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Programmable Analog Hard Real-Time Controller

***Abstract**. This elaboration describes the structure of the Programmable Analog Controller (PAC), its configuration, features and limitations. This universal hardware platform based on analog signal processors is dedicated to many scientific and industrial applications. This reconfigurable apparatus is suitable for computation, diagnosis and control tasks processed in the hardware layer in hard real-time regime. The main feature of the presented hardware-software solution is flexibility for applications determined by a configurable number of inputs and outputs as well as functionality. The modular construction allows to adapt the apparatus for the purpose of monitoring, control and signal processing tasks. Such a device can be easily configured to a dedicated application. The detailed description of available modules is given to show the computing and signal processing power*

***Streszczenie.** Niniejsze opracowanie przedstawia Programowalny Sterownik Analogowy (PAC), jego konfigurację, możliwości i ograniczenia. Opracowana uniwersalna platforma sprzętowa wykorzystująca procesory analogowe jest dedykowana do prac badawczych jak i zastosowań przemysłowych. Aparatura jest w pełni konfigurowana sprzętowo i programowo, a jej modułowa architektura pozwala na elastyczne zastosowanie urządzenia. Szczegółowy opis modułów pokazuje możliwości aparatury. (**Programowalny sterownik analogowy**)*

Keywords: dpASP, Dynamically Programmable Analog Signal Processor, FPAA, Field Programmable Analog Array, Programmable Analog Controller (PAC), Reconfigurable Hardware, Embedded Computing, Dynamic Reconfiguration, Hard Real-Time Controller.
Słowa kluczowe: dpASP, FPAA, procesor analogowy, Programowalny Sterownik Analogowy, dynamiczna rekonfiguracja, konfigurowana platforma sprzętowa, sterowanie w reżimie twardego czasu rzeczywistego.

Introduction

In the past decades most of the signal processing has been realised using analog circuits. Fast hard real-time signal processing realised in the analog form allows to obtain many practical applications. In general, analog control functions simplified the design and engineering process. Some of devices are meant to operate in the analog form due to their properties and performance guaranteed by the hard real-time feedback. The disadvantages like fixed architecture of the composed electronics, parameters variation and degradation under environmental conditions as well as age related degradation caused that the well-known analog computers in the 60-70s of XX century were replaced by digital machines. There are so many advantages of digital technology, that the analog based solutions are mostly used to establish a bridge between the real world and digital machines. Nowadays, most computations are realised by Digital Signal Processing (DSP) systems on the basis of digital data with the support of computers, microcontrollers, DSP processors and Field Programmable Gate Arrays (FPGA). Particularly, in the case of control, the digital processing allows to realise many sophisticated algorithms that were unavailable for analog configurations due to their fixed architecture and parameters. However, a serious problem with low jitter, high sampling frequencies and parallel execution of control algorithm still exists in the digital real-time control systems. This time, the increasing frequency of a computer's clock and resolution of A/D converters emulates the analog computing. Although, in last years one can find a new trend, where A/D and D/A converters are removed and specialised analog hardware solutions are used by [6] in the hardware layer.

Does it mean that an analog signal processing is going to come back to scientific and industrial applications?

The open problem is, if the many benefits of analog technology can be used in the field of computing, signal processing, and control?

A discussion on the configurable analog signal processing is pending for three decades. A historical overview of the FPPA design issues including discrete and continuous time approach, voltage and current mode and CAB design is provided by [10]. As the result of studying the Motorola FPAA solution [36] conclude that a typical digital processing is used for high complexity tasks with a rather low frequency of operation while the analog processing is used for high frequency operation at rather low complexity. The floating gate transistors technology used to construct the FPAA device is discussed by [13]. The authors of [31] present recent results in the programmable and configurable analog signal processing describing the widespread potential of these approaches. They discuss issues with configurable systems, including size, power, and computational tradeoffs, as well as address the computational efficiency of these approaches. Paper [32] presents the FPAA device based on 56 CABs, and a comparative diagram of power consumption between programmable analog and digital devices. A 20 years leap is observed between the programmable analog and digital technology for the benefit of the analog one in the power consumption. In this case scientific research on the programmable analog technology as well complex solutions with their application is an actual research problem now. This elaboration presents a new solution based on configurable analog units that is able to offer some functionality to replace and/or extend the digital solutions to achieve the complex structure computational device. At the beginning have a look at well-known analog and digital technology. From Figure 1a one can notice that the analog solution has a simple and reliable form. First of all, there are not A/D and D/A converters because the analog circuit operates on analog input/output signals, although it can generate digital signals too. In this case the cost is minimised proportionally to the number of inputs if the parallel A/D processing is realised or minimised by the cost of a multiplexer and analog converter. Moreover, the A/D handling software is not required at all. The same situation occurs in the case of D/A converters. The PWM signals can be generated by the analog electronics, too with the support of signal generators and comparators. On the other hand, the digital control architecture contains many elements but has a flexible configuration for a wide range of applied signal processing tasks (Fig.1b). The analog-to-digital (A/D) transducers are required to transform analog data from the real world to the digital one. The multiplex or parallel A/D solutions are usually used but problems of mutual interference or numerous of devices still exist. The processed data is done digitally with the user-defined accuracy by application of the appropriate data formats. When the results of data processing are used for control purposes, then the control signal is applied to actuators in the analogue form through the digital-to-analog (D/A) transducers or the digital one by application of the PWM technique. In both cases, when changing the signal form there are some disadvantages like: digital communication (serial/parallel) to/from the converter, settling time, glitch area, PWM resolution and frequency. All these facts make the control hardware very complex. In both cases the I/O analog signal conditioning electronic circuits (for offset and gain adjustments) are required.

