A Sensor Modeling Technique Using SystemC-AMS for Fast Simulation of System-in-Package based Bio-Medical Systems

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Abstract— Use of biomedical systems, which includes healthcare systems and bio-medical implants, is increasing rapidly. These systems consist of analog and digital blocks. In order to develop these systems in short time while meeting strict size, energy and cost constraints there is need for a new design methodology. This research is focused on developing an application specific instruction-set processor (ASIP) and system in package (SiP) based common hardware platform, which could be used by different health monitoring and bio-medical systems. For fast design space exploration there a fast simulation model of complete system is also needed. Different blocks of SiP have been modeled, at different abstraction levels, using SystemC and SystemC-AMS. In this paper a sensor modeling technique, for modeling of available analog sensors, will be presented using SystemC-AMS, which will be used in the SiP simulation model.

I. Introduction

Healthcare and medical devices, especially those that are implanted in the human body, are some of the most complex and cutting-edge products available today. While they can improve the quality of human life, they also pose some of the biggest engineering challenges. Most of these systems consist of a sensor block (data acquisition), an Analog to Digital Convertor (ADC), a data processing block, and a data communication block, as shown in Fig. 1. Sensors are used to acquire desired information about human health. In most of cases sensors output is analog, which is converted to digital form by using ADCs. A data processing block usually consists of a processor, which processes acquired data before transmission. A data communication block transmits the acquired data for further analysis, or actions using wireless or wired communication.

In most bio-medical applications data processing block and communication block remain the same (or may need a few modifications in order to improve the performance e.g. adding application specific special instructions to a processor), while the data acquisition block (sensors) is mostly application dependent. There are several constraints in designing todays biomedical systems and designing these systems under these constraints is a real challenge. From medical doctor point of view today's bio-medical systems should offer:

- Less invasion
- Less restraint
- Less awareness
- Less heat generation
- Long term and real time measurement
- Higher dependability

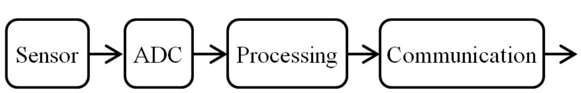

Fig. 1: Basic blocks of a biomedical system

In order to monitor/assist human health bio-medical systems need to be continuously operational over a long period. Therefore these systems must be extremely energy efficient and low power. For systems buried inside the body there should be a non-invasive mechanism for power and data transmission. Due to the criticality of information exchange between system outside and inside body the communication must be error free. Some of these systems need to be extremely small due to limitation of available space in human body, e.g. eye implants.

In order to meet the various design constraints of these systems an ASIP and SiP based common hardware platform is proposed in this paper. The proposed common hardware platform can be used by different bio-medical systems. For fast design space exploration of the hardware architecture and early application software development, a simulation model of a complete SiP using SystemC and SystemC-AMS is under development.

This paper presents a unique technique for modeling real sensors at a higher abstraction level using SystemC-AMS. Use of SystemC and SystemC-AMS also enables modeling of entire system at different abstraction levels and as close as possible to real hardware implementation, while using same modeling language.

