Evolution In Materio : Evolving Logic Gates in Liquid Crystal

Simon Harding and Julian F. Miller

Department of Electronics
University of York
York, UK
{slh,jfm}@evolutioninmaterio.com
http://www.evolutioninmaterio.com

Abstract. Intrinsic evolution has been shown to be capable of exploiting the physical properties of materials to solve problems, however most researchers have chosen to limit themselves to using standard electronic components. However, these components are human designed and intentionally have predictable responses, so they may not be the most suitable physical devices to use when using a stochastic search technique. Indeed allowing computer controlled evolution (CCE) to manipulate novel physical media might allow much greater scope for the discovery of unconventional solutions. Last year the authors demonstrated, for the first time, that CCE could manipulate liquid crystal to perform computational tasks (i.e frequency discrimination, robot control). In this paper, we demonstrate that it is also possible to evolve logic gates in liquid crystal.

1 Introduction

Miller and Downing argued that evolution in hardware ought to be able to benefit from access to a richer physical environment [14]. This is because materials with rich, complex, non-linear dynamics would have many subtle physical internal interactions that could be utilized in potentially unexpected ways when external signals are applied (i.e. voltages). At present most evolvable hardware research is focused on conventional component based evolution. It is unlikely that conventional logic components that have been built to be as digital as possible would provide enough physical richness to allow evolution much scope for exploitation of the embedded physics. Evolving the configuration of actual physical variables applied to materials (we call this *in materio* evolution) may allow us to develop new computational systems that are based on exploiting hitherto unknown physical properties of a complex system. Thompson in his work with FPGA circuits found that an evolutionary algorithm used some subtle physical properties of the system to solve problems [19]. To this day, it is not fully understood what properties of the FPGA were used. Of course, this lack of knowledge of how the system works prevents humans from designing systems that exploit these subtle and complex physical characteristics. However it does not prevent exploitation through artificial evolution. Thus there is a real chance that evolution in materio may allow the discovery of new physical effects that can be harnessed for computation.

In [7] Harding and Miller gave the first demonstration that an unknown complex physics could be exploited for computation by showing that liquid crystal could be used. They were able to evolve simple transistor like behaviour and the discrimination of pairs of dissimilar frequencies surprisingly rapidly (the latter task being inspired by Thompson's groundbreaking work) [6]. Very recently they have shown that a real time robot controller can be evolved in liquid crystal [8]. In this paper we present work demonstrating that it is even possible to evolve a liquid crystal display to perform digital logic operators.

2 The Field Programmable Matter Array

In [14] a conceptual device was described that the authors called a Field Programmable Matter Array(FPMA). The idea behind the FPMA is that applied voltages may induce physical changes within a substance, and that these changes may interact in unexpected ways that may be exploitable under evolution.

They suggested a number of materials that could potentially be used as the evolvable substrate in the FPMA. They all share several characteristics : the material should be configurable by an applied voltage/current, the material should affect an incident signal (e.g. optical and electronic) and should be able to be reset back to its original state. Examples of these include electroactive polymers, voltage controlled colloids, bacterial consortia, liquid crystal, and nanoparticle suspensions. In our previous work we have demonstrated that liquid crystal is indeed a suitable material to form the basis of the FPMA.

2.1 Liquid Crystal

Liquid crystal (LC) is commonly defined as a substance that can exist in a mesomorphic state [5][11]. Mesomorphic states have a degree of molecular order that lies between that of a solid crystal (long-range positional and orientational) and a liquid, gas or amorphous solid (no long-range order). It is possible to control the orientation of liquid crystal molecules using electric fields. Normally the molecules in a liquid crystal align themselves along a common director, however this orientation is essentially random. By applying an electric field it is possible to change the angle of this director and force the molecules to rotate into a desired orientation. Changing the orientation of the liquid crystal changes its behaviour. The most well known of these effects is the change in its optical properties. Rotating the molecules changes the refractive index of the liquid, it is this effect that is used in liquid crystal displays(LCDs).

