Programmable Analog Array in Control-Systems Laboratory

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Abstract - In electrical engineering schools, control systems are usually taught through lectures, tutorials, projects and labs. Obviously, it is during projects and labs that students acquire most of their know-how in this field. Nowadays, because real systems are complex and expensive, students learn more and more often from virtual systems. The objective of this paper is to propose the use of Field Programmable Analog Array to assist teachers in their education task. With this programmable analog components, students are able to create classical systems and extract from it real measurements.

I. INTRODUCTION

For many years, Polytech'Montpellier University Engineering Graduate School has offered a wide range of lectures, laboratory works and project surveys particularly in control systems [1]. Practical works take a significant place in a student's curriculum. To this end, during three years, future engineers get about 180-hours of labs to acquire a maximum amount of know-how in control system sciences. Therefore, in our laboratory class, because of the expensive cost of real systems, we get no more than 6 actual setups (e.g. magnetic suspension, inverted pendulum, speed motor control with variable load, three tanks system ...). So, to enhance students' skill in the domain, teachers' tendency is to implement systems by the use of simulation tools such as Matlab and/or Simulink [2]. The original idea proposed in this paper, is an intermediate approach between the real system and the fully abstracted one. Indeed, with our methodology, students can implement a system from CAD tools and extract real measurements from it.

The paper is structured as follows. Section 2, introduces the domain of competences addressed by this tutorial. Section 3 is devoted to the Field Programmable Analog Array's inner architecture. The fourth section details a project example. A didactic approach is developed through two progressive lab sessions. Finally, section 5 presents our conclusions and future works.

II. TUTORIAL SKILLS OVERVIEW

This class is supposed to take place early in students' curriculum. So, it is limited to the study of first and second order linear systems. With the first order system, students will study the feedback effects on the system performance. The second order system will be employed to highlight stability issues. A progressive approach will be used by students to compensate the system and consequently improve stability.

Taking into account the duality of our students’ curriculum (i.e. control systems and general purpose electronics), the use of an innovative programmable analog device enhances their know-how in advanced electronics.

III. THE FIELD PROGRAMMABLE ANALOG ARRAY

An FPAA is an analog programmable integrated circuit. The FPAAAs bring to analog what FPGAs brought to digital; extremely rapid production and prototyping with field re-programmability. For this lab, we propose to use an FPAA from Anadigm [3]. These family circuits are built on switched-capacitor architecture [4]. The essence of the switched-capacitor elementary cell is the use of capacitors and analog switches to perform the same function as a resistor. This replacement resistor, along with op-amp based structures, then forms active analog functions. An alternative to such discrete time domain FPAA is provided by Lattice Semiconductor [5]. In the case of continuous time domain architecture, the base cell is built around an instrument amplifier with a programmable transconductance (gm).

The core of the Anadigm's FPAA is an array of identical configurable analog blocks (CABs) connected by mean of a configurable network (see Fig. 1.). A very flexible switching infrastructure surrounds the capacitor banks, enabling users to create complex configurations. This allows the FPAA to implement an almost infinite range of analog signal processing functions.

The firmware of the FPAA offers a library of ready-to-use circuits for common analog requirements. There are a numerous Configurable Analog Modules (CAM) functions available including for example amplifiers,
summing amplifiers, differentiators, integrators, comparators, filters, multipliers, etc.

Fig. 1. Anadigm AN231E04 FPAA architecture

The AnadigmDesigner2™ software design tool provides the user an intuitive drag and drop GUI (Fig. 2.a) in which you simply select desired CAM functions from the library, drop them onto a graphical representation of the chip, fill in functional parameters, wire up the internal and I/O connections, and hit a button to generate the configuration bit stream. The stream is then sent to the development board through the serial RS232 port of the PC in few milliseconds.

For example, Fig. 2.b presents the use of the "Low Pass Bilinear Filter" CAM's. The field menu named "Clocks" is explained hereafter.

A standard Master Clock (16MHz) drives the switch capacitor structure for each CAM. In Fig. 2.c, the four non-overlapping clocks s1, s2, s3 and s4 issued from the master clock, determine the behavior of the low pass filter CAM. So, to extend the functional flexibility of a CAM, four different sub-frequencies can be chosen (by default). Each of them may be 1, 1/4, 1/8, 1/64 of master clock frequency.

In a previous paper [6], Znamirowski et al. use the FPAA circuits to implement adaptive controllers and plant simulators. From this experimental study it is clear that FPAA are quite interesting for use in control-systems. In the same way, we propose now to use these programmable components in students' laboratories.

IV. LABORATORY

The circuit used in this tutorial is the Anadigm's AN231E04. This FPAA is included in a development board: AN231K04-DVLP3. This board provides the entire feature set required to simplify hosting, system and I/O connection for evaluation, debug and test. Moreover, the board includes a microcontroller which can dynamically modify the FPAA functionality by loading a new configuration file at any time. In addition, students need a square-wave generator, an oscilloscope and a computer running AnadigmDesigner2™ and PSPICE (the electrical simulation suite from Orcad™). It is interesting to note that the AnadigmDesigner2™ CAD tool can be freely downloaded from the Anadigm website [3].

