# Programmable analog hardware for control systems exampled by magnetic suspension

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**Abstract** *This paper presents the application of the Field Programmable Analog Arrays (FPAA) technology for control purposes. The main characteristics of the FPAA is presented and hardware and software configuration dedicated to control tasks are described. The electronic circuits that must be used when connecting sensors or actuators to the FPAA circuits are discussed. The sensor and actuator used in the magnetic levitation system are used to show the advantages of the FPAA technology. The research was realized using the AN221E04 FPAA chip.*
*The FPAA was applied as a sensor response linearization, PWM signal generator and PD controller of the magnetic levitation system.*
*This paper is an introduction to the FPAA applications in a control science. This technology will be used in the signal processing and for controllers design*
*.Investigations of such a hardware in application to adaptive signal filtering and process control equipped with dynamical reconfiguration are in progress.*

**1. The FPAA technology.** The Anadigm® AN221E04 is a reconfigurable analog device based on switched capacitor technology [1]. See figure 1 for a schematic of the chip. The device can accept either an external clock or generate its own clock using an on chip oscillator and an external crystal. The resulting internal clock frequency can be divided down into four synchronized internal switched capacitor clocks of different frequencies by programmable dividers. Different circuit configurations are achieved through manipulation of switches between various circuit components inside four configurable analog blocks (CABs). Each CAB contains two operating amplifiers (op-amps), a comparator and 8 variable capacitors (see figure 2).

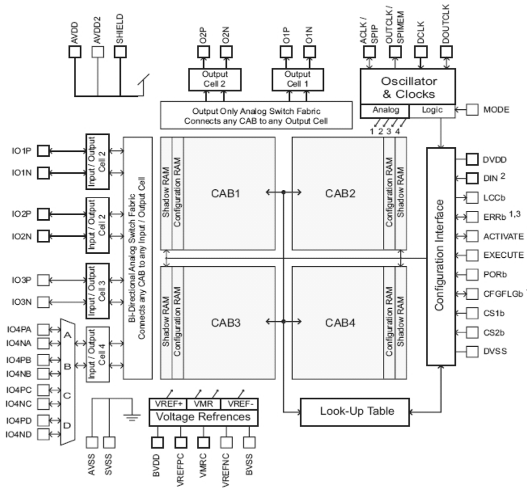


Fig. 1. Architecture of the FPAA device

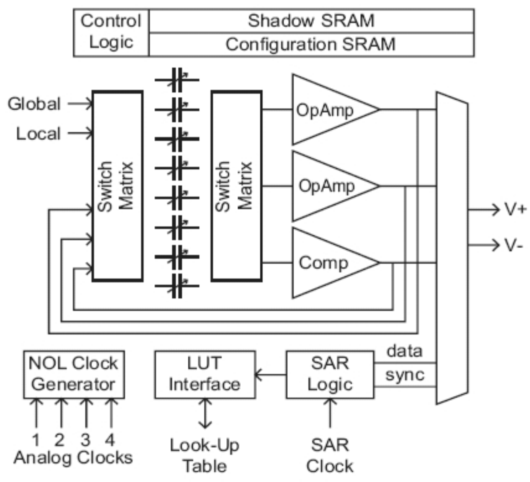


Fig. 2. Interior of the CAB block

The configuration data is stored in the on chip configuration memory. The device has four configurable bi-directional cells which can be used as either an input or an output and two dedicated output cells. In this case the FPAA can be used in the I/O signal processing. Additionally the 8-bit SAR A/D converter and 256 bytes lookup table extends the functionality of the chip.

**1.1. Development stage.** A combination of hardware and CAD/CAE software simplifies the design of analog circuits using field-programmable analog arrays manufactured by Anadigm. The FPAA depend on the AnadigmDesigner®2 CAD/CAE software [2] to quickly and easily construct complex analog circuits by selecting and interconnecting building-block sub circuits referred to as configurable analog modules (CAMs). The next step in design is to download the analog circuits derived from AnadigmDesigner2 to the FPAA, which will then function as the software-designed circuit (see Fig. 3). After downloading it is possible to immediately view the results of the analog circuit design using a analog signal sources and oscilloscope. he software also contains an API that allows the design interface to be manipulated from an external program.

