A Hardware Implementation of the Cell Matrix Self-Configurable Architecture: The Cell Matrix MOD 88™

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Abstract

A hardware version of the Cell Matrix self-configurable architecture is described. Its main features are summarized, and the advantages of the hardware system over software simulators are discussed. Further details of the MOD 88's operation and software are given. An overview of the relation of the Cell Matrix and the MOD 88 to the field of Evolvable Hardware is given. Research and educational ideas are presented. A freely available, shared, online MOD 88 system is discussed.

1 Introduction

We have previously reported on plans to create a hardware implementation of a Cell Matrix system, and to make this platform available to the Evolvable Hardware community [1]. This paper reports on the completion of that work, and describes details of the Cell Matrix MOD 88™, which is that implementation.

The Cell Matrix is a fine-grained reconfigurable system, composed of a homogeneous tiling of reconfigurable elements called cells. The MOD 88 implements a two-dimensional, 8x8 array of four-sided cells, each internal cell being connected thus to four immediate neighbors. A cell receives one bit of data (called a "D Input") from each neighbor, and produces two outputs bits (called a "D Output" and a "C Output") to each neighbor. Any combinatorial mapping from a cell's four D Inputs to its C and D Outputs may be specified by loading the cell's *truth table*, which is a 128-bit memory (organized as a 16x8 RAM: 16 rows for the 2^4 input combinations; and 8 columns for the 2*4 output values). Each of a cell's outputs can thus implement any four-input logic function.

A cell contains no other internal functions (flip flops, arithmetic units, etc.) besides its truth table. However, each cell does contain a configuration mechanism: the C Inputs to a cell (which are provided by the C Outputs of its neighbors) control the configuration of a cell's truth table. If any C Input is 1, then the cell's truth table is itself being modified by a neighboring cell (and the cell is said th be in "C-Mode"). If instead all of a cell's C Inputs are 0, then the truth table is being used to map D Inputs to C and D Outputs (and the cell is said to be in"D-Mode"). Thus, D-Mode is the mode in which a cell is processing data, and C-Mode is the mode in which a cell is being reconfigured. Note that in C-Mode a cell's current configuration can also be read by a neighboring cell.

The Cell Matrix is an excellent Evolvable Hardware (EHW) platform. Because any cell can configure (or be configured by) any of its neighbors, it supports intrinsic (on-chip) evolution, which has great potential for implementing robust systems. This paper assumes a basic familiarity with the Cell Matrix architecture. Further details can be found in [2,3].

The MOD 88 (Figure 1) is a hardware board which implements an 8x8 array of four-sided Cell Matrix cells, connected in a 2-D, nearest-neighbor topology. It can be used as a stand-alone system, with the 32 edge cells accessed via edge connectors around the perimeter of the board (two inputs and two outputs per cell edge). It can also be connected to n external computer using the PC Interface Board (Figure 2). With this interface board and the supplied software, one can read and write edge cells' I/O lines, as well as manipulate the system clocks and the system reset line. Software is provided to allow one to bootstrap the MOD 88 with Cell Matrix configurations developed using the Graphical Layout Editor [4], available from the Cell Matrix website.

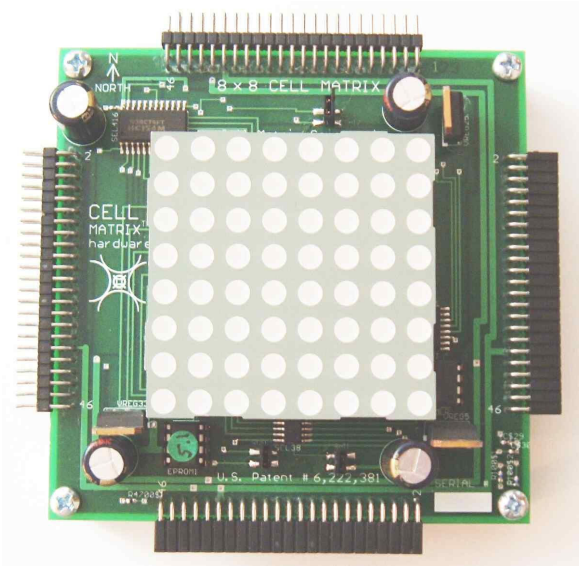

Figure 1. The Cell Matrix MOD 88 board Edge connectors allow connection to an external PC Interface Board, or to other MOD 88 boards. The LED array shows the state of each cell within the 8x8 Cell Matrix array.

2 Features

The Cell Matrix MOD 88 board includes an LED array of 64 bi-color LEDs. Each LED corresponds to a single cell, and its color indicates the state of the cell:unlit for D-mode with all outputs=0; green for D-mode and at least one asserted output; and red for C-mode. This is similar to the display model used by some Cell Matrix simulators, and has proven to be an effective window into the state of the system.

