Motorola Field Programmable Analog Arrays in Simulation, Control, and Circuit Design Laboratories

Olgierd A. Palusinski, David Anderson*, Doug Gettman, Cezary Marcjan*, Howard Anderson*
University of Arizona, Tucson, AZ 85721
palusinski@ece.arizona.edu
*LATG, Motorola SPS, Tempe, AZ 85284
dander@sst.sps.mot.com
USA

ABSTRACT

Motorola's field programmable analog arrays can be utilized to enrich educational laboratories by providing a platform for experiments in control systems engineering, analog signal filtering, switched capacitor circuit design, and simulation of dynamic systems. The field programmable analog array package includes an excellent PC based software support system for application design. Additional hardware requirements are minimal as field programmable analog array is almost a self contained, stand-alone system. Primary application of field programmable analog array is analog signal processing and filtering. However, universal features of the hardware make it very suitable for applications in many other engineering disciplines.

Keywords: field programmable analog arrays, switched capacitor circuits, analog filtering, continuous system simulation, analog controllers, simulation education, simulation laboratories.

INTRODUCTION

Newly developed at Motorola, field programmable analog arrays (FPAA) are very suitable and inexpensive tools for a variety of applications in engineering laboratories. The FPAA is available together with an excellent design support software which runs on a PC. The FPAA requires a minimal hardware support commonly found in most laboratories: a power supply, a signal generator, an oscilloscope, and appropriate cables to implement an application and observe the behavior of the realized devices. Such hardware support equipment is typically available in students laboratories and is inexpensive to acquire, if necessary. The FPAA can be used in control and simulation laboratories of Electrical, Chemical, Mechanical Engineering and is especially suitable for education in circuit and filter design laboratories of Electrical Engineering Departments.

TECHNOLOGY DESCRIPTION

Motorola's first FPAA contains a number of CMOS operational amplifiers, programmable capacitors, and electronic switches. All of these components can be configured to perform a customer specified function [Altonen 1996]. The configuration and parameter selection is done by electronic switches which are under digital control determined by an application and provided by a user or user system. There are two types of switches: (1) static and (2) dynamic switches. The static switches are activated during the programming phase and are fixed during the processing-operating phase of the device function. These static switches are used to control both the circuit structure, which defines its function, and the capacitor values. The dynamic switches are used to periodically switch capacitors on and off during the processing phase in order to obtain appropriate average values of capacitor current and eventually simulate a desired function of the device. A resulting device function is defined by the theory of switched capacitor circuits and the physical properties of the hardware. The theory of switched capacitor circuits, description of basic MOS analog technology, technical details of actual circuitry, and numerous examples of specific structures utilizing switched capacitor circuits are included in [Gregorian and Temes 1986]. The operational amplifiers, static and dynamic switches, and switched capacitors in the FPAA are all implemented in CMOS technology designed and manufactured by Motorola.

BASIC COMPONENTS

The FPAA developed by Motorola can be utilized in a variety of analog functions such as signal amplification (gain stages with offset cancellation) or summing or differencing of analog input signals. The FPAA can be programmed to perform signal conditioning (sample and track, track and hold, interpolation stages, decimation, etc.), integration, approximate differentiation, and general filtering. Filtering is accomplished using a series of high-Q and low-Q biquads. The FPAA can also be programmed to act as various kinds of oscillators (i.e. they can generate signals of prescribed waveform). In addition to those linear functions FPAA can be programmed to perform non-linear operations. Some of the most common non-linear operations that can be implemented using FPAA are a multiplication and both half- and full-wave rectification. Other non-linear operators such as limiters, peak detectors, and Schmidt triggers can be also be implemented. An FPAA chip includes digital to analog and analog to digital converters which are used to interface the internal analog circuits with internal and external digital signals.

