and robotic production

The integration of fabrication technology in architectural design promotes decentralized approaches in production processes and facilitates mass-customization. Open-source computation in design and production leads to the democratization of fabrication routines, effectively allowing both designers and users to access and operate industrial machinery on demand.

This has been explored at *InDeSem 2015* with a deployable setup (figure 3), which has been installed and became operational within a day. The production capacity of three industrial robots equipped with different tools allowed production of customized building components, the small programmable factory continuously operated 24/7 with design and fabrication data being shared between parametric models and robotic workstations.

The multi-technique robotic setup, focused on optimizing production workflow for subtractive fabrication and additive fabrication. It combined two subtractive fabrication techniques for prototyping, volumetric cutting for fast material removal and robotic milling to add further details and porosity. The efficiency of this multi-mode robotic fabrication approach resulted in the extension of both design space and production space. While all these applications used robotic motion as a tool for interacting with both digital and physical environments, the research aimed at integrating robotic technology into architectural design in order to achieve automation of building processes.

FIGURE 3 InDeSem: Deployable setup of three robots using several fabrication techniques (wire cutting, milling and drawing)

FIGURE 4 Scalable Porosity: Customised robotic set-up for 3D printing on ruled surfaces

With focus on Additive Manufacturing, another example of technology integration for automation of building processes, is the *Scalable Porosity* project (figure 4). The aim was to use robotically fabricated polystyrene components with ruled surfaces[2] as substrate to expand pre-existing fabrication capacity of ceramic clay, on curved surfaces. This research and operation implementation benefited from the clay extruder system[3] developed as part of the project. The numerically controlled plunger-based system for additive manufacturing employed small-medium range of robotic arms, with low payload but high precision, and effective speed for architectural scale.

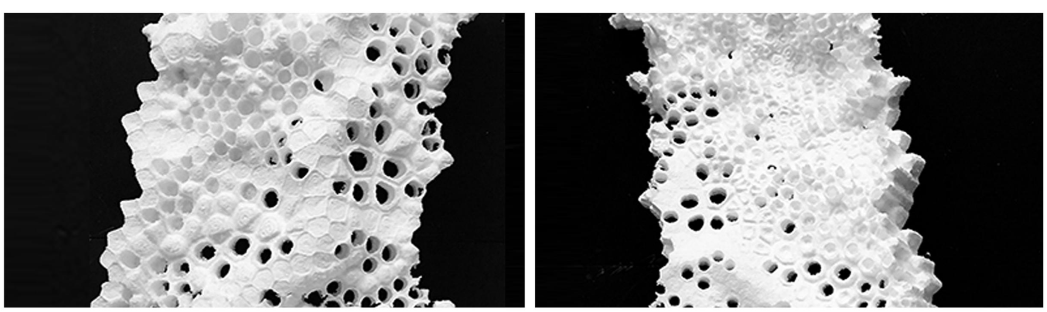

FIGURE 5 Porous Assembly: Exterior (left) and interior (right) sides

2 Pottmann, H., Asperl, A., Hofer, M. and Kilian, A. (2007). Ruled Surfaces, in Architectural Geometry. Exton: Bentley University Press, p.312.

3 Mostafavi, S., Bier, H., Bodea, S. and Anton, A. (2015). Informed Design to Robotic Production Systems. in eCAADe 2015 Volume 2 Real Time. Vienna: eCAADe, p.294.

3 Informed Materialization

In the presented case studies, informed materialization relies on multiple robotic production methods and materials in order to achieve quantifiable design performances. This has been reached through computational design and robotic materialization of porosity, hybridity and assembly at multiple scales ranging from macro-architectural and meso-componential to micro-material levels. As interface between digital design space and physical fabrication, materiality is mainly defined along three performance criteria: spatial functionality, structural capacity and environmental efficiency.

For instance, the *Porous Assembly* project implied differentiation in material thickness and variation in porosity, while considering multiple structural and environmental parameters (figure 5). The material was robotically approached from multiple directions, the strategy for robotic path generation being that of removing material where not needed. This project introduced a three-dimensional finger joint system, only producible through robotic fabrication, for the assembly of the mass customized components.

Hybrid Assembly (figure 6) focused on multi-materiality. Materials are distributed following properties and behaviors based on multiple design objectives. The project introduces one material namely cork to improve environmental acoustic performance of the building envelope. The three-dimensional intertwining of cork with structural polystyrene components creates a hybrid material system. The flexibility of the cork component is achieved through carving material from multiple directions with multiple resolutions.

4 Conclusion

By integrating computation, automation and materialization D2RP introduces strategies for extending and associating design space, fabrication space and material property space. Design space is enhanced by computation implemented at multiple scales, and fabrication relies on multimode robotic setups enhanced by several fabrication techniques, while materialization fuses porosity, hybridity and assembly for the production of informed architectural components and large-scale building assemblages

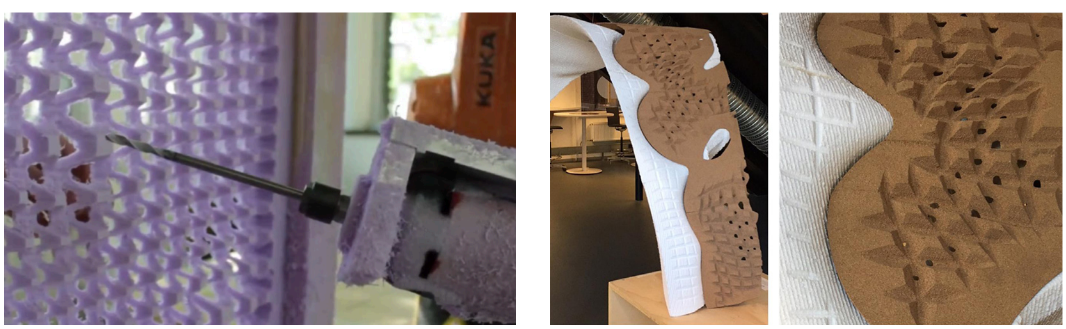

FIGURE 6 Hybrid Assembly, extending material properties to enhance the performance through integration of multiple materials and fabrication methods

Mostafavi, S., Anton, A, Serban, B. (2017). Design to Robotic Production for Informed Materialization Processes.
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From architectured materials to the development of large-scale additive manufacturing

Justin Dirrenberger

ENSAM
Paris, France

Abstract

Architectured materials are a rising class of materials that bring new possibilities in terms of functional properties, filling the gaps and pushing the limits of Ashby's materials performance maps for the specific flexural rigidity of plates. The term architectured materials encompasses any microstructure designed in a thoughtful fashion, such that some of its materials properties have been improved in comparison to those of its constituents, due to both structure and composite effects, which depend on the multiphase morphology, i.e. the relative topological arrangement between each phase.

Capitalising on the concepts of architectured materials, our group at Laboratoire PIMM explored the potential applications of large-scale 3D printing techniques to civil engineering structures, based on a collaboration with the ENSA Paris-Malaquais Digital Knowledge department, lead by Philippe Morel, and INRIA (French national research center for computation and automation), through the DEMOCRITE project, which was funded by HESAM Université.

Keywords

Architectured materials; 3D printing; additive manufacturingl microstructure

 Dirrenberger, J. (2017). From architectured material to the development of large-scale additive manufacturing.
SPOOL, 4 (1). doi:10.7480/spool.2017.1.1910

Architectured materials are a rising class of materials that bring new possibilities in terms of functional properties, filling the gaps and pushing the limits of Ashby's materials performance maps[1], as shown on Figure 1 for the specific flexural rigidity of plates. The term architectured materials encompasses any microstructure designed in a thoughtful fashion, such that some of its materials properties have been improved in comparison to those of its constituents, due to both structure and composite effects, which depend on the multiphase morphology, i.e. the relative topological arrangement between each phase[2].

There are many examples: particulate and fibrous composites, foams, sandwich structures, woven materials, lattice structures, etc. One can play on many parameters in order to obtain architectured materials, but all of them are related either to the microstructure or the geometry. Parameters related to the microstructure can be optimised for specific needs using a materials-by-design approach, which has been thoroughly developed by chemists, materials scientists and metallurgists. Properties improvements related to microstructural design are intrinsically linked to the synthesis and processing of materials and are therefore due to micro and nanoscale phenomena, taking place at a scale ranging from 1 nm to 10 μm. This scale is below the scope of the present project work, in terms of topology optimisation, but has been extensively studied in the literature[3].

Processing is the key technological issue for further development of architectured materials, and progress is made every day in this direction, as it was done in[4] by using a sequence of several processing techniques in order to fabricate ultralight metallic microlattice materials. From a macroscopic viewpoint, parameters related to the geometry have mainly been the responsibility of structural and civil engineers for centuries: to efficiently distribute materials within structures. An obvious example would be the many different strategies available for building bridges. At the millimetre scale, materials can be considered as structures, i.e. one can enhance the bending stiffness of a component by modifying its geometry while keeping the lineic mass (for beams) or surfacic mass (for plates) unchanged[5]. On the other hand, one might need a lower flexural strength for specific applications, with the same lineic and/or surfacic masses. This can be achieved with strand structures, i.e. by creating topological interfaces in the material.

Architectured materials thus lie between the microscale and the macroscale. This class of materials involves geometrically engineered distributions of microstructural phases at a scale comparable to the scale of the component, thus calling for enriched models of continuum mechanics, i.e. generalized continua theories, in order to describe the behaviour of architectured materials, strain-gradient elasticity[66], and strain-gradient plasticity for instance. This topic has been especially fruitful these last few years for the French mechanics of materials community ; this results in the availability of versatile models able to describe the various situations encountered with architectured materials. Given mature processing techniques, architectured materials are promised to a bright future in industrial applications due to their enticing customisable and multifunctional specific properties.

1 M. Ashby, Designing Architectured Materials, Scripta Materialia, vol. 68, no. 1, pp. 4-7, 2013.

2 Ibid. and M. F. Ashby and Y. Bréchet, Designing hybrid materials, Acta Materialia, vol. 51, pp. 5801-5821, 2003.

3 D. Embury and O. Bouaziz, Steel-Based Composites: Driving Forces and Classifications, Annual Review of Materials Research, vol. 40, pp. 213-241, 2010.

4 T. A. Schaedler, A. J. Jacobsen, A. Torrents, A. E. Sorensen, J. Lian, J. R. Greer, L. Valdevit and W. B. Carter, Ultralight Metallic Microlattices, Science, vol. 334, pp. 962-965, 2011.

5 P. Weaver and M. F. Ashby, The Optimal Selection of Material and Section-shape, Journal of Engineering Design, vol. 7, no. 2, pp. 129-150, 1996.

6 N. Auffray, J. Dirrenberger and G. Rosi, A complete description of bi-dimensional anisotropic strain-gradient elasticity, International Journal of Solids and Structures, vol. 69, pp. 195-210, 2015.

Capitalising on the concepts of architectured materials, our group at Laboratoire PIMM explored the potential applications of large-scale 3D printing techniques to civil engineering structures, based on a collaboration with the ENSA Paris-Malaquais Digital Knowledge department, lead by Philippe Morel, and INRIA (French national research center for computation and automation), through the DEMOCRITE project, which was funded by HESAM Université for 150k€.

Until recently, additive manufacturing (AM) techniques were confined to high value adding sectors such as the aeronautical and biomedical industries, mainly due to the steep cost of primary materials used for such processes. In the last decade, the development of large-scale AM in such domains as design, construction and architecture, using various materials such as polymers, metals and cementitious materials. The deposition process developed in the project was designed for cement-based 3D printing.

Based upon an understanding of the limitations identified in previous projects present in the literature, the DEMOCRITE project dealt with the large-scale additive manufacturing of selective deposition for ultra-high performance concrete (UHPC). The 3D involved printing process is based on a FDM-like technique, in the sense that a material is deposited layer by layer through an extrusion printhead. The project also explored the possibilities offered by computer-aided design (CAD) and optimisation, and their integration within the product design process in the case of large-scale AM. Thus, the introduced technology succeeded in solving many of the problems that could be found in the literature. Most notably, the process enabled the production of 3D large-scale complex geometries, without the use of temporary supports, as opposed to 2.5D examples found in the literature for concrete 3D printing. Multifunctionality enabled by arbitrary complex geometry is studied for a large-scale structural element.

