The Prototyping of a Shading Device Controlled by a Cellular Automaton

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A shading device controlled by a cellular automaton (CA) for use in architecture has been prototyped. The implementation consists of selecting the class of CA, designing the logic circuits, and fabricating the units, followed by design of the liquid crystal display (LCD) panel and the acrylic casings.

1. Introduction

For quite a while architects have been dreaming of architecture that can change its appearance. The motivation for such a change ranges from rational adaptation to environmental variation according to a time of day, season, or temperature, to pure aesthetics and ordinary commercialism. One of the most recognized examples is Jean Nouvel's Arab World Institute in Paris, where 30 000 light-sensitive diaphragms were installed on the south facade. The diaphragms are high-tech photosensitive mechanical devices for controlling light levels and transparency of the facade. Most notably, they stopped operating soon after the facility launched [1].

This paper presents the fabrication process for a prototype of a modular system built from identical units that could be applied on a building facade. This system is based on one-dimensional cellular automata (1D CAs). It creates interesting patterns and can be controlled to a certain extent [2].

The most important reasons for applying CAs in this case are:

- Emergent behavior manifested by the complex geometrical patterns that are generated.
- Modularity, with every cell having the same structure.
- Low cost.
- Robustness of the system that can operate despite local damage to the array.
- Flexibility that allows CAs to be applied on any topologically regular grid, not only rectangular.

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Although the presented array is two-dimensional (2D), the CAs used are 1D. The convention for presenting a 1D CA is to show the history of generation changes, where each row corresponds to a step in the history. Every row becomes the initial condition for the next row and so forth. Use of a 2D CA may seem more intuitive because the domain of 2D CAs is greater than for one dimension, making the chances of finding an amazing CA greater, the inter-cell wiring seems to be easier, and so on. Nevertheless, as mentioned in the previous paper [2], there are major concerns involved with the application of 2D CAs. The most difficult problem is that, although their behavior is often truly amazing, it is difficult to control the states of cells. 2D CAs continuously update all cells until an equilibrium is reached, which almost always leads to an uninteresting, mostly uniform state. That is, all the cells remain black or white with some artifacts left over (small islands of the opposite color) and often locally strobing cells (switching their state at every step forever). Usually, the final state of the whole array is difficult or impossible to predict due to the computational irreducibility, or not useful for the shading device due to the strobing effect. Controlling the state of 2D arrays is difficult, or perhaps impossible. This problem could be solved by freezing the array at a certain step and not allowing it to evolve further, but at present it seems to be a difficult technical problem. With the adopted common convention of displaying 1D CAs, this problem does not occur because every row displays the state at a certain step, and once set the state is maintained. The second major problem with 2D CAs is the setting of initial conditions. How is the initial input given to the cells of a 2D array? It seems possible to use only cells on the edges of the array, as done in the 1D case, but further investigation and experimentation is required. In the presented case of a 1D CA, a row of cells receives input from the row above and becomes the initial condition for the row below and so forth. This process continues in a cascade and propagates down the whole array of cells.

Since this is one of the first engineering projects involving a physical device using the concept of a CA, the prototype intends for demonstrative purposes to be not only a shading device, but also to explain the idea of a CA. Instead of realizing one or both CAs selected in [2], and since it was decided to make the actual hardware, it was rational to build a universal circuit capable of demonstrating all four classes of CA behavior. A universal elementary CA unit circuit capable of emulating any of 256 elementary 1D CAs was designed. In order to show other possible applications of the idea, a low-tech approach was applied. And finally, it is hoped that this project will encourage others to span various disciplines and build further examples not yet envisaged.

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2. The Logic for the Cellular Automaton Module

The logic for an electrical circuit that is an analog of a CA cell was designed. Figure 1 shows the primary design to directly realize the concept of an elementary CA:

- The inputs are collected from three cells, one above and two adjacent cells on each side.
- Three independent inputs i_1, i_2, i_3 of binary values 0,1 give $2^3 = 8$ possible combinations of inputs.
- Any of the $2^8 = 256$ combinations of these triplet inputs can be set by the use of switches between the AND gates and XOR gate.
- Single binary output 0,1 is sent to the next three cells, one below and two adjacent neighbors.

