Design-to-Robotic-Production and -Operation for Activating Bio-Cyber-Physical Environments

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Chapter 4
Design-to-Robotic-Production and -Operation for Activating Bio-Cyber-Physical Environments

Henriette Bier, Arwin Hidding, Max Latour, Pierre Oskam, Hamed Alavi, and Alara Külekci

4.1 Urban Context

Residual spaces resulting from inter al. abandonment of vernacular or industrial buildings due to de-industrialization, migration, political and economic shifts, and ineffective planning (Accordino and Johnson 2000; Haase et al. 2016; Oskam et al. 2021) contain valuable assets, for instance, unique animal and plant species that inhabit such abandoned places (inter al. Laurie 1979). These places offer potential environments for wildlife and natural growth within the urban fabric (Kawata 2014), accommodating species that often find no place because of inter al. intensified agriculture (Harrison and Davies 2002; Kowarik 2013; Schwarz 1980). Furthermore, they serve as meeting places for the youth engaging in artistic creation, play, and exploration (Edensor 2005). Residual spaces introduce thus new opportunities for material and social interaction although their ecosystems remain fragile and they may often be misused for illegal activities. Hence, the challenge to find solutions that improve socio-ecological value for those places without requiring large investments remains.

In the first presented case study, the chosen strategy to enhance residual spaces relies on applying 'minimal interventions' (Lassus 1998; Oskam et al. 2021) that stimulate both biodiversity and social accessibility. The proposed interventions resemble miniature planets, as they are roughly spherical in shape and have differentiated interiors (Schmidt et al. 2007). These 'planetoids' are 0.5–1.0 m diameter artefacts (Fig. 4.1) large enough to relate to the architecture of the site and small enough to be easily handled by humans. Their interior porosity contributes to the development of ecosystems by hosting various species (Oskam et al. 2021) either

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Fig. 4.1 Minimal interventions in residual spaces have the potential to stimulate biodiversity and social accessibility

growing from earth balls[1] with plant seeds placed in those cavities, or from colonizing insects and animals. The goal is to mitigate the negative effects of climate change on a local level involving biodiversity loss and urban heat islands (Selwood and Zimmer 2020) by introducing microclimatic heterogeneity that buffers species against local extirpations (inter al. Suggitt et al. 2018).

In order for bypassers to interact with the plant growth and animal colonization processes, the 'planetoids' contain sensors that identify the location, temperature, humidity, etc. Data is recorded and shared via the Internet, where changes detected in the 'planetoids' are visualized and made accessible to potential visitors. The sensors may, for instance, 'indicate' that the soil of the plants is too dry, thus 'inviting' visitors to water them (Oskam et al. 2021) or pick them up and move them to locations that have less sun or are better protected from the wind.

4.2 Design-to-Robotic-Production and -Operation

Numerous applications involving Cyber-physical Systems (CpS) and Artificial Intelligence (AI) are being increasingly employed (inter al. Rajkumar et al. 2010) in architecture. Furniture scale examples such as The Big Data (2016)[2] furniture and Media Block Chair (2012)[3] are relevant examples wherein the furniture reacts to people's movement by changing colour. Such furniture takes advantage of location-based context-aware services and Internet connectivity that are ubiquitously available. It has an embedded intelligent system able to connect with, anticipate, and respond to users' desires by utilizing a variety of sensors and actuators located inside the system.

Big Data furniture, for instance, analyzes its surroundings and communicates with users by changing colours in response to movement and changing spatial factors. It

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[1] Earth balls consist of a variety of seeds integrated into balls of clay, humus and/or compost.

[2] Link to Bassala website: sn.pub/zif69e and sn.pub/MJOW31.

[3] Link to TL website: sn.pub/nAwQ17.

communicates with users and other smart devices in the same room to influence their behaviour via a Twitter account. The movement and behaviour of users as well as environmental data patterns are shown in an online database. Data collected over time on the distance of users to the furniture or information on temperature, air quality, humidity, and light intensity is used to improve users' experience.

At urban furniture scale, Data-Space (van Ameijde 2019) uses a field of nodes that each incorporate a sensor and LED illumination to monitor and communicate with people within the site. The nodes are suspended above the ground in a gridded field, forming a virtual ceiling or canopy with infrared sensors to provide a real-time data stream of user locations. Movement patterns are examined and incorporated in dynamic lighting patterns that are exhibited around the visitors using a variety of evaluation algorithms and criteria aiming at motivating users to walk along light paths or encouraging physical proximity or distance between visitors. When there are too many people on the site at once, the system displays 'angry' ripple patterns giving incentives to leave.

