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Robotic Building(s)

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Technological and conceptual advances in fields such as artificial intelligence, robotics, and material science have enabled robotic building to be in the last decade prototypically implemented. In this context, robotic building implies both physically built robotic environments and robotically supported building processes, whereas reconfigurable, robotic environments incorporating sensor-actuator mechanisms that enable buildings to interact with their users and surroundings in real-time require design to production, assembly, and operation chains that may be (in part or as whole) implemented by robotic means. This paper presents and discusses research and experimental developments in robotic building implemented more recently at Hyperbody.

Keywords: Robotic Architecture, Robotic Fabrication and Building, Embedded Mechatronic and Intelligent Control Systems, Internet of Things and People.

1. Introduction

In the last decade, technological and conceptual advances in fields such as artificial intelligence, robotics, and material science have enabled interactive and robotic architecture to be implemented by Hyperbody in physically built robotic prototypes. These accommodate, on the one hand human needs addressing imperative requirements for responsiveness, adaptation, flexibility, energy efficiency and reconfiguration; on the other hand, they extend human needs by establishing interactive relations with the environment. Reconfigurable, robotic environments incorporating mechatronic devices that enable buildings to interact with their users and surroundings in real-time (Bier & Knight, 2010; Oosterhuis, 2011) through physical or sensory change and variation allow multiple, changing functions in condensed time frames and address inter al. local issues of inefficient use of built space but also global issues of rapid urbanization and environmental protection.

Development of concepts and practical applications for interactive, robotic building, leading to the emergence of interactive and proactive building components, which act and interact in ever-changing environments is based on understanding buildings from a life-cycle perspective with respect to their socio-economical and ecological impact. Furthermore, seamless, computer numerically and robotically supported design to production and operation chains enabling implementation of robotic buildings from conceptualisation to use imply use of modelling, simulation, and 1:1 prototyping environments facilitating

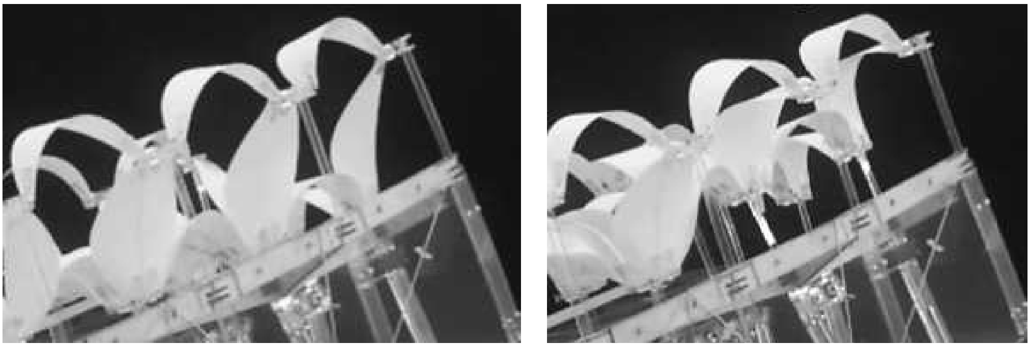

Figure 1. Hyperbody MSc 4 project (2012) featuring interactive skin components employed for energy generation and ventilation purposes

collaboration and exchange between experts from different disciplines. Robotic buildings as physically built environments incorporating robotic devices and robotic building as a robotically supported, seamless design to production and use process are focus of recent research at Hyperbody as presented in this paper.

2. Robotic Buildings

Robotic buildings are physically built environments consisting of building components with embedded robotic devices. Such robotic building components exhibit behaviours that follow simple rules in order to satisfy structural, climatic, or spatial requirements and build collectively a dynamic, intelligent environment (Oosterhuis, 2010). For that purpose, components are tagged and incorporate information regarding inter al. their design, structure, materialisation, production, assembly, and operation. Furthermore, they are equipped with sensors and actuators that enable them to not only perceive but also act on their surrounding environment. This ability to act may imply physical such as geometrical, material, or sensorial transformation and reconfiguration.

