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

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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.

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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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1 Liu Cheng, A. (2016). "Towards embedding high-resolution intelligence into the built-environment". Archidoct, 4(1), 29–40.

2 Bier, H. H. (2016). "Robotic Building as Integration of Design-to-Robotic-Production & Operation". *Next Generation Building*, (3).

3 Liu Cheng, A., & Bier, H. H. (2016a). "An Extended Ambient Intelligence Implementation for Enhanced Human-Space Interaction". In *Proceedings of the 33rd International Symposium on Automation and Robotics in Construction and Mining* (ISARC 2016) .

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.

5 Bluyssen, P. M. (2014). The healthy indoor environment: How to assess occupants' wellbeing in buildings. London, New York: Routledge/ Taylor & Francis Group

6 Acampora, G., Cook, D. J., Rashidi, P., & Vasilakos, A. V. (2013). "A Survey on Ambient Intelligence in Healthcare". Proceedings of the IEEE, 101(12), 2470–2494. doi:10.1109/JPROC.2013.2262913

7 Mohamed, A., Novais, P., Pereira, A., González, G. V., & Fernández-Caballero, A. (2015). Ambient intelligence -- software and applications: 6th International Symposium on Ambient Intelligence (ISAmI 2015). Advances in intelligent systems and computing: volume 376. Cham: Springer.

8 Sheng, Q. Z., Shakshuki, E. M., & Ma, J. (2014). Advances in ambient intelligence technologies. Journal of Ambient Intelligence and Humanized Computing, 5(3), 341–342. doi:10.1007/s12652-013-0200-0

9 Chatzidiakou, L., Pathan, A., Summerfield, A., & Mumovic, D. (2012). Environmental and Behavioral Factors Affecting Residential Air Conditioning Use in Athens and London. In S. T. Rassia & P. M. Pardalos (Eds.), Springer optimization and its applications: v. 56. Sustainable environmental design in architecture. Impacts on health (pp. 109–141). New York, NY: Springer.

10 Sakhare, V. V., & Ralegaonkar, R. V. (2014). Indoor environmental quality: Review of parameters and assessment models. Architectural Science Review, 57(2), 147–154. doi:10.1080/00038628.2013.862609

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.

11 Bluyssen, P. M., Aries, M., & van Dommelen, P. (2011). Comfort of workers in office buildings: The European HOPE project. Building and Environment, 46(1), 280–288. doi:10.1016/j.buildenv.2010.07.024

12 Roulet, C.-A., Bluyssen, P. M., Müller, B., & Oliveira Fernandes, E. de. (2012). Design of Healthy, Comfortable, and Energy-Efficient Buildings. In S. T. Rassia & P. M. Pardalos (Eds.), Springer optimization and its applications: v. 56. Sustainable environmental design in architecture. Impacts on health (pp. 83–108). New York, NY: Springer.

13 Al Horr, Y., Arif, M., Katafygiotou, M., Mazroei, A., Kaushik, A., & Elsarrag, E. (2016). Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. *International Journal of Sustainable Built Environment*, 5(1), 1–11. doi:10.1016/j.ijsbe.2016.03.006

14 Nakaso, S., Güttler, J., Mita, A., & Bock, T. (2016). Human state estimation system implemented in an Office Deployable Getaway based on multiple bio information. In Proceedings of the 33rd *International Symposium on Automation and Robotics in Construction and Mining* (ISARC 2016) .

REFERENCES

Acampora, G., Cook, D. J., Rashidi, P., & Vasilakos, A. V. (2013). A Survey on Ambient Intelligence in Healthcare. *Proceedings of the IEEE*, 101(12), 2470–2494.

Al Horr, Y., Arif, M., Katafygiotou, M., Mazroei, A., Kaushik, A., & Elsarrag, E. (2016). Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. *International Journal of Sustainable Built Environment*, 5(1), 1–11.

Bier, H. H. (2016). Robotic Building as Integration of Design-to-Robotic-Production & Operation. *Next Generation Building*, (3).

Bluyssen, P. M. (2014). The healthy indoor environment: *How to assess occupants' wellbeing in buildings*. London, New York: Routledge/ Taylor & Francis Group.

Bluyssen, P. M., Aries, M., & van Dommelen, P. (2011). Comfort of workers in office buildings: The European HOPE project. *Building and Environment*, 46(1), 280–288.

Chatzidiakou, L., Pathan, A., Summerfield, A., & Mumovic, D. (2012). Environmental and Behavioral Factors Affecting Residential Air Conditioning Use in Athens and London. In S. T. Rassia & P. M. Pardalos (Eds.), *Springer optimization and its applications: v. 56. Sustainable environmental design in architecture. Impacts on health* (pp. 109–141). New York, NY: Springer.

Liu Cheng, A. (2016). Towards embedding high-resolution intelligence into the built-environment. *Archidoct*, 4(1), 29–40. Retrieved September 15, 2016, from http://www.enhsa.net/archidoct/Issues/ ArchiDoct_vol4_iss1.pdf.

Liu Cheng, A., & Bier, H. H. (2016a). An Extended Ambient Intelligence Implementation for Enhanced Human-Space Interaction. In *Proceedings of the 33rd International Symposium on Automation and Robotics in Construction and Mining* (ISARC 2016) .

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.

Mohamed, A., Novais, P., Pereira, A., González, G. V., & Fernández-Caballero, A. (2015). *Ambient intelligence -- software and applications: 6th International Symposium on Ambient Intelligence* (ISAmI 2015). *Advances in intelligent systems and computing: volume 376*. Cham: Springer.

Nakaso, S., Güttler, J., Mita, A., & Bock, T. (2016). Human state estimation system implemented in an Office Deployable Getaway based on multiple bio information. In *Proceedings of the 33rd International Symposium on Automation and Robotics in Construction and Mining (ISARC 2016)* .

