Evolution in Materio: Exploiting the Physics of Materials for Non-Classical Computation

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Abstract

In this position paper we report on our work on programming materials for non conventional computing, using an evolutionary algorithm as the programming technique. The aim is to use the complexity of the physical world to allow sophisticated computation, and in particular as a platform for non-Von Neumann computation. We have demonstrated this technique using liquid crystal for signal processing and robot control, however we believe that there are many materials that could be programmed in a similar way. It is hoped that such a methodology will provide a general technique for extracting useful computation from matter, possibly at a molecular level.

1 Introduction

There are many physical processes that can be described as a computation. For example, crystal growth from nucleation, corrosion-dendrites on an electrochemical electrode, a drop of ink dispersing in a glass of water, are all physical/chemical processes of increasing complexity that can be thought of as a computation. Further, since biological systems are part of the physical universe then the development of an organism from a fertilized egg is also a computational process. The common element in each of these processes is the fact that the computation is taking place only between nearest neighbours. There is no global clock, or central processor to distribute tasks to the individual processes comprising the overall system.

Many of these processes are either difficult or way beyond current computational abilities for modelling. It is likely given a supercomputer and the set of differential equations and boundary conditions that describe some of these processes we would find that our computed results are only an approximation of the real-world system. We find that the world is a better model of itself than the models we can induce from our data. Many of these problems are not only computationally intractable, but also computationally undecidable [15] [11].

As an example, consider an array of magnetic spins in which each site takes on only one of two spin states. At a high temperature the spins will be randomized, but as we cool the array down to much lower temperatures we will find spatial correlations among the spins. This system is computationally tractable only if we make certain simplifying assumptions. But even then, we cannot compute the exact spatial correlations, only the general picture. This example is a particularly interesting problem because we can compute correlations either using detailed quantum mechanics and differential equations, or we can utilize automata theory and obtain essentially the same result (more on this later). Of course the automata theory approach is computationally much faster then the differential equation approach, and the real-world process is even faster. Feynman has implied that the automata theory approach is a potentially more realistic description of the dynamics at the meso- micro- and nano-scale, than systems of differential equations. The tiny ”computational agents” at those scales do not compute differential equations. They simply interact with their nearest neighbours and swap information, Garzon cites a Feynman quotation[4]:

> ”It always bothers me that according to the laws [of physics] as we understand them today, it takes a computing machine an infinite number of logical operations to figure out what goes on in no matter how tiny a region of space and no matter how tiny a region of time. How can all that be going on in that tiny space? Why should it take an infinite amount of logic to figure out what one tiny piece of space-time is going to do?” (Richard Feynman)

If the only process taking place is information being

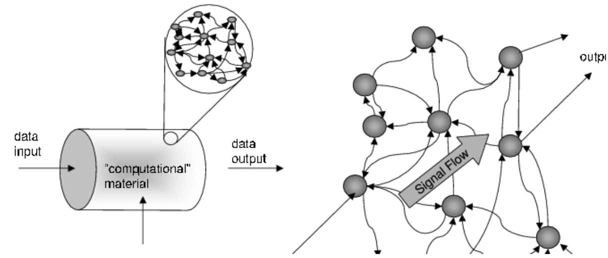

Figure 1. Schematic of proposed computational system with bulk matter

swapped by nearest neighbours, then as Stephen Wolfram proposes, there may be a universal rule set that governs nearly all the dynamics observed in the universe at all scales [16].