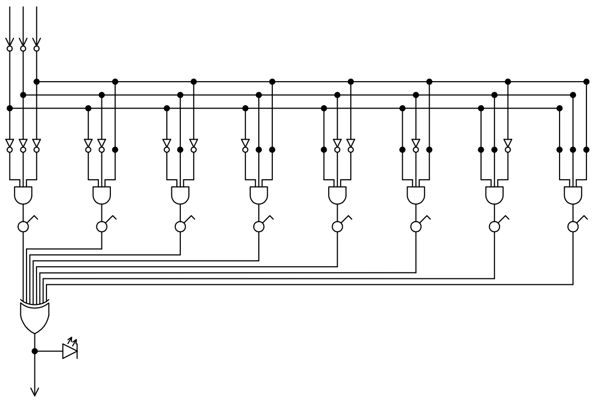

Figure 1. Primary scheme of the logic of a universal unit cell of an elementary CA.

The scheme consisted of the following logic gates: eight triple AND (3-input), one octuple XOR (8-input), twelve INV (inverters), and eight switches. This scheme was then modified according to the following criteria:

- Use cheap and commonly available integrated circuits (CMOS).
- Make a simple and easy to assemble electrical circuit board.
- Use by students as their first exercise in soldering.

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The smallest possible logic scheme for the circuit was designed, as shown in Figure 2.

The electrical circuit based on this logic scheme utilizes four dual AND (using all the gates of a Quad 2-Input AND CMOS), six dual XOR (using all gates of one Quad XOR CMOS and only half of another), one inverter gate (using only one of four gates of a Hex INV CMOS), and nine switches (using one integrated 10-DIP switch with nine out of 10 switches used). Each circuit was equipped with 12 resistors (ground for all four CMOS plus eight for switches) to prevent floating within the circuit, and a light emitting diode (LED) lighting set with LED, transistor, and two resistors.

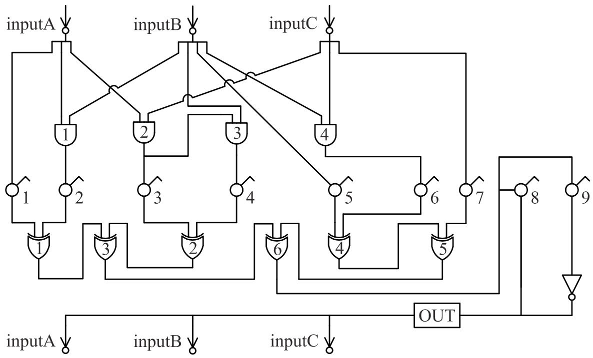

Figure 2. The smallest logic to emulate any of 256 elementary CAs.

3. Electrical Circuit of a Cellular Automaton Cell

The first circuit was made as shown in Figure 3. For testing and demonstration purposes the circuit was equipped with three additional input switches and LEDs.

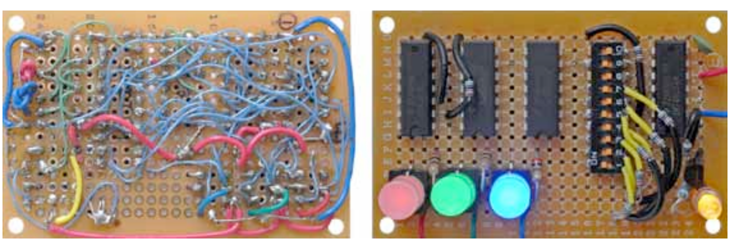

Figure 3. Bottom and top view of the first CA circuit.

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Since the intention was to make 24 individual circuits, the board was redesigned to meet the following criteria:

- Ease and speed of assembly.
- Error-proof and easy to test.
- Minimal labor.

The improved circuit diagram is shown in Figure 4.

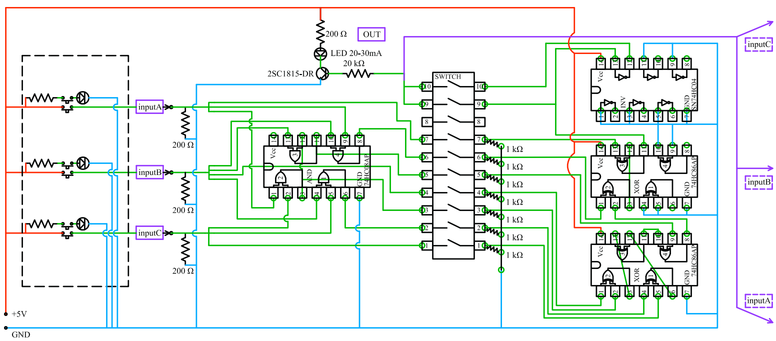

Figure 4. The electrical diagram of the CA unit. The dotted rectangle contains additional switches and LEDs used for the test unit only.

The paths were redesigned; seven resistors to prevent the switch from floating were replaced with one 8 SIP-resistor. A special “E-jisu pen” was used to create an inexpensive equivalent of a printed circuit board (PCB) as shown in Figure 5. The circuit became much easier to make and took approximately one hour including testing and fixing.

