Immediate Systems in Architecture
Continuous adaptability at the speed of human intention

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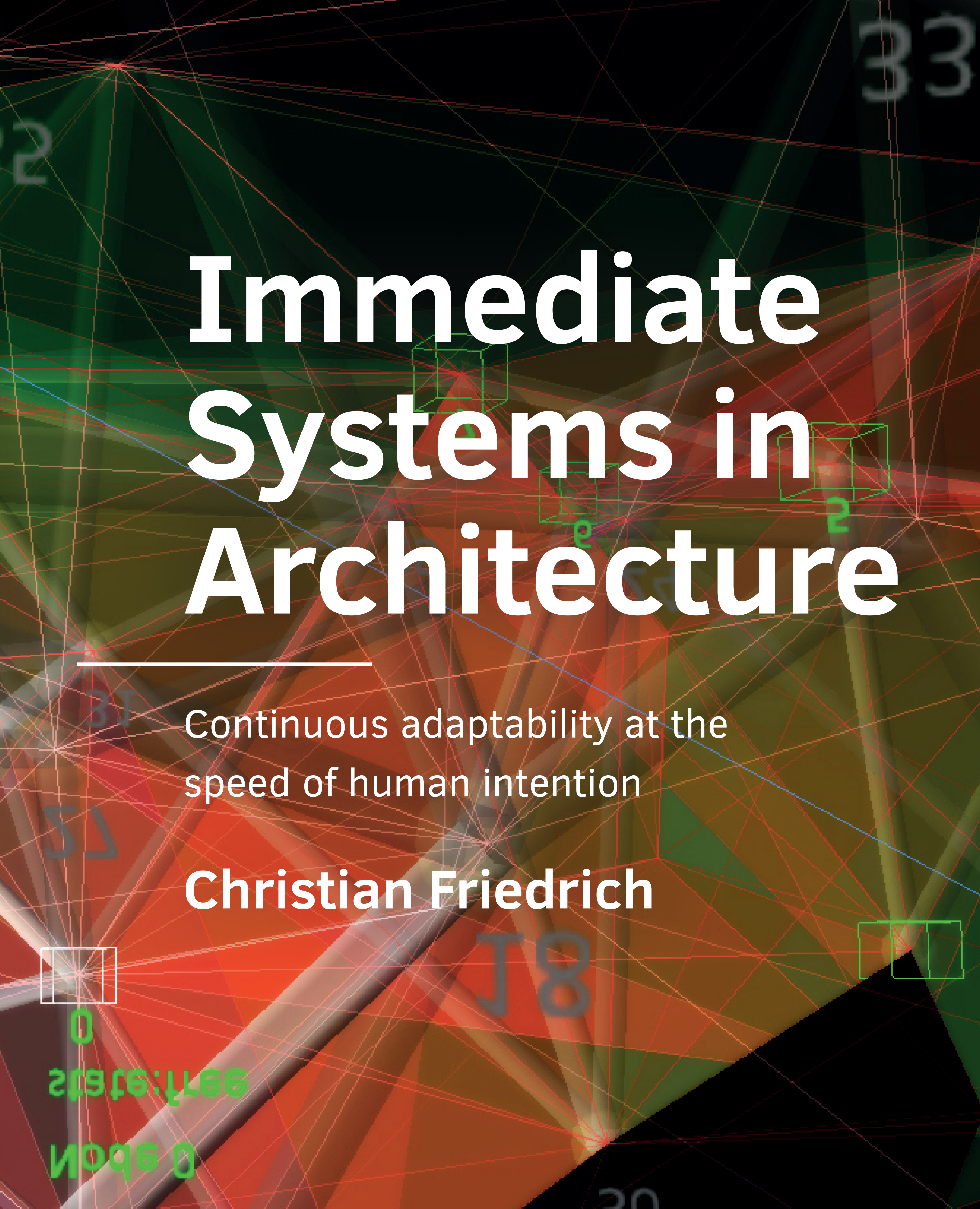

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Continuous adaptability at the speed of human intention

Christian Friedrich

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Immediate Systems in Architecture

Continuous adaptability at the speed of human intention

Dissertation

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Preface

The research described in this thesis was performed within the chair of Digital Architecture also known as Hyperbody, and was concluded within the Robotic Building lab, as part of the departments of Architectural Engineering and Technology and Architecture, within the faculty of Architecture at Delft University of Technology.

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Summary

The presented research on *Immediate Systems in Architecture* (IS-A) is an attempt to afford a better human-technology match in architecture, pursuing a state of immediacy where humans can simultaneously use and design, apply and amend the technical system they engage with.

The thesis contains both theoretical and experimental contributions on IS-A. Initially, the notion of *Immediate Systems* (IS) is introduced and framed. IS offer interaction in the style of *direct manipulation*, embed design and implementation in situations of use, and overcome limitations of remote design. IS are related to psychological concepts and described through the lens of Gibson's *Theory of Affordances*. Characteristics and conditions of IS are distilled from the presentation and discussion of a series of examples.

The application of IS in architecture is approached from three angles. First, from the lived perspective of a user-designer, as adhocist mode of action. Second, from the methodology and technology, as accelerated design transfer. Third, in an ecological perspective, as human-architecture symbiosis. Each of these readings is hypothesized to be more feasible by implementing IS-A as *Human-in-the-Loop Cyber-Physical Systems* (HiLCPS).

Following the method of research by design, prototypes were developed in a series of experiments. The experiments result in multiple tools for real-time multi-directional volumetric design exploration that allows users to interactively model and ad-hoc reconceptualize parametric geometry, topology and components of architectural assemblies. A combination of these tools with digital fabrication and interactive building components lead to the most encompassing IS-A prototype, an attempt to realize an open-ended building system that joins simultaneous design, adaptation, construction and reconfiguration as interaction possibilities embedded in the built environment.

Samenvatting

Het gepresenteerde onderzoek van *Immediate Systems in Architecture* (IS-A) is een poging voor betere samenkomst van mens en technologie te zorgen. IS-A omvatten mensen en omgevingen in een dichte koppeling tussen menselijke intentie en onmiddellijke aanpassing. Zij verschaffen een toestand van onmiddellijkheid waarin mensen de technologische omgeving waaraan zij betrokken zijn tegelijk kunnen gebruiken en ontwerpen, toepassen en aanpassen.

Deze dissertatie bevat zowel theoretische als ook experimentele bijdrages over IS-A. Ten eerste wordt het begrip *Immediate Systems* (IS) geïntroduceerd en omkaderd. IS bieden interactie in de vorm van *direct manipulation*, plaatsen ontwerp en implementatie in gebruikssituaties, en overkomen de beperkingen van afgezonderd ontwerpen. IS worden gerelateerd aan psychologische concepten en beschreven door de lens van *Gibson's Theory of Affordances*. Karakteristieken en condities van IS worden afgeleid uit de presentatie en discussie van een serie voorbeelden.

De toepassing van IS in architectuur wordt benaderd vanuit drie oogpunten. Ten eerste, vanuit het geleefde perspectief van de gebruiker-ontwerper: als adhocist vorm van handelen. Ten tweede, vanuit de methodologie en technologie, als versneld design transfer. Ten derde, in een ecologisch perspectief, als men-computer symbiose. Voor ieder van deze lezingen wordt de hypothese opgesteld dat zij maakbaarder worden door IS-A uit te voeren als *Human-in-the-Loop Cyber-Physical Systems* (HiLCPS).

Volgens de *research by design* methode werden in een reeks experimenten prototypes ontwikkeld. De experimenten resulteerden in meerdere tools voor *real-time multi-directional volumetric design exploration* die de gebruiker toestaat om parametrische geometrieën, topologie en componenten van architectonische assemblages interactief te modelleren en ad hoc te herconceptualiseren. Een combinatie van deze tool met digitale fabricatie en interactieve onderdelen leidde tot het meest omvattende IS-A prototype, een poging tot realisatie van een onbeperkt bouwsysteem dat tegelijk ontwerp, aanpassing, constructie en herschikken omvat als interactie mogelijkheden die zijn ingebed in de gebouwde omgeving.

PART 1 Theory

1 Introduction

1.1 Immediate Architecture

The term immediacy originates from Latin and means without anything between. Depending on context this means the immediately related is not separated by distance in space or duration in time, nor by intermediary objects or causations. The immediate is close, direct, adjacent, happens instantly and without delay. When applied to architecture, specifically within the context of this thesis, it is useful to further define the meaning of the term immediacy. In the context of this thesis, immediacy applies to creation, perception of and interaction with the built environment. It is specifically used to define systems which create a direct feedback loop between perception and creation by immediate adaptation of the built environment. Such systems encompass the entirety of the design to construction process, which conventionally is of long duration and is separated in phases. It starts with the existing environment and passes through design and construction towards an actuated environment. Such systems allow all these activities to occur simultaneously and unfold as fluidly and continuously as possible, ideally beyond the speed of human perception. In short, such Immediate Systems (IS) support direct engagement of users with the built environment.

1.2 Immediate Systems in Architecture

In Immediate Systems (IS), design actions are no longer separated from construction, and activities of design and use increasingly merge. Design transfer becomes immediate, and the conventionally phased architectural process turns into a real-time network of simultaneous activities of design, construction, and use. Architectural praxis is no longer contained in design projects but accompanies built environments over their entire life cycle. IS are a hybrid of plan and artefact, of virtual and real: Building plans and planning interfaces are increasingly distributed and embedded into smart building components. A multitude of possible transformations between virtual and physical are increasingly available for both construction and actuation.

IS establish a situation currently unknown in the architectural field, defined as praxis of design, separated from both construction and use in time, space, medium and modality. In this sense, IS form a focal point, an event horizon to the field of architecture. From within the domain of architecture, they therefore can never be fully approached. Most (if not all) forms of architectural practice and theory, concepts and products radically change at or near this extreme. IS are a frontier of architectural research, waiting for the first explorers of new grounds of immediacy.

It is however possible to steer towards the realization of IS and investigate effects in the vicinity. Architectural immediacy is one of these effects. It is a specific quality which can be experienced as IS are approached. Based on the definition and framing of IS the research question can be stated and an adequate experimental research method will be described, to be followed by a series of experiments.

1.3 Research Question

Architecture is an adaptation of the environment according to human intentions. Architecture as praxis is conventionally defined through its separation from the praxes of construction and use. Due to this separation conventional architectural design has to rely on speculation (hypothesis) regarding future needs of inhabitants. In order to be able respond to actual needs, design and construction have to be immediately embedded in the use and inhabitation of architecture. Hence, the initial formulation of the research question is: how can architecture facilitate an immediate adaptation of the built environment?

Creative immediacy is a productive mode of inhabitation of architecture. It exhibits qualities of freshness, fluidity and inter-activity and thereby enables design to be purpose-driven by actual needs and validated by feedback loops, to generate copy-proof and additional value (Kelly, 2008), to establish incremental involvement and improvement. Such an architecture is defined in the context of this thesis as Immediate Architecture (IA), wherein immediacy is understood as a desirable quality in architecture.

In IS, design transfer (Foqué, 1975, 2010) becomes immediate and the conventionally phased architectural process turns into a real-time network of simultaneous activities of design, construction and use. Such systems have been explored since couple of decades in particular within concepts such as Interactive Architecture, Data-driven Design to Production and Operation, Cyber-physical Architecture, etc. They all have, however, missed to specify **how human-in-the-loop cyber-physical systems, operating as IS, can be created in architecture.**

1.4 Research Methodology

In Sciences of the Artificial, Herbert Simon wrote that "everyone designs who devises courses of action aimed at changing situations into preferred ones." (Simon, 1996, p. 111). To find such a course of action is a highly complex endeavour. Design problems are considered ill-defined problems. (Churchman, 1967) (Rittel, 1973; Simon, 1996)

For one, we have to find out which preferred situations can exist and how much effort one would have to put into reaching these situations. Then, still, it will be unknown which of the solutions is the most preferable one - "In the real world, we usually do not have a choice between satisfactory and optimal solutions, for we only rarely have a method for finding the optimum." (Simon, 1996, p.120) Even when such tools are available and fit for the situation, any search for optima is limited to the scope given by the search criteria. With each design solution new desirable criteria may be found and the designers' notion of a preferable solution will be affected.

Design thus is an open-ended endeavour where each proposed solution is an addition to the original problem statement. Such an incremental process is called design exploration, defined by Axel Kilian as the "variation of design solutions and goals to ultimately reach a better design solution" (Kilian, 2006, p.10)

As Nigel Cross (Cross, 1982), Herbert Simon (Simon, 1996), Chris Jones (Jones, 1992) and others (Foqué, 2010, pp.41-42) have argued, design is a way to acquire and develop knowledge just as legitimate as research in the mathematical, natural or human sciences. Design research does, however, differ qualitatively from research methods in other fields. Where scientific research is occupied with ‘the natural world’ {Cross, 1982 #134) and ‘how things are’ (Simon, 1996), design research studies ‘the man-made world’ (Cross, 1982), or ‘how things could be’ (Simon, 1996). Yet while design research has different aims, it is a hybrid activity that depends on art and science and should not be confused with either of them (Jones, 1992). According to Herbert Simon we even “might question whether the forms of reasoning that are appropriate to natural science are suitable also for design.” (Simon, 1996, pp. 114-115)

Subject of this research are a series of experiments in which prototypes of immediate architectural systems are created and applied. Only in this manner, by taking an inside perspective of the system, it can be ensured that the subjects of investigation are not hypothetical or theoretical but actual architectural systems. IA can only be validated in immediate experimentation with prototypes. The method of inquiry is thus that of Research by Design.

Starting with the development of digital design for architectural design and production, the experiments realized immediate sub-systems within phases of the design to construction process. The basic consideration here is the choice of an ontology and speed of response which could allow the sub-system to become part of an immediate system of the whole process. The choices made are based on design hypotheses.

1.5 Overview of the Dissertation

This dissertation addresses challenges and opportunities of Immediate Systems in theory and praxis. The presented research therefore is two-fold, first as theoretical definition and framing of IS and then as a series of realized prototypes of IS and sub-systems for IS.

The section Theory contains three theoretical contributions. First one proposes and frames the very notion of Immediate Systems. Second one, presents and discusses a series of examples of such systems. Third contribution, identifies conditions for and characteristics of Immediate Systems derived from the first two contributions. It introduces the notion of Immediate Systems (IS) which overcome the limitations of remote design by embedding design and implementation in situations of use.

The theoretical framing of IS then is extended with three approaches towards IS in architecture: as adhocist mode of action, as acceleration of design transfer and as human-architecture symbiosis. These three approaches consider the same phenomenon from different perspectives respectively, that of the lived experience of the user-designer, that of the designer's methodology and technology, and that of ecology.

Last but not least a series of experiments are presented, each of which constitutes a prototypical subsystem for IS in architecture. This series of prototypical IS, or components of IS, were developed within the educational and research agenda of the Digital Architecture chair at TU Delft also known as Hyperbody. The experiments are hybrids of virtual and augmented environments, parametric tools for design exploration, digital design to production processes and interactive environments. They are presented to corroborate the argument that IS overcome the limitations of remote design by embedding design and implementation in situations of use. From adaptive Voronoi power diagramming for real-time volumetric design exploration to point cloud-based multi-directional real-time Swarm Architecture design exploration, and modular spatial robotics, the experiments are part of a larger research effort in Immediate Architecture which relies on research-by-design methods.

Within Hyperbody's educational and research agenda, a series of prototypical IS, or components of IS were developed. For the protoSpace collaborative design laboratory, a data exchange system was conceptualized and prototyped as graphing tool for actionable relationships between parameters in different software applications. The system would allow users to construct ad-hoc real-time information feeds between diverse and specialized applications used in the daily work of building industry professionals, and bind them to live parametric models made in the swarm architecture paradigm (Oosterhuis et. al., 2008). Another field of investigation were prototypes of Computer Aided Design (CAD) modeling tools that offer real-time volumetric design exploration, and should allow users to interactively model and ad-hoc reconceptualize geometry, topology and components of architectural assemblies (Friedrich, 2007, 2009). A combination of these techniques with digital fabrication and interactive building components lead to the most encompassing IS prototype, an attempt to realize an open-ended building system that encompasses simultaneous design, adaptation, construction and reconfiguration as interaction possibilities embedded in the built environment (Friedrich, 2013).

Content of presented research is based on papers that have been published in the journals Archidoct (Friedrich, 2020b), SPOOL (Friedrich, 2020a), Lecture Notes for Computer Science (Friedrich, 2007), and in the proceedings of the 15th International Conference on Virtual Systems and Multimedia (Friedrich, 2009) and of the International Adaptive Architecture Conference 2011 in London (Friedrich, 2011). These prior publications were designed and written as contributions to this dissertation and are here integrated as chapters 2, 3, 5, 6 and 7 respectively.

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2 Immediate Systems

Human-In-The-Loop Cyber-Physical Systems that Embed Design and Implementation in Situations of Use

This article has been previously published in the journal *Archidoct*: Friedrich, C. (2020b). Immediate Systems. Human-in-the-loop cyber-physical systems that embed design and emplementation in situations of use. Archidoct, 7(2), 27-39. Retrieved from https://archidoct.net/issue14.html

ABSTRACT

Design activity, especially in architectural praxis, takes place in spatial and temporal remoteness from the use of its outputs. This remoteness impedes the ability to respond to actual needs that arise in situations of use. Ultimately it makes design dependent on hyp\othesis. Aim of this paper is to introduce the notion of Immediate Systems which embed design and implementation in situations of use and thus overcome the limitations of remoteness.

Immediate Systems, as defined by author, are cyber-physical systems comprised of interacting digital, analog, physical, and human components. As meta-systems they include people and environments in a tight loop between human intention and immediate adaptation. Immediacy in this context indicates a state of continuously available adaptability at the speed of human intention. Such meta design systems take design methodology to an extreme which paradoxically resembles the situation before design emerged as separate praxis.

The paper contains three theoretical contributions. First one proposes and frames the very notion of Immediate Systems. Second one, presents and discusses a series of examples of such systems. Third contribution, identifies conditions for and characteristics of Immediate Systems derived from the first two contributions.

KEYWORDS

Immediacy, Immediate Systems, design by use, design environments, design methods

2.1 Introduction

Aim of this article is to introduce the notion of Immediate Systems (IS) which overcome the limitations of remote design by embedding design and implementation in situations of use. The article binds into a larger research effort in *Immediate Architecture* which is focused on research-by-design of IS.

The term immediacy here indicates a state of continuously available adaptability at the speed of human intention. *Immediate* differs from *instantaneous* in that instantaneous indicates just a temporal direct response, whereas immediate can denote a direct relationship or state which is maintained over time and can include any combination of multiple modalities, for example temporal, spatial, tactile, embedded or intentional.

IS are meta-systems; they connect and surpass, in psychological terms between the self and the other, in terms of human-computer interfaces (HCI) between user and computational systems, in ecological terms between animal and habitat, and in architectural terms that between inhabitant and built environment. The notion of IS applies to all these world-views. For the remainder of this article the terms *user* and *environment* will be used for generalized descriptions of IS.

In the following section of this article, the notion of IS will be further defined, in their relevance to architecture, through the psychological phenomena of the i*mmediacy effect* and the state of *flow experience*, through the concept of *direct manipulation* developed in the field of human-computer interfaces, and by relating them to the *Theory of Affordances* (Gibson, 1986). The third section of the article discusses characteristics of IS which are highlighted in description of examples. Based on the findings of these sections the article concludes with a summary of the initial framing, of the conditions and characteristic of IS, and perspectives for future work.

2.2 Framing Immediate Systems

2.2.1 Relevance to architecture

Design activity, especially in architectural praxis, takes place in spatial and temporal remoteness from the use of its products. This remoteness makes design dependent on hypothesis and impedes the ability to respond to actual needs that may arise in situations of use.

To illustrate different aspects of immediacy, the architectural example of the igloo is considered. Developed as cultural technique in a natural habitat, the igloo is constructed entirely from snow, a material which is readily available in its builders' environment, following techniques with minimal use of tools and constructed literally as a bubble around the body of the human. It offers protection against weather and predators, has excellent insulating properties and will strengthen over time as surfaces of the enclosure repeatedly melt and freeze, reinforcing weak spots and closing gaps with newly built ice. When it no longer is in use it will literally melt with the environment, leaving no waste products. Even though an igloo is traditionally constructed with the temporal immediacy required for adaptability at the speed of human intention, it is immediate in the aspects of resource gathering, to the human body, in applicability, in constructive rationale, in its structural and functional self-reinforcement and in its ecological disposal.

Contemporary technological developments increase the feasibility of IS which offer the types of immediacy mentioned in the example offer even temporally immediate adaptation. Robotic building, the Internet of Things, interactive environments, to artificial intelligence, smart materials and a digitally driven circular economy, all can contribute to involve even activities of fabrication and construction within feedback loops at the speed of human intention. To design an IS is not the same as designing a specific part of the built environment, it is its meta-design in the sense that it takes traditional remote design methodology to an extreme where it paradoxically resembles a situation before design, implementation and use were separated. IS take a special case in the discussion on *Cyber-Physical Systems* in architecture in that they do not exclude the human user, as designers, builders and inhabitants, but conceptualize them as essential and integral to the system.

