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Wearable FPGA Based Wireless Sensor Platform

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***Abstract*— A new wearable sensor platform has been developed. It is based on a Field Programmable Gate Array (FPGA) device. Because of this the hardware is very flexible and gives the platform unique opportunities for research of a wide range of architectures, applications and signal processing algorithms. The platform has been named NWSP, for Nokia Wrist–Attached Sensor Platform. This document describes the hardware, the firmware and applications of the platform.**

I. INTRODUCTION

A. Motivation

Microcontroller based sensor platforms exist in a great variety [1][2][3]. The advance in miniaturization as well as the new sensor and wireless technologies have enabled wearable sensor systems which allow measurements on the human body. There are, for example, systems to measure body motion [4]. The use of microcontroller based systems is mostly limited to research of software architectures and applications. Research of hardware architectures and solutions to maximize efficiency and minimize power consumption is possible by using programmable logic. Field Programmable Gate Array (FPGA) devices today are very powerful. They allow the system to be quickly re–configured with a suitable soft–core processor and a perfect set of peripheral interfaces. The software–hardware partitioning can be experimented with freely. Some software functions can be implemented by configurable logic instead, either to accelerate computation or to minimize power consumption. Also, a successful FPGA implementation can be easily transferred to a full–custom Application Specific Integrated Circuit (ASIC) to reduce cost for a large scale production.

B. Background

The development of the Nokia Wrist–Attached Sensor Platform (NWSP) combines results and efforts from several previous research projects at Nokia Research Center. As a part of larger architecture research program [5] an intelligent services based sensor system was developed, the so called Advanced Sensor Processor (ASP) [6]. The ASP project investigated ultra low power measurement circuits and modular software and hardware architectures for sensor processing.

The Simple Sensor Interface [7] (SSI), which is a generic light weight communication protocol for smart sensors, was created among other things in the EU funded project MIMOSA [8]. The demand for a wearable platform originated from the wellness and healthcare project NUADU [9]. NUADU develops end–to–end wellness concepts including body area networks (BAN), where the focus is on sensor data processing via wireless links, sensor and actuator network interoperability, and interaction and user feedback concepts.

C. Applications

There are many applications of a wearable sensor platform. Applications range from real time monitoring to long time data logging. Real time use requires a user interface whereas data logging requires a large memory and a long lasting energy source. Our platform supports both of these, although long time data logging is compromised by battery capacity and a not so low energy consumption of the device.

Activity logging is a long time data logging application for example for everyday activities of the elderly [10] or for fitness and sports [11]. A variation of this topic is fall detection and fall risk analysis [12] for the elderly. Heart Rate Variability [13] is another interesting research topic. It can be applied to sleep evaluation [14], disease management, stress analysis and many other topics.

Sensor controlled games has gained popularity. The accelerometer sensor is the most widely used sensor for gaming. It allows the game to respond to various movements of the player. A wrist–worn platform is also attractive for user–interface studies. For example, mobile phone calls can be picked up or text messages can be read by these devices. For sports and wellness applications running on the mobile phone a remote user interface from the wrist could be very attractive.

II. PLATFORM ARCHITECTURE

A. Advanced Sensor Processor (ASP)

The main target of ASP architecture (Fig. 1) was to minimize the power consumption by performing sensor signal processing on a compact and energy efficient processor unit while keeping the complex application processing environment idle for most of the time. The sensor processor has high level service interfaces, which provide a method for the host system to request high–level services from the sensor sub–system. As an example (Fig. 2), the host system can request the sensor sub–system to detect specific motion patterns and to send an event notification to the host system once a gesture has been recognized. Using independent sub–systems with embedded intelligence and high level service interfaces allow each sub–system to be implemented with optimal technology and to perform power management on a sub–system level. The low–power advantage of the ASP is

