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Developing Responsive Environments based on Design-to-Robotic-Production and -Operation Principles

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Abstract –

The development of physical and computational mechanisms aimed at augmenting architectural environments has been one of the foci of research implemented at the Faculty of Architecture and the Built Environment, Delft University of Technology (TUD) for more than a decade. This paper presents the integration of distributed responsive climate control into the built environment based on Design-to-Robotic-Production and -Operation (D2RP&O) principles. These connect computational design with robotic production and operation of buildings. In the presented case study structural elements meet load-bearing as well as functional requirements. Their spatial arrangement creates variable densities for accommodating sensor-actuators that are operating heating and cooling. This mechatronic operation relies on activity recognition for achieving responsive climate control in the built-environment.

Keywords –

Design-to-Robotic-Production and -Operation; Wireless Sensor and Actuator Networks; Responsive Environments

1 Introduction

In the past, spaces were designed to meet human needs by identifying activities for which generic spaces composed of vertical walls and horizontal floors were created. These were adapted to specific needs by furnishing. Today, technological advancements in architectural engineering [1] as well as new scientific insights into health and human comfort [2] provide the basis to design mass-customizable building components and responsive indoor climates by means of Design-to-Robotic-Production and -Operation (D2RP&O).

By connecting robotic production and operation with computational design, D2RP&O contributes to improving both manufacturing processes and performance of buildings. While, D2RO relies on sensor-actuator networks that are establishing cyber-physical mechanisms aimed at introducing responsiveness in the built-environment, D2RP facilitates designing and building such environments. Together D2RP&O establish an unprecedented feedback loop based on human-nonhuman interactions, which have properties that are not reducible to neither human nor nonhuman aspects; instead, they result from the relationships and dependencies they form.

2 D2RP&O

D2RP&O relies on hybrid componentiality. This implies that building components are cyber-physical and that their design is informed by functional, structural, and environmental requirements, while taking into consideration both passive (i.e. structural strength, thermal insulation, etc.) and active (i.e. responsive, etc.) behaviors.

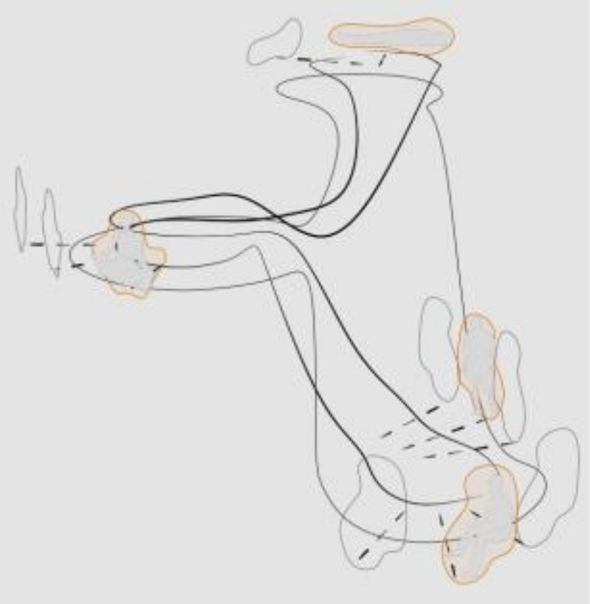

Figure 1-1. Design of the outer skin following body positions and schematic movement of activities