2.2.2 Human-in-the-Loop Cyber-Physical Systems

IS can be conceived as *Cyber-Physical Systems* (CPS) (Lee, 2015) comprised of interacting digital, analog, physical, and human components. A typical CPS contains feedback loops between embedded computers and physical processes, where computers track and direct physical processes but not without being affected by them in turn. As a special type of Human-in-the-Loop Cyber-Physical Systems (HiLCPS) (Schirner, Erdogmus, Chowdhury, & Padir, 2013), they include people and environments in a tight loop between human intention and immediate adaptation.

The term *cybernetic*, derived from the Greek word for *steersman* (Wiener, 2009), pre-dates digital computers and stood for *the field of control and communication theory, whether in the machine or the animal*. A human constructing an igloo could be considered a Human-Physical System in which the human takes a central role as helmsman who interacts with components of the environments, navigating the entirety of the system towards habitable configuration. With contemporary technologies that make a wide range of transformations between the realms of the digital and the physical readily available, e.g. Computer Numerically Controlled (CNC) and robotic fabrication and construction, sensor-actuator networks, the Internet of Things, gesture detection and brain activity analysis, IS can be conceived as true cyber-physical systems even in the narrowest definition of the term.

2.2.3 Immediacy Effect

In behavioral psychology and economics, the term *immediacy effect* refers to the tendency of decision makers to amplify the significance of immediately experienced outcome relative to delayed outcomes. When confronted with intertemporal choices, with choices between two or more alternative outcomes expected to be realized at different points in time, experiments have shown that time discounting is not determined by comparing present values discounted by a fixed discount rate. People tend to overweigh more immediate outcomes. In this sense, regarding human behavior, there are close interrelationships and a high level of similarity between risky decisions and intertemporal decisions (Keren, 1995), best illustrated in the *immediacy effect* and *certainty effect*. The *certainty effect* refers to the observation that people overweigh outcomes that are considered certain relative to outcomes which are merely probable. When offered the choice, people will assign a far higher value to an immediate outcome than to a delayed one.

Since the purpose of IS is to provide immediate feedback, an embedded user can be assumed to be affected by the immediacy effect. The directness of outcome, as the immediacy effect suggests, is preferred and may provide a sense of certainty and control. As suggested by Roberts (2014), the immediacy effect may impact the user's decision-making processes and lead them to best practices by affording quick execution.

2.2.4 Flow Experience

Immediate feedback is one of the prerequisite conditions for the flow experience, a psychological concept developed by Csikszentmihalyi in the late 1960s. Flow is a subjective state people report when they are fully invested in the task at hand and function at their fullest capacity.

Csikszentmihalyi identified three conditions for the flow experience to emerge. A *clear set of goals* directs attention and adds purpose, *immediate feedback* promotes a sense of control and a *balance between perceived challenges and skills*. When these conditions are met, one enters a subjective state of flow for which a series of characteristics have been found. These characteristics include i*ntense and focused concentration*, *merging of action and awareness*, *loss of reflective self-consciousness*, *a sense of control over one's actions and their impact*, *distortion of temporal experience* and an *autotelic experience of the activity* in that it is intrinsically rewarding and self-sufficient to the extent that it is valued higher than the original set of goals (Nakamura and Csikszentmihalyi, 2009).

IS as defined in this paper can provide some of the conditions for flow experience to arise, but for the condition of a clear set of goals, formed by direction and purpose, they depend on the user to develop their intentions. For flow to emerge, the need for a balance between skills and challenges is brought to attention. The autotelic, intrinsically rewarding nature of the flow experience suggests that users can be expected to actively sustain the flow experience once it is established.

While the literature on flow experience presents flow as a generally desirable state which allows people to unfold their operational potential to the fullest, it also mentions as pitfalls the narrow focus and loss of reflective capacity that are associated with it.

2.2.5 Direct Manipulation

Computer scientist Shneiderman coined the term 'direct manipulation' (Shneiderman, 1983) for a human-computer interaction style which involves continuous representation, reversible operations through physical actions, immediate visibility of results and a scaffolded approach to learning that affords experimentation with minimal prior knowledge. As examples for such systems in the early 1980s, Shneiderman listed display editors, spatial data management interfaces, video games, interactive CAD/CAM systems and driving an automobile. Users experience direct manipulation interfaces as lively and enjoyable. They are easy to learn, faster to operate and more satisfying to use. Immediate feedback affords users to adjust input as soon as the effect is undesired, often removing the need for instruction and error messages. According to Shneiderman, direct manipulation is both beneficial for learning situations and affords fluid and extensible operation to expert users. Even though Shneiderman did not refer to Csikszentmihalyi's flow concept, his description of the conditions and user experience of direct manipulation bears strong similarities to the psychological concept of flow experience.

A seminal paper on the topic, *Direct Manipulation Interfaces* (Hutchins, Hollan, & Norman, 1985), was written with the goal of giving cognitive account of direct manipulation. It was rooted in the assumption that the feeling of *directness* which emerges in direct manipulation originates in the commitment of fewer cognitive resources. Two underlying phenomena of the feeling of directness were identified, called *distance* and *engagement*. Distance is the information processing distance between intentions of the user and executions of actions by the machine. Direct engagement occurs as appropriate application of the model-world metaphor. Following this metaphor the world is explicitly represented and the user has the sensation of acting immediately upon the objects of the task domain. The other of the two major metaphors for the nature of human-computer interaction, the conversation metaphor, would have the interface act as medium in which user and system have a conversation about a not explicitly represented world.

2.2.6 Theory of Affordances

The IS includes the embedded user similar to the way in which an animal is embedded within its natural environment, in an environmental niche. The abstraction of habitat applies itself to formulate a holistic approach to design modeling because it indicates a type of socio-technical systems, comprised of the interactions between people, devices, codes and processes that join them (May and Kristensen, 2004).

The Theory of Affordances (Gibson, 1986) is based on the idea of a world of ecological reality, a conception of the world through its meaningful relations to the animal. The relationship between animal and environment is reciprocal, they can only exist as each other's complement. *Affordances* are what the environments offers, or affords, to animals and humans. Raw materials afford manufacture, surfaces afford pose, mobility, contact and handling, shapes of certain form and size can afford protection from the elements. To a skilled animal or human, objects can afford to be used as tool or as weapon.

At the core of Gibson's theory of affordances stands the argument that affordances are invariants which are not affected by their perception or misperception. Their meanings are not to be imposed upon them; they are to be discovered. Because of this they have been described as *actionable relationships* (Norman, 1999) between animal and environment.

IS can be further framed through the affordances that can occur in them.

1 **Immediate Systems afford their use in a state of immediacy.**

Affordances are actionable relationships between animal and environment which exist entirely independently of being perceived or misperceived. In this sense, immediate systems offer the user immediacy independently of their perception, but they depend on successful perception and activation for the user to engage with them. Being human-centered, the IS requires with the human to be in the loop. Human and IS have a reciprocal relationship. The IS can be conceived as ecological niche.

2 **Immediate systems shift the boundaries between self and environment.**

Gibson describes how tools in use are no longer part of the environment but become an extension of the body of the user. They have capacity to attach to the body, suggesting that there is no strict separation between animal and environment but a shifting boundary. Like Gibson's affordances, the notion of IS is based on a world of ecological reality. In an architectural setting this means that IS shift the relation between human inhabitant and built environment.

3 **Immediate systems can afford furnishing the environment with new affordances.**

IS are essentially meta-affordant because they afford to furnish the environment with new affordances, and they afford to do so in a state of creative immediacy Architectural immediacies are special affordances for modification of the environment. They let the inhabitant to project intended affordances onto their surroundings and to explore and navigate alternative constitutions of the environment for their affordances.

4 **Immediate Systems in general provide a characteristic set of affordances.**

In the following section, a series of examples shall be discussed with the aim of deriving further affordances specific to IS. In the following, these affordances will be called *characteristics* of IS.

2.3 Characteristics of Immediate Systems

2.3.1 Introduction

In order to further define the notion of IS, a series of examples will be described and discussed. They were found in the fields of human-computer interaction, behavioral psychology, performative art, algorithmic art, architecture and industrial design methodology.

While all the following examples share the following characteristics, they are individually described by one of the main characteristics they each exemplify for immediate systems in general:

awareness, **guidance**, **intimacy**, **embeddedness**, mastery and **re-framing**.

A model of these characteristics can show them as complementary pairs mirrored in the tight feedback loop between the user and the environment:

TOC

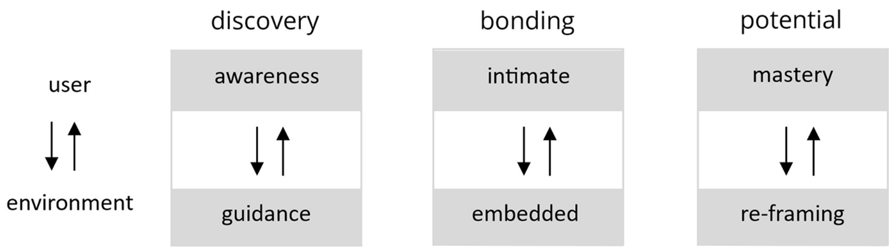

FIG. 2.1 Characteristics of Immediate Systems

Discovery

The user's **awareness** of the environment grows through the use of its actionable properties. The environment provides **guidance** through vectors of beneficial action revealed by the interaction.

Bonding

The user encounters the environment **intimately**, as they are **embedded** in it. IS have minimal resource footprint in terms of e.g. cognitive and material resources.

Potential

The immediate system affords **masterful** action, including continuous **re-framing** of the user's objective.

2.3.2 Examples

2.3.2.1 Awareness – IS stimulate merging of awareness and activity

In his text Video in Relation to Architecture, Graham describes the notion of immediacy in modernist art as follows: "A premise of 1960s modernist art was to present the present as immediacy—as pure phenomenological consciousness without the contamination of historical or other a priori meaning" (Graham, 1993). Immediacy was thought to bring self-sufficiency and novelty: "The world could be experienced as pure presence, and without memory. Each privileged present-time situation was to be totally unique or new."

Graham built art installations that confronted spectators with mirror images and video feedback loops. He intended to critique the modernist notion of immediacy by demonstrating that it is impossible to locate a pure present tense. He noticed that the installation challenged the spectator's awareness. Temporal immediacy allowed the spectators to see themselves as both subject and object at the same time, a sensation that is usually visually unavailable. In this way the viewer was made aware of the difference between intended and actual behavior, immediately influencing future intentions and behavior. Due to the feedback viewers could enter a process of continuous learning. Since the intentions are interior to the observer and the self-observed behavior is exterior to them, the observer's notion of interior and exterior self is challenged. The immediate mediation of images as provided by video/television takes on an architectural function, it permeates public and private boundaries between rooms and social classes.

The installations of Dan Graham focus on performance, not production. They have no memory and the users' activity does not leave a trace. What persists is the mechanism of re-presentations in mirrors and video-cache. Still, the installations can affect experience and behavior of users through otherwise unavailable sensations, challenging their **awareness**.

2.3.2.2 Intimacy – An IS is experienced as extension of self

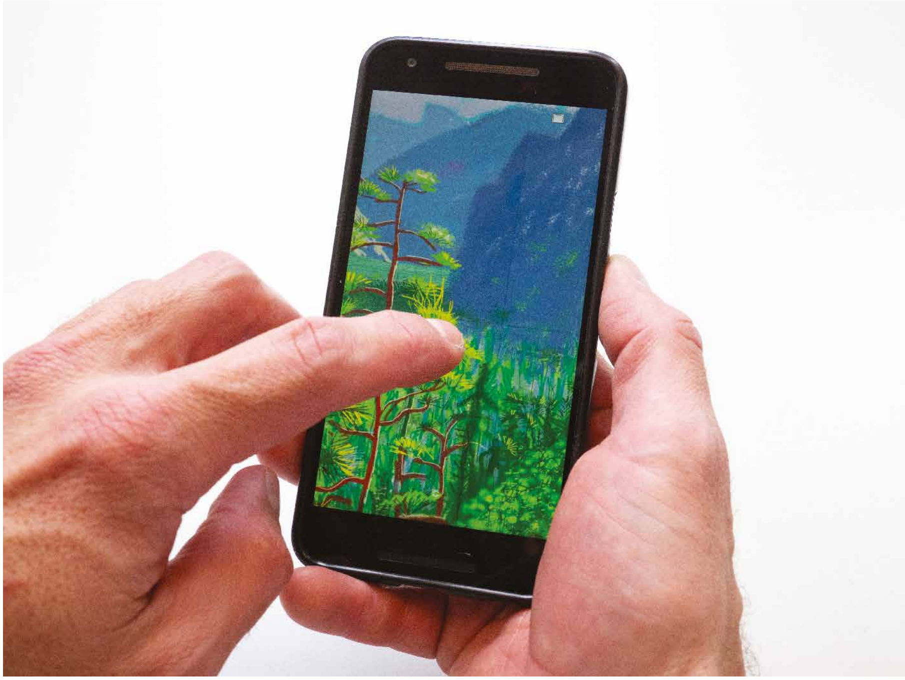

FIG. 2.2 A Hockney iPhone painting, opened in a drawing app on the author's phone.

For British painter David Hockney (Weschler, 2009) the IS is a smartphone used as canvas for painting – a convergent device which combines screen, touch interface, computer, memory and communication to deliver a coherent, fast-responding experience. The IS affords Hockney, a master-painter, to enter an uninterrupted flow of work due to the multiple ways in which it immediately embeds into his creative process. The smartphone as pocketable instrument it can always be at hand, work can commence without the need to prepare and collect drafting equipment, and afterwards there is no waste and the output can be shared with peers. Hockney even states that it pervades the activity with a quality of freshness. The IS is experienced as an extension of the acting self and lets the artist proceed at a natural pace that allows for the emergence of a feeling **intimacy**.

2.3.2.3 Mastery – An IS offers a sense of control

In his PhD thesis on Immediacy in Creative Coding Environments, Roberts (Roberts, 2014) combined the concept of direct manipulation interfaces (Shneiderman, 1983) with the notion of the immediacy effect from behavioral economics (Keren, 1995), to define immediacy as “the effect of latency on the perception of control in interactive, real-time systems and the impact of time discounting on the decision-making processes of interactive system end-users. Systems that are immediate provide a sense of fluid productivity and lead people toward best practices by affording their quick execution. […] We can infer from this that we should lead users towards best practices for creative authoring by making such practices as rapid and as unobtrusive as possible.”

Roberts developed a live coding environment called Gibber.cc which allows simultaneous coding and code execution for creation of audio-visual content and live performances. It is set up to guide users towards an enjoyable and productive experience.

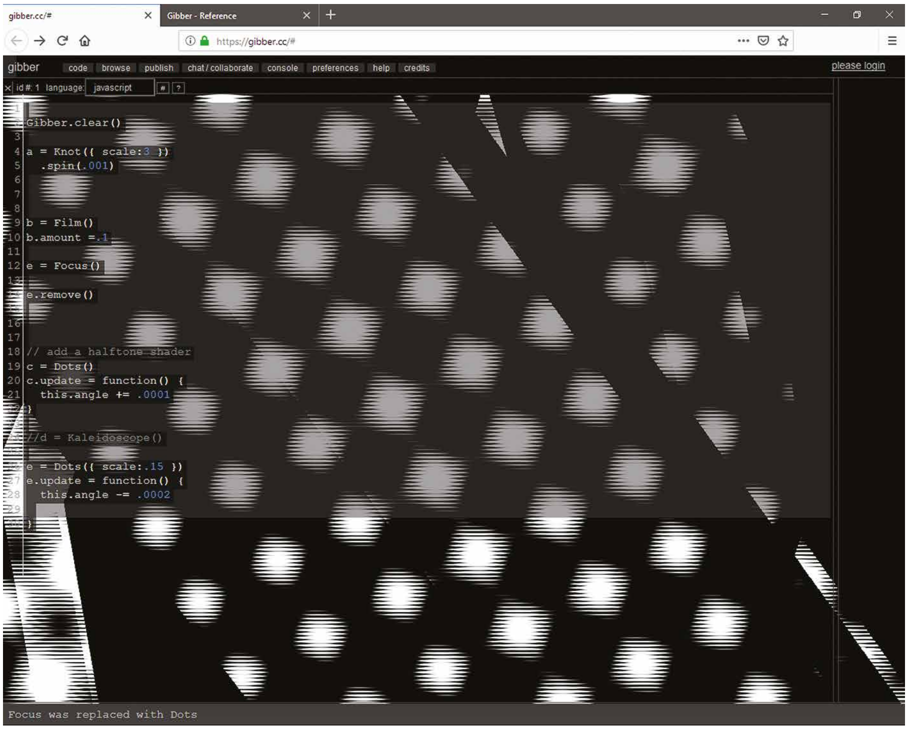

FIG. 2.3 Screenshot of a Gibber live-coding session.

The developed live coding environment Gibber.cc allows for a certain amount of simultaneity but not for convergence of manipulation by coded instructions and representation of visual and auditory results. The interface overlays a coding pad on the visualization area, and written instructions can be added to the live execution in their entirety or as selections of parts of the code. Thus the transfer from intention to changed behavior mostly depends on code formulation in the mind of the user and input via keyboard, the information processing distance (Hutchins et al., 1985) is direct only when parts of written code are selected and executed. Still the environment allows for a feeling of direct engagement to emerge. One of Roberts' aims was to lead the user towards best practices by employing immediately available actions as a form of **guidance**.

2.3.2.4 Embeddedness – An IS is bound to and specific to its environment

Keinonen (Keinonen, 2009) suggested the term immediate design for "a mode of design characterized by responsiveness to users' current needs, intensive layperson participation, continuous incremental improvements, and the implementation of do-it-yourself developmental platforms. It takes place where the activity and challenge are on the site, and aims at solving the problem directly without withdrawing to product development fortresses."

Keinonen opposes immediate design to remote design, which is meant to produce general solutions and foundations for others to develop products or local practices. The development project for a general-purpose product ends when the product is launched, but immediate design aims at improving specific human-technology systems and is open ended. Immediate design fosters temporal and spatial immediacy, and direct interaction between designers and users. It also changes causes for design action, as it is driven by the explicit and implicit needs of users, instead of being driven by trends, economic rationale or technology. Immediate design optimizes the human-technology match in a fluid process of continuous improvements.

In immediate design, design collaboration is not something that takes place only between designers and engineers, it takes place between designers and users. Design and use take place simultaneously, the designer acting side by side with users, separated by neither hierarchy no value. This **embeddedness** of design activities, directly in the practices of use, occurs as normal work and improvement of the environment coincide, generating specific and context dependent solutions.

2.3.2.5 Re-framing – An IS affords to continuously re-formulate the user's objective

Artist Martino developed for her doctoral thesis research a digital drawing instrument which provides creative immediacy by maintaining the artists' mark (Martino, 2006). Her thesis focuses on digital instruments based on the shape grammar approach (G. Stiny, 1972) (Stiny, 1980) because the immediacy of the artist's mark in visual creation has historically been lost in computation. Neither did digital design tools do not answer the fluid demands of the artistic process, nor did prior research address the immediacy of drawing and painting as a device in computational art.

According to Martino, the practice of visual creation is a shifting process, in which the artist has the role of a creator who dynamically re-creates problem space. The canvas into which a sketch is drawn changes with every stroke of the pen. This leads to new visual realizations and re-formulates the artistic task at hand at that specific moment in the process of creation, which "occurs in the tight loop between the hand and the eye where every mark influences every other mark in a re-framing of the picture plane." (Martino, 2006, p. 14) The immediate, dynamic input allows the designer to operate outside of the constraints of a static model or boundary system.

A system which allows for such practice should accommodate process at both the conceptual and implementation level. Such a system should combine flexibility with repeatability and furthermore be adaptive, with an elastic schema that allows a visual designer to identify and use emergent features. The design environment affords the designer to continuously and simultaneously frame and solve the problem. Design and implementation coincide in this process of **re-framing**.

2.3.3 Overview

The examples are discussed from two perspectives: One perspective is the internal, connected view of the human users which are embedded in them, as the system shapes their experience and affects their consciousness, their behavior and potential. The other is the external and detached view which allows for analysis of system components and of characteristics of specific instances of IS on a technical level. As previously described the characteristics found in the examples can be described in complementary pairs:

2.3.3.1 Awareness & Guidance

Regarding **awareness**, all examples contain tight feedback loops which offer confrontations between intended and actual behavior. In this feedback loop adequate action is continuously validated, and it allows the users to adjust their actions accordingly, matching intentions with results. The user becomes aware of their relationships to the environment through its actionable properties. All IS implicitly afford **guidance** through vectors of beneficial action revealed by the interaction. Some examples were attributed to lead to continuous learning, others were explicitly designed to offer guidance through the availability of immediate action opportunities.

