Evolution *in materio*: Initial experiments with liquid crystal

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Abstract

Intrinsic evolution is often limited to using standard electronic components as the media for problem solving. It has been argued that because such components are human designed and intentionally have predictable responses, they may not be the optimal medium to use when trying to get a naturally inspired search technique to solve a problem. Evolution has been demonstrated as capable of exploiting the physical properties of material to form solutions, however, by giving evolution only conventional components, we may be limiting ourselves to solving certain problems. It is hoped by allowing evolution to explore a physically rich environment, it will be able to find novel solutions to tasks presented. This paper investigates the use of liquid crystal as a novel substrate for evolution and demonstrates the feasibility of moving beyond the silicon box.

1. Introduction

It has been argued that evolution in hardware would benefit from access to a richer physical environment [8], however much of the current research still focuses on conventional component based evolution. Evolving in materio may allow us to develop new systems that are based on exploiting the physical properties of a complex system. In [10] we saw that an evolutionary algorithm used some subtle physical properties of an FPGA to solve a problem. It is not fully understood what properties of the FPGA were used. This lack of knowledge of how the system works prevents humans from designing systems that are intended to exploit these subtle and complex physical characteristics. However it does not prevent exploitation through artificial evolution.

This paper introduces liquid crystal as another medium for intrinsic hardware evolution, and demonstrates proof of principle of in materio evolution.

2. The Field Programmable Matter Array

In [8] a device known as a Field Programmable Matter Array(FPMA) was described. 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.

Different candidate materials have been cited for possible use 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, nanoparticle suspensions. In this paper we explorer the use of liquid crystal.

2.1. Liquid Crystal

Liquid crystal (LC) is commonly defined as a substance that can exist in a mesomorphic state [4][5]. 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). In LC there is long-range orientational order but no long-range positional order.

Aromatic LC is often called a benzene derivative. There is also heterocyclic LC where one or more of the benzene rings are replaced with pyridine, pyrimidine or other similar group. LC can also have a metallic atoms (as a terminal group) in which case they are called organometallic compounds. Chemical stability is strongly influenced by the linkage group. Compounds where the aromatic rings are directly linked are extremely stable. LC tends to be transparent in the visible and near infrared and quite absorptive in UV.
There are three distinct types of LC: lyotropic, polymeric and thermotropic. Thermotropic LC (TLC) is the most com-

mon form and is widely used. TLC exhibit various liquid crystalline phases as a function of temperature. They can be depicted as rod-like molecules and interact with each other in distinctive ordered structures. TLC exists in three main forms: nematic, cholesteric and smectic. In nematic LC the molecules are arranged positionally randomly but all share a common alignment axis. Cholesteric LC (or chiral nematic) is like nematic however they have a chiral orientation. In smectic LC there is typically a layered positionally disordered structure. In type A the molecules are oriented in alignment with the natural physical axes (i.e normal to the glass container, depicted by the arrow), however in type C the common molecular axes of orientation is at an angle to the container.

There is a vast range of different types of liquid crystal. LC of different types can be mixed. LC can be doped (as in Dye-Doped LC) to alter their light absorption characteristics. Dye-Doped LC film has been made that is optically addressable and can undergo very large changes in refractive index [6]. There are Polymer-Dispersed Liquid Crystals these can have tailored electrically controlled light refractive properties. Another interesting form of LC being actively investigated is Discotic LC. These have the form of disordered stacks (1-dimensional fluids) of disc-shaped molecules on a two dimensional lattice. Although discotic LC is an electrical insulator, it can be made to conduct by doping with oxidants [1]. LC is widely known as useful in electronic displays, however, there are in fact, many non-display applications too. There are many applications of LC to electrically controlled light modulation: phase modulation, optical correlation, optical interconnects and switches, wavelength filters, optical neural networks. In the latter case LC is used to encode the weights in a neural network [3].

