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Programmable VLSI Extended Analog Computer for Cyclotron Beam Control

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Programmable VLSI Extended Analog Computer for Cyclotron Beam Control

1. Introduction

Extended analog computers (EACs) are conductive sheets surrounded by multiple Lukasiewicz logic arrays (LLAs). CMOS VLSI conductive sheets consist of one or more layers in an integrated circuit with ohmic contacts assigned as input current source/sinks and either voltage or current output probes. LLAs are arrays of current mirrors or diodes that implement the primitive continuous-valued function $A \supset B$, algebraically equivalent to $\min(1, 1-A+B)$. The topology of the conductive sheet, the material from which it is constructed, and the boundary-value LLA functions determine the computation that the EAC performs.

A VLSI EAC beam line controller with a fully-analog computation path and digital inputs to dynamically reconfigure the control function was designed, simulated, and is now being fabricated as a MOSIS 'TinyChip'. Each chip can be configured to control either a dipole or a quadrupole electromagnet in the Indiana University Cyclotron Facility's cyclotron beam lines and adjusted to take into account the beam optics at each magnet's location. The EAC solves the inverse of the electromagnetic wave equation, "looking" at the resulting surface with an LLA retina to locate the beam's position, then generating the magnet control signal with two digitally-programmable LLA function generators.

2. Previous work

The extended analog computer (EAC) was defined in [Rubel 1993]. VLSI EACs, originally called Kirchhoff machines, were first proposed in [Mills 1995]. A VLSI EAC does not use a CPU or op-amps to perform arithmetic and logic functions, but subsumes these functions by combining conductive sheets with programmable Lukasiewicz logic arrays. Conductive sheets and diode function generators that are similar to LLAs were used separately in previous analog computers [Karplus 1958, Hausner 1971, Korn/Korn 1964].

EACs are more flexible than conductive sheets alone or their discretized versions, resistive meshes [Harris/Koch/Luo/Wyatt 1990]. Conductive sheets and resistive meshes have long been known to solve the ordinary and partial differential equations that describe problems in electrostatics, electron ballistics, electric fields, magnetic fields, elasticity (including stress analysis), heat transfer, and viscous and nonviscous fluid flow [Kirchhoff 1845, Karplus 1958]. EACs can also solve problems based on reaction-diffusion equations, such as morphogenesis, neural field computing, and basal ganglia models for robot path planning and control [Mills 1995, Turing 1992, Murray 1993, MacLennan 1990, Connolly/Burns 1993].

Lukasiewicz logic arrays (LLAs) were described in [Mills/Beavers/Daffinger 1990, Mills 1990]. LLAs were reduced to simple circuits, some consisting of trees of diodes in [Mills 1992]. LLAs are thus similar to the diode-resistor function generators of [Wilkinson 1963]. LLAs were used to implement a silicon retina and characterized in [Biswas 1994]. The performance of LLAs compares favorably to digital equivalents [Montante 1994, Montante 1995].

Research in beam instrumentation and control is reported in the proceedings of various workshops held on the topic. From these proceedings it appears that the use of digitally-reconfigurable analog control that embeds a conductive sheet simulator is new, although use of operational amplifiers, filters, etc. for beam control is well-known [Cresswell/Heywood/Gurd/Johnson/Lacey 1972].

3. Design of the VLSI EAC beam line controller

IUCF currently uses open-loop control of the steering and focusing magnets on the beam line. Sensor data from beam position monitors (BPMs) is presented to a human operator, who adjusts the magnetic field of each dipole and quadrupole magnet to maximize beam intensity. There is no direct feedback from the BPMs to the dipole and quadrupole magnets, which means that deviations from the engineered trajectory must be manually tuned each time the beam is restarted for a new experiment. Closed-loop control with a digitally-reconfigurable VLSI EAC provides feedback from a BPM to a specific dipole or quadrupole magnet. The EAC can be adjusted for the beam optics at each magnet's location, as well as operational variations detected by the human beam line operator (Figure 1). Improvements anticipated are reduced time to tune the beam, increased beam temperature, and increased beam stability.