a) b)

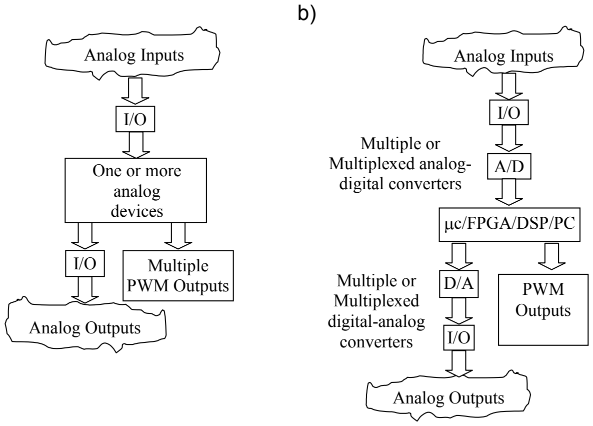

Fig. 1. Comparison of configurable digital and analog signal processing solutions

Finally, coming back to the Figure 1a and replacing the analog circuit with a modern programmable analog device the same functionality as previously has been obtained, and much more due to some new features of the applied device. In this case a configuration of the analogue controller is based on the dynamically programmable Analog Signal Processor (dpASP) or the Field Programmable Analog Array (FPAA) device (see Figure 1a). This programmable analog unit operates on analog input/outputs signals, although can generate digital signals too. When power actuators require the PWM type signal, it is possible to generate such a signal from the FPAA unit [20], too. Now, the question is how universal and reliable the programmable analog devices are?

Overview of FPAA technology

The configurable analog solution is well-known. Last 30 years were focused on the configurable analog devices. The research on the devices capacity, functionality, power consumption and designing methods is still in progress. In the late eighties, the first programmable analog devices were developed and on the market they became available in the nineties of XX century. The technological growth in microelectronics allows to manufacture new devices with extended functionality and features in the e.g. QFP or QFN-type packages. At this moment, on the market there are a few mixed signals hardware solutions where the analog signal processing is embedded into signal-mixed structure device. The most advanced devices come from the Anadigm company that manufactures FPAA and dpASP devices with a wide range of analog functions to be embedded. The Cypress company offers the Programmable System on a Chip (PSoC) where a few basic analog functions are available. The Lattice company manufactures Programmable Analog ICs (isPAC) devices for signal conditioning, control loop and the 5th order low pass filter.

The Anadigm Company is a world leader in the FPAA based devices manufacturing. Additionally, their complex solution including the EDA software and extra tools allows to obtain the best technology features. Therefore, the AN221E04 [1] device has been chosen for the first experiments, and this time the dpASP AN231E04 [3] is used. Very important feature is that the analogue controller can operate on analogue signals in a parallel way (today only the FPGAs and grid controllers can process digital data in a parallel way). In the analog solution, there is no scheduling and multitasking mechanisms as exist in the microcomputer or the FPGA based applications.

Both FPAA and FPGA based devices are driven by the clock pulses. In the case of the programmable analog unit the maximal available clock frequency is 40 MHz, but the sampling frequency depends on the used analogue component modules (in some cases it is limited to 2MHz). In the analogue controller the most important components are I/O bocks based on op-amps that allow to scale and shift voltage signals to the acceptable range. Additional precision and low noise op-amps are required for the successful signal processing and interfacing with the dpASPs [2]. In the case of the analogue controller a number of external components necessary in a digital controller construction can be eliminated, thus the control unit is simplified and its costs are reduced. The observed repeatability of the signal processing, low integration error (0.007%) and jitter in the range of a few nanoseconds were investigated and [23] confirms that these devices can be practically applied to solve many scientific and industrial problems.

Selected remarks on FPAA and dpASP technology

Thanks to the switched capacitors technology embedded into the dpASP or FPAA devices the analog signals can be processed now. This technology allows to process signals that are continuous in the voltage but discrete in time and thus they are categorised as Sampled Data System [11]. These devices have been developed for a wide range of signal processing, especially in the field of control applications. Their ability to be reconfigured and their simplicity allow to obtain low cost integrated controller [4]. During the prototyping stage of a few hardware platforms [7], [15] equipped with up to three FPAAs, a number of advantages and disadvantages related to the applied devices has been observed.

- Advantages of the realised hardware: direct parallel analogue signal processing via elimination of quantization effects, reconfiguration ability in the one clock cycle, sampling frequency up to 40MHz, sampling of analog blocks with four different sample rates, library of configurable analog modules (CAMs), chain configuration, reconfiguration for serial and/or parallel signal processing, simple and fast reconfiguration via SPI interface, minimal jitter (in the range of nanoseconds), repeatability of the signal processing, high bandwidth, programmable filtration, integration, safety guaranteed by the hardware,
- Disadvantages of the applied technology: small capacity of the FPAA devices, sampling of analogue signals (the base of this technology), no EEPROM or FLASH memory - the primary configuration must be loaded from the external device, required external op-amps for the world interface and signal conditioning, weak multiplication and division calculation, required scaling and signal processing calculations prior to configuration, huge effort in a configuration of complex signal processing.