2.3.3.2 Intimacy & Embeddedness

The examples show that IS occur with the user's body in the loop and become extensions of the body. Hence, they let the user proceed at such a natural pace that it allows for a feeling **intimacy** to emerge. From an outside perspective the user is embedded, and in this **embeddedness** as temporal, spatial, social and architectural intermediaries dissolve and roles of designer and user overlap.

2.3.3.3 Mastery & Re-framing

IS are geared for emergence of the psychological flow experience, they thus can help individuals to function at their fullest capacity and to enhance their competence. IS let users act in a mode of direct manipulation, where they are initiators of action and feel in control, gaining confidence and mastery. The problem space is a dynamic re-creation of problem space by framing and solving the problem simultaneously, in a fluid process of continuous **re-framing**.

2.4 Conclusions

2.4.3.1 Overview

In this paper IS have been introduced and framed as Cyber-Physical Systems and through the lens of Gibson's Theory of Affordances, alongside the notions of flow experience and the immediacy effect from psychology, and related to the direct manipulation interaction style from the field of human-computer interfaces. A series of examples have been described and discussed. Based on this effort characteristics and conditions of Immediate Systems have been presented. In conclusion of the article, the findings will be listed in short and a glimpse at future work will be given.

Initial **framing** of IS indicated that they embed design and implementation in situations of use, overcome limitations of remote design, offer a form of direct manipulation interaction style, leverage the psychology of the Immediacy Effect and Flow Experience. Their implementation as HiLCPS radically improves applicability of the concept.

As **conditions** were named that IS are meta-systems binding user and environment, provide a tight feedback loop between intention and adaptation, establish and maintain a state of continuously available adaptivity and can include any combination of multiple modalities, e.g. temporal, spatial, tactile, embedded, intentional or procedural.

IS, framed within Gibson's original Theory of Affordances, offer the **affordances** to shift boundaries between self and environment, afford creative immediacy and afford furnishing the environment with new affordances. Additional affordances derived from examples are awareness, guidance, intimacy, embeddedness, mastery and re-framing. Outside of the section on affordance theory, these affordances were referred to as **characteristics** of IS.

2.4.3.2 Future Work

The presented description of IS makes it possible to position them in history and contemporary discourse. It identifies predecessors and technical as well as socio-cultural contributions and eventual pitfalls. It also makes it easier to relate the notion of IS to architectural research and praxis.

Additionally, the presented work serves as guide for research on innovative architectural systems, which the author is invested in. The development of architectural systems as IS, involves the discovery of new applications and the unraveling of potential synergies of emergent technologies. Inherently it involves research into the relationship between humans and the built environment. Hence developing IS in architecture is an agenda that reaches beyond mere design and performance optimization, it requires a transdisciplinary approach relying on a constructive assessment of the quantitative and qualitative impact of technological change on architecture and its users.

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3 Immediate Systems in Architectural Research and Praxis

This article has been previously published in the journal *SPOOL*: Friedrich, C. (2020a). Immediate Systems in Architectural Research and Praxis. SPOOL, 7(3), 37-46.

ABSTRACT

Design activity, especially in architectural praxis, takes place in spatial and temporal remoteness from the use of its outputs. This remoteness impedes the ability to respond to actual needs that arise in situations of use. Ultimately it makes design dependent on hypothesis.
Design activity, especially in architectural praxis, takes place in spatial and temporal remoteness from the use of its outputs. This remoteness impedes the ability to respond to actual needs that arise in situations of use. Ultimately it makes design dependent on hypothesis.
Immediate Systems (IS), as defined by the author, overcome the limitations of remoteness by embedding design and implementation in situations of use. As Human-in-The-Loop Cyber-Physical Systems (HiLCPS), they are comprised of interacting digital, analog, physical, and human components. They link people and environments in a tight loop between human intention and immediate adaptation. Immediacy in this context indicates a state of continuously available adaptability at the speed of human intention.

This paper extends previously published framing of IS and traces three approaches towards IS in architecture: as adhocist mode of action, as acceleration of design transfer and as human-architecture symbiosis.

KEYWORDS

Immediacy, immediate systems, design by use, design environments, design methods

3.1 Introduction

The aim of architecture is to adapt the environment according to human wants and needs. In praxis however, architectural processes are detached and slow to respond to actual needs. Design usually takes place in environments which are spatially and temporally separated from construction, and both design and construction are separated from actual use. To the degree of this remoteness architecture must rely on hypothesis. In the words of architectural historian and critic Mario Carpo, this is the essence of design "as it has been known since the Renaissance: design is a predictive tool, it models something before it happens." (Carpo, 2017)

Digitally-driven mass customization, performance optimization and building information modeling and management are well-discussed and employed practices in architecture which emerged in the wake of the digital revolution (Kolarevic, 2003) (Kalay, 2004) (Carpo, 2017). They are foreboding what has been called the fourth industrial revolution, aimed not primarily at increased production capabilities but instead at unprecedented levels of flexibility, adaptability and integration. Products and services are increasingly linked with one another and their environment, driven by the ability to cater directly to customer wishes, affecting the value creation chain and effectively inverting the relationship between industry and its customers (Sendler, 2013, 2018). Whereas the first three industrial revolutions provided increasingly economic answers to the question 'how' to produce, the fourth industrial revolution increasingly links design and production to situations of end-use, offering value by answering the 'what' and 'why' questions in exhaustive detail.

3.2 Immediate Systems

Immediate Systems (IS), as defined by the author (Friedrich, 2020), can be conceptualized as a special form of Human-in-The-Loop Cyber-Physical Systems (HiLCPS) (Schirner, Erdogmus, Chowdhury, & Padir, 2013). They are comprised of interacting digital, analog, physical, and human components, forming systems where people and environments are bound in a tight loop between human intention and immediate adaptation. They embed design and implementation in situations of use, overcoming the limitations of remote design.

Recapitulating prior framing of IS (Friedrich, 2020), IS offer interaction in the style of direct manipulation (Hutchins, Hollan, & Norman, 1985; Shneiderman, 1983), and leverage the psychology of the Immediacy Effect and Flow Experience (Keren, 1995; Nakamura & Csikszentmihalyi, 2009).

As conditions were named that IS are meta-systems binding user and environment, provide a tight feedback loop between intention and adaptation, establish and maintain a state of continuously available adaptivity and can include any combination of multiple modalities, e.g. temporal, spatial, tactile, embedded, intentional or procedural.

Framed as habitat (May & Kristensen, 2004) or environmental niche, and related to Gibson's original Theory of Affordances (Gibson, 1986), IS offer the affordances to shift boundaries between self and environment, afford creative immediacy and afford furnishing the environment with new affordances.

Awareness, guidance, intimacy, embeddedness, mastery and re-framing are additional affordances or characteristics, that were discussed and derived from examples (Graham, 1993; Keinonen, 2009; Martino, 2006; Roberts, 2014; Shneiderman, 1983; Weschler, 2009)

3.3 Immediate or Mediated?

The term immediate here is used to incite multiple connotations:

- as indicating a quality of human experience,
- as a quantitative difference in speed relative to conventional approaches,
- indicating a discrete qualitative difference obtained through methodical or technological improvements that cut middleware,
- as continuous integrated end-to-end process, in which intention and action may not be limited to one locus but be distributed across the entire system and
- as the state of being of an emergent system, which constitutes itself in the relationships of all its parts all at once.

While these connotations may each be legitimate, one should be aware that the notion of immediacy is often perceived as semantic construct with no relation to the real world. Immediacy eludes our grasp in its paradoxical nature. Any immediacy in space and time can itself be recognized only through the mediate knowledge of physiology; any immediate experience is inseparable from sub-conscious inference and interpretation; and if immediate ideas exist, they cannot be differentiated from prior knowledge. Understood as absolute absence of mediation, the notion of immediacy falls prey to scientific realism (Wallraff, 1961).

Applying this phenomenological critique to a discussion on media technology, the argument can be made that an attempt to achieve immediacy by means of technological mediation is paradoxically a hyper-mediacy. For example, attempts to create intuitive user interfaces that make themselves invisible ('transparent immediacy'), are in turn embedded in human's conscious efforts to manipulate a high-tech apparatus (Bolter & Grusin, 1999).

Martin Heidegger's famous example of using a hammer (Heidegger, 1967, pp. 68-70) shows how technology mediates an immediate experience of the world. A person that puts a nail in the wall works on the nail, while the hammer, being ready-at-hand, withdraws itself from attention. It is only in malfunction that is no longer ready-to-hand. As a hammer is bent it becomes conspicuous and asks for our attention again. According to Heidegger, this readiness-to-hand is the mode being of equipment, which is revealed only in use. The ancient Greek term for things matches this understanding of the world, it is prágmata, that which one encounters in praxis. Heidegger's texts are ontological, the matter of his philosophy is not the properties or relations of things that exist in the world but their very existence. Putting down the hammer allows for other modes of reflection and perception, but equipment reveals its being only and immediately through its use. In this sense, inversing the skepticism of Wallraff, the mediate is primarily immediate, only to be recognized in malfunction. This recognition of the primarily immediate as mediate is not reserved for equipment: a hammer may break, but so may a hand.

The equipment ready-to hand never is on its own, but always situated in an equipment totality. The hammer is bound to the nail by its adequacy for putting it into a wall, and similarly is bound into the equipment totality by references in-order-to. In the context of previous framing of IS it is tentative to draw a brisk parallel to Gibson's Theory of Affordances. Affordances too are situated neither in the user's perception nor an object's independent reality, they only exist and are to be revealed in a relationship of use. Yet affordances are not limited to the being of tools or equipment; every thing and substance could afford something.

3.4 Approaches to IS in Architecture

In order to situate IS within architectural history and theory, three possible readings of the effects of IS in architecture will be discussed:

1. **New adhocism**, a mode of action where the environment is adapted ad-hoc using any means available, possibly utilizing but not dependent on any pre-existing technology or framework.
2. **Accelerated design transfer**, as consequence of evolving information and communication technologies, which lead to increasing interaction density between humans and their environment in combination with an expansion of their environment due to increasing interactions between the systems of which it is constituted.
3. **Human-architecture symbiosis**, which arises as consequence of cyber-physical systems which include both humans and the built environment.

These three readings offer different angles on approaching IS, with adhocism being situated in the context of the user, design transfer in the context of the designer and human-architecture symbiosis as perspective on technological mediation in the built environment, not as artifact but systemic. They have in common that they all originate in the 60s and 70s and were deemed newly relevant a generation later. The different perspectives are offered to indicate that IS touches on the subjects of design participation and user empowerment, on design methodology and design technologies, on habitats and human-technology relations. The reader may be familiar with one or several of these subjects, which can be considered as stepping stones towards a better understanding of different facets of the main theme of IS.

3.4.1 New Adhocism

In the early 70s, Charles Jencks proposed architectural adhocism as strategy to overcome the disjunct between the needs of the individual and generic design solutions; the ideal of adhocism thus is the immediate fulfillment of purposes. Jencks argued that by taking initiative and combining parts ad hoc, the individual could overcome the distance and estrangement caused by specialization, bureaucracy, and hierarchy. In doing so, the individual would not only answer their immediate needs but create, sustain and transcend themselves (Jencks & Silver, 1972, p. 15).

Adhocism preached the power of improvisation where technological means and social conventions failed to support the fulfilment of human purpose. As manifesto it walked the line between parody and political agitation for a more participatory architectural praxis, a more democratic style, through the application of readily available technological means.

In 2008, Matthew Fuller and Usman Haque (Fuller & Haque, 2008) proposed a new adhocism on the urban scale: the production of cities beginning immediately with building and construction. Any form of design or planning, sketching, modeling, or brainstorm session should be discarded. Their place should be taken by activities performed on actual building materials and thought processes expressed at full scale, immediately on the artifact inhabited. Fuller and Haque took the ideas of the 60s and 70s, including the adhocism of Jencks and the concept of underspecified architecture of Pask, who proposed to design buildings as evolutionary systems (Pask, 1969) (Haque, 2007). They combined them with contemporary technology and best practices that emerged in open source software development, embracing modularity and granularity to simplify re-use and re-development.

The New Adhocism approach is no longer fully dependent on make-shift solutions, as systems and components can passively, actively and pro-actively adapt and be adapted to custom causes.

3.4.2 Accelerated Design Transfer

Architect and researcher Richard Foqué introduced the concept of design transfer (Foqué, 1975, 2010) in analogy to the concept of technology transfer. Design transfer indicates how a new design affects its environment and spreads out in time. Foqué related design transfer to the concepts of densification of human space (Skolimowski, 1969) and expanding environments (Hall, 1962). Human space is described by the interactions between a human being and their environment; its density is measured by the number of patterns in which one is required to participate. The concept of expanding environments entails that constituents of natural and man-made systems interact in increasing numbers, affecting each other's behavior fundamentally.

According to Foqué, the evolution of information and communication technologies cause the expansion of interaction environments and the densification of human interaction space to augment one another, leading to an increasingly complex design situation. Foqué calls this an explosion of the design situation which coincides with

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the implosion of design transfer time caused by the radical acceleration of design transfer. Both developments contribute to a situation of design impotence which necessitates a new conceptualization of design activity and its methods.

In the new situation, leveraged by the Building Information Modeling (BIM), the traditionally consecutive phases of briefing, design, construction and operation are linked to one another. They enter a continuum where they can overlap and increasingly merge, resulting in an interactive designing-building process, in which previously consecutive activities are integrated and executed concurrently.

The account of Foqué bears similarities to Kalay's (Kalay, 2004) descriptions of the design process becoming a network of design which includes manufacturing, marketing and distribution organizations, and also a distributed design process which spans across professions, organizations and geographic locations. Both developments challenge the traditional hierarchy of the design process. Furthermore, embedded and networked computing devices in building components and machines for production and assembly can respond to occupant's needs as they arise, resulting in reduced waste and more efficient building and use.

The acceleration of design transfer, which coincides with the replacement of linear processes with networked concurrent processes, includes material fabrication and construction. According to Achim Menges (Menges, 2015), construction is becoming not only computerized, i.e. automated for the sake of improved precision and efficiency, but increasingly computational, i.e. an indeterminate process of materialization which extends the design process and is driven by cyber-physical feedback. As Menges states, predictive modelling may eventually be replaced by continual (re)construction, as design and materialization merge. "This potential fusion of the processes of design and making provides a considerable challenge to both established design thinking and current design techniques."

Menges's account of cyber-physical making however does not mention the users who interact with these systems, for example the architect, the builder, the inhabitant. Ultimately, it is them who pose a need for building, who set up and maintain the systems, who are bound into the ongoing process. As phenomenon of the fourth industrial revolution (Sendler, 2018), cyber-physical making ultimately would not stop at merging design and materialization but be driven by the far end of the value chain.

Accelerated Design Transfer shifts architectural praxis from a linear, sequential process towards processes executed in parallel, as a network of simultaneous activities, in which humans and things together compute, connect, sense, actuate and communicate.

3.4.3 Human-Architecture Symbiosis

In his 1960 article Man-Computer Symbiosis (Licklider, 1990, pp. 3-4), Licklider predicted the development of computer-human symbiosis, a kind of man-machine system positioned between mechanically extended man and autonomous artificial intelligence. The first aim of this development is to make machines that help formulate technical problems, for example machines that help identify the questions to the answers they provide or machines which cooperate in intuitively guided trial- and error procedures. The second aim, which Licklider considered closely related, is to develop machines that can participate in real-time processes in order to achieve immediate man-machine communication.

The cybernetic architecture movement of the 60s and 70s explored the architectural potential of the emerging computation revolution. The 1969 article Cybermation (Rabeneck, 1969), for example, considered the limited capabilities of then already existing automated mass-customized production in the building industry to answer changing demands. "Imagine we can improve the built environment through developments in performance design and industrialized building, but that people's need of change accelerates faster than our ability to satisfy it. Our predictive ability remains inadequate. [...] Buildings ought to allow any degree of change over time [...] given the constraints of our current technology" (Rabeneck, 1969, p. 497).

By applying computational systems to the design, construction and use of architecture, the notion of human-architecture symbiosis can be posited between modernist architecture, whose development was driven by the mechanically extended capability of industrialized production, and futuristic visions of artificially intelligent built environments which are autonomous and self-reliant. The Architecture Machine Group of Nicholas Negroponte was one of the pioneers in exploring cybernetic architecture. On the most extreme end existed the idea of architecture being artificially intelligent, self-producing and autogenic (Negroponte, 1975, pp. 144-145). The more conservative concept of a designer-machine symbiosis (Negroponte, 1969) maintains the remoteness of the designer, and therefore requires a machine that is able to work with missing information (Negroponte, 1970). An approach that encompasses user, technology and designer directly is the agenda of making the built environment responsive to me and you (Negroponte, 1975, p. x), which in context could be understood as human-architecture symbiosis.

Architects and architectural researchers aim to make the built environment increasingly adaptive (Eastman, 1972) (Yiannoudes, 2016) and interactive (Fox & Kemp, 2009; K. Oosterhuis, 2012), by embedding intelligent (Cheng, 2016) and robotic (Menges, 2015; K. Oosterhuis & Bier, 2013) constituents, affecting conception, construction and use. Human-Architecture Symbiosis, as HiLCPS, makes the built environment more adaptive and responsive by establishing systems where designers, users and technological artifacts strive for a dynamic fit in their ecological niches amidst changing balances between them.

3.5 Bringing IS into Praxis

The research effort in IS originated at the Hyperbody group at Delft University of Technology, under direction of Kas Oosterhuis. Situated originally in the department of Design Methodology of the faculty of Architecture, the group investigated non-standard and interactive architecture. Leading visions of adaptive built environments were given with the concept of e-motive environments (K. Oosterhuis, 2002; K. Oosterhuis, 2003), which are relatively coherent and relatable to the inhabitant, and with the paradigm of out-of-control swarm architecture (K. Oosterhuis, 2006). Within Hyperbody's educational and research agenda, the author developed a series of prototypical IS, or components of IS. For the protoSpace collaborative design laboratory, a data exchange system was conceptualized and prototyped as graphing tool for actionable relationships between parameters in different software applications. The system would allow users to construct ad-hoc real-time information feeds between diverse and specialized applications used in the daily work of building industry professionals, and bind them to live parametric models made in the swarm architecture paradigm (K. Oosterhuis, Friedrich, H.C., Jaskiewicz, T.J., Vandoren, D., Pool, M., Xia, X., 2008). Another field of investigation were prototypes of CAD modeling tools that offer real-time volumetric design exploration, and should allow users to interactively model and ad-hoc reconceptualize geometry, topology and components of architectural assemblies (Friedrich, 2007, 2009). A combination of these techniques with digital fabrication and interactive building components lead to the most encompassing IS prototype, an attempt to realize an open-ended building system that encompasses simultaneous design, adaptation, construction and reconfiguration as interaction possibilities embedded in the built environment (Friedrich, 2013).

3.6 Conclusion and Outlook

The application of IS in architecture can be understood in a threefold manner: an adhocist mode of action, as accelerated design transfer, and as human-architecture symbiosis. These three approaches consider the same phenomenon from different perspectives respectively, that of the lived experience of the user-designer, that of the designer's methodology and technology, and that of ecology.

The ongoing digital revolution and emergence of ubiquitous computing, and cyber-physical systems may affect the form and feasibility of each of these readings:

A The New Adhocism approach is no longer fully dependent on make-shift solutions
B Accelerated Design Transfer may shift architectural praxis from sequential process towards a network of simultaneous activities
C Human-Architecture Symbiosis may emerge as a reading of HiLCPS with the agenda of making the built environment more adaptive and responsive

Research in IS re-examines these visions in their historical context and in the context of new technology. As was discussed, it is primarily through praxis that humans encounter the world. Design research that is limited to the technological mediation perspective of design technologies is in danger of falling back onto remote design thinking. IS research is an attempt to escape this circularity, it seeks to unveil the hidden affordances of design-by-use praxis.

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PART 2 Experiments

4 SmartVolumes

Adaptive Voronoi power diagramming for real-time volumetric design exploration

This article has been previously published in the journal *Lecture Notes for Computer Science*: Friedrich, C. (2007). SmartVolumes - Adaptive Voronoi power diagramming for real-time volumetric design exploration. Lecture Notes for Computer Science, 4820/2008(VSMM07 Brisbane Proceedings), 132-142.

ABSTRACT

Voronoi Diagrams and Delaunay Triangulations are two concepts fundamental to computational geometry, which have been applied in the most varied disciplines. In recent years, they are increasingly used in architectural design. In this paper, a novel method for volumetric design exploration based on three-dimensional (additively weighted) Voronoi power diagrams is described. The method combines fast calculation of three-dimensional weighted Voronoi Power Diagrams with a volume-dependent feedback loop, resulting in a real-time interactive modeling tool. This tool, named SmartVolumes, has been integrated into the modeling environment BehaviourLinks, where the interaction between parametric volumes and other entities can be further elaborated through behavioral linkages. Applications of SmartVolumes in urban design and architectural design are described, implications of the use of Voronoi diagrams for architectural modeling and environments are explained and directions of consecutive developments are indicated.

