

Towards Hardware Support for Common Sensor Processing Tasks

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Abstract—Sensor processing is a common task within many embedded system domains, such as in control systems sensor feedback used for actuator control, etc. In this paper we have surveyed several embedded system domains, and extracted kernels of computation that are common across applications within a given domain, or across domains. We have shown that adding architectural support for executing these common kernels of computation can yield an overall better system performance. We present a light weight, simplified prototype of a Sensor Processing Unit (SPU) that offloads these computations from the main Arithmetic Logic Unit (ALU) of an embedded processor, and that accesses sensor data in a low latency manner. Our SPU prototype shows an average speed up factor of 2.48 over executing these kernels on an embedded PowerPC processor. A large portion of this speed up is due to our low latency method for accessing sensor data. Isolating our speed up to purely computation still shows an average speed up factor of 1.38 for these kernels.

Index Terms—component; formatting; style; styling;

I. INTRODUCTION

The severe constraints placed on embedded systems in terms of power consumption, memory availability and processing capability, and the ever increasing computational demands placed on these systems make it crucial embedded processors are designed to efficiently perform the tasks required of them. A majority of embedded systems involve interaction with the physical world through some kind of sensing mechanisms. However, based on our survey of a wide range of microprocessors/microcontrollers that have been conveniently organized by researches such as Bokareva [1], it is clear there are no specific resources available on these devices for efficiently processing sensor data. Given this is such a common task, exploring how the addition of sensor processing resources can improve system efficiency appears to be a path worth pursuing, and is the focus of this paper.

Figure 1 gives a high level summary of the contributions of this paper. There are three specific areas of contribution. First, a number of common computational kernels for sensor processing have been identified. This helps justify the allocation of hardware resources for the processing of sensor data. Second, we have proposed a specialized functional unit call the sensor processing unit (SPU) to efficiently assist in the execution of these computations. In addition, we have noted that the autonomous nature

of our approach lends itself to potentially act as a base for creating an intelligent power management scheme. Third, we have integrated a simplified prototype of our functional unit with an embedded processor and evaluated its performance on an FPGA-based platform.

II. RELATED WORK

This section reviews three areas of related work. First, embedded system benchmarks are discussed. Research in this area is used as the starting point for our work. Then the current state of the art in embedded processors, and their relevant features are discussed in order to place our work in perspective.

A. Embedded Benchmarks

The industry standard Embedded Microprocessor Benchmark Consortium (EEMBC) benchmarks [2] aims to standardize a set of common benchmarks for different embedded system domains. These benchmarks are based on common processing tasks that are found in each respective domain (e.g. Controls, Automotive, Communications). Having a set of such benchmarks is useful for evaluating a processor's suitability for a given application, and for characterizing the strengths and weaknesses of different processors. MiBench [3] is another benchmark that targets embedded systems. MiBench was developed in the same spirit as EEMBC, but unlike EEMBC it is freely available to academia.

These benchmarks provide a nice organization of the processing tasks found in embedded systems. However, neither the MiBench or the EEMBC benchmarks clearly isolate kernels of computation associated with sensor processing. The EEMBC benchmarks does have a suite of tests that focus on signal processing type tasks for which digit signal processors (DSPs) are likely most appropriate. Our work aims to extract simpler and more common sensor processing kernels. It is envisioned that these kernels can act as a starting point for developing a more extensive sensor processing test suite in the future.

B. Embedded Processors

Bokareva surveys a number of sensor network nodes (also know as motes), and processors that are used within

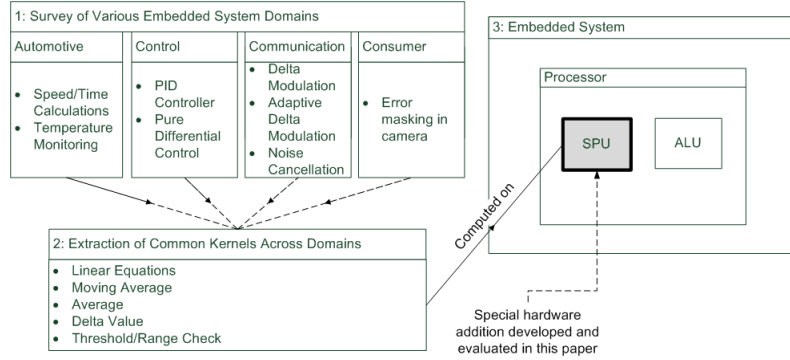


Fig. 1. 1) illustrates some high-level sensor dependent tasks identified within various embedded domains, 2) highlights common kernels of computation that were identified, 3) shows conceptually how our sensor processing unit (SPU) integrates into an embedded system.