The main conclusion from the conducted research has been drawn that in general, the programmable analogue devices are a perfect complement for digital reprogrammable devices and simple reconfigurable stand-alone controllers but external peripherals, flexible signal routing and software supporting design, configuration and execution are required to fetch the power of this technology. It is expected that this technology will be used together with the digital one [17]. From the literature overview one can find, that a number of task was realised with the application of a single or a few FPAA devices. The FPAA technology has been used for: flexible ECG acquisition system [18], real time QRS detector [16], autopilot for Micro Air Vehicles [28], Atomic Force Microscope control [29], a Self-Adapted PID [35], simulation tool of Gm -cells for active filters [8], topology switching [12], reconfigurable filter for rotating machine [33], dynamic reconfiguration for adaptive filtering with switched multiplexer [36], state detection of contactless electrical energy transmission [30], sigma-delta analog converters using the FPAA device [34]. Most of the listed realised research with the support of the FPAA or dpASP devices from Anadigm was based on a single device installed on the evaluation board, a few boards connected into a chain, or custom prototyped board containing a few of them.

The universal evaluation boards are used and routed together to extend single FPAA resources. The missing flexibility in the signals routing, devices interconnections, application of a few more dpASPs, and their configuration was one of the incentives to develop the described solution. Research experience and the observed disadvantages of the application of a single or a few analog units was a knowledge base for the design and development of the Programmable Analog Controller (PAC).

Motivation to PAC design

The main motivation for the design and manufacturing of the reconfigurable embedded apparatus dedicated to fast computing and signal processing has originated from the conducted research on the active magnetic levitation systems (suspension and bearing). The applied hardware-software solutions of special control-related requirements, resulting from dynamic properties and causing relatively high sampling frequencies within the range of 1-20 kHz and more, depending on a configuration, have particular drawbacks and virtues. These systems require high sampling frequency feedback to keep the required closed loop properties that are configured and realised by the controller [19]. The Field Programmable Analog Array (FPAA) devices have been successfully applied to keep the ferromagnetic ball levitated [20]. The simplification of the control circuit was a motivation to design universal hardware for signal processing. The need for realising control tasks in the hardware environment after having been tested in the integrated DSP based surroundings of the design, modelling and simulation contributed to the presented hardware/software solution. A decision was taken to construct a particular hardware-software solution of a particular capacity and with features which are relevant for the diagnostic and control applications of multidimensional systems. Moreover, due to the time requirements of active magnetic levitation systems it was necessary to develop a platform which would meet the determined time constraints imposed by the dynamics of the active magnetic levitation systems. It should be mentioned that the versatile solutions which already exist on the market and are offered by leading manufacturers of the apparatus are feasible in diagnostic and control applications. Some of them are characterized by the lack of computational or data exchange power and complexity of solutions to signal processing due to flexibility and versatile applications [27]. Moreover, their high price was a motivating factor in the development of a particular solution. The manufactured apparatus is financially competitive and provides full control over the operations of signal processing and the managing of the input and output equipment.

As it has been mentioned the main motivation for the development of the described apparatus was the conducted research on the active magnetic levitation systems which make high demands on control applications due to the possibility of the programmable adjustment of the dynamic properties.

PAC architecture

Owing to the high requirements set by the active magnetic levitation systems the developed platform was designed in such a way that it is possible to use it for monitoring and control applications of various devices and technological processes. The developed solution allows for the adjustment of the apparatus configuration for a particular application. The signal and data buses allow for a free transfer of analog and digital signals between particular modules. The modular construction makes it possible to develop and equip the apparatus with consecutive modules depending on the demand.

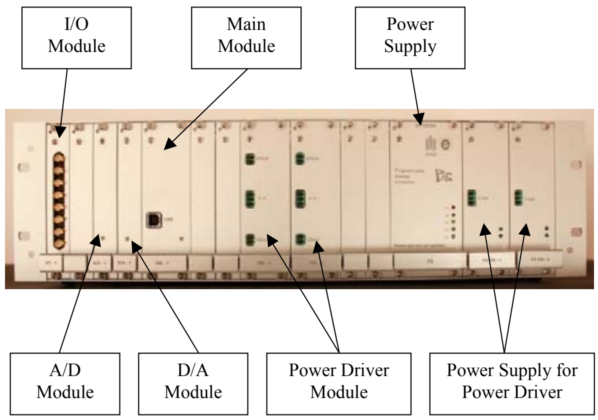

Fig. 2. Programmable Analog Controller in the industrial chasis

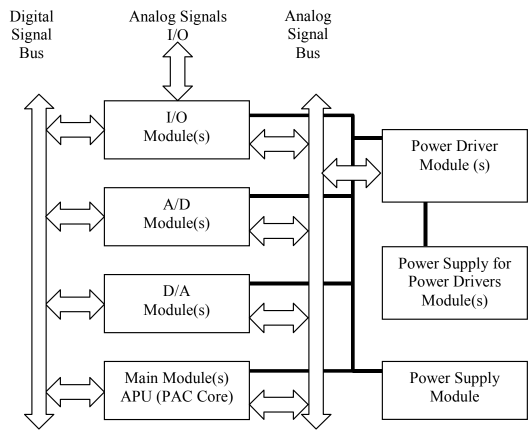

Fig. 3. PAC Architecture

As refers to the computer, the PAC architecture is similar to the digital multicore and multi processor computer. Moreover, the PAC resources can be extended by the installation of additional modules. The main module with the dpASP stands as a PAC core, while other modules are peripherals. A few PACs can be connected by the I/O modules exchanging analog signals in both directions, therefore they can be configured in a stack-able form to extend the functionality and peripherals.

PAC core - Analog Processing Unit

The dpASP technology by Anadigm [3] has been chosen for the basic component of the PAC due to the commercial product of high quality and performance, the available Electronic Design Automation (EDA) software, automation programming technology for remote reconfiguration. The assumption for the PAC design was to develop a universal hardware and software reconfigurable platform for any kind of application. It is especially important in the field of control where MIMO systems are steered and/or pre and post signal processing (like filtering) is required. This goal has been achieved by the modular architecture of the signal handling board and appropriate architecture of particular units. The main module (see Fig. 4) contains up to four dpASPs and their chain extension to a few dual units for each of them. It allows to have up to 20 dpASPs in the serial-parallel configuration.