In contrast, Flora Robotica is an automated urban garden[4] in which robots and plants perform symbiotic interactions and collaborate on the development of self-growing bio-cyber-physical structures. These structures are created using robotic controllers and mechatronic nodes with sensors and high-power LEDs that control the growth of natural climbing plants. The robots are equipped with sensors that inform them if a plant is growing nearby. They can then communicate this information amongst themselves to orchestrate the emission of lights and control the formation. Environmental impacts of the plants can be read in real time, which gives the possibility to create loop systems and to train the plants through feedback (Wahby et al. 2018a, b).

As a small-scale interactive urban furniture, the 'planetoid' relies on a methodological framework developed in 2014 in the Robotic Building (RB) lab at Technical University (TU) Delft, D2RP&O, which aims to integrate Cyber-physical Systems (CpS) into buildings and building processes (Bier et al. 2018). The goal is to link virtual and physical worlds in order to extend human capabilities and improve human and non-human interactions.

D2RP is implemented by means of parametric design and robotic production involving 3D printing with wood-based biopolymers, while D2RO techniques are implemented for the integration of sensors–actuators in order to track microclimates within and around the 'planetoid'. Data is then streamed to an app, on which users/visitors can read the real-time data and choose to interact with the 'planetoids' and their microclimates by, for instance, irrigating the plants or just playfully interacting with their light- and/or sound-based actuators (Figs. 4.1, 4.2, and 4.3).

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[4] Link to FR website: sn.pub/71rCfE.

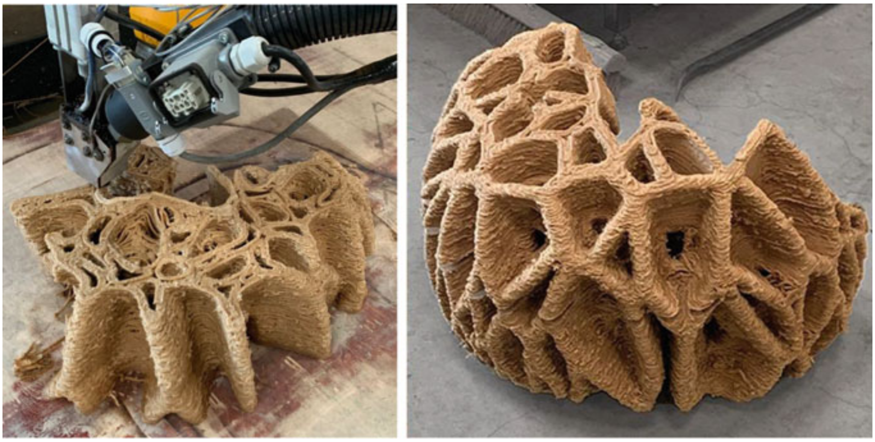

Fig. 4.2 D2RP process (left) and robotically 3D printed fragment of the 'planetoid' (right)

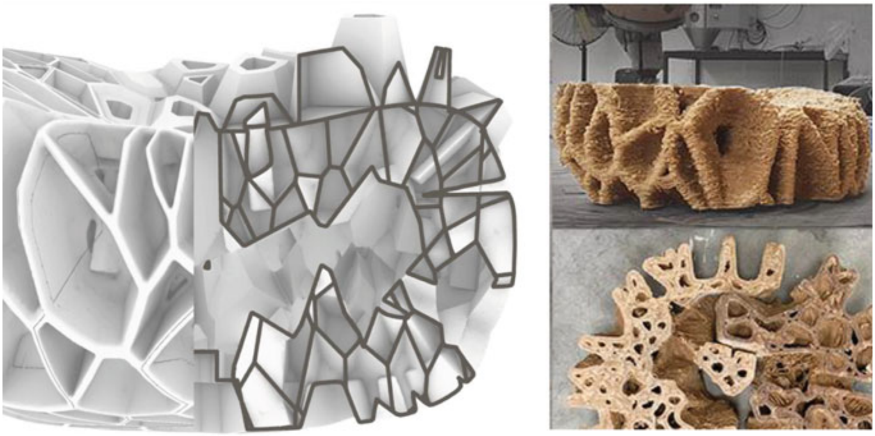

Fig. 4.3 The Voronoi structure facilitates the creation of convex and concave areas that offer opportunities for catching or repelling sun and rain and foster animal and plant species as well as sensors–actuators

D2RP

The overall shape is informed by the various functionalities of the 'planetoid' from hosting plants, insects, and small animals to harbouring sensors–actuators for monitoring the environment and communicating with visitors. These functionalities require a material design that accommodates variable porosity while catering to environmental and structural requirements. Hence, an adaptive Voronoi mesh approach is adopted (Fig. 4.3) and various aspects from function, form, material, component, and materialization are considered.