In general terms, application of embedded robotics in architecture has been identified in areas dealing with (a) health, demographic change and well-being, as well as (b) sustainable climate control and energy production. For each of these areas, robotics may be employed as follows:

Robotic building components (such as doors, walls, floors, etc.) may support daily life activities offering solutions for dealing with rapid increase of population and urban densification as well as contemporary inefficient use (25%) of built space. Furthermore, in building components embedded robotics may assist health care and recuperation, whereas physical, cognitive, mental, sensory, emotional, developmental, or some combination of these impairments may be reduced or minimized by means of Assistive Technology (Smith, 2010) and spatial responsiveness.

Robotically supported sun and wind energy production devices embedded in building components may enable sustainable energy generation, whereas distributed climate control may allow improving indoor climate with the aim to address sustainability issues and building life-cycle to be considered together with operating costs from the very beginning of the design.

In principle, application of embedded robotics in architecture implies allowing for downtime (referring to time periods when the system, in this case the building, is non-operational) to be reduced through physical reconfiguration. This is accomplished through advancement of collective behaviour systems so that several autonomous building components operate in cooperation in order to accomplish major reconfiguration and adaptation tasks.

The aim of robotic building is to address **societal issues** such as the current vacant office space (16%) in Netherlands by increasing up to 50–75% the 24/7 use of built space through changing and multiple uses in reduced timeframes. Furthermore, the increase of urban population from 3.2 billion to nearly 5 billion by 2030 with, according to UN, 3 out of 5 people living in cities is addressed by improving inefficient use of built space (25%) trough spatial reconfiguration. Last but not least, the advancement of embedded, interactive or robotic, energy and climate control systems employing renewable energy sources such as solar and wind power (Oosterhuis, 2011) are aiming at reducing architecture's ecological footprint while enabling energy efficient, human-centred, and demand-driven use of space. In this context, RoboSPACE has been developed as framework for investigating applications of robotics to responsive and reconfigurable architecture.

Figure 2. Protospace 4.0 consisting of integrated, customizable, specialized and interactive building components was developed by Hyperbody (2010)

Reconfigurable, robotic environments incorporating digital control namely sensor-actuator mechanisms that enable buildings to interact with their users and surroundings in real-time (Bier and Knight, 2010; Oosterhuis, 2011) through physical or sensory change and variation imply multi-disciplinary research with respect to architectural design and engineering of reconfigurable, robotic systems employing horizontal and vertical spatial expansion based on additive-subtractive and folding principles, materialisation research for rapid computer-numerically controlled (CNC) or robotic fabrication and assembly as well as sustainable operation in-situ. In this context, **roboSPACE** (with reference to protoSPACE 4.0) is envisioned as a modular (Friedrich, 2011) or foldable (Jaskiewicz, 2011) by spatial motion (kinematics) self-assembling and self-adjustable system for which the following architectural sub-systems are considered:

1. RoboSKIN is separating inside from outside space and addressing mainly climatic (light, temperature, ventilation, etc.) and energy control at building scale;
2. RoboWALL as the InteractiveWall (Hosale and Kievid, 2010) is separating interior spaces, addressing mainly enclosure, acoustic, visual, and indoor climate control needs at small and medium scale. It is enabling subdivision of space in order to facilitate 24/7 diverse and changing use of space;
3. RoboFLOOR/CEILING implying a vertical split level system, where the splits can bend, fold, or move up and down, allowing for multiple connectivities between different levels in the building, thus changing configurations for diverse functional layout, by expansion or shrinkage of floor/ceiling areas, enabling diverse and changing use of space;