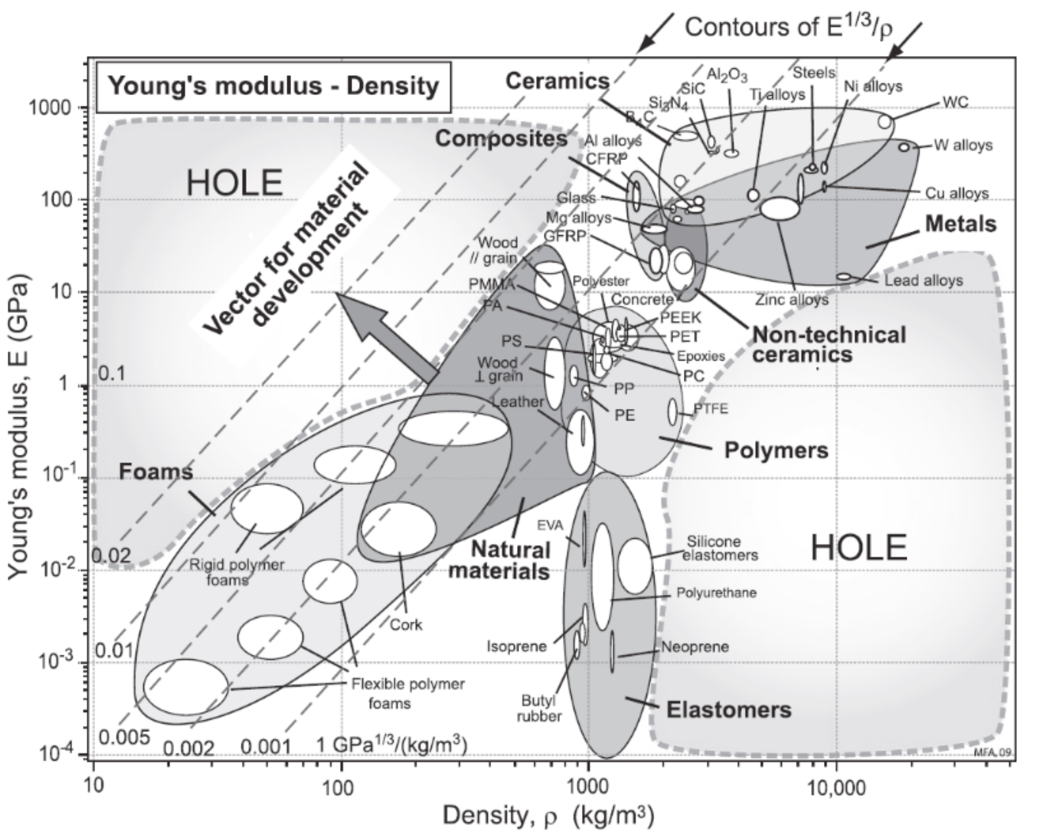

FIGURE 1 Material performance map for Young's modulus, taken from: M. Ashby, Designing Architectured Materials, Scripta Materialia, vol. 68, no. 1, pp. 4-7, 2013.

The DEMOCRITE project was designed upon the following challenge: developing a large-scale additive manufacturing technology capable of producing multifunctional structural elements with increased performance. With this work, the aim of our group was also to take part in the redefinition of architecture and design in the light of integral computation and fully automated processes. The results of the DEMOCRITE project, including tangential continuity slicing, optimization for low thermal conductivity, as well as actual built structural elements, were published in Materials & Design[7]. An example of the structures developed and printed in DEMOCRITE is shown on Fig.2, along with a more recent construction by XtreeE[8]. As a continuation of the project, a spin-off company, XtreeE, was created in order to develop and commercialise the 3D printing technology introduced.


FIGURE 2 UHPC 3D printing. From: C. Gosselin, R. Duballet, P. Roux, N. Gaudillière, J. Dirrenberger ans P. Morel, Large-scale 3D printing of ultra-high performance concrete–a new processing route for architects and builders, Materials and Design, vol. 100, pp. 102-109, 2016. and XtreeE, http://www.xtreee.com

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7 C. Gosselin, R. Duballet, P. Roux, N. Gaudillière, J. Dirrenberger ans P. Morel, Large-scale 3D printing of ultra-high performance concrete–a new processing route for architects and builders, Materials and Design, vol. 100, pp. 102-109, 2016.

8 XtreeE, http://www.xtreee.com

Swarm Robotics, or: The Smartness of 'a bunch of cheap dumb things'

Sebastian Vehlken

Leuphana University
Lüneburg, Germany

Abstract

Not only recent Science Fiction – e.g., Star Trek Beyond (USA 2016) – celebrates the capacities of robot collectives. Also RoboCup, an annual robot soccer competition, or Harvard University's Kilobot Project show stunning examples of the central idea behind Swarm Robotics: »[U]sing swarms is the same as getting a bunch of small cheap dumb things to do the same job as an expensive smart thing« (Beni/Wang 1989). This article examines some crucial aspects of the techno-history of a research field which intertwines engineering and biological knowledge and whose applications deal with compelling questions about synchronization and self-organization in changing environments – on the ground, in the air, and under water. Swarm Robotics, I argue, thereby challenge traditional architectural concepts by exhibiting a thorough »vision of process« (Gramazio/Kohler et al. 2013).

Keywords

Swarm robotics; Swarm Intelligence (SI); agent-based modeling (ABM); architectural design

1 Going wild

Swarming, as I have argued elsewhere[1], can be understood as a novel cultural technique: Swarms, flocks and schools first emerged as operational collective structures by means of the reciprocal computerization of biology and biologization of computer science. In a recursive loop, swarms inspired agent-based modelling and simulation (ABM), which in turn provided biology researchers with enduring knowledge about dynamic collectives. This conglomerate led to the development of advanced, software-based 'particle systems'. Agent-based applications are used to model solution strategies in a number of areas where opaque and complex problems present themselves – from epidemiology to logistics, from market simulations to crowd control. Swarm intelligence (SI) has thus become a fundamental cultural technique for governing dynamic processes.

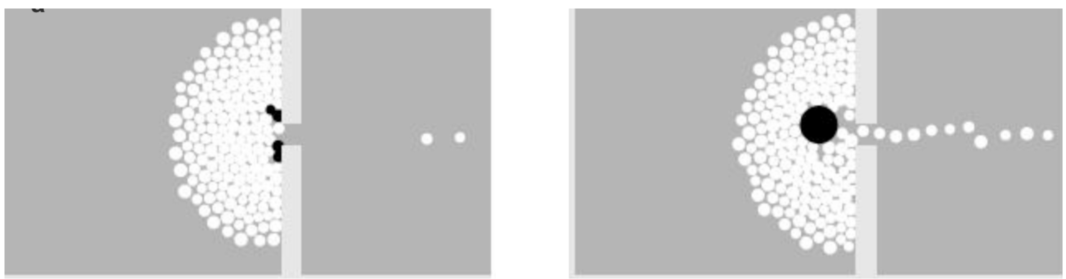


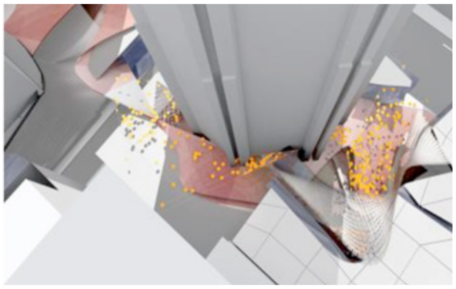
FIGURE 1 Dirk Helbing, Imre Farkas, and Tamás Vicsek, 'Simulation dynamical features of escape panic', in Nature 407 (2000), 487-490: 488.

This capacity also appeals to architectural and building processes. The application of ABM, for instance, proved effective in evacuation studies. Computer simulations of the collective movement of agents in 3D-space can reveal counter-intuitive solutions for architectures which smoothen the flow and increase the speed of movement – like placing pillars directly in front of an exit. In such cases, swarming affects the *inner structure* of a building.[2] (Fig. 1) In urban planning, the simulation of traffic or pedestrians flows and patterns has been used to also shape the *outer appearance* of buildings and public spaces. As an example, the experimental architecture research practice Kokkugia modelled force fields of the dynamic surroundings of buildings in a city scape by means of point clouds or used SI models which are inspired by termites for the optimization of routing by simulated pheromone trails.[3] (Fig. 2)

1 Sebastian Vehlken, 'Zootechnologies. Swarming as a Cultural Technique', *Theory, Culture and Society* 30/6, *Special issue Cultural Techniques* (2013): 110-131.

2 Compare e.g. Dirk Helbing and Anders Johansson, 'Pedestrian, Crowd and Evacuation Dynamics,' in *Encyclopedia of Complexity and Systems Science*, ed. Robert A. Meyers, (New York: Springer, 2009), 6476-6495; Dirk Helbing et. al., 'Self-organized pedestrian crowd dynamics: Experiments, simulations, and design solution,' *Transp Sci* 39(1) (2005):1–24.

3 See: 'Interview with Roland Snooks,' *suckerPUNCH*, April 25, 2010, accessed November 28, 2016, http://www.suckerpunchdaily.com/2010/04/25/interview-with-roland-snooks/. In *Emergent Field* (2003), Kokkugia uses the example of a plaza around Melbourne's Nauru House: the project attempts to develop an emergent form of urban space in a critique of the modernist object-ground relationship. Instead, it views the urban condition as a gradient field of influence. Kokkugia's *Swarm Urbanism* project (2009) uses SI as a self-organising generative environment for a redesign of the Melbourne Docklands. A category of agents aggregate matter to form in a stigmeric process, following rules of interaction similar to termite swarms.



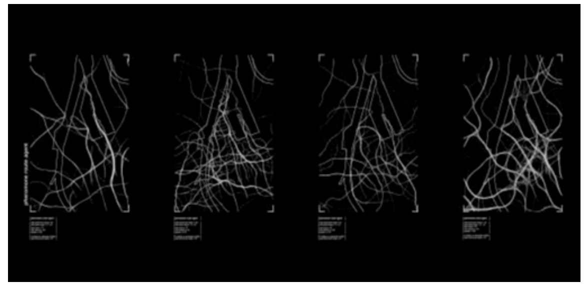


FIGURE 2 a) URL: http://www.kokkugia.com/swarm-urbanism/emergent-field and b) URL: http://www.kokkugia.com/swarm-urbanism

On a more conceptual level, Kas Oosterhuis referred to *swarming* as a novel mode of thinking about architectural design which would replace substantial forms and orderings with an encompassing notion of architecture as information flow.[4] It centered around the structuring of various movement vectors in a distributed system of different interacting agents – that is, people, materials, or environmental forces: »An individual architect will no longer be tempted to have the illusion of complete control over the process. [...]. Now, in the beginning of the twenty-first century architecture is going wild [...].«[5]

Architectural design can benefit from the algorithmic logics of SI and ABM: *First*, such softwares extend the possibilities of handling and optimizing the complex interplay of various input variables for building processes. *Second*, the agent collectives – if appropriately tuned – will self-organize in a number of probably interesting or desirable forms *over time*. In this transformation towards a time-based perspective, architecture becomes based on movements. *Third*, it introduces a novel kind of futurology into architecture. With computer experiments in ABM software, a great number of different scenarios can be tested and evaluated against each other, opening insight in a variety of different desirable futures. And *fourth*, the capacity of adding ever more elements to the ABM allows for a seamless synthesis of multiple ideas or for a feedback of opinions by customers or future users during an ongoing design process.

All this indicates a turn from an analytical to a synthetic approach and to a novel cultural technique to dispose of and to arrange the world we live in – with novel potentials for architectural design and construction.[6]

4 Kas Oosterhuis: 'Swarm Architecture,' accessed November 28, 2016, http://www.oosterhuis.nl/quickstart/index.php?id=538.

5 Ibid.

6 This is reflected in a number of further conceptual papers, e.g. Sebastian von Mammen and Christian Jacob, 'Swarm-Driven Idea Models – From Insect Nests to Modern Architecture', *WIT Transactions on Ecology and Environment* 113 (2008), 117-26; Yifeng Zeng, Jorge Codero, et. al., 'SwarmArchitect. A Swarm Framework for Collaborative Construction', in *Proceedings of the 9th Annual Conference on Genetic and Evolutionary Computation* (2007), 186; Pablo Miranda Carranza and Paul Coates, 'Swarm Modelling. The Use of Swarm Intelligence to Generate Architectural Form,' accessed November 28, 2016, http://www.generativeart.com/on/cic/2000/CARRANZA_COATES.HTM; Julian Nembrini et al., 'Mascarillion: Flying Swarm Intelligence for Architectural Research,' accessed November 28, 2016, http://infoscience.epfl.ch/record/50996; see as an overview also Sebastian Vehlken: 'Swarming. A Novel Cultural Technique for Generative Architecture,' *Footprint* 15 (2014) (= Special Issue Data-Driven Design, ed. Henriette Bier, Terry Knight), 9-17.