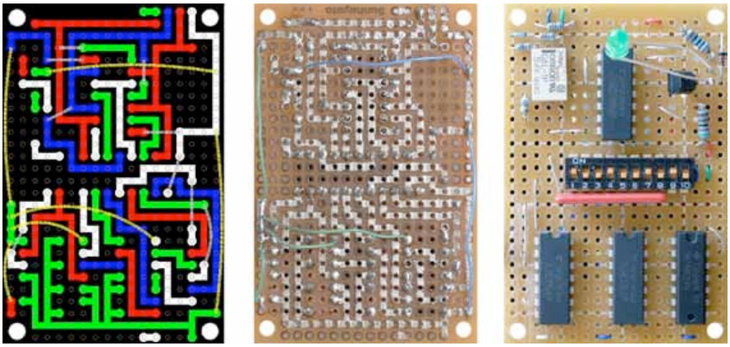

Figure 5. The optimized unit cell for fabrication. From the left: the scheme of the circuit’s paths, paths made with an E-jisu pen, and the front side of the unit.

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Initially, the cost of a single cell was 9.85 USD (excluding the costs of soldering and wires). A supply list of all components with prices is given in Table 1. An array of such cells can demonstrate CAs, but will not work with a liquid crystal display (LCD) panel that requires alternating current for proper operation and longevity, so additional relay switches must be installed.

The CA array also requires input switches as listed in Table 2.

In order for the LCD units to work properly, a 45 Hz inverter was designed. Table 3 lists the components used.

All 24 units were updated to work properly with the LCD panel. The changes are listed in Table 4.

Part Name	Manufacturer's Code	Price	Number per Unit	Subtotal
Board 47×72 mm	ICB288	0.91	1	0.91
Quad 2-Input AND	74HCT08AP	0.79	1	0.79
Quad XOR	74HC86AP	0.79	2	1.58
Hex INV	SN74HC04N	0.46	1	0.46
Transistor	2SC1815GR	0.23	1	0.23
LED	FA506G7CA2C01	1.48	1	1.48
DIP Switch	A6T0104	2.12	1	2.12
SIP Resistor 10 kΩ	M9 1-1-103J	1.14	1	1.14
Resistor 200 Ω		0.23	1	0.23
Resistor 10 kΩ		0.23	3	0.69
Resistor 20 kΩ		0.23	1	0.23
			Total	9.85

Table 1. Components for a single CA unit circuit. (Prices in USD.)

Part Name	Manufacturer's Code	Price	Number per Unit	Subtotal
Switch w/ LED	PB61303AL1	2.51	8	20.10
Resistor 200 Ω		0.23	1	0.23
			Total	21.91

Table 2. Additional parts for the CA array to include eight input switches. (Prices in USD.)

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Part Name	Manufacturer's Code	Price	Number per Unit	Subtotal
Board 47×72 mm	ICB288	0.91	1	0.91
Hex INV	TC4069UBP	0.34	1	0.34
Operational amplifier	BA4558	1.30	1	1.30
Capacitor 0.047 μF	CCDC50V473	0.06	2	0.12
Capacitor 10 μF 25V	BSME250ELL100ME11D	0.46	1	0.46
Resistor 1.5 kΩ		0.23	1	0.23
Resistor 4.7 kΩ		0.23	1	0.23
Resistor 39 kΩ		0.23	1	0.23
Resistor 56 kΩ		0.23	1	0.23
Resistor 91 kΩ		0.23	1	0.23
Resistor 100 kΩ		0.23	1	0.23
Resistor 200 kΩ		0.23	1	0.23
			Total	4.74

Table 3. Components of the inverter for the LCD panel. (Prices in USD.)

Part Name	Manufacturer's Code	Price Difference	Number per Unit	Subtotal
Relay switch	G6L-1P-DC5V	+ 3.20	1	3.20
Diode	1N4148	+0.11	1	0.11
Resistor 100 Ω	Replaced 200 Ω	-	1	0
Resistor 5.1 kΩ	Replaced 20 kΩ	-	1	0
Resistor 200 kΩ	Extra	+0.23	1	0.23
			Δ per unit	3.53

Table 4. Replacements and additional components for the CA units. (Prices in USD.)

The cost of the whole system was 348 USD. The cost of a single CA unit was 13.40 USD, or 9.86 USD without integrating an LCD panel.

