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The Latest Trend in Nanobiosensor System Architectures

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***Abstract*—Nanobiosensors are an interesting topic of research. However, interfacing with a nanobiosensor requires an analyser system. A number of researchers have proposed different system architecture to interface with nanobiosensors. In this paper, comparison of the existing system architectures for nanobiosensors is discussed. Criteria in designing nanobiosensor system architecture is evaluated, such as the characteristics of the nanobiosensor, a signal processing algorithm, device connectivity, signal interface, processor, data busses and memory requirements. Based on the analysis, an automatic nanobiosensor system architecture is proposed to simplify and accelerate the measurement process.**

Keywords— nanobiosensor; biosensor; biosensor analyser; system architecture; platform

I. INTRODUCTION

A biosensor is an analytical device that is able to detect specific biological substances through biological reaction and produce the result in the form of electrical signal or other response depending on its sensing mechanism. Biosensors have been in existence for more than 50 years. They are widely used in health science, agriculture, military and industries. With the recent development of nanotechnology, nanobiosensors such as nanotubes, nanowires and interdigitated electrodes (IDE) have been introduced [1].

Nanobiosensors provide advantages in a number of applications, especially in health science. Examples of applications are early disease detection [2], [3], biosensor-based monitoring systems [4], pharmacogenomics [5] and glucose detection [6]. Nowadays, a number of researchers are working with nanobiosensor technology, including IT nanomaterial, fabrication processes, sensing mechanisms and bio signal processing.

Nanobiosensors can be classified into five different sensing mechanisms, electrochemical transducer, electrical transducer, optical transducer, piezoelectric transducer and thermometric transducer [1]. For example, an electrochemical transducer-based nanobiosensor produces an electrical signal as output response when a biological reaction occurs between the sample under test and the sensor [1]. The electrical signal is measured and calculated by the system to produce the final result [1].

In order to fully utilise the function of a nanobiosensor, a dedicated bio signal processing algorithm, a platform system and a special signal conversion circuit is needed by the nanobiosensor to analyse the input signal. The algorithm processes the bio signal using various techniques. A signal conversion circuit, such as an analogue to digital converter (ADC), is used to alter the signal level and properties into a level suitable for the platform system. While a platform system controls the process activities from sensor input into understandable output.

However, interfacing with the nanobiosensor itself requires a high performance instrument, such as a signal analyser. A professional operator is also needed to interface the instrument and carry out analysis on the bio signal for the purpose of obtaining the information in the signal. In order to make the system more portable, some researchers are studying the development of an on-chip system that is able to analyse the bio signal, such as lab-on-chip and instrument-on-chip [4] [5].

In this paper, several existing system architectures for nanobiosensors are discussed. Section II presents existing system architectures, while Section III discusses the comparison between different architectures. In Section IV, an automatic nanobiosensor analyser system is proposed. Finally, Section IV concludes this paper.

II. LATEST TRENDS IN NANOBIOSENSOR SYSTEM ARCHITECTURES

Several researchers have worked on developing a universal platform for nanobiosensors. Among the studies, a multi-core processor system architecture design for universal biomedical signal processing is proposed by the authors in paper [2]. Based on the authors [2], the multicore processor system can carry out more complicated and heavy load processing work compared to a single core processor. A two-way pipeline processing unit (PPU), as illustrated in Fig. 1, is introduced to provide flexibility and energy efficiency for the biomedical signal processing.

The PPU contains four major modules, processing core, instruction module, data module and output module. In each PPU, each of the modules is interconnected with wishbone buses. The architecture of a two-way PPU can be expanded into a parallel architecture, as illustrated in Fig. 2 (a) by using a slave switcher, as illustrated in Fig. 2 (b). The expansion allows more complicated biomedical signal processing, such as high dimensional feature extraction. A test case is carried out to apply a three type electrocardiogram (ECG) analysis algorithm in a two-way PPU. It is proven that the flexibility of the system

allows it to correspond to any algorithm applied to it with minimum change in power consumption. The results also show the power consumption of two-way PPU is 91% lower than a four core symmetric multiprocessing (SMP)-based processor.