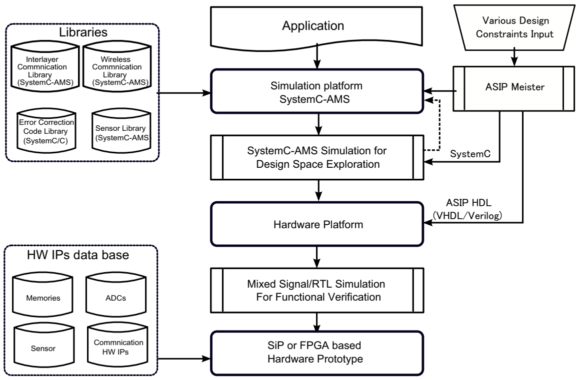

Fig. 2: Proposed design flow for SiP based design

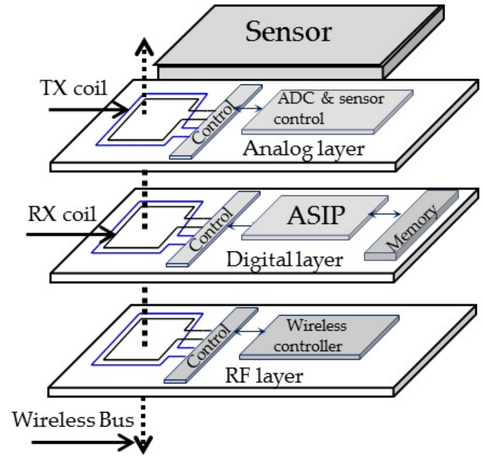

Fig. 3: Basic SiP Configurations

Rest of the paper is organized as follows. In Sect. II SiP based hardware platform and an overview of proposed SiP designframework will be presented, which will be followed by details of SystemC-AMS based simulation model of the SiP in Sect. III. In Sect. IV we will explain modeling of real sensors using SystemC-AMS, which will be followed by simulation results in Sect. V. In Sect. VI discussion and conclusion will be presented.

II. SiP Based Hardware Design

In this section the proposed design flow for a SiP based design and the proposed SiP based hardware platform will be covered.

A. *SiP Based Design Flow*

The proposed design flow, for development of a SiP based healthcare monitoring systems, is shown in Fig. 2.

In the proposed design flow a SystemC and SystemC-AMS simulation model is used for design space exploration of the hardware platform. In the proposed design flow a simulation platform is created using several available libraries. Some of the libraries are available as open source [1] [2] while others have been developed in-house. The simulation platform is used for design space exploration as well as application software development and optimization. An electronic system level (ESL) tool, ASIP Meister [3], developed by ASIP Solution, Inc. is used for automatic generation of SystemC and VHDL/Verilog code of an ASIP. After design space exploration and application optimization, using the simulation model, SiP/SoC/FPGA based hardware implementation of the system is carried out. For the hardware implementation of the system off-the-shelf and in-house developed hardware intellectual property (IP) cores are used, while HDL code of the ASIP is automatically generated by ASIP Meister.

B. *Proposed SiP Based Hardware Platform*

SiP is an advanced technology to incorporate multiple components into a single package assembled in layers. A SiP can consists of a variety of components such as CPU, hardware accelerators, analog circuitry, MEMS sensors and memory blocks, reducing overall system size. The various layers communicate with each other either using physical connection e.g. wire bonding or through silicon via (TSV), or communicates wirelessly (using inductive or capacitive coupling). SiP based devices have small size, light weight, low power and energy consumption (hence low heat generation) [4]. Therefore SiP based design is most suitable for bio-medical implants because of small size and low power consumption. Fig. 3 shows the proposed SiP based hardware platform for bio-medical systems, consisting of three layers.

- Analog layer: This layer consists of Analog to Digital convertor (ADC) and sensor control logic and sensor interface
- Digital layer: Digital layer consists of and an ASIP, which is based on 32 bit RISC processor Brownie Std 32 [5] of ASIP Solutions, Inc., data and program memories
- Wireless communication layer: Wireless communication or Radio Frequency (RF) layer consists of wireless communication hardware (e.g. Bluetooth or custom protocol

For inter layer communication inductive coupling based wireless communication [6] is proposed, although wire bonding or TSV can also be used.

One of the important components of a biomedical system is the processing engine. Traditionally an application specific integrated circuit (ASIC) or a general purpose embedded processor (GPP) is used as processing engine. Although an ASIC has an advantage of being the most efficient in terms of power consumption and provides high performance, but the lack of programmability limits its use to a single or a few applications. Designing individual ASIC for each application is not cost effective, and use of multiple ASICs, in order to include more functionality, will increase the size of the system. On the other hand GPPs provide programmability, and can be used for multiple applications, but they are power hungry, and are not area