The costs do not include:

- Power supply of DC 5 V/AC ± 15 V (approximately 50 USD for a new one; in this case a salvaged unit was used at zero cost).
- E-jisu pen (2×27 = 54 USD).
- The acrylic casings for the CA array and LCD. The price for these is difficult to estimate since they were custom made using CNC machines at the university workshop.
- The LCD units, which cost approximately 5 USD per piece.
- Wires and soldering.

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4. Array of 32 Cells

For economic reasons, periodic boundary conditions were introduced (the minimum number of cells in a row is two less than in regular boundary conditions), as shown in Figure 6.

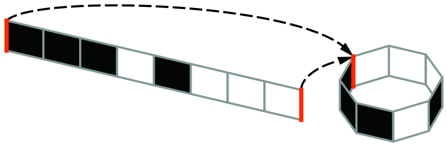

Figure 6. A conceptual visualization of how the periodic boundary condition is constructed.

Eight is the minimum number of cells with periodic boundary conditions that can demonstrate all possible initial conditions {1, 1, 1}, {1, 1, 0}, {1, 0, 1}, {1, 0, 0}, {0, 1, 1}, {0, 1, 0}, {0, 0, 1}, {0, 0, 0}, as shown in Figure 7.

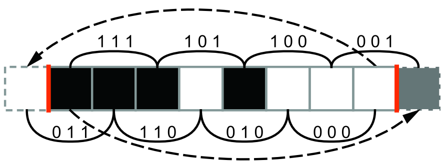

Figure 7. The shortest sequence of cells with all possible triplets of 0,1.

To document all 256 elementary 1D CAs by generating 256 unique patterns, it is sufficient to use just eight output cells of the second step, but a bigger array was built for demonstration purposes. The prototype consists of four rows, where the first row will become the manually set initial condition, and the next three upper rows will demonstrate three consecutive CA generation steps as shown in Figure 8.

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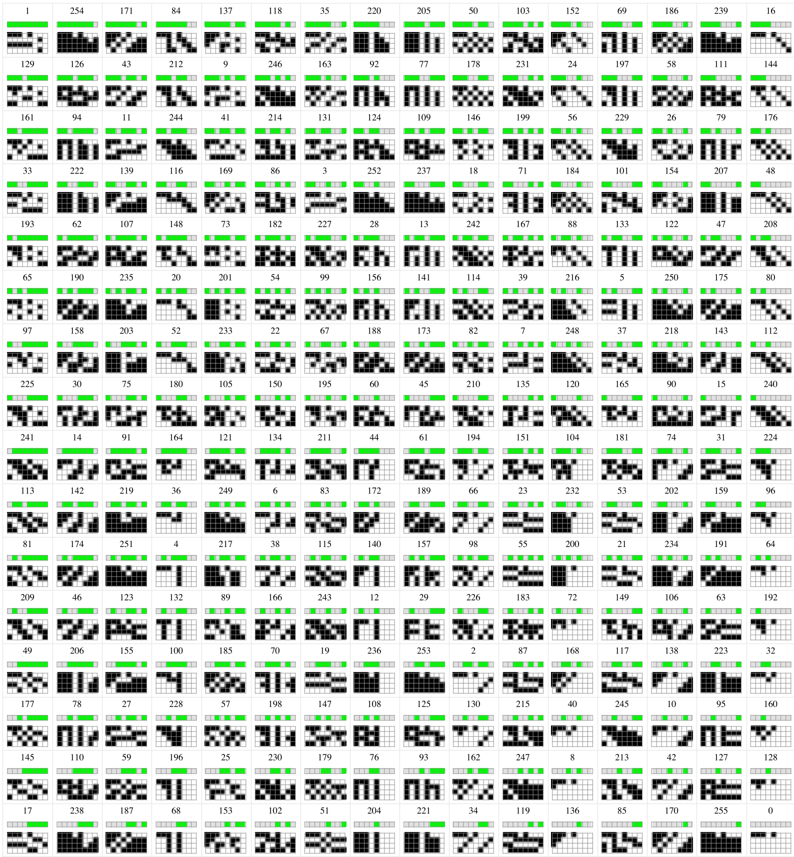

Figure 8. A computer simulation of a 32 cell array (24 CA circuits and eight inputs). Every circuit has eight switches. By setting the switches, every cell can emulate any of the 256 elementary CAs. The rows over the 48 arrays represent the switch settings (green for on, gray for off). All circuits have the same switch settings. $2^8 = 256$ different configurations of switches return 256 different CA patterns. The rule number of a simulated CA is displayed above each switch combination.