Functional Layout and Form-Finding

The overall form, porosity, and surface tectonics are informed by the use, structural requirements, and environmental conditions of the ‘planetoid’. Structural forces, shadows, solar radiation, as well as rain data, are mapped onto the overall basic geometry, which is generated with the main use in mind, to protect an earthy ball with seeds. If the seeds require more exposure to the sun, there are larger openings on the parts of the shell that have the highest solar radiation. If the seeds need to be protected from direct sunlight, the openings are smaller, while the rainwater is guided either away from or towards the seeds depending on the type of seeds and the respective environmental conditions. In this context, solar radiation is calculated for the location of the object as well as the relevant time of the year, i.e., blooming period. For that purpose, Energy Plus Weather Files (EPWF) for the chosen location in Rotterdam were employed from the Climate website.[5] The data was imported into Ladybug, which is a Grasshopper plugin, in order to calculate the solar radiation.

Material Design

The Voronoi mesh is robotically 3D printed using a biopolymer consisting of cellulose, hemicelluloses, and lignin, which is processed from sawdust that is mixed with a binder, in this case, a thermoplastic elastomer (TPE). The use of biopolymers is of particular interest because of their potential to promote sustainable approaches by reducing environmental footprints (inter al. Correa et al. 2015; Kariz et al. 2016). Considering that the CO_2 released when they degrade can be reabsorbed by trees grown to replace them, biopolymers are close to being carbon neutral.

Support free 3D printing is achieved by controlling the angles of the Voronoi cells to be within the printing limitations. The maximum achievable printing angle depends on the viscosity of the material at extrusion temperature as well as cooling, i.e., crystallization speed. The printing angles are limited to 45–55 degrees in relation to the printing bed. Since the Voronoi cellular structure is an inherently stable self-supporting type of geometry, the cells can be printed at more extreme angles. The overall geometry is subdivided into Voronoi cells that enable the control of global and local porosity. The ‘planetoids’ are more porous in some areas than in others in order to accommodate structural and environmental requirements and most importantly programmatic requirements for plants, insects, and small animals of various sizes as well as sensors-actuators (Fig. 4.3). The overall goal is to have multiple performances addressed with a consistent material design at macro, meso, and micro scales.

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[5] Climate website: sn.pub/aP7d3n.

Fig. 4.4 Integration of sensors and batteries (white boxes) in component (left), componential logic (middle), and assembled prototype

Componential Logic

The prototype was subdivided into multiple components, allowing the ‘planetoid’ to be printed in multiple parts. Based on this strategy larger objects can be created out of multiple components. The total size of the assembled object then is not limited to the size of the 3D printing system (Fig. 4.4). Also, easy transportation and assembly are accounted for.

Tool Paths

Continuous toolpaths ensure that the printing process is efficient. The production time is only defined by the object size, layer height, and speed of the 3D printer. With a layer height of 2.0 mm and a printing speed of around 300 mm per second, the process took about 20 hours. It was important to optimize the tool path and eliminate travel moves because, at the start and end points of the travel moves, the 3D printer has to stop and start printing. Every starting and stopping location leaves a mark in the 3d print, so it is best to minimize these starting and stopping moments. Hence, the continuous toolpaths that were generated ensured efficient production time and improved quality.

Prototype

While the D2RP part has already been completed (Figs. 4.1 and 4.2), the D2RO work is still in progress. Multiple sensors–actuators are integrated into the ‘planetoid’ in order to monitor microclimates and initiate activities. Data is streamed to an app, on which users/potential visitors are notified in real time and are ‘invited’ to interact with the ‘planetoids’ and their microclimates.