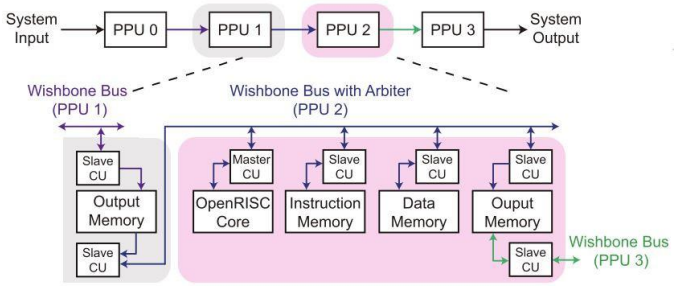
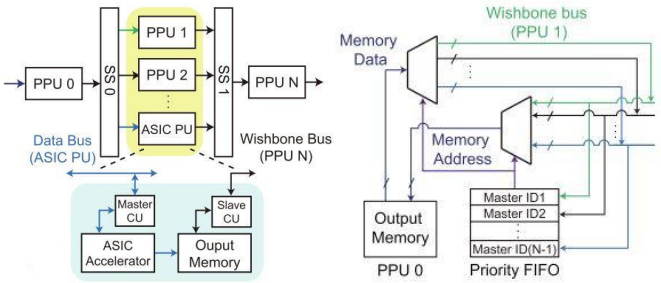


Fig. 1. Two-way pipeline processing units (PPUs) [2]



(a) (b)

Fig. 2. (a) Parallel extension of two-way PPU with slave switcher[2] (b) Block diagram of slave switcher [2]

Based on paper [3], a bio signal processing platform for an array sensor is introduced. The platform is designed to measure aptamers, which are small Ribonucleic acid (RNA) or Deoxyribonucleic acid (DNA) molecules, through a capacitance reaction in the array sensor. The architecture of the platform is illustrated in Fig. 3. The platform consists of a processor, on-chip debugger (OCD), external buses, Liquid Crystal Display (LCD), memory block, array sensor and ADC. The system architecture is designed, synthesised and implemented into the FPGA core, except for the array sensor and ADC.

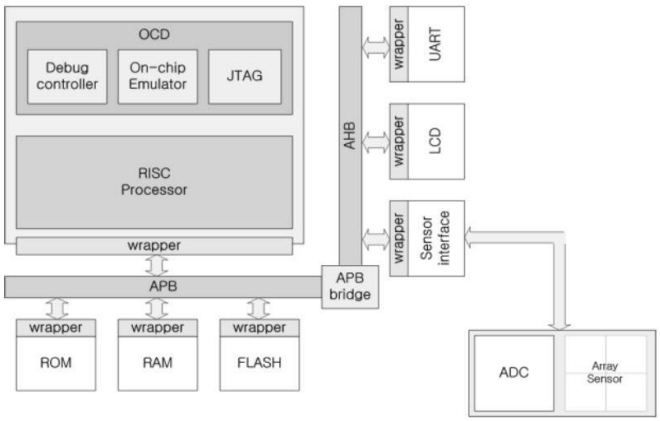


Fig. 3. Block diagram of platform system [3]

The bio signal processor is a 32-bit Reduce Instruction Set Computing (RISC) processor. In this system, the sensor interface is designed by arranging the array sensor in 2x2 array with a commercial ADC chip, AD7466. In order to receive sensor input in digital data form, the processor communicates with ADC via inter-integrated circuit (I2C) protocol. In this work [3], the system is implemented in a Xilinx Vertex-IV LX40 FPGA development board.

A unique platform nanobiosensor system architecture is introduced in paper [7]. The platform system is a reconfigurable system architecture for physiological signal monitoring. This system is developed to provide a smarter diagnostic and accurate real time physiological parameters analysis. The physiological signals analysed by the system are blood pressure, heart rate and ECG. The system architecture, as shown in Fig. 4, consists of four modules, namely physiological signal modules, control and decision modules, multiple feature extraction modules and main controller modules.