Roulet, C.-A., Bluyssen, P. M., Müller, B., & Oliveira Fernandes, E. de (2012). Design of Healthy, Comfortable, and Energy-Efficient Buildings. In S. T. Rassia & P. M. Pardalos (Eds.), *Springer optimization and its applications: v. 56. Sustainable environmental design in architecture. Impacts on health* (pp. 83–108). New York, NY: Springer.

Sakhare, V. V., & Ralegaonkar, R. V. (2014). Indoor environmental quality: Review of parameters and assessment models. *Architectural Science Review*, 57(2), 147–154.

Sheng, Q. Z., Shakshuki, E. M., & Ma, J. (2014). Advances in ambient intelligence technologies. *Journal of Ambient Intelligence and Humanized Computing*, 5(3), 341–342.

Robotic fabrication beyond factory settings

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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

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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].

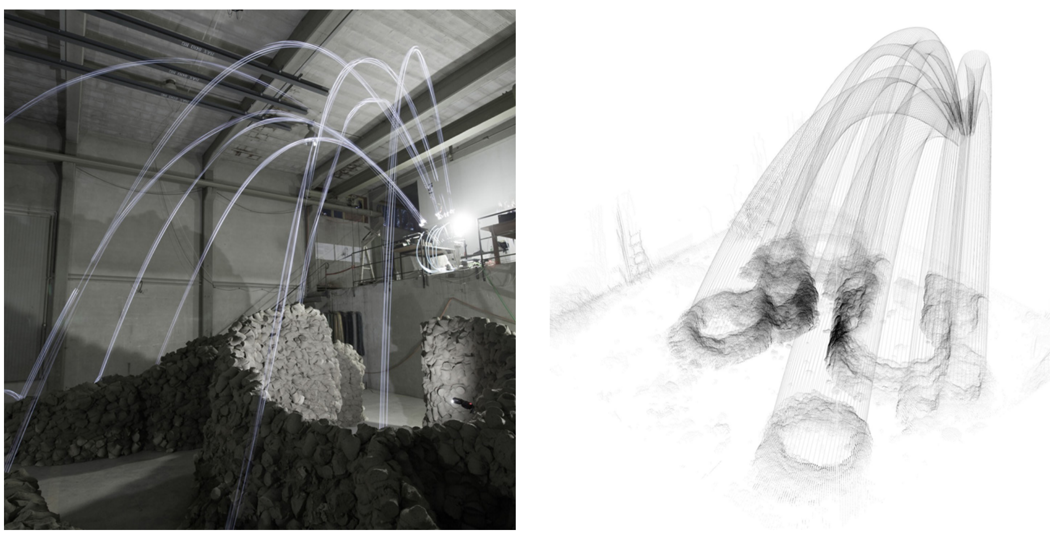

FIGURE 1 Ballistic trajectories of light projectiles through bulb exposure. © Gramazio Kohler Research
The implementation of 3D scanning during the build up process allowed to establish a feedback-loop on a geometrical level and therefore to intervene directly in the materialization process. © Gramazio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

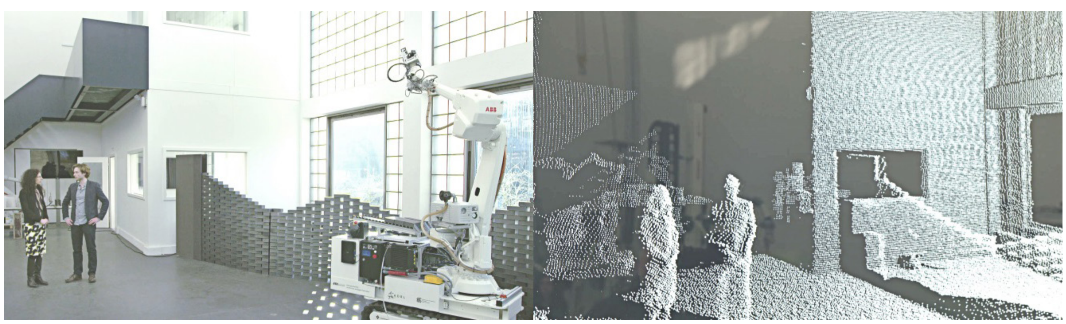

FIGURE 3 The robots arm is equipped with a laser range finder. As the robot sweeps its arm, the laser measures points in space to generate a 3D map of its surroundings. This map is registered against an initial scan of the context in order to calculate the robot's position. (© NCCR Digital Fabrication)

3 Dörfler, K., Sandy, T., Giftthaler, M., Gramazio, F., Kohler, M., Buchli, J.: Mobile Robotic Brickwork - Automation of a Discrete Robotic Fabrication Process Using an Autonomous Mobile Robot. In: Robotic Fabrication in Architecture, Art and Design, pp. 205–217 (2016) and Helm, V., Ercan, S., Gramazio, F., Kohler, M.: Mobile robotic fabrication on construction sites: Dim-rob. In: 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (2012)

Rerefences

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

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)

Dörfler, K., Sandy, T., Giftthaler, M., Gramazio, F., Kohler, M., Buchli, J.: Mobile Robotic Brickwork - Automation of a Discrete Robotic Fabrication Process Using an Autonomous Mobile Robot. In: Robotic Fabrication in Architecture, Art and Design, pp. 205–217 (2016)

Helm, V., Ercan, S., Gramazio, F., Kohler, M.: Mobile robotic fabrication on construction sites: Dim-rob. In: 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (2012)

Willmann, J., Knauss, M., Bonwetsch, T., Apolinarska, A.A., Gramazio, F., Kohler, M.: Robotic timber construction expanding additive fabrication to new dimensions. Automation in Construction 61, 16 – 23 (2016)