The Not So Digital Future of Digital Signal Processing

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I. INTRODUCTION

Before the digital revolution, image and signal processing was performed using analog circuitry. Today digital signal processing (DSP) has defined our lives. Although some mixed-signal designs are of current interest, DSP dominates everything that we own or use everyday. DSP chips exist in many devices such as our cell phones, our iPods, our wireless router, our new HDTV.

The purpose of this paper is to consider possibilities of DSP outside the semiconductor or electronic domain. Organic elements (such as DNA and polymers) that conduct electricity can be used to build organic semiconductors at the molecular level [1]. However, more fundamental questions can be asked. Can DSP be performed in exotic materials, such as chemical substrates, cells, organisms, or even DNA, without the use of electrical currents? Will we be able to build fully blown DSP systems out of these materials? Or will some DSP functions (such as storage and data archiving) be implemented with such materials? We do not attempt to provide a thorough scientific review of such means but to stir the engineering community towards a possible not-so-electronic future of DSP.

II. CHEMICAL-BASED DSP

There has been an extensive amount of research on reaction-diffusion media, which are implementations of chemical oscillators. Chemical oscillators are systems of chemical reactions that exhibit oscillatory behavior when not in the equilibrium state. The concentration of reagents and products varies over time. A certain category of those are light-sensitive and can store input information during long periods of time. When stimulated by light and controlled by the acidity of the medium (mixture of chemical compounds), basic or complex image transformations such as contour enhancement, image segmentation, image halftoning, and others can be achieved (see [2, ch. 3, 4]). The mathematics behind the above processes are systems of nonlinear differential equations. Although nonlinear image processing with computers is not new, it is extremely fascinating to see chemical media perform complicated image-processing tasks in a short period of time.

III. ORGANISM BASED DSP

The beautiful colors found in Impressionistic paintings were the result of scientific discovery of novel pigments.

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But sometimes art can drive scientific evolution. Take, for example, the artist/scientist Cameron Jones from Australia. He used fungi to process audio signals. He recorded music on compact discs (CDs) and then used the CDs as substrates to grow fungi. He put the CDs in his CD player and watched how the optically recorded sound was distorted by the fungi. Surprisingly the fungus growth patterns were dependent on the optical grooves recorded on the CD. The fungi were reacting to the recorded information. The audio track was "processed" by the grown fungus. This interface of optics and biomaterials was a clear demonstration that signal processing can be performed with other means.

Going into a smaller scale, individual proteins can be used to perform processing. For example, protein-based memories utilize the light sensitivity of a special category of proteins. A protein that is often used is *bacteriorhodopsin*. This protein is found in the bacterium *Halobacterium halobium*, which thrives in environments with high salt and low oxygen concentration. If oxygen levels drop, the purple membrane of the bacterium grows to expose bacteriorhodopsin. The protein converts light into energy by pumping a proton through the membrane, creating a chemical and osmotic potential. This cycle can be repeated millions of times, and the protein can survive high temperatures. In a few words, the protein is an excellent medium for storing information, since it can last a long time and has rewritable abilities and truly nanoscale size. A film of the protein can be deposited as a layer on an appropriate substrate. Light exposure, via direct light or laser, can be used to stimulate the protein and thus record the input light information (could be an image). Information can be read out using a laser as well.

The fact that biological materials are used for storage opens the door to a unique method of material optimization. Although such optimization is complex and requires extensive knowledge of the substance's properties, evolution through genetic modifications can be used to generate altered versions of the substance. Each outcome can be tested for its performance, and new and improved generations of substances can be further generated as mutations of the previous outcomes.

In fact, this has happened already. Light-sensitive proteins are taken from one bacterium and are placed in more "programmable" bacteria such as *E.coli* (since its genetic code has been studied longer). Synthetic biology is doing exactly this. It modifies the genetic code of organisms to add "novel" functionality, such as light responsivity, NOT, AND, and OR gates. There is a lot of activity in this area with conferences and dedicated journals, and an established database of standard biological parts (BioBricks^{TM}). There is even a competition (the International Genetically Engineered Machine Competition) where students compete in designing biological systems that can perform simple computations. In the 2005 competition, students made a biofilm (layer) of bacteria that could perform distributed edge detection on an image. *E.coli* cells were modified to react to light using a light-sensing protein and change their state according to their neighbor cells. All the needed parts were taken from the bioBricks database. As a result, the edges of a projected image were found. In another example [3], *E.coli* was modified in a similar fashion to store image data with a theoretical resolution of 100-Mpixels/in^2 (or 108 bacteria/in^2). An image was projected to the bacteria layer and read using a weak laser.