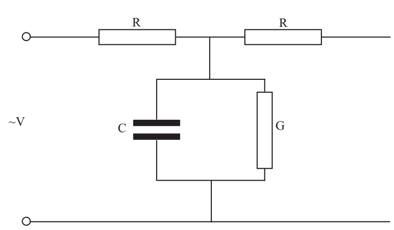

Figure 1. Equivalent circuit for LC

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[9].

3. An Evolvable Motherboard with a FPMA

3.1. Evolvable Motherboards

An evolvable motherboard(EM)[7] 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[7][2] - however they can also be used to evolve in materio by replacing the standard components with a candidate material.

An EM is connected to an Evolvatron. This is essentially a PC that is used to control the evolutionary processes. The Evolvatron also has digital and analog I/O, and can be used to provide test signals and record the response of the material under evolution.

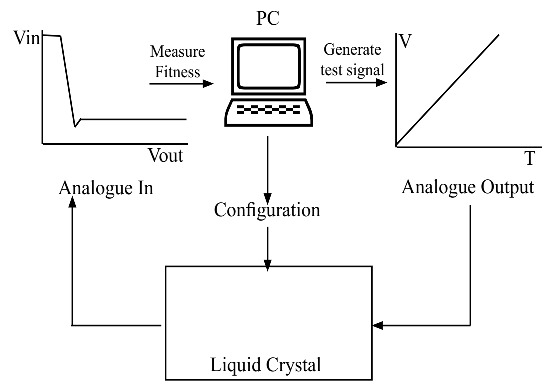

Figure 2. Equipment configuration

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. To clarify, a pixel is a small area of liquid crystal that is affected by voltage applied to an electrode. LC displays are made up of several layers, as shown in figure 3. 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).

It is 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 number of outputs that connect to the

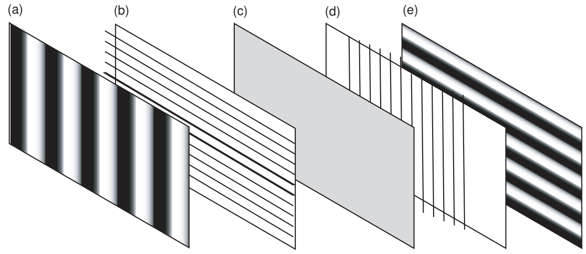

Figure 3. Layers in a LCD

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.

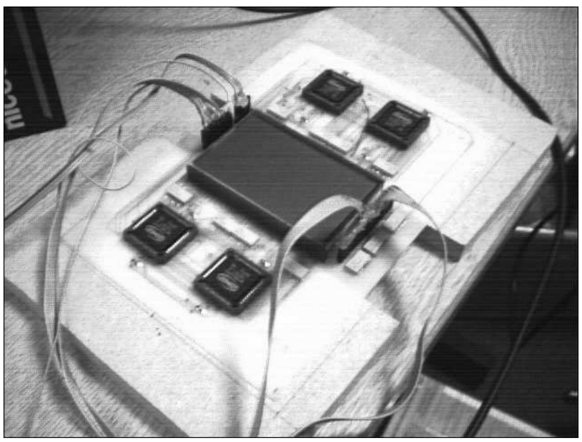

Figure 4. The LCEM

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. One connection was assigned for the incident signal, one for measurement and the other for fixed voltages. The value of the fixed voltages is determined by the evolutionary algorithm, but is constant throughout each evaluation.

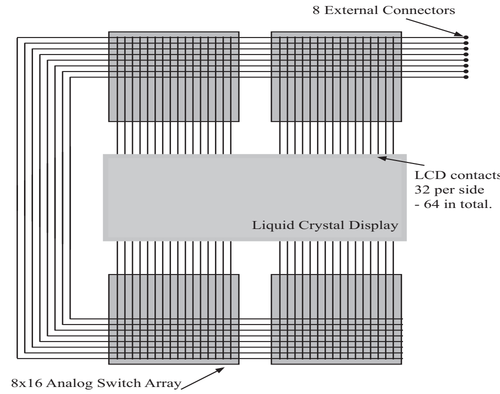

Figure 5. Schematic of LCEM

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 apply configuration voltages (chosen by the evolutionary algorithm) 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.