Changing the orientation of the molecules also alters the electrical properties of the liquid crystal. Figure 1 shows the equivalent electrical circuit for liquid crystal between two electrodes when an AC voltage is applied. The distributed resistors, R, are produced by the electrodes. The capacitance, C, and the conductance, G, are produced by the liquid crystal layer[15]. Changing the orientation alters these constants, and in this work we aim to exploit these electrical properties (and possibly other properties) by using applied fields to alter the molecular configuration.

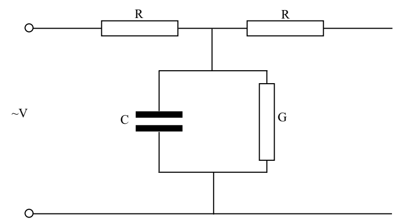

Fig. 1. Equivalent circuit for LC

3 An Evolvable Motherboard with a FPMA

3.1 Previous Evolvable Motherboards

An evolvable motherboard(EM) was a term first coined by Layzell, [12] it is a circuit that can be used to investigate intrinsic evolution. The EM is a reconfigurable circuit that rewires a circuit under computer control. Previous EMs have been used to evolve circuits containing electronic components[12][3] - however they can also be used to evolve in materio by replacing the standard components with a candidate material.

An EM is connected to a PC that is used to control the evolutionary processes. The PC also has digital and analog I/O, and can be used to provide test signals and record the response of the material under evolution, as shown in figure 4.

3.2 The Liquid Crystal EM

In the experiments presented here, a standard liquid crystal display with twisted nematic liquid crystals was used as the medium for evolution.

The display is a monochromatic matrix LCD with a resolution for 180 by 120 pixels. The displays are made up of several layers, as shown in figure 2. The liquid crystal layer(c) is sandwiched between the two sheets which are coated in electric connections(b,d). These layers are then positioned between two polarising filters, one in a horizontal orientation(a) the other vertically(e).

We have assumed that the electrodes are indium tin oxide. Typically such a display would be connected to a driver circuit. The driver circuit has a configuration bus on which commands can be given for writing text or individually addressing pixels so that images can be displayed. The driver circuit has a large

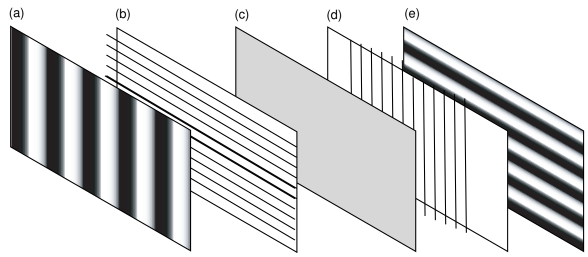

Fig. 2. Layers in a LCD

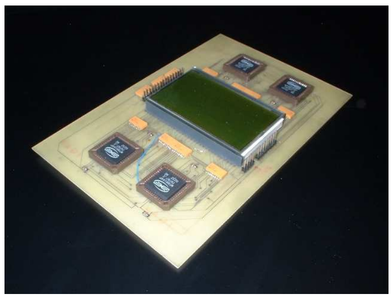

Fig. 3. The LCEM

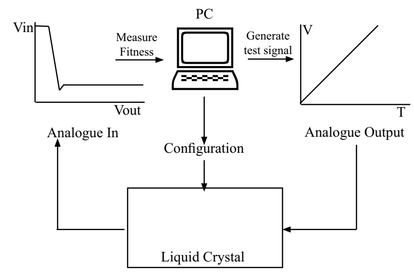

Fig. 4. Equipment configuration

number of outputs that connect to the wires on the matrix display. When displaying an image appropriate connections are held high, at a fixed voltage - the outputs are typically either fully on or fully off.

Such a driver circuit is unsuitable for our task of intrinsic evolution. We need to be able to apply both control signals and incident signals to the display, and also record the response from a particular connector. Evolution should be allowed to determine the correct voltages to apply, and may choose to apply several different values. The evolutionary algorithm should also be able to select suitable positions to apply and record values. A standard driver circuit would be unable to do this satisfactorily.

Hence a variation of the evolvable motherboard was developed in order to meet these requirements.