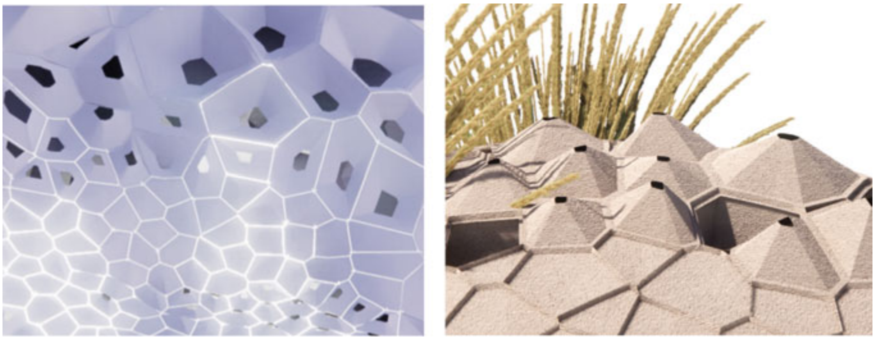

Fig. 4.5 Sensors–actuators proximity sensors and light actuators (left) and plants (right) integrated into the Voronoi structure

D2RO

The ‘planetoid’ offers a protected environment for hosting earth balls with seeds that develop into plants as well as animals and sensors-actuators. If the natural systems consist of (i) plants such as dandelions, camomile, and poppies, (ii) insects such as butterflies, dragonflies, and bees, and (iii) small animals such as snails, hedgehogs, and rodents, the integrated sensor–actuator system consists of various components that require further definition.

Sensing Modules

Each sensing module (Fig. 4.5) carries a unique identifier, defining its function as well as modes of functioning including frequency of data collection and communication. Each ‘planetoid’ hosts several sensing modules which, independent of the others, can be added, maintained, and modified. The sensors require a remarkably low amount of energy and can operate on a battery for several months.

Gateway

One gateway collects, via Bluetooth, the data transmitted by all the sensing modules in its physical proximity. It broadcasts the sensor data along with the identifier of the sensing module to the LTE urban antenna. The transmitted data also contains information about the cloud service associated with this setup as well as the credentials to access the cloud database.

Network

The LTE (Long-Term Evolution) networks are available in most European cities by various commercial providers and will be used.

Communication

Through the Message Queue Telemetry Transport (MQTT) protocol the cloud database ‘subscribes’ to receive the data collected by sensing modules with certain identifiers. The data will be stored and made available for queries through any web-based application. Data is made accessible to the users through either the Quick Response (QR) code associated with the ‘planetoid’, or simply its placement. Gamified presentation of data aims to be engaging and leading to action (Figs. 4.6 and 4.7).

Various sensors concerned with monitoring humidity, light, temperature, and the presence of humans and actuators involving light and sound are integrated into the ‘planetoids’. In its future development, the ‘planetoid’ will rely on learning capacities to predict moments—depending on the patterns of human and non-human activities around the planetoid—when opportunities arise for interaction with the

Fig. 4.6 App with interaction modalities for discovering, co-caring, and co-creating environments populated with ‘planetoids’

Fig. 4.7 Urban furniture accommodating human activities such as climbing, sitting, and lying down developed with students

evolving nature (vegetation, insects, etc.) and humans. K-means and Hierarchical Clustering (HC) as established Artificial Intelligence (AI) methods will be applied to discern correlations between presence, movement, and actions with weather variables, to be able to offer a structured prediction of opportune interaction moments and to promote them through an open access mobile application.

AI has been used in the built environment for applications involving transportation networks, water, lighting, and heating systems. It also has been increasingly employed to provide safer public spaces and services (inter al. Cugurullo 2020; Chew et al. 2021). The interaction scenarios for the 'planetoids' engage users in discovering, co-caring, and co-creating (Fig. 4.6) by involving users in learning about plants, animals and their needs, encouraging them to water, weed, plant new seeds, depending on the monitored development reconfiguring 'planetoids' by moving or adding more 'planetoids', etc.

Interaction Scenarios

The interaction scenarios involve activities such as (a) monitoring plants, insects, and animals and (b) involving users. The goal is to engage neighbours and passers-by with the 'planetoids' and their environments that go through several stages of development and transformation from bare to by plants overgrown planetoids. By employing real-time sensing of the natural and human activities around the planetoid such as passing by, sitting, lying down, etc., users are made aware of various forms of life and engage with them in interactive experiences that can reap some of the potentials of abandoned areas as public urban spaces. The system is sensing environmental parameters such as temperature, humidity, and light, as well as information related to the presence and movements of humans, animals, and insects around the ‘planetoids’. The main actuation is in the form of mobile application (app) notifications informing the users about the emerging activities around the planetoids or the need for their action (e.g., watering the plants).