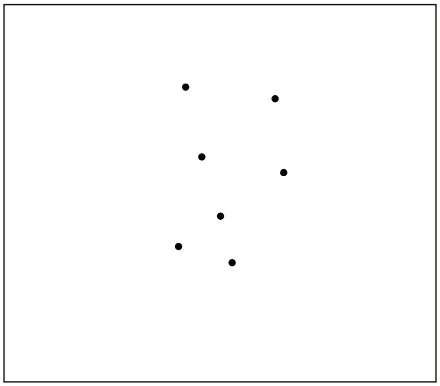
4.1 Introduction

The Voronoi diagram may be a concept of considerable antiquity, since it resembles many different kinds of natural structures. One of the first known appearances is an illustration showing the disposition of matter in the solar system published by Descartes in 1644, which resembles a weighted Voronoi diagram. Though the first comprehensive representations date back to the mid-nineteenth and early twentieth century, given by respectively Dirichlet and Voronoï, Voronoi diagrams were repeatedly rediscovered in various disciplines, even up to the 1980's. In more recent times the discovery of mathematical generalizations of the Voronoi Diagram has found a similar fate, with the additively and multiplicatively weighted Voronoi diagrams being repeatedly rediscovered in the 1990's (Okabe, 2000). During the first decade of the third millennium, Voronoi diagrams are increasingly applied in urban and architectural design. Two-dimensional Voronoi diagrams have been used in interactive environments for the dynamic assignment of regions of augmented space (Snibbe, 1998), in urban design stakeholder games for dividing an urban area into parcels, iteratively optimizing plots (Kaisersrot, 2001), and structural surface tessellations (T. Verebes, 2006). Three-dimensional Voronoi diagrams have been used for space-filling structural design (Fischer, 2005), and functional optimization of various environmental aspects in architectural design (T. A. Verebes, I., Araiza, J., Loreto, F. M. and Sukkar, A., 2006). In all architectural applications Voronoi diagrams were arguably also used for their inherent aesthetics.

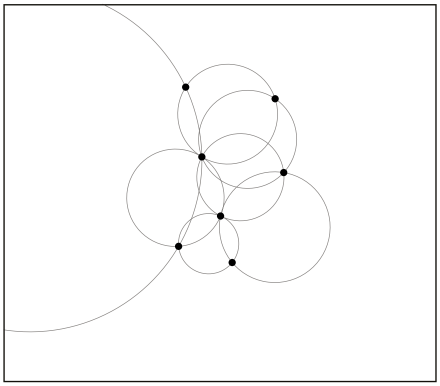
In this paper, a novel method for volumetric design exploration based on three-dimensional (additively weighted) Voronoi power diagrams is described. The method combines fast calculation of three-dimensional weighted Voronoi Power Diagrams with a volume-dependent feedback loop, resulting in a real-time interactive modeling tool. This tool, named SmartVolumes, has been integrated into the modeling environment BehaviourLinks, where the interaction between parametric volumes and other entities can be further elaborated through behavioral linkages. Applications of SmartVolumes in urban design and architectural design are described, implications of the use of Voronoi diagrams for architectural modeling and environments are explained and directions of consecutive developments are indicated.

4.2 Voronoi Diagrams and Delaunay Triangulations

Manual approaches to architectural geometric design are generally based on the construction of drawings with the use of points, lines, circles, metrics, and various types of grids and structures derived from these. The application of computers as drawing medium adds a third or even more dimensions, and an undo stack. Also, it makes architectural geometric design techniques enter the realm of computational geometry, where the focus is not only on how to solve a geometric problem for one or several objects, but primarily on cases where large sets of *n* objects are involved. The application of computers to architectural geometric design lets the designer address entire populations of objects, within the limits of computability. In the exploration of the affordances of computational design media, many techniques have been developed (Farin, 2002).



1 a set of points



2 empty circles over 3 points

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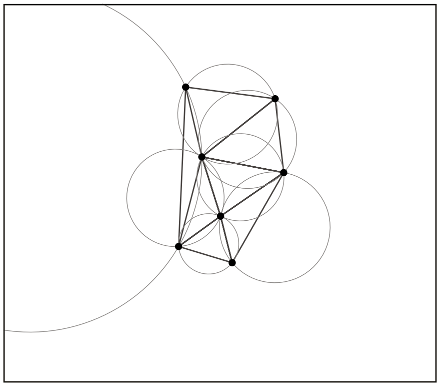
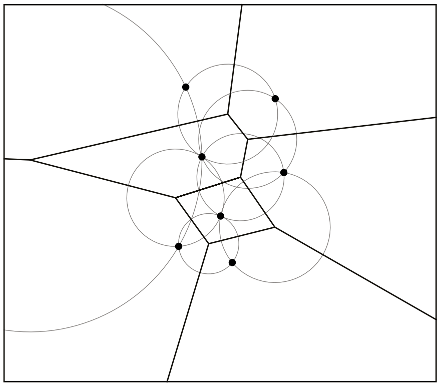


3 Delaunay Triangulation



4 Voronoi Diagram

FIG. 4.1 Construction of Delaynay Triangulaiton and Voronoi Diagram

Figure 5.1 illustrates the construction of Delaunay Triangulation and Voronoi Diagram of a given set of points. First all circles are found which touch three points but do not contain other points. These circles are circumcircles to the triangles of the Delaunay triangulation. The Voronoi Diagram is the dual diagram of the Delaunay triangulation, it has the circumcircle centers as vertices of the boundaries of the Voronoi regions.

Computation facilitates parametric design, for making designs whose actual geometry is a function of a given set of parameters and constraints upon features. A widely applied form of parametric design is solid modeling, in which features can be applied to solids and the exact measurements and amounts of these features can be defined parametrically. Next to making drawings malleable, computational design highly accelerates the construction of geometric features. Through computation, design techniques have become possible which utilize the acceleration of geometric construction up to direct user interaction with the result of the geometric construction. This allows for design exploration with immediate visual feedback from parameter changes. A very popular concept utilizing acceleration are splines, which are curves or surfaces, generated by interpolating over the elements of ordered sets of points (R.M.J. Ten Damme, 2002).

Next to the broad application of off-the-shelf tools, custom made algorithmic techniques are only marginally used in architectural design. Examples would be neural networks, cellular automata, genetic algorithms, shape grammars, swarm-solvers, particle-spring systems.

Common to all these approaches is that they are algorithmic geometric constructions, and as such are based on sets of rules, and sets of features like points which define a line, grid or other kind of structure. In contrast, Voronoi diagrams are not constructions but properties of a set of points in regard to a given metric. Voronoi diagrams enable design directly on a population of points, without the need to first define a structure according to which the geometric construction has to be laid out.

The Voronoi diagram and Delaunay triangulation of a point set can be understood as a dual map to its topology. The Voronoi Diagram maps for each point of the cloud the region of space which it dominates according to a given metric. The Delaunay triangulation maps the relationships of neighboring Voronoi of a given point set. Both Voronoi diagram and Delaunay triangulations are not geometric constructions, they are implicit properties of a point set under a chosen metric. They are maps to the spaces a point set generates, representing them as a set of locations and providing insight into the relationships between these locations. They provide notions of space given in connections and separations, characteristics whose interrelation and primordial nature Georg Simmel described in the essay Bridge and Door:

“Only to humanity, in contrast to nature, has the right to connect and separate been granted, and in the distinctive manner that one of these activities is always the presupposition of the other. […] The forms that dominate the dynamics of our lives are thus transferred by bridge and door into the fixed permanence of visible action.” (Simmel, 1997)

In different context, a similar notion of the clearing of space can be found the in Martin Heidegger‘s essay Building, Dwelling, Thinking¸ in the description of a bridge gathering landscape:

“The bridge[…] does not just connect banks that are already there. The banks emerge as banks only as the bridge crosses the stream. The bridge designedly causes them to lie across from each other. One side is set off against the other by the bridge. Nor do the banks stretch along the stream as indifferent border strips of the dry land. With the banks, the bridge brings to the stream the one and the other expanse of the landscape lying behind them. It brings stream and bank and land into each other’s neighborhood. The bridge gathers the earth as landscape around the stream.” (Heidegger, 1997)

Given the fundamental geometric nature of Voronoi diagrams, and its possible theoretical implications, it may seem surprising they have found use in architecture only in recent years. This may be due to the fact that they take a long time to manually construct, and that they generally lead to non-standard elements which used to be very time-consuming and expensive to produce and assemble. Several developments of the near past may have made Voronoi diagrams more applicable in architectural design:

- The changes to architectural praxis effected by the digital revolution,
- The off-the-self availability of Voronoi solvers in commercial CAD software, e.g. the 'Point set reconstruction tool' for Rhino
- The availability of open source of computational graphics libraries containing algorithms for the construction of 2D and 3D Voronoi diagrams and Delaunay triangulations, e.g. VTK (Kitware, 2015), CGAL (CGAL) and Qhull (Barber, 1996).
- The growing number of architects literate in the use of computational tools and programming,
- The advances of non-standard design and production in architecture

4.3 Smartvolumes

The complex interrelationships between the location of points, their weight, and the geometry of the Delaunay triangulation and its Voronoi diagram demand for 'an efficient tool for design exploration. SmartVolumes is a design tool developed to meet this demand. It is based on real-time interaction between the set of weighted points, properties of its Voronoi diagram, a user and possible parametric relationships the user has set. The adaptation of the parametric plan is taking place in real-time, several times per second, as users interact with the diagram that results from the rules and constrains they have set. This interaction is set up in a game loop. In each execution of the loop, the user interfaces are read, the parameters they control are updated, the SmartVolumes are computed, the point set is adapted so it approaches the user demand, and eventually the frame is drawn to screen. In the real-time design exploration, weights and positions of points so the volumes of the individual Voronoi cells are adapted to comply with the designer's demands.

The geometry of the SmartVolume cells is contructed anew during each game loop:

1. **Determine the boundary condition**
   The boundary for the volumetric Voronoi diagram is derived from a set of 'boundary' points as their three-dimensional convex hull. It is found by making a Delaunay Triangulation of the point set and collecting all facets incident to infinite cells of the Delaunay triangulation.

2 Weighted Delaunay triangulation

Temporarily eight points are added to the set of SmartVolume points, forming a relatively very large cube around the original set of points. A weighted Delaunay triangulation of the SmartVolume points plus the eight additional points is computed using the CGAL library (CGAL). The weighted Delaunay triangulation in CGAL is based on the power product for determining distance between points:
Let $\boldsymbol{S}^{(w)}$ be a set of weighted points in $\boldsymbol{R}^3$. Let $p_i(w)$ and $p_j(w)$ be two weighted points with positions p_i, $p_j \in \boldsymbol{R}^3$ and weights w_i, $w_j \in \boldsymbol{R}$. The weighted points can be seen as spheres of centers p_i, p_j and radii w_i, w_j. Then the *power product* between $p_i^{(w)}$ and $p_j^{(w)}$ is defined as: $\prod (p_i^{(w)}, p_j^{(w)}) = ||p_i - p_j||^2 - w_i - w_j$, where $||p_i - p_j||^2$ is the Euclidean distance between p_i and p_j (CGAL). The result of this triangulation is equivalent to the triangulations in the second row of figure 5.2.

3 Determine Voronoi cells

The weighted centers of the circumspheres of the tetrahedrons which are the outcome of the weighted Delaunay triangulation are calculated. For each SmartVolume point, the set of circumsphere centers of tetrahedrons to which the point is incident are collected. From these sets of circumsphere centers the Voronoi Cells of the SmartVolume points are determined by computing their convex hulls.

4 Intersect cells with the boundary

The intersections of the Voronoi cells with the boundary volume are determined. The result is equivalent to the diagrams in the third row of Figure 5.2. This diagram is the Power Diagram, with the Voronoi generation distance $d(p_i, p_j) = \|\mathbf{x} - \mathbf{x_i}\|^2 - w_i$ (Okabe, 2000).

5 Tessellate

Each cell of the bounded Voronoi diagram is tessellated up to a chosen depth.

6 Shrink-wrap

All vertices of the tessellated cells, whose distance from their generator point is larger than the square of its weight, are translated towards the point so the distance equals the square of its weight. The result of this ‘shrinking’ is equivalent to the diagrams in the fourth row of Figure 5.2.

7 Adapt

The volume of each SmartVolume is calculated from the resulting geometry. The weight of each SmartVolumes point is adapted according to the difference between the volume of its SmartVolume and the user demand.

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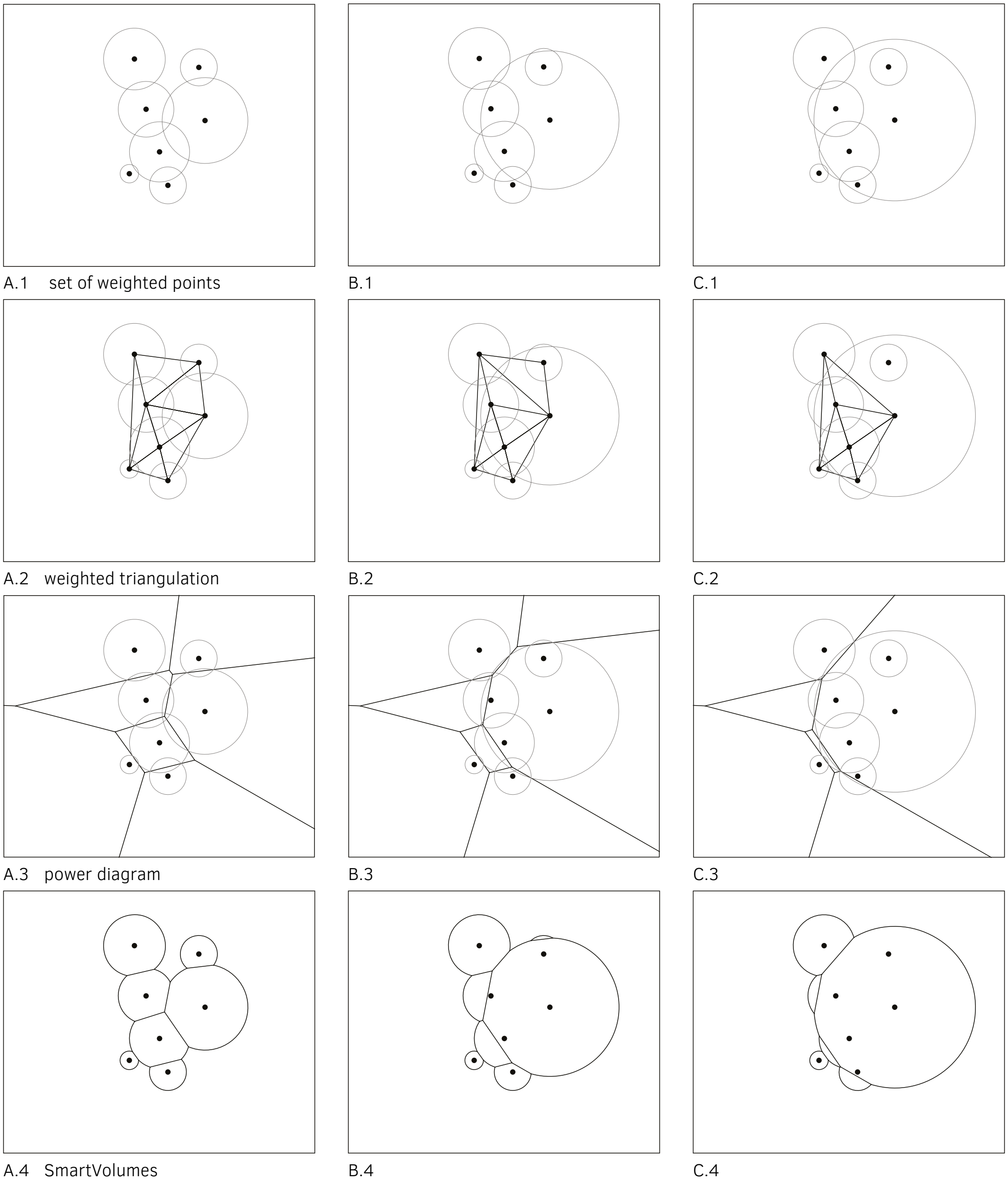


FIG. 4.2 Construction of SmartVolumes geometry from three distinct sets of weighted points A, B and C

4.4 Applications

4.4.1 Urban Design: BehaviourLinks :: Urban Mode

SmartVolumes is developed as spatial design extension for the design environment BehaviourLinks :: Urban Mode. The agenda of BehaviourLinks is to reshape the way architects employ digital techniques by proposing a dynamic, open, collaborative design praxis. A BehaviourLink is a piece of programming code that is executed in real-time. It defines interactions between conceptual entities. These entities can represent architectural concepts but also digital interfaces to sensors, users and exchange data.

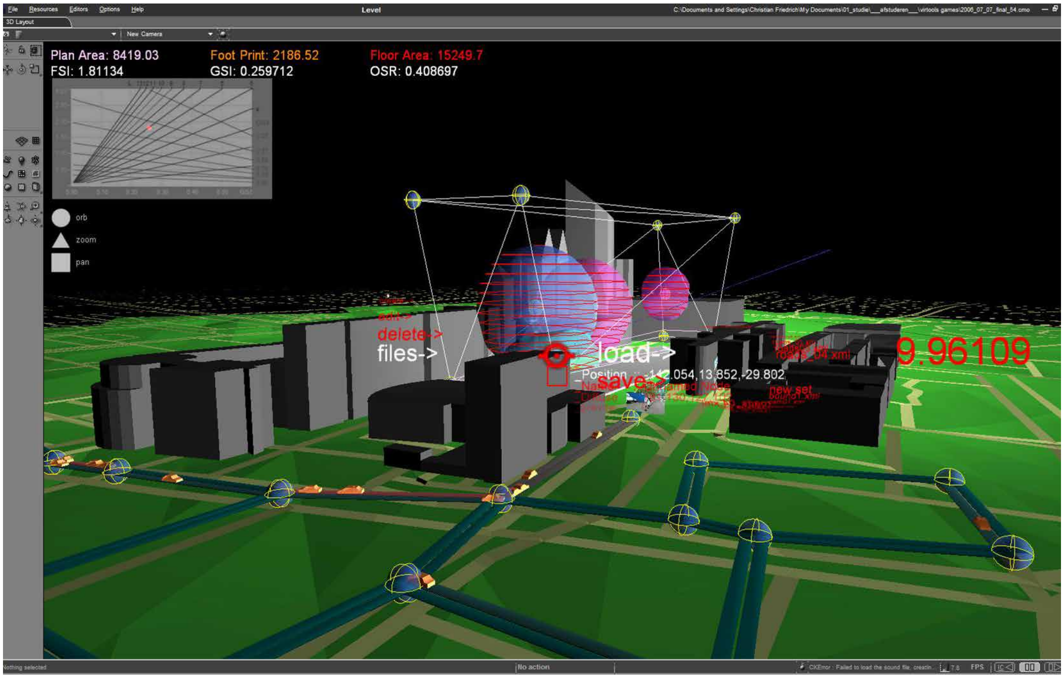


FIG. 4.3 An in-game screenshot of BehaviourLinks :: Urban Mode. Visible within the urban scene are SmartVolume building proposals, traffic modeling, statistical data derived from the proposal and the user interface.

By defining conceptual nodes and laying behavioral links, users can grow a parametric diagram of the urban plan. Its shape, structure and visualization originate from the behavioral design rules and decisions made by the users as well as the feedback negotiation between interacting nodes. The interactive diagram lets a group of stakeholders make fast and well-informed urban design decisions.

In BehaviourLinks::Urban mode, all data is subject to real-time interactive, iterative adaptation by the behavioral links the user laid between entities. Functional extensions of BehaviourLinks consist of node typifications and behaviors. For BehaviourLinks :: Urban Mode, extensions have been implemented that let the users simultaneously explore how the program of demands, volumetric plan, traffic models, parametric spatial relationships, shadow volumes, façade styles, plan boundaries and urban data affect each other, with direct visual feedback and embedded media of the actual site.