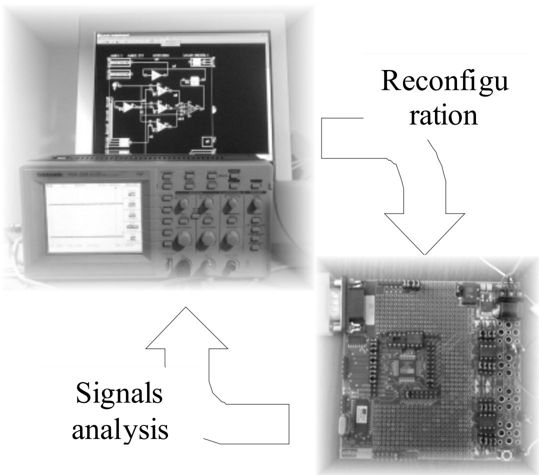


Fig. 3. Software-designed circuit

**1.2. Interfacing the FPAA.** The Anadigm family of FPAAs uses analog signals that are referenced to +2V (VMR) and are limited to range 0 to +4V. There is a number of methods for interfacing signals to the FPAA. The device can be used in single ended or differential mode. Typical methods are: D.C. biased input, CAMs, A.C. coupling, chopper amplifier, resistors dividers, Zener diodes, op-amp circuits, differerential op-amps.

**2. Signals conditioning for control purposes.** In many practical control applications it is necessary to convert the measured signal to the appropriate form for the controller or to linearize the sensor characteristics. When creating the circuit-process interface the signal matching for the actuator input is required. The most popular example – PWM signal generation is realized in the FPAA. Both examples are discussed below.

**2.1. Sensor characteristics linearization.** Sensors used in practical applications usually have nonlinear characteristics. In the control loop the characteristics is linearized to obtain the value corresponding to the process variable. In the digital control system this signal transformation can be done in many ways. Using the FPAA technology the user specified transfer function with 256 quantization steps can be used.

The magnetic levitation system position sensor has a nonlinear characteristics presented in Fig. 4.

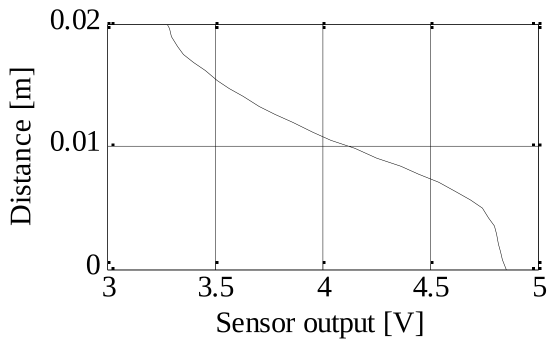


Fig. 4. Sensor characteristics

The user defined Voltage Transfer Function CAM block can be used to solve the characteristics linearization problem. This CAM implements a user specified voltage transfer function with 256 quantization steps. The measured characteristics must be converted to the coma separated data file for uploading to the CAM. The number of points must correspond to the size of the LUT (Look-Up Table). The dedicated CAM produces a specified output voltage in response to the value of the sampled input voltage. The Successive Approximation Register (SAR) logic makes eight successive measurements on the input signal during the sampling phase of the analog signal. This CAM uses two clocks. The frequency of the clock 2 should be set at 16 times the frequency of clock 1. The clock 1 is driving the switched capacitor in the circuit. Clock 2 is driving the SAR and the LUT.

The faster SAR clock is required for correct operation of this circuit. In order to insure correct data conversion, these eight measurements must all be made on the same input voltage.