5. Assembling the Light Emitting Diode Demonstration Array

All 24 modules and eight input switches were connected into a hardware CA array. For the ease of manipulating the input (initial conditions), the orientation of the CA grid was reversed, that is, the input cells are on the bottom, the first step is located above, and so forth as shown in Figures 9 through 11.

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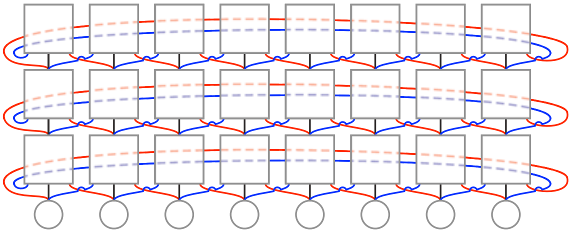

Figure 9. The cell interconnection scheme. The circles at the bottom indicate the initial input cells. Starting from the bottom, every row becomes an initial condition for the row above (except the top row).

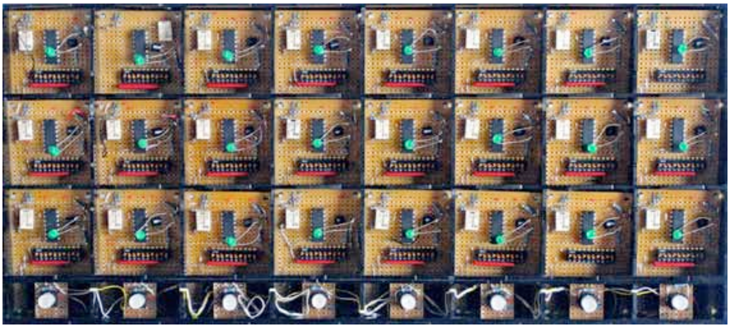

Figure 10. A photograph of the assembled array of 32 CA cells (24 CA units and eight initial input cells).

Figure 11. For aesthetic reasons, the rectangular circuit boards were fitted into squares by overlapping them slightly as a common convention of showing CA patterns on a square grid.

A special acrylic casing was designed and constructed for the prototype as shown in Figure 12.

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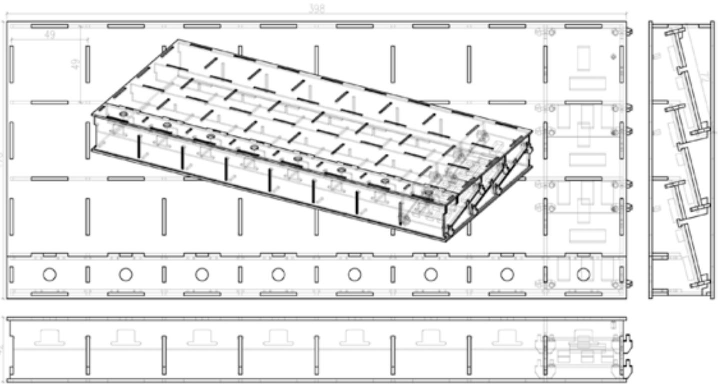

Figure 12. The casing for the units. Top, front, side, and isometric views with dimensions in mm.

6. Playing with Cellular Automata

The 32 cell CA device can demonstrate the concept of elementary CAs by a "hands-on" experience as shown in Figure 13. Removing the front cover and manually switching the settings of every cell allow students an understanding of how complex behavior (of the whole array) emerges from multiple interferences of simple "decisions" taken by individual cells.

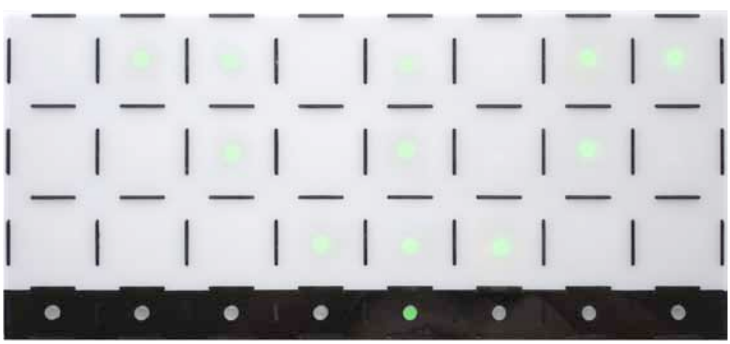

Figure 13. A prototype with the green LEDs showing the pattern of the CA rule 218 at a single input cell (bottom switch, fifth from the left).