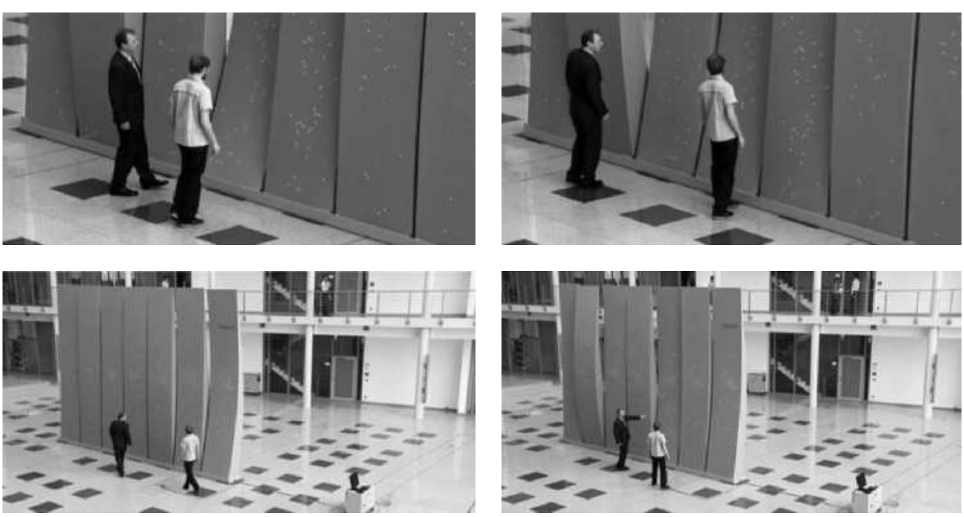

Figure 3. InteractiveWall developed by Hyperbody in collaboration with Festo responds to people's movement (2009).

4. RoboCELL (with reference to protoCELL) is consisting of building components that are neither wall nor floor/ceiling but a *new* component enabling reconfiguration of spatial subdivision, providing or blocking light, influencing the flow of air in the building, participating in playful interactions and servicing the use of space. RoboCELLs can *immediately* unfold, expand or shrink and act as to accommodate rapidly changing demands with respect to use of the space.

In RoboSPACE all robotic components act together as a whole in permanent connectivity with all other building components as for building a swarm of cooperating devices aiming to prove that robotics embedded in architectural components enables adaptation and change from physical to sensorial and climatic reconfiguration. Application of RoboSPACE to health and building industry may allow development of a range of *new* products from the sub-component to the component and building scale. For instance, RoboWALL, -FLOOR/CEILING, and -CELL may be employed in health and building industry for creating spatial reconfiguration in order to (a) facilitate or restrict movement in space or use of appliances and (b) optimize 24/7 use of space. Also, RoboSKIN may contribute to a sustainable climate control while operating together with distributed sub-components integrated into RoboWALL, -FLOOR/CEILING, and –CELL.

RoboSPACE builds up on knowledge in non-standard and interactive architecture developed at Hyperbody in the last decade (Figures 2&3) and has been preliminarily explored with MSc 4 students (2012) as adaptive systems embedded into public buildings (Figure 1) and further prototypically developed with MSc 2 students (2013) as reconfigurable, multimodal apartments. Furthermore, indoor climate regulating system we explored with MSc 1 and 3 students (2013–14). These investigations yielded relevant results: While the multimodal apartment (http://multimod.hyperbody.nl) has proven, as in case of the Pop-up apartment (Figure 4) that spatial reconfiguration can optimize 24/7 use of built space, the climate control related investigation has shown that integrating distributed interactive climate control devices into building components may contribute considerably to improving indoor climate.

Considering that the aim for the Multimodal Apartment was to design a small apartment of 50m2/150m3 that has all the spatial qualities and functional performances of a standard 100m2/300m3 apartment, the initial assumption was that when a user is in the living room, this user does not use the sleeping room at the same time implying that at one moment of the day large sections of the space could cater to only 1-2 functions. Basic recommendations for the design were inter al. use of dry assembly, scripting (the designed structures is generated and handled through scripted algorithms), CNC fabrication, as well as use of Design Information Models (DIM). The proof of concept implied building 1:1 prototypes, which in case of the Pop-up apartment (Figure 4) shows that spatial subdivision and furniture reconfiguration exploiting material and geometrical properties easily facilitate 24/7 change of use.