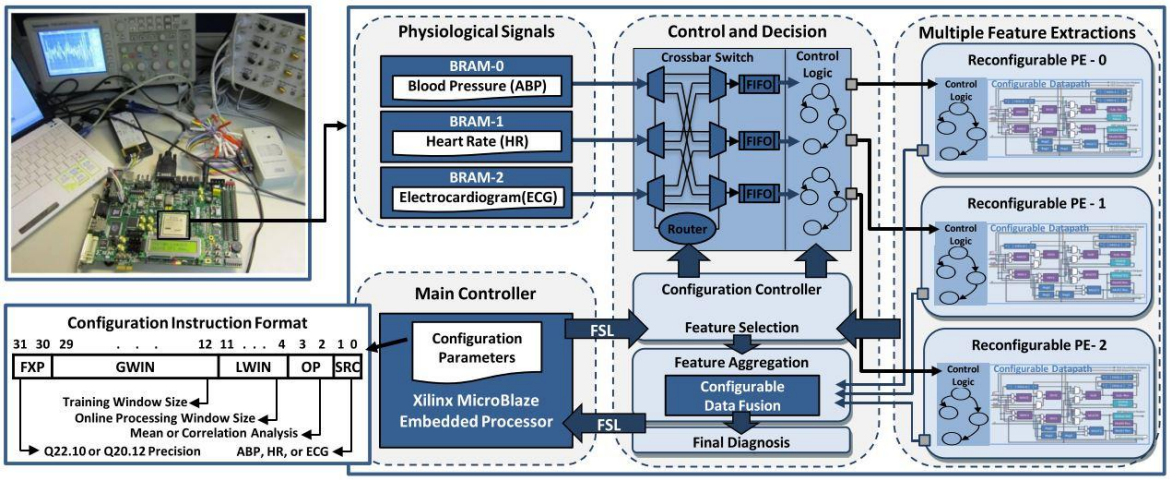


Fig. 4. Block diagram of reconfigurable system architecture for medical monitoring [7]

Physiological signal modules are a biosensor input interface that receives bio signals from the sensor and transfers it to control and decision modules. Control and decision modules control the signal flow between all other modules. In addition, it also compares and finalises the result from multiple feature extraction modules and sends it to the main controller modules. The multiple feature extraction modules contain a number of reconfiguration processing elements (PE) that are used to process various bio signal processing algorithms. A complicated algorithm can be performed by separating the algorithm into a number of PEs. The main controller modules provide instruction to the control and decision modules. They also carry the final result for further action, such as displaying or storing the data. In paper [7], the system is tested under a multi-parameter cardiac monitoring scenario, where the physiological signals are constantly being analysed to detect abnormalities. The result shows improved accuracy as compared to existing rule-based monitoring schemes.

The author of paper [8] proposed a lab-on-chip (LoC) architecture for high throughput bio-sensing. The system architecture is designed for magnetoresistive biochips or sensor arrays. The system architecture that is illustrated in Fig. 5 was implemented into Xilinx Zynq 7000 Extensible Processing Platform. The system architecture contains an ARM processor, Fast Fourier Transform (FFT) Co-processors, number of ADC with Serial Peripheral Interface (SPI) bus driver, Signal generators, I/O Peripherals, network interface and DDR-RAM with memory controller. An ARM processor is used to control the activities of the system. A signal generator that consists of direct digital synthesiser (DDS) is used to provide stimulus signal to sensor arrays, while ADC with bus driver is used to receive the output signal from sensor arrays. A digitalized output signal from ADC is processed by FFT Co-processor and the processed data is sent to the memory. Since the system is implemented in Zynq SoC, an AMBA bus, Advanced eXtensible Interface (AXI) bus is used to interconnect between the ARM processor and modules from programmable logic such as co-processor and driver. A user interface is developed in the system for user to view the result. A network interface is used to transfer processed data to an external database.

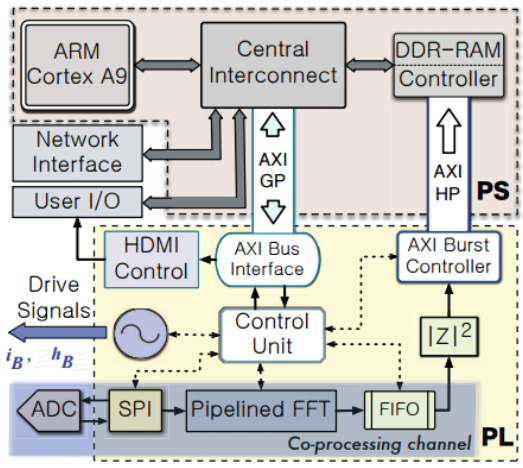


Fig. 5. Architecture of bio-sensing platform [8]

In paper [4], instrument-on-chip for label-free biomedical application is introduced. The instrument-on-chip is a handheld bio-impedance measurement system that uses two-phase square wave lock-in technique for signal processing. The impedance measurement system is illustrated in Fig. 7. The system architecture is separated into two parts, known as the integrated circuit module and FPGA chip. The integrated circuit module consists of a low-noise current amplifier, multiplier and ADC. The FPGA chip performs signal generation, system control and data processing, and consists of a digital filter and DDS.

