

## **protoCology**

### **Integrating Modular Robotics and Non Standard Fabrication**

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#### **Biography**

Christian Friedrich was born in Germany. After studies of Physics and Philosophy in Berlin and completion of an architectural engineering degree at Hanzehogeschool Groningen, he finished his graduate education (MSc) in architecture at Delft University of Technology, Netherlands. He co-founded media artist collective Ezthetics, is part of Hyperbod and has worked on projects for architectural office ONL. Christian is currently immersed in his PhD thesis research "Immediate Architecture - How to design, build and house near the speed of human desire"

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### Integrating Modular Robotics and Non Standard Fabrication

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#### Abstract

Modular robotics and architectural designs built from CNC-fabricated unique components are two emergent research areas in which technologies such as integrated parametric design and fabrication, digital control and mechatronics affect construction and (re) configuration of built environments. These two areas belong to larger fields of research, interactive architecture and non-standard architecture, respectively. protoCology is a system that combines both fields to at least partially solve the human-architecture mismatch<sup>1</sup>, which is seen as an incapacity of buildings to change at the speed and to the extent user's desire. The protoCology system is aimed at establishing an ongoing dialogue between users and built environments by means of interaction, reconfiguration and CNC fabrication. ProtoCology 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.

#### Introduction

Bert Bongers defines the *Human-Computer Mismatch*<sup>1</sup> as a 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 at speeds that users may desire. As stated by Miles Kempers, "Our current static environments are predetermined, and grossly under-performing in the potentials they can offer their users."<sup>2</sup>

Both HCI (Human-Computer Interaction) and HBI (Human-Building Interaction) are affected by the *disappearing computer*. Computers are becoming increasingly small, distributed, networked and embodied in our environment. New kinds of physical interfaces establish spatial adaptation as modality of building interaction. On this overlap of HCI and HBI we locate robotic architecture: buildings with embedded components that sense, process, actuate and most importantly interact and cooperate.

ProtoCology is not primarily developed to be *self-organizing*, *self-building*, *self-reconfiguring* or *self-replicating*. The goal is to establish a dialogue between architectural systems and users, within which the experience of autonomous action may emerge. With protoCology, different modalities of physical building interaction can be engaged by users:

- **Mechatronic Interaction** with an assembly of robotic components as-is,
- **Tactile Reconfiguration**, i.e. the possibility for users to manually re-assemble a set of components in different configurations, thereby changing structure, shape and interactive performance
- **Allocated rapid fabrication** of additional components of non-standard shape and performance as requested by users in specific situations in their unique environment

Along these lines, *protoCology* is an attempt to sketch a solution to 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, and immediately. ProtoCology is a real-time system encompassing all phases of the architectural process – use, design, and construction, including fabrication, – as consequent strategy to integrate robotics and architecture.

## Precedents

### Overview

Robots are versatile tools with diverse applications in architecture. In the design process they can aid the digitization of existing spaces and serve as kinetic models. They can be employed to CNC (computer numerically controlled) fabricate of building components, and in construction robotic arms as known from the automotive industry are employed in the assembly of buildings. A building may contain embedded robotic devices or act as a robot in its entirety. Robotics can be present in the entire architectural process, following the lifecycle of a building from design and construction to use and adaptation.

Robotic Architecture may seem a contradictory term. While *robot* suggests a spatially and functionally autonomous entity, architectural design establishes mereologic relationships between performances of robotic parts and the whole of the building they constitute. ProtoCology is an attempt to maintain the autonomy of robotic components, without sacrificing qualities of architectural design.

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

### Modular Spatial Robotics

In Modular spatial robotics robots are connected to form larger structures that behave according to the combined capabilities and behaviour of the incorporated robotic components. Examples for such projects are the Self-Replication Module by Cornell Computational Synthesis Lab<sup>3</sup>, M-Tran 1, 2 and 3 by Distributed System Design Research Group at AIST<sup>4</sup>, Claytronics by the Claytronics Team at Carnegie Mellon<sup>5</sup> and Metamorph by Miles Kemp<sup>2</sup>.