With respect to the climatically regulated building, the aim was to develop ideas for self-sustaining climatic ecologies by investigating potentially synergistic relations between

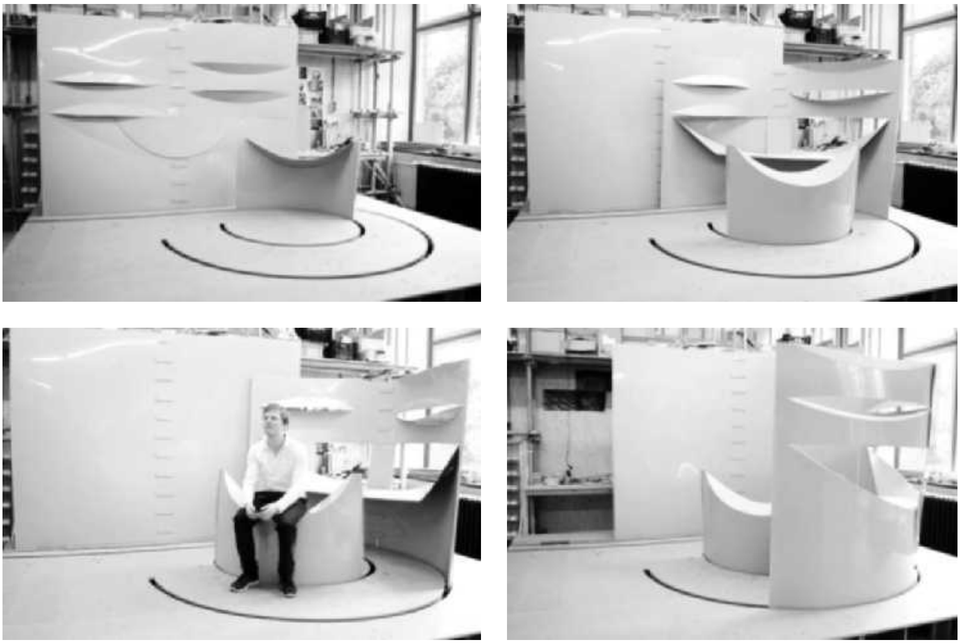

Figure 4. Reconfigurable apartment developed by Hyperbody with MSc 2 students and industry partners (Pop-up Apartment, 2013)

the environment, architectural space and its respective urban context (http://2628climator.hyperbody.nl/ and http://ceco.hyperbody.nl/). Problems such as inefficient climate control and unhealthy indoor climate were addressed through distributed (in building components embedded) intelligent climate control by employing efficient sensor-actuator mechanisms and intelligent control strategies. Development of such robotic building components and buildings requires, however, effective design to operation processes. While Hyperbody has been developing and exploiting in the last decade CNC (Computer-Numerically Controlled) design to fabrication systems explored mainly in Protospace, only more recently robotic fabrication has become focus of investigation.

3. Robotic Building

If robotic building implies robotically supported design to production and operation chains, Hyperbody has been recently started implementing robotic fabrication processes with two large ABB robots, which are customized to perform specific tasks by employing specialized operating tools and programs (Oosterhuis, 2011). A series of experiments were implemented with MSc 2 students in order to develop and test robotic fabrication methods by establishing a feedback loop between design and fabrication. The assumption was that by employing robotic fabrication, customized designs could be easily implemented so that users may change (extend, shrink, expand, etc.) built environments on demand.