The Liquid Crystal Evolvable Motherboard (LCEM) is circuit that uses four cross-switch matrix devices to dynamically configure circuits connecting to the liquid crystal. The switches are used to wire the 64 connections on the LCD to one of 8 external connections. The external connections are: input voltages, grounding, signals and connections to measurement devices. Each of the external connectors can be wired to any of the connections to the LCD.

The external connections of the LCEM are connected to the Evolvatron's analogue inputs and outputs. Connections can be assigned for the input signals, measurement, and for fixed voltages (plus a ground connection). The value of the

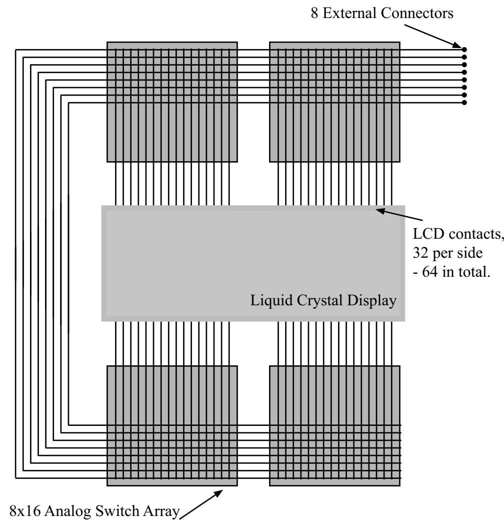

Fig. 5. Schematic of LCEM

fixed voltages is determined by a genetic algorithm[9], but is constant throughout each evaluation.

In these experiments the liquid crystal glass sandwich was removed from the display controller it was originally mounted on, and placed on the LCEM. The display has a large number of connections (in excess of 200), however because of PCB manufacturing constraints we are limited in the size of connection we can make, and hence the number of connections. The LCD is therefore roughly positioned over the pads on the PCB, with many of the PCB pads touching more than 1 of the connectors on the LCD. This means that we are applying configuration voltages to several areas of LC at the same time.

Unfortunately neither the internal structure nor the electrical characteristics of the LCD are known. This raises the possibility that a configuration may be applied that would damage the device. The wires inside the LCD are made of an extremely thin material that could easily be burnt out if too much current flows through them. To guard against this, each connection to the LCD is made through a 4.7Kohm resistor in order to provide protection against short circuits and to help limit the current in the LCD. The current supplied to the LCD is limited to 100mA. The software controlling the evolution is also responsible for avoiding configurations that may endanger the device (such as short circuits).

It is important to note that other than the control circuitry for the switch arrays there are no other active components on the motherboard - only analog switches, smoothing capacitors, resistors and the LCD are present.

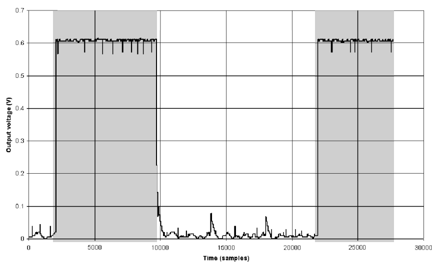

Fig. 6. Tone discriminator response. Dark areas indicate 5kHz input, light 100Hz

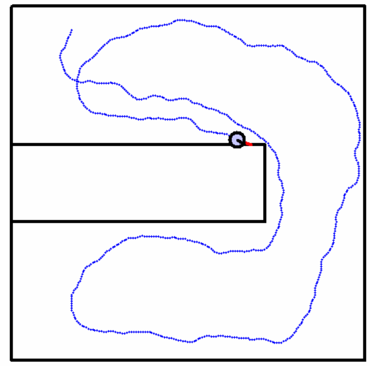

Fig. 7. Path of an robot controlled using liquid crystal

4 Previous Systems Evolved In Liquid Crystal

4.1 Tone Discriminator

A tone discriminator is a device which when presented with one of two signals input signals returns a different response for the each signal. In [7] a device was evolved in liquid crystal to perform this task. In [19], on which this experiment is loosely based, the task is to differentiate two different frequency square waves, giving a low output for one and a high output for the other. We have evolved a system in liquid crystal that was also able to perform this task. It was found that it was easier to evolve solution in liquid crystal than it was to evolve a circuit in an FPGA as reported by Thompson. An example of the evolved response in shown in figure 6.