As is well known, the building blocks of a DSP processor are addition, multiplication, and buffering or delay. One can envision the possibility of designing gene circuits that behave like digital filters and process input information.

IV. DSP WITH DNA

Similarly, logic circuits can be built using just DNA molecules. The DNA double helix is made from two single strands of DNA, each of which is a sequence from the quaternary alphabet (A,T,G,C). The two single strands are held together due to hybridization of the complementary sequences. A complement sequence of a strand is the one found by performing the Watson–Crick complement rule (A-T, G-C). Using DNA strands as input and processing elements, the simple hybridization force can act as a powerful computational tool. The sequence of input and processing strands can be designed in such a way that their hybridization can be predicted and controlled. Using this basic principle, complex molecular structures and basic arithmetic operations can be performed. DNA computing is the field that utilizes DNA to perform computation.

The literature abounds with demonstrations of DNA circuits that behave like transistors and adders and point to the future when complex DNA circuits acting as digital filters are realizable. For example, Winfree's group at Caltech presented a method for the self-assembling computation of the Sierpinski triangle [4]. DNA single strands hybridize with each other to form tiles (building blocks) that self-assemble to build complex structures (like the triangle). They described the correlation between the Sierpiński triangle and the binary version of wavelet and Fourier transforms, as well as the Hadamard transform. Self-assembly and tiling can also be used to study Markov fields, which have been extensively used in image processing. In the future, one can imagine a self-assembly approach to image processing following similar principles. The same group has demonstrated a hybridization-only [5] and entropy driven [6] protocols for implementing logical gates, signal restoration, amplification, cascade, and feedback, thus developing DNA-based logical circuits. Such development brought us closer to the possible realization of DNA-based DSP circuits.

Our group at Northwestern has been studying the use of DNA for DSP for a number of years [7]. Due to its

unique characteristics, DNA is an excellent medium for storing information, resulting in the creation of a DNA-based database of digital signals [8]. Digital samples can be recorded in DNA strands using, instead of their binary representation, the quaternary DNA alphabet. After they are synthesized, DNA sequences can be kept in liquid form placed in test tubes, freeze-dried to save volume, or even piggybacked among the genome of organisms (i.e., bacteria). Once they are stored, DNA sequences can be replicated economically with commonly used laboratory techniques. This allows for the creation of database replicas with low cost. The most attractive aspect of this approach is that querying the database can be implemented with a plethora of techniques. With digital databases, the query time increases proportionally to the size of the database. However, in DNA databases with appropriate search mechanisms, the querying time is independent of the database size under certain conditions.

V. CONCLUSION

If we were allowed to be naïve as to offer a prediction for the future, we believe that the turning point in the organic future of DSP is to see which technology, from the aforementioned or from the ones to come, will allow for the implementation of a fast Fourier transform combined with elegant and not tedious input–output procedures. We believe that DNA-based logical circuit design will materialize first followed by synthetic gene networks. DNA exploration is driven by two large forces: i) human sustainability, as in understanding organism formation, development, evolution, and function, and hence finding cures for diseases, and ii) engineering curiosity, as in trying to utilize DNA and genes to do computations. This has led to a growth and cost reduction similar to that witnessed by the semiconductor industry (see Moore's law). The cost and delivery time of DNA synthesis is being reduced exponentially, thus making data input elegant and economical. DNA sequencing, replication, and filtering are getting cheaper and faster everyday, having a similar effect on data output. For example, sequencing the human genome the first time took ten years and a couple of billion dollars. Now there exist commercially available sequencers (for example, from 454 Life Sciences) that can do it in months at a fraction of the cost, with prospects to reduce it to days and below $1000, as set by The $1000 Genome Project and the recently announced X-Prize. DNA equipment is getting even smaller, considering, for example, NEC's portable DNA lab in a briefcase, and cheaper, such that anybody can process the signals in the office and later at home pull out their Discovery's DNA Explorer Kit or CSI's DNA Lab Kit and with their kids (or alone satisfying their inner child) manipulate and analyze DNA in their living room. But of course don't forget to feed the bacteria that nurture your precious jazz collection. ■

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