**USING HARDWARE CELLULAR AUTOMATA TO SIMULATE USE IN ADAPTIVE ARCHITECTURE**

CHRISTIANE M. HERR
*Department of Architecture, The University of Hong Kong*
*ydnac@graduate.hku.hk*

THOMAS FISCHER
*School of Design, The Hong Kong Polytechnic University*
*sdtom@polyu.edu.hk*

**Abstract.** In this paper we give an account of our development of a hardware machine-readable cellular automata model for simulating dynamic patterns of use and adaptation in vernacular high-density architecture. In a hypothetical architectural setting that draws its formal expression from illegal façade extensions in Hong Kong and its conceptual framework from the Open Building movement, we examine state evolutions in monotonous matrices of adaptable residential units. The primary objective is to gain a better understanding not only of architectural form but also of dynamic processes in the built environment and hence of the factors that cause adaptive architectures to tend towards different types of overall attractor states. The paper gives a discussion of the project's theoretical background as well as a detailed description of the hardware model and its modes of application.

## 1. Introduction

Cellular Automata and patterns of development and use in architectural and urban design are both frequently described as, or likened to, "complex systems". These systems are dynamically evolving and difficult to model and in this sense similar to the weather or stock markets. Complex systems typically contain large numbers of autonomous elements that interact simultaneously, giving rise to nonlinear dynamics resulting from inherent circular causation and feedback effects. Architects have been fascinated and influenced by the intricate dynamics of cellular automata and other complex systems since related research began to gain strong momentum some twenty years ago (see for example Frazer, 1995; Jencks, 1997). More recently, other fields of study have also begun to explore the analogy between complex systems theory and urban dynamic processes (see for example DeLanda, 2002, p. 71 ff.). Ideas of flexibility and dynamic change in architecture, however, predate the current fascination with complex systems. They have influenced design strategies ever since utopian proposals like the plug-in city by Archigram, Constant's *New Babylon* or Price's *Generator Project* became popular during the 1960s. In the few of these projects that were actually built, however, it proved difficult to establish a building as a platform for continuous change and flexible adjustments as initially planned. As in the case of Kurokawa's *Nakagin Capsule Tower*, basic units were typically designed to be easily movable and reconfigurable, but were rarely changed after the building began to be used. Changeable and adaptable architecture seems to elude traditional planning methods. Despite all intentions, its highly specific components even seem to render "adaptive architecture" less adaptive than conventional structures that are based on more generic planning and materials.

In the context of some vernacular high-density architectures, the dynamics of complex systems are obvious in the way that repetitive, tightly packed living units are constantly altered by their inhabitants. Examples include South American Barrio structures (see Perdomo and Bolíva in Fernandes and Varley, 1998, p. 123 ff.) and Hong Kong "illegal building structures" (Wojtowicz, 1984; Girard and Lambot, 1999). In this paper, we focus our discussion on the latter case since it involves designers and inhabitants as separate groups. In Hong Kong illegal structures, changes occur rapidly due to restrictions in living space coupled with a need not only for additional space but also a desire to convert generic living spaces into personalized homes. The façades of many high-rise buildings in Hong Kong thus become architectural expressions of the dynamics of user needs. This phenomenon is currently disappearing due to increased law enforcement efforts. Precedence nevertheless suggests considerable positive potential of user-adaptable architecture and it is one of the long-term objectives of this research to explore alternatives to the criminalization of this phenomenon.

Complex systems theory describes a limited number of behaviors that can be displayed by systems, called attractors. They include static (point) attractors, periodic, quasi-periodic and chaotic attractors. Similarly, different types of cellular systems have been distinguished based on their behavior. Cellular automata can evolve to homogeneous states, to periodic structures, to chaotic patterns or to complex localized structures (see Wolfram, 1984). As a model for adaptable architecture, such views can be used to account for unexpectedly static performances of buildings that were initially planned to perform dynamically. An understanding of adaptable buildings as complex systems can therefore potentially allow the development of design strategies, which can support dynamic performances of this type of architecture in the future. A necessary first step into this direction is the establishment of an observational and experimental basis upon which to develop the necessary understanding. With this objective we have designed and implemented a physical, machine-readable hardware cellular automata system that models Hong Kong high-density urban living units. The model allows temporally fully decentralized automaton evolution while being simultaneously manipulated on two layers of user interaction, which emulate the open dynamics of contextual urban fabric and computer I/O for programmed manipulation and monitoring purposes. We intend to use the model as an experimental "what if?" machine to generate new questions, and hopefully answers, in the above-described context of dynamic adaptation in high-density residential architecture.