4. Genetic Representation

4.1 The Genotype

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 applied to the pins on the external connector that are not used for signal injection / monitoring. Three of the external connectors are always connected to ground, the incident signal and to the data recorder. The remaining five have voltages, determined by evolution, that are used to configure the liquid crystal display. Each voltage is represented as a 16-bit integer, the 65536 possible values map to the voltage levels output from -10V to +10V. The second section of the genotype is therefore represented as a string of five 16bit integers.

To clarify this further, the evolutionary algorithm determines five 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 signal will be applied, the connector used to read the modified signal from and which connectors should be grounded.

4.2 Constraints

To help prevent damage and misreading output signals, the genotype has to be limited to configurations that will not be harmful to its phenotypic expression, for example shorting connections together. To achieve this certain connections (for example where the output is measured) are limited to a certain number of appearances within the genotype.

By preventing the genotype from going outside these constraints it is hoped that no damaging configurations can be downloaded into the LCEM. We limit the signal to being applied to only one contact on the LCD and we measure only from one contact.

Unconstrained, the number of possible configurations is $9^{64}X2^{80}$.

4.3. Parameters

In all the following experiments, a population of 40 individuals was used. The mutation rate was set to 5 mutations per individual. 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 100 generations. With each generation taking approximately 30s to evaluate.

5. Experiments

5.1 Evolving a Non-linear Function

The first experiment was designed to discover if the system was capable of evolving a response that was not linear - a system with interesting and complex behaviour. A system would be not linear if its actual recorded response was different to that inferred (by interpolation) from neighbouring samples. A non-linear response in this instance is defined as the variation of $\frac{\Delta VoltageOut}{\Delta VoltageIn}$ against $\Delta VoltageOut$. Where VoltageOut is the signal generated by the PC, and VoltageIn is the signal recorded by the PC from the LC. It was quickly determined that the system could evolve potential dividers or route one of the fixed configuration voltages back to the input, however such a system is trivial. There are many ways that this can be evolved - and some may not require the LC itself.

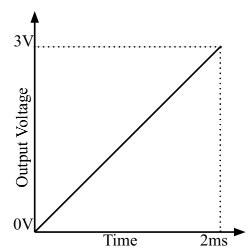

Figure 6. Output from PC

A fitness function was devised to return a measure of the non-linearity of a response. A voltage/time sample was made and an ”edge detection” algorithm was applied (see below). The algorithm has the same effect as a applying a edge detection convolution filter to a 1d image, and is an easy way of detecting inflexions in the response.

A voltage was applied to the EM and ramped from 0V to 3V over a period of approximately 2ms, figure 6. The response from the EM was sampled over this period using the analogue inputs of the PC. The fitness function then parsed the sample and averaged over a number of contiguous samples to produce an expected value for the result in the middle of a small window (of length w, where w=3), figure 7. If the LC response was linear the expected voltage value would be the same as the measured output value. If the response is non-linear (e.g. a step change) then the expected value will