These projects are developed as generalist systems in which just one atomic type of robotic component is used. They are however developed in absence of current practical applications or concrete architectural or furniture designs. In contrast, ProtoCology as system is designed for a specific use case, as environment that supports group design sessions by adapting to spatial needs that arise from both design process and team formation. Users can choose the modality of adaptation. A specific assembly state could be achieved by activation of dynamic components, by reconfiguration of existing components or by fabrication of additional components of specific shape and performance.

### Accessible reconfiguration

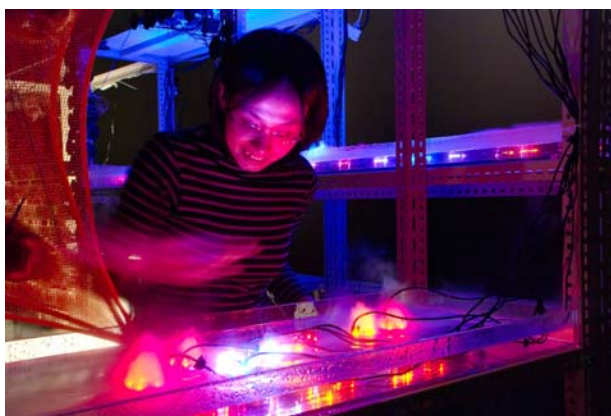


Figure 1: Reconfigurable House, Adam Somlai Fischer e.a. <sup>7</sup>

While the possibilities of self-organizing robotic structures are intriguing, in order to solve the human-building mismatch a robotic structure has to be directly accessible to manipulation and extension by users. The Reconfigurable House (Figure 2) is an example for such user-adaptable interactive environments:

*“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”<sup>7</sup>.*

The Reconfigurable House is an example of *layered* reconfigurability. The interactive layer is accessible 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 and kept in the background. In the protoCology system, performative layering is less predetermined and can be subject to change.

### **Seamless non-standard fabrication**

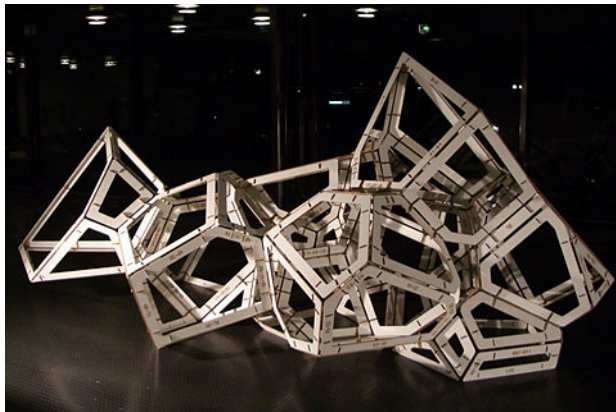


Figure 2: m.any<sup>6</sup>

m.any (Figure 1)<sup>6</sup>, an ETHZ graduation project from 2004/5, is just one example out of the abundance of projects in which mass-customized production of building components with CNC machines allows for direct materialization of a real-time generated digital model. The project is an early example of a non-standard fabrication setup which creates a space-filling Voronoi diagram structure that is flexible in terms of geometry as well as topology, and in which each part is unique. The lack of symmetries in such a structure denies reconfiguration by permutation of existent parts. Since each part is made to measure for its unique topological and geometrical neighbourhood, change of the structure requires fabrication of new components. In such a structure, reconfiguration becomes feasible only when the fabrication process can be executed very quickly.