The full-scale input range of the SAR is +/- 3 V, based on the internal reference voltage. Input voltages that exceed this full-scale range will produce results as if the input voltage was equal to the full-scale.

| Requested [-4 to 4] | Realized |
|---|---|
| -1.558 | -1.559 |
| -1.528 | -1.535 |
| -1.497 | -1.488 |
| -1.467 | -1.465 |
| -1.435 | -1.441 |
| -1.404 | -1.394 |
| -1.372 | -1.370 |
| -1.340 | -1.346 |
| -1.307 | -1.299 |
| -1.275 | -1.276 |
| -1.241 | -1.252 |
| -1.208 | -1.205 |

Fig. 5. Look-Up table -
Voltage Transfer Function CAM

A part of the LUT is presented in Fig. 5. After uploading it is necessary to check the realized voltage. The mismatch may cause improper operation of the circuit for some range of data. The realized circuit can be tested at the simulation stage (see Fig. 6).

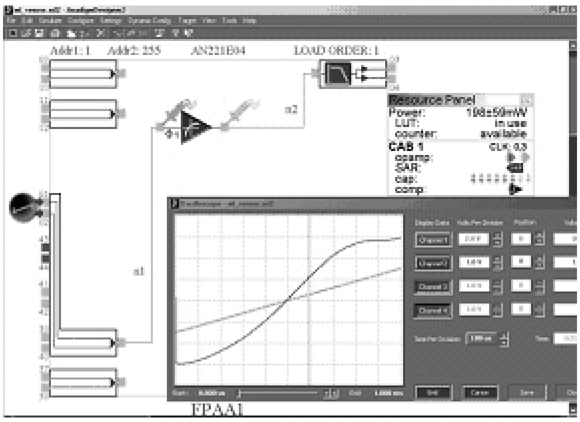


Fig. 6. Sensor characteristics linearization – verification at the simulation stage.

The user can put some probes on element pads and browse results on the chart. The simulation stage allows to check the proper circuit operation before downloading.

This example shows the practical application of the FPAA forming a sensor signal for the control loop.

**2.2. PWM signal generator.** In many practical applications it is necessary to use the PWM signal as control signal. The control value corresponds to the duty cycle. One of many possibilities to form the PWM signal is to use an analog sine wave as a signal source (see Fig. 7). The voltage source with gain can be used to obtain an offset from the zero level. This kind of operation allows to set the PWM duty at the value corresponding to the steady-state control. This kind of control strategy (that the control signal vary around the constant value) is very popular in practical control applications. The best example is the stabilization problem (e.g. stabilization of the levitated object [3]) when the control signal has small changes around the constant value, obtained as the control level for steady state point.

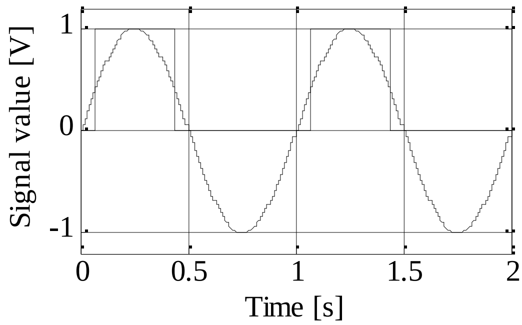


Fig. 7. PMW signal generation
based on sine wave signal

The application of the comparator block allows to compare analog signals and makes a bridge between analog and digital part of the circuit. The output of the FPAA was configured to drive digital signal. The CAM comparator was applied to generate the PWM signal. The frequency of the generated PWM signal depends on the frequency of the generated sine wave. The PWM duty corresponds to the threshold voltage set at the comparator input. The detailed diagram of the realized circuit in the FPAA is presented in Fig. 8.