PROGRAMMING SUPPORT

Creation of a specific circuit configuration using the FPAA is complex and requires setting of many static switches on the chip. Manual control of switches would be tedious, time consuming, and absolutely impractical. The necessary assistance in this task is provided by a specialized design support software named the Motorola Interactive Design Tool (MIDT). This software allows a user to quickly and easily generate and manipulate FPAA circuits. Such support is essential to the success of the technology. The software is provide by Motorola with the FPAA. The software is targeted for PC machines running windows (W3.1, W95 or NT) to be easily used in educational environment. MIDT was constructed as an object-oriented system using Microsoft Visual C++ and components of the Microsoft Foundation Library. The MIDT window displays a schematic view of the chip with sub-circuits (gain stages, filters, rectifiers, oscillators, integrators, etc.) displayed as icons. The user is allowed to select and place the subcircuit icons and connect them (wire) together interactively. Each subcircuit's function is defined by the use of pop-up windows which allow the user to select the parameters of the subcircuit, e.g., the undamped frequency, w_o, and the quality factor, Q, of a filter, or the gain of a gain stage. When the functions and parameters of the subcircuits are selected and the "wiring" (interconnections between icons) is completed, the software allows the user to download the information, containing all of the static switch settings, to the FPAA through the PC's serial port. After the download the circuitry will be ready to perform its intended processing.

APPLICATION IN CONTROL LABORATORIES

An FPAA can perform various functions as described in the section on basic components. In particular, it can be used to implement P, PI, or PID regulators. These regulators can be easily programmed by undergraduate students by specifying a transfer function and its parameters according to the needs of the control system under study. The FPAA can also be utilized in adaptive systems where the functions and/or parameters need to be changed during the controlling operations. Such an adaptive change can be easily accomplished because FPAA configuration and parameter settings are controlled by external digital signals. Some nonlinear operations on input signals such as saturation, signal comparison, squaring, multiplication, rectification (both half-wave and full-wave) can be implemented in the FPAA. Laboratory experiments can be designed to illustrate the effects of nonlinearities in sensors, controllers, and actuators on control system performance. An application to automatically control the position of a two mass-spring-damper (shock absorber) electromechanical system often used in control laboratories is planned. The specific system considered for first experiments in this area using the FPAA is the rectilinear plant supplied by Educational Control Products [ECP 1996].

APPLICATION IN FILTER AND CIRCUIT DESIGN LABORATORIES

One of the most complex functions that a FPAA can perform is filtering of analog signals. This is done by arranging the FPAA cells in series of low-Q and/or high-Q biquads. Each biquad is realized by a network of switched capacitors and operational amplifiers within the FPAA. The biquad capacitor values are functions of filtering parameters specified by the customer. The capacitor values are established using static switches which form parallel connections of unit capacitors arranged in banks of 63, 127, 255, or 511 units. Manufacturing and quantization errors may result in capacitor and consequently filter parameter values other than those required by a customer. A model for the bound of capacitor errors was constructed to determine the minimum acceptable size of each capacitor bank for a class of FPAA functions. In addition, this error model can assist in programming the FPAA for a specific application. The error model is composed of three components describing: (1) quantization error, (2) microscopic manufacturing errors of unit capacitors, and (3) macroscopic variations due to gradients in oxide thickness and contributions from parasitic capacitances of switches and interconnections. The quantization error component is determined by the number of bits [the number of unit capacitors] used in forming the capacitor of desired value. The remaining two components have parameters that are derived from the set of measurements of an FPAA programmed to perform a gain stage function. The relationships between the capacitor errors and the resulting errors in the biquad filter parameters were established. Explicit formulas for the upper bound of the error in the magnitude of the filter frequency response and the errors of biquad parameters were developed. The error model was applied to a specific FPAA arrangement implementing low-Q and high-Q biquads. Several sets of useful design curves were generated using this error model. As stated before the model allows for optimization of capacitor bank sizes. The design curves generated to date show the monotonic decrease of the error bound as the capacitor size increases. This behavior is particularly pronounced, well understood and fully supported by detailed theoretical analysis in cases where the quantization error dominates the other components in the capacitor error model.