## 2. Re-Configurable Architecture

Our discussion draws its conceptual framework from the Open Building movement, which we apply using a system of re-configurable façade extensions to a façade grid inspired by illegal building extensions observed on high-density residential architecture in Hong Kong. Open Building, as proposed by Habraken (1976) since the early 1960s, is based on the observation that, in order to maintain their quality over long periods of time, residential buildings need to remain open to their inhabitants' initiative. In this sense, Open Building retains elements of 'organically' grown structures, which often emerge without large-scale planning and can typically be observed in slums and squatter areas in places of rapid urbanisation (see Fernandes and Varley, 1998). It therefore bears a potential for reducing overly repetitive monotony in large-scale top-down planned residential building and lack of individuality as also found in Hong Kong.

*Figure 1. Illegal building extensions in Hong Kong; façade evolution*

The Open Building architectural design paradigm has implications for both efficiency and inhabitant-driven diversity in residential architecture. It divides buildings conceptually into support (structure) and infill (interior fittings and removable parts). Since infill elements are determined by the immediate needs of a building's inhabitants, our model follows Habraken's suggestion that these building elements are to be changed and improved by, or in collaboration with, the inhabitants over time, while the support elements are designed to last for a long time without interfering with the changing uses and infill elements. This type of structure allows more dynamic buildings that adapt to the personal preferences and needs of their inhabitants. In the context of high-density architecture as it is found in cities like Hong Kong, the Open Building approach has not been explicitly accommodated.

We use Hong Kong as a design context and as a case study for our scenario since illegal building structures that are commonly found in this city (Wojtowicz, 1984), indicate the desire of inhabitants to change and to adapt their living spaces. A second reason is that in contrast to other adaptive vernacular structures this type of structures involves both designers and users as separate agencies, which makes this model particularly interesting from the perspective of design tool development. Conditions of high density in Hong Kong have shaped a characteristic form of vertical illegal structure, which is cantilevered out from existing building façades to claim additional space for gardens, balconies, storage spaces or entire rooms. While illegal structures result in part inhabitants' attempts to increase the size of their apartments, many of the illegal building alterations are not related to just increasing habitable space. Often, changes are made to existing apartments to express the uniqueness of a particular space and its inhabitants and to create individuality within an environment of highly self-similar repetition of living units and buildings. This type of alteration includes the changing of window types or adding of colors and individual surface finishes to the façades. They also show some attention to ornamental detail as well as general living quality, allowing for example the introduction of plants and birds to extremely dense living spaces.