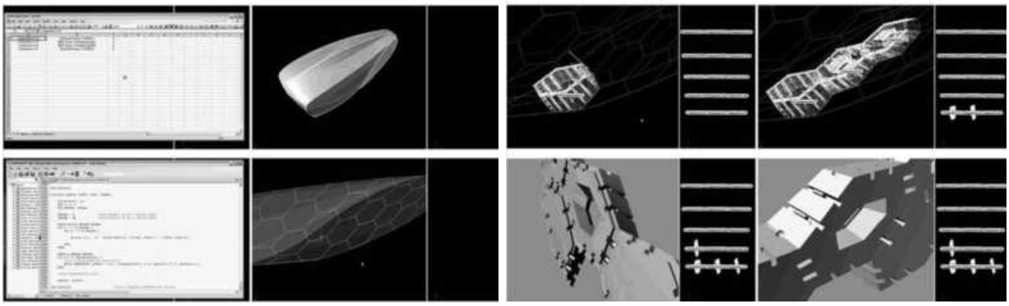

Figure 5. CNC (Computer-Numerically Controlled) modelling, simulation to production and operation chain as set-up and tested for Protospace 4.0

Such explorations with robotic fabrication indicate that architectural production becomes procedural instead of object-oriented and form emerges from a process in which the interaction between all (human and non-human) parts of the system generates the result.

4. Conclusion

Research and experimental developments in interactive buildings and processes implemented at Hyperbody in the last decade such as Protospace 4.0, Interactive Skin (Figures 1-3), and Interactive Wall (http://www.hyperbody.nl/research/projects/interactivewall/) employing multiple and distributed sensor-actuators integrated into architectural components confirms that distributed intelligent control is a viable option for addressing contemporary needs for reconfiguration and demand-driven use of physically built environments. This enables Hyperbody to take the next step in the development towards robotic building.

Interactive and robotic systems imply that all components act together as a whole in permanent connectivity with all other components as for building a *swarm* of cooperating components. While some of them are acting slow in yearly and monthly cycles, in order to address seasonal change in use, some of them act quickly in weekly or daily cycles, in order to address work, leisure, rehabilitation activities or climate control, while the fastest adapt to immediate changes at hourly rate, acting as adaptive furniture pieces or appliances. Thus an ecology of complex adaptive building components and sub-components of different interlacing species operates through changing cycles, while the Hive System developed at Hyperbody (2012) provides the technological basis for the connectivity between all interactive components. The Hive System establishes a communication platform for distributed sensor-actuators networks (http://www.hive-systems.net/applications) where nodes may be floor tiles, wall panels, lights or objects, equipped with a variety of sensors to connect with its surroundings (via microphone, touchscreen or proximity sensor) and actuators (such as light, display, speaker or motor).

Figure 6. MSc 2 prototype developed by means of robotic fabrication implemented with two large ABB robots operating wire-cutting tools (2012)

The innovation aspects are to be seen in the way building components operate as an intelligent distributed system and the necessary technological steps to be taken such as advancement of knowledge for (A) Optimized distributed intelligent control, (B) Development and rapid deployment of sensors and actuators, fast state estimation, and optimized control algorithms, (C) State-of-the-art modelling and simulation frameworks for distributed systems.

The novelty of the research methods lies in establishing a direct link between design, building and operation of proposed mechatronic systems through CNC design to fabrication and operation chain. Multi- and trans-disciplinary architectural and engineering research as well as CNC or robotic prototype production (Figure 5) is collaboratively implemented in Protospace, which is equipped with milling and laser and wire-cutting machines (http://www.hyperbody.nl/protospace/).

Technological, economic and- or societal risks (failure probabilities) are recognized in the areas where components require easy access and are effortlessly replaceable, also components are expensive as they incorporate sensors and actuators and production of electronic waste needs to be acknowledged and investigated. However, contemporary societal urgencies such as rapid increase of population, natural resources depletion, environmental pollution and climate change require intelligent solutions that make use of the opportunities offered by embedded robotics.

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