7. Liquid Crystal Display Shading Panel

For demonstrating the shading action, LCD technology was used. Figure 14 shows schematically the liquid crystal unit between two gray linear polarizing films (by TECHSPEC) rotated by 90 degrees

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(normally white position). The light transmission through a liquid crystal cell can be varied from 0 to 100% by the bias. The position of the two polarizers determines whether the cell is normally black (0% transmission at 0 V) or normally white (100% transmission at 0 V). The polarizing material transmission characteristics within visible wavelengths are given in Figure 15. The single layer of film has approximately 38% transmittance for unpolarized light. Two parallel sheets (transparent state) have an average transmission of 27% and for two crossed sheets (opaque state) it is 0.04%. At 550 nm, the center of the visible spectrum, the crossed transmission is less than 0.01.

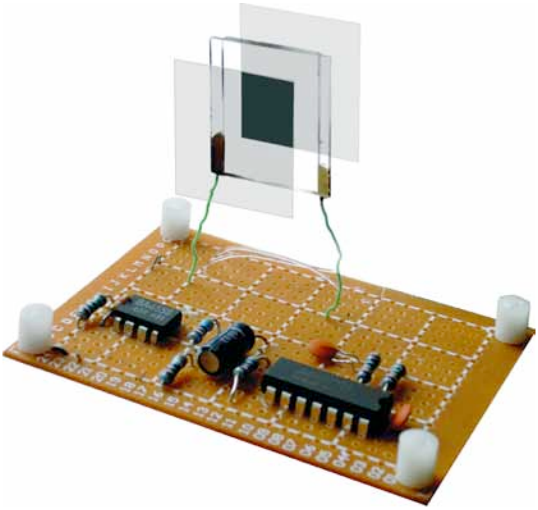

Figure 14. An LCD unit with two sheets of polarized film at normally white position shown with the inverter circuit. When voltage is applied, the LCD unit turns opaque.

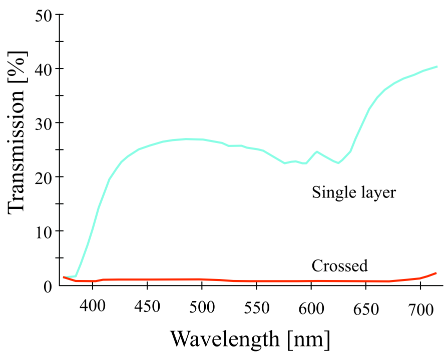

Figure 15. The polarizing transmission characteristics of the TECHSPEC gray commercial film. The blue line represents a single film layer; the red line shows two crossed layers.

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For proper operation and longevity, LCDs require alternating voltage, thus a special inverter circuit was designed and built. Every CA cell was slightly modified and equipped with a relay switch (Figure 16).

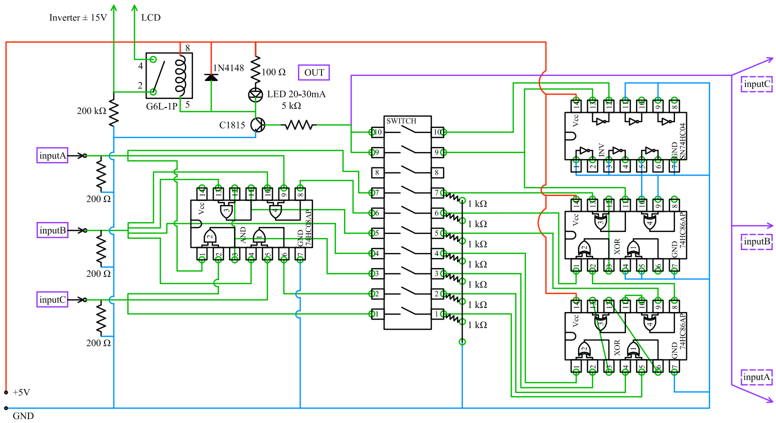

Figure 16. The final CA circuit suitable for controlling the LCD panel.

A special acrylic casing was designed and manufactured for the LCD panel as depicted in Figures 17 and 18.

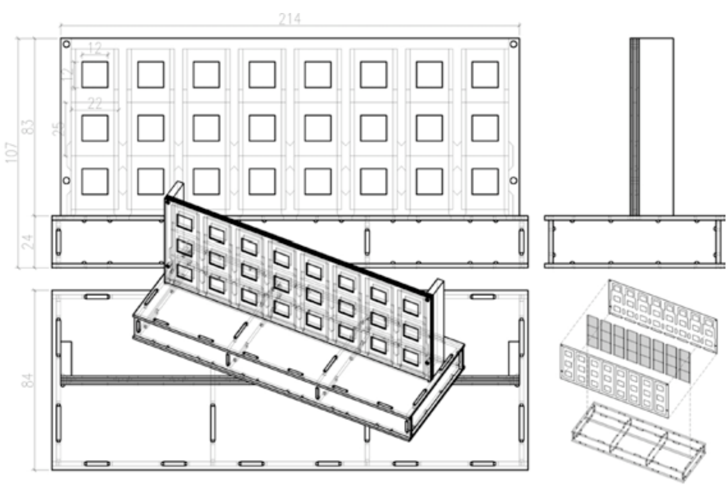

Figure 17. The casing for the LCD units. Front, top, side, and isometric views with dimensions in mm. The bottom right corner is the assembly diagram (LCD units are indicated in gray).