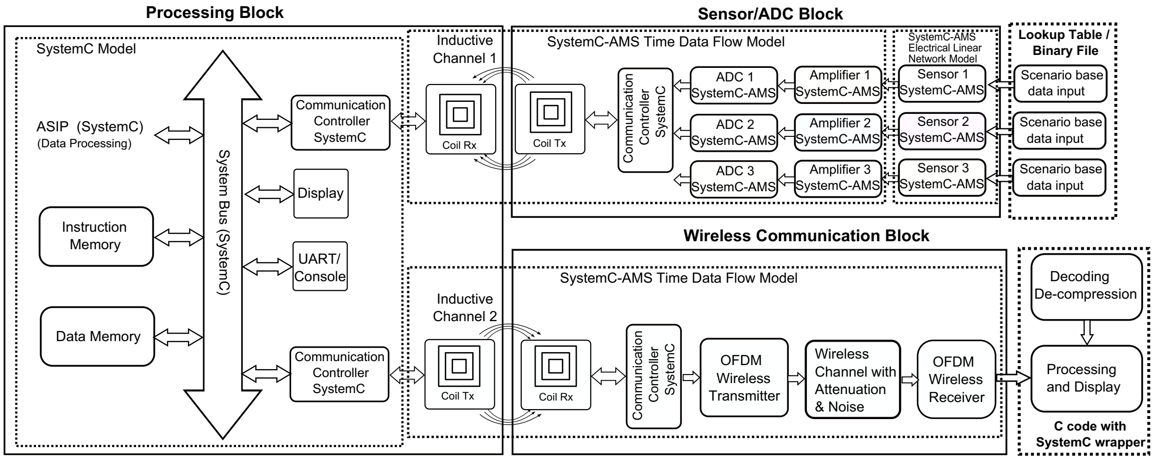

Fig. 4: SiP simulation model

efficient. Another novel way of designing embedded system is to use an ASIP [3]. An ASIP is a hybrid of an ASIC and a GPP, having programmability of a GPP, while performance of an ASIC. In an ASIP the computation intensive parts of the common functionality of applications (e.g. data compression, communication, and error correction) are implemented as special instructions while rest of the application code is executed using general load/store and common arithmetic instructions. By using ESL tool, ASIP Meister, custom ASIPs can be quickly designed at higher abstraction level in a short time.

III. SiP Simulation Model

A simulation model of a complete SiP using SystemC and SystemC-AMS is under development. Fig. 4 shows block diagram of the simulation model.

The simulation model can used for software development, functional verification of different system blocks, design space exploration to find best system implementation in term of hardware and software. Following are main features of the simulation model:

- Several channel models: Wireless, Inductive channel, conductive
- Various communication schemes: OFDM, BPSK, QPSK etc.
- Various error correction methods: Low Density Parity Check, Reed Solomon, etc.
- Several sensor models: Accelerometer, Human body temperature sensor, heart rate monitoring sensor
- 32 bit RISC processor: Automatically generated by ASIP Meister with flexibility of addition of application specific special instructions

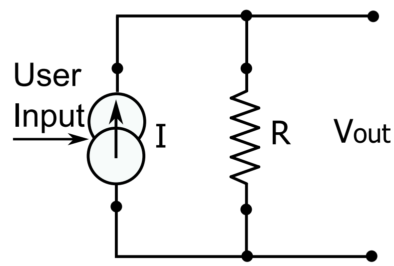

Fig. 5: Electrical equivalent circuit of an analog sensor

IV. Sensor Modeling Using SystemC-AMS

In order to make smooth transition from simulation model to real hardware implementation it is necessary to model most components of the system as accurate, to the real hardware, as possible. One of the most important components of a biomedical system is the sensor. Accurate modeling of a sensor will not only ensure smooth transition to hardware implementation, but also a few modifications to application software will be required. Output of most of the sensor is analog electrical signal, which varies according to the sensor input. Electrical equivalent of a sensor can be represented by a current source whose output varies according to input as shown in Fig. 5.

For modeling sensors input-output characteristics of real available sensors are determined, which is followed by development of SystemC-AMS simulation model.