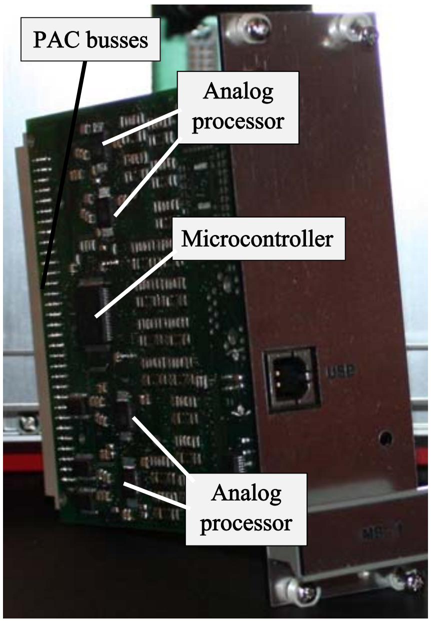

Fig. 4. PAC Core APU

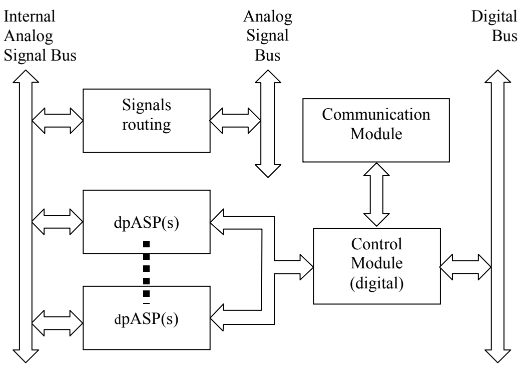

Fig. 5. PAC - APU architecture

Every of the on-board dpASPs is equipped with inputs and outputs realised with the support of op-amps for appropriate signal conditioning realised by the analog processor. The extension modules are installed additionally in a chain for every on-board dpASP to extend the signal processing capacitance. The main feature of the PAC is presence of configurable signal routing that allows to connect devices to each other and to route input and output signals [5]. The obtained signal processing path is user-defined under constraints of the main module configuration.

PAC - modules

The assumption of modularisation and ability to configure the equipment has been realised and it is possible to set-up the PAC according to the application. The platform is predestined for computing, signal processing, research and industrial control of multidimensional systems.

- Main module (PAC M01) - The main controller module is indispensable for configuring of the apparatus, that is the reciprocal connections between modules, and it is a communication unit between the external host computer through the USB link and/or the Ethernet. The main module contains the central control unit based on the 32-bit microprocessor which is dedicated to superior control tasks and the data exchange between external devices and the controller modules. This module contains the dpASP and optional extension slots. The analog signals are processed with the support of this module and therefore it is called APU (Analog Processing Unit). The APU resources can be extended by the extension modules (PAC M01db) with the dpASPs that are chained together. Up to six M01 modules can be installed in the PAC chassis.
- Input/output module (PAC M02) - The input/output module allows for an optional configuration of the input or output signals in the number up to 8 items. The module can be used up to 8 times in the apparatus in order to ensure a sufficient number of inputs/outputs to the management of the controlled process. The input signals are conducted by precisely gold-coated low-noise connectors and the Input/output direction is also configurable.
- Power supply unit (PAC M03) - The main power supply module of the apparatus. It has a fixed location in the PAC chassis and allows to supply all PAC modules.
- A/D module (PAC M06) - The acquisition module contains up to 8 inputs as well as a memory of the configurable volume from 1MB to 2GB. This module realises both the acquisition and calculation (controlling) tasks. The central unit - a 32-bit microprocessor is programmed to acquire data and communicate with other modules.
- D/A module (PAC M07) - The C/A controlling module contains up to 8 outputs as well as memory of the configurable volume from 1MB to 2GB. This module realises digital calculation and control tasks. The central unit – a 32-bit microprocessor is programmed to convert digital signals to analog ones, process digital data and communicate with other modules.
- Power supply module (PAC M04) for power driver module - this module is dedicated to supply the power driver module (M05) with a voltage and current in a given range.
- Power driver module (PAC M05) - this module contains 2 controlled power outputs to supply power to the external equipment such as DC engines, pumps, electromagnets and other automated devices. The range of output voltages is from 0 to 50V and the current intensity is from 0 to 3A per line (track, channel). For each module of the power terminal a module of power terminal supply is necessary.

The PAC hardware layer is prepared for many architecture variants depending on the target application. Some typical configuration variants are presented in the next chapter.

PAC - Configurations

The apparatus consists of a set of modules which are placed in the industrial housing (standard 19). The housing contains a rear panel which is an element used for connecting the modules. The panel contains 9 sockets for connecting particular modules, and an extra socket for connecting a power supply module and a place for the instalment of the power terminal modules. The designed apparatus has been constructed so that it can be inserted into standard housings according to the IEC standards. Also it can be installed in a euro-cassette used for mounting in industrial control cabinet and if needed it can be moved on site and encapsulated in a portable casing of a compact type. In the case of laboratory/research application it is encapsulated in a neat ratiopac PRO casing which may be a type of the 19" cassette with handles, in a type of tower casing or an oscilloscope casing with a carrying handle. The PAC functionality has been obtained by the custom design of hardware and software. The hardware layer was especially planned to be universal and flexible to configure. The embedded microprocessors for digital signals management allows to realise a number of tasks like: data acquisition and storage, signal generation, data exchange by the digital bus, static and dynamic configuration of dpASPs, communication with the host. The high level software layer running in the host computer is devoted to the PAC static configuration and dynamic re-configuration, data acquisition, data storage, high level signal processing and visualisation. In order to illustrate PAC configuration possibilities a compilation of selected and typical configurations is given in table 1.