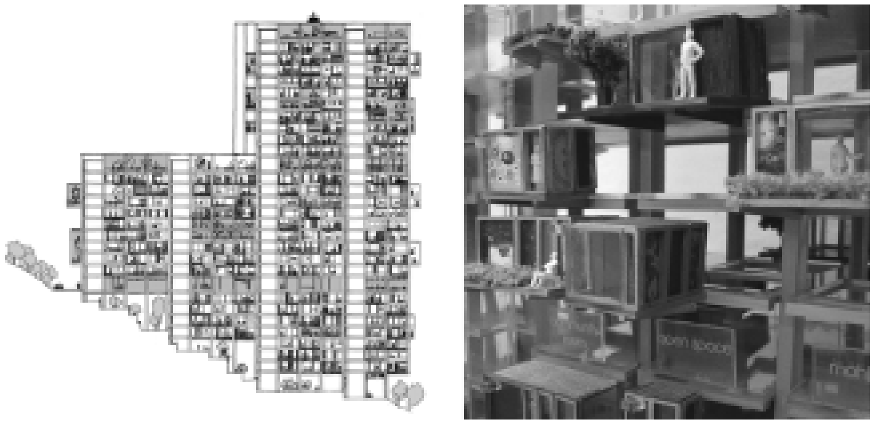

*Figure 2. Vertical Village reconfigurable high-density housing proposal*

The architectural model discussed in this paper is based on a previously proposed *Vertical Village* (Herr, 2003a) for Hong Kong: a high-rise structure that provides a rigid frame structure with completely flexible internal spaces and external additions. The *Vertical Village* building is seen not only as a stack of residential units, but also as a community similar to a village. Flexible unit sizes, removable floors and walls as well as a reconfigurable service infrastructure provide the basis for spatial diversity within the building. On the exterior, inhabitants can change the façade of their flat or add semi-prefabricated extension modules to their living space using a crane that forms an integral element of the constantly changing building. Within the overall structure, a network of small community spaces provides the platform for local neighborhoods, enabling communication between inhabitants. The initial *Vertical Village* project features small-scale variance that arises from the process of inhabitation as an alternative to the monotony arising out of typical top-down planned residential high-rise architecture. With the proposed hardware model, we intend to study the dynamics made possible by architectural settings such as the *Vertical Village* more closely. In the future we intend to make use of the findings of this investigation to potentially confront the common notion that this adaptable type of architecture 'doesn't work'. The reality of vernacular structures in Hong Kong and in other places as well (see Brand, 1994; Habraken, 1998), shows that adaptable architecture can work. Already existing successful top-down planned projects with strong formal references to vernacular generation include Moshe Safdie's *Habitat 67* (see, Wolin, 1974, pp. 62-87), the more recent *Housing Settlement*, *Guanabara Bay* (McGuire, 2000) and the *Ju'er Hutong* rehabilitation (Wu, 1999). The current challenge is to integrate ongoing vernacular dynamics with top-down planning. Recent projects such as *Next21* (Kendall and Teicher, 2000, pp. 126-129) generate increasingly exciting impulses in the field of timeline-focused and dynamic housing schemes.

## 3. Machine-Readable Models and Cellular Automata

In the late 1970s, Frazer began to pioneer research into *machine-readable models* (sometimes also referred to as *intelligent models*) in an approach that understands architecture as an expression of logic in space (Frazer, 1995, p. 45). During the subsequent decades Frazer et al. (1980; 1982) have proposed a series of spatially re-configurable and electronically enhanced systems that could be evaluated and logically manipulated by external computers. Implications of this work range from human-computer interface design issues to CAAD theory and participatory design. As a most prominent example of this work, the *Universal Constructor* is a computer-enhanced three-dimensional system of cubes, which users can stack vertically (plug or unplug) on a baseboard. The system has been used in experimental applications to configure structural or environmental data and a miniaturized successor model has been developed into an interface for a *haptic programming* language (Fischer et al., 2001). Later efforts were aimed at facilitating the explanation and understanding of complex architectural form finding processes (Fischer et al., 2003). Related work has been undertaken at Xerox Parc, following Engelbart's (Engelbart and English 1968) and others' early work on *human-computer interfaces*, in the context of *modular robotics* research aiming at the development of *digital clay* – an ambition that is reminiscent of Frazer's objective to amalgamate physical structures and data structures. Ishii and Ullmer at MIT have developed a series of *tangible interfaces* with the aim of giving physical form to digital information. Further related studies have been undertaken by others in the computer science, human-computer interaction and computer-aided design fields. Excellent overviews of key developments in this field are given by Ullmer and Ishii (2000) and by Marks (2001).

Being electronically enhanced, machine-readable models allow the modeling of tempo-spatial dynamics far beyond the static representations of traditional architectural models. Architectural designs that aim to transcend the traditional notions of "tombs and monuments" and to focus for instance on the dynamics of use and adaptation largely depend on models with these new capabilities. Accordingly, Frazer and his colleagues have supported Price's design of the Generator project as technical consultants (see Spiller, 2002, p. 84-89). Frazer (1995), in particular with the *Universal Constructor*, has integrated machine-readable model development with the cellular automata paradigm in the architectural context.