4.2 Real-time Robot Controller

This year we have recently demonstrated that it is also possible to evolve a robot controller in liquid crystal. A controller was evolved that allowed a simulated robot to move around an enclosed environment with obstacles without colliding with the walls, as shown in figure 7. The task is significantly harder than that of our previous work with liquid crystal (if only because the number of inputs and outputs to the display device has been doubled). Yet we found that it was relatively easy (in evolutionary terms) to evolve a sophisticated robot controller. The quality of results when compared to previous work is also high. The environment is more complex than that of comparable work, and unlike much work on evolving GP robot controllers or neural network controllers, we solve a real-time control task. The results also indicated an evolutionary computational effort that is comparable to other examples of evolved controller (with simpler tasks).

5 Logic Gates

Our previous experiments reported on evolution in liquid crystal have evolved solutions that are analogue in nature. In this paper the potential of evolving digital circuits is explored. A digital circuit is one in which there are are only two possible states. In circuits these states are called HIGH and LOW, and represent the states of TRUE and FALSE in Boolean logic[10]. HIGH and LOW relate to the voltage present. In [6] non-linear functions were evolved - that had an interesting non-linear, step behaviour and suggested that liquid crystal could be capable of being evolved to act in a digital fashion.

5.1 Gates : The Building Blocks of Digital Circuits

Each of the logical operators in Boolean logic has an equivalent digital circuit - known as a gate. The main types of gates are inverters (NOT), AND, inverted AND (NAND), OR, inverted OR (NOR) and exclusive OR (XOR).

By building combinations of NOR or NAND gates it is possible to construct any logical function. This is an important observation, as it relates to Turing completeness. If a system is logically sufficient then it is possible to use it as a component of a Turing complete system, and hence use it to perform any arbitrary computation.

Hence, if it can be shown that combinatorial circuits can be evolved in liquid crystal, it can be shown that liquid crystal can be used to perform an arbitrary computation. This is in addition to any non-Von Neumann computation that it capable of performing.

But why, when transistor based technology is so good at implementing logic gates, would we want to try to produce them in a substance like liquid crystal? In [17], the authors conclude that:

> What is the purpose of demonstrating the feasibility of chemical-based computational devices? In comparison with electronic-based computations, chemical computations occur on time scales that are orders of magnitude longer and require space scales that are orders of magnitude larger. There can be only one reason for constructing computational devices based on excitable chemical media: to determine what such chemical systems can and cannot do. In so doing, we explore the possibilities for information processing by all excitable media, chemical and biological, with the chance of garnering insights into the workings of information processing in living systems.

de Silva argues that building molecular level gates out of chemical systems will have many practical uses, especially when constructing small devices - for example operating within a cell. He states that non-silicon will be "be natural for such logic devices to find ready application in physiology, medicine and biotechnology as sensors and diagnostic systems." [4]. Silicon devices are power and space hungry when compared to molecular level digital circuits, and de Silva suggests that "wet chemistry" may provide a superior alternative in some situations.

5.2 Gates in unusual materials

Logic gates in computers are made of transistors, however it is relatively easy to construct gates from other materials. There are many ways to use chemical systems to perform logical operations. For example, Steinbock [17] uses the propagation of chemicals through designed channels to produce several gates. There are several example of producing logic gates using DNA [16]. These DNA gates are designed, which is unfortunate given the previously demonstrated evolutionary properties of DNA. Moving up some levels Knight and Sussman described a technique that exploits the mechanisms in a biological cell[18]. In [2], Adamatzky describes gates made from chemical reactions, in particular utilising the properties of reaction diffusion wave fronts passing through specially designed channels.