Table 1. Selected PAC configurations

Config. / Slot	I	II	III	IV	V	VI
1	M02	M02	M02	M02	M02	M02
2	M01	M06	M02	M02	M02	M02
3		M07	M02	M06	M02	M02
4			M06	M06	M02	M02
5		M01	M06	M05	M06	M06
6			M07	M05	M06	M06
7			M05	M05	M07	M06
8			M05	M05	M07	M06
9			M01	M01	M01	M01
10	M03	M03	M03	M03	M03	M03
11				M04	M04	
12				M04	M04	

They are characterized by different numbers of particular modules depending on the target application. At this stage it should be pointed out that autonomous configurations of the apparatus may be connected with each other by the input/output module which constitutes an analog bridge between the items of the apparatus. Thanks to that it is possible to configure one set as a typically research-oriented one and the other one directly controlling the equipment (with the power terminal modules). Due to the additional versatility and modularity it is possible to realise complex tasks involving the monitoring and control of multidimensional processes and objects. The PAC hardware configuration is fixed for installation of power supply module M03 to slot 10 and power driver supply modules M04 in slots 11 and 12.

The configuration no. I represents the pure and minimal PAC resources ready to compute analog signals. Thanks to the APU equipped with the communication and configuration unit the PAC can be connected to any host computer or controller. The configuration I allows to realise many computational tasks on the base of input signals and put results to the PAC M02 output connectors. With this configuration the PAC can operate as external feedback (from SISO up to MIMO architectures) controller depending of the signal configuration and processing. The available free slots can be used for additional M01 and M02 PAC modules depending on required computational power and number of signals to be processed. The second configuration (no. II) is the extended version of configuration I by the A/D and D/A modules for data acquisition and generation purposes. The acquired data by PAC M02 module can be transferred to the M01 module by the digital bus, and then to the host computer or processed directly by the on-board micro-controller. In this case the digital data can be processed by one or both microcontrollers installed on PAC modules M01 and M02. The on-board software can be used for on-board reconfiguration of the analog processors. Configuration III is a set dedicated to control tasks. The modules are configured as input or output channels. Due to that the first two modules are meant to deliver signals to the A/C converters and the third one to move controlling signals out

of the controller. Additionally, in this configuration two dual channel power terminals allow for the direct control of four devices. Eventually, in this configuration the systems of maximum 16 inputs and 10 outputs can be controlled. Controller IV has a similar architecture where exclusive power drivers have been used for control purposes. With regard to the previous configuration, 8 executive devices are controlled, however, no external power device is required. Configuration V assumes that the system possesses its own power for the executive equipment, and it is needed to convert 16 input and 16 output signals. Such a configuration allows for control of multidimensional systems. By replacing the C/A module with the A/C module it is possible to measure 24 signals and to generate 8 control actions. Configuration VI is dedicated to the realisation of research-oriented tasks as it enables signals to be read out from 32 sources. The initial tests of parallel signal processing by the A/D and D/A modules was reported by [4] and shows that the PAC can be used without analog signal processing too, as the digital control platform with parallel data acquisition and signal generation.

PAC - Management by Software

Because the PAC is a combined unit of devices a set of software is required for its functioning. The embedded microcontrollers are programmed to achieve the required module properties and functionality. The PAC software allows full configuration of signals and data flow between modules as well as configuration of signal processing by the APU. The analog signal processors are configured with the support of the manufacturer's EDA software. The tool chain and information flow is shown in Figure 6.

The signal processing given in the form of mathematical formula is processed by the Configuration Generator – predefined PAC Toolbox functions with the bi-directional data exchange with EDA software. The auto placement, routing and verification functionality are handled using the COM technology embedded in EDA software [21].

This semi-automatic generation and verification tool allows to check the configuration correctness and signal processing results before downloading. It is an important stage due to the limited dpASP resources resulting in CAM parameters round-off.

The PAC Toolbox and embedded PAC software support the configuration download and configuration of all analog signal processors in all PAC M01 modules. The PAC processes signals immediately when the configuration download procedure has been finished. The main module which constitutes the central unit allows for the data exchange between the apparatus and the master computer.

The configuring software and the data exchange software allow for configuration of the apparatus as well as experimentation. The integration of the OS platform with the MATLAB/ Simulink software allows for the data acquisition, visualisation, programming of the C/A conversion modules as well as realisation of control and optimization master tasks. This can be done in a soft real-time mode triggered by OS timer or PAC communication events [23].

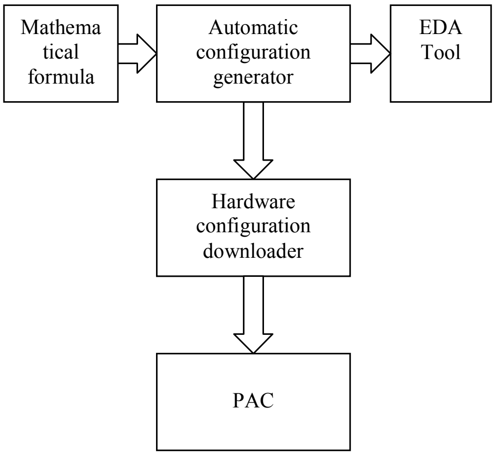

Fig. 6. PAC - tool chain

At the host level the data analysis, modification and control tasks as well as reconfiguration of the apparatus can be conducted within soft-time constraints. The most advanced application of the apparatus is its use for the target control system with the master optimization layer and the control adaptation (see Fig. 7). The buffered data exchange allows for various experimentation and the apparatus application for a lot of industrial (medical, chemical, heat transport, mass, electromechanical, mechatronic) uses as well as for research purposes.