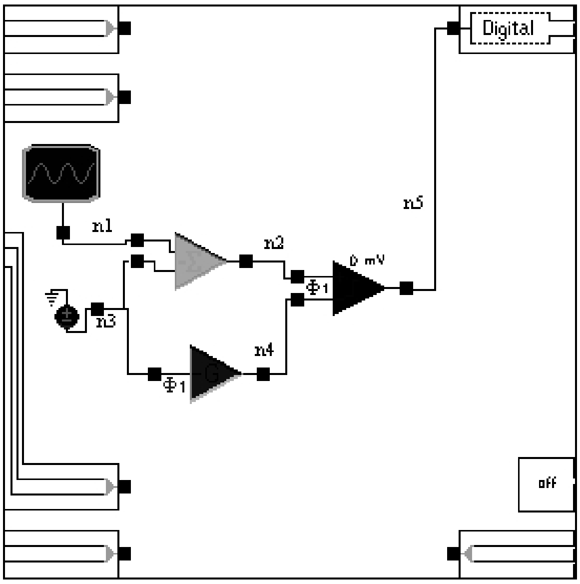


Fig. 8. PWM signal generator

The realized circuit was downloaded and tested. The frequency of the generated signal was set to 2kHz and PWM duty to 40% (see Fig. 9).

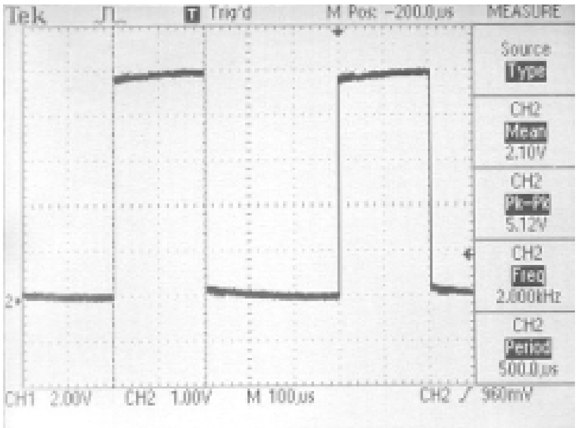


Fig. 9. Generated PWM signal

**3. Dynamical reconfiguration of the FPAA.** The AN221E04 devices that are geared towards high-volume applications requiring consolidation analog functionality and are further optimized to enable dynamic reconfiguration - a breakthrough capability that allows analog functions to be integrated within the system and controlled by the system processor.

The reconfiguration availability was tested at the PC platform. The dedicated software allows to generate C-code for selected CAM blocks. The obtained set of procedures can be used in any C++ application (as default the MS Visual C++ was used). When the code is generated the user can create user interface and use function corresponding to appropriate CAMs for future parameters change. The applied set of functions for serial port data exchange allows to download the modified set of parameters to the chip. The reconfiguration of the whole chip or of the single parameter is available. The realized application is shown in Fig. 10.

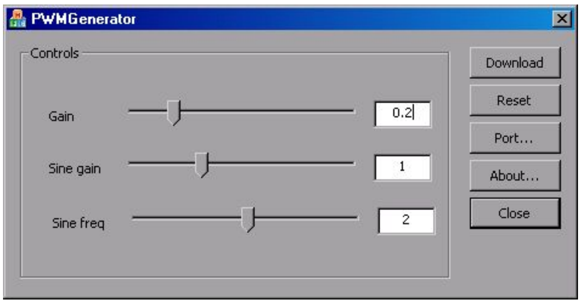


Fig. 10. Windows application for dynamic reconfiguration of the PWM generator

The dynamical reconfiguration of the FPAA can be done in the real-time. Parameters are transmitted to the registry and when completed, applied in the next clock cycle of the FPAA chip.

**4. Practical control application.** The main goal of this paper is to present the FPAA as a unit for practical control application. As the example the Magnetic Levitation system was chosen [4]. This is an nonlinear and unstable system. The sphere is kept by the electromagnetic force generated by the current flow in the coil (see Fig. 11). Sphere position is measured using optical sensor. The distance is a nonlinear function of voltage $V_x$ (see Fig. 4).