A. *Air Temperature Sensor*

Air temperature sensors are used for wide range of biomedical and industrial applications. For modeling air temperature sensor we use HS-2000V temperature and relative humidity sensor manufactured by Kele Precision [7]. HS-2000V has ratiometric voltage output proportional to the input temperature. The input (temperature) and output (voltage) characteristic of HS-2000V with supply voltage of 3.25 [V] is shown in Fig. 6.

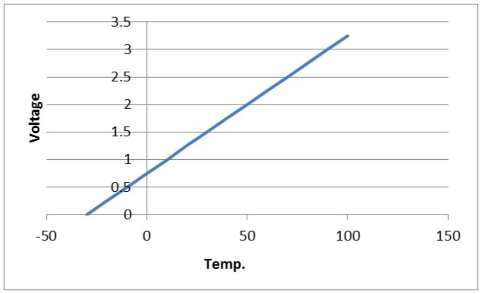

Fig. 6: Temp. Vs. Output voltage characteristic of HS2000V

```
1 SC_MODULE(air_temp_sensor)  // Air sensor model using ELN primitive modules
2 {
3 sca_tdf::sca_in< double >    in;
4 sca_eln::sca_terminal        out;
5 sca_eln::sca_node_ref        gnd;
6  sca_eln::sca_tdf_isource    *i1; // current source declaration
7 sca_eln::sca_r              *r1; // resistor declaration
8 SC_CTOR(air_temp_sensor) // standard constructor
9 {
10 r1 = new sca_eln::sca_r ( "r1" ); // resistor instantiation
11 r1->p ( out );
12 r1->n ( gnd );
13 i1 = new sca_eln::sca_tdf_isource ( "i1", 0.025 ); // current source Instantiation
14 r1->value = 1;  // R=1 ohm
15 i1->p   ( gnd );
16 i1->n   ( out );  // 0.0-3.25 (V)
17 i1->inp ( in );
18 }
19 };
```

Fig. 7: SystemC-AMS code of air temperature sensor

The electrical output of the sensor changes from 0 [V] to 3.25 [V] when input temperature changes from -30 [°C] to 100 [°C]. The electrical equivalent circuit of the air temperature sensor is same as Fig. 5 with value of current source set to 0.025 [A] and R is set to 1 [ohm]. The electrical equivalent circuit is modeled using SystemC-AMS.

SystemC-AMS code of the air temperature sensor is shown in Fig. 7. To model the temperature sensor a current source, which realizes scaled conversion of a timed data flow (TDF) signal to an electrical linear network (ELN) [8] available as primitive sca_eln::sca_tdf_isource is used as shown on line 6 of Fig. 7. The output of the current source i1 is controlled by TDF signal, which is fixed to a constant value of 0,025 [A] (line 13 of Fig. 7). A primitive module for ELN that represents a resistor, sca_eln::sca_r, is used as parallel resistance (Fig. 7, line 7), and has been assigned a fixed value of 1 [ohm] (Fig. 7, line 14).

B. *SystemC-AMS 1D Accelerometer Modeling*

Most of the available accelerometers are capacitive based MEMS devices. Mechanical and electrical equivalent circuits of capacitive based accelerometers are shown in Fig. 8.

Due to acceleration capacitance of the capacitors C1 and C2 is changed, which results in change in the output voltage V_{out}. Relation between output voltage and the acceleration [g] is linear over wide range of [g]. In this research ST Micro-electronics LIS344ALH [9] accelerometer was used for modeling. LIS344ALH is an ultra-compact low-power three axis linear accelerometer having full scale sensitivity of ±2 [g] / ±6 [g], and has ratiometric output. The input-output characteristic of LIS344ALH is shown in Fig. 9. Electrical behavior of LIS344ALH is modeled using SystemC-AMS by using a current source with output current proportional to acceleration input as shown in Fig. 10.