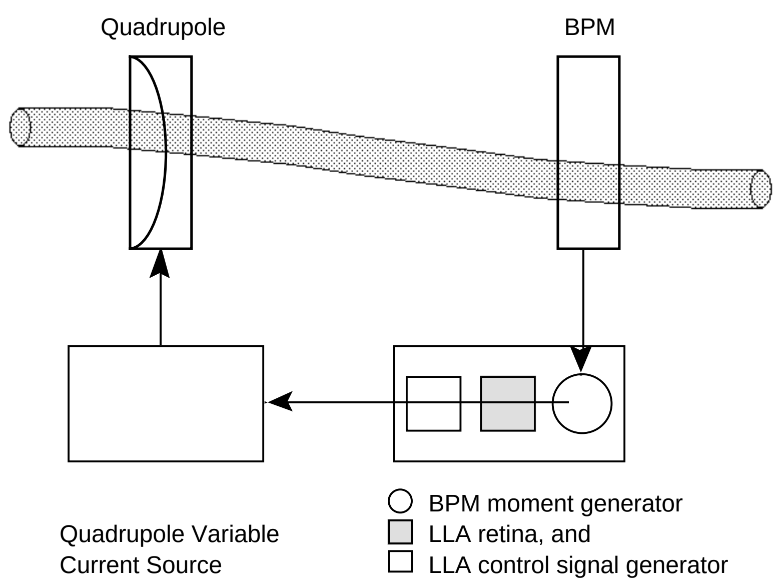


Figure 1.

The beam line controller is implemented as a digitally-reconfigurable VLSI EAC. It was designed visually by creating an *object analog* for the beam cross section, a *sensor analog* to 'view' the beam cross section, and a *response analog* to generate the control signal based on the difference between the beam's measured and desired positions. This technique is certainly not general to all problems, but is indicative of one simple, modular, and structured approach to controller design with an EAC.

The object analog is a conductive sheet that generates a surface that combines the inverse of the beam's moments. The sensor analog is an LLA retina. The response analog is a pair of LLAs that generate an adjustable control signal proportional to surface gradients along the X- and Y-axis of the beam cross-section reconstructed by the conductive sheet. These gradients are proportional to the beam moments, which need not be computed explicitly to generate a real-time control signal for the dipole and quadrupole magnets in the IUCF beam line.

3. Simulation of the beam inverse moment generator

The major question in EAC design concerned the conductive sheet. A foam conductive sheet was built that generated surfaces combining the inverses of the zeroth (intensity), first (position), and second (aspect) beam moments from simulated BPM data (Figure 2). The mathematical basis for the foam's computation is the equation for wall current density induced in the BPM sensors [Yin 1990, Yin/Rawnsley/Mackenzie 1994].