In [4], de Silva describes the current technologies for creating molecular scale logic gates. He compares the many techniques including "chemically-controlled fluorescent and transmittance- based switches concerned with small molecules, DNA oligo nucleotides with fluorescence readout, oligonucleotide reactions with DNA-based catalysts, chemically-gated photochromics, reversibly denaturable proteins, molecular machines with optical and electronic signals, two-photon fluorophores and multichromophoric transient optical switches".

There are also many example of building logic gates out of mechanical systems, many systems are described in Merkle [13]. There is even a set of logic gates made of Lego [1].

6 Evolving Gates in Liquid Crystal

A number of experiments were performed, each one to evolve a different gate. The target functions were NOT, OR, AND, NAND, NOR and XOR. Each experiment was repeated 10 times, and allowed to run for 100 epochs.

6.1 The Genotype and Genetic Operators

The genetic representation for each individual is made of two parts. The first part specifies the connectivity; the second part determines the configuration voltages applied to the the LCD.

Each of the 64 connectors on the LCD can be connected to one of the eight external connectors or left to float, figure 5. Each of the connectors is represented by a number from 0 to 7 and no connection is represented by 8. Hence the genotype for connectivity is a string of 64 integers in the range 0 to 8.

The remainder of the genotype specifies the voltages, in the range -10V to +10V that are supplied to the liquid crystal. In this configuration, four of the

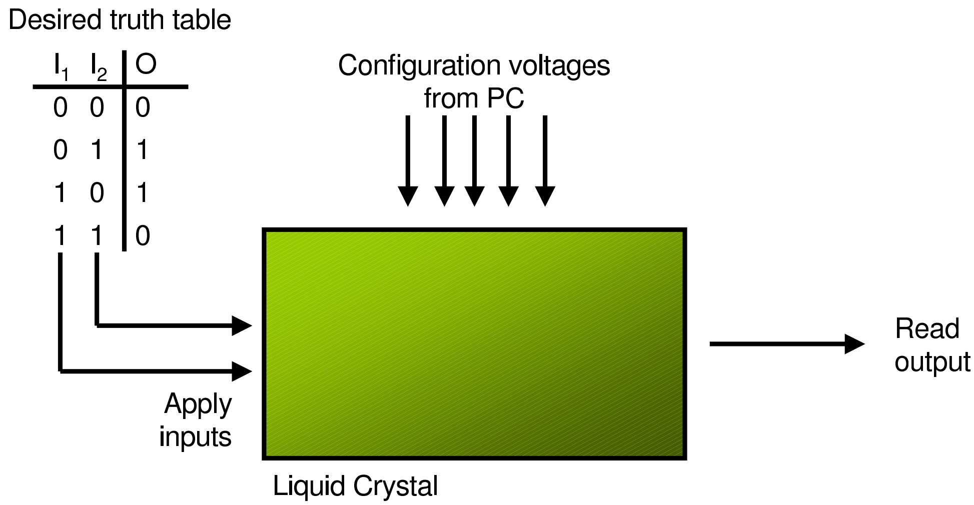

Fig. 8. Diagram showing evolution of logic gates

eight connections to the LCD are already predefined (ground, two incident signals and an output), leaving four voltages to be specified by evolution for configuration.

To clarify this further, the evolutionary algorithm determines three possible voltages and where they may be applied to any of the 64 connectors on the LCD. The algorithm also determines to which of the connectors on the LCD the incident signals will be applied, the connector used to read the output signals from and which connectors should be grounded.

In all the following experiments, a population of 40 individuals was used. The mutation rate was set to 5 mutations per individual. A mutation is defined as randomly taking an element in one part of the genotype and setting it to a randomly selected new value. Elitism was used, with 5 individuals selected from the population going through to the next generation. Selection was performed using tournament selection based on a sample of 5 individuals. Evolutionary runs were limited to 200 generations.