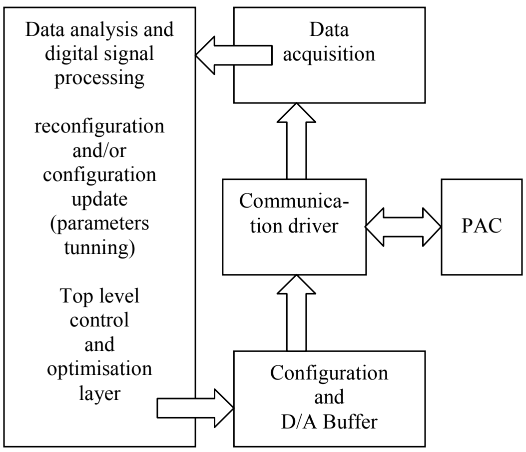

Fig. 7. PAC - software based management

Testing PAC real-time regime and discussion on features and limitations

DpASP technology allows analog sampled signals to be processed directly in the hardware layer. The embedded signal processing can therefore be categorized as hard real-time, since the processing time is determined by the driving clock and signal processing path. From the control system architect or signal processing point of view, the accuracy and punctuality of the signal processing is a crucial matter. Because there is no software or operating system installed in either single or multiple dpASPs, the signal is processed, in the parallel, serial or mixed manner, directly by analog processors, depending on the signal routing in the PAC architecture. Moreover, no tasks, processes or other mechanisms are well known from software-based, real-time systems.The processed signal is therefore being realized with an accuracy determined solely by the analog processor and internal CAM's signal processing and driving clock. From the point of view of real-time signal processing application, knowing when the processed signal will be available at the output is critical. To test the PAC core (dpASP) performance, the configuration presented in Fig 8 was created. The data acquisition was carried out using a Rigol DS1042C digital oscilloscope, with the analog signals being acquired at the possible highest sampling rate, namely 10MHz. In order to present and validate the performance of the processed signals, the three tests described below were conducted [23].

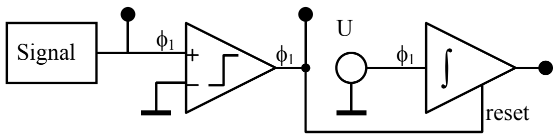

Fig. 8. Signal processing configuration for the real-time processing quality tests

When performing the linear approximation of the rising edge of the integrator CAM output (Fig. 9a) for the 20 cycles diagnosed during the tests, the mismatch error is at a level of 0.007%, including the data acquisition performed by the digital oscilloscope. The result obtained confirms high accuracy and repeatability of the signal processing. The Integrator CAM was being precisely reset by the comparator output signal. The next test focused on the internal sinusoidal signal generation. The data collected was analyzed by means of the Fourier transform and resulted in a frequency match with an accuracy of 0.006% (Fig. 9b).

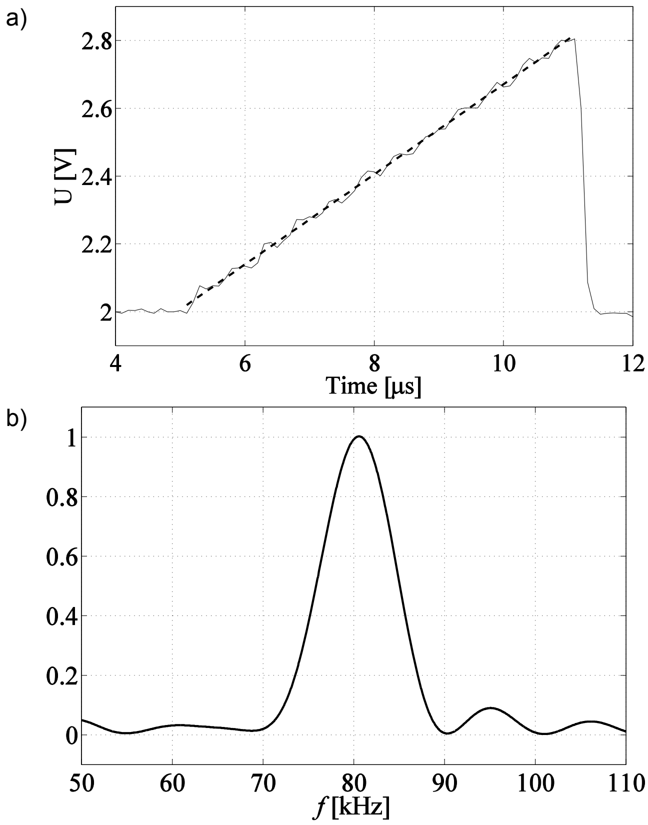

Fig. 9. Signal processing: a) integrator output with its linear approximation; b) Fourier transform of generated sinusoid

The third test was carried out on the basis of comparator action for an input signal characterized by a fixed frequency but variable duty cycle. For the purpose of analyzing the comparator output, the differential signal was collected and a rising and falling edges versus mean signal value was detected (Fig. 10). The rising edge event times were registered at the 4μs, 8μs and 12μs periods of the signal phases. They were then counted and are shown here in the form of a histogram (Fig. 11). The results presented shows the signal processing's 100% repeatability. Moreover, no jitter was observed with the measurement technology applied, which means that the jitter is at the nanosecond level.