A single Cell Matrix MOD 88 board implements a two-dimensional, 8x8 array of four-sided cells. However, since the Cell Matrix architecture is infinitely scalable [3], and all edge I/O is available via edge connectors, it is possible to hook together multiple MOD 88 boards to create larger matrices. Figure 3 shows, for example, a set of four boards, connected to implement a 32x32 Cell Matrix.

The configuration mechanism of a Cell Matrix is fundamentally different from most other reconfigurable devices, because in a Cell Matrix, *there is no built-in configuration mechanism*. Rather, any cell may be configured by any neighboring cell (and edge cells may also be configured from outside the Matrix). The specific process of configuring a cell is:

- place the cell to be configured into C Mode by setting one of its C Inputs to 1;
- send the desired truth table bits to the D Input on the same side where the C Input=1;
- modulate these D Input bits in synchronization with the system programming clock; and
- after 128 bits have been loaded, return the cell to D Mode by setting the C Input to 0.

Any edge cell to which an outside system has access can thus be configured, i.e., its truth table can be loaded with whatever program is desired. And that truth table might direct the edge cell to configure an *internal cell*, by asserting a C Output and passing a D Input to a D Output. Thus, an outside system can configure internal cells as well as edge cells. By proper coordination of such configuration sequences, the entire Matrix can be configured from just a small number of edge cells.

The supplied software can be used, with an external computer and the PC Interface Board, to bootstrap the MOD 88 in this way, i.e., to load a desired set of cell truth tables into the cells of the MOD 88. It is also possible, once the board has been so configured, to remove it from the external computer without disturbing the configuration. This undocking procedure allows one to configure the Cell Matrix using a PC, and then have the Cell Matrix operate autonomously, aboard a robotic system, for example.

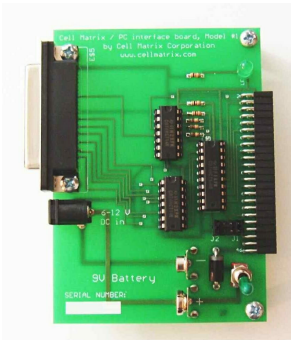

Figure 2. PC Interface Board Connector on the left connects to a standard parallel port cable. Connector on right connects to a MOD 88 board. Power is supplied via external supply or a 9V battery.

Other features of the Cell Matrix MOD 88 include:

- single power supply operation: 6-12 volts DC (external jack or on-board 9V battery), with on-board power regulation;
- direct hardware access to C and D inputs and outputs of all edge cells;
- standard .100” x 2-row edge connector footprint;
- TTL-compatible inputs and outputs; and
- internal pulldown of unconnected inputs.

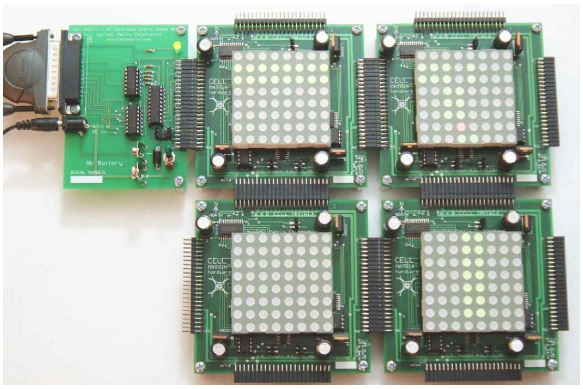

Figure 3. Four MOD 88 boards connected as a 32x32 Matrix
A single PC Interface Board controls all four boards via the upper-left board, using the distributed control of the Cell Matrix architecture.

3 Evolvable Hardware Support

The Cell Matrix has a number of features that make it very well suited to EHW work. Note that some of these are characteristics of the Cell Matrix architecture itself, but may not be feasible on a small (8x8) hardware board:

- it is impossible to physically damage the MOD 88 by "incorrect" configuration. Unlike some other types of FPGAs, in a Cell Matrix, inputs can only be connected to outputs, and vice versa. This means a circuit's genome can describe not only the logical operations of each cell, but also the interconnect among those logic blocks.
- The configuration of a Cell Matrix is simply the collection of the truth tables of all the cells. This is a very natural configuration mechanism that is very easy to work with, which is an important consideration in *intrinsic evolution*, i.e., when the creation and manipulation of configuration strings is to be performed from inside the Cell Matrix itself. The simplicity of the configuration stream is also useful for educational environments.
- Because the Cell Matrix's cells can modify each other's configuration, it is possible to evolve *dynamic* circuits, i.e., circuits whose configuration changes over time. It may also be possible to combine this with intrinsic evolution, and design systems where the evolutionary algorithm itself is evolved over time.
- It is possible to control the precise placement of every cell configuration inside the Cell Matrix. One can confidently assign a particular truth table to a particular [row,column], without fear of that cell being relocated.
- The Cell Matrix is extremely fine-grained, making it well suited for gate-level evolution.
- The Cell Matrix supports intrinsic, *run-time* configuration (in fact, there is no distinction between run-time and compile-time), which affords interesting opportunities for evolution of sub-circuits within larger, predominantly static circuits.
- The Cell Matrix architecture has been fully disclosed via patents, publications, lectures, and the Cell Matrix website [5], thus allowing users to create custom software, tools, etc.