those nodes [1]. These processors range from simple 8-bit microcontrollers (e.g. Atmel Atmega 128) to 32-bit microprocessors (e.g. Intel XScale processor family). However, from an examination of a representative set of processor Datasheets [4] [5] [6] [7], none of these processor were found to have any special functionality to support sensor processing tasks. The closest feature found was on the Intel XScale processor family, an external interface for a DSP coprocessor. Our work puts forth a lightweight architectural extension for processing common sensor data computations for which using a full blown DSP would be an overkill.

Two features related to our work that are currently found in either sensor network nodes and/or current high performance processors are 1) waking up on the occurrence of an event, and 2) raising an exception when the processor has surpassed a given temperature threshold. Many processors/microcontrollers [8] [4] [5] [6], some of which are currently used in sensor network nodes, have the ability to go into a low power operating mode until an interrupt indicates they should wake up. The Intel Centrino chips also have the ability to come out of hibernation on receiving data on their network interface (e.g. wake on LAN technology [9]). Current chipsets such as the Intel System Controller Hub can wake the main processor up when a peripheral sends an event [10]. With respect to thermal events, some microprocessors, such as the Intel Atom Processor [11], have the ability to monitor their on-chip temperature and response if this temperature surpasses a given threshold (e.g. shutdown or transition into a lower performance mode). The architecture of our light weight SPU naturally allows interrupts to be used to notify the main processor when simple to fairly complex combinations of sensors values are detected. This capability and its potential implications are discussed further in Section IV while some common kernels of computation identified by us are described in Section III.

III. COMMON KERNELS OF COMPUTATION

Due to the large and diverse set of domains in which embedded systems are used, past works [2] [3] have tried to identify common computational kernels that are used across domains by abstracting away the specifics of individual applications. Similarly, we have tried to boil down the diverse set of sensor processing tasks to a small set of core kernels that are generic enough to find application in many fields, and common enough to warrant the allocation of processor chip real estate.

While many applications require massive processing of sensor data using digital signal processing type algorithms, there is a large base of applications [12] [13] [14] [15] that consist of simpler processing tasks, and do not warrant the overhead of having a full blown DSP. We have identified and extracted five such tasks from the MiBench benchmark and various other sources: Linear Equations, Moving Average, Average, Delta Value, and Threshold/Range Check.

Linear Equations: One of the simplest tasks that can be performed on sensor data is the execution of a linear mathematical operation on a single value or multiple values. In the automotive domain converting between radians and degrees is identified as a common task in [3]. In the controls system domain the Proportional-Integral-Derivative (PID) controller is one of the most common control algorithms used [16]. [17] and [14] give examples of advanced PID controllers that can be boiled down to calculating a set of linear equations involving sensor values along with other computational functions.

Moving Average: Sometimes, sensors can be prone to spurious spikes in their output. The moving average is one method for reducing the effects of random “noise” on sensor output. Over time measurements are averaged together, and this average is used by the end application. The impact of spikes in measurements are mitigated, while actual changes in the physical quantity being measured are eventually reflected by the average. The responsiveness of the moving average can be tuned to reflect the known phys-

ical dynamics of the quantity being measured by added appropriate weights to the previously computed average, and the current sensor measurement (weighted moving average). The moving average is a common method for filtering sensor data [12] [18] [19] [20].

Average: Applications, such as sensor networks, often measure physical quantities over a distributed area (e.g. temperature). Averaging these distributed measurements is a simple means for aggregating this information into a compact form. This approach was used by Goebel [13], Ganeriwal [21], and Nakamura [22]. In [12] Hellerstein uses averaging as means of “cleaning” data obtained from a group of sensors.

Delta Value: Often, the difference between the current and previous value of the sensor (called delta) is used in a lot of computation. eg: the “communication” suite of benchmarks in [3] includes delta modulation, a process of encoding which may be used to encode the output of sensors before transmission. [15] presents another example of using the “delta” value in a sensor based system.

Threshold/Range Check: There are various applications in which the sensors values are required to be within particular range or below/above a certain threshold for the proper operation of the system. In such systems, some sort of mechanism is needed to monitor the sensor values. Alternatively, the systems might need to take some kind of action when the sensor value breaches the defined range/threshold bound.