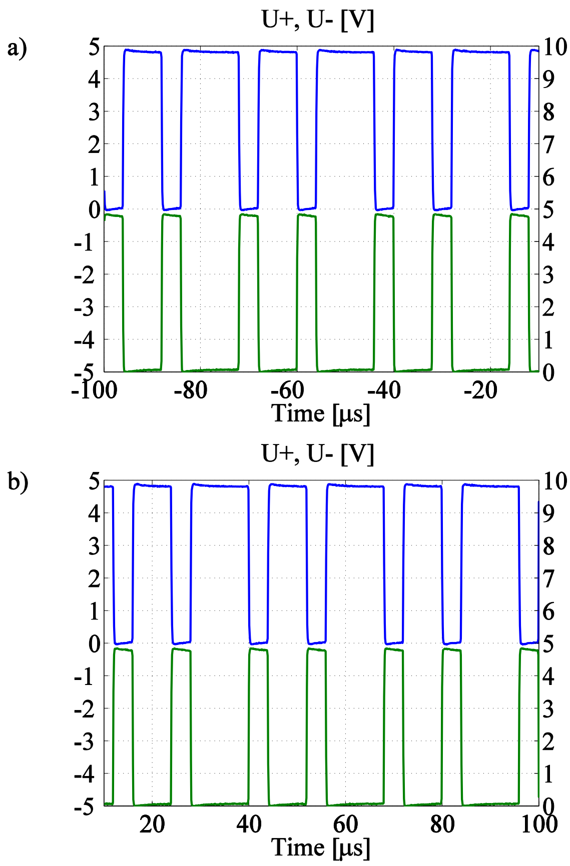

Fig. 10. Comparator output for the user-defined input signal

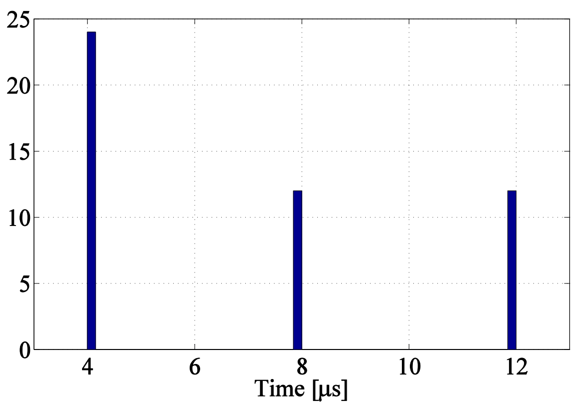

Fig. 11. Histogram of time periods detected between edges of the processed signal

In conclusion, the tests conducted and the computations, signal processing and real-time control experiments provided suggest that the proposed PAC solution, based on analog signal processors, constitutes a new solution in the field of deterministic hard real-time processing. This is particularly the case as regards the control, since the minimal jitter, and the precision and repeatability of the signal processing guaranteed by hardware signal processing and the driving clock are the most important advantages over other software based solutions.

Comparing PAC to the existing solutions is difficult owing to the hardware specific architecture and resources. However, let us compare it to the FPGA-based solution with A/D and D/A converters in the I/O space. In both cases, the signals/ data can be processed in the parallel manner, both devices can be configured and reconfigured if such a feature is implemented in the FPGA processes, both solutions are based on the master hardware clock driving the electronic device, and both solutions can use the internal clock to drive the signal processing. The dpASP configuration is totally different from that of the FPGA. In the case of the analog processor, the EDA software is used with hardware-specific resources. In the case of the FPGA, the VHDL can easily be used to create a user-defined configuration, but the synthesis, routing and optimization stage takes some time and depends on the complexity of the signal processing. The synthesis time is shorter in the case of the analog processor than in that of the FPGA, because the configuration is done in the EDA software, with all the features and limitations of the signal processing components. Creating very complex signal processing and preparing custom optimization for several analog signal processors, or more, could take some time, though, depending on the abilities of the user. The analog processor configuration is validated at the configuration software level, as are the CAM properties and signal processing results. Finally, the EDA software allows the programming configuration data to be generated.

The main features of the PAC are the reconfigurable analog resources with signal routing, configuration, and on-line reconfiguration. The properties of the signal processing path can be updated in real-time mode. The reconfiguration time corresponds to the reconfiguration data length transmitted by the SPI interface from the host micro-controller. The reconfiguration is executed in one sample clock, which drives the dpASP.

The main disadvantage of the programmable analog technology is its small capacity. It is for this reason that the PAC architecture has been designed. The cost of the Main Module depends on the dpASP installed and is ranges from 900 euro net for a configuration with 4 dpASP up to 1400 euro for 20 dpASP. The additional cost of the routing board, power supply and chassis is approximately 850 euro. With this configuration, hard, multi- channel, parallel, real-time signal processing can be carried out. Additional effort is accorded to the configuration task, when the CAMs are placed and routed in either single or multiple dpASPs. This process has been accelerated with remote handling by EDA software control. At present, a number of the functions for remote configuration have been created in MATLAB and C++ for research purposes. The development cost is very low owing to the free EDA software for analog processors, PAC predefined software and PC drivers.

Another difference between existing solutions and the PAC is the signal processing method. In the case of typical real-time FPGA, micro-controller or computer based solutions, the analog signals are sampled and held at every specified period of time, which is known as the sample time. The digital data is then processed and, finally, converted to analog form. In this case, the complete signal processing is carried out with a predefined sampling frequency. During the sampling period, a number of computations is provided. In the case of the PAC and analog processors, the signal flow is continuous, despite being sampled. The chained and clock driven CAMs process the analog signal with a user-defined frequency. The chained components thus process the signals in every driving-clock phase.