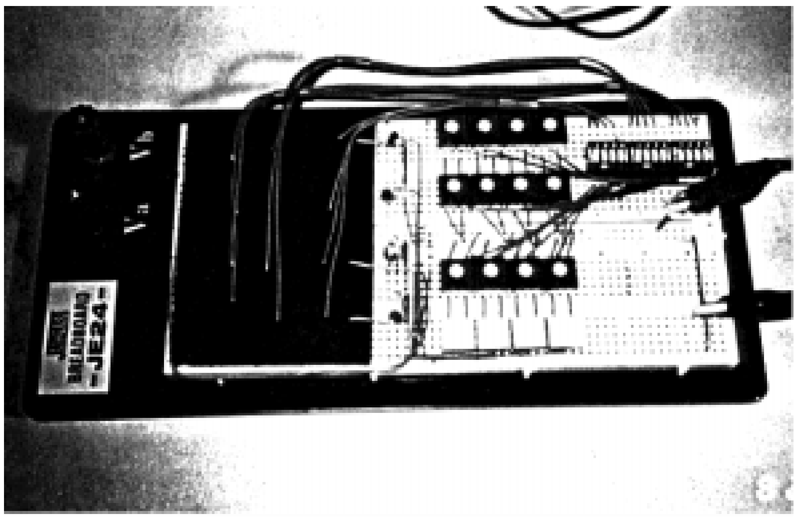
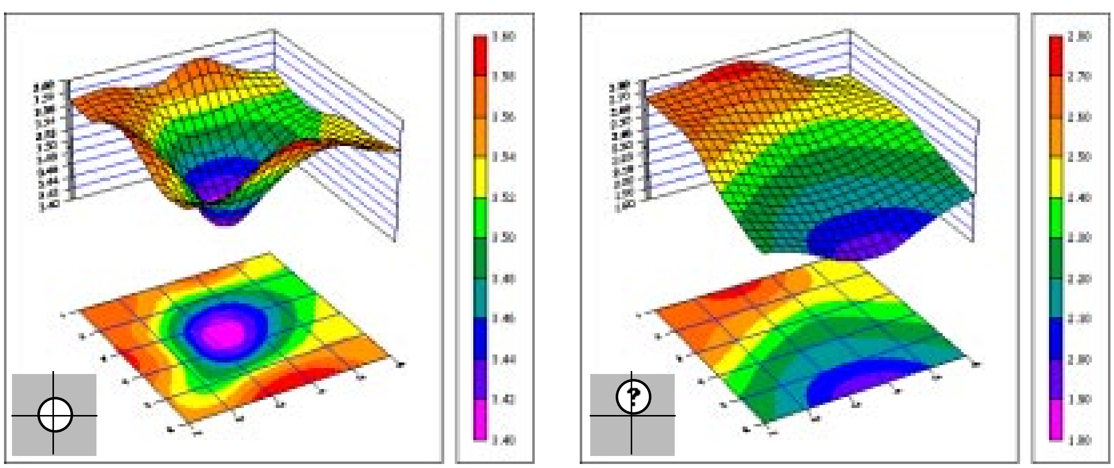


Figure 2.

Because the BPMs in use at the IUCF have only four sensors, second moments are not uniquely determined unless the beam is highly elliptic along either the X or Y axis of the BPM sensor pairs. The foam sheet, which can be considered a random mesh, computed the beam moments from simulated BPM readings, but also indicated that foam has fixed but unpredictable inhomogeneities (Figure 3).



a. Beam centered and circular

b. Beam centered on Y-Axis but above X-Axis, aspect unknown

Figure 3.

The correctness of the conductive foam computation was tested with a SPICE simulation of the sheet as a 50x50-element square resistive mesh. The SPICE output is smoother and shows certain features, specifically the points at which current is input into the sheet, in greater detail (Figure 4).