In the FPGA chip, a DDS is designed to interface with a commercial digital to analogue converter (DAC) chip. The DDS and DAC are used to generate signals for sample under test. In this system, a sinusoidal voltage is applied as an excitation signal to the sample under test via a microelectrode. The measured signal from the other microelectrode is amplified using a low-noise amplifier. Then, it is demodulated with a phase shift multiplier before being converted into a digital signal. To obtain its real and imaginary part of admittance, the digital signal is filtered through a low pass filter. The final result will be transferred to a PC via USB communication.

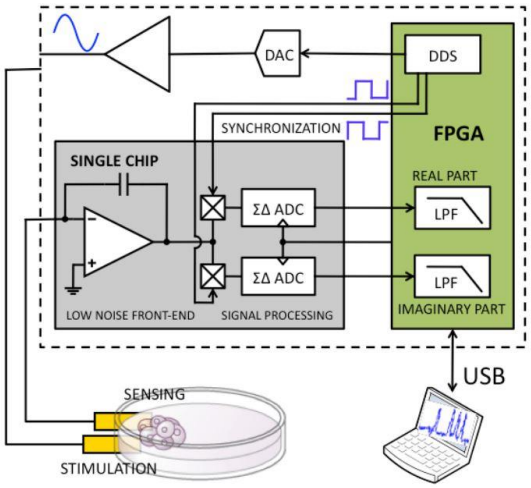


Fig. 6. Block diagram of bio-impedance measurement system [4].

A dual bio-sensing platform system using VLSI technique is proposed in paper [6]. The system is based on a FPGA platform interfaced together with glucose and cholesterol sensing. The block diagram of the dual sensing system is illustrated in Fig. 8. The system contains a dual glucose/cholesterol readout circuit, a 12-bit RC hybrid successive approximation ADC, a digital controller, a serial electrically erasable programmable read-only memory (EEPROM), and an LCD. For bio-sensing, an amperometric method is used in the readout circuit. Based on the amperometric method, current is generated to the readout circuit during oxidation between the potential applied electrodes. An ADC will digitalise the output signal from the readout circuit and send it to the digital controller. In this work, an Altera DE2-115 FGPA board is used to implement the digital controller and external device driver. The platform connects all external components, including EERPOM, LCD, Biosensor readout circuit and 12-bit ADC.

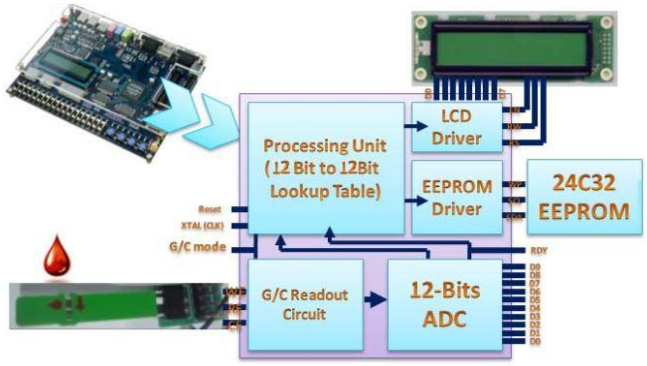


Fig. 7. Architecture of a dual glucose/cholesterol sensing system [6].

III. Architecture Comparison Between Different Design Approaches

In this section, the existing system architecture, as discussed in Section II, will be analysed. Table I summarises the comparison between these architectures. Overall, interfacing with a nanobiosensor requires a platform that is able to capture an analogue signal from the biological reaction between the biosensor and sample under test. Then, the signal is converted into readable data or a visual through a dedicated circuitry, algorithm or signal processing. This process step is important and common in most of nanobiosensor platform research.