## **ProtoCology**

### ***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 behavioural control.

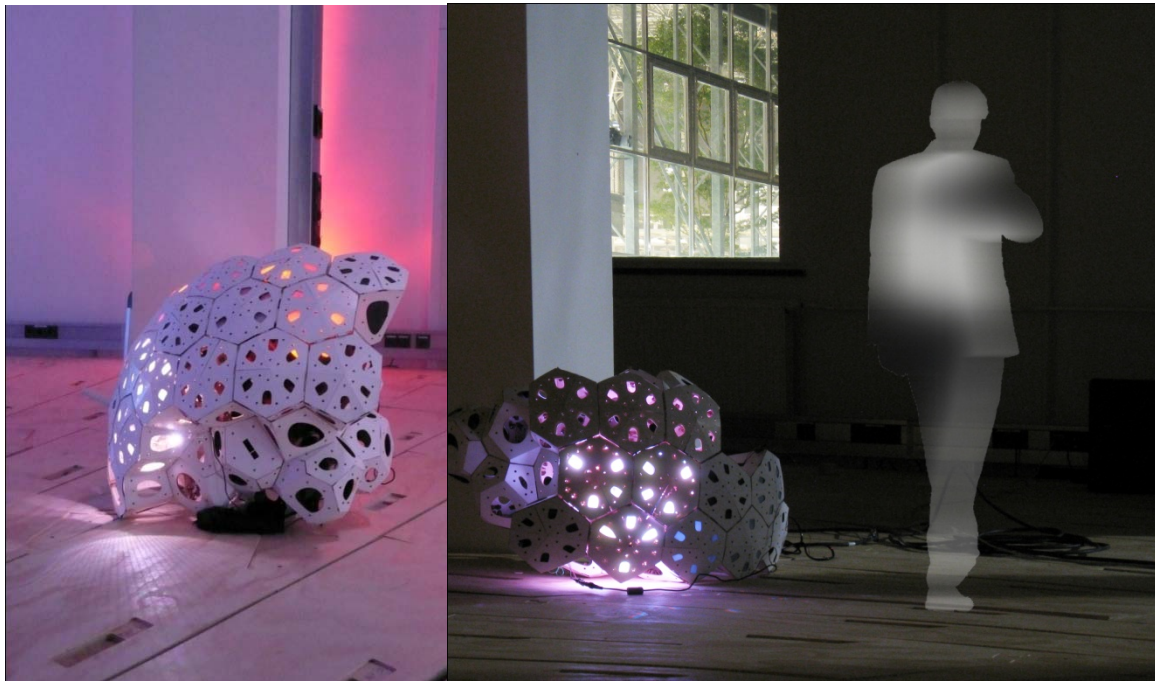


Figure 3: ProtoCology assembly in ProtoSpace

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.



Figure 4: Reconfiguring the Assembly

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 neighbours in the assembly and start to communicate with their neighbours, 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.

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.

### **System development**

Design sessions are complex processes in which unpredictable social behaviour 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 behavioural 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.

### **Component geometry**

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 modeller 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' modelling 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 neighbourhood 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 neighbours.

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 modeller 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.

### **Interaction design**

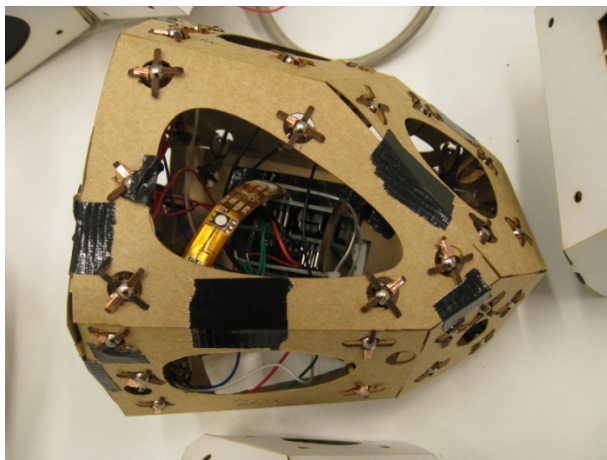


Figure 5: Component interior

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.



Figure 6: Moveable Rock - Interaction scenario

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.



Figure 7: Interaction by gesture

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 behaviour 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.

## 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. 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. A protoCology environment is generated and adapted in interactive use. This building interaction encompasses design, fabrication and construction – the entire environment is literally *built by use*.



With the protoCology system realized over a semester, a new component could be modelled 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.

## 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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