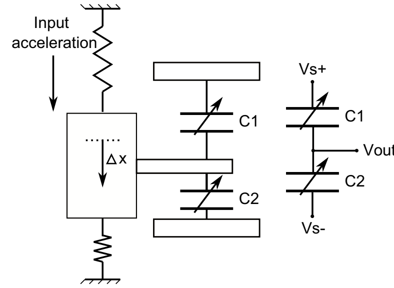

Fig. 8: Electrical equivalent model of comb capacitive accelerometer

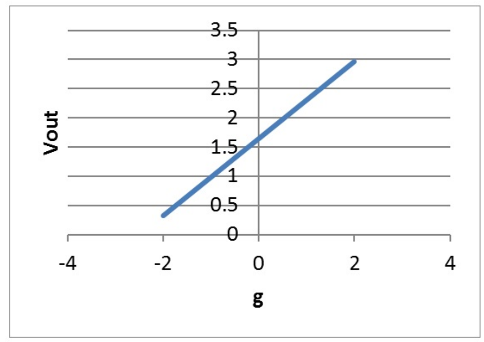

Fig. 9: IO characteristic of LIS344ALH accelerometer

For input voltage V_{in} = 3.3 [V], when using full scale acceleration detection of ±6 [g], full scale output voltage is from 0 [V] to 2.64 [V], and the input detection sensitivity is 0.0035 [g]. The electrical circuit of the accelerometer is modeled in SystemC-AMS, in similar way as explained in Sect.A, by using a scaled current source (sca_eln::sca_tdf_isource) and a resistor. In the SystemC-AMS model a current source of 0.065 [A] and a resistance R1 = 100 [ohm] is used.

V. Simulation Result

For verification of sensors models, and application software development, ARM based platform is used. Fig. 11 shows basic blocks of the simulation platform, which consist of trans-

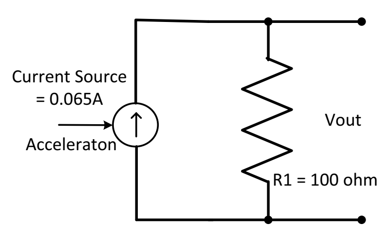

Fig. 10: Electrical equivalent of LIS344ALH

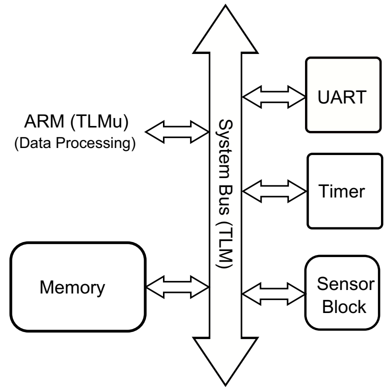

Fig. 11: Simulation platform

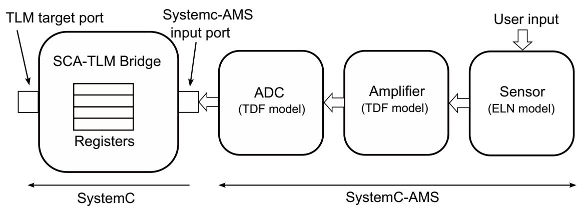

Fig. 12: Sensing block

action level eMulator (TLMu) based ARM model, a UART, a memory module, a timer, a sensing block, and a transaction-level modeling (TLM) based system bus. The sensing block consists of a SystemC-AMS model of a sensor, an amplifier, and an ADC as shown in Fig. 12.

A SystemC-AMS to TLM bridge is used for interfacing sensing block with system bus. In current implementation polling based communication is used between the sensing block and processor. ADC having resolution of 10 bits, and reference voltage of ADC set to 4.096 [V], was used. Temperature and acceleration input to the sensor modules were stored in a text file. With the help of the simulation model using temperature sensor model a heat stroke alert application was developed, and fine-tuned in a short period of time.

VI. Summary and Conclusion

In this paper a design methodology for designing of SiP bio-medical systems, and a comprehensive technique for modeling real analog sensors using SystemC-AMS is presented. SiP based design not only reduces size, but will also reduce the cost of the bio-medical systems. The proposed modeling technique will also enable fast transition from a simulation model to real hardware implementation of the system without need of major modifications in the application software. Using the simulation model heat stroke alert application was developed in a short time. In future other blocks of SiP will be modeled using SystemC and SystemC-AMS to make a more detailed model of a SiP.

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