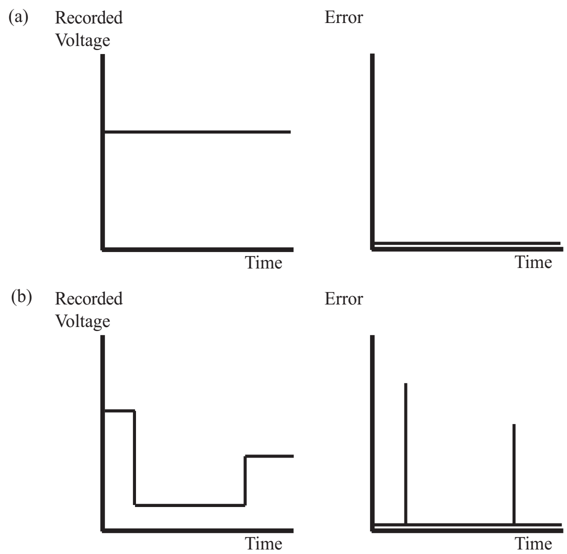

Figure 7. Detecting of inflexions in a voltage/time sample

be different from the recorded value. The total fitness of the response was calculated as the sum of the differences of the expected value for a sample and its actual value. As a side effect, by averaging several values to find the expected response the sample was "smoothed" and noise reduced. Let S be a set of L samples, the input and output samples are represented as $S_{in}$and S_{out}. The jth element of the set is $S\left[j\right]$.

$$fitness = \sum_{i=\frac{w}{2}}^{L-\frac{w}{2}} \left(\frac{\sum_{j=i-\frac{w}{2}}^{i+\frac{w}{2}} S_{out}\left[j\right]}{w} - S_{out}\left[i\right] \right)$$

Several different but common types of response were observed. Sometimes the output held at particular level or was proportional to the input. Over time, responses were evolved that have interesting steps. The fitness function will reward strongly this type of response as there are large differences between the expected and the actual response. Examples of these responses are in figures 8 and 9. It was also noted that the steps disappeared if the analogue signal fed to the LC was slowed (so that it took more than 2ms to apply a voltage sweep), however we have been unable to investigate this phenomena at this time.

Figure 11 shows the best individual's responses from an evolutionary run. The x-axis is voltage in and the y-axis is voltage out. Both axis are in volts.

5.2. Comparisons to Random Search

It was noted that small step responses were often generated within only a few generations, typically less than 5