The software provided with the MOD 88 [6] includes an example of a simple Evolvable Hardware (EHW) experiment: the evolution of a 5-bit odd parity generator on a 3x5 Cell Matrix. The evolutionary algorithm implements one candidate circuit at a time, which is tested exhaustively. A population of 20 such individuals is evolved using single-point crossover plus mutation. In the example, a perfect parity generator was evolved in 29 generations.

We believe the availability of an open, fine-grained reconfigurable platform such as the Cell Matrix MOD 88 may be beneficial to the Evolvable Hardware community [7].

4 Research/Educational Ideas

We believe the Cell Matrix MOD 88 can be useful as both a research and an educational tool. In the classroom, it can provide a hands-on introduction to digital circuits. For example, Figure 4 shows an 8x8 Matrix configured as a self-triggering 21-bit binary counter. The circuit is activated by setting cell [0,1]'s D North input to 1, which causes the inverter's output to feed back to its own input, thus causing an oscillating output. This output is fed into the first of 21 cascaded toggle flip flops, thus producing a 21 bit counter. In this circuit, each cell labeled "T-FF" implements the equations:

(!E)N + ES -> S;
(!E)N+E(!S)->N; and
S->W.

The MOD 88 can also be used to introduce concepts in reconfigurable systems and evolvable hardware, as well as more exotic concepts such as self-modifying hardware. Because the MOD 88 cannot be damaged by any particular programming sequences, it is safe for students to experiment with, to try their own ideas, or to try arbitrary ideas and analyze the resulting behaviors. The combination of the LED array and the

interface software provides a number of feedback options. The simple configuration mechanism makes it feasible to configure and control individual cells at the bit-level, i.e., by sending individual 1's and 0's into the board. Because there is no inherent minimum length for a configuration string, useful circuits can be configured by sending only a few bits into the MOD 88. A number of included tutorials walk the user through increasingly complex examples, from the manipulation of individual LEDs through the development of simple self-modifying circuits.

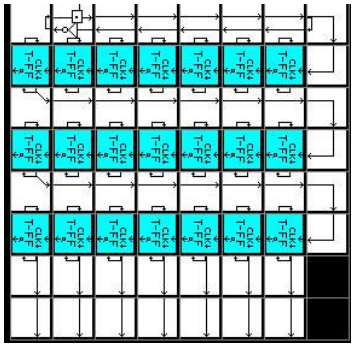

Figure 4. 21-bit counter on an 8x8 Matrix

In the laboratory, the MOD 88 can be useful for initial EHW experimentation with the Cell Matrix. Whereas software EHW experiments are generally constrained to evolution of only D-mode cells, the hardware Cell Matrix has no such constraints. Therefore, once can freely evolve circuits whose cells are asserting their C-outputs, i.e., dynamic circuits whose cells modify other cells. Despite the small size of circuits that can be implemented on a single MOD 88 (64 cells), this may still be an extremely interesting area of research.

5 Online Version

It is possible to experiment with a set of MOD 88 boards using the *Online MOD 88* pages, available at [6]. From this page, one can view a set of four MOD 88 boards, and can interact with the boards using a version of the command line interface. This interface allows one to: set inputs; read outputs; operate the matrix's clock and reset lines; bootstrap the matrix from certain provided configuration files; and run some provided demos. A camera shows the LED arrays of the MOD 88 boards, giving a visual feedback of the boards' operation (there's also a light switch that can be operated via the web page to allow one to see the boards themselves). Multiple users can connect to the site, with one user operating the board while others can observe. In the future, it will be possible to upload custom configuration files and bootstrap the matrix from those files. Therefore, it may be possible to perform evolutionary experiments remotely.

6 Conclusions

The Cell Matrix MOD 88 is a hardware implementation of the Cell Matrix: a novel self-configurable architecture. It can be used in a number of settings, both with an external computer and as a stand-alone device. The MOD 88 can be used for experiments in evolvable hardware (EHW), taking advantage of a number of Cell Matrix features that are particularly suited to the EHW field. The MOD 88 should be useful both in educational as well as research settings. An online version of the MOD 88 provides a free, shared resource for initial experimentation with Cell Matrix hardware.

Acknowledgments

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