The purpose of the model described in this paper is to experiment with, to help in formulating new questions about architecture as a complex system to inform processes of design of adaptable architecture. As a classic model for massively parallel dynamic systems, our model applies the cellular automata paradigm. Cellular automata are idealized finite state systems, typically arranged in close-packed two or three dimensional spatial configurations. Neighborhood relationships define communication infrastructures within cellular automata systems and provide a basis for decentralized processes, which result in dynamic automata state changes (see Burks, 1970). The complex dynamics and the spatial properties of these systems have inspired a number of architectural research efforts and design proposals. Nevertheless, in particular due to the tremendous versatility of cellular automata in the computer-aided architectural design field, this area and its implications are still very far from being exhaustively examined or understood. Existing studies include Frazer (1995), who investigates the evolutionary aspects of processes in cellular automata and also relates cellular automata to the area of machine-readable models through a series of hardware designs, Coates et al. (1996), who emphasize the role of CA as a tool for exploring function-driven generation of architectural morphology, Krawcyk (2002) who focuses on the spatialisation of CA-generated volumetric clusters and Fischer et al. (2002), who describe applications of cellular automata to model morphogenetic and developmental form finding processes in architecture and construction. Cellular automata are also believed to bear potential clues for the generative design of non-uniform building structures (for a more detailed discussion see Herr, 2003b).

Cellular automata are known for the typically striking simplicity of their internal rule sets. Therefore, our research must address the critical question of whether cellular automata can be an appropriate means to investigate complex human needs and action. It has recently been presumed that there exists an upper limit to the complexity that systems can display. Once a system is computationally universal (and the programmable microcontrollers on which our cells are based surely are), it could simulate the behavior of any other, also internally more complicated system (the so-called "principle of computational equivalence", see Wolfram, 2002, p. 719 ff.). In this view, a human population and its actions can be seen as a complex system that, ignoring its underlying internal rules and processes, can be fully simulated using any simpler (as long as computationally universal) system. The described principle has however not remained undisputed (see for example Foundalis, 2003). The critical issue regarding this argument seems to be the role of observation and the observer's ignorance of a system's internal working principles. Since this project is primarily concerned with the net physical effects of human actions inspired by needs rather than a deep understanding of the needs that inspire these actions, their reduction to trivial circuitry seems appropriate since the intention is to only emulate what is apparent and not the simulation of its underlying processes.

## 4. Model Implementation

Our model is designed to implement high-density façade scenarios based on 48 individual sub-units, which operate as cellular automata. The sub-units are scaled to explicitly correspond with residential apartment units in full-scale buildings. They autonomously mimic inhabitant behavior and emerging needs by means of a flexible decentralized communication and control network, which connects the automata circuits that are accommodated inside the sub-units. These circuits generate and communicate massively parallel dynamic patterns of simulated usage and needs, but also have the capability of triggering simulated local need individually, for instance after certain periods of idleness. Our model implementation is tabletop-sized and allows runtime user interaction in re-configurable architectural model scenarios.

*Figure 3. Hardware cellular automata model with building extension modules*

User interaction is possible in two ways: On the front side of the model, users can attach and detach extension modules of three different sizes, representing façade extensions as they are commonly found in Hong Kong. One module can be attached to a given cellular unit at a time. The unit circuit can read the size of the attached module. On the backside of the model, the user can wire intercellular connections using cable sockets not unlike a telephone plug board, which, in the early days of telecommunication, was used to establish dynamic links between residential units in similar ways.