TABLE I. Comparison Between Different System Architectures

Method	[2]	[3]	[4]	[6]	[7]	[8]
Application	Heart Disease detection	Liver cancer detection	Impedance detection	Glucose & cholesterol detection	Health monitoring	biological analysis
Test target	ECG	Aptamer	cells	Glucose & cholesterol solution	Blood pressure, heart rate & ECG	DNA
Sensor/data Source	Database	Capacitive sensor array	Micro-electrode	Glucose strip & cholesterol strip	Database	Magneto resistive biochip
Analog Circuit	No	ADC chip	ASIC	ASIC	No	ADC
Processor	OpenRISC, OR1200	Custom 32 bit RISC	No	Digital controller unit	Configuration controller	ARM & FFT Co-processor
BUS	Wishbone	AMBA	No	No	Fast simplex link (FSL)	AMBA
Memory	16KB data memory, 16KB output memory	9Mb SRAM, 32Mb FLASH	No	EEPROM	Yes	DDR
USB	No	Yes	Yes	No	No	Yes
Output	Yes	LCD, UART, USB	USB	LCD	Yes	Monitor, Network
Clock speed	15MHz	50MHz	50MHz for ADC & DDS 10MHz for ΣΔ	50MHz	-	180MHz
Algorithm execution	Dedicated	µP	Circuit	dedicated	Dedicated	FFT Co-processor

From the perspective of architecture, each of the system architectures is designed depending on the algorithm, sensor mechanism and design approach. Some architectures are designed specifically for a nanobiosensor or an application, while some of the architectures are designed based on a specific algorithm. An example of an algorithm-based approach is bio-impedance measurement instrument-on-chip, where it uses a two-phase lock-in method [4]. From Section II, the comparison between system architectures is tabulated in Table I.

Based on data collected in Table I, each of the systems is designed in different ways and used in different applications. Example of applications are heart disease detection [2], liver cancer detection [3], impendence detection [4], bio-recognition [8], glucose and cholesterol detection [6] and health monitoring [7]. In each application, a different sample under test and a different input source or sensor to the system are selected.

Based on the existing system architectures, most of the systems use a 32-bit RISC processor to execute algorithms and control the activity within the system. A conventional low power processor, such as an ARM processor, is used for bio-recognition application in [8]. This is because the processor is simple to use and energy efficient. However, a custom design processor, such as the 32-bit RISC custom processor in [3], is more power efficient and has smaller logic size and a smaller instruction set. This is because conventional processors may consist of additional components which are not used when executing an algorithm, whereas a custom processor consists only of components required by the system.

Comparing the algorithm-based approach with other design approaches, processor-based architecture, such as ARM processor, have a better flexibility, more powerful processing unit and higher processing speed, as discussed in [3], [8]. A processor-based architecture is capable of processing various algorithms, where these are loaded in memory as part of the program. By using a high-speed processor, a real-time output can be obtained from the sensor.

A flexible platform, such as a Pipeline Processing Unit (PPU) [2], and embedded reconfiguration architecture [7] are capable of interfacing with different types of sensor as well as executing various algorithms. Compared to processor-based architecture, a flexible platform executes complicated algorithms more efficiently in terms of power consumption and speed. A faster result can be obtained from this method due to its architecture, because the algorithm can be divided into smaller parts and executed by a number of processing units [2]. Furthermore, the flexible platform system allows system optimisation in order to meet the desired performance [7]. However, developing a flexible platform may prove difficult to design the architecture and troublesome in loading algorithms into the system.

In architecture [2], the modules in the PPU are interconnected by a wishbone bus for data transfer. The wishbone bus is suitable for smaller architecture due to its simple design. An AMBA bus is used to interconnect the processor, memory and peripheral devices in architectures [3], [8]. AMBA allows efficient data transfer between components due to it hierarchy level and pipeline feature. Fast Simplex Link (FSL) is used in [7] for fast data transfer within the architecture.

Most architectures require a memory component for data storage purposes, such as SRAM, FLASH, Programmable Read Only Memory (PROM) or EEROM. In processor-based architectures [3], PROM is used as instruction memory to store system coding and SRAM is used as a temporary register for data processing, while a larger capacity of FLASH is used as data storage to store the input data and output result. In architecture [2], small capacity of data memory, instruction memory and output memory is used in the PPU. The memory acts as a buffer register and allows the processor easy access to it via the wishbone bus. A serial-interfaced EEPROM is used in [6] for data storage.

Certain biosensor system architecture, such as the bio-impedance measurement system in [4], uses analogue components in the architecture. For example, an amplifier and filter are used for improving the quality of the input signal. In this architecture [4], a dedicated analogue circuit is designed as part of the algorithm or detection method. In signal conversion, a number of platforms use a commercial ADC chip to convert analogue signal into digital signal. This method reduces the complexity of the signal conversion circuit or circuit driver in the system architecture. However, communicating with an ADC chip requires a communication protocol, such as I2C protocol [3].