2 Fast, cheap, and out of control

Since serveral years, yet another connection of swarming and architecture becomes apparent. In February 2014, a robotics team of Harvard University presented a robot collective called *TERMES*. Inspired by the decentralized communication structure and collective behavior of termites, the team developed an interaction algorithm for a multi-agent system motivated »by the goal of relatively simple, independent robots with limited capabilities, able to autonomously build a large class of nontrivial structures using a single type of prefabricated building material.«[7] After running the algorithm with software agents, the research group implement it in a group of physical robots to test its functioning ›in vivo‹. Quite strikingly, *TERMES* commenced to collectively put together the building bricks: Swarms, in this example, not only participate in the architectural design process in the form of ABM, but actually serve as *builders* of architectural structures. (Fig. 3)

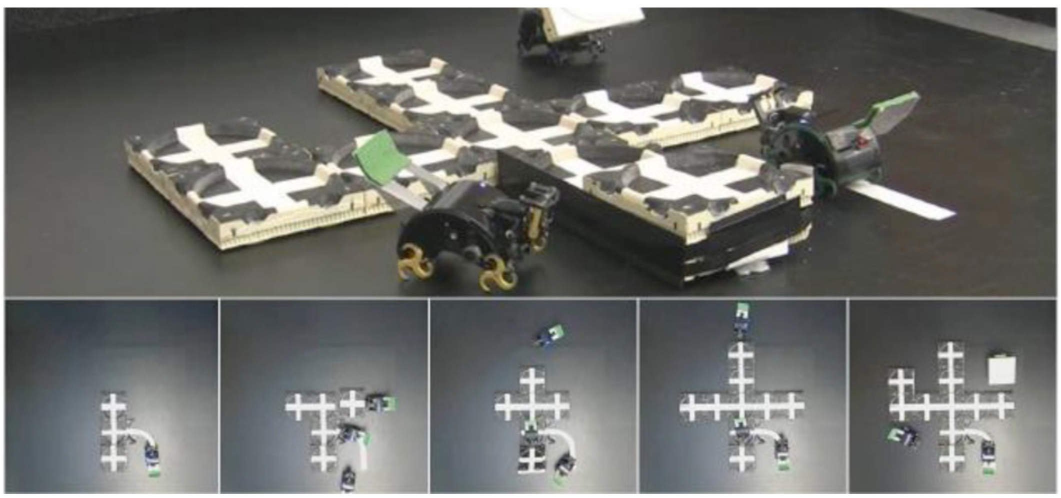


FIGURE 3 Kirstin Petersen, 'Collective Construction by Termite-Inspired Robots,' (PhD thesis, Harvard University, 2014), 72.

TERMES can be perceived as a temporary apex of the scientific field of swarm robotics, a research area which is highly connected with the media history of swarm intelligence. A brief historical account on swarm robotics highlights the basic ideas that until today guide projects like *TERMES*, and which, at the same time, also inform the conception of *Robotic Building*.

Three seminal examples are worth mentioning. The first is *Genghis*, one of the first hexapod robots, on first sight resembling a cockroach and not a swarm. (Fig. 4) But this view is misguided. Developed by Rodney Brooks at MIT in 1989, *Genghis* followed an novel Artificial Intelligence paradigm.[8] Instead of the highly abstract, top-down-designed electronic minds of GOFAI, he explored the capabilities of relatively simple robots to adaptively self-organize in a complex environment. The key term was *embeddedness*, and the conceptual principle was bottom-up: A robot based on the autonomous collection and coordination of information from a dynamic environment by a massive parallel coupling of simple elements.

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7 Justin Werfel, Kristin Petersen and Radhika Nagpal, 'Designing Collective Behavior in a Termite-Inspired Robot Construction Team', *Science* 343 (2014): 754-758.

8 Rodney A. Brooks and Anita M. Flynn, 'Fast, Cheap, and out of Control: A Robot Invasion of the Solar System,' *Journal of The British Interplanetary Society* Vol. 42 (1989): 478-485.

With its internal network of 57 Finite-State-Machines – most of them for the independent motor control of every leg, the rest for sensing purposes – *Genghis* performed self-organised, robust movements. Without being programmed to ›move forward‹, and based only on the local combination of partial information of the system in its sub-elements, the neighborly coordination of leg positions produced this behavior. It wasn't *Genghis* walking with its legs, but its legs – communicating like a swarm – walked the robot.

The second example is a conceptual paper by Gerardo Beni and Jing Wang on the topic of Cellular Robotics from 1989. At that time, this field was closely related to the theory of cellular automata and to mathematical optimization theory, and thus far from physical implementation. At the heart of their paper – which originated the term *swarm intelligence* – was a principle that the computer scientist Erol Sahin later described as follows: »Swarm robotics is the study of how a large number of relatively simple physically embodied agents can be designed such that a desired collective behavior emerges from the local interactions among agents and between the agents and the environment.«[9] The advantages of such a design compared to more complex single robots consist – theoretically, at least – in its greater robustness, flexibility, and scalability. Or, simply put: »[U]sing swarms is the same as ›getting a bunch of small cheap dumb things to do the same job as an expensive smart thing‹.«[10]

And as distributed systems, swarm robotics come with an explicit spatial advantage. Researchers imagined a whole range of possible applications like collective minesweeping or the distributed monitoring of geographic spaces and eco-systems. Swarming elements were imagined to also take on counter measures by self-assembling into blockings against leakages of hazardous materials, thereby being scalable according to the graveness of a situation.[11] The swarm-bots would synchronize with events in space by tracking, anticipating, and level them by self-formation.

A third example derives from a publication that presented an ABM which accomplished a variety of building procedures by combining the biological principle of *stigmergy* – which is known from social insects – with a genetic optimization algorithm.[12] In the model, agents move in a three-dimensional grid and drop elementary building blocks depending on the configuration of blocks in their neighborhood. By evaluating a large number of iterated processes of self-assembly of random space-filling forms by a genetic algorithm, 'interesting' spatial structures emerge, some even looking like wasp nests.[13] As an outcome, the authors were able to find interaction patterns which would lead to collectively built regular structures, without involving a central controller.

9 Erol Sahin, 'Swarm Robotics: From Sources of Inspiration to Domains of Application', in: *Swarm Robotics*, ed. Erol Sahin and William M. Spears (New York: Springer, 2008),10-20.

10 Joshua J. Corner and Gary B. Lamont, 'Parallel Simulation of UAV Swarm Scenarios,' in *Proceedings of the 2004 Winter Simulation Conference*, ed. R. G. Ingalls, M. D. Rossetti, J. S. Smith, B. A. Peters, 355-363.

11 Gerardo Beni: 'From Swarm Intelligence to Swarm Robotics,' in: *Swarm Robotics*, ed. Erol Sahin and William M. Spears (New York: Springer, 2008), 3-9. Gerardo Beni 'Order by Disordered Action in Swarms', in: *Swarm Robotics*, ed. Erol Sahin and William M. Spears (New York: Springer, 2008), 153-172.

12 Eric Bonabeau, Marco Dorigo and Guy Theraulaz, *Swarm Intelligence. From Natural to Artificial Systems* (New York: Oxford University Press, 1999).

13 See ibid.

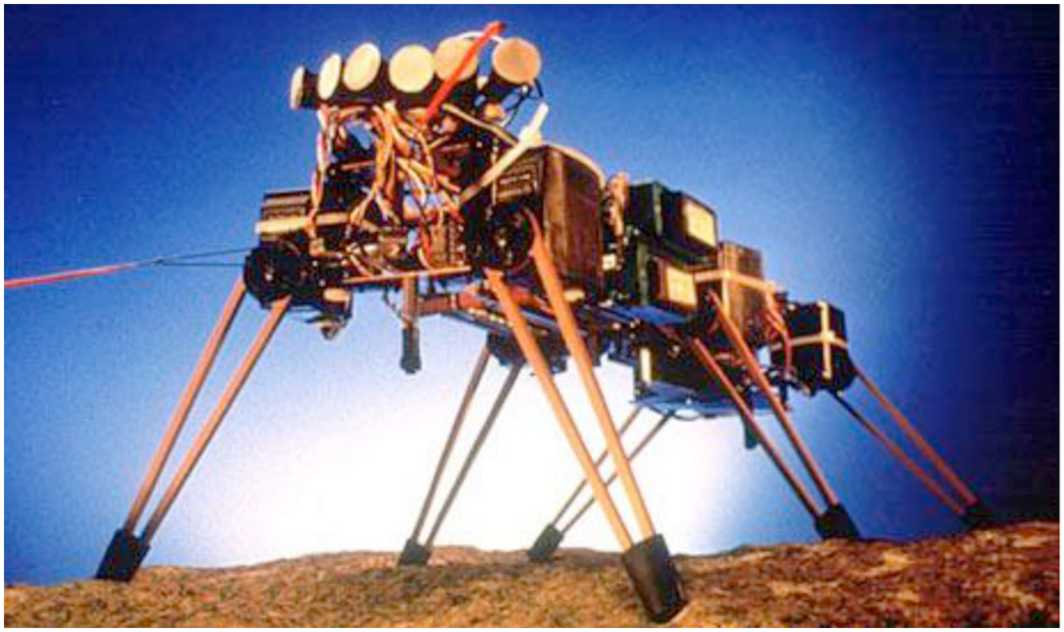

FIGURE 4 URL: http://groups.csail.mit.edu/lbr/genghis/

FIGURE 5 URL: http://motherboard.vice.com/de/read/ein-schwarm-von-1000-robotern-in-perfekter-zusammenarbeit

3 Making arrangements

Despite the fact that the epistemological background for the actual implementation of swarm robotics already formed in the late 1980 and 1990s, and although a search on this keywords today retrieves about 1,500 hits on the *IEEE Xplore* platform alone, still very few of these projects and papers actually explore the usablity of swarm robotics for architectural building. Even if robots have been successfully used in construction already in the 1990s, the application of theoretical and computer-experimental work on swarm robotics to physical robots, and the use of autonomous swarms in construction is still work in progress. Swarm robotics develops along three different relations between swarms and space which can only be briefly sketched here and which respective relation to robotic building will need further specification:

First, swarm robotics explores the architecture of swarms, that is, their modes of interaction, synchronization, and emergent collective motion. They test the self-assembly of autonomous elements into a dynamic, but cohesive arrangement – airborne, like in drone collectives such as COLLMOT of ELTE University Budapest, or on the ground, like in the KILOBOT project of Harvard University. In these cases, swarms establish a specific ›swarm space‹, which then can be used, for instance, to more efficiently monitor a physical space than a single robot or drone.[14] (Fig. 5)

Second, swarm robotics achieve tasks of *a manipulation of objects in space* in a self-organized fashion. In a coordinated effort, the collectives push or drag objects around, thus leading to a re-arrangement or sorting of elements of a given space.[15] (Fig. 6)

Third, swarm robotics engages in *actual building tasks* – also with aerial and grounded collectives. For instance, a research group of ETH Zürich experiments with *Aerial Robotic Construction*, based on a quadrocopter collective that arranges standardized lightweight brick elements to non-trivial architectural shapes. (Fig. 7) And the abovementioned *TERMES* collective follows the trail of stigmergy-based building processes, transforming computer simulations like Eric Bonabeau's wasp nests into physical architectural forms.[16]

14 See e.g. Bence Ferdinandy, Kunal Bhattacharya, D. Ábel and Tamás Vicsek, 'Landing together: How flocks arrive at a coherent action in time and space in the presence of perturbations,' *Physica A* 391 (2012), 1207-1215; Michael Rubenstein, Christian Ahler and Radhika Nagpal, 'Kilobot: A Low Cost Scalable Robot System for Collective Behaviors,' *Proceedings of 2012 IEEE International Conference on Robotics and Automation* (2012).

15 Adrian Cabrera de Luis, 'Collective transport in large swarms of simple robots'(MA thesis, Harvard University, 2012), accessed November 28, 2016, https://www.eecs.harvard.edu/ssr/papers/epflmasters12-cabrera.pdf; C. Ronald Kube and Hong Zhang, 'Collective Robotics: From Social Insects to Robots,' *Adaptive Behavior* vol. 2 no. 2 (1993): 189-219; R. Groß, M. Bonani, F. Mondada, M. Dorigo, 'Autonomous Self-assembly in a Swarm-bot', *IEEE Transactions on Robotics* vol. 22(6) (2006): 1115-1130; Vito Trianni and Marco Dorigo: 'Self-Organisation and Communication in Groups of Simulated and Physical Robots,' *Biological Cybernetics* 95(3) (2006): 213-231.

16 See Federico Augugliaro et al., 'Building Tensile Structures with Flying Machines,' (paper presented at IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) November 3-7, 2013); see Jan Willmann et al., 'Aerial Robotic Construction Towards a New Field of Architectural Research,' International Journal of Architectural Computing 3/10 (2012), 439-459.

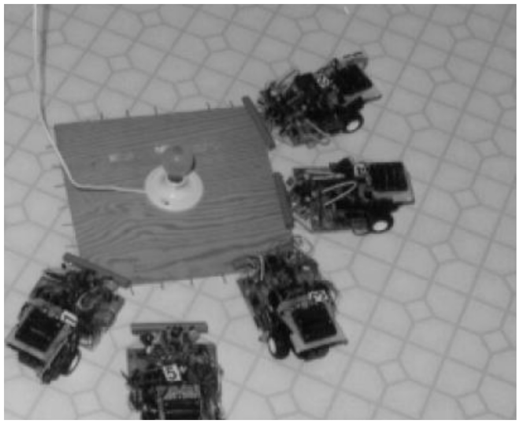

FIGURE 6 C. Ronald Kube and Hong Zhang, 'Collective Robotics: From Social Insects to Robots,' Adaptive Behavior vol. 2 no. 2 (1993), 189-219: 216.