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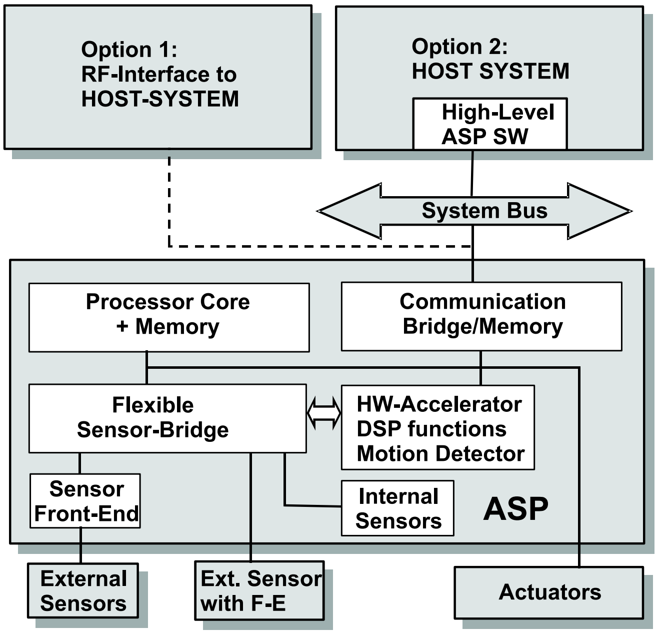

Fig. 1. The ASP architecture. The ASP can interface to the application processor via a wireless radio (Option 1) or via the system bus (Option 2).

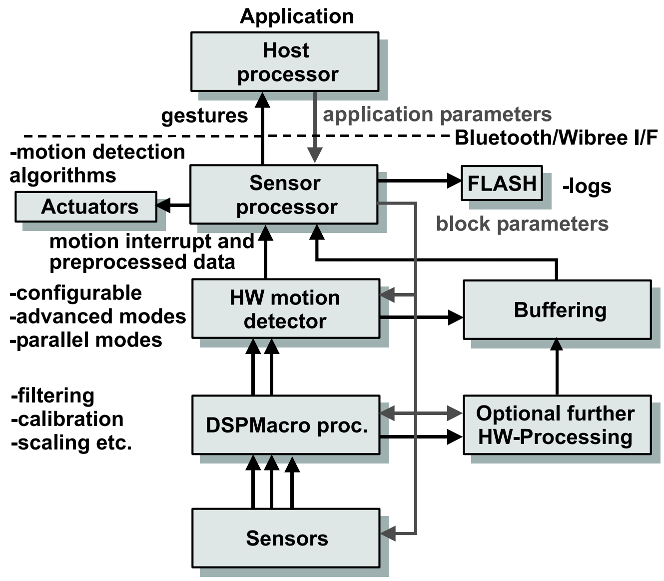

Fig. 2. An example of power efficient accelerometer processing using ASP. Configurable DSP macros process the raw sensor data to reduce data bandwidth. A motion detector implemented in hardware can detect events and alert the processor. Sensor data from these events is optionally further processed by hardware and buffered. Finally the processor does gesture recognition from the data and alerts the application host processor.

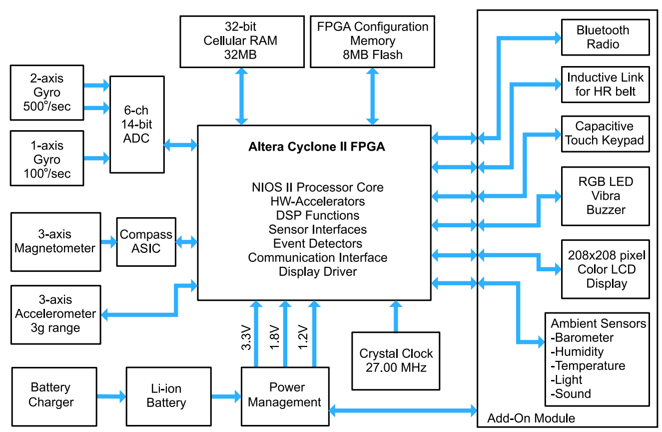

Fig. 3. Diagram of the hardware. The base platform includes the FPGA. Additional sensors, user interface components and wireless connectivity is provided with an add–on module.

fully obtained only with an ASIC implemetation. An FPGA implementation, however, is good for research and validation of the architecture.