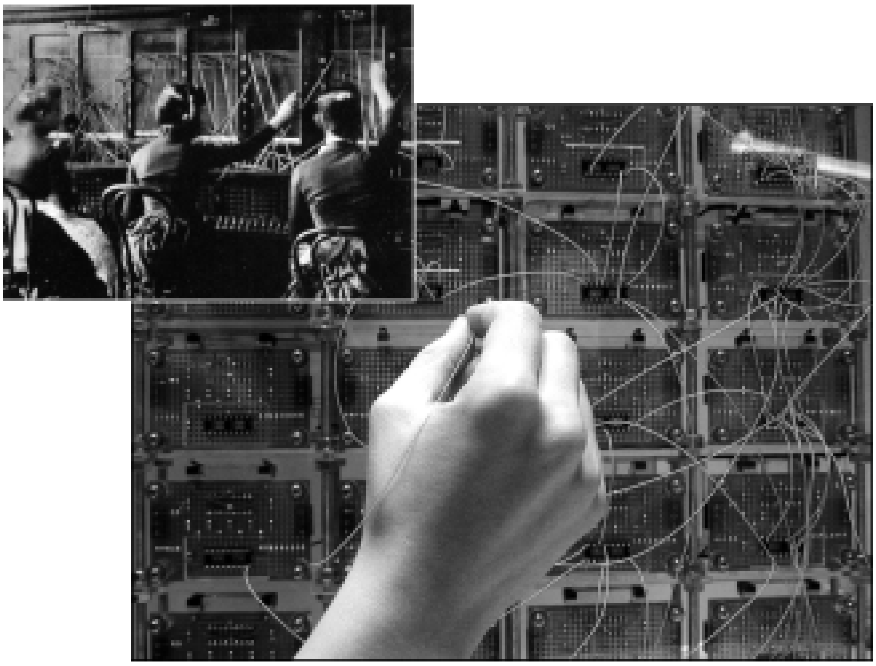

*Figure 4. Flexible neighborhood switchboarding*

In contrast to traditional cellular automata systems, the intercellular relations are hence neither limited to adjacent neighbors nor fixed. They are flexible and in the user's full control at all times. This configuration makes it possible for two users to interact with the model simultaneously. One user can for instance establish intensive and changing intercellular relationships and communication to stimulate user interaction patterns, which result in need for more or less living space. This need can then be addressed by the second user, who, changing module extensions at the model's front side, works to maintain an overall equilibrium of simulated user satisfaction. Physically, the model consists of two laser-cut Perspex frames of about 45 cm height and width, each of which accommodates 24 units arranged in a four by six grid. The primary intention behind partitioning the model into two separate frames is to allow some flexibility in creating different spatial configurations. The two frames can be positioned on top of each other, side-by-side, back to back etc. It also allows the easy integration of additional logic circuitry between both halves of the model for logically processing and mapping communication signals. Moreover, the separation into two frames makes the model better suitable for transportation. Every unit inside the model is fitted with an automaton circuit that is configured around an 8-bit microcontroller, clocked at a speed of 4MHz with access to 2kb of flash program memory. This memory can accommodate different programs to allow the execution of different cellular programs to simulate different architectural and use scenarios. It also allows uniform and non-uniform setups of rule sets.