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Figure 18. A photograph of the acrylic panel with LCD units.

The LCD panel was integrated with the CA array. The diagram with the connections between the CA units, the LCD panel, and the inverter is shown in Figure 19. A photograph of the complete prototype is shown in Figure 20.

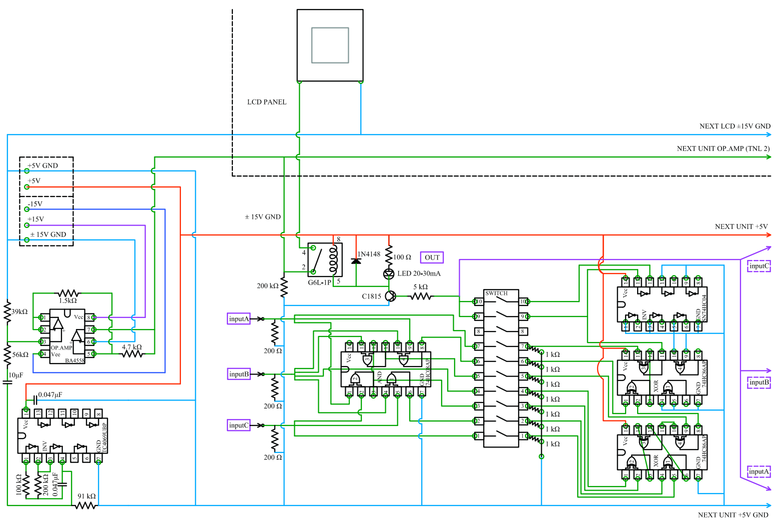

Figure 19. The connections between the CA units, the LCD panel, and the inverter.

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Figure 20. A photograph of the CA shading prototype.

8. Possible Practical Issues Related to Cellular Automaton Shading

Many technical and practical issues occur. Some result from the nature of CAs, while some are common to any design based on discovery methods.

What should be the size of the cell? Obviously, the bigger the cell, the easier the pattern is to see, while a smaller cell allows a higher precision control of the average opacity of the building facade. Since optimal size of a cell depends on the perception of the human eye, it is difficult to give a single answer for all possible cases. The best size should be determined according to particular visibility conditions including distance, exposition, and air pollution. Nevertheless, the cell size should be within the macroscopic scale, that is, in the range of centimeters, from a couple to a few dozen. The LCD prototype consists of cells that are 2.2 × 2.5 cm in size, where the active part has an area of approximately 1 square cm. This was the size of the available pieces for the experiment at the university.

A glare problem may occur when certain parts of the building facade are opaque and some transparent. This is certainly a major concern, since one of the main purposes of any shading device should be to protect from glare. Is it possible to tune the CA pattern in such a way that a certain patch of excess light can be removed (Figure 21)? There are a number of ways.

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Figure 21. Consider the area marked red to cause glare.

Supposedly the simplest way of reducing the problem is to disperse the light indoors by a layer of matte glass on the inside as shown in Figure 22. The light diffusion effect by such a film is often measured by the Haze number. Since the liquid cell is just a shutter, the transmittance specifications of the unit cell are determined by the polarizing films (and a diffuser if applied).

Figure 22. Dispersing the incoming light reduces the size of the area of glare and therefore its intensity.

The pattern can be clear on the outside and blurred on the inside. The problematic area was significantly reduced. Adjusting the dispersion of light using glass of different properties can improve the performance further. Such a solution may not be desirable though, since the clarity of the pattern seen from the inside is lost. Another approach is to alter the input of the initial conditions. One fundamental property of the chosen CA is the monotonicity of its grayness function, which means that the white/black ratio in initial conditions closely corresponds to the white/black ratio in the whole array of cells. Consequently, it should be possible to find alternative sequences of initial conditions that will give nearly identical values of grayness function with 0.4315 on the left and 0.4361 on the right but which generate different patterns, as shown in Figure 23. In the top row for both cases (the initial conditions indicated by blue color) there are 13 white and 20 black cells (grayness value of the initial row $= 13/(13+20) = 0.39$). The first sequence is {0, 1, 0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 1, 1, 0, 1, 0, 1, 1, 1, 1, 0, 0, 0, 1, 1}. The second sequence is {0, 0, 0, 1, 1, 1, 0, 0, 1, 0, 1, 1, 1, 0, 1, 0, 1, 1, 0, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0, 1, 0, 0, 0}.