As Yashihito [17] and many others, have pointed out that as the device sizes shrink and the level of integration in microcircuits increases we will more closely approach the nanoscale. What was clearly articulated by Yashihito is that we should be able to use matter itself for our computations. We should be able to exploit the molecular dynamics and meso-scale physics for computations. Yashihito did not make explicit suggestions on how to undertake this task. It is amusing to note that in the 1950s an eccentric scientist was conducting experiments to grow neural structures using electrochemical assemblages[12, 13, 1]. Gordon Pask's goal was to create a device sensitive to either sound or magnetic fields that could perform some form of signal processing - a kind of ear. Using electric currents, wires can be made to self-assemble in an acidic aqueous metal-salt solution. Changing the electric currents can alter the structure of these wires and their positions - the behaviour of the system can be modified through external influence. Pask used an array of electrodes suspended in a dish containing the metal-salt solution, and by applying current (either transiently or a slowly changing source) was able to build iron wires that responded different to two different frequencies of sound- 50Hz and 100Hz.
Recently, Miller suggested a variety of physical systems that might be configured to carry out computation[9]. One of the suggestions was liquid crystal. This has recently be shown to be possible; Harding and Miller [6, 5] have demonstrated for the first time that liquid crystal can be evolved to do analogue filtering. This will be discussed in the following section.

Figure 1 shows a schematic of the proposed technology. Basically we will utilize a block of matter (solid, liquid, or gas) for which we can change its properties/behavior by external forces. The external forces induce property/behavior changes, which we will call the "computer program." So there is a direct link between the external forces that we have control over and the induced changes in the block of matter. Now by measuring the behavior of the altered block of matter we can essentially submit input data to the sample and receive output data. In this way we have performed a type of computation.

Of course we cannot directly program the molecular dynamics and we do not have control of the molecules, at least not directly. The molecules will interact with their nearest neighbor and we can exploit this phenomena along with the state changes in regions of the block of matter, in order to perform computations. Figure 1 shows a nanoscale schematic. In this work, we use liquid crystal as the bulk matter, and demonstrate a technique that can be used to "program" liquid crystal to perform computation in the form of signal processing.

2 Evolution In Materio

2.1 Introduction

Miller and Downning[10] argued that the lesson that should be drawn from the work of Thompson[14] is that evolution may be used to exploit the properties of a wider range of materials than silicon. They refer to this as evolution in materio. Thompson had found that an evolutionary algorithm used some subtle physical properties of an FPGA to solve a problem[14]. 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. Miller suggested that a good candidate for evolution in materio was liquid crystal[10]. Recently this suggestion has been vindicated by recent work by Harding and Miller[5] who showed that it is relatively easy to configure (using computer controlled evolution) liquid crystal to perform various forms of computation.

2.1.1 Liquid Crystal

Liquid crystal (LC) is commonly defined as a substance that can exist in a mesomorphic state [3][7]. 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.

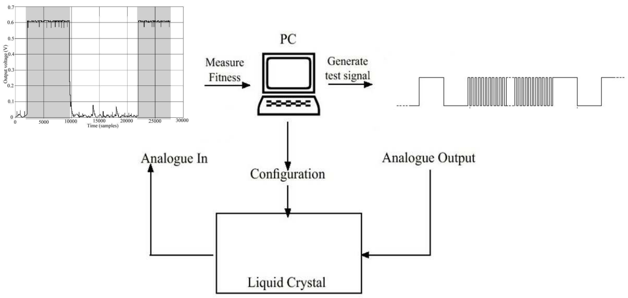

Figure 2. Equipment configuration

2.2 An Evolvable Motherboard with a FPMA

An evolvable motherboard(EM)[8] 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 [8, 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.

In the experiments presented here, a standard liquid crystal display with twisted nematic liquid crystals was used as the medium for evolution. 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 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 was unsuitable for the task of intrinsic evolution. There is a 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

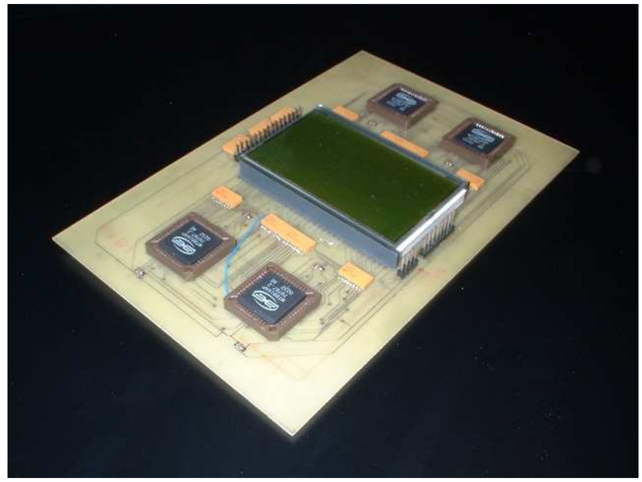

Figure 3. The LCEM

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.