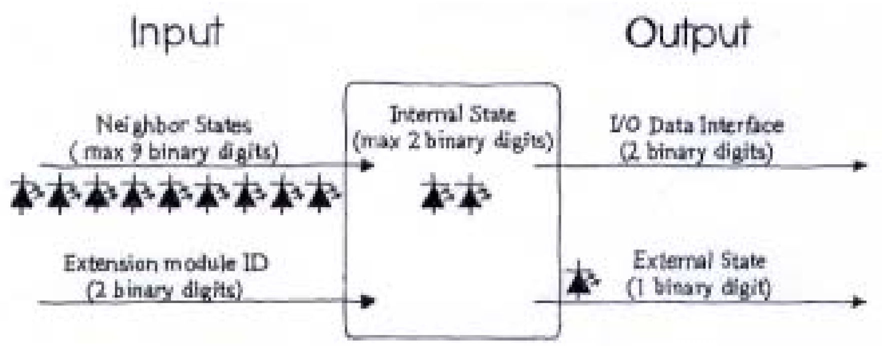


*Figure 5. Individual cell input and output*

We have designed the electronics of each cellular unit to accommodate a set of four internal cellular states. These four states are continuously represented using binary coding and two yellow LEDs. Moreover, each cell is designed to maintain communication with a "neighborhood" of up to nine other cells. (other Cellular automata systems are often based on the so-called von-Neumann or Moore neighborhoods with four and eight neighbors respectively). In the case of our model, between zero and nine incoming and outgoing communication links can be established and changed by the user over runtime as described above. The internal four states are mapped to a two-state signal for outgoing communication links. This binary signal is continuously represented using one red LED per unit. The binary content of all nine incoming communication links is continuously represented using nine green LEDs per cell. Cellular automata systems are typically modeled in software and executed on single processing units. As a side effect, these systems show a very rigid overall sequencing and synchronicity. The cells in our models are totally autonomous and their rule set execution is fully decentralized without any synchronicity. Cells even have the capacity to alter their individual execution speed based on communication, module extension, internal state data or even stochastic influences (randomness). As a consequence, some cells inside the model might execute their rule sets very quickly in fractions of seconds while, in other parts of the model, execution is very slow taking up to several minutes. This timing is determined in the microcontroller code allowing the experimenter to map model time onto real time (e.g. 5 minutes of model time to be equivalent to 1 month of real time).

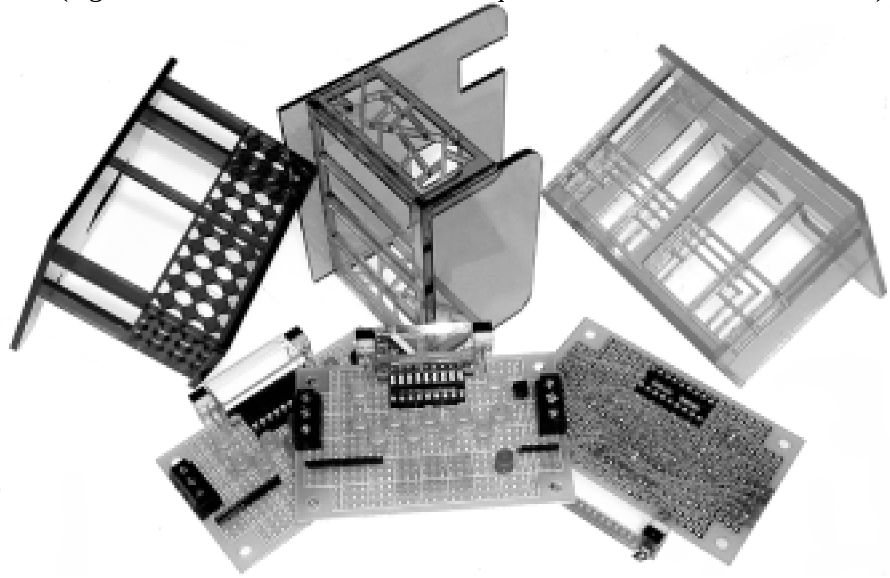

*Figure 6. Model building extensions and automata circuit boards*

Both model frames can be connected to an external PC for data logging purposes via a high-speed 96 bit parallel connection that is established through four programmable peripheral interface chips. A program running on the PC polls the model at a user-configurable frequency to retrieve the internal 2-bit state of each of the 48 cells. This data can be processed in various ways, either in real time or stored in a database and processed at a later point. The latter has proven to be the more practical choice for computation-intensive data evaluations such as generative visualizations since typically the models produce data at a much faster rate than can be handled by image rendering software. The parallel connection can also be used to feed data from the PC into the model if this is required by a particular model application. Since the model’s behavior is based on its own internal processing power, it can implement many applications without an external PC being attached to it.