6.2 The Fitness Function

Fitness evaluation was performed by applying each row in the truth table three times, and measuring the response of the liquid crystal. The order in which the input patterns was presented was randomized. The fitness was then calculated as the number of correct output responses given. A perfectly correct solution would receive a maximum fitness score of twelve. A solution where the output was always either HIGH or LOW or where the output was random would receive a fitness of 6. The responses for each evaluation are recorded as a truth table so that it is possible to determine if the evolved solution produced an intermittently

Gate	Min. Evals.	Max. Evals.	Avg. Eval.s	Std. dev
AND	2	1788	910	527.45
OR	1	1779	769	576.01
XOR	44	1255	649	605.50
NOT	3	1750	536	749.58
NAND	13	1763	880	623.18
NOR	1	1788	907	526.97

Table 1. Results showing the minimum, maximum and average number of evaluations required to find a good solution, i.e. where fitness $\geq$ 10 out of 12

working gate. For example, a fitness score of 10 would indicate that for at least one of the applications of the truth table all responses were correct.

We presented the digital inputs to the liquid crystal as static voltages. With +1V representing TRUE and 0V representing FALSE. The threshold voltage on the output was set at 0.1V, i.e. a response of more than +0.1V was accepted as a TRUE output and any other value was FALSE. After presenting an input combination to the liquid crystal, a pause of 20ms was given before reading the response. The sampling of the response was averaged over a short period. This was to ensure that any physical changes in the liquid crystal had time to take effect.

7 Results

The results show that it is possible to evolve many gate types. The effort required to evolve each gate type is shown in table 1. The results show that most of the gate types are extremely fast to evolve, with most of the gates sometimes being produced in the initial population. However, it often takes much longer for the gates to be found. It is possible that the liquid crystal has some sort of memory of previous configurations which may solve the problem, and as the system may not be fully reset it would allow rapid evolution in some circumstances. As expected, XOR proves hardest to evolve. This is probably due to the fitness landscape of the XOR problem - there is very little information in the four test cases for it to learn from. In addition, it is not linearly separable.

The results shown in table 2 show the detailed results from each run. It can be seen that it is rare for a fully functioning logic gate to be produced, and that the system normally only produces intermittently functioning devices. If a configuration has a fitness of 10 or more, then it can be assumed that in at least one of the applications of the truth table all the outputs were correct.

8 Conclusions

We have shown that it is possible to evolve logic gates using liquid crystal, however the evolved gates are intermittent in their behaviour. In this instance,

Gate	Run	Max. Fitness	Evaluation	Gate	Run	Max. Fitness	Evaluation
AND	0	10	48	NOT	0	10	3
	1	11	77		1	10	48
	2	10	6		2	9	23
	3	10	18		3	9	82
	4	10	18		4	11	101
	5	11	484		5	10	43
	6	10	16		6	11	120
OR	0	11	17	NAND	0	10	53
	1	10	184		1	10	18
	2	11	452		2	10	382
	3	11	24		3	10	13
	4	10	10		4	10	35
	5	11	6		5	10	14
	6	12	1500		6	10	149
XOR	0	9	1221	NOR	0	11	13
	1	9	31		1	11	349
	2	9	329		2	11	1405
	3	10	1255		3	11	12
	4	9	953		4	11	1342
	5	9	734		5	11	77
	6	9	319		6	11	957

Table 2. Results from gate evolution. Maximum fitness is 12. A good solution should get at least a fitness of 10 to be considered as intermittently functional.

it is unclear if producing logic gates in liquid crystal is viable. However, previous work has shown that it is a suitable medium for less precise devices - such as robot controllers. It is our belief that the benefits of utilising unusual materials for computation will become more evident when performing non-Von Neumann computation. Here the inherent non-linear and chaotic behaviour may allow for more interesting computation. We have also demonstrated that computer controlled evolution is a suitable programming methodology for computation in materials. It is currently unclear if there is any mechanism by which such systems could be directly programmed by hand.

We have only explored a tiny fraction of the potential of computational matter. We have demonstrated that it is possible to program material systems, in this case using evolution, to provide computation in both classical and non-classical senses. At present our experimental set up is rather crude. In the future we will construct field programmable matter arrays that will allow us to control the material in more sophisticated ways. We believe that this will enable the development of computational devices that offer advantages over conventional devices. It may be possible to build small devices operating at a molecular level, that require low power and may be more resistant to environmental factors.

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