As described above, an FPAA macrocell can be configured as a biquad whose poles and zeros can be set to user-selected values. A series of biquads can be used to implement low-pass, band-pass, or high-pass filters. In particular, a student can easily implement Butterworth or Chebyshev filters of assigned degree, verify their performance in the laboratory, compare with theoretical predictions, analyze the implementation, and identify sources of error. Construction and laboratory testing of other types of filters, based on other theories, is also possible and easily implementable. Another specific task would be the theoretical prediction of the limitations of filter performance and comparison with proper laboratory measurements. An FPAA can be also used to demonstrate properties of operational amplifiers [Wait et al. 1994] and the wide variety of switched capacitor circuits. It is anticipated that FPAA's will offer suitable features for laboratory studies of behavior of integrated circuits processing mixed digital-analog signals. These types of circuits are important, for example, in communication systems and are difficult to analyze theoretically. Laboratory experiments would include evaluation of performance and measurement of noise levels as a function of the operating speed determined by both the clock cycle of the switched capacitor circuits and the clock cycle of the logic circuits.

NETWORKS OF FPAA'S AS DIFFERENTIAL ANALYZERS

The FPAA's can be used to assemble networks of integrators, summers, gain stages, and nonlinear operators. Such networks can be easily designed and utilized to solve ordinary differential equations via analog simulation. There are systematic ways to design networks, composed of these basic analog components, which solve ordinary differential equations via simulation [Korn and Korn 1972, Korn 1989]. A network of properly programmed FPAA elements can be connected under digital control using the MIDT support software. These networks could be used in optimization, solution of partial differential equations via iterative methods, sensitivity studies, parameter identification, statistical analysis, Monte-Carlo studies of field problems etc. Repetitive solutions of dozens or hundreds of ordinary differential equations are often required in such applications. The FPAA technology will allow for quick, simultaneous solution of systems of differential equations. Thus, FPAA networks can be used as hardware accelerators in general purpose simulator technology.

CONCLUSIONS

The FPAA technology offers a device with very attractive and universal features which can be used and exploited in various applications. The FPAA can be very easily and inexpensively utilized in students laboratories. The FPAA technology presents the following advantages for student laboratories: (1) the MIDT interface provides virtual wiring (drag and drop) and removes the requirement for linking of hardware components, (2) students can quickly build complex analog hardware, (3) students can see the relationship between analog and digital signal processing, can experience design work, and hardware testing, etc. , (4) students use the "cutting edge" technology, decreasing their training time after graduation, (5) students are stimulated to perform additional experiments and develop new features of FPAA for practical use. A laboratory work with FPAA's will develop student's engineering creativity and will make them more "marketable". A particularly attractive feature is the interconnecting capability. This capability will allow automatic construction of networks of analog elements that can be used to teach simulation of dynamic systems. Such networks can also be used as hardware accelerators in larger general purpose simulators where they would simultaneously solve systems of ordinary differential equations. FPAA will undoubtedly find more applications because of its flexibility, low cost and ease of programming. Some interesting potential application examples in the area of neural networks are given in [Korn 1995].

REFERENCES

1. D. Anderson, C. Marcjan, D. Bersch, H. Anderson, P. Hu, O. Palusinski, D. Gettman, I. Macbeth, A. Bratt, "A Field Programmable Analog Array and its Application," *1997 Custom Integrated Circuits Conference Proceedings,* May, 5-8 , 1997, Santa Clara, California, USA.
2. ECP Systems in Action (manufacturer's literature), 1996, Published by Educational Control Products (ECP), Woodland Hills, CA 91367, pp. 18.
3. Gregorian, R. and G. C. Temes, 1986, Analog MOS Integrated Circuits for Signal Processing, J. Wiley & Sons, Inc., pp. 598.
4. Huelsman, L. P., 1993, Active and Passive Analog Filter Design, McGraw-Hill, Inc., pp. 480.
5. Korn, G.A. and M. T. Korn, 1972, Electronic Analog and Hybrid Computers, McGraw- Hill, Inc., pp 421.
6. Korn, G. A., 1989, Interactive Dynamic System Simulation, McGraw- Hill, Inc., pp. 196.
7. Korn, G. A., 1995, Neural Network Experimentation on Personal Computers and Workstations, MIT Press, pp. 380.
8. Van Valkenburg, M. E., 1982, Analog Filter Design, Holt, Rinehart and Winston Publ., pp. 608.
9. Wait, J. V., L. P. Huelsman, G. A. Korn, 1994, Introduction to Operational

Amplifier Theory and Applications, McGraw-Hill, Inc., pp. 396.