The lab is split into two sessions. The first session has duration of two hours while the second is six hours long. Consequently, the laboratory we propose has duration of eight hours. To guarantee a didactic approach, in the first session students only implement a basic first order system. In the second part, students design a second order system. These kinds of systems are very important for the system-control engineer. Indeed, these systems represent the dynamic behavior of many real-life applications.
found in the field of servomechanisms, space vehicle control, chemical process control, aircraft control systems, etc. Moreover, most control designs are based on second-order system analysis. Even if the system is of higher order, as it usually is, the system may be approximated by a second-order system in order to obtain a first approximation for preliminary design with reasonable accuracy.

**Session 1 : First order system**

The fig. 3. shows the classical diagram of a closed-loop control system. Here, the process is represented by a first order transfer function.

$$\frac{k}{1 + \tau s}$$

Fig. 3. First order closed-loop control system

At first, students observe the step input response of both the open-loop and closed-loop system. From their measurement, they have to perform system identification (i.e. the speed response $\tau$ and the gain factor $k$) in the two configurations. Fig. 4. presents the bloc schematic of the two configurations (open and closed-loop) in the AnadigmDesigner2™ environment.

Fig. 4. First order open and closed loop

The equivalent FPAA implementation requires two analog functions such as two first order low-pass filters. In the case of the closed-loop schematic an additional adder amplifier is included. The parameters of the filters are set to 1 for the static gain and to 1kHz for the cutoff frequency. After the configuration stream is sent to the FPAA, the students connect the square-wave generator to the FPAA inputs pin “in”. Fig. 5. shows the two responses, as acquired by an oscilloscope connected to the outputs outOL and outCL. From the open-loop measurement (outOL) students are able to characterize $\tau$ and $k$. In this case, the values are $\tau=160\mu$s and $k=1$.

**Session 2 : Second order system**

The second part of the lab is devoted to characterize and improve the response of a second order system (see Fig. 6.a).

For this study, the values of the gain $K=3$ is given, the frequency $f_0$ is set at 5kHz and the damping factor $\xi=0.2$. For didactic purpose, this second order system is voluntarily set underdamped.

First of all, students must implement this second order system into the FPAA (Fig. 6.b). Afterward, they apply a step input to the closed-loop configuration. Fig. 7. shows the response obtained with an oscilloscope. As students can notice, the system exhibits several overshoots and presents a lack of accuracy.
To corroborate their previous observation of the oscillations around the steady state, students now use the electrical simulator (PSPICE) [7] to compute the open loop frequency response (Fig. 8.). From the simulation result, they are able to extract the phase margin at 0dB gain (see Fig. 8.b.). Because of the weak phase margin ($\phi < 45^\circ$), it also clearly appears for students that the system is not enough damped.

\[
\begin{align*}
&\text{v1 in 0 ac 1} \\
&ebo outbo 0 laplace \\
+\{v(in)\} = \frac{k}{1 + (2 \cdot \text{dzeta} \cdot s) + \text{pwr}(s/(2 \cdot \text{pi} \cdot \text{f0}),2)} \\
&\text{.ac dec 100 1 100} \\
&\text{.probe} \\
&\text{.end}
\end{align*}
\]

The phase-lead network must create a sufficient phase shift for 10kHz, the corresponding 0dB frequency, to increase the phase margin at this frequency.

For this purpose, the phase-lead network [8] of Fig. 10.a, needs to be well sized. The sizing of passive component values is relatively straightforward using the equations of Fig. 10.a. Using a given time constant ratio of $a = 4$, students obtain a phase shift of approximately $37^\circ$ (Fig. 10.b). Finally, the computed parameter values obtained are $R1=3.3k\Omega$, $R2=1k\Omega$ and $C=10nF$.

\[
J(s) = \frac{1}{a} \cdot \frac{1 + a \cdot \tau}{1 + a^2}
\]

with: 
\[
a = 1 + \frac{R1}{R2}
\]

\[
\tau = \frac{R1 \cdot R2 \cdot C}{R1 + R2}
\]

\[
\text{a) Passive phase-lead network schematic}
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\text{b) Phase-lead network spice simulation}
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Fig. 10. Compensating phase-lead network

Fig. 11.a shows the schematic of the compensated second order system. As it can be observed, the phase-lead network is external to the FPAA. The wiring of the passive network (two resistors and one capacitor) to the development board is rather easy. As a final point, students verify the dimensioning of their compensated network by measuring the compensated system step response. As we can see in Fig. 11.b, now the system behaves with a better step response and presents a significant overshoot numbers diminution.

In this practical work, the precision of the system is intentionally let unconsidered, mainly to keep the lab duration short.
V. CONCLUSION AND FUTURE WORKS

This control system lab has been used for two years in our engineering school and it turns out to be of great help regarding students' enthusiasm. Students are highly satisfied with this method. Likewise, it has been confirmed by professors in charge of control systems lectures that the students' ability in this field also improves their attention in class. One of our future efforts will be the implementation of a PID controller in the loop. Indeed, Anadigm provides a free software tool dedicated to analog PID design. Therefore, because of the complexity of a PID controller, it will be necessary to develop a new board including several programmable analog circuits.

REFERENCES