B. Operating System

An operating system (OS) provides a well defined environment for applications. It can provide a file system, network sockets, peripheral interfaces and possibly a user interface and memory and process management. Small embedded systems usually have less powerful processors and other limitations due to small size and low–power operation. There are many specialized operating systems targeted for such platforms. Examples of commercial ones are: MicroC/OS-II (Micrium), Nucleus (Mentor Graphics) and ThreadX (Express Logic). Since the NWSP platform is mainly targeted for research, an open source operating system is clearly beneficial. Examples of these are: TinyOS [15], eCos [16] and μCLinux [17]. The NWSP will mainly use eCos because the ASP architecture was developed upon it. The eCos is quite light–weight and it has real–time performance. In the future some applications using μCLinux will be investigated.

III. IMPLEMENTATION

A. Hardware Design

1) Modularity: The hardware was designed to be semi–modular. A diagram of the hardware is shown in figure 3. The base platform includes the FPGA device, battery power management and basic sensors (accelerometer, gyro and magnetometer). To the base platform an add–on board can be attached via compact connectors. By the different add–on boards the platform can be adapted to different applications.

2) The FPGA: It can be configured to any kind of architecture of interest. It can include one or more processors, peripheral interfaces, logic for accelerated sensor data processing and much more. The FPGA chosen was an Altera Cyclone II device: EP2C20F256C7N. It has 18752 logic elements (LEs), 52 RAM blocks (4 kilobits each), 26 embedded multipliers and 4 PLLs. The package is a 256 pin FBGA. It is clocked externally by a 27.00 MHz crystal oscillator. Clock signals with frequencies up to 500 MHz can be generated internally by the PLLs.

3) The accelerometer sensor: Its signals provide the most useful information for activity recognition. This is usually done by comparing the extracted features to characteristic threshold values of activity types. The 3g dynamic range of the used 3–axis accelerometer (KXPS5 series by Kionix) is adequate for most of the daily movements and gestures. Sports activities can have much larger peak accelerations, but the activity can still be measured and analyzed from partly saturated sensor signals. Gaming, user interface (gesture recognition) and fall detection applications also need the accelerometer.

4) The gyroscope sensor: It provides supplementary rotational information for changes in direction and postures. A dual–axis device IDG-300 from Invensense and a single–axis device XV-3500 from Epson Toyocom are MEMS gyroscopes, that when combined can sense angular rates in all three orthogonal directions. These have analog outputs, which are sampled by an 14–bit AD converter (LT1408). The ranges are $\pm 500°/\text{sec}$ and $\pm 300°/\text{sec}$ for the IDG-300 and XV-3500 devices respectively.

5) The magnetometer sensor: It provides an absolute direction referenced to the earth's magnetic field. A 3–axis magnetoresistive bridge sensor HMC-1043 by Honeywell is used. The front–end for the sensor is an ASIC developed by Nokia. The UART serial interface of the ASIC is used for sensor control and data output.

6) The add–on board: For the NWSP an add–on board with user–interface components, additional sensors and Bluetooth connectivity was designed. As a display a 208×208 pixel color LCD is used. Other indicators on the board are an RGB LED, a vibra and a buzzer. For user input there are four touch–sensitive capacitive sensors handled by the AD7142 chip from Analog Devices. The LMX9830 module from National Semiconductor was chosen as the Bluetooth radio. The inductive receiver for heart beat chest belts uses a Neosid MS-18K coil for pick–up. It has an inductance of 12 mH and it is tuned to 5.5 kHz by a parallel capacitor. For ambient sensors small and low–power sensors were chosen. The air–pressure sensor is the SCP1000 by VTI (range 30 kPa–120 kPa, resolution 2 Pa). The humidity sensor is the SHT11 by Sensirion. Both of these devices include temperature sensors and have a digital interface. The sound sensor is based on SPM0103NE3, which is a MEMS microphone by Knowles Acoustics. The light detector is based on a silicon photodiode (HSDL-9001) and an operational amplifier based oscillator circuit. The output frequency of the circuit is proportional to ambient light intensity.