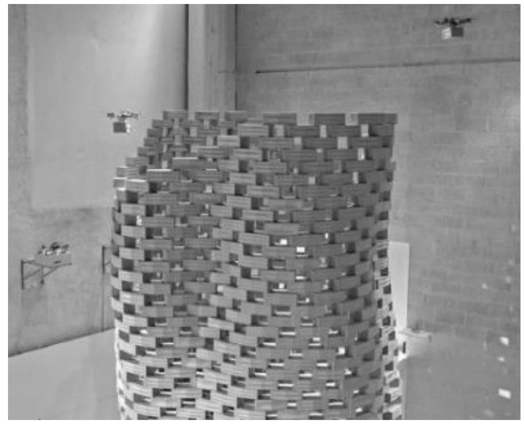

FIGURE 7 Jan Willmann et al., 'Aerial Robotic Construction Towards a New Field of Architectural Research,' International Journal of Architectural Computing 3/10 (2012), 439-459: 454.

In contrast to already existing forms of robotic building, one can stress several advantages: Unlike common robotic building systems which still are centered around human involvement, swarm robotics could be employed in contexts where a direct human involvement is impractical or too dangerous. Furthermore, swarm robotics overcome the stationary method of already established robotic building platforms. Unlike the latter, they are not restricted by the size of the platform, which in common systems have a footprint which must be larger than the final structure. And eventually, multi-robot assembly makes use of parallelism and offers error tolerance by substitution, as the sub-tasks can be carried out by any robot of the collective.[17]

However, the actual construction of reliable real-size buildings by autonomous swarm robots poses a number of challenges. To date, even the aforementioned *experimental* systems prove to be far too unreliable, error-prone, and ineffective to question existing top-down methods. But nonetheless, it can be correctly stated that the introduction of swarm robotics to architecture »radically extends the traditional spectrum of architectural manufacturing methods«[18], and creates a new level of robotic use in architecture. Swarm Robotics pursues and concretizes the shift in architectural computation brought about by a discourse of swarm intelligence, thereby putting an emphasis on the significance of synchronization and timing of parallel tasks. Or, to reformulate a statement by the *Aerial Robotic Construction* working group, to a far greater extend as other automaticized building methods, swarm robotics is »a vision of process.«[19] A vision which demands further attention and explication.

17 See Kirstin Petersen, 'Collective Construction by Termite-Inspired Robots,' (PhD thesis, Harvard University, 2014), accessed November 28, 2016, https://dash.harvard.edu/bitstream/handle/1/13068244/Petersen_gsas.harvard.inactive_0084L_11836.pdf?sequence=1.

18 Jan Willmann et al., 'Aerial Robotic Construction Towards a New Field of Architectural Research,' *International Journal of Architectural Computing* 3/10 (2012), 439-459: 456.

19 Ibid., 456.

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Why Make the World Move?

Motivations for Adaptive Environments, a Next Horizon of Human Computer Interaction

Keith Evan Green

Cornell University
Ithaca, USA

Abstract

The next horizons of human-computer interaction promise a whirling world of digital bytes, physical bits, and their hybrids. Are human beings prepared to inhabit such cyber-physical, adaptive environments? Assuming an optimistic view, this chapter offers a reply, drawing from art and art history, environmental design, literature, psychology, and evolutionary anthropology, to identify wide-ranging motivations for the design of such “new places” of human-computer interaction. Moreover, the author makes a plea to researchers focused in the domain of adaptive environments to pause and take a longer, more comprehensive, more self-reflective view to see what we’re doing, to recognize where we are, and to possibly find ourselves and others within our designed artifacts and systems that make the world move.

Keywords

Adaptive environments; Architectural robotics; Interactive Environments; Theory; Human-Machine Interaction; Intelligent Systems; Internet of Things [IoT]; Cyber-Physical Systems [CPS].

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1 Introduction

It is well recognized that human-computer interaction (HCI) today is no longer bound by computer displays ("one human–one computer") or by Weiser's vision of ubiquitous computing ("people connected by an invisible web"). Today, the horizons of human-computer interaction are defined, in part, by physical scale. At one end of the physical spectrum. where HCI approaches nothingness, computing resides not only around us but also *on* us and *in* us, embedded notably as a bionic second-skin forging a connection between our bodies and the external world.[1] At the other end of the physical spectrum, computing is embedded in the very fabric of our everyday living environments, manifested as networked smart appliances (the Internet of Things [IoT]), physical and tangible computing (Tangible User Interface [TUI]), assistive, humanoid robots (Human-Robot Interaction [HRI]), and as shape-shifting furniture, rooms (figure 1), building façades, and urban infrastructure that include Architecture Robotics [AR]).

The umbrella term for this grander scale of the physical spectrum assumes the namesake of this journal, Adaptive Environments (AE) or, alternatively, Intelligent Environments (IE). Characterized as computing hardware made spatial and inhabitable, Adaptive Environments are meticulously designed, inhabitable environments made interactive, adaptive, and at least partly intelligent. A key behavioral trait of Adaptive Environments is their capacity to respond and adjust to external, often dynamic input, whether this input be the needs and wants of human inhabitants, or changes in environmental or climactic conditions, or updated information supplied by the internet. The response of Adaptive Environments to external input can manifest itself as a change in colors, sound, and shape. In the author's *Architectural Robotics Lab* at Cornell University, previously established in 2005 with collaborator Ian Walker at Clemson University, Adaptive Environments have assumed the form of: an Assistive Robotic Table (ART)[2] enabling, in particular, post-stroke patients; an Animated Working Environment[3] that re-conforms to support the working life of co-located, information Age workers working at once with digital and analog materials and tools; and a LIT ROOM[4] cultivating literacy in children (figure 1) by transforming the everyday space of the public library into the imaginary space of the book.

1 Someya, T. (2013). Building bionic skin. IEEE Spectrum, 50(9), pp.50-56.

2 Houayek, H., Green, K., Gugerty, L., Walker, I. and Witte, J. (2013). AWE: an animated work environment for working with physical and digital tools and artifacts. Personal and Ubiquitous Computing, 18(5), pp.1227-1241.

3 Threatt, A. L., Merino, J., Green, K. E. and Walker, I. D. (2014). An Assistive Robotic Table for Older and Post-Stroke Adults: Results from Participatory Design and Evaluation Activities with Clinical Staff. Proceedings of CHI 2014: the ACM Conference on Human Factors in Computing Systems, Toronto, Ontario, Canada, pp. 673–682.

4 Schafer, G., Green, K. E., Walker, I. D., Fullerton, S. K. and Lewis, E. (2014). An Interactive, Cyber-Physical Read-Aloud Environment: Results and Lessons from an Evaluation Activity with Children and their Teachers. Proceedings of DIS 2014: the ACM conference on Designing Interactive Systems, Vancouver, B.C., pp. 865–874.

FIGURE 1 Adaptive environment from the author's ARCHITECTURAL ROBOTICS LAB at Cornell Univeristy: The LIT ROOM (photos by author). Delighted young users within the author's cyber-physical LIT ROOM at a public library prompted the author to dwell on the significance of such "new places" in HCI.

Across the physical spectrum, recent triumphs in these new horizons of HCI nevertheless remind us of that old, unsettling adage: *Just because you can, doesn't mean you should*. The same sentiment has been attributed recently to assistive humanoid robots and Artificial Intelligence (AI), the latter which will form, likely, the glue that binds together the various scales of next horizon HCI artifacts to form cyber-physical (eco)systems [CPS] of smaller and larger, interactive and intelligent, computing artifacts. In this expanded CPS, the human users in HCI become inhabitants of a whirling world of physical bits, digital bytes, and their hybrids. This "world on the move" begs the question (borrowing words from Science on the future of AI), "What will the world be like if [this kind of computing] comes to coexist with human kind?"[5] While the AI community addresses this question, some with fear, others with anticipation,[6] the HCI research community appears more satisfied with reporting on research triumphs, neglecting meanwhile to consider the meta question, What is it about human beings and being human that compels these next horizons of HCI?—*Why make our world move?* Offered as an impetus for much needed self-reflection, this short paper is an effort to address this core question from a cautiously optimistic stance. While the philosophical (i.e. phenomenological) dimension has been addressed for HCI, adeptly, by Dourish,[7] the response here draws instead from art and art history, environmental design, literature, psychology, and evolutionary anthropology.

5 Stajic, J., Stone, R., Chin, G. and Wible, B. (2015). Special issue on artificial intelligence. Science. 349(6245). pp.248-278

6 IEEE Spectrum: Technology, Engineering, and Science News. (2015). Special Report: The Singularity. [online] Available at: http://spectrum.ieee.org/static/singularity [Accessed 18 Dec. 2016].

7 Dourish, P. (2001). Where the Action Is: The Foundations of Embodied Interaction. Cambridge, Mass.: MIT Press.

2 Drawing from art and art history

Imagine a collection of appliances (IoT) or a robotic workplace (IE) that intelligently reconfigures to support changes in the workflow, recognizing the need for a particular adaption or reconfiguration that will better support it. The design of such systems requires the design team to envision (theoretically) innumerable pathways to adaption and reconfiguration: to essentially recognize in one form still other forms. This is a very different way to think about form for designers where convention assumes that form is singular and stable. Art historian Henri Focillon thought other than conventionally, grappling with the notion that a single form is neither singular nor stable but rather has within it a multitude of forms. "Although form is our most strict definition of space," wrote Focillon, "it also suggests to us the existence of other forms."[8] We must "never think of forms, in their different states, as simply suspended in some remote, abstract zone; they mingle with life, whence they come; they translate into space certain movements of the mind."[9] As forms are conceived and engaged by their users, "each form," writes Focillon, "is in continual movement, deep within the maze of tests and trials" to which their users submit them.[10] In art, perhaps the clearest statement of this reciprocity between the dynamism of form and human perception is found in Italian Futurism, the artistic movement of the early 20th century, evidenced by the words of the movement's founder, F. T. Marinetti: "A house in construction symbolizes our burning passion for the coming-into-being of things. Things already built and finished, bivouacs of cowardice and sleep, disgust us! We love the immense, mobile, and impassioned framework that we can consolidate, always differently, at every moment."[11] The thinking of Focillon and Marinetti suggest to the designers of the next horizons of HCI that an artifact is not singular and isolated but an "open work," a kind of "hypertext," an artifact open to users' interpretations as imparted by memory and by the physical, virtual, and cultural contexts in which the artifact resides.[12]

3 Drawing from environmental design

With few exceptions, designing the built environment for movement, for *reconfigurability*, has been resisted by designers throughout history. Resistance to reconfigurability is motivated by the requirement of buildings to maintain continuity, to defy or at least to resist the impositions of nature and unfamiliar humankind. Curiously, today's homes and workplaces remain largely incapable of responding to changes occurring in their inhabitants as these inhabitants grow, grow old, and sometimes grow sick, and as groups of inhabitants grow and shrink in their numbers and exhibit varied and fluctuating needs and wants. Environmental design (mostly equated with architecture) has mostly ignored this flux endemic to life.

8 Focillon, H. (1989). The life of forms in art. New York: Zone Books, pp.97-98.

9 Ibid., 60.

10 Ibid., 123-124

11 Marinetti, F. T. (1991). The Birth of a Futurist Aesthetic. In Let's Murder the Moonshine. Los Angeles: Sun & Moon Press.

12 Eco, U. (1989). The open work. Cambridge, Mass.: Harvard University Press.

From the aesthetic, formal side, resistance to reconfigurability is motivated by the quest for a universal standard for measuring it: in designing its parts, and in organizing these parts to constitute the whole work. From architects Vitruvius to Le Corbusier—two millennia between them—the dimensional and proportional systems of buildings and other aspects of the built environment were modeled on an idealized and yet motionless human body: Vitruvian and Modular men. Maintaining the continuity bridging these two figures is the Renaissance ideal of a "timeless" and "beautiful" building in which "nothing may be added, taken away or altered."[13]

This "immobility" of architecture has its historical exceptions. It is not entirely novel for a piece of furniture or even a building interior to permit changes to its physical form to afford different functions supporting different human objectives or activities. These kinds of mechanical affordances or *action possibilities* date back centuries, for example, in the form of tatami mats and sliding shoji screens found in traditional Japanese houses. Most notably in architecture, the Rietveld Schröder House (1924, Utrecht), designed by cabinetmaker and architect Gerrit Thomas Rietveld, extended the concept of the sliding screen to permit the manual reconfiguration and repositioning of various components of the home's second story. Carlo Mollino, a mid-twentieth century architect known for his own reconfigurable architectural contrivances, imaginatively characterized the manually reconfigurable house as "a jack-in-the-box, a play of easily changeable rooms and furnishings, a fickle scenography of embroidered furnishings and sliding, transforming rooms, separating and creating halls and lounges with the turn of the seasons, in states of animation, reflecting the ceremonies of 'domestic' happenings... When importune, the furnishings truly disappear into the wall."[14] The "easily changeable rooms and furnishings" that Mollino describes are alive with possibilities for reconfiguring them. What fascinated this Turinese architect was not so much the physical movement afforded by the sliding partitions and furnishings (their mechanics), but mostly how these architectural elements, in their flexibility, reflected things external to them: the passing of the seasons, the unfolding rituals of domestic life, our own inner selves. In the rooms and furnishings of his own design, Mollino invited inhabitants to tune the mechanical features of these strange places to reflect the conditions of their interior lives—to reflect themselves in the environments in which they live, *to make themselves more at home*. In the number of interior domiciles he designed for himself, the frenetic Mollino sought a sense of restfulness for himself, but recognized, in states of torment and elation, the difficulty of capturing this peace, even for the duration of the shutter movement of his Leica camera.