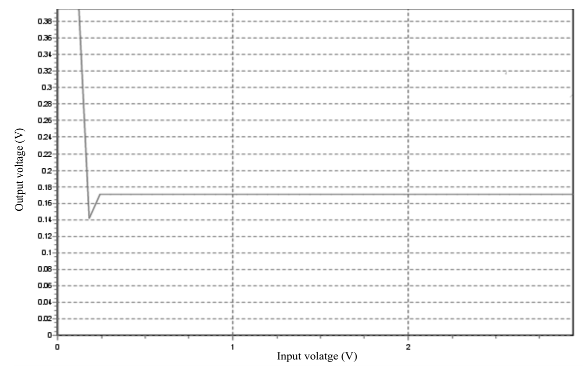

Figure 8. Example 1 of LC response

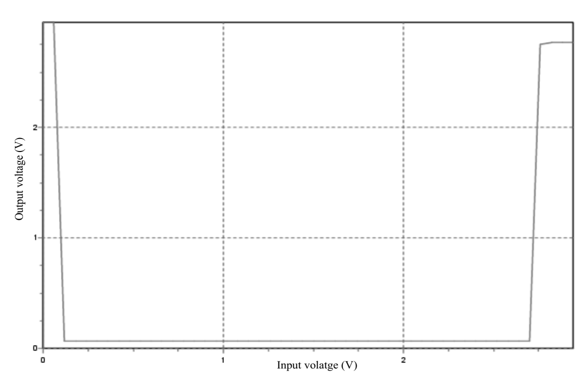

Figure 9. Example 2 of LC response

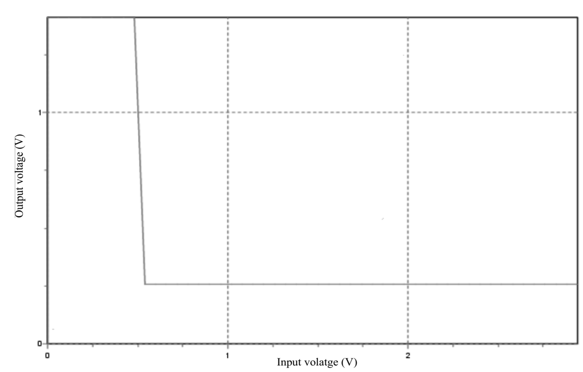

Figure 10. Example 3 of LC response

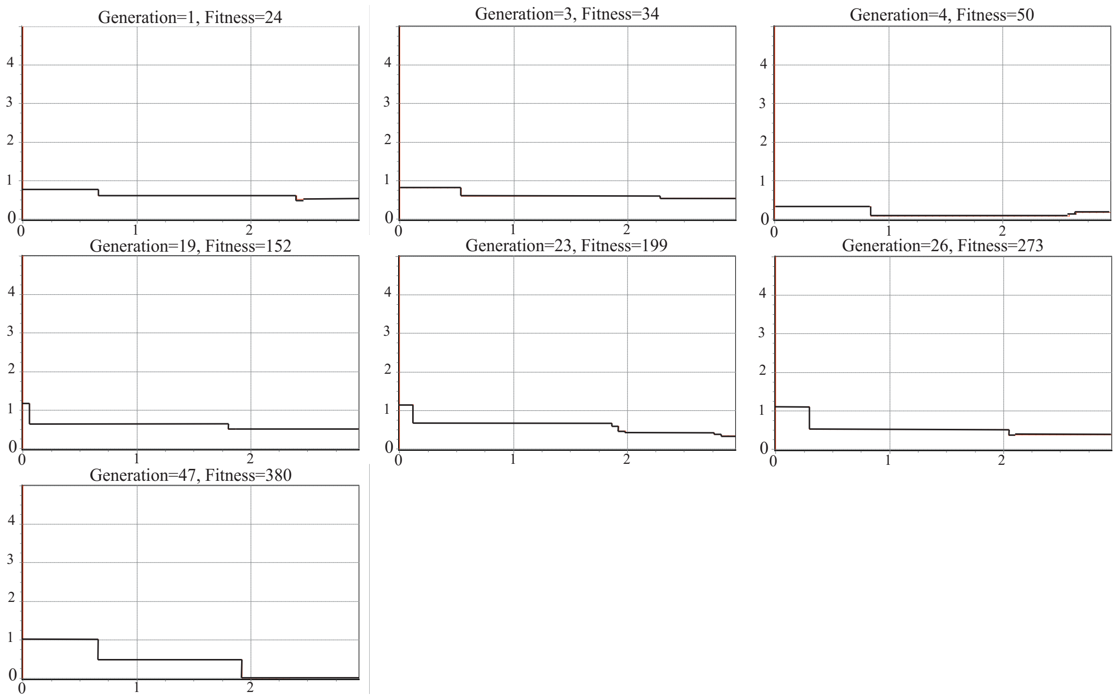

Figure 11. Sequence showing evolution of a non-linear response (output v input voltage)

were needed before a noticeable step occurred. To check that the results were found by an evolutionary process and not by random search the previous experiment was repeated but using random search. In this instance, step functions were not frequently observed. Typically no response was obtained from the LCEM.

As these results were surprising, it was important to try and discover what was causing the responses observed. The inputs and outputs of the LCEM were verified with an oscilloscope, and matched with the results that the Evolvatron was recording. The next experiment was to try the evolution without the LCD. The display was removed from the circuit, and the first experiment repeated. No response was found from the EM. This does not demonstrate that the LC itself is responsible, however it removes the chance that it is some feature of the control circuitry. More experiments will be performed in future to try and demonstrate that it is the LC modifying the input signal - however at this stage we have not constructed a suitable ”dummy” display.

5.3. Evolving a transistor

The next experiment was to try and evolve a transistor. The desired response here is a low output when the input voltage is below a certain threshold and high otherwise. The target threshold was set to 1.5V (in the middle of input voltage range), with a response of 0V below the threshold and at least 3V above. Evolution failed to find a response with the desired characteristics. However, observations of the step functions produced were interesting. It appeared that there were several distinct input voltages at which the steps occurred, and that the switch was from high to low (the opposite of the desired transistor). It is not clear what the causes the step to occur at these input voltages and configurations, and it is hoped future experimentation may provide clues to the mechanism.