This is by no means an exhaustive list of such kernels, but having identified some common kernels of computation across fields, in the next section we propose a unit, the SPU, which could be a part of the architectures of future embedded processors.

IV. SENSOR PROCESSING UNIT (SPU) ARCHITECTURE

This section presents our lightweight mechanism for sensor processing. First we provide an overview of the SPU and some possible applications. Then we describe its architecture. Finally we describe the development platform and the prototype limitations.

A. Overview

The SPU is designed to be a functional unit within an embedded processor. It has two main purposes 1) to efficiently offload the execution of common sensor processing tasks from the main ALU, and 2) to detect events that are a function of sensor values. Here we discuss the two major uses of the SPU, and how it could potentially be used for power management.

Sensor Processing Offload: The SPU has been designed to operate in the following manner. First a user application programs the SPU with functions that need to be performed on the output of one or more sensors. Once programmed the SPU computes these functions continuously as sensors

data flows into the SPU. The output of the sensors are directly connected to the SPU, thus the SPU reevaluates its programmed functions autonomously of the rest of the processor. When the user application requires the result of one of the programmed function, it simply issues a single instruction to fetch this value from a special register. This is opposed to the traditional approach of 1) reading all sensor values required by a function, and 2) computing the function in software. In addition to increasing the speed at which a given sensor processing function can be computed, discussed in Section V, the SPU allows the rest of the processor to focus on other tasks.

Event Detection: Each function programmed into the SPU can have an event associated with it. An event checks if the result of a given function is $<$, $>$, or $=$ to a fixed value, or if the result of a function is within or outside a given range. If the associated condition is true then an interrupt is sent to the main processor. The purpose of this functionality is to allow the processor to work on other tasks until a given event fires off, as opposed to having to continuously poll sensor values and compute this event checks in software. This capability targets application that need to take actions when sensor values surpass a given threshold (e.g. thermal shutdown condition), or fall outside an acceptable range (e.g. voltage supply stability). As indicated in Section II, current processors do have the ability to react to simple events such as a thermal overload. The SPU is a lightweight means to generalize the type of events that a processor can detect and respond to.

Power Management: Again, as discussed in Section II, many processors and microcontrollers support a low power mode from which they can be woken up by an interrupt. Given the SPU’s ability to operate on sensor data autonomously of the rest of the processor, the SPU could potentially be used as a lightweight mechanism that allows the rest of the processor to go into, or come out of a low power state based on sensor data.

B. Architecture

In this section we discuss the architecture of the SPU, which is made up of five major components: Sensor Data Extractor, Configuration Storage, Processing Unit, Result Storage, and Interrupt Generator. Figure 2 illustrates the architectural layout of the SPU.

Sensor Data Extractor: This block is responsible for connecting the SPU to available sensors. It continuously streams sensor data to the SPU’s Processing Unit, and Interrupt Generator.

Configuration Storage: This is where configuration information sent by a user application is stored. This information includes the set of sensors a given function operates on, the operations and constants that define a function, and threshold and range values associated with events that can generate interrupts to the main processor.

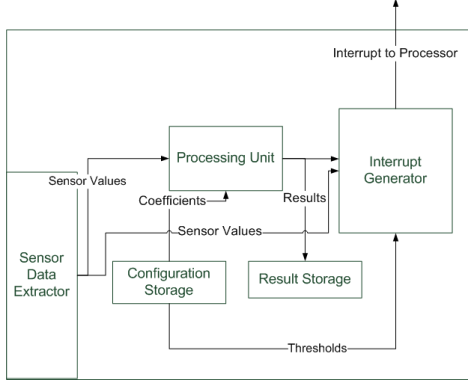


Fig. 2. Architecture of the SPU

Processing Unit: This unit is responsible for all computations in the SPU. It is a simple Multiply-Accumulate module that multiplies sensor values with their associated weights (found in Configuration Storage). After a function has been computed, its value is stored in the Result Storage block, and the Processing Unit is reinitialized. Then the configuration parameters, and sensor values for the next function are loaded into the Processing Unit. This allows the Processing Unit to be time shared among many functions. If each function is assumed to be executed in a single clock cycle, then this unit can scale to a large number of functions before noticeable latency issues associated with stale data arise.

Result Storage: This block is used to store the results calculated by the Processing Unit. When an application requests the result of a given function, the value is fetched from this block. As the number of functions computed by the Processing Unit increases the staleness of the data stored in the Result Storage block increases. However, given that the clock rate of a processor is typically much higher than the rate of change of sensors, the relatively small time lag should be acceptable for most applications, even for a computing a significantly large number of functions.