Despite the best efforts of environmental design, its works are no more static than the lives living within them. When we enter a building, we bring with us the dimension of time. No inhabitant will ever have precisely the same experience here, nor will any other inhabitant have precisely the same experience here as someone else inhabiting the same space. The human experience, framed by the physical environment, is never precisely the same at two points in time. A work that is reconfigurable is one that, at least in conventional architectural terms, is *unfinished*: room is made in the very design of such a place for the inhabitants to, in a word, play. Architectural works, like all works of art, are "quite literally 'unfinished,'" Umberto Eco contended: "the author seems to hand them on to the performer more or less like the components of a construction kit."[15] For Eco, as might be said for F. T. Marinetti, "the comprehension and interpretation of a form can be achieved only ... by repossessing the form in movement and not in static contemplation."[16] In the strange built environments described here, designers of IoT, IE, HRI and broadly CPS can discern compelling precedents for designing cyber-physical environments that actively grow and adapt with their users over time.

13 Alberti, L. (1988). On the art of building in ten books. Cambridge, Mass.: MIT Press, book VI, c.2, p.156.

14 Mollino, C. (1949). Utopia e Ambientazione. Domus (August 1949): 16 (author's translation).

15 Eco, U. (1989). The open work. Cambridge, Mass.: Harvard University Press. p.4.

16 Ibid., 163.

4 Drawing from literature

The means of computing (including robotics) can be integrated into the physical fabric of things to forge a more interactive, more intimate relationship between the built environment and us. Embedding digital technologies in selected aspects of the built environment, from small appliances to the metropolis, renders these a semblance of vitality: the capacity to move with and respond to things external to them, whether these things are living (people and pets), or inanimate (physical property), or phenomena far less tangible (data streaming over the Internet, the detection of weather). In this very active way—of engaging the world, drawing inferences, and responding in kind—cyber-physical artifacts are, to a degree, a reflection of us: our needs, our aspirations as vital beings that "change shape".

As evidenced by its centrality in classical Greek mythology, "shape-shifting" has fascinated us for millennia. As Steven Levy asserts in *Artificial Life*, today's human-made, life-like artifacts are founded not only in the contemporary imagination, but equally so in the many "ancient legends and tales" devoted to the theme of "inanimate objects" infused "with the breath of life."[17]

Following Levy and recognizing physical reconfigurability as a pathway, today, to a more intimate correspondence between our physical environments and ourselves, it is not such a stretch to learn from the myth of Proteus, the Greek god who, more than other shape-shifters in Greek mythology, was capable of transforming himself into countless different forms. This captivating capacity of Proteus to shape-shift led to his ultimate "transformation": into the familiar adjective, *protean*, which wonderfully captures a core behavior of the next horizons of HCI. Despite his advanced age and waning stamina, the Proteus of this poem of the eighth century B.C. has led an active and prolonged life under the same name but in different guises. Notably, Proteus is the name given to characters in Milton's *Paradise Lost* and in Shakespeare's *Henry VI* and *The Two Gentlemen of Verona*. Proteus is also the name given to historic warships (both USS *Proteus* and HMS *Proteus* of the Royal Navy), and to a novel, contemporary sailing vessel (the Proteus WAM-V, which features a reconfigurable hull that conforms to the surface geometry of water currents). Proteus is also the name given to, respectively, a medical syndrome popularly identified with "the Elephant Man," a bacteria having a remarkable ability to evade the host's immune system, and a family of flower having more than 1,400 varieties. Our fascination with shape-shifting is evidenced not only by this extended and variegated procession of forms under the name Proteus, but also by the contemporary usage of the word *protean*, defined by the *Oxford English Dictionary* as: *adopting or existing in various shapes, variable in form; able to do many different things;* and *versatile*. All of these definitions aptly describe the strivings of researchers engaged in developing the next horizons of HCI.

17 Levy, S. (1993). Artificial life: A Report from the Frontier Where Computers Meet Biology. New York: Vintage Books, p.18.

5 Drawing from psychology

There remains one more Proteus that will prove useful in uncovering the promise of the next horizons of human-computer interaction: the Proteus of psychology. Both the Proteus of Heinrich Khunrath, the sixteenth century German physician-alchemist, and the Proteus of Swiss psychologist Carl Jung in the twentieth century personified the elusive unconscious. But for our purposes, the more useful Proteus is the one that names a contemporary, psychological profile considered by psychiatrist Robert Jay Lifton. In *The Protean Self: Human Resilience in an Age of Fragmentation*, Lifton characterizes this modern-day Proteus as "fluid and many sided" and "evolving from a sense of self [that is] appropriate to the restlessness and flux of our time."[18] This Proteus, a "willful eclectic," draws strength from the variety, disorderliness, and general acceleration of historical change and upheaval. As Lifton writes, "One's loss of a sense of place or location, of home—psychological, ethical, and sometime geographical as well—can initiate searches for new 'places' in which to exist and function. The protean pattern becomes a quest for 'relocation.'"[19] According to Lifton, the protean self actively responds to life's challenges and opportunities—whether pedestrian (working life, family life) or grand-scaled (social, economic, political)—by seeking "new 'places'" best suited for improvement, advancement, or at least escape (figure 2). For the CHI community, we discover in the Protean Self a human personality that is amenable to and even drawn to flux and fluidity.

6 Drawing from evolutionary anthropology

The protean way—to be fluid, resilient, and on the move—is not only a tactical, cognitive response to living today, but is, according to anthropology researchers Antón, Potts, and Aiello, *the outstanding trait distinguishing the human species*. The protean way is defined as "adaptive flexibility," the cornerstone of this new paradigm for human evolution, as published by these three researchers in the journal, *Science*.[20] Antón, Potts, and Aiello find evidence for adaptive flexibility in all the "benchmarks" defining our species: "dietary, developmental, cognitive, and social."[21] Moreover, and critical to establishing the motivation for the next horizons of HCI, adaptive flexibility in the human species arose in response to "environmental instability" [2]. As argued by Antón, Potts, and Aiello, the human species did not evolve in "a stable or progressively arid savanna" as suggested in earlier paradigms of evolution, but rather "in the face of a dynamic and fluctuating environment" composed of "diverse temporal and spatial scales."[22] What distinguishes humans from other mammals is our adaptive flexibility, the capacity to "buffer and adjust to environmental dynamics."[23] The significance for our research community is clear: the human species is super-adaptive to "diverse spatial scales" and "environmental dynamics." This new paradigm for evolution, along with Lifton's concept of the Protean self, suggest that we are prepared for, and can in all probability make use of, controlled reconfigurations and adaptions of cyber-physical ecosystems under those life circumstances that warrant their application.

18 Lifton, R. (1994). The protean self: Human Resilience in an Age of Fragmentation. New York, NY: BasicBooks, p.1.

19 Ibid., 14–15.

20 Anton, S., Potts, R. and Aiello, L. (2014). Evolution of early Homo: An integrated biological perspective. Science, 345(6192):1236828, pp.7-8.

21 Ibid., 1236828, 8.

22 Ibid., 1236828, 9 and 1236828, 7.

23 Ibid., 1236828, 7.

7 Many and new places for adaptive beings

Cutting across the diverse perspectives briefly surveyed here, from art and art history, to environmental design, to Greek mythology, to psychology, and to human evolution, is a recognition of the vibrant exchange between the dynamic world in which we live and the intimate and social nature of our being. Central to what it means to be human is to be fluid, resilient, and on the move. The next horizons of human-computer interaction, borrowing Lifton's words, have the potential to cultivate "many and new places" for individuals and groups of individuals facing wide-ranging challenges and opportunities.

For the research community focused in adaptive environments, there are at least a number of ways to arrive at these new places: by selecting a new place among programmed places to match life needs and opportunities; by fine-tuning and then saving patterns of adaption and configuration to create new places; and by allowing the cyber-physical environment to anticipate needs and wants, reconfiguring itself a new place for us.

The new cyber-physical "places" promise to provide inhabitants the means for creating a careful balance between stability and flexibility in a given moment. At their best, these places will afford inhabitants the capacity, borrowing Lifton's words again, to "modify the self to include connections virtually anywhere while clinging to a measure of coherence."[24] What this chapter strives to offer is the recognition that we and the cyber-physical (eco)systems on the near horizon are well matched: diverse, dynamic, adaptive and sometimes blurred. Manifested as health-care facilities, classrooms, workspaces, assisted-care homes, and potentially as mass public transit and road systems (traversed by autonomous cars), the next horizons of HCI will collapse further the boundaries that distinguish us from our surroundings when the conditions suggest (we hope) the greatest benefit to the individuals and the groups inhabiting them.

Obviously the short space of a book chapter is woefully inadequate to elaborate, from six disciplinary perspectives, the motivations for the next horizons of HCI. The intent here, more so, is to offer the adaptive environments research community the impetus to reflect—to assume the "1000-mile view" that permits us *to see* (what we're doing), and to *recognize where we are*. From this vantage, Ivan Ilich saw in new technology "tools of conviviality" fostering "self-realization" and "play."[25] Buckminster Fuller saw a "spaceship earth" that lacked an operating manual that he could write, informed by "long-range, anticipatory, design science" characterized by "comprehensive," not only "specialized thinking."[26] This author sees, with *Superstudio* (figure 2) and John Cage as guides, "gardens of technology" where every "inanimate object has a spirit."[27] *What do you see?*

24 Lifton, R. (1994). The protean self: Human Resilience in an Age of Fragmentation. New York, NY: BasicBooks, p.230.

25 Illich, I. (2009). Tools for conviviality. London: Marion Boyars, p.24.

26 Fuller, R. (2014). Operating manual for spaceship earth. Baden, Switzerland: Lars Müller Publishers, pp.22 and 24.

27 Cage, J. (1980) Mesostic for Elfriede Fischinger. Center for Visual Music, Elfriede Fischinger Collection; and Cage, J. (1990) I-VI. The Charles Eliot Norton Lectures. Harvard University Press

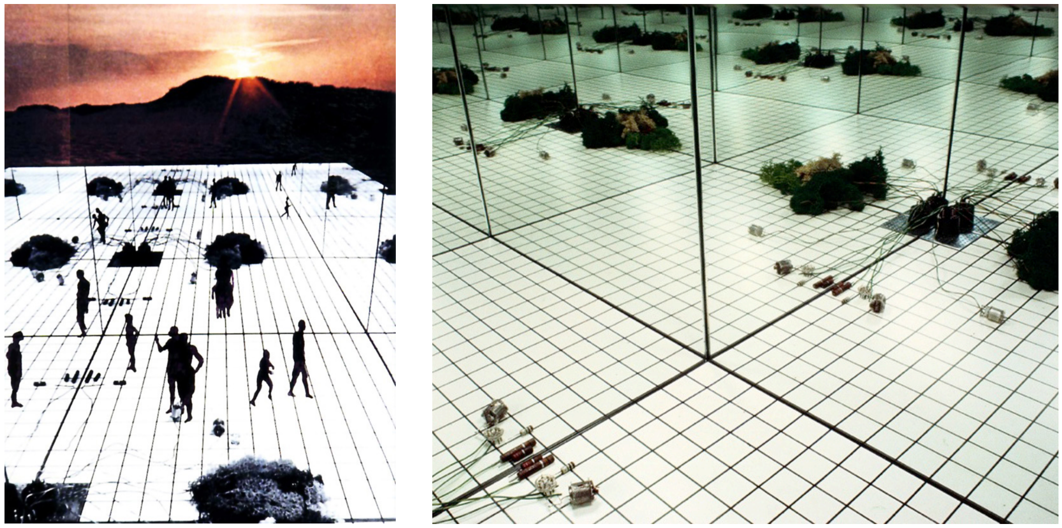

FIGURE 2 Photo collage by Superstudio from the "New Domestic Architecture" exhibition (MoMA, 1972)

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Inhabiting Adaptive Architecture

Holger Schnädelbach

University of Nottingham
UK

Abstract

Adaptive Architecture concerns buildings that are specifically designed to adapt to their inhabitants and to their environments. Work in this space has a very long history, with a number of adaptive buildings emerging during the modernist period, such as Rietveld's Schröder house, Gaudi's Casa Batlló and Chareau's Maison de Verre. Such early work included manual adaptivity, even if that was motor-assisted. Today, buildings have started to combine this with varying degrees of automation and designed-for adaptivity is commonplace in office buildings and eco homes, where lighting, air conditioning, access and energy generation respond to and influence the behaviour of people, and the internal and external climate.

In addition, over the last two decades, the availability of cheaper computation, more accessible programming interfaces and a wider spread of the necessary development skills has exponentially increased the level of experimentation in this exciting field. This is very visible in a series of publications that discuss interactive[1], responsive[2] and robotic architecture[3]. Working in this space is a loose network of research labs for example at MIT, UCL and TU Delft, which pushes this work, crossing the disciplinary boundaries between Architecture, Computer Science, Engineering, Social Sciences and Art.