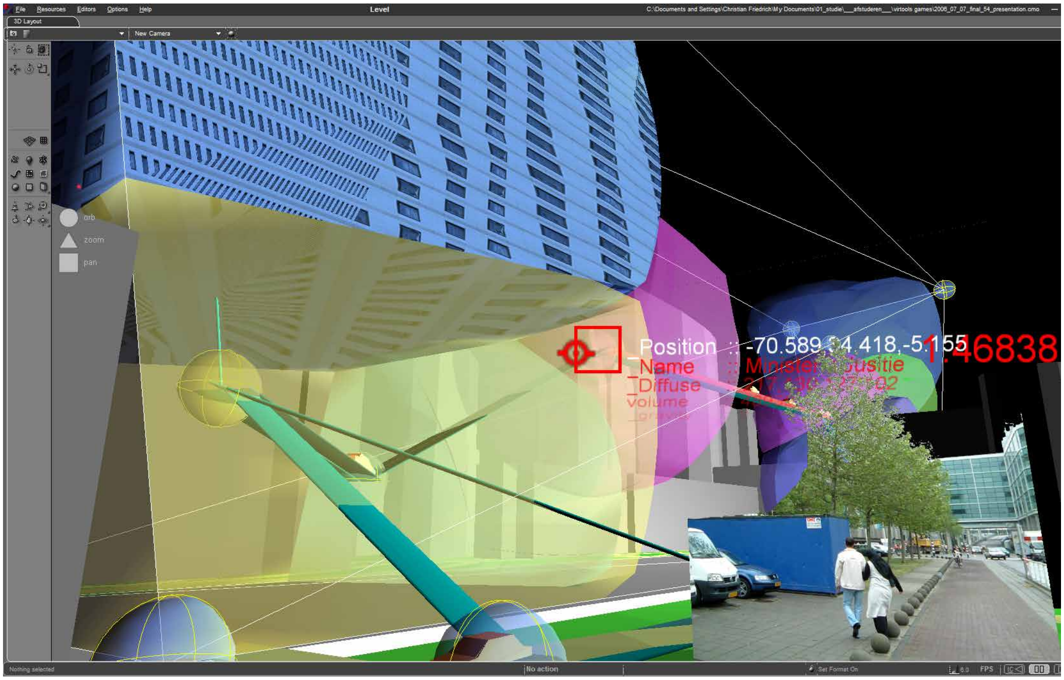


FIG. 4.4 An in-game screenshot of BehaviourLinks :: Urban Mode, shiowing embedded media, facade styles and contextual node data displayed next to the node which is closest to the cursor. Some nodes typified as SmartVolumes are integrated into the path-finding graph of the traffic modeler.

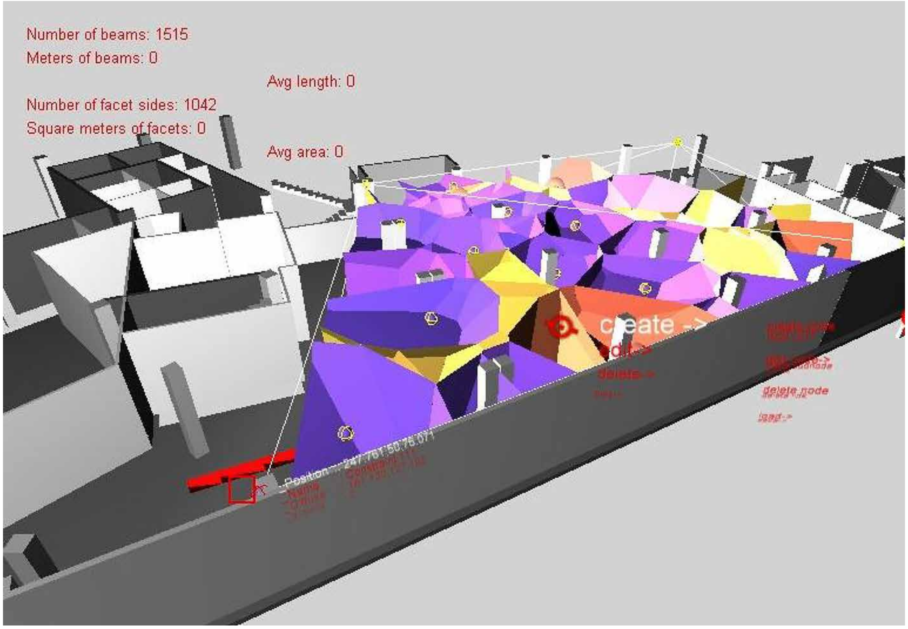
SmartVolumes has been integrated into BehaviourLinks as a possible typification of nodes, which makes behavioral nodes act as parametric volumes. The resulting volumes can be analyzed for their properties. Volumes, floor area estimates and surface area of the SmartVolumes then can be used as input for behavioral links that affect the entire set of nodes. In this way, for example, a node typified as SmartVolume can request traffic from a path-finding graph modeled on the street pattern. The effects of making different access routes to the proposed building volumes and the overall impact of their position and spatial relations can then be explored.

4.4.2 Architectural Design: DP Korea project

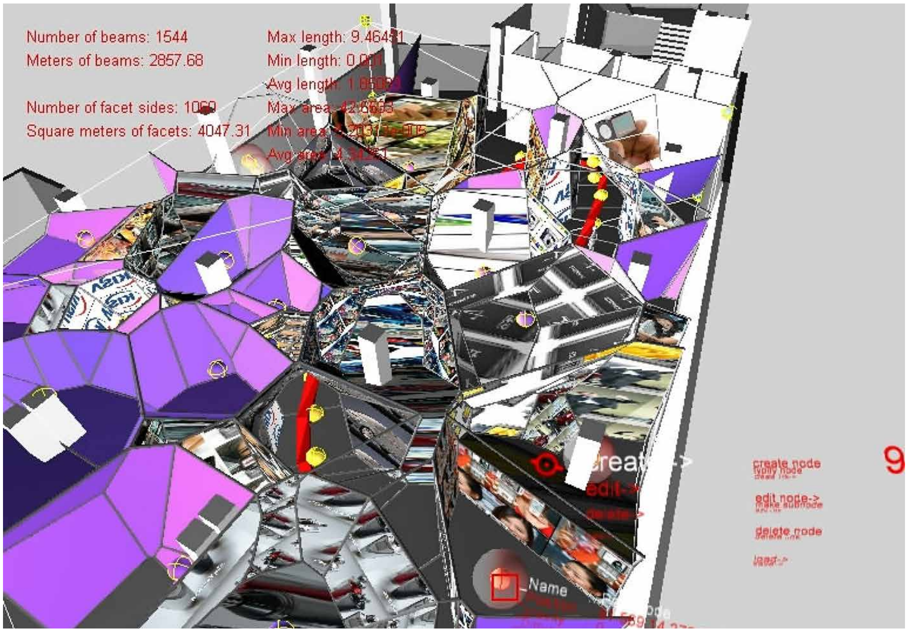
A first application of SmartVolumes in architectural praxis was at ONL, office of Kas Oosterhuis and Ilona Lénárd (ONL, 2006), with the Digital Pavilion Korea project. For this project, a design environment for a technology exhibition was made based on SmartVolumes and BehaviourLinks. The application would allow exhibitors to specify their demands in area and location, and to collaboratively explore possible solutions. A chosen solution could be written file to formats for CAD/CAM, graphic designers and web navigation, as well as to spreadsheets containing lists and statistics of the needed elements.

The SmartVolumes modeler was modified to directly connect a spatial layout of an exhibition space to the partitioning and detailing of the space. In the game, several algorithmic tools for generating a point cloud are available, so the chance of having a point cloud with a desirable Voronoi solution is enhanced. Next to placing points manually the following algorithms can be used for placing points:

- Groups of points can be placed in elements of the buildings construction (columns, walls) ensure these elements can be entirely hidden in spatial partitions, which does not differ in form or structure from its surroundings.
- Groups of points can be placed with a radial distribution relative to a specified center, This results in a three-dimensional density gradient in the point set, and its Voronoi diagram.
- Groups of points can be placed along paths defined by splines, to create passages.

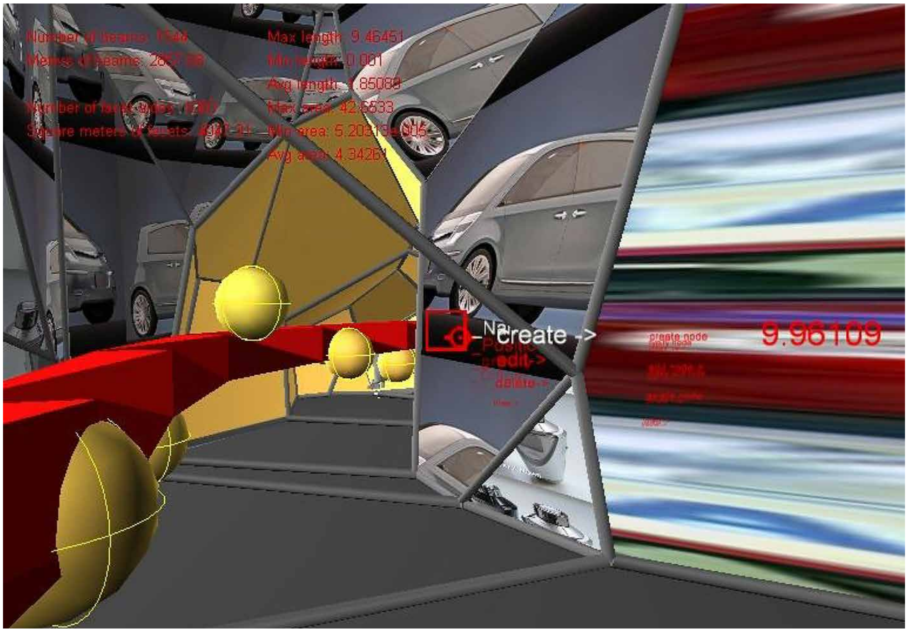


1 Smartvolumes

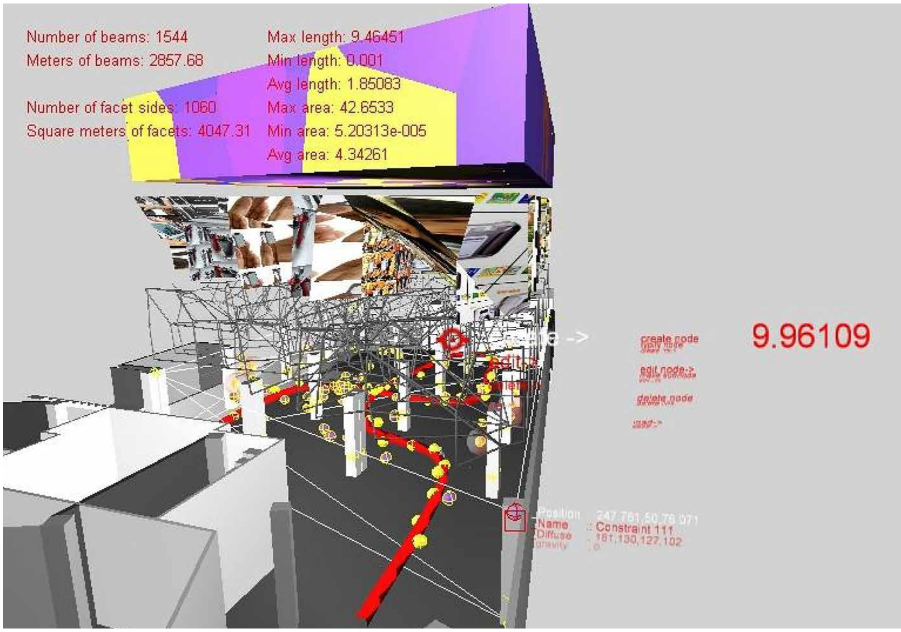


2 Algorithmic generation of geometry for construction beams and showroom displays, presentation of resulting numerical data as overlay

FIG. 4.5 In-game screenshots of an exhibition floor design for the Digital Pavilion project, part I



1 Interior view, visualizing voronoi generator points and routing spline connecting cells



2 Algorithmically generated point set, struts, facets and volumes in etruded view

FIG. 4.6 In-game screenshots of an exhibition floor design for the Digital Pavilion project, part II

In the generatin of the Voronoi so lution, the three-dimensional volumes of the cells are generated for each point, together with the facets that lie between two cells and edges of the facets. Cells, edges and facets can be looked up for each point individually. In this way it is possible to directly remove facets which are between specific neighboring cells. Voronoi cells belonging to a group of points forming a path can be opened to each other, making a passage, and the cells of one exhibition stand can be combined to form a greater, more complex volume.

Due to the additional computation involved in building a multi-relational database of cells, facets and edges, the changes in the point set could not result in direct visual feedback of the entire structure. Once the complete structure is generated however, it is ready to be exported as annotated production drawing in DXF and SVG format, and tables containing the metric data of a solution for cost calculation and production planning.

4.5 Discussion

SmartVolumes is a generic spatial modeling tool, with a wide range of possible uses in architectural design and environments. It can be used in the initial, conceptual phase of the building process. From there it can directly, or after further manipulations, lead to specific data for computer aided manufacturing of the design. It could also be used for spatial analysis needed to control distributed participators in interactive architectural environments, be it humans or elements of the architectural object itself.

In a three-dimensional Voronoi diagram the location of points, the volumes of cells, the faces of cell surfaces, the edges of these facets and the endpoints of these edges are all implicitly related to each other. Each change to the generative point cloud simultaneously affects structure, building physics, details, aesthetics and other performances of the design. These complex interrelations demand for a tool to efficiently explore possible solution spaces. SmartVolumes is intended to meet these demands.

SmartVolumes enables the designer to apply algorithms that explicitly shape the point set, and to directly see the implicit effect on the point set’s Voronoi diagram. However, since the resulting geometries are always implicitly defined, in order to individually relate further parametric geometric operations to individual elements of the geometry derived from the Voronoi diagram, the original point set has to be fixed. This makes it difficult to further develop Voronoi-based designs without dismissing their parametric, malleable nature. Possible ways of relating explicit descriptions of desirable shape manipulations of Voronoi diagrams, without sacrificing malleability, form a wide field which has not yet been researched from an architectural point of view.

SmartVolumes makes use of adapting (additively weighted) Voronoi power diagrams in real-time. A similar iterative, adaptive Voronoi diagramming method has been developed R. Reitsma, S. Trubin and S. Sethia (Reitsma, 2004), for regionalizing an information space based on a set information items with given locations and predetermined area. This regionalization method is an application of multiplicatively weighted Voronoi diagrams, and intended for visualization optimization, not interactive design exploration during an open-ended adaptation process. Applications of multiplicatively weighted Voronoi diagrams and other generalizations of Voronoi diagrams for explorative design techniques like SmartVolumes yet have to be investigated.

In its current implementation, on contemporary workstations, the application of SmartVolumes in real-time is limited to several dozen volumes. With more elements, the geometry becomes too complex not only to compute within time, but also to transfer to the graphics processor. Within the near future, similar real-time design exploration techniques should be expected to be not only available but also more applicable in office situations as the computational power of desktop workstation increases.

4.6 Conclusions

With SmartVolumes, a novel use for Voronoi diagrams in computer aided architectural and urban design has been developed. Two practical applications have been made which show the high potential of the technique, in conceptual urban design and in architectural design, bridging from the conceptual phase directly to the planning phase. Other applications, for example in interactive architectural environments, structural and environmental design, have been described in theory and should be investigated in the near future.

Acknowledgements

This article presents a technique developed for the author's Master of Science final thesis project BehaviourLinks :: Urban Mode which was made at Hyperbody , the educational program and research group at TU Delft. Hyperbody is directed by Prof. Ir. Kas Oosterhuis, who has proven to be a very insightful and supportive mentor. The thesis is created as part of Hyperbody's efforts to realize the group design environment Protospace, which is installed in the iWeb building at the department of architecture of Delft University of Technology.

This article also describes an application of this technique in the Digital Pavilion Korea project of ONL (ONL, 2006), office of Kas Oosterhuis and Ilona Lénárd.

The basic principle of the BehaviourLinks environment was inspired by a data exchange course given by Bige Tunçer of the Building Technology department of the Faculty of Architecture.

The SmartVolumes technique, and the BehaviourLinks design environment were to equal parts implemented in the Virtools game development environment and Visual C++. The fast computation of three-dimensional Delaunay Triangulation and Voronoi Diagrams was originally tested using VTK, the open source Visualization ToolKit C++ library (Kitware, 2015). Eventually CGAL, the Computational Graphics Library (CGAL), was chosen for its wider range of features and robustness. Sylvain Pion and Monique Teillaud of INRIA Sophia Antipolis have been very helpful hosts on the CGAL User Mailing List.

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5 SpaceQueries

Pointcloud-based multi-directional real-time Swarm Architecture design exploration

This article has been previously published in the proceedings of the *15th International Conference on Virtual Systems and Multimedia*: Friedrich, C. (2009, 9-12 September 2009). SpaceQueries Design Toolset - Pointcloud-Based Multi-Directional Real-Time Swarm Architecture Design Exploration. Paper presented at the 2009 15th International Conference on Virtual Systems and Multimedia (VSMM 2009), Vienna, Austria.

ABSTRACT An important application of virtual reality environments in architecture are real-time design environments. In this article, a tool set for architectural design exploration based on swarming point clouds is presented. The toolset consists of the BehaviourLinks method to shape the point cloud, the SpaceQueries method to map the space spanned by the point cloud as a relational graph of geometric entities given by its partitioning, and the SpaceQuery method for deriving subsets of geometries from the SpaceGraph. All method can be applied simultaneously or in turn, resulting in a tool which allows for multi-directional design exploration. Ways of representation of and interaction with the complex spatial data contained within the tool set are discussed.

KEYWORDS Architecture, Design Exploration, Real-Time, Voronoi Diagram, Delaunay Triangulation

5.1 Introduction

The presented toolset is a real-time design application developed within the Hyperbody agenda of Swarm architecture. In Swarm Architecture as defined by Kas Oosterhuis, “the essential components of every building construct, is a swarm of reference points, which are in the process of building relations with each other. [...] I do consider the development of any building construct – from furniture to the city – as an informed swarm of relatively stupid reference points behaving in real time” (K. Oosterhuis, 2006) [1]. A building is thus seen as an assembly made of interconnected, communicating and dynamic components. This assembly is open to change not only in terms of shape, but also topology. It is important to notice that the swarm paradigm be applied to material constructs by the use of building-embedded ubiquitous computing, sensors, actuators and media.

The SpaceQueries tool set is a real-time virtual design environment developed for explorative swarm architecture design. Real-time design tools offer the possibility to steer and control an iterative adaptation while it is taking place. The adaptation can be seen as optimization to a goal defined by programming code, the user can steer in real-time which the parameters of adaptation, the initial condition and the applied code are at any given time.

5.2 SpaceQueries Tool Set

5.2.1 Introduction

The presented toolset is a combination of three operations which are built one upon another. Starting with a point cloud, the first operation forms a point cloud by behavioral rules, forming a spatial layout. In the second operation a spatial partition is derived from the point cloud, not only as geometry but as SpaceGraph, i.e. as relational database which keeps track of the relationships of geometric components of the partition. The SpaceGraph is a topological basis for the creation of geometry. The third operation, SpaceQueries, searches the SpaceGraph for geometric components in specific user-defined neighborhood relationships, and returns the resulting geometry subset. All three operations are executed in real-time and simultaneously. The designer immediately sees the outcome of the rules set on each operation and can explore design solutions. Modeling is no longer push-button interaction but turns into a game in which the design continually adapts and the designer interacts in an immersive flow. In the following subchapters, all three operations will be described in detail.

5.2.2 Point Cloud Shaping

There are three basic ways behaviorally shape point clouds. For one the point cloud can be in its entirety or parts laid out by a top-down algorithm. Then, each point can be given individual or instanced behaviors which let it move in regard to circumstances external and internal of the point cloud. External circumstances can be attractors or repellors, internal circumstances can be contiguous and avoidance behavior between points. Another way is to link specific individual or group of points behaviorally, establishing virtual neighborhood next to the spatial one. While the first two may be known well, the third is mainly applied in special cases where the application is evident, e.g. for particle spring systems, yet tools which contain the operation as a generic operation used to apply diverse behavioral linkages are rare.

The behavioral linking method has been formalized in the BehaviourLinks modeling tool [2]. A BehaviourLink is a script that takes data from one point as input and changes data in another point as output. In the modeling environment BehaviourLinks are visualized as links that can be laid between selection sets of points, setting up the pointcloud as a parametric assembly. When the properties of one point are changed, the entire network of behaviorally linked points changes accordingly.

The SwarmCad tool set by Tomasz Jaskiewicz (K. Oosterhuis, Friedrich, H.C., Jaskiewicz, T.J., Vandoren, D., Pool, M., Xia, X., 2008) combines both individual behavior and behavioral linking approach in one system.

5.2.3 SpaceGraph

How can we use the point cloud to construct building geometry? The solution chosen in the presented tool set is to take the point cloud as basis for a mapping of space and spatial relationships, shown in figure 5.1. This map has two constituents. The

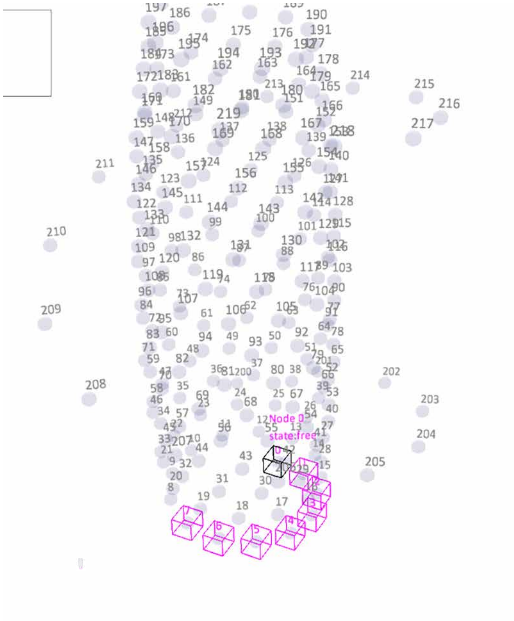
TOC

first is the Delaunay triangulation, shown in figure 5.3, which is partitioning the space inhabited by the point cloud into tetrahedral chunks, which have each four of the points as corners. This partitioning is filling the convex hull of the point-cloud completely, and contains structures which can be achieved by connecting points to their nearest neighbors. The second constituent is the Voronoi Diagram, shown in figure 5.2, which is the dual diagram of the Delaunay triangulation. The Voronoi Diagram is partitioning space into areas which are dominated by a point each. The Voronoi diagram is partitioning space up to infinity, and again the Voronoi cells do not overlap and fill the space completely. Therefore both space partitions have an important property: all solutions are non-intersecting, as they would be in the material world. The SpaceGraph contains all geometric elements of both Voronoi Diagram and Delaunay Triangulation, points, edges, surfaces and volumes, the topological map of the connectivity of all these components to each other.