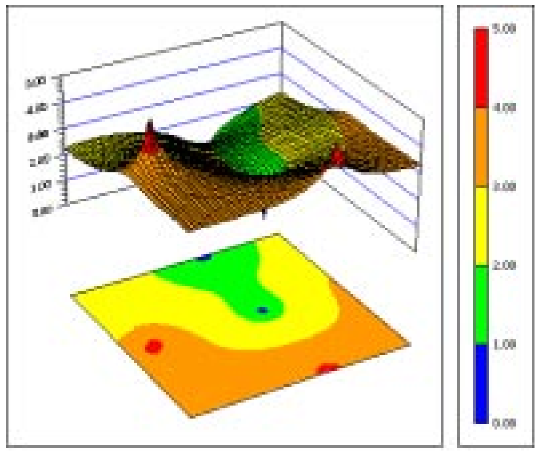
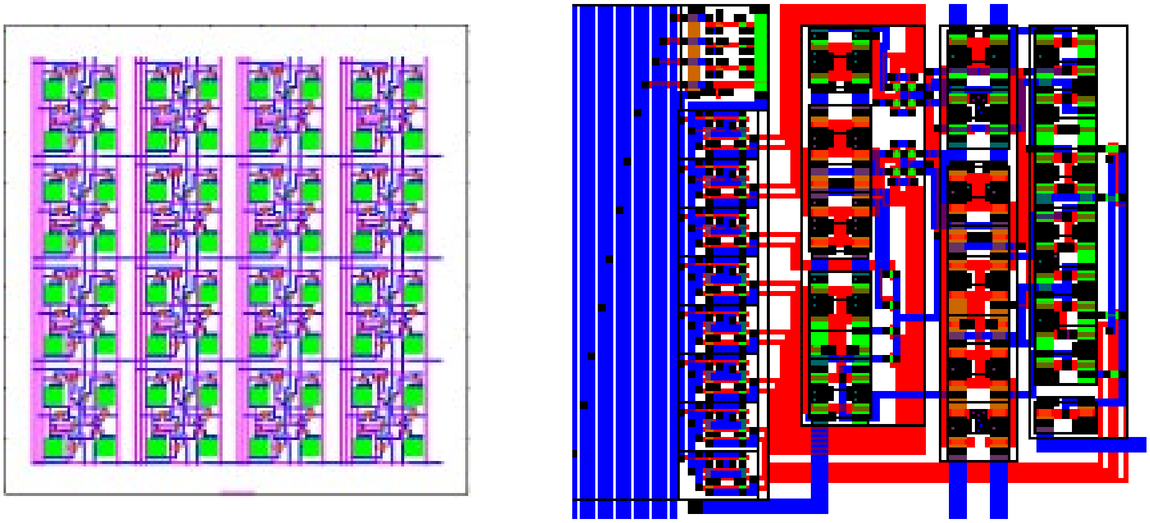


Figure 4.

Neither the conductive foam nor the SPICE simulation accurately describes the smooth implantation gradients that affect the homogeneity, uniformity, and isotropicity of CMOS VLSI conductive sheets. PISCES, a material-level device simulator, has been suggested to simulate the conductive sheet and its interactions with the input and output contacts [Dutton/Yu 1993].

4. The LLA retina and digitally-reconfigurable function generator

Operational LLA circuits for the retina and various function generators have been previously fabricated [Mills 1992, Biswas 1994, Montante 1995]. Examples of both circuits are shown (Figure 5).



8x8 pixel LLA retina (shown in MOSIS "TinyChip" active area)

Bus, Address Decoder and 8-bit Memory

LLA Standard Cells Implementing Analog Multi-function Unit

Figure 5.

The LLA retina circuit used in the VLSI EAC is much smaller than those built before because the LLA's inputs are driven by contacts to the conductive sheet instead of the much-larger phototransistors.

The digitally-reconfigurable LLA (Figure 5) is smaller than the original H-tree array of Lukasiewicz implication [Mills/Beavers/Daffinger 1990, Mills 1990, Mills 1992]. H-trees are reconfigured to compute different functions by enabling or disabling subtrees as *true* or *false* inputs are applied at the leaf nodes of the tree. This is an inefficient and wasteful use of circuit area. The LLA function generators in the beam line controller use multiplexed inputs and outputs to reconfigure the LLA. 256 analog functions are digitally programmable; of these 27 are *basis functions* that result from the piecewise-linear covering of the continuous [0,1] range and domain dissected by the constants {0, .5, 1} (Figure 6).