B. The Mechanics

Figure 4 shows a photo of the mechanics designed for the platform. It is intended to be attached to the wrist where it is most convenient to access the user interface. It is also possible to attach the device to any other part of the body for measurements. The large display and Li–ion battery restricts a slimline design. The device is designed to be splash–proof. The ambient sensors (microphone, air pressure, humidity and temperature) are located in a vented and isolated chamber in the corner of the device. It is, however, expected that the self–heating and the thermal mass of the device will still degrade accuracy of the humidity and temperature measurements. The RGB LED and ambient light sensor have round light guides

Fig. 4. A photo of the wrist unit mechanics ($72 \times 51 \times 22$ mm).

leading from the cover to the circuit board. To be able to charge the device a stand was designed. It has spring contacts that touch two charging terminals on the side of the device when it is placed in the stand.

C. Software Design

The first step in software design has been to develop drivers for the hardware. The LCD contains a pixel map memory only that stores the display image. Fonts and graphics need to be generated by software. For this a C++ class library for graphics was developed. The default user interface is based on soft menu buttons as shown in figure 5. A C++ class library for handling soft menus and user input was developed. Also drivers for the sensors and the Bluetooth radio has been designed. Upon the system many software applications has been implemented to demonstrate various functions of the sensor platform. The development will continue.

D. Development Tools

For Altera FPGA development Quartus II and NIOS II IDE tools are used. System–on–a–programmable–chip (SOPC) builder is included with Quartus and is used to configure the system graphically. Components from libraries provided by Altera or IP blocks from third party vendors can be dragged into your design with the mouse. These components include the NIOS II processor, Direct memory Access (DMA) controller, UART serial interface, timers, etc. Configuring the components, connecting buses and specifying memory locations and interrupts are all done within the tool. Additional hardware can be described with a hardware description language (HDL) and compiled together with the system generated by the SOPC builder.

The software is developed within Eclipse based NIOS II IDE. Either Ansi C or C++ can be compiled. The IDE uses information from SOPC builder to automatically create

Fig. 5. An example of a user interface for the sensor platform. Below the LCD display there are four capacitive sensors that are touch sensitive.

a hardware abstraction layer for the underlying system. This means the software can be successfully compiled for different systems providing that the required peripherals are present. The development tools also allow automatic creation of hardware accelerated functions from C–code. No writing of HDL code is needed.

The sensor platform is programmed via a Joint Test Action Group (JTAG) port. The FPGA configuration and software can be directly downloaded to the device for execution and debugging. For standalone operation the configuration memory on the platform also can be flashed via the JTAG port. Programming software is included with the Quartus II development tools.

IV. CONCLUSIONS AND FUTURE WORK

A. Conclusions

Most sensor platform systems are quite voluminous and bulky. This is largely due to the power consumption, which does not only determine the size of the battery required and thus the whole system, but also the overall operation time. The NWSP is no exception in this regard. The current consumption is more than 50 mA in all cases and slightly above 100 mA on the average in active mode. This gives an operation time of only a few hours. However, as a research platform the NWSP platform is very attractive. This is because of its flexibility. By re–configuring the FPGA the platform can take many different roles, adapting itself to research of many different areas. If later an ASIC implementation would be made of the design, the power consumption and size would automatically be reduced.

B. Future Work

The leakage current of present high–density FPGA devices is the biggest problem for power–saving. The device must always be powered up because critical logic is implemented on the device. Regardless of logic activity or clock frequencies the leakage currents cause a large static power consumption. Some new low–power FPGA devices will implement techniques to reduce these leakage currents with special focus on power consumption suitable for battery operated applications. The most notable new devices are Polarpro by Quicklogic and Igloo by Actel. These devices are attractive as the building blocks for a second version of the NWSP.

The wireless connectivity standard to adapt for the platform must be very user–friendly and widely supported. We chose Bluetooth for the first version because it is available on most computers and mobile phones. In the wireless systems the communication link can be one of the biggest energy consumers. Bluetooth is not optimal for a battery operated small device. Wibree [18] technology will be an ideal solution in these cases and will be considered for the next version of the sensor platform. In the future Bluetooth and Wibree will co–exist in mobile phones, computers and other host systems.

V. ACKNOWLEDGMENTS

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