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

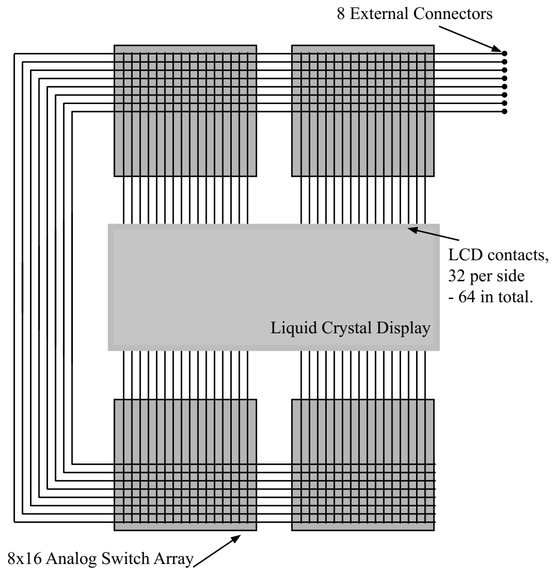

Figure 4. Schematic of LCEM

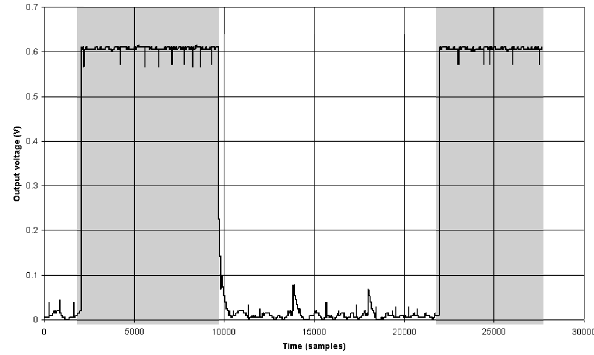

Figure 5. Tone discriminator response. Dark areas indicate 5kHz input, light 100Hz

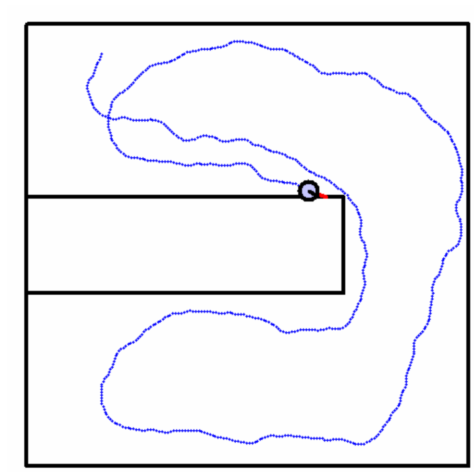

Figure 6. Path of an robot controlled using liquid crystal

for the switch arrays there are no other active components on the motherboard - only analog switches, smoothing capacitors, resistors and the LCD are present.

2.3 Systems Evolved In Liquid Crystal

2.3.1 Tone Discriminator

A tone discriminator as a device which when presented with one of two signals input signals returns a different response for the each signal. In [14], on which this experiment is loosely based, the configuration 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. An example of the evolved response in shown in figure 5.

2.3.2 Real-time Robot Controller

We have recently demonstrated, for the first time, that it is 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 6. 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).

2.3.3 Logic Gates

We have recently demonstrated that it is possible to evolve logic gates exhibiting digital behaviour in liquid crystal. As expected, they operate at much slower speeds than conventional devices and the behaviour can be intermittent. We do not feel that systems such as liquid crystal should be used in this manner, and that they are much more suited to non-classical computation.

2.4 Conclusions

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.

Such devices may be more appropriate than existing technology for un-conventional and non-Von Neumann computing. The work with liquid crystal has demonstrated the viability of programmable materials and that an appropriate programming technique exists in the form of evolutionary search.

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