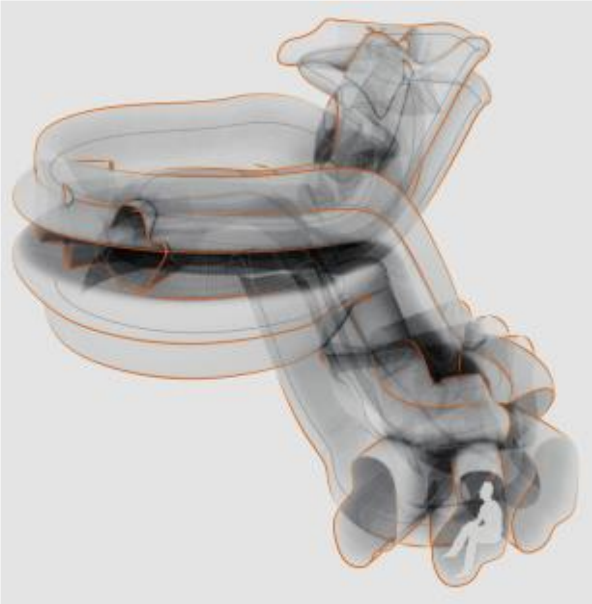

Figure 1-2. Design of spatial envelope based on mapped body positions and schematic movement of activities

In the presented case study, the focus is on the development of student housing units. Spaces are generated by mapping the movement of the human body during daily activities such as exercising, studying/working, relaxing, and sleeping. Each of these activities is described in terms of specific body positions, movement ranges, and their corresponding spatial requirements. These spatial requirements are basis for generating a schematic shape i.e. envelope onto which furnishing and climate control requirements are projected (Figure 1-1 and -2 and Figure 2). While requirements for furnishing focus on accommodating the human body during daily activities (such as seating, lying down, etc.), requirements for climate control provide distributed local comfort. Such an approach takes not only individual comfort in consideration, but also energy-efficiency, in particular when environments are inhabited or used with variable frequency.

2.1 Local Comfort and Distributed Climate Control

The proposed distributed approach to climate control is presently implemented while taking in consideration the uneven distribution and density of heat- and cold-perceiving thermo-receptors [2] in the human body. While the three areas of highest concentration of thermo-receptors are located in the head, the abdomen, and the extremities, their sensibilities vary. For example, cooling is most effective when applied to the head and the extremities [3]. Furthermore, direction of the air flow and variation of physical activity (e.g. sleeping, studying, working out, etc.) need to be considered. Such complex sometime even conflicting requirements require a locally responsive distributed approach.

The presented case study explores requirements for a student housing unit that is accommodating up to three persons at the same time. It answers the question of how the building envelope may be equipped with a set of sensor-actuators that respond to changing physiological requirements. These requirements are first mapped onto the envelope modeled from the simulated movement of the human body in space (Figure 2). Requirements vary in distribution and are effectuated by devices with various sizes. Presently considered heating devices consist of infrared lamps, whose energy is gained from photovoltaic cells integrated in the building envelope, while the cooling system employs vaporized water-streams.

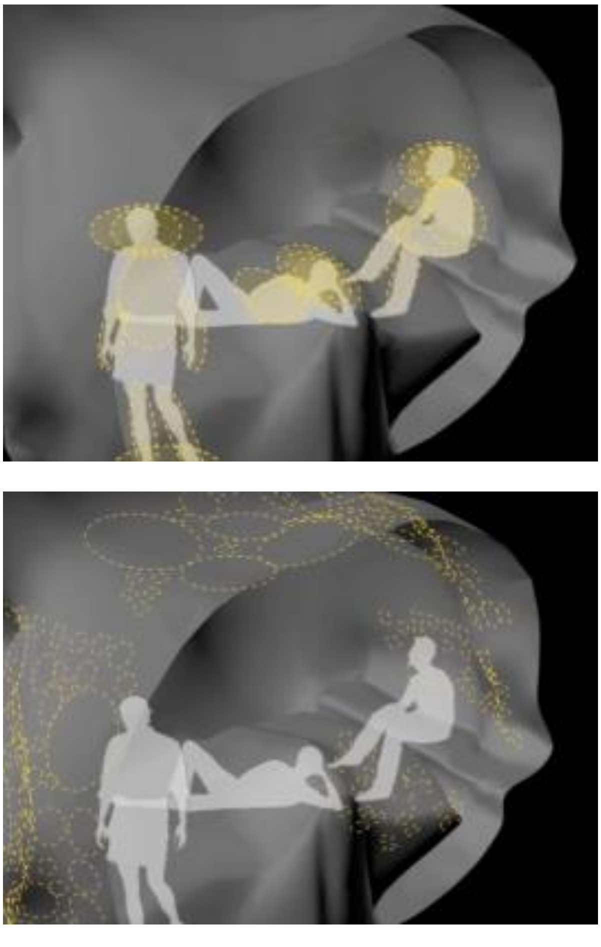

Figure 2. Mapping of physiological requirements on human body (top) and projection of local comfort requirements onto envelope (bottom)