Interrupt Generator: The Interrupt Generator is responsible for detecting when a sensor value, or function computed by the Processing Unit satisfies criteria specified by a user application. If a criteria is met, then an “event” is said to have taken place. On the occurrence of an event this unit sends an interrupt to the main processor.

C. Implementation

Here we describe the developmental platform used to implement the SPU and point out the limitations of the simplified prototype.

1) **Development Platform:** The platform used for this work is based on reconfigurable hardware technology called Field Programmable Gate Arrays (FPGAs). FPGAs

are devices that consist of a sea of generic logic gates that can be configured to realize any arbitrary hardware logic function. In addition to this powerful capability, advanced families of FPGAs have on-chip resources such as PowerPC processor cores, high-performance multipliers, SRAM based memory blocks, sophisticated programmable clock managers, and analog to digital converters that allow sensors to connect directly to the FPGA’s computation fabric. Specifically, our platform is the ML507 evaluation platform. It is manufactured by Xilinx Corporation [23]. The development board hosts one of the most advanced FPGA devices called the Virtex-5.

2) **Prototype:** A simplified prototype, which was similar to the proposed method except for being non scalable, was implemented in order to run the experiments for evaluation. The main limitations of the prototype were 1) the prototype included an adder and multiplier for each of the sensors instead of having the Processing Unit time-shared, 2) the System Monitor was used for extracting sensor data in some of the test cases, while others simply used a dummy sensor which supplied a constant value, 3) the prototype only supports a single user program function, and 4) it only supports three sensors.

Table I gives the logic resources consumed by the SPU prototype implemented on the Virtex-5. As can be seen, the SPU is very lightweight.

TABLE I
RESOURCE UTILIZATION ON VIRTEX 5

| Resource | Used | Available |
|-----------------|-----------|-----------|
| Slice Registers | 108(0.2%) | 44800 |
| Slice LUTs | 206(0.4%) | 44800 |

V. EVALUATION

In this section we present our methodology along with our observations and analysis.

A. Methodology

A prototype of the SPU was implemented on an Xilinx Virtex 5 FPGA on a Xilinx ML507 evaluation board [23]. The embedded PowerPC 440 is used as the processor while the SPU is implemented in the FPGA fabric. The SPU is connected to the processor using the Fabric Coprocessor Bus (FCB). Both the FCB and the processor are run at 200 MHz. The FCB connection allows User Defined Instructions (UDIs) to be used to read the sensor data. A Processor Local Bus(PLB) [24] also connects the PowerPC to a pseudo sensor. Evaluation experiments the following three setup:

- **PLB :** The pseudo sensor was read over the PLB by the processor. The PLB is a part of the CoreConnect specification and hence is the way in which many

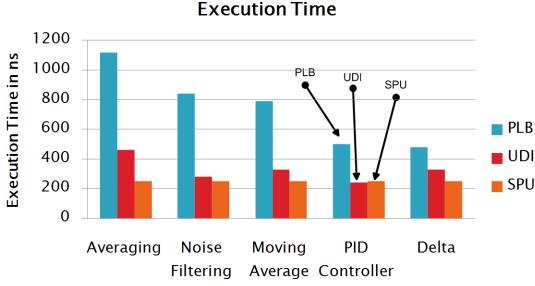


Fig. 3. Comparing the execution time of various common kernels on all three experimental setups. As seen here, the SPU is typically fastest for most kernels.

cores are interfaced with the embedded PowerPC. On such an embedded chip, the sensor signals would usually be available to the processor only over the PLB.

- **UDI** : The fact that the FCB is faster than the PLB contributes somewhat to the improved performance of the propose architecture. However, to show that this is not the sole reason for the improvement we have included this additional case, where the data is read over the faster FCB, but without the SPU.
- **SPU** : The SPU was implemented on the FPGA, and connected over the FCB. The processor used UDIs to program the SPU, as well as to read data from it.

The three setups were compared with respect to three metrics:

- **Execution Time** The amount of time required to complete a certain number of iterations of the control loop.
- **Code Density** Size of the compiled programs.
- **Response Latency** Latency between an event occurring and its response starting execution (used for the interrupt generation feature of the SPU).

B. Observations and Analysis

In this section we present the results of experimentation on our prototype implementations described in section IV-C.