With the aim to support the community in not loosing the conceptual and historical overview of this work, we are maintaining a categorised view of adaptive architecture at:
http://www.adaptivearchitectureframework.org. This interactive map classifies the field by highlighting four top-level categories: in response to what is architecture responsive, what elements are adaptive, what methods are employed and what effect that adaptivity has. The map is illustrated with an extensive list of historical examples, and it also allows for crowd-sourced extensions of the map.

Keywords

Adaptive Architecture; automation; Mixed Reality Architecture

1 Fox, Michael Aug, and Miles Kemp. 2009. Interactive architecture. New York: Princeton Architectural Press.

2 Beesley, Philip, and Omar Khan. 2009. "Responsive Architecture / Performing Instruments." Situated Technologies Pamphlets 2 (4).

3 Bier, Henriette. 2014. "Robotic Building(s)." Next Generation Building 1 (1):83-92. doi: 10.7564/14-NGBJ8. and Green, Keith Evan. 2016. Architectural robotics : ecosystems of bits, bytes, and biology. Cambridge, Massachusetts: The MIT Press.

1 Inhabitation

While important, creating such overviews, whether via the aforementioned books, research group websites or indeed the interactive map, cannot tell us much about how people inhabit such structures. But, it is critical to develop such an understanding alongside prototypes, if this experimental work is designed to find wider use and acceptance.

A diverse range of previous publications can frame the broader context of developing such an understanding. Banham traced the early introduction of technologies into architecture[4]. Weiser proposed the merging of computing and environment [5]. Suchman demonstrated how technology must be understood in the context it is developed for[6]. And finally, Brand highlighted how buildings become adapted well beyond the original intentions of architects by inhabitants over time[7].

In the above context, Adaptive Architecture must be understood as a social-technical concern. Understanding must involve understanding the technology and social interaction with, within and through it. How people might inhabit adaptive architecture has been a focus of research at the Mixed Reality Lab, Nottingham. We address this question by designing, constructing and evaluating prototypes to expose basic and applied knowledge about the relationship between people and adaptive architecture.

In what follows, four pieces of experimental work in this space will be briefly introduced and discussed, before describing the generalised feedback loops that emerge between adaptive environments and inhabitants.

FIGURE 1 View into shared virtual environment of Mixed Reality Architecture (left) and view into one of the connected offices, showing map and video mirror of one's own space (right)

4 Banham, Reyner. 1984. The architecture of the well-tempered environment. 2nd ed. Chicago: University of Chicago Press.

5 Weiser, Mark. 1991. "The Computer for the Twenty-First Century." Scientific American 265 (3):94-104.

6 Suchman, Lucy A. 1987. Plans and situated actions : the problems of human machine communication. Cambridge: Cambridge University Press.

7 Brand, Stewart. 1994. How buildings learn : what happens after they're built. London, UK; New York, USA: Viking.

2 Mixed Reality Architecture

The first work is Mixed Reality Architecture (MRA). It embeds always-on audio and video connections within an office environment. MRA combines research into Media Spaces[8] and into shared virtual environment[9] with an understanding of architecture influencing social interaction through its topology[10].
Each connected office has a large screen, a video camera, microphones and speakers, and it is represented by an adaptive cube in a shared virtual environment, as shown in Figure 1.
Any occupant of any of the connected offices can virtually move their office to be closer to any of the other office. When two or more offices are close, audio and video streaming are enabled.

A longitudinal study in a high-network bandwidth academic context, spanning research partners at University College London and Bath universities, showed how MRA enabled and shaped spontaneous and planned interactions. It replicated spatial aspects of communication, especially how this becomes accountable to others[11]. Our attempts to get this adopted outside academia failed. Partly this was because of technical issues, available networking speeds being too slow at the time. Partly, it was due to differences in organisational culture, where hierarchies in commercial organisations are a lot less flat than in the academic organisations we had worked with previously.

Architecturally, the most important outcome was the immediate adaptivity of topology and how architecture, technology and people shape this. In MRA, it is inhabitants (not architects) who adapted architectural topologies on the fly to enable social interaction. The resulting ever-changing topologies then in turn shape what social interaction is possible[12].

3 Screens in the Wild

A second project to highlight is the Screens in the Wild project, which investigated the concept of connecting remote physical places in a different, an urban context. This occurred with the background of the development of interactive media facades[13] and the ubiquitous use of digital screens for advertising in urban spaces being criticised for not being relevant to communities that are being faced with them[14].

8 Mantei, Marilyn M., Ronald M. Baecker, Abigail Sellen, Bill Buxton, and Thomas Milligan. 1991. "Experiences in the Use of a Media Space." CHI, New Orleans, USA.

9 Greenhalgh, Chris. 1999. Large scale collaborative virtual environments, Distinguished Dissertations. London, UK: Springer.

10 Hillier, Bill, and Julienne Hanson. 1984. The social logic of space. Cambridge, UK: Cambridge University Press.

11 Schnädelbach, Holger, Alan Penn, Philip Steadman, Steve Benford, Boriana Koleva, and Tom Rodden. 2006. "Moving Office: Inhabiting a Dynamic Building." CSCW, Banff, Canada.

12 Schnädelbach, Holger. 2012. "Hybrid Spatial Topologies." Journal of Space Syntax 3 (2):204-222.

13 Wiethoff, Alexander. "Designing Interaction with Media Facades: A Case Study."

14 Schieck, Ava Fatah gen., Ghislaine Boddington, and Peter Fink. 2009. Framework for the implementation of urban big screens in the public space. London, UK: University College London. and Struppek, Mirjam. 2006. "The social potential of Urban Screens." Visual Communication 5 (2):173-188. doi: 10.1177/1470357206065333.

In collaboration with UCL, we developed the Screens in the Wild network to involve communities in the content of such screens. We had four nodes in total. Each node was installed in a 'shop front'. It could be interacted with from the outside using a through-glass touch technology. Each node had a screen, a camera, speakers and a microphone. The network was unique in the way that it provided for networked interaction between multiple city areas.
We engaged people in workshops and meetings to discuss what purpose such screens have in enhancing urban life. And we used the results to generate ideas and content for the screens[15]. The results led to sustained engagement of people on the streets of the connected places. We implemented a whole host of different applications: From slide and video slide shows to something to express your mood, something to teach you about ADHD and an urban photo booth. With that photo booth, we captured more than 40,000 photos[16].

People appreciated the ad-hoc, free engagement having a very low entry barrier for engagement. The screens were also valued for adding to urban life and the street scene and this is were the greatest architectural impact lied, making aspects of urban space that usually corporate accessible to all parts of society, at least in principle. Organisationally, it was difficult to keep content fresh and we did not find a route to commercially support the type of content that we found was engaging communities.

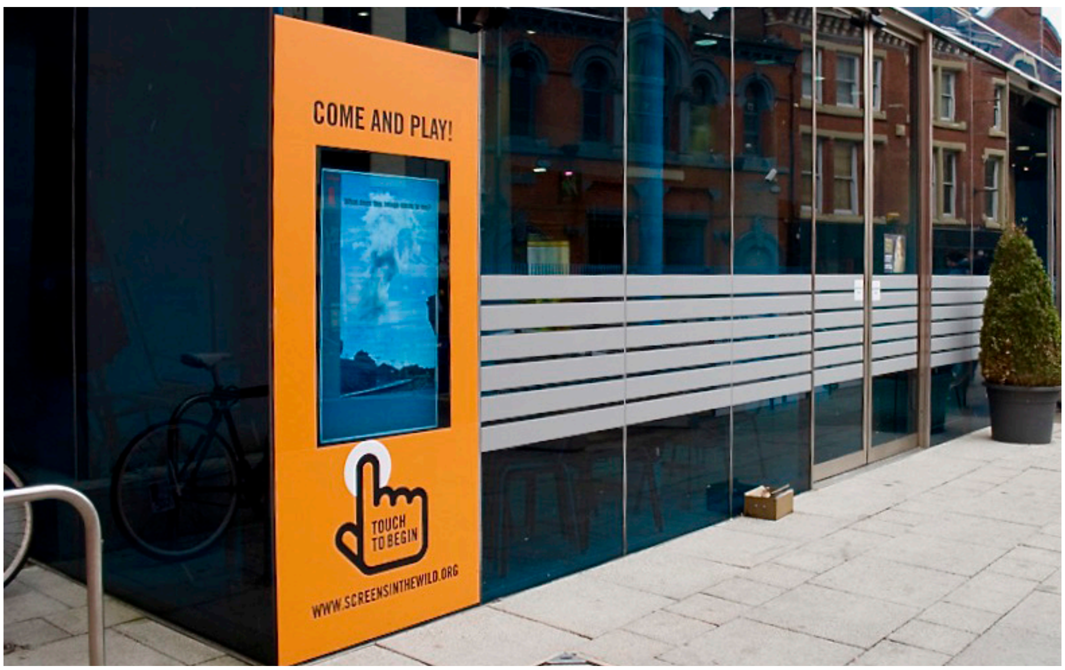

FIGURE 2 Screens in the Wild interactive the screen on the facade of a cinema and media centre. Walk-up interaction helping to define urban space

15 Motta, Wallis, AvaFatahgen Schieck, Holger Schnädelbach, Efstathia Kostopoulou, Moritz Behrens, Steve North, and Lei Ye. 2013. "Considering Communities, Diversity and the Production of Locality in the Design of Networked Urban Screens." In Human Computer Interaction - INTERACT 2013, edited by Paula Kotzé, Gary Marsden, Gitte Lindgaard, Janet Wesson and Marco Winckler, 315-322. Heidelberg, Germany: Springer.

16 Memarovic, Nemanja, Ava Fatah gen Schieck, Holger Schnädelbach, Efstathia Kostopoulou, Steve North, and Lei Ye. 2015. "Capture the Moment: "In the Wild" Longitudinal Case Study of Situated Snapshots Captured Through an Urban Screen in a Community Setting." CSCW, Vancouver, Canada.

4 ExoBuilding

The ExoBuilding series of prototypes link physiological data from inhabitants (e.g. heart beat, respiration, skin conductance) to actuations in the environment (e.g. movement, sound, graphics). The most commonly explored version maps respiration to movement: when its inhabitant inhales, the building increases in size and when they exhale, it decreases in size. ExoBuilding was developed in the broad context of physiological computing[17], making use of such personal data as an interaction input and developments around the 'quantified self', making data part of all aspects of a person's life[18].

ExoBuilding creates an immersive, multi-sensory and embodied experience. It moves the air in and out, creating a gentle breeze. The fabric occasionally touches your hand. The motors sound a little like breathing and your heartbeat vibrates the floor. Inhabitants see the blue circle in front of them grow and shrink in the rhythm of their respiration. From very early on, reactions to this prototype of experimental architecture were very distinct, describing the generated experience as very relaxing and generating a deep connection to one's own body[19].

Prompted by this, we stepped through a series of lab studies to investigate this prototype in more detail. In a first study, we compared a biofeedback condition, with regular movement of the structure and with no adaptation at all. We found that biofeedback-driven Adaptive Architecture can indeed trigger behavioural and physiological adaptations without giving people instructions. Specifically, it supports people to breathe slower and more deeply and this triggers deep relaxation in some people[20]. We then compared the biofeedback loop between people inside ExoBuilding to people sitting outside ExoBuilding. We found that Immersion creates embodied interactivity and relaxation compared to the same non-immersed interactivity, where the environment remains an external object[21]. In a third lab study, we shifted from biofeedback control to an automated movement, hiding this shift from people. Our finding was that, following immersive feedback; regular movements can be used to trigger behavioural changes as well. This hints at the fact that even without biofeedback, architecture could measurably affect our physiological responses[22] .

Finally, in a first non-experimental application of ExoBuilding, we collaborated with yoga teachers and students. The control of breathing is an essential part of Yoga practice. The work involved adaptations to yoga practice, for example a concentration on aspects of yoga that fit into the raised ExoBuilding as you can see of the images. And, these adjustments also resulted in change to ExoBuilding itself, mainly in the way it is controlled by one or two yoga practitioners. We found that ExoBuilding can provide new and useful information to teachers about the current internal state of their students, basically surfacing internal states for everyone to see. And, when a machine drives the environment in a regular and predictable pattern, self-reported group cohesion improves dramatically[23].

17 Fairclough, Stephen, and Kiel Gilleade, eds. 2014. Advances in physiological computing, Human-computer interaction series. London ; New York: Springer.

18 Wolf, Gary, and Kevin Kelly. 2014. "Quantified Self: Self Knowledge Through Numbers." Accessed 02/01. http://quantifiedself.com.

19 Schnädelbach, Holger, Kevin Glover, and Alex Irune. 2010. "ExoBuilding - Breathing Life into Architecture." NordiCHI, Reykjavik, Iceland.

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22 Jäger, Nils, Holger Schnädelbach, Jonathan Hale, Dave Kirk, and Kevin Glover. In Press. "Reciprocal Control in Adaptive Architecture." Interacting with Computers.