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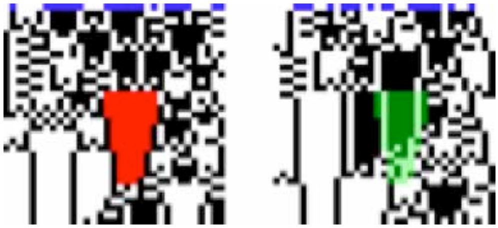

Figure 23. These two patterns from different initial conditions have nearly identical values of grayness function but the distribution of black and white cells on the whole array is different.

Is it possible to adjust the pattern locally? Since the 1D CAs were considered, every change of the pattern depends on the initial conditions (the very top row of the array) therefore the nature of the change is global. Nevertheless, the distinction between "global" and "local" change is rather ambiguous. The range of influence depends on many conditions, very often on the size of the neighborhood of a CA (Figure 24), a particular rule, and the initial conditions.

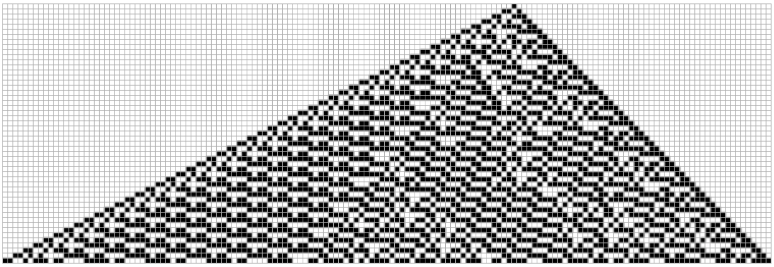

Figure 24. A range-2 CA starting from a single cell. The range of influence in this case is asymmetrical.

Would it be possible in this case to change the pattern locally, without changing the pattern elsewhere? In general, no.

How does the system respond to the outdoor lighting conditions? The proposed system does not directly respond to the daylight conditions. It is possible to change initial conditions according to the outdoor luminosity level. But this would require additional sensors to detect the extra environmental conditions and additional infrastructure.

Is it possible to use different CAs to serve the same purpose but generate different patterns? In general, no. In this shading project, a single CA was selected and all the units were made alike. Although theoretically a "universal" CA could emulate any other CA and therefore create "any" pattern, this possibility was not considered.

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9. Conclusions and Future Work

The project demonstrates a physical device based on a cellular automaton (CA) with possible practical application. The prototype was made inexpensively in the university laboratory, using very basic tools and skills.

Since the scale of the considered application to a building facade is rather large, the cost of a unit is an important issue. The circuit for a single CA (even range-2) would be much simpler than the universal unit presented in this paper, therefore mass production of an optimized integrated circuit will result in a significantly lower cost for each unit.

The choice of the electronics used had educational purposes and were not based on price. Students have learned the basic building blocks of logical circuits and simple analog circuits for driving optoelectronic devices such as light emitting diodes (LEDs) and liquid crystal displays (LCDs) and some soldering skills. In industry, the combination of a field programmable gate array (FPGA) and a printed circuit board (PCB) is almost always employed for implementing logical circuits [3]. A small investment here would drastically reduce the cost and physical size of the electronics for a large-scale application of this technology.

Our shading device application employs a plain liquid crystal cell without a thin film transistor (TFT). Namely, a TFT consists of two transparent substrates with conductive electrodes on one side, a polarizing film on the other, and a thin layer of liquid crystal placed in between. Therefore, its cost would be much smaller than the LCD. For the past two decades, a number of innovations for manufacturing millions of TFTs on a glass substrate have drastically reduced the manufacturing cost of an active-matrix LCD. This is accomplished because TFTs dominate the cost structure of an LCD. Even more dramatic cost reduction is expected by some ongoing efforts to fabricate TFTs and optical films, such as a polarizer on a plastic substrate by a continuous roll-to-roll process [4]. The process can also benefit this application and other passive-matrix LCD applications because it involves continuous fabrication of a polarizing layer directly on top of a plastic substrate [5].

A system with physically rotating (and much larger) elements may be a rational option and is under consideration along with the development of color displays.

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