The following conclusion can be formulated on the basis of the experiment with FPGA programming; at present, the configuration of complex signal processing to be embedded into PAC-like devices is much more complicated owing to the constraints of the processors' CAMs and their properties. On the other hand, is faster, since the synthesis time is short, thanks to the direct configuration in EDA software.

In terms of real-time signal processing and control systems, the PAC-based solution offers a higher bandwidth. The following remarks can be formulated on the basis of the PAC experiment; the programmable analog solution constitutes perfect hardware for hard, real-time, simple control, feedback architecture, high order filters, and adaptable signal processing. The limits of the processor restricts the application of complex mathematical linear and nonlinear calculations, some of which can be carried out, though the processor available must be carefully analyzed.

The most complicated part of the configuration design is the estimation of the requisite resources and signal routing across several dpASPs. This task has to be performed manually or semi-automatically. Research into fully automated configuration is in progress as regards specific signal processing tasks and dedicated methods and tools will be considered in future research. Because, as an open architecture platform, the PAC is easily adaptable to any signal processing task, it can be used successfully as the hardware for real-time embedded control systems. In the case of the PAC, the signal is processed by the hardware layer and the risk of software virus infection is therefore eliminated. Moreover, the configuration created and executed is algorithm-free. There are thus no bugs or unexpected situations such as thread suspension, algorithm mistakes, and so forth. Thanks to this, the PAC solution is dedicated to hard, real-time, critical applications, especially in the field of control or other signal processing.

Given that the programmable analog technology is a solution fresh to the commercial market, the forthcoming years will show whether the analog solution will extend the functionality of digital solutions. Even now, analog components can already be found embedded in some processors.

PAC - application for active magnetic levitation control

Finally, the Programmable Analog Controller has been applied to control the Active Magnetic Levitation system [25]. The PD control law and low pass filter are embedded into a single analog processor [20], [22]. The controller CAM modules have been driven by the 40kHz clock, and appropriate gains were adjusted to achieve the requested performance. One can find that to stabilise the ferromagnetic object the complete control law has been implemented in a single dpASP device. Such a situation will occur in many other controlled devices, when simplification and increased performance of the control law is affected by the highest sampling frequencies. The AML application shows the the PAC can operate with external hardware and power electronics. It allows to use the PAC to replace existing computational devices when its features will improve control quality. The most important feature in this application is that the controller structure and parameters can be reconfigured to achieve requested feedback performance. The pre-study of the FPAA application in the industrial levitation devices has been provided for Active Magnetic Bearing [19]. The features and limitations of this technology applied in the control field for active levitation devices are discussed in [22] where other signal processing and control configurations are analysed. One can find in the literature, that active levitation can be realised with the support of discrete analogue elements. However, there are many disadvantages of this method, such as: fixed parameters, drift, non-robust and adaptive feature. Nowadays, the analogue technology can be used in a programmable way with many advantages and configuration features. The realised PAC becomes an industrial controller for Active Levitation Systems, too.

Conclusions

Thanks to the Anadigm's dpASP and EDA software it was possible to build up the architecture of the Programmable Analog Controller (PAC). The embedded digital and analog electronic devices organised in a set of different modules allowed to obtain a complete control system functionality: computing, data set-up and acquisition, input/output bridge and power peripherals. The elaborated PAC is characterized by the modular architecture, hardware based parallel signal processing, configuration of signal flow, configuration of its functionality, reconfiguration of parameters, and user defined tasks realised in the digital data processing devices (both - embedded into the PAC and external host computer). The PAC offers a hardware solution supported by the software layer that is suitable for users that would like to be focussed on the computational aspects. Its hardware structure allows for a number of configurations that can be easily obtained by the installation of appropriate modules and signals routing. The absence of the operating system and program execution while processing signals guarantees high quality due to the minimal jitter and punctuality fulfilled by the hardware driven CLOCK. It is important to remind that thanks to the dpASP technology the PAC can process signals in some configurations up to 2MHz bandwidth. The open architecture allows to instal PAC modules as well as to connect a few PACs together in a stack, routing them by the analog I/O module.

The designed and developed universal, configurable hardware allows to implement many computational mathematical operations and execute them in the hard real-time regime with support of parallel computational architecture. The user-defined PAC configuration (even in a stack architecture if more resources are required) makes it flexible to many applications. The configurable routing, signal processing path and parameters allows to adjust this apparatus to many scientific and industrial applications. The investigation of chained analog processor has been reported in [24].

The realised hard-real time controller for Active Magnetic Levitation system confirms the PAC availability for industrial applications. The study on state feedback controller [26] shows configuration dependent signal processing.

The PAC possesses a lot of properties significant for direct and master control. Multichannel data acquisition with the programmed frequency allows for a simultaneous diagnosis of a whole system's condition. In addition, the simultaneous signal generation eliminates the occurrence of delays on the controlled signal channel. The developed PAC is a breakthrough to many hardware embedded signal processing applications, although the limits of the programmable analog signal processing devices must be precisely studied before the implementation stage. The dpASP capacity and CAM constraints affect the requested PAC structure. In some cases the required signal processing cannot be realised due to the hardware limitations and especially signal processing parameters dependence on the sampling frequency. The PAC system together with dedicated software constitutes a custom rapid prototyping control system. This aspect of the automatic control and real-time controller design require an extra research for other control methods.

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