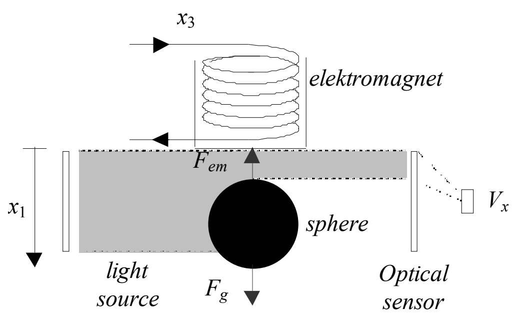


Fig. 11. Idea of MagLev operation

The behavior of the magnetic levitation system can be described by a set of differential equations (1).

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -\frac{F_{em}}{m} + g \\ \dot{x}_3 &= \frac{1}{f_i(x_1)}\left(k_i u + c_i - x_3\right) \end{aligned} \qquad (1)$$

where: $x_1$ – sphere position, $x_2$ – sphere velocity, $x_3$ – coil current, $F_{em}$ – electromagnetic force, $g$ – gravity constant, $m$ – sphere mass, $k_i$ , $c_i$ , $f_i$ – actuator parameters,

The minimal configuration of the required controller for the stabilization problem is PD controller in the following form:

$$G_R(s) = K_p + K_D s \qquad (2)$$

The analysis of the model gives the necessary parameters of the controller: $K_P = 0.5$, $K_D = 40$ ms. The PD controller consist of the following blocks (see Fig. 12

- *Sum1* to produces an position error,
- *Sum1* and *Gain1* with connection of 2nd input of *Sum2* realizes the derivative action,
- 1st input of the *Sum2* makes the proportional action,
- *Gain2* to obtain constant control value for steady state point,
- *Sum3* to produce the analog control signal.

Setting the value of *GAIN1* to 1.00 FPAA parameters of controller elements are calculated using the following formula:

$$\begin{aligned} \text{SUMin1} &= K_D \cdot F_C \\ \text{SUMin2} &= K_P + \text{SUMin1} \end{aligned} \qquad (3)$$

Because of the specific realization of the PD controller in the FPAA chip it is necessary to calculate gains of responsible CAMs. The parameters of circuit elements are summarized in the table 1.

**Table 1**

| Element | Value |
|---|---|
| SP Voltage Source | 3.00 |
| SUM1 input 1 | 0.40 |
| SUM2 input 1 (SUMin1) | 40.46 |
| SUM2 input 2 (SUMin2) | 39.96 |
| Gain2 | 0.75 |

Elements or inputs not listed in the table 1 were set to value 1.00.

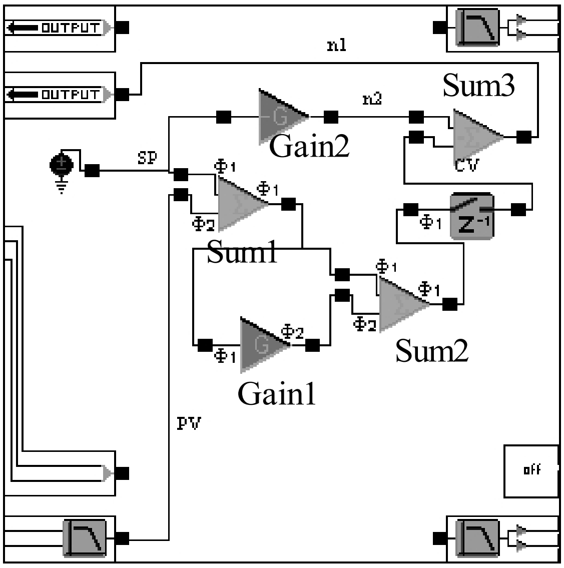


Fig. 12. PD controller realized in the FPAA.