Additional actuation is envisioned as serving educational, playful, and cautionary purposes. All three rely on outputs such as text, charts, images, movies, steamed videos, lights, and sounds as elements of the sensor–actuator system aiming to respond to environmental and human input. In this context, three scenarios are envisioned:

(a) Educational: By locating ‘planetoids’ within the urban context on the app and by learning about their microclimates users develop awareness and may increasingly engage with the ‘planetoids’ to help them thrive.
(b) Cautionary: By notifying users via text, light, and sound when humidity in the ‘planetoid’ is low or other hazards including vandalism, the ‘planetoid’ engages users in a ‘supportive’ relationship.
(c) Playful: By turning on the integrated sources of lights and sounds on and off, changing their intensity and colour, etc., users become co-creators of the emerging bio-cyber-physical environment.

In this context, the app is meant to customize interaction. If the usual interaction is based on simple patterns of light and sound responding to passers-by, the app allows users to potentially co-create AI-supported music and light compositions. The most important interactions are (i) engage, (ii) co-create, and (iii) disengage: As soon as the system ‘notices’ movement, the lights pulsate in one colour—i.e., oscillates between intensities of the same color indicating that the ‘planetoid’ comes to ‘life’. The intention is to instigate interest and curiosity in the users, inviting them to engage with it. When engagement is established a gradual shift from the initial colour and pulsating pattern, to changing colours and patterns that are customizable by users takes place. When more users and planetoids are engaging in interaction AI comes into play to direct and moderate the interaction by reinterpreting and recomposing music using AI Virtual Artist (Barreau 2018) or AI Duet by Google that is trained to respond to midi tones in a harmonious way. Instrument samples are combined and the resulting musical composition is dynamically visualized through light using an approach similar to the Music Animation Machine (Adli et al. 2007). The main purpose is to encourage social interaction and facilitate social gatherings. The disengagement is activated when users leave the physical and/or virtual space in which the ‘planetoids’ are located. In the disengaged ‘dormant’ state the ‘planetoid’ only reacts to vandalism by activating shrill sounds and lights.

The sound-light compositions change in time as the imbued AI learns from the communities interacting with the ‘planetoids’ that can be aggregated into groups to create harmonious spatial-sound-light compositions. Some areas may become more frequented by youth engaging in creating sound-light compositions for outdoor parties, while others may become more suitable for the elderly by contributing to the revitalization of residual spaces. In order to serve such revitalization, the AI has to monitor the well-being of all actors and adjust interaction scenarios accordingly at all times.

Scaling up Scenarios

Explorations towards scaling up the system by combining ‘planetoid’-sized components into larger pieces of urban furniture (Fig. 4.7) has been initiated with consideration to human needs. The possible combinations of components are explored on the app (Fig. 4.6) in order to customize designs depending on specific needs, for instance, sitting, lying down, climbing, etc. The combinatorial logic has been investigated in studies implemented with Ph.D. and M.Sc. students in connection to several funded projects in collaboration with academic and industrial partners (Bier et al. 2021; Oskam et al. 2021). The conceptual design involved the study of activities and potential new activities in respective locations ranging from playing to lounging or doing sports. In addition, factors such as environment, pre-existing infrastructure, urban context, flora and fauna, etc., were considered. Once the parameters to inform the design were identified, the form-finding process was initiated using the driving force activity patterns and materialization by means of robotic 3D printing using biopolymers.

4.3 Discussion

Socio-technical interventions made in natural environments to improve biodiversity and human–robot interaction are not new. Various projects involving artificial reefs and 3D printed scaffolding for microorganisms (inter al. Gautier-Debernardi et al. 2017) have shown that eco-friendly solutions can meet the needs for increasing biodiversity in various natural environments. Also, projects involving sensor–actuator networks such as Data-Space (van Ameijde 2019) using a field of nodes that each incorporate a sensor and LED illumination to monitor and communicate with people within the site prove their potential to engage humans in various interactions.

The ‘planetoids’ described in this chapter act as socio-technical interventions that not only improve biodiversity, but also increase human–nature interaction as well as social accessibility of leftover spaces by employing sensor–actuator networks. These allow monitoring of development in a time of newly established habitats on the ‘bio-cyber-physical planetoid’ app that is inviting potential visitors to irrigate the ‘planetoids’ or protect them from the sun, or playfully interact with them and with each other.

The novel opportunities offered by cybernetic social-ecological systems involving AI and their ability to identify in this case correlations between the evolving nature, weather variables, and actions of humans in order to offer a structured prediction of opportune interaction moments and to promote them through open access web-based platforms and mobile applications establish bio-cyber-physical feedback loops that render human and non-human agents as co-creators of processes and events.[6]

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[6] Cyber-physical Space and Urban Furniture wikis: sn.pub/uyTFMl and sn.pub/YQrlk8.

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