23 Moran, Stuart, Nils Jäger, Holger Schnädelbach, and Kevin Glover. 2016. "ExoPranayama: a biofeedback-driven actuated environment for supporting yoga breathing practices." Personal and Ubiquitous Computing 20 (2):261-275. doi: 10.1007/s00779-016-0910-3.

5 Move

Most recently, we have started to experiment with a movement-controlled prototype. The broader architectural context is provided by the growing interest in physical movement in buildings[24] and robotic control of such movements[25]. This is coupled by the broad availability of movement detection sensors.

MOVE is a hardware and software platform that allows experimentation with mappings of human movement to architectural movements. MOVE detects key body movements of a single person via a Kinect and flexibly maps them to up to 16 engines via Processing and Phidgets. It can be used to actuate architectural building components of different types and it allows the scaling of movements and frequency mappings[26].

Initially this was to explore the creation of architectural form through body movement. From the standpoint of a single inhabitant, ego-centric form is created and 'makes sense' for that inhabitant. We have also explored the use of MOVE in the context of the Tetsudo martial arts. Study participants fed back how such an adaptive environment can be useful to reflect back movement in way that can be studied and how performers adapt their behaviour to what is technically available.

FIGURE 3 ExoBuilding mapping physiological data of its inhabitant to its appearance, form and sound scape (left) & ExoBuilding interior (right)

24 Schumacher, Michael, Oliver Schaeffer, and Michael-Marcus Vogt. 2010. MOVE: Architecture in Motion - Dynamic Components and Elements: Birkhäuser.

25 Bier, Henriette. 2014. "Robotic Building(s)." Next Generation Building 1 (1):83-92. doi: 10.7564/14-NGBJ8. and Green, Keith Evan. 2016. Architectural robotics : ecosystems of bits, bytes, and biology. Cambridge, Massachusetts: The MIT Press.

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6 Feedback loops in Adaptive Architecture

In some sense, the prototypes presented above are very diverse. Diverse in the settings that they are employed in, the way that they are generating or integrating with architectural space, the aims for their use, the employed technologies and the way that they have been evaluated. The overarching aim for all of them though has been to better understand what it means to inhabit Adaptive Architecture; and that is being built in many different guises and circumstances.

There are also clear commonalities. All presented prototypes are hybrids, combining physical space with digital interactivity. The architectural material itself often becomes what people interact with, instead of architecture acting as a site of interaction interfaces only. Investigating the prototypes' relationships with their inhabitants then also demonstrates another commonality, namely the ways in which interaction between inhabitant and environment can be described as a feedback loop.

Through some technology, a chosen set of personal data is captured from an inhabitant or inhabitants (e.g. often a combination of their interaction input, voice and video, physiological data, movement data). This data can then be used in its raw format. It can also be manipulated in different ways, it could be aggregated incorporate multiple people. It could also be interpreted, attempting to infer something about the state of the inhabitant, such as their psychological or mental state. The filtered data is then used to drive adaptations in a space. Such actuations can be anything that it is possible to actuate in architecture from the lighting infrastructure to environmental controls or media display. These have an effect on architecture, for example on the architectural topology, the appearance, information content and interactivity of facades, the space created by architecture or indeed architecture's form, as seen in the prototype presented in this abstract. These changes then in turn have an effect on the inhabitants, feeding back to the person, contributing one of the original streams of data for adaptations. For example, the environmental effects triggered might mean that inhabitants feel more comfortable, feel more relaxed or indeed more anxious.

Actions and reactions by both the building and its inhabitants influence each other. In this way, buildings and inhabitants become interaction partners in a very specific way and it is this feedback loop that requires much further investigation in future.

FIGURE 4 MOVE protoype used by a Tetsudo martial arts performer

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Design-to-Robotic-Operation Principles and Strategies as Drivers of Interior Environmental Quality

Alexander Liu Cheng

TU Delft,
Faculty of Architecture and the Built Environment
Delft, the Netherlands

Abstract

This paper presents a high-resolution intelligence implementation based on Design-to-Robotic-Operation (D2RO) principles and strategies specifically employed to attain and to sustain Interior Environmental Quality (IEQ) within a dynamic built-environment. This implementation focuses on two IEQ-parameters, namely illumination and ventilation; and is developed in three main steps. In the first step, a formal design-criteria based on D2RO principles is developed in order to imbue considerations of intelligence into the early stages of the design process. In the second step, illumination and ventilation systems are developed as IEQ-regulating mechanisms whose behavior is determined by machine-learning models that continuously learn from the occupants and their preferences with respect to interior environmental comfort. In the third and final step, the resulting implementation is tested with probands in order to demonstrate continuous intelligent adaptation with respect to illumination and ventilation, which in turn demonstrates that a D2RO approach to IEQ yields a more intelligent adaptive mechanism that promotes occupant well-being in an invisible, unobtrusive, intuitive manner.

Keywords

Adaptive Architecture, Cyber-Physical Systems, Robotic Building, Ambient Intelligence, Interior Environmental Quality.

 Liu Cheng, A. (2017). Design-to-Robotic-Operation Principles and Strategies as Drivers of Interior Environmental Quality.
SPOOL, 4 (1). doi:10.7480/spool.2017.1.1909

This paper presents a high-resolution intelligence[1] implementation based on *Design-to-Robotic-Operation* (D2RO)[2] principles and strategies specifically employed to attain and to sustain *Interior Environmental Quality* (IEQ) within a dynamic built-environment. The present implementation builds on a series of limited *proofs-of-concept*, each intended to demonstrate key advantages of employing a D2RO approach in different areas and contexts of the built-environment. The first *proof-of-concept* developed an extended *Ambient Intelligence* (AmI)[3] where (a) the scope of service extended beyond a defined structured environment via remote and wearable sensors; (b) the system architecture was deliberately extended to contain a variety of local, embedded, and remote proprietary and non-proprietary protocols, products, and services unified in a self-healing and meshed *Wireless Sensor and Actuator Network* (WSAN); and where (c) an actuated transformable architecture was correlated with processed sensed-data to instantiate spatial configurations and computational services intended to promote the well-being of its occupant(s). Building on the first implementation, the second *proof-of-concept* developed an adaptive building-skin system[4] where (i) each of its context-aware components functioned as independent yet interrelated and correlated nodes within the established WSAN; and where (ii) the behavior of every node was informed by and informing of the behavior of every other node in the building-skin system as well as of those deployed locally the interior built-environment (via embedded / locally ambulant sensors) or remotely on the user (via wearables, remote sensors). This building-skin system demonstrated that a D2RO-driven interface between interior and exterior space provided an adaptive resilience and flexibility absent from conventional building envelopes, and ones capable of corresponding to both environmental conditions as well as occupant preferences in a continuously optimized manner. The previous *proofs-of-concept* enable the present implementation to instantiate built-environments capable of maintaining individual and independent environmental conditions, which is necessary in order to target interventions and to maintain optimal conditions in specific built-environments. This enables IEQ-sustaining D2RO to be the focus of the present paper, which is particularly pertinent since IEQ is directly related to occupant well-being[5]—i.e., a principal objective of the AmI / intelligent built-environments discourse[6],[7],[8]—and since people spend the majority of their time indoors[9]. IEQ depends on thermal, acoustic, illumination, ventilation, and related parameters[10], yet it is not

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4 Liu Cheng, A., & Bier, H. H. (2016b). "Adaptive Building-Skin Components as Context-Aware Nodes in an Extended Cyber-Physical Network". In *Proceedings of the 3rd IEEE World Forum on Internet of Things* (pp. 257–262). IEEE.

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reduced to the sum of their averages[11], nor is it measured by a globally accepted index10. Nevertheless, when said parameters deviate from comfortable thresholds, stress mechanisms are occasioned in the human body that—if left unmitigated—may potentially cause or exacerbate disorders and diseases[5].

The present *proof-of-concept* focuses on two IEQ-parameters, namely illumination and ventilation; and is developed in three main steps. In the first step, a formal design-criteria based on D2RO principles is developed in order to imbue considerations of intelligence into the early stages of the design process. These considerations complement and/or address a variety of formal and material aspects—for example, orientation, window glass type, thermal insulation properties of prescribed materials will affect both energy-efficiency as well as IEQ, which consequently impacts well-being and productivity10,[12]. Since IEQ-parameters are invariably related to environmental conditions, there may be an inclination to associate IEQ with sustainable building practices indiscriminately. While there are indeed instances where such association is justified, there are also instances where IEQ and sustainability are mutually exclusive—for instance, sustainable strategies call for higher rates of natural ventilation, but an uninformed ventilation mechanism may deteriorate the acoustic qualities of a space given the accompanying noise permeated from exterior sources[13]. The design-criteria developed in this step yields and justifies a function-specialized fuzzy typology and form intended to complement and be complemented by the functions of subsequent components to be installed therein, in order to attain and to sustain IEQ continuously and optimally.

In the second step, illumination and ventilation systems are developed as IEQ-regulating mechanisms formally complementary of the previously yielded and justified form. With respect to the first system, if via the correlation of various sensed-data (e.g., activity recognition, heartrate, body temperature, etc.) the occupant is perceived to be fatigued[14], a deliberately positioned cluster of lights will activate—in correlation to the proximity to the occupant—and regulate the intensity and color as well as the diffusion of artificial lighting in order to contribute to the mitigation of said fatigue. Similarly, and with respect to the second system, if a particular region of the space requires ventilation due to detected air pollution / contamination and/or uncomfortably high temperature, architecture-embedded vents activate to operate in conjunction with the nodes of the previously developed building-skin in order to regulate location-specific air-quality and thermal comfort, which is arguably the most important parameter in IEQ13,10. The behavior of both illumination and ventilation systems is determined by machine-learning models (i.e., *Support Vector Machine* classifiers) that continuously learn from the occupants, their habits, and their preferences with respect to interior environmental comfort. In the third and final step, the resulting implementation is tested with probands in order to demonstrate continuous, near-real time, and intelligent adaptation that attains and sustains IEQ with respect to illumination and ventilation. The results from this final step demonstrate that a D2RO approach to IEQ yields a more intelligent adaptive mechanism in order to promote occupant well-being in an invisible, unobtrusive, intuitive, and continuous manner.

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Robotic fabrication beyond factory settings

Kathrin Dörfler

Gramazio Kohler Research
ETH Zürich
Zürich, Switzerland

Abstract

Significant effort in raising the degree of automation in building construction and architecture has been most successful in the area of off-site prefabrication. Smaller components of a building are made in a dedicated factory and subsequently transported to the building site for final assembly. Directly on construction sites, however, the level of automation is still comparably low. The final assembly of building components is heavily dominated by manual labor as opposed to other production industries, e.g. the automotive sector. It is then this very final step in construction which breaks the digital process chain between design and making.

What if - instead of building factories to fabricate building components - we begin seeing the construction site itself as the arena, within which the whole building is constructed by digitally controlled machinery at the spot? What possibilities would open up with the implementation of robotized in situ fabrication processes as opposed to digital fabrication in prefabrication? Can we utilize in situ digital fabrication to lower the expense for transport and energy by using local, ad-hoc available materials? And can we eventually redefine conventional construction processes, augment them with the use of robots and develop alternative tectonics to foster a sustainable use of resources, to minimize material waste and increase work safety on construction sites.

In order to find answers to these questions, Gramazio Kohler Research is investigating into these realms on the base of a variety of case studies, tackling the problem from different perspectives. Common to all is the notion to not only advance the efficiency of construction processes, but also the performance and aesthetics of the structures being built: after all, to find form generation and rationalisation to be directly influenced by the logic of making, whether this is concerning the choice of material and assembly systems or the specific features of a certain type of robot or robotic manipulation process. As such, three projects are described in the following which demonstrate indicative steps towards enabling the robotic construction of complex structures beyond factory conditions.

Keywords

Robotic fabrications; automation; digitally controlled machinery

 Dorfler, K. (2017). Robotic fabrication beyond factory settings. SPOOL. 4 (1). doi:10.7480/spool.2017.1.1915

1 Remote Material Deposition

Remote Material Deposition follows the simple idea to expand the predefined workspace of a fixed base robot through the digitally controlled throwing of material to a remote location. Its formal expression results of its unique material morphologies as a direct expression of a dynamic and adaptive fabrication process, mapping out a new architectural landscape of 'Digital Materiality'[1].

2 Rock Print

Rock Print investigates on the principle of 'jamming', which refers to aggregate granular materials crammed together in such a way that it holds its form and shape like a solid. The project investigates and develops methods and techniques for the design and robotic aggregation of low-grade building material into load-bearing architectural structures. Due to the nature of the aggregation process, the structures have to be fabricated at the spot, but remain reusable and reconfigurable, and therefore offer a high geometrical flexibility with minimal material waste[2].