Figure 3. Wooden beams are designed and manufactured to bend around specialized climate control components

Evaporative cooling employs jets of cold air or vapor and takes advantage of the enthalpy of vaporization [5]. The system sprinkles water onto a membrane or pad, through which air is blown. Thus, cooled vapor is created, which can be stored or delivered to the cooling devices (Figure 3). Distributed sensors gather data with respect to occupancy, temperature, humidity, etc. that is feed to the computational nodes, which in turn activate the mechanical system. Both heating and cooling systems turn on and off on demand and while these systems cannot be described as entirely off-the-shelf due to customization requirements, most of their components are already implemented in everyday life scenarios, especially open-air environments needing larger thermal control such as cafes with outdoor seating, etc.

This implementation of D2RP&O builds up on knowledge with respect to user needs [3] and wireless sensor-actuator networks for distributed climate control [4]. Such climate control functions through the use of mechanical devices that are operated by computational nodes establishing together a cyber-physical system. This distributed approach makes indoor environments adaptive and energy-efficient since vast amounts of energy required by traditional centralized climate comfort systems are saved. The novelty of the proposed system lies not in the individual components but in their synergetic operation with users based on computational feedback. This enables an immediate response to changing physiological demands. Devices are distributed and are able to rotate in three directions, in order to follow a moving person. They dynamically respond to the users' movement in space and create personalized climatic areas surrounding them.

2.2 Responsiveness and Interaction

The framework of local climate comfort requires that the building possesses the capacity of *identifying* occupants and environmental conditions in terms of temperature, humidity, etc. This is achieved through the use of architecture-embedded as well as wearable sensors i.e. smart phones.

Sensors collect data from the environment and users, which is then processed in computational nodes that activate or deactivate the distributed devices. They instantiate a responsive behavior that in a next step will be imbued with computational intelligence allowing the system to not only respond but anticipate, learn, and actively propose climatic changes by monitoring physiological and environmental data. In this implementation devices are turned on-off and rotate to track users moving in 3D space (Figure 4). The number of devices that are activated at the same time depends on climatic requirements at that time. While in this case only two kinds of devices were considered for heating and cooling, additional devices for lighting and ventilating that are combining natural and mechanical means would also need in a next step to be considered.

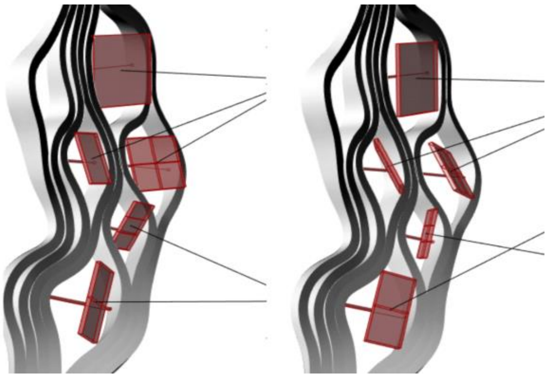

Figure 4. The infrared lamps turn on when people are approaching and rotate to follow their movement in space

2.3 Materialization

In the proposed design, the structural elements create in-between spaces to accommodate mechanical devices of varying sizes and distributions while maintaining structural integrity. Wood has been chosen because of its relative malleability allowing continuous bended beams to accommodate varying porosity requirements. Thus beams are distributed according to structural forces and porosity requirements (Figure 3). Variation in distribution of beams is accomplished through densification and rarefication, respectively. If densification creates an increasingly compact surface, rarefication introduces porosity that accommodates windows and climate control devices.