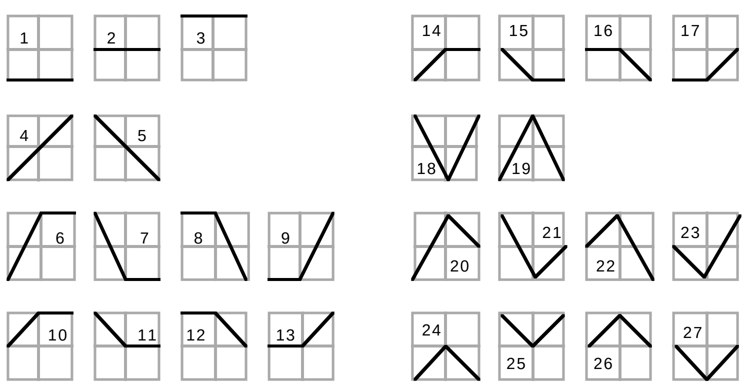


Figure 6.

The beam line controller sums the output of a pair of LLAs to generate a control signal for the dipole or quadropole magnet. The signal varies with the beam X and Y position according to the surface resulting from the pair of functions selected, and can be varied during beam operation (Figure 7). The LLAs can be viewed as a compactly-encoded continuous-valued look-up table.

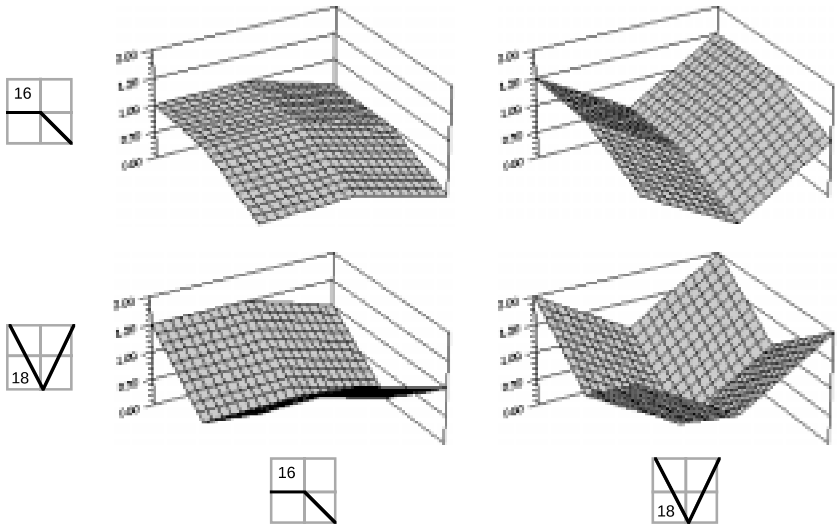


Figure 7.

4. Testing the EAC beam controller

The VLSI EAC beam controller must be thoroughly tested before installation on the IUCF cyclotron beam line. Even though earlier LLAs demonstrated up to 10-bit precision, and accuracy to 1% of full range in the laboratory, the beam line is a hostile environment, subject to EMF interference and large transients due to corona discharges.

Performance of the controller will be evaluated using the analog test board [Montante 1994] and data files obtained during live beam line operation before installing them on the IUCF beam line. The output of EACs from different MOSIS fabrication runs will be compared to determine the mean and standard deviation of the control signals computed. The control signals from the EAC tests will be compared to the signals actually used to control the selected magnets. Measured beam trajectories from live runs, the trajectory computed by the beam modeling program TRANSPORT [Brown/Carey/Iselin 1977], and the trajectory resulting from simulated operation of the VLSI EAC controller will be compared. The "smoke" test of the beam controller is installation of a single controller on a BPM-magnet pair, and operation during a live beam run.

5. Conclusions

An extended analog computer was designed as a cyclotron beam line controller. It has a fully-analog computation path with digital inputs to dynamically reconfigure the control function. Each chip can be configured to control either a dipole or a quadrupole electromagnet in the Indiana University Cyclotron Facility's cyclotron beam line and adjusted for the beam optics at each magnet's location. Simulation with SPICE and a conductive foam sheet suggest that the design is sound. PISCES simulations may offer additional insight, but the low effort needed to build the chip makes fabrication equally attractive compared to further simulation. Testing the beam controller is even more time-consuming than its design, due to the hostile environment in which it must operate.

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