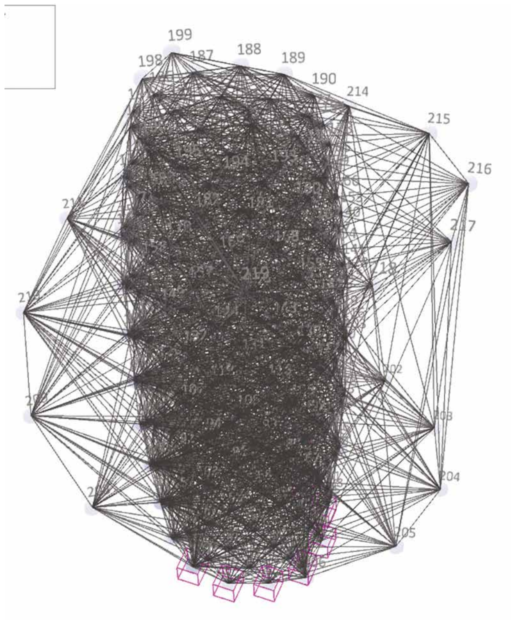
The SpaceGraph does contain both charts of point-cloud space. The main difference to geometric construction of the diagrams as already available in modeling programs is that all it generates and updates linked lists of all relationships of the space spanned by the point cloud in a relational database. These are relations regarding all geometric elements of the partition, e.g. which volumes are neighbors of one another, which surfaces are between these volumes, which lines form these volumes, which the points at the ends of these lines. This database does work in any direction between these constituents, for both the Voronoi Diagram and Delaunay triangulation. SpaceGraph is not just a graphic representation, it is a complete virtual relationship map which is updated in real-time.

5.2.4 SpaceQueries

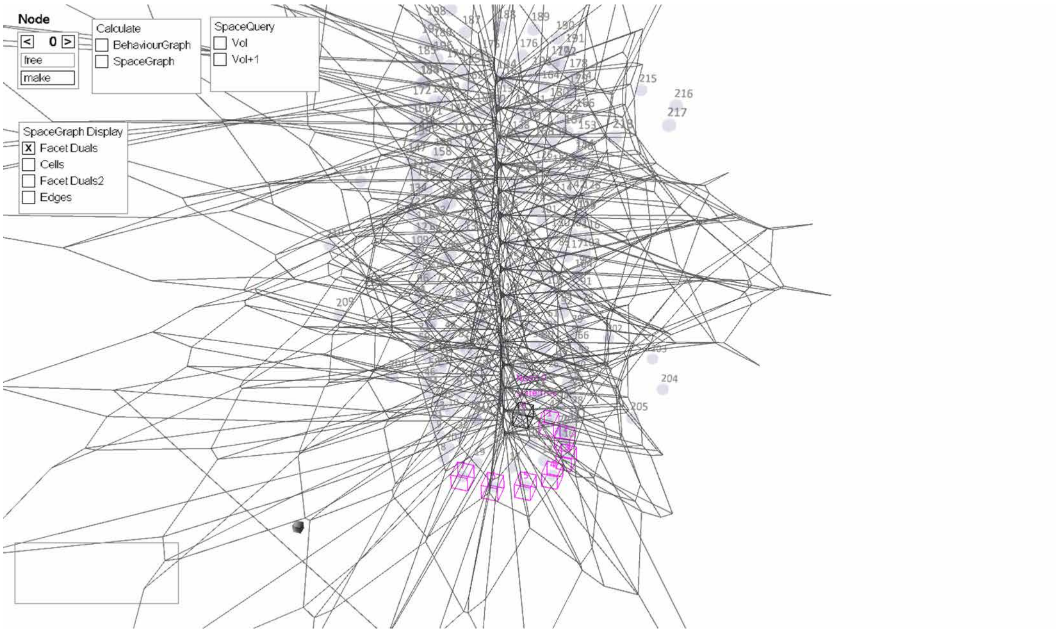
th Voronoi Diagram and Delaunay Triangulation the designer receives a space fully filled with undifferentiated geometry, which is very coherent in appearance, proportion and angularity. This makes it very hard to continue working on the resultant geometry with other tools, a break of the continuity will occur. Furthermore, distilling from the diagrams the needed geometry becomes a very hard time-consuming endeavor, especially as within the diagrams all faces are connected to other faces, all edges are meeting points of several possible surfaces. For these reasons, in any application of these diagrams, the designer has to have a method of marking, traversing and differentiating specific subsets of the SpaceGraph.



1 Point cloud for spatial layout

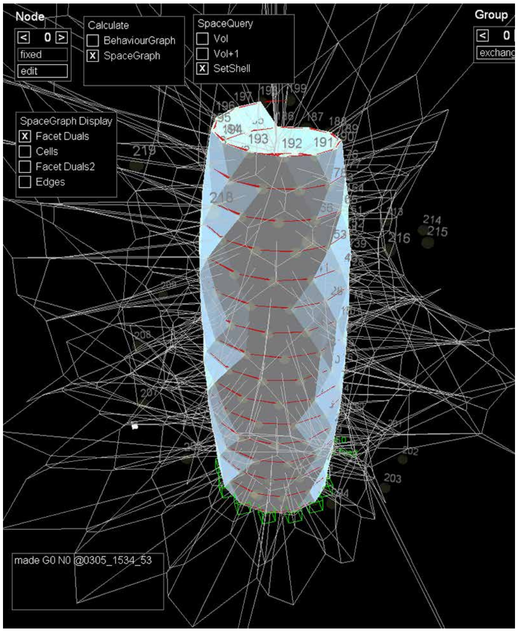


2 Partial visualization: only Voronoi Diagram edges

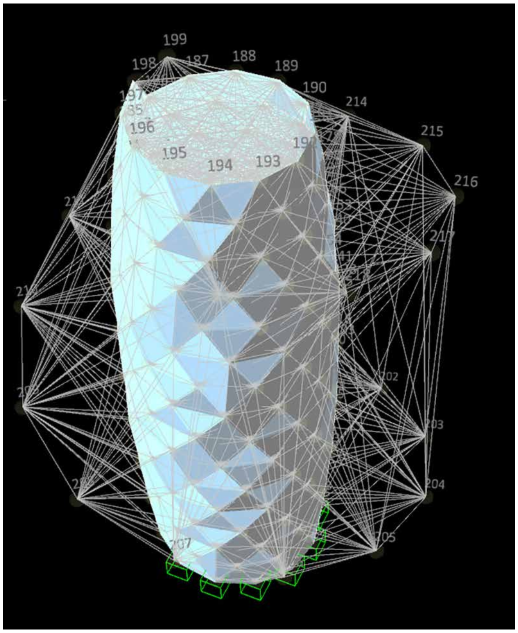


3 Partial visualization: only Delaunay Triangulation edges

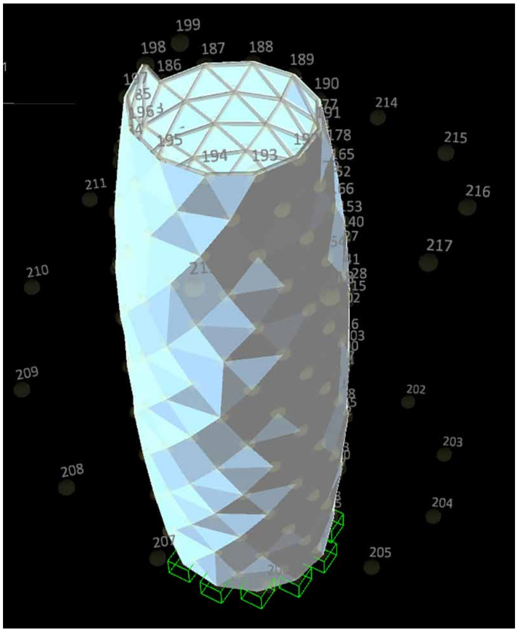
FIG. 5.1 SpaceGraph



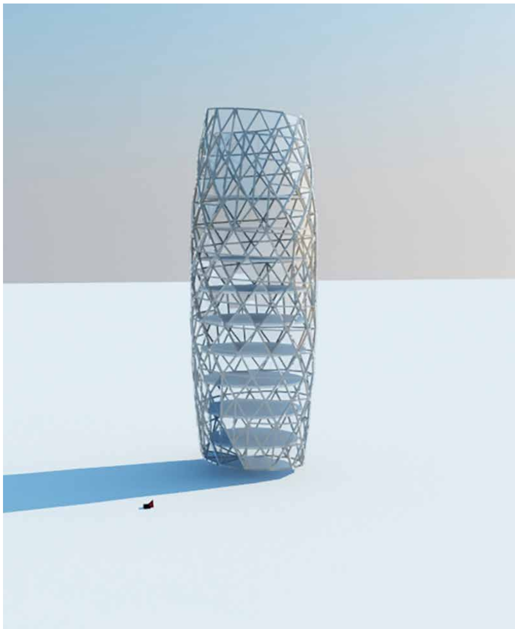
1 Point Cloud modeled with BehaiourLinks, resulting Surface



2 Surface with Delaunay Triangulation shown for reference



3 Surface and beams



4 Rendering

FIG. 5.2 SpaceQueries - Point cloud modelling, SpaceGraph generation, geometry extraction by SpaceQuery, Several tools which contain such a differentiation within diagrams based on differentiation within the point cloud have been previously presented, yet each they follow only a fixed set of rules related to specific projects (Friedrich, 2007). The SpaceQueries tool generalizes the differentiation of SpaceGraph components in a direct manner. Starting from a set of points of the point cloud, based on either their position or their additional properties, the entire SpaceGraph, seen as a relational database, can be traversed with a specific search, a database query, which is looking up components of the SpaceGraph which are related to the original point set in a certain manner.

5.2.5 Example

In the example given in Figure 5.2, the point cloud is consisting of two differentiated sets of points. To the SpaceGraph of this point-cloud a specific query is submitted, which is selecting of cells all the Delaunay triangulation which have three vertices of one group and one vertex of the other group as corner points. From these cells, then the faces which have only vertices of group A are selected. This results in a subset of the entire geometry present in the SpaceGraph, which is just the surfaces which are on group A and bordering on group B. A second query is requesting only the edges of this surface. In this manner, surface and beams for possible structural elements are derived from the SpaceGraph. As this action is taking place in real-time simultaneously with the BehaviourLink adaptation and the SpaceGraph calculation, valid design solutions within the applied rule-set can be explored in a multi-directional manner.

5.2.6 Technical Realization

The presented design tool is developed in Virtools ("Virtools, a Behaviour Company,"), which is by origin a game development environment. Virtools is applicable for developing real-time design tools as it has an accessible graphic scripting interface, which can be used to change parameters even when a game is running. The environment is natively coupled to a game engine, which is handling a 3D environment and executing behavior in real-time within a game loop.

Within Virtools and in specifically written C++ code which was wrapped in Virtools building blocks, the possibilities of Virtools were extended for complex geometries and data handling. The real-time calculation of the Voronoi Diagram and Delaunay

Triangulation is partly based on the CGAL library (CGAL, 2015), and extended with custom-made code where CGAL does not offer calculation of the entire diagrams as needed here for representation.

5.2.7 Visualizing Spatial Depth

Visualizing point cloud and to a far grater extent visualizing partitions of space with the complexity of SpaceGraphs is a challenge to the implementation of any virtual environment. Point clouds lack any visual guidance to depth, unlike 3D surfaces which follow curves and can be shaded. There are several techniques employed to inform the user working on a 2D display about the spatial shape of the point cloud. Commonly used techniques are fog, which makes points further away blend away in the background, or slow rotation of the camera around the point cloud. Additionally, graphic representation of SpaceGraph components can greatly help see the spatial depth of the point cloud, and also to recognize features within, as occurring lines, concentric configurations, regularities.

For visualizing manipulation of point cloud elements, a point-cloud gizmo has been developed which from the centre of gravity of the point cloud proposes a level indicated by centered disks, from which lines go up or down to the exact location of points. While this visual help cannot deliver the instant recognition a stereoscopic 3D display could offer, it operates as a ruler and allows the designer to see the relative position of points.

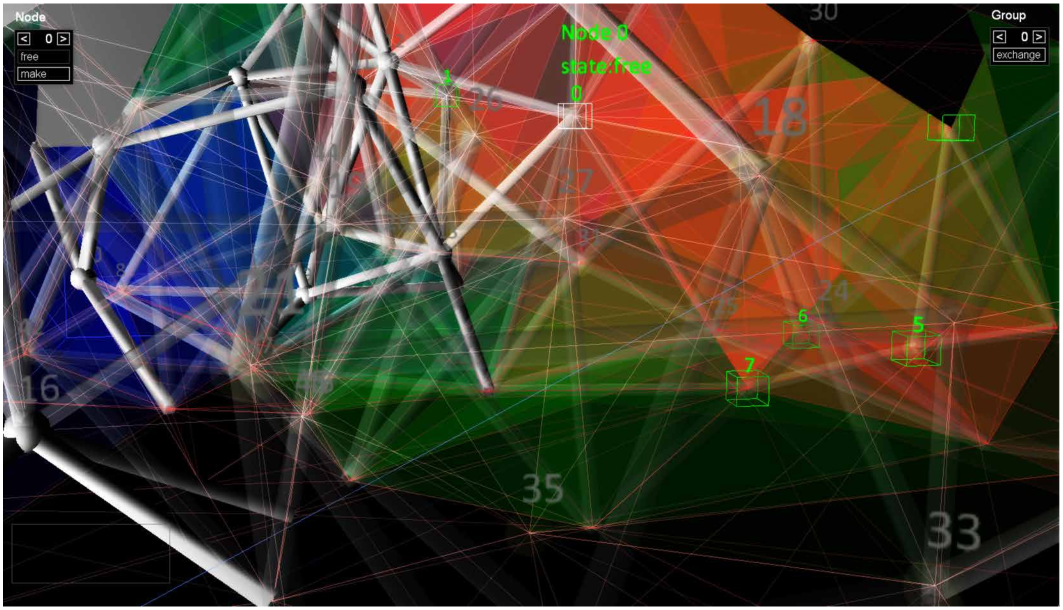


FIG. 5.3 Visualization of depth of a partitioned space

5.3 Discussion

5.3.1 Depth of Space

A point cloud is a set of unconnected, unstructured points in space. The very nature of it is that it is lacking structure and the interesting part about it is that is open to application of various structure and partitions of space to lay onto it. In this sense, point cloud modeling is about positioning and shifting points in space, to form clouds of different shape and distributions. The purpose of a point cloud modeling is spatial layout in the most general sense. Structures on the point cloud are to be established in another mode of operation, topological modeling, which may be lead by the point cloud layout to achieve certain kinds of structures of overall shape of the design.

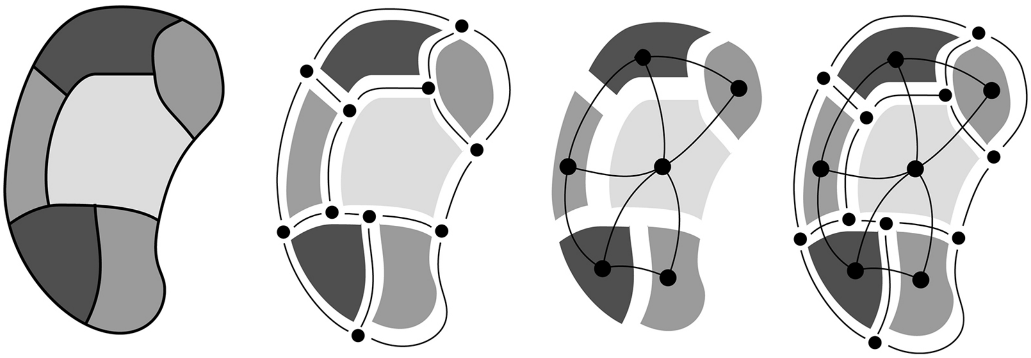


FIG. 5.4 Dee p Space in two dimensions: a) Spatial assembly, b) points, interrelated lines and shapes as elements of spatial topology, c) representation of topological connectivity of shapes only, d) overlay

The topology of a building is set up of the interrelation of its elements, relations which are subject to strict mathematical law. This is ‘law for the construction of space’, as already indicated by Bill Hillier in his work on space syntax (Hillier, 1985). In his analysis of the spatial structure of houses, Bill Hillier introduces depth as a property, meaning that to go from one room to another it is necessary, i.e. not merely possible, to pass through intervening rooms. This law for the construction of space does not only operate for the relationships of rooms to one another, it is ruling the connectivity of all elements of Deep Space. Figure 5.4 illustrates these relationships in two-dimensional space, in three dimensional space the involved elements include volumes next to points, lines and surfaces. A spatial assembly in two dimensions, 5.4-a, is given by its shapes, the lines which lie between these shapes and the points at which these lines are connected, 5.4-b. The assembly is also set up by the graph of connectivity between the shapes, 5.4-c, which is equivalent to the relations analyzed by Hillier in the before mentioned article. Next to this exist the graphs of connectivity between lines and points, and the connectivity graph of relations between instances of all different types of elements. A complete spatial graph would contain all this information, which is only partially displayed in 5.4-d for sake of clarity. Only a model which is aware of the complete topological connectivity of the model lets the designer truly operate in deep space. In such a model, in order to reach one point from another, one has to pass either along a network of lines connecting points, or possibly over surfaces which the lines bound, or through volumes given between these surfaces. While any of these relationships could be applied in order to traverse through deep space and collect elements of a specific degree and quality of connectivity, only a model of space which updates the presence of these connections in real-time and allows us to explore them at any moment at will, is fit for a design tool that lets us effectively operate in deep space.

The concept of Deep Space is implemented in the presented tool set as model which contains and updates this information, and allows the designer to traverse and query the network of relationships in qualitative and quantitative formulations of depth. For the modeling process leading to the spatial assembly, the shaped point cloud can be interpreted as either the edge points of the assembly elements and as connecting nodes of the topology graph.

SpaceQueries is a whole allows the designer to interact with a tool that is aware of these relationships in spatial depth, and to perform modeling operations derived from it.

The term topological modeling insinuates that the connectivity of the components of a building can be modeled independently of their eventual geometry. When the topological connectivity model is stretched and twisted without breaking its topology, we are exploring possible geometry instances which are all part of the same topological model. Yet topological modeling only takes place when we purely model the connections themselves, which can but does not have to change the result of geometric shape. Geometric modeling in this way is built on the topological model, that serves as flexible reference framework.

In the SpaceQueries tool set, the SpaceGraph serves as complete topological map of a spatial partition. From this topological model, a SpaceQuery can derive a selection subset to realized as designed geometry.

5.3.2 Multi-Directional Design Exploration

In the presented tool set, with the use of BehaviourLinks, SpaceGraph and SpaceQueries, the design space can be explored in a multi-directional manner. For one the spatial formation of the point-cloud can be defined by applying BehaviourLinks to the point cloud nodes. These BehaviourLinks are links which represent scripted algorithms that can be executed in real-time. A simple example of this functionality is a particle-spring system set up with BehaviourLinks which make on node keep distance to another node. Independently of this possible real-time adaptation, the SpaceGraph which contains relationships of geometric features, i.e. the interrelation of nodes, edges, faces and cells, of the spatial triangulation and partitioning derived by the point cloud with a distance rule. This relationship graph can be updated to a new configuration of the point cloud. This update process can also take place in real-time. Finally, the SpaceGraph can be searched by SpaceQueries, which are queries of the relational database given by the SpaceGraph in order to collect and select sub-sets of the geometric features in the space graph.

All three modeling operations, which are execution of BehaviourLinks, calculation of updated SpaceGraph network and SpaceQueries for feature subsets of the SpaceGraph, can take place independently of each other and simultaneously in real-time. This allows the user of the toolset to explore in any preferred sequence of simultaneously the form, structure and feature sets of the design. An example is given with the design for a high-rise building, illustrated in Figure 5.2. At the start of the game a point cloud set is generated, in which the points are related to each other by BehaviourLinks. The behaviors cause them to form the shape of a helix, and to keep a defined horizontal distance to each other. As boundary for the spatial partition, a second set of points is placed with similar rules but greater helix radius around the first helix. From both subsets of the point cloud, the SpaceGraph is calculated, and a SpaceQuery is placed which contains as result only faces which are part of volumes spanned by partitions which are formed between the two subsets of the point cloud, and which have only points of the first subset on their perimeter. As a result, from the point clouds a façade design for a high-rise building is generated, which is however by no means final. Now the design can be further explored, be either deforming the façade structure derived from the space graph and filtered out by the SpaceQuery, which can be at any point in time accompanied by updating the SpaceGraph and a new SpaceQuery.