## 5. Summary and Outlook

To date, there have been few examples of successful planning for continuous adaptability and change in architecture. Often, processes in the built environment are complex and unpredictable, and designing solutions for this type of problem is a complicated task. Based on the understanding that architecture designed for change has much in common with complex systems, we propose an architectural model that accommodates ongoing change in software and hardware. With the hardware model presented in this paper, we aim to integrate research on complex systems theory, cellular automata and planning for high-density residential architecture. Drawing on the Open Building movement in architectural design as well as observations on illegal building structures made in Hong Kong, we describe an architectural model that uses hardware cellular automata to generate and experiment with dynamic processes. Software implementations generally represent inhabitants' needs resulting from self-initiated changes as well as communication between single cells or groups of cells. Connections between cells can be dynamically reconfigured by a user throughout the model's runtime. Interaction between cells and subsequent expression of needs result in change of external form, which follows the architectural language of illegal building extensions in Hong Kong.

In planning for dynamic architectural settings, in particular in high-density environments, we intend to use the hardware model to study the relationships between behavior and needs (rule sets in cellular automata) and modes of formal expression (exchanging and adding or deletion of façade modules). Experimental future applications of the model will include the study of differences between formal expressions resulting from global rule sets and those resulting from local conditions and interactions. This could improve understanding of more performance-based criteria in dynamic processes (see Kolarevic, 2003), especially for interventions with design intent. A further area of interest is the relationship between rule sets, time-based change and façade dynamics, also in the context of economic aspects. Our model can be helpful in studying the process of change over time, with special regard to possible (desired or undesired) attractor states and their characteristics. Such experiments seem especially relevant for attempts to design for and with dynamic systems, in particular in fast-changing, high-density environments such as Hong Kong.

## Acknowledgements

We gratefully acknowledge the support and feedback from our colleagues at The University of Hong Kong and at The Hong Kong Polytechnic University. For their valuable comments and suggestions we are particularly indebted to our colleagues John Frazer, Timothy Jachna, Thomas Kvan and Brygg Ullmer. The small telephone switchboard image shown in the upper left for figure 4 was reproduced from Grosvenor and Wesson (1997), p. 123. The discussed hardware implementation was supported by Departmental General Research Funds of the School of Design at The Hong Kong Polytechnic University (project code A-PB84).

## References

Brand, S.: 1994, *How Buildings Learn: What happens after they're built*. Viking, New York.

Burks, A. W., (ed.): 1970, *Essays on Cellular Automata*. University of Illinois Press, Urbana, Chicago and London.

Coates, P., Healy, N., Lamb, C. and Voon, W. L.: 1996, The Use of Cellular Automata to Explore Bottom-Up Architectonic Rules. Paper presented at *Eurographics UK Chapter 14th Annual Conference*, Imperial College London, UK.

DeLanda, M.: 2000, *A Thousand Years of Non-Linear History*. Swerve Editions, New York.

Engelbart, D. C. and English, W. K.: 1968, A Research Center for Augmenting Human Intellect. *AFIPS Conference Proceedings of the 1968 Fall Joint Computer Conference*, San Francisco, CA, December 1968, Vol. 33, pp. 395-410.

Fernandes, E. and Varley, A. (eds.): 1998, *Illegal Cities. Law and Urban Change in Developing Countries*. Zed Books, London and New York.

Fischer, T., Ceccato, C. and Frazer, J.: 2001, Haptic Programming with Machine-Readable Models. In: Burry, M. et al. (eds.): *Proc. Mathematics and Design 2001. The Third Internat. Conf.*, School of Arch. and Building, Deakin University Australia, pp. 158-165.

Fischer, T., Fischer, T. and Ceccato, C.: 2002, Distributed Agents for Morphologic and Behavioral Expression in Cellular Design Systems. In: Proctor, G. (ed.): *Thresholds. ACADIA 2002 Proceedings*. Dept. of Architecture, College of Environmental Design, California State Polytechnic University, Pomona, Los Angeles, pp. 113-123.

Fischer, T., Herr, C. M., Burry, M. C. and Frazer, J. H.: 2003, Tangible Interfaces to Explain Gaudí's use of Ruled-Surface Geometries. Interactive Systems Design for Haptic, Non-Verbal Learning. *Automation in Construction* Vol. 12, Issue 5 (September 2003), pp. 467-471.

Foundalis, H. E., 2003: *Wolfram's Principle of Computational Equivalence: a Reality Check. A demonstration of why Stephen Wolfram's PCE is void of content*. URL: http://www.cogsci.indiana.edu/farg/harry/mat/pce/pce.htm [15Feb2004].