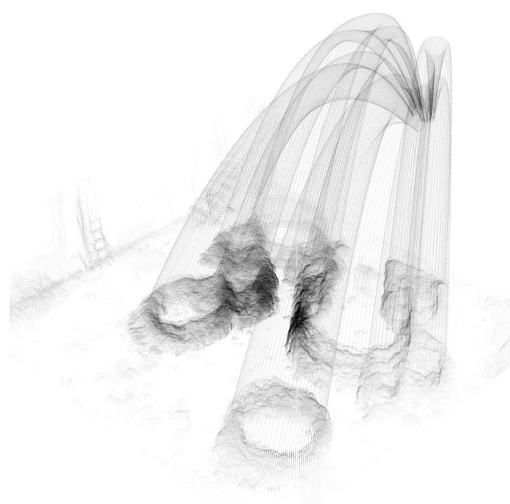

FIGURE 1 Ballistic trajectories of light projectiles through bulb exposure. © Gramazio Kohler Research
The implementation of 3D scanning during the build up process allowed to establish a feedback-loop on a geometrical level and therefore to intervene directly in the materialization process. © Gramazio Kohler Research

1 Dörfler, K., Ernst, S., Piskorec L., Willmann J., Helm, V., Gramazio, F., Kohler, M.: Remote Material Deposition: Exploration of Reciprocal Digital and Material Computational Capacities. In: What's the Matter: Materiality and Materialism at the Age of Computation, ed. Maria Voyatzaki, 361–77. Barcelona (2014)

2 Aejmelaeus-Lindström, P., Willmann, J., Tibbits, S., Gramazio, F., Kohler, M: Jammed architectural structures: towards large-scale reversible construction. In: Granular Matter.(2016)

3 In situ Fabricator

The development of the mobile robotic research platform - the In situ Fabricator - demonstrates a significant step towards enabling the automated material deposition and assembly processes beyond factory settings, but rather in an unstructured and ever changing environment such as a construction site. The mobility of the robotic machinery allows to build structures significantly larger than itself, and its location awareness and awareness of its surroundings allow for maximal flexibility and adaptability during a build up process[3] .

FIGURE 2 Rock Print - a jammed architectural structure consisting of gravel and string towering a mass of 1.2 x 1.5 x 6 m, demonstrated in 2015 at the Chicago Architecture Biennial. © Gramazio Kohler Research and Self-Assembly Lab, MIT
The structure was fabricated out of 10 m^3 of aggregates and 8 km of tensile reinforcement. © Gramazio Kohler Research and Self-Assembly Lab, MIT

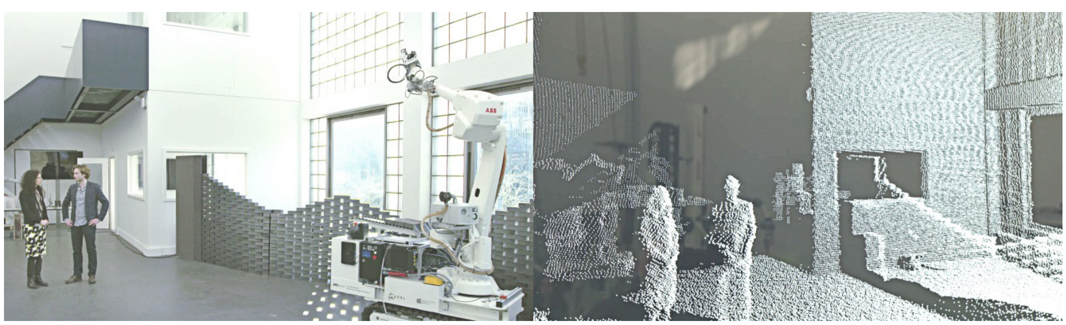

FIGURE 3 The robots arm is equipped with a laser range finder. As the robot sweeps its arm, the laser measures points in space to generate a 3D map of its surroundings. This map is registered against an initial scan of the context in order to calculate the robot's position. (© NCCR Digital Fabrication)

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Materialdesign

An interdisciplinary material-based design approach

Markus Holzbach

University of Art and Design
Offenbach, Germany

Abstract

The Institute for Materialdesign (IMD) understands itself as a hub for inspiration – analog and digital methods are combined - along an interdisciplinary context - to create cross-material innovations. Ideas are frequently generated through the characteristics of the material itself, its qualities and its possibilities as well as its limits. Through the speculative combination of materials, transferring traditional processes of fabrication into innovative contexts, surprising results are achieved. Experimenting, questioning and researching become ever more important in an interdisciplinary context – especially at art college. Many of the student's design came about through playful investigation, which also involved unconventional routes. The primary concerns were getting to know materials, structures and systems, technical, physical and chemical characteristics, and a feel for sensory qualities. This interdisciplinary experimental approach and freedom of creative research is a characteristic of the IMD's approach to teaching. Here, research-driven projects stand alongside object-related product design. Many of the works addresses the relation between man and material. The extended understanding of the material shifts toward the role of the actual object. This new role of materials also comprises the intersection of nature and artifact. Materials are brought to life through layering and combining natural and synthetic elements and blending in digital techniques. The borders of perception are erased and the material itself is redefined. Designing with materials creates a new context between art and science. Material-centered design opens up the field of design to new possibilities and creates a broad space of conceivable tasks.

In the following text we want to present the experimental and material driven approach of the IMD alongside selected student works from the last two years that are located in the areas of interaction, generative design, adaption, digital fabrication, bionic and form generation.

Keywords

Materialdesign; cross-material innovations

 Holzbach, M. (2017). Materialdesign: An interdisciplinarymaterial-design approach. SPOOL. 4 (1). doi:10.7480/spool.2017.1.1916

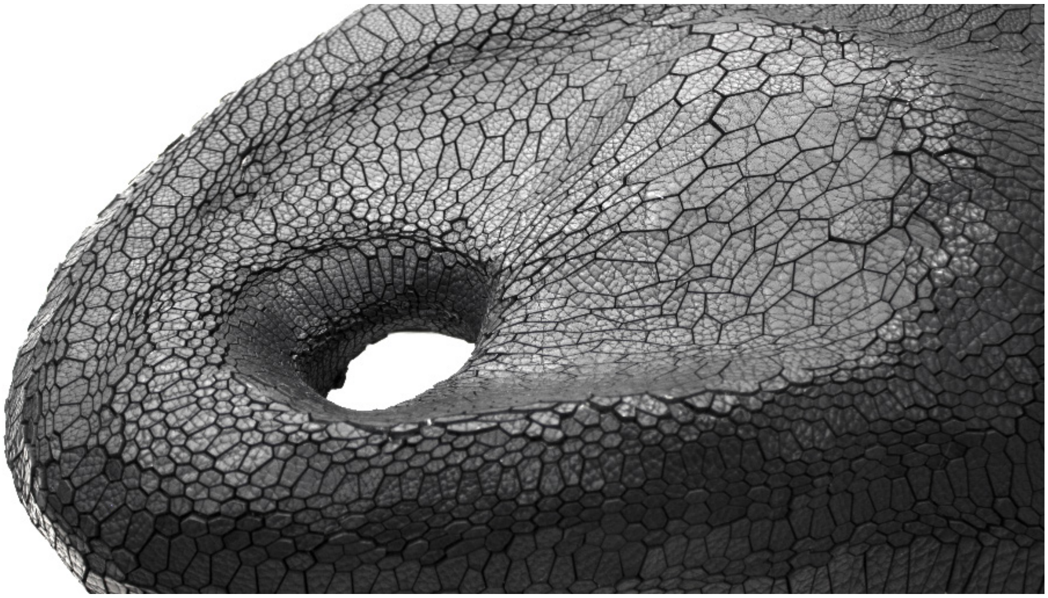

FIGURE 1 'Parametric Skin' by Johannes Wöhrlin, IMD

Parametric Skin

Parametric Skin is a structure that enables us to experience leather in a new way. The design superimposes a graphic, computer-generated honeycomb structure on the natural micro-structure of leather. This artificial structural pattern changes the natural appearance of leather by exaggerating it, in particular in the transition from the two to the three-dimensional. The digital net structure that Parametric Skin is based on is made by parametric programming of the organic leather grain. This is why it adapts to any surface shape. The distortion of the structure emphasizes the edges and specific areas of an object. Using several such 'informed' leather areas, complex spatial objects without no seams can be made. The leather gives objects such as these, inherent stability though they remain flexible.

Intuitive Brain

In cooperation with BMW AG

Functional surfaces are reinterpreted as an aesthetic medium of communication and of information. How can materials and experimental research help to achieve more tangible and intuitive interfaces? Through combining creative and scientific research with human-centered design new functionalities are created. The main priority was to layer physical materialities and interaction. Experimental series, material patterns as well as physical and digital processing lead to a broad variety of projects. Interactive mock-ups where developed to enhance feasibility and perception.

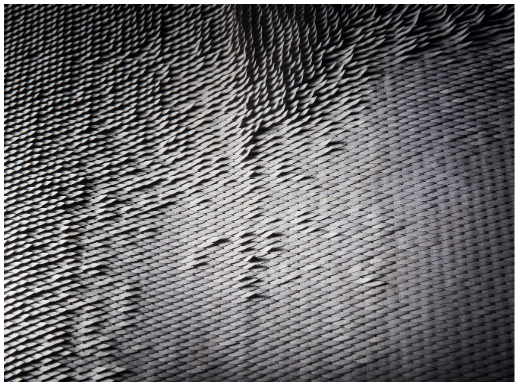

FIGURE 2 Interactive Wood' by Johannes Wöhrlin, IMD

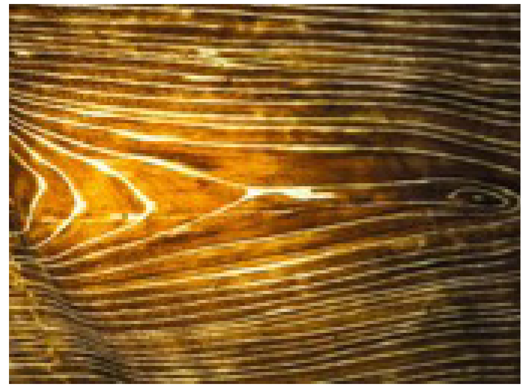

FIGURE 3 'Transformative Paper' by Florian Hundt, IMD

1 Transformative Paper

The anisotropic material properties of moisture expansion in industrially produced paper and natural wood are similar and mostly tried to be avoided. Combined with other materials though, the expansion of the paper reveals interesting effects, which can be used in rather atypical contexts.

The project is a layered structure, which reacts to short-term environmental conditions, morphing into various states. Thoroughly dry, it creates a tactile and exciting surface by raising the seperate segments. Exposed to minimal change of humidity it creates a gesture so subtle it is almost invisible, while it performs a vast transformation when it gets wet. Under the influence of rain the layers shape a closed surface and respond by glowing gently.

2 Interactive Wood

Wood is perceived as a high-quality material and creates a surface with anisotropic properties and individual grain. Every piece of wood is as unique as a finger print.

In this project the aesthetic of the wooden surface brings light to the dark interior of the car.
The shimmering glow of the wooden grain improves the orientation while driving. Through touching the surface, the light is activated on-spot, creating a gesturally controlled functionality. After activation the light is dimmed over time and the grain emits a soft light for a further while. Re-narrating the connection between the hand and the material, the glowing surface resembles a path which is expires after time.

3 Magnetic Fabrics

The goal of this work was to explore new limits of fabrics, to experimentally further develop familiar features of them through unexpected modifications.

To create these modifications different aspects of magnetism are incorporated into traditional fabrics.
The combination of methodically arranged magnetically active and passive components causes a mechanical accumulation of elements and thus a dynamic rearrangement of the entire medium. Over and above the original intention to set the fabric in motion, a surprising set of innovative aesthetics was achieved.
The work illustrates the relationship between media and shape by unique motion sequences.

Ceramic Woods

Ceramic woods, which is short for ceramics made from wood, is the result of a material-inspired process which addresses the question of the composition of contrary material properties. Combining the technology involved in ceramics production and the properties of natural wood produces biomorphic ceramics. This extraordinary material preserves the structural makeup of plants in ceramics. Each variety of timber is different and so each of these ceramic objects is a one-off. All of the lumbers have their natural blueprint of carbon compounds in common. When subjected to great heat, these carbon structures com-bine with silicon to produce silicon carbide ceramic. The combination of plant structures with ceramic properties opens up previously un-tapped potential for design. In biomorphic ceramics, the results of natural evolution can be used to enhance technological systems.

FIGURE 4 'Ceramic Woods' by IMD

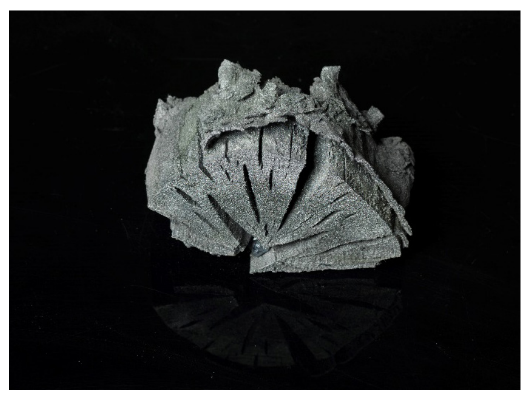

FIGURE 5 'Magnetic Fabrics' by Lilian Dedio, IMD

Acknowledgements

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