In the PD controller the realization of the derivative action is required. The direct signal path between *SUM1* and *SUM2* takes place on phase 1, however the signal path through *GAIN1* takes place on phase 2. Since the second signal is delayed by a constant and precisely determined amount it is possible to derive a simple formula which relates the "difference" constant $K_D$ to the gains of the two stages and the common clock frequency.
The PD controller implemented in the FPAA produces the output voltage proportional to the duty of the PWM signal. The external PWM signal generator was used with connection of the coil actuator unit. The signal flow between Magnetic Levitation system and the FPAA is presented in figure 13. Some hardware elements was necessary to build to provide signals adjustment.
With the realized controller circuit the FPAA was programmed and the sphere was suspended below the electromagnet. The levitation action of the system is presented in Fig. 14. The control and position signals were measured via oscilloscope and are shown in Fig. 15.
The stabilization problem was realized experimentally at three frequencies: 0.5kHz, 1kHz, 2.5kHz. When changing the frequency of the chip it is necessary to recalculate and modify controller parameters using formula (3).

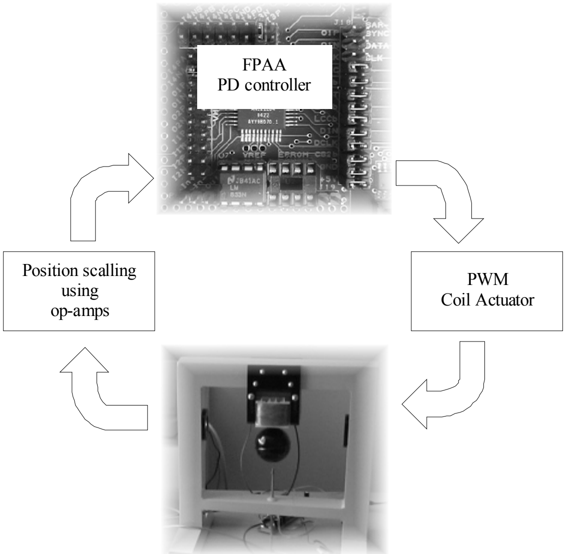


Fig. 13. Signals flow between FPAA and Magnetic Levitation system

Fig. 14. Stabilization of the levitated sphere

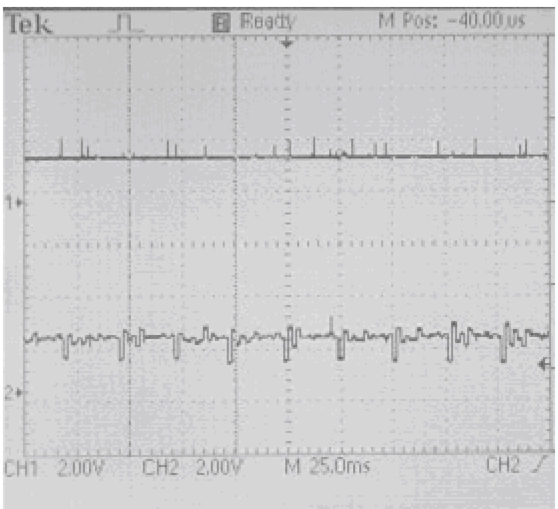


Fig. 15. Position and control signals

**Conclusions.** The FPAA technology can be practically used in many control applications. The main advantages of this technology:

- shorten time to practical realization by reducing analog design complexity,
- work at a higher functional level instead of low level components,
- dynamic re-configurability,
- allows to design elements that adapt to their environment (auto-calibration, automatic gain control, etc),
- allows to design products that can change functionality ,
- drift free performance immune to process, temperature and aging.

The disadvantage of this technology is the capacity of single element and to realize more complicated task it will be necessary to connect few FPAAs together.

The FPAA application for control systems is now in progress. The programming phase from the FPGA and microprocessor is under development. The MATLAB interface is now at the testing phase and allows the user to modify circuit parameters from the higher level environment. The FPAA technology can be used not only signal processing applications but also in control applications realizing linear and nonlinear control strategies.

**Literature**

[1] Field Programmable Analog Arrays - User Manual, Anadigm 2003

[2] AnadigmDesigner®2 User Manual, Anadigm 2004

[3] Piłat A. Sterowanie układami magnetycznej lewitacji. Rozprawa Doktorska, AGH Katedra Automatyki, 2002.

[4] Magnetic Levitation System, INTECO Ltd. Kraków 2005

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