However it is our current opinion that these may be related to the energy thresholds of transitions in state of the LC, where a certain voltage is required before the molecules in the LC will change their orientation. The following experiment describes a more unconstrained approach to evolving a transistor, where no target switch voltage was defined.

5.4. Finding The Hot Spots

Following the observation of the step-like responses at particular input voltages, an experiment was set up to try to identify ranges of voltages where evolution could evolve a switching response, i.e. where the LCD exhibits non-linear behaviour to an input voltage. This is essentially the same as attempting to evolve a transistor, however in

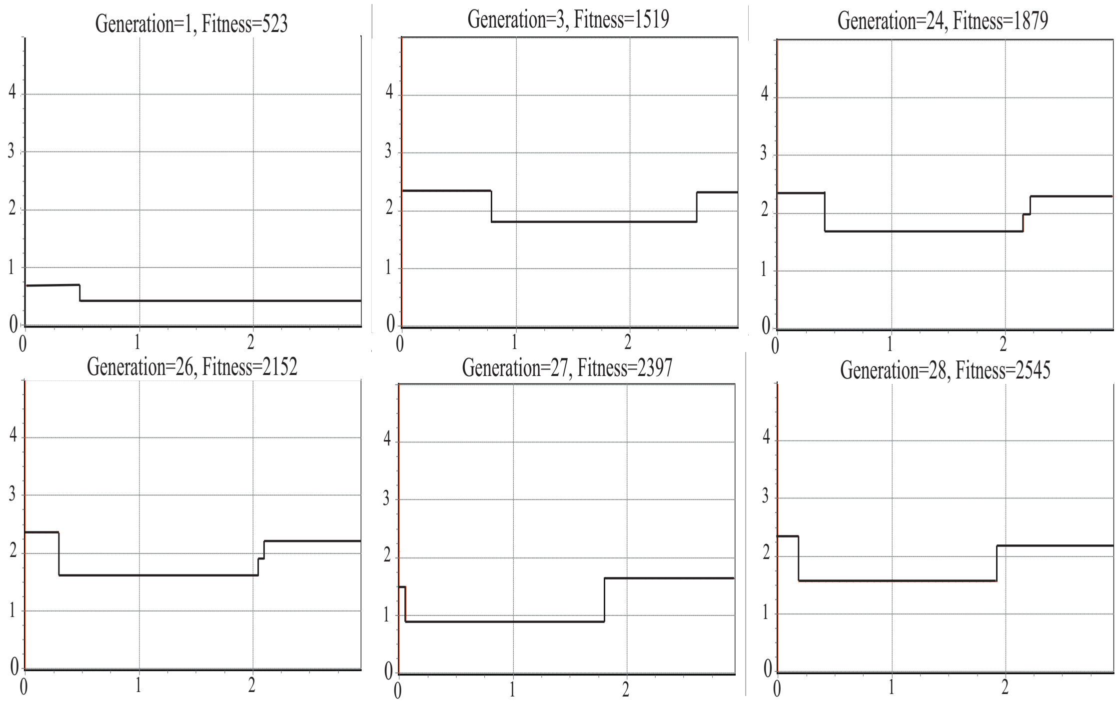

Figure 12. Sequence showing evolution of response at 2V (output vs. input voltage)

this experiment there was no requirement for a switch to occur at any particular input voltage. In this experiment the error on each expected value was weighted (by D) according to its distance from the target switch voltage(T). T was varied between 0.1V and 3V at increments of 0.2V.

$$D = ((MaximumInputVoltage)^2 - (S_{in}[j] - T)^2)$$

$$fitness = \sum_{i=\frac{w}{2}}^{L-\frac{w}{2}} \left(\left(\frac{\sum_{j=i-\frac{w}{2}}^{i+\frac{w}{2}} S_{out}[j]}{w} - S_{out}[i]\right) \times D\right)$$

Figure 12 shows the responses of the best individuals from a typical run. Here the target voltage for a step was 2V. We can see that evolution is able to move the solution toward the target but cannot position the step exactly at 2V.