With current connectivity technology, most platforms have a USB support feature which allow them to interface with the PC [3]. Through USB communication, the data can be transferred to the PC for data storage or data analysis using custom software [4]. Some platform systems support Universal Asynchronous Receiver or Transmitter (UART) communication. This allows an alternative communication solution to PC and other UART-supported devices [3]. With wireless and network support, the system can transfer data to the data storage over the air or through network [8]. A LCD display is also used in the platform to provide real-time results. A portable system can be created by integrating the LCD into the system [3].

IV. Proposed Automatic Nanobiosensor Analyser System

From Section III, the criteria of a nanobiosensor platform system includes the connectivity of the system, sensor interface, busses or interconnection link in the system and the processor specification. In order to reduce complexity in interfacing with the nanobiosensor, an automatic nanobiosensor platform system is proposed.

The block diagram of the proposed platform architecture is illustrated in Fig. 9, and consists of a 32-bit RISC processor, internal bus, RAM, ROM, UART controller, USB controller, ADC driver and GPIO for external interface. A 32-bit RISC processor has a high processing speed which allows faster code execution. RAM and ROM are memory components that are used to store program code, such as algorithms, and as data storage for nanobiosensor input. An internal bus is used to interconnect between the processor, memory, ADC driver, USB controller, UART controller and GPIO. The ADC driver is designed to allow data transfer between the ADC chip and the platform system with minimum processor load. A USB controller and UART controller are used for data communication, such as transferring data to a PC or to other platforms. A GPIO is designed to interface with external components, such as LCD, LED, push button and keypad. In order to design and develop the platform system, an FPGA approach, called a system-on-a-programmable-chip, will be used to integrate the required components into the system using a core or modules library [9]. The advantage of this approach is simple in design and it takes less time in development.

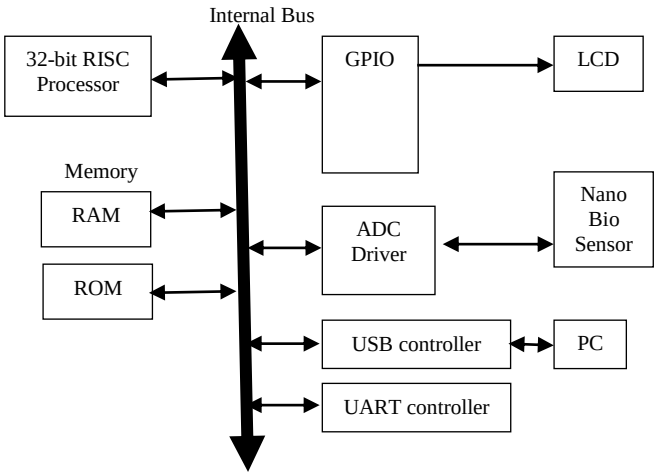


Fig. 8. Block diafgram of an automatic nanobiosensor platform system.

A dedicated signal processing algorithm will be loaded into the system in order to allow the system to automatically analyse the nanobiosensor input. Once the raw data is transferred from the nanobiosensor to the memory via ADC, the processor will process the data into understandable data based on the algorithm. The data will be displayed on the LCD for users to observe or transferred to the PC for data storage. The proposed platform system will be prototyped and developed in an FPGA platform. The final product of the system will be integrated on-chip with a nanobiosensor and fabricated into a single integrated circuit.

V. Conclusion

In this paper, a number of existing nanobiosensor system architectures are reviewed and the design approach on each of the architectures is shown to be different. The characteristics of the existing systems were studied in order to identify the criteria of the nanobiosensor system. The sensing mechanism of the nanobiosensor and the bio signal processing algorithm are the aspects of concern in the system architecture. System connectivity, analogue to digital interface, processor specification, data busses and selection of memory are the criteria in designing nanobiosensor system architecture. An automatic nanobiosensor platform system is proposed, which contains a 32-bit RISC processor, data busses, RAM, ROM, UART controller, USB controller, ADC driver and GPIO. The proposed system will be prototyped on an FPGA platform and the end product will be fabricated into a single chip together with the nanobiosensor.

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