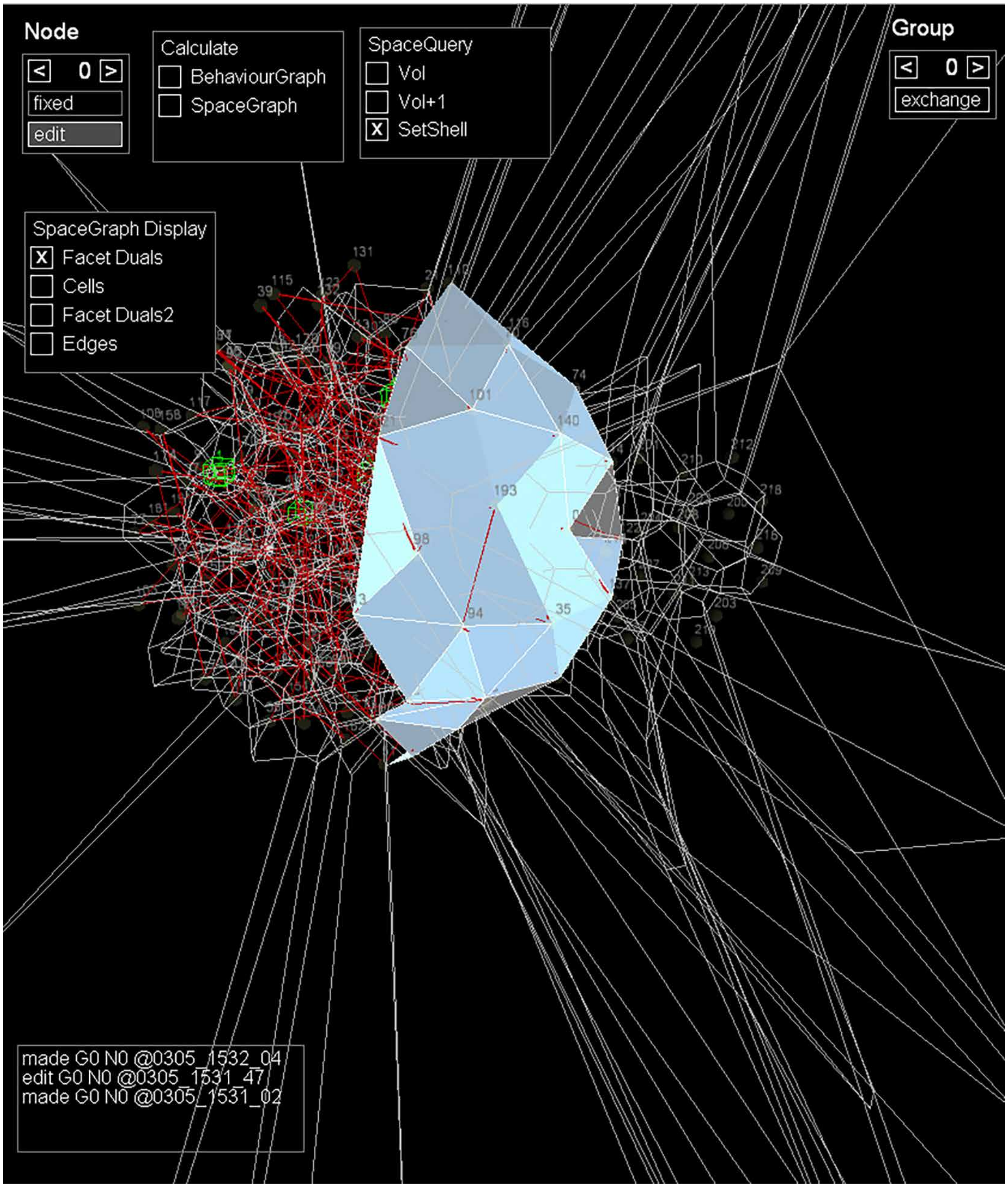


FIG. 5.5 The toolset with interface. BehaviourLinks pointcloud shaping in red, partial SpaceGraph indication in grey, a surface resulting omr a SpaceQuery in blue.

5.3.3 Conclusions

SpaceQueries is not only a tool supporting a radical strategy for architectural design, but also a challenge for developers of virtual reality environments. As the design software employed by architects develops away from the tools developed for virtual simulations, towards tools which can actually behave closer to the nature of material and social constructs, and contain actual calculation of space beneath the visualized surfaces. The issues which arise in representing these dynamic spatial models in a comprehensive manner and the ways in which users can efficiently interact in the construction of meaningful designs are only partly touched in the development of the presented toolset. Therefore, while being a novel development of its own account in the area of architectural design software, in the domain of virtual reality applications it should be recognized as incentive to further investigate possible improvements.

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6 Protocology

Interactive integration of robotic architecture and non-standard fabrication

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ABSTRACT

Modular spatial robotics and architectural designs built of CNC-fabricated unique components are two emergent technologies by which digital control, computation and communication affect the construction and constitution of the built environment. They are specific techniques in the larger fields of respectively interactive architecture and non-standard architecture.

The ProtoCology system combines both techniques in order to at least partially solve the *human-architecture mismatch*, which is the incapacity of buildings to change at the speed and to the extent we desire. It is aimed at an ongoing dialogue between users and built environment, by interaction, reconfiguration and fabrication. The system consists of a real-time virtual model for fabrication and interaction control, a *streaming fabrication* pipeline, a database for tracking individual components, and intelligent building components.

6.1 Introduction

Bert Bongers calls the *Human-Computer Mismatch* (Bongers, 2004), the lack of exchange between human minds and computer programs due to the inefficiency of physical interfaces. In analogy, we can speak of the Human-Building Mismatch, as the incapability of buildings to conform to personal, social or environmental needs to the extent and at the speed we desire. As stated by Miles Kemps, "Our current static environments are predetermined, and grossly under-performing in the potentials they can offer their users." (Kemp, 2009)

Both HCI (Human-Computer Interaction) and HBI (Human-Building Interaction) are affected by the disappearing computer. Computers are becoming increasingly small, networked, distributed and embodied in our environment. New kinds of physical interfaces that widen possibilities of building interaction have to be developed. On this overlap of HCI and HBI we locate robotic architecture: buildings with embedded components that sense, process, actuate and most importantly can be cooperative and interactive.

ProtoCology aims to resolve the human-building mismatch. It is developed to enhance capabilities of users and designers to improve the performance of their built environment with minimal effort, anytime, immediately. *ProtoCology* is a real-time system encompassing all phases of the architectural process – use, design, construction including fabrication – as un-sacrificing strategy to integrate robotics and architecture.

ProtoCology is not primarily developed to be 'self-organizing', 'self-building', 'self-reconfiguring' or 'self-replicating'. Instead, it is aimed at a dialogue between architectural system and users. Three different modes of physical building interaction can be engaged by users:

- **Interaction** with an assembly of robotic components as-is,
- **Reconfiguration**, i.e. the possibility for users to manually re-assemble a set of components in a different configuration, thereby changing structure, shape and interactive performance
- **Fabrication**, on-demand and rapidly, of additional components of non-standard shape and performance

The last mode, on-demand non-standard fabrication, is necessary for any modular robotic system to answer to architectural design. It allows design of form and structure beyond the limited degrees of freedom system with a limited vocabulary of quickly available component types. Also, it will have to be employed whenever an additional component of specific shape or function is needed for a design update. For this strategy to unfold its full potential, the fabrication process should ideally take place as fast as existing components can be repositioned, it should be not just rapid but immediate.

6.2 Precedents

6.2.1 Overview

As robots are universal tools, their application in architecture is varied. They find use in the design process as aids for digitizing data and as kinetic models. They are used for fabrication of building components; where next to specialized machines for CNC (computer numerically controlled) fabrication robotic arms as used in the automotive industry are employed. They are used in the assembly of buildings. And finally, a building itself may be robotic, either as a whole or because some, many or all parts of a building are robotic devices. While robotic architecture is generally understood as term for the last category, buildings with embedded robotic devices, the range of already employed robotic applications in the entire architectural process – use, design, build – indicates that the application of robotics in architecture may blur the distinction between phases of the architectural process.

Robotic Architecture may be a contradictory term. While 'robot' suggests a spatially and functionally autonomous entity, architecture relies on the holistic relationship – pars pro toto – between (robotic) parts and entire building design. ProtoCology is an attempt to maintain the autonomy of robotic components, without sacrificing freedom of architectural expression. It also is an investigation in architectural qualities that may emerge from a marriage of architecture and robotics:

- **Embodied, not representational design medium**
  Robots are not a medium but an embodiment (physical presence/ autonomous agents).

- **Blend of design, use and assembly phases**
  Robotic architecture blends use, design and assembly phases of the architectural process. Fabrication needs to be in the picture so architectural quality is not sacrificed.

In the following subchapters, several aspects of ProtoCology shall be approached from reference projects

6.2.2 Modular Spatial Robotics

Modular spatial robotics is the research field of robots which can be connected to form larger structures that behave according to the capabilities and programming of the incorporated robotic components. Examples for such projects are the Self-Replication Module by Cornell Computational Synthesis Lab (Zykov, Mytilinaios, Adams, & Lipson, 2005), M-Tran 1, 2 and 3 by Distributed System Design Research Group at AIST (Kurokawa et al., 2008), Claytronics by the Claytronics Team at Carnegie Mellon (Claytronics) and Metamorph by Miles Kemp (Kemp, 2009).

These projects are developed as generalist systems of just one type of part, with the intention to eventually be built at much smaller scale, probably even nano-scale, as constituents of smart matter. They are however developed in absence of current practical applications or concrete architectural or furniture designs that could result. In contrast, ProtoCology as system is designed for specific use cases. It lets users decide whether they want to achieve a specific assembly state by activation of dynamic components, reconfiguration of existing components or fabrication of additional components of specific shape and performance. A combination of these adaptation methods would be most efficient in day-to-day use.

6.2.3 Seamless Non-Standard Fabrication

While it is not a robotic architecture project, m.any (Bonwetsch et al., 2005), an ETHZ graduation project from 2004/5, is presented here exemplary for the abundance of projects in which mass-customized production of building components with a CNC machine allows direct materialization of a real-time generated flexible digital model. The project is an early example of a non-standard fabrication setup which creates a space-filling structure, which is flexible in terms of geometry as well as topology and in which each part is unique. While m.any is a shining example of non-standard design and production, such structure is not ideal for reconfiguration: any change of the structure requires fabrication of new components, since each of the components is fabricated for its unique topological and geometric neighborhood. Reconfiguration in this case becomes feasible only when the fabrication process can be executed very quickly.

6.2.4 Accessible reconfiguration

"*The Reconfigurable House is an environment constructed from thousands of low tech components that can be 'rewired' by visitors. The project is a critique of ubiquitous computing 'smart homes', which are based on the idea that technology should be invisible to prevent DIY*" (Somlai-Fischer et al., 2008). This project makes a statement for user accessibility. While the possibilities of self-organizing robotic structures are intriguing, in order to solve the human-building mismatch a robotic structure has to be open to manipulation and extension by its users.

The Reconfigurable House is a striking example of *layered* reconfigurability. The interactive layer is visually and experientially foregrounded and can be directly modified by the users, yet the structural layer of the exhibit, a steel storage shelf, is not intended to be modified by the users and is kept in the background. ProtoCology strives for a system in which performative layering is not predetermined, but subject to change.

6.3 Case Study: ProtoCology

6.3.1 An applied, integrated system

In Hyperbody's 2009/10 MSc2 studio Immediate Architecture, the hybridization of Interactive and Non-Standard Architecture was taken to a higher level. The assignment was a response to the real world observation of intended and actual use of protoSPACE, Hyperbody's real-time collaborative design environment.
In protoSPace 3.0, lack of an intermediate layer between interactive building envelope and work places lead to employment of regular furniture, which resulted in suboptimal use of the interactive environment. Therefore the project assignment was to create an architectural system for the support of design sessions in protoSPACE. This system should allow adaptation of protoSpace to match diverse team design situations and spatial settings. Students were instructed to develop a reconfigurable assembly of interactive components. Following concise assignments they developed interactive scenarios and made designs for environments based on specific interactive interventions. Concurrently to the architectural design of the environment, they were instructed to develop the protoCology system for its production, maintenance and behavioral control.

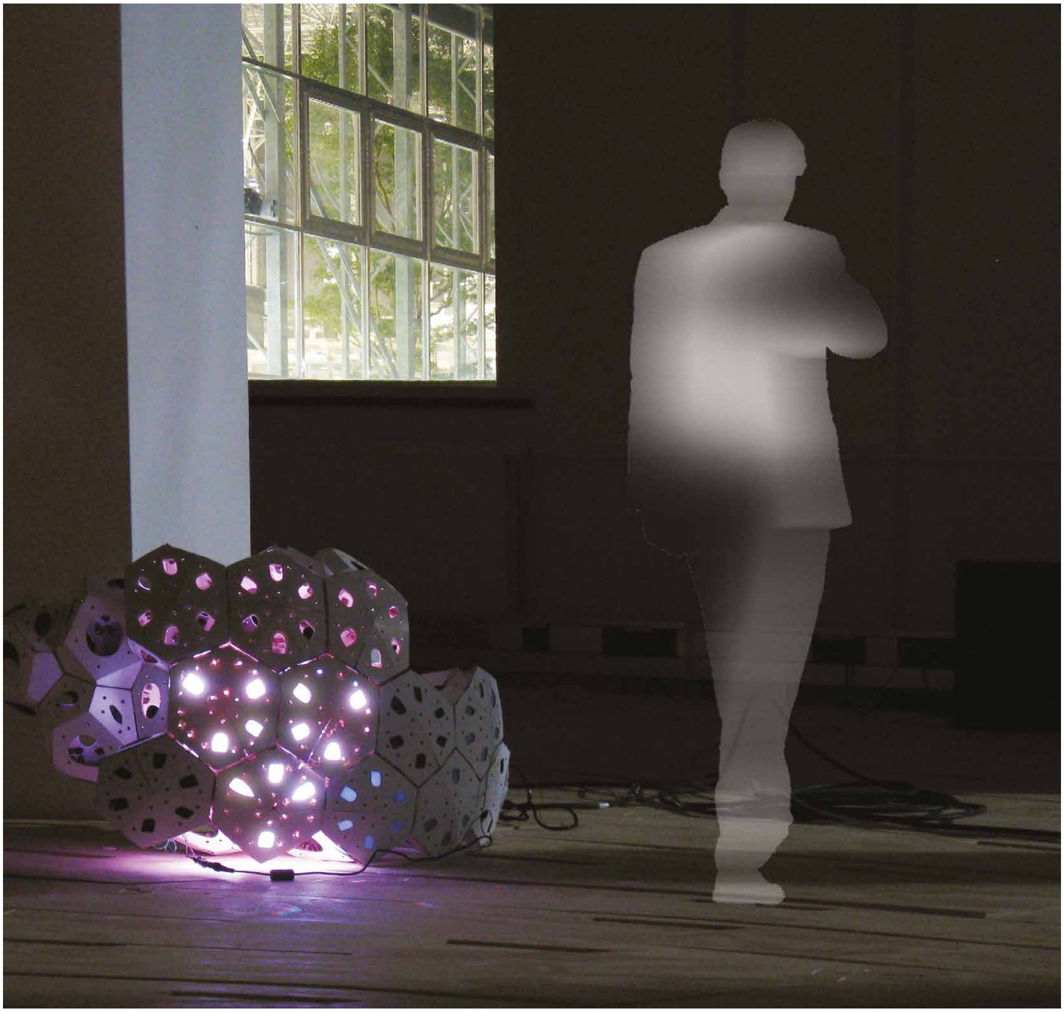

FIG. 6.1 ProtoCology assembly in ProtoSpace.

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6.3.2 System development

Design sessions are complex processes in which unpredictable social behavior and design proposals may arise. In such dynamic activities an interactive adaptive environment could positively influence teamwork. With this idea in mind, the students analyzed their collaborative design processes. Real-world design sessions were video documented and reviewed for key moments in which the design team collaboration could have profited from an interactive intervention. From this analysis emerged a series of interaction intervention proposals, which were evaluated for feasibility and commonalities. In the end, a basic set of interactive components which could be combined to give supportive interactive interventions in several situations was found.

Independently from the design studio timeline, technological development took place in parallel strands of iterative improvement of all constituents of the system. From the very start of the semester students were asked to continuously produce components, to improve the fabrication process and the material aspects of the components, and to expand component performances for interaction and reconfiguration. With this fabrication and development setup, students iteratively explored alternatives for materials, connections, interactive performances. A real-time behavioral design model was gradually integrated into the fabrication stream. Goal of the technological process was integral optimization of the component system for interaction, for reconfiguration, and even for on-demand fabrication as strategies for immediate architectural adaptation.

Out of different the time-scales of adaptation arises temporal complexity. Building lifecycle, component lifecycles, and continuous adaptation in use necessitate means to trace the life-cycle for each individual component. This life-cycle trace functionality would help to sustain functionality of a protoCology assembly, and even when applied to conventional non-intelligent components it would improve sustainable building maintenance.

These considerations regarding rapid on-demand fabrication and component lifecycle tracking, lead to the development of the assembly as digital material hybrid. Hybridization takes place by linking digital model and material components at each stage of a component's lifecycle:

- A real-time virtual model generates visualizations for assembly, geometries for fabrication geometry and offers a control interface for interaction,
- A streaming fabrication pipeline enables rapid on-demand manufacturing of components,
- A database tracks component data and lifecycle, and
- Intelligent building components are actively communicating with model and database.

Digital structure and material structure of the system are connected bi-directionally and remain connected throughout design, construction and interactive reconfigurable use. Design and construction become integral part of interactive use and adaptation.

FIG. 6.2 Reconfiguring the assembly

6.3.3 Component geometry

A prime consideration in the development of the system was to achieve balance between easy reconfiguration and component differentiation, a balance which affects both shape and interactive performance of the environment. A system which allows only one component form and type, for example cubes, would maximize reconfiguration possibilities between components since any component could be combined with any other component following the standardized cubic symmetries. In such a super-standardized system freedom for architectural expression and meaningful combination of interactive components however are limited. Besides, one standardized component type will hardly suffice to address all needs that arise in the construction of an entire building. When she relies on standardized components, the architect has to include different types of components for differentiated performances - for example, special types for floors, walls, doors, and windows. And then still, a good portion of the standardized components has to be trimmed to fit within the building geometry. Therefore the chosen strategy was to develop a system that by default is irregular. In order to compensate for the loss of recombination possibilities in a set of irregular components, a technique for rapid on-demand fabrication of components is integrated into protoCology.

The digital model of a protoCology structure has to generate robust fabrication geometry, without sacrificing the range of possible shapes. It has to be useable as real-time interaction control, as fabrication modeler and it has to be capable of tracking the structure of the assembly as it is reconfigured. These diverse functional requirements were met with a "flat" modeling method, in which three-dimensional components were derived from points of a point-cloud. In the model, based on Delaunay Triangulations and Voronoi Diagrams, all of space is subdivided into parts and each part can be either empty space or a component. In this topological model, each point owns a part of space. The location of the point and its neighborhood is used for construction of a geometrical model of the point's part of space. This modular yet topologically flexible model of space was expected to be adequate to the speed of interaction and to the continuous permutation and open-ended extension of a collection of components.

A new component in this system does not have to be constructed, since it is already defined as a chunk of space. It only has to be defined by changing the boundaries between this chunk of space and its neighbors.

In the developed protoCology system, the component pattern without external or design influence is that of Weaire-Phelan cells. This pattern fills a given volume with foam with the least material. In this sense, the basic Weaire-Phelan pattern is as generic to foam-like space filling system as a sphere is to a soap-bubble or a cube is to salt crystals. The modeler expects space to be filled with this pattern up to infinity, unless it is diversified by design interventions.

The digital model was implemented in the development environment Virtools. The model allows users to create and change assemblies using both already generated components found in the StreamLog database and components which are to be fabricated and have yet to be defined.