From figure 13 we can see that there appear to be step functions that cannot be obtained. The diagram maps areas of activity in the liquid crystal by showing at which voltages the response becomes non-linear(a), and what degree of step change we see at these voltages(b). The horizontal axis shows what the voltage was when a response occurred, the vertical what voltage was read from the LCEM. The darker the spot the more frequently a step was observed at this point. If the response from the liquid crystal was purely linear the map would appear all white, however we see that the liquid crystal is capable of behaving in a non-linear way at large range of voltages. However it's ability to do this is non-uniform, in other words it is harder to evolve step functions at certain transition voltages than others. The response seen in figure 12 is in a region where a lower number of steps seems obtainable.

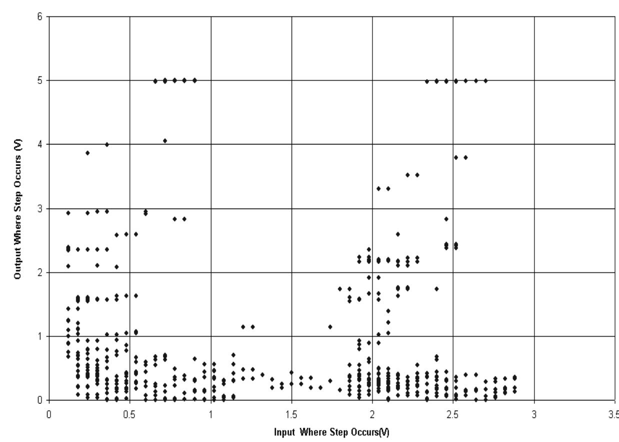

Figure 13. Response hot spots

6. Conclusions

This is the first time that evolution has been attempted in liquid crystal, and these experiments have demonstrated that a LCD can be used as a FPMA. The experiments show that evolutionary refinement can be used to adjust the response. Although these experiments are very limited, they show that the FPMA model described is feasible and that intrinsic evolution has the potential to exploit the physics of a complex system in a controllable manner. More work is required to prove that the LC is responsible for the observed results and to attempt to discover how the LC is being exploited.

7. Acknowledgments

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www.evolutioninmaterio.com

References

[1] S. Chandrasekhar. *Handbook of Liquid Crystals*, volume 2B. 1998.

[2] J. Crooks. Evolvable analogue hardware. Meng project report, The University Of York, 2002.

[3] W. A. Crossland and T. D. Wilkinson. *Nondisplay applications of liquid crystals*, volume 1. 1998.

[4] D. Demus, J. Goodby, G. W. Gray, H. W. Spiess, and V. Vill, editors. *Handbook of Liquid Crystals*, volume 1,2A,2B,3. July 1998.

[5] I. C. Khoo. *Liquid Crystals: physical properties and nonlinear optical phenomena*. Wiley, 1995.

[6] I.-C. Khoo, S. Slussarenko, B. D. Guenther, M.-Y. Shih, P. Chen, and W. V. Wood. Optically induced space-charge fields, dc voltage, and extraordinarily large nonlinearity in dyedoped nematic liquid crystals. *Optics Letter*, 23(4):253–255, 1998.

[7] P. Layzell. A new research tool for intrinsic hardware evolution. *Proceedings of The Second International Conference on Evolvable Systems: From Biology to Hardware, LNCS*, 1478:47–56, 1998.

[8] J. F. Miller and K. Downing. Evolution in materio: Looking beyond the silicon box. *Proceedings of NASA/DoD Evolvable Hardware Workshop*, pages 167–176, July 2002.

[9] A. F. Naumov and M. Y. L. et al. Liquid-crystal adaptive lenses with modal control. In *Optics Letters*, volume 23, pages 992–994, 1998.

[10] A. Thompson. An evolved circuit, intrinsic in silicon, entwined with physics. In *ICES*, pages 390–405, 1996.