Figure 5. Materialization experiments and robotic production process involve robotic milling (top), preliminary research on the geometry of the milled section (middle) and robotically fabricated component (bottom)

Beams were manufactured using D2RP for kerf bending. This implies material removal for torqueing purposes. By milling a series of parallel cuts into the beam, a bending behavior is generated in the direction opposed to the milling direction. The assumption is that this process is a better alternative to the lengthy and wasteful approaches employing steaming and molding. Given the complexity of the design, this implementation requires extensive preliminary investigations regarding (1) the geometry of the milled sections, which directly affects the torque, (2) the distance between milled sections, which affects the bending angle and (3) the distribution on different sides in order to create torsion.

In a first step, extruded polystyrene (EPS) is introduced as a testing material. While the two materials are very different, EPS is instrumental in understanding the underlying principles and possible limits of the system (Figure 4). D2RP tests yielded relevant results in terms of precision of the computational system and the challenges of the robotic production. For instance, the higher the proximity of the milled sections is, the more the beam would start bending during the production process, resulting in imprecision or even breakage. These criteria are then fed back into the design and computational strategy, thereby establishing a loop of information exchange between the material and computational aspects of the project.

3 Methodology and Implementation

D2RP is integrated with D2RO in order to achieve hybrid architectural components that are able to respond to changing needs by employing motion and proximity recognition.

D2RP involved parametric modeling and structural simulations in Grasshopper and Karamba 3D while environmental simulations will be implemented in a next step. In terms of robotic production, a combined additive-transformative approach was carried out. The additive aspect of this approach refers to the multiple materials and components such as wood beams, mechanical devices, and building envelope that are incorporated into a hybrid whole. The transformative aspect refers to the bending of the wooden beams, which will be implemented in a next step using two robots. The process will start with first inserting a bundle of beams into a feeder. Each beam will be picked up by one of the two robots and will be transferred to a moveable spanning device with an appropriate high retaining system designed for longer beams, which will allow the robots to process the beams. The proposed bending in 3D is of interest because it is accommodating both structural and distributed climate control requirements and is particularly suitable for robotic transformative techniques. This system of bended structural elements works with spatial displacement as well as variation in depth and width in order to meet structural requirements and accommodate user-defined requirements for illumination, ventilation, heating or cooling (Figure 6). At this stage, the design addresses only heating and cooling requirements, and physical experimentation stays at the level where beams have been only tested in EPS. Furthermore, as proof of concept, D2RO involves the use of distributed proximity and distance ultrasonic sensors, actuators (Servo Motors), and microcontrollers (Arduino Mega). While sensors detect users, the actuators turn on-off and rotate devices according to input from the microcontrollers, which have the programmed behavior to follow the movement of users.

Figure 6. Fragment showing bended beams system accommodating mechatronic devices: (1) heating devices, (2) variable-depth structural elements, (3) small windows for natural illumination, (4) water storage compartment, (5) large window for illumination and views, (6) cooled-air chamber and wetted pads, (7) variable-depth structural elements, and (8) cooling devices.

4 Conclusion

The concept of the presented D2RP&O method relies on linking computational design with robotic production and operation. The implementation by means of D2RP&O of a building envelope that integrates functional, structural, and distributed local climate control requirements demonstrates the potential of this method to develop architectural spaces that accommodate a range of varying user-needs. The integration into the architectural envelope of climate control devices for local comfort using an additive and transformative D2RP approach is of particular interest because of its potential to address customization needs as well as structural- and energy-efficiency requirements. Furthermore, through the development of cyber-physical mechanisms, human capabilities in the physically built environment are extended. Even though in the present development only motion and proximity recognition are deployed, they enable the system to identify users and respond in terms of cooling and heating according to occupancy and use.

D2RP&O proves to be effective in linking computational design with robotic production and operation of buildings. It establishes human-nonhuman interactions in the built-environment, which have properties that are not reducible to those of individual components; instead, they emerge from the relationships they form. Climate control is local and customized to individual needs, where sensor-actuators respond to physiological and environmental variations. While building processes become increasingly automated, buildings evolve towards developing awareness with respect to their occupants as well as their indoor environments by interacting with both via cyber-physical mechanisms.

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