6.3.4 Interaction design

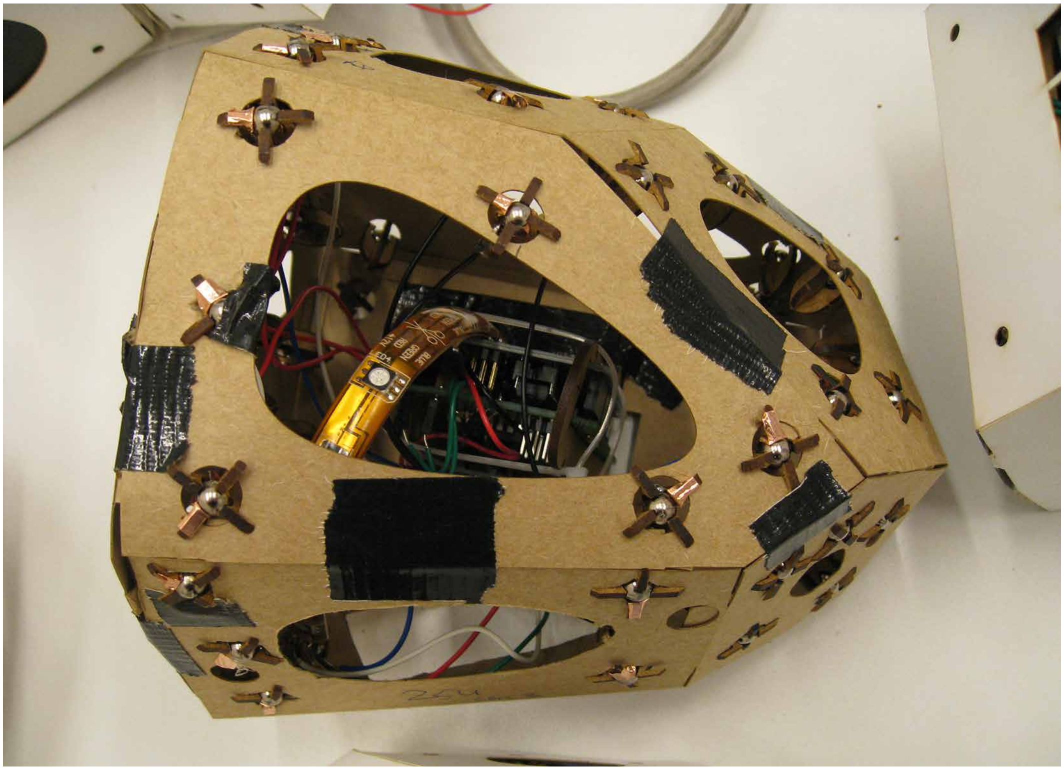

FIG. 6.3 Component Interior

Based on video analysis and real-life experiences, several interaction scenarios were developed. These scenarios consisted of an explicit design for the shape of the assembly, and the distribution and function of interactive components within this shape. All proposed scenarios were evaluated against three criteria; the spatial qualities of the design, how it supports team communication and how it connects the physical environment to digital design space. The balance between these criteria shifted per proposal. For example, proposal The Cloud would descend from the ceiling and allow users to pull down vortexes of intelligent components which would suck up and distribute design data, while the cloud would visually express data streams and conflicts. Movable Rock (Figure 6) on the other hand focused more on constructive and spatial aspects. It looks like a cave, into which users can dig intimate places, surrounded by roots and crystals.

For different types of components, diverse interaction modalities were proposed relating to all human senses. Sensor components could register sound and even speech patterns, brightness, proximity and movement of users (Figure 7), touch, whether they are connected to each other and whether they are shook or turned. In prototypes, all of these sensing modalities were implemented except for speech pattern recognition. Proposed modalities for output components were light, sound, movement, vibration, wind and even olfactory. For these output modalities technical plans were made, however during the semester only light and sound were realized in prototypes.

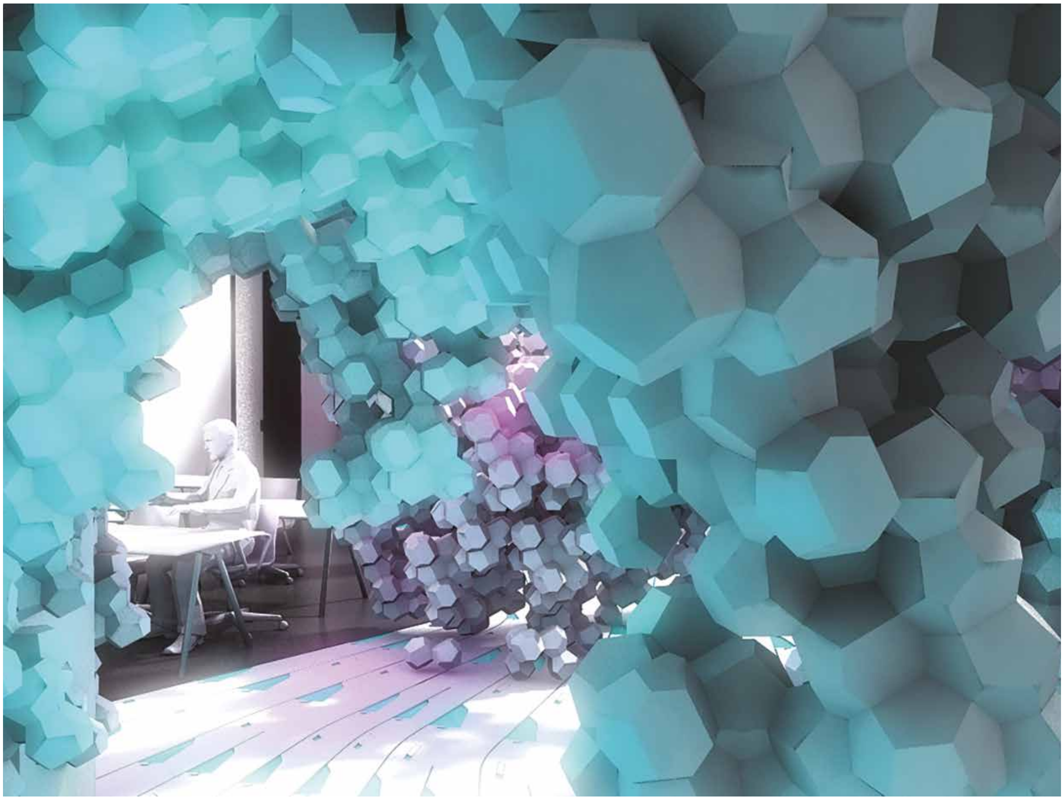

FIG. 6.4 Moveable rock interaction scenario (by Bao An Nguyen Phuoc)

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ProtoCology components connect magnetically. Therefore be attached and removed from an assembly without the use of any tools or fixtures. As soon as they are attached, through the magnets they receive power from their neighbors in the assembly and start to communicate with their neighbors, immediately contributing to the interactive performance of the assembly. Users can put together and modify a component structure with ease, and with a simple set of components many diverse configurations can be achieved. Replacement of defunct or outdated components becomes trivial.

When combined in clusters, components of different kinds form functional units which can perform interactive interventions. Proposed interventions were to welcome arriving team members, to let users model data by reconfiguration and visualize results, to provide ambient display extension for presentations, to give visible feedback on speech patterns occurring in discussions and lectures, and to serve as controller either by recognition of user position and gestures or as hand-held controller.

The possibility of kinetic structures was considered. To equip the already intelligent components with servo motors would have been a trivial action. Yet, in the chosen geometry and fast reconfiguration environment, the development of meaningful structural movement requires more development time than was available, for two main reasons.

The first reason is the possibility of manual reconfiguration, which was found to be more direct and interactive while introduction of axes of movement needed for mechatronic actuation was found to be limiting at this early stage of development. Kinetics however is a logical extension of the capabilities of the protoCology system and should be added in future reincarnations of the project.

The second reason is the chosen geometry, which is space-filling and expects irregularity. Only directed, planned interventions would generate symmetries along which kinetic movement can take place. Besides, protoCology's geometric approach is to cut up three-dimensional space into parts. A, actually space-filling structure is more affected by kinetic behavior than e.g. a one-dimensional beam which can be bent or a two-dimensional surface which can be easily folded. While one- and two dimensional structures are naturally part of the chosen three-dimensional approach and any one- or two dimensional solution could be applied to respective elements of the chosen structure, to the developers of protoCology implementation of kinetic movement would have made sense only if it addresses the volumetric nature of the component logic.

FIG. 6.5 Interaction by gesture

6.4 Conclusion

protoCology is an explorative research project on hybrid modalities of human-building interaction. In a protoCology environment, mechatronic interaction is placed beside tactile reconfiguration and allocated rapid fabrication of interactive components. Goal of the project is to establish an architectural environment in which all three building interaction modalities as equally approachable, effortless, fast and cheap. With the protoCology system realized over a semester, a new component could be modeled in real-time and fabricated in about half an hour at a cost of €15 for structural and €40 for interactive component prototypes. While fabrication time and cost could definitely be improved, ProtoCology components already exhibit an impressive range of build by use performances. While choice of adaptations and its modality are up to the user's input, the protoCology system guarantees that desired interventions are sustainably and seamlessly executed. The protoCology system is generated and adapted in interactive use, showcasing the potential of robotic architecture. Robotic building interaction encompasses design, fabrication and construction as the constituents of the environment offer the affordances to be built and adapted by use.

Acknowledgements

The project was a case study for the author's PhD research on Immediate Architecture, which is aimed at resolving the human-building mismatch with ways to build, use and design near the speed of human desire. ProtoCology was developed during the 2009/10 winter semester MSc2/BSc6 course 'Non-Standard and Interactive Architecture', and would have been impossible without the commitment of collaborating colleagues and students:

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- MSc2 Students: Sander Apperlo, Gerben Knol, Rene-Paul van Leeuwen, Michel Stienstra
- BSc6 Students: Frank Brunschot, Igor Leffertstra, Marjolein Overtoom, Bao An Nguyen Phuoc, Jasper Schaap, Jaimy Siebel, Wilson Wong
- Programming Expert: Vera Laszlo
- Interaction Expert: Mark-David Hosale
- Fabrication Expert: Marco Verde

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7 Conclusions

In this thesis, both theoretical and experimental contributions on Immediate Systems (IS) in Architecture were presented, together with the argument that their implementation as HiLCPS radically improves applicability of the concept. The experiments presented in chapters 4 to 7 investigated this hypothesis by design.

Even though technology extends the reach of human action, in its use humans encounter constraints not only of physical nature but also of systemic design and socio-cultural convention. This implies that even the most advanced Immediate System will not change this fundamental condition. Nonetheless, the presented research on IS was an attempt to afford their users a better human-technology match, a near-optimal state of immediacy where humans can both use and design, apply and amend the technological system they engage with.

7.1 How the research was framed

The theoretical introduction of the thesis was formed by chapters 2 and 3. Here the concept of Immediate Systems is introduced, framed, and situated in the field of architecture.

7.1.1 Introducing Immediate Systems (IS)

In chapter 2 (Friedrich, 2020b), the notion of Immediate Systems (IS) has been introduced and framed as Human-in-the-Loop Cyber Physical Systems (HiLCPS), which include people and environments in a tight loop between human intention and immediate adaptation. IS were determined to embed design and implementation in situations of use, overcome limitations of remote design, offer a form of direct manipulation interaction style, leverage the psychology of both Immediacy Effect and Flow Experience. Additionally, IS were described through the lens of Gibson's

Theory of Affordances. Characteristics and conditions of IS were distilled from the presentation and discussion of a series of examples, most notably that they offer a specific sense of awareness, guidance, intimacy, embeddedness, mastery and essentially should allow for conceptual re-framing.

7.1.2 Application in Architecture

In chapter 3 (Friedrich, 2020a), the application of IS in architecture was approached from three angles. First, from the lived perspective of a user-designer: as adhocist mode of action. Second, from the methodology and technology, as accelerated design transfer. Third, in an ecological perspective, as human-architecture symbiosis.

Each of these readings was hypothesized to be more feasible with the ongoing digital revolution, with the emergence of ubiquitous computing and with cyber-physical systems. New Adhocism was determined to be no longer dependent on make-shift solutions, as constituents of the environment have increasingly innate affordance for systemic reconfiguration. Acceleration of design transfer was hypothesized to shift architectural praxis from a sequential process towards a network of simultaneous activities. A Human-Architecture Symbiosis was said to emerge as a reading of HiLCPS with the agenda of making the built environment more adaptive and responsive.

7.2 Experimental prototypes that were developed

In the design of the prototypes of IS, the development of IS took place on multiple scales. Firstly, on the scale of the entire series of experiments, where each prototype included another step in the architectural process of initiative, analysis, design, fabrication, construction, use and reconfiguration.

On this largest scale, the challenge was to establish a continuum of immediate interactions across the entirety of the architectural process. The leading hypothesis was that once the system as a whole is established, all previously consecutive

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phases take place simultaneously, shifting all order and causality between them. In the engaging with an IS, it would still be possible to first design, then fabricate, then construct, then use. But in an IS, fabrication is use the system for fabrication and design exploration. A reversal of the entire chain of phases and activities would be equally valid: reconfiguration of the system is its ultimate use in order to construct, for which ongoing fabrication of parts is updated, which leads to formulation of the design, which is an exploration of the real-world situation, which directs intention.

On the scale of individual prototypes, each in itself embodied an IS. The developed prototypes were described in chapters 4-6.

The prototypes proposed automated yet malleable solutions for transformations that occur within and between the phases of the architectural process. One example introduced ways to collect information and data from the environment to inform the design. Another one presented ways to organize and structure this information conceptually. Yet another framed ways to establish on basis of this information rules for the creation of shapes in space, geometries constrained within the solution space expressed as design rules. Furthermore, it explored different modalities for adaptation of the built environment, firstly as sum of changes of interactive building elements, secondly as reconfiguration of an assembly of elements, thirdly through the manufacturing process of new elements, and fourthly through the tracking of their life-cycles. Ultimately, the system was a prototype a human-environment interface for directing all of these transformations.

7.2.1 Topological-volumetric modelling

In chapter 4 (Friedrich, 2007), the SmartVolumes modeling tool set was discussed, an IS that supported conceptual architectural design in virtual space. Within the tool set, BehaviourLinks allowed the user to express their design intention in terms of conceptual objects, their location and relational behavior to one another. BehaviourLinks was an adaptive, executable semantic network. In this semantic network, conceptual design objects were the nodes, which were pure data containers. The links in the network were executable scripts which were directed from one node to another and transform form the data in the nodes. While the user could establish a network of relations between the design objects, SmartVolumes was an algorithm for constructing building masses in divisions of contiguous space that was implicitly defined by this layout. The Smartvolumes algorithm served to transform the conceptual design objects, abstract collections of data, into objects in space, objects which had geometry, shape and form.

The tool set allowed the user to add known or proposed design parameters and explore the solution space these offer, interacting in real time, with the freedom to adjust any variable at any point in time. Hence it allowed the user to change the goals it optimized towards as integral part of the computation of the optimal. The user-designer acted in the loop of the optimization process.

Several applications for the Smartvolumes tool set were shown. For urban design BehaviorLinks :: Urban Mode, with extensions that allowed the user to simultaneously explore the program of demands, volumetric plan, traffic models, parametric spatial relationships, shared volumes, facade styles, plan boundaries, and urban data affecting each other, with direct visual feedback and embedded media of the actual site. As integral part of the control of interactive environments it was proposed for the Digital Pavilion project of ONL, its integration in a digital design and production system was prototyped at the Streaming Fabrication workshop at UTS Sydney, and as a combination of both interactive environmental control and production system it was integrated in the final prototype, protoCology, the description of which followed in chapter 6.

7.2.2 Multi-directional design exploration

In chapter 6 (Friedrich, 2009), SpaceQueries was presented, a successor of SmartVolumes that had advanced capabilities for extracting geometric features through topological queries of the Voronoi and Delaunay graphs that were used in the computation of SmartVolumes. In this way, SpaceQueries allowed for multi-directional design exploration, where the user could change components, the topology of their connections and the the overall design geometry they form, both implicitly and explicitly, simultaneously.

7.2.3 Adding robotic fabrication and reconfiguration

Chapter 7 (Friedrich, 2011) described work on protoCology, a complete IS prototype that encompassed the entire architectural process. Utilizing the SmartVolumes tool set for geometry generation, as part of a digital design and fabrication system, interactive components were built and connected. The components contained microprocessors, sensors, lights, speakers and actuators. They could be connected to form assemblies and communicate through the connection points. The life cycle of all built components, from inception to fabrication to assembly, interaction and ongoing reconfiguration of the assembly, was tracked in a database that was connected to the SmartVolumes tool set.

The prototype was built to establish a dialogue between architectural system and users, who could engage with it in three modes of physical interaction with the built environment:

- Interaction with the assembly of robotic components as-is,

- Reconfiguration, i.e the possibility for users to manually re-assemble a set of components in a different configuration, thereby changing structure, shape and interactive performance

- On-demand rapid fabrication of additional components of non-standard shape and performance.

7.3 Discussion

7.3.1 Layers

An overarching theme of the presented work has been to connect separate systems as to form supersystems where activity spaces that were previously remote to one another would allow for direct manipulation from end to end. For example, the practices of design, construction and use can be seen as separate systems that are connected in IS. From a technological perspective, different types of systems can be found in either interactive environments, reconfigurable environments, or in environments that support instant construction. The developed Prototypes were incremental attempts to combine these into one IS.

The question arose whether connecting multiple systems into one continuum would not necessarily add up constraints and failures from all constituting subsystems. Was the quest for more immediacy a zero-sum game, or even worse, did optimization of the supersystem toward immediacy for certain courses of actions result in a situation which was more rigid and unchangeable? After all, the principle of shearing layers (Brand, 1994) constituted that traditional buildings can adapt because they allow slippage of layers, and the principle of pace-layering (Brand, 1999) even advocated a layer arrangement that allows for maximum adaptability.

Following those principles, IS should work best if they are made of multiple systems that do interact with one another casually, which are loosely coupled and exchangeable. The innovation brought by IS then would be that they offer opportunities to re-arrange the shearing layers. In the traditional model, layers are formed by a structural hierarchy of physical building elements. In the application of IS architecture, the structural function of those physical bodies would be affected by possibilities of actuation, and mapped to the physical objects there exist structures of communication and computation, which connect to them for example sensors, actuators, robots, building components, production and construction devices. Hence, a new model of shearing layers could be obtained.

Throughout and across the traditional physical layers, IS could be established as layers that allow slippage between them. When IS encompass both service and structure layers, the IS themselves could become the layers between which shearing can occur. This would still follow the reasoning of the shearing layers principle, as faster layers would not be obstructed by slower ones. Thus, IS could operate in real-time but at different speeds, next to one another, in the same environment, and alongside the traditional model.

7.3.2 Scales

The rearrangement of layers is also reflected in terms of scale. Material components are scaled in metric size and mass, computational scaling is determined in connectivity, communication bandwidth, processing power. In IS implemented as HiLCPS, these different concepts of scaling connect, and time scaling gains importance. The pace layering principle suggests to layer IS onto the environment by time scale. At the fastest scale, direct interaction via sensors and actuators, on intermediate scales in-place fabrication, on-site fabrication and assembly, an on more remote timescales systems that include off-site fabrication.

7.3.3 The human in the loop

In this dissertation, IS were investigated as technological systems with the human in the loop. From the perspective of that human, the system is an extension of the body, of the self. The appeal of such systems is that they can be pleasurable to interact with. They can empower users, who are embedded in the environment and engage in a holistic experience.

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TOC

Curriculum Vitae

Christian Friedrich was born in Germany and commenced studies in Physics and Philosophy in Berlin, only to switch country of residence to the Netherlands and discipline of study to architecture. After obtaining a degree as architectural engineer in Groningen, he completed his graduate education in architecture at Delft University of Technology. From 2002-2012, he was working at Kas Oosterhuis' Hyperbody group, as student assistant, researcher, and PhD candidate. During these ten years, he taught technical and design courses on bachelor and master level, gave workshops and lectures, and built prototypes which were exhibited across Europe and beyond. Since then, he has accumulated more than a decade of hands-on experience in design and development of serious games, parametric tools, and interactive environments. He has been involved with start-ups in various disciplines and helped to develop innovative products to market-readiness.

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Immediate Systems in Architecture

Continuous adaptability at the speed of human intention

Christian Friedrich

The presented research on Immediate Systems in Architecture (IS-A) is an attempt to afford a better human-technology match in architecture, pursuing a state where humans can simultaneously use and design, apply and amend the technical system they engage with.

The thesis contains both theoretical and experimental contributions on IS-A. Initially, the notion of Immediate Systems (IS) is introduced and framed. IS offer interaction in the style of direct manipulation, embed design and implementation in situations of use, and overcome limitations of remote design. IS are related to psychological concepts and described through the lens of Gibson's Theory of Affordances. Characteristics and conditions of IS are distilled from the presentation and discussion of a series of examples.

The application of IS in architecture is approached from three angles. First, from the lived perspective of a user-designer, as adhocist mode of action. Second, from the methodology and technology, as accelerated design transfer. Third, in an ecological perspective, as human-architecture symbiosis.

Following the method of research by design, prototypes were developed in a series of experiments. The experiments result in multiple tools for real-time multi-directional volumetric design exploration that allows users to interactively model and ad-hoc reconceptualize parametric geometry, topology and components of architectural assemblies. A combination of these tools with digital fabrication and interactive building components lead to the most encompassing IS-A prototype, an attempt to realize an open-ended building system that joins simultaneous design, adaptation, construction and reconfiguration as interaction possibilities embedded in the built environment.

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