Frazer, J. H., Frazer, J. M. and Frazer, P. A.: 1980, Intelligent Physical Three-Dimensional Modelling Systems. *Computer Graphics 80 Conference Proceedings*, Online Publications, pp. 359-370.

Frazer, J. H., Frazer, J. M. and Frazer, P. A.: 1982, Three-Dimensional Data Input Devices. Paper given at the *Computers/Graphics in the Building Process Conference*, Washington, March 1982.

Frazer, J. H.: 1995, *An Evolutionary Architecture*. Architectural Association, London.

Girard, G. and Lambot, I.: 1999, *City of Darkness. Life in Kowloon Walled City*. Watermark Publications, Surrey, UK.

Grosvenor, E. S. and Wesson M.: 1997, Alexander Graham Bell. The Life and Times of the Man Who Invented the Telephone. Harry N. Abrahams Publishers, New York.

Habraken, N. J. et al.: 1976, *Variations: The Systematic Design of Supports*. Laboratory of Architecture and Planning, MIT, Cambridge, Massachusetts.

Habraken, H. J. and Teicher, J. (ed.): 1998, *The Structure of the Ordinary. Form and Control in the Built Environment*. MIT Press, Cambridge, Massachusetts.

Herr, C. M.: 2003a, *Vertical Village*. Master's thesis project at the Department of Architecture, The University of Hong Kong.

Herr, C. M.: 2003b, Using Cellular Automata to Challenge Cookie-Cutter Architecture. In: Soddu, C. (ed), *Proceedings of the 6th Conference on Generative Art 2003*. Generative Design Lab, DiAP, Politechnico di Milano University, Italy 2003, pp. 72-81.

Jencks, C.: 1997, *Architecture of the Jumping Universe. A Polemic: How Complexity Science is Changing Architecture and Culture*. Academic Editions, London.

Kendall, S. and Teicher, J.: 2000, *Residential Open Building*. E & FN Spon, London and New York.

Krawcyk, R.: 2002, Architectural Interpretation of Cellular Automata. In: Soddu, C. (ed.): The 5th International Conference on Generative Art 2002.Generative Design Lab, DiAP, Politectnico di Milano University, Italy, pp. 7.1-7.8.

Kolarevic, B.: 2003, Computing the Performative in Architecture, In: Dokonal, W. and Hirschberg, U. (eds.): *Digital Design. Proceedings of the 21st International eCAADe Conference*, Graz University of Technology, Austria, pp. 457-464.

McGuire, P.: 2000, Act of Settlement, *Arch. Review*, Feb. 2000, Vol. 207, Issue 1236, 67-69.

Marks, J.: 2001, Computational Construction Kits for Geometric Modeling and Design. Aish, R.; Frankel, J.L.; Frazer, J.H.; Patera, A.T.; Marks, J.W., Computational Construction Kits for Geometric Modeling and Design (Panel), *ACM Symposium on Interactive 3D Graphics (I3D)*, March 2001.

Spiller, N. (ed): 2002, *Cyber Reader – Critical Writings for the Digital Era*. Phaidon Press Limited, London and New York.

Ullmer, B. and Ishii, H.: 2000, Emerging Frameworks for Tangible User Interfaces, *IBM Systems Journal*, 39 (3 & 4), pp. 915-931.

Wojtowicz, J.: 1984, *Illegal Facades*. Privately published, Hong Kong.

Wolfram, S.: 1984, Universality and Complexity in Cellular Automata In: *Physica D*, Vol. 10, January 1984, pp. 1-35.

Wolfram, S.: 2002, *A New Kind of Science*. Wolfram Media, Champaign, IL.

Wolin, J. (ed.): 1974, *For Everyone a Garden. Moshe Safdie*. MIT Press, Cambridge, Massachusetts.

Wu, L.: 1999, *Rehabilitating the Old City of Beijing. A Project in the Ju'er Hutong Neighbourhood*. UBC Press, Vancouver.