1) **Execution Time**: As can be seen from Figure 3, the execution time for the SPU was the lowest for most of the kernels. When a function is implemented in hardware it is usually expected that it will be faster, hence this result presents no surprise. Also the execution time of both the PLB and UDI cases varies as the tasks become more complex, and will also vary as the number of sensors that are used is varied (see Figure 4). On the other hand, for the SPU the execution time remains more or less constant for functions directly supported by the SPU. For functions not directly supported by the SPU, execution times do increase with the complexity. However, the execution time

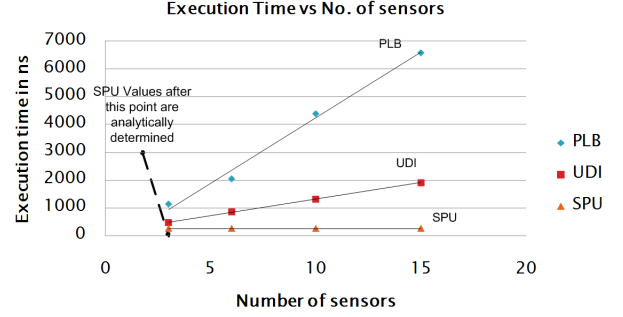


Fig. 4. Experiments to show the effect of increasing the number of sensors on the execution time of the “Average” kernel. As seen here, regardless of the number of sensors, the time taken for reading the result from the SPU will remain constant.

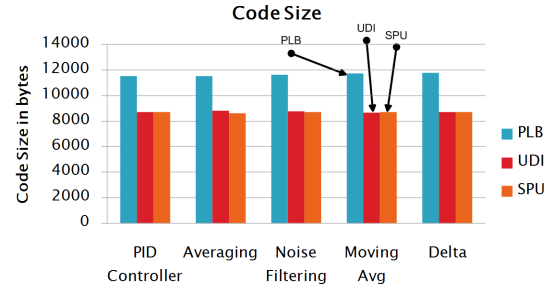


Fig. 5. Comparing the executable size for various common kernels on all three experimental setups. As seen here, the SPU case is the smallest in most cases.

of the SPU will remain constant as the number of sensors increases. It should be noted that as the number of sensors increases the result provided by the SPU will become more and more stale. Also as the number of sensors supported increases, the resources required also increases. Across all cases, the average speedup obtained using the SPU was 2.48 fold faster then the PLB setup. Against the UDI setup, the SPU showed an average speedup factor of 1.38. This shows the speedups obtained over the PLB setup are not just because of the SPU using the faster FCB interface.

2) **Code Density**: As seen in Figure 5, the SPU presents a clear advantage over the PLB setup in terms of code density. This is again expected since communicating over the PLB would entail some extra instructions for the arbitration of the PLB. The SPU cases remain almost the same as the UDI cases in terms of code density. The SPU being only slightly better. On average the programs that use the SPU were 68.6% the size of programs that used the PLB. The difference in code size between the SPU and UDI cases were negligible. It should be noted that the size of the programs using the SPU varies very little with the number of sensors being used, while the size of both the PLB and UDI setups will increase.

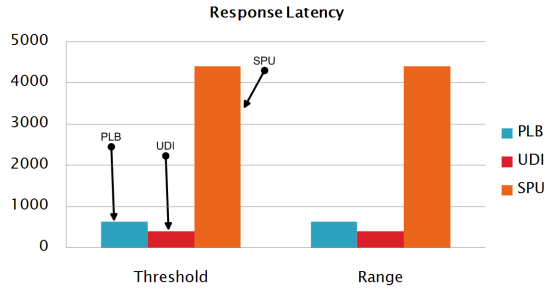


Fig. 6. Comparing the response latency across setups. The PLB and UDI setups use polling, and the SPU generates interrupts. Although the SPU case has a large latency, it gives a higher throughput from the processor.

Another interesting point that should be noted is that there is very little difference in the code sizes between the UDI and SPU setups. Thus, even if the SPU itself is not implemented on a processor, simply including such a single instruction method of sensor access also gives improvements in code size.

3) *Response Time*: As is clearly seen in Figure 6, the response time of the SPU is much higher than the other two setups due to the overhead of performing a context switch by the interrupt handler. However, we have considered only the simplest of cases where in the PLB and UDI setups continuously polls the sensor without doing anything else. In situations where the response time is tightly constrained, such tight polling may be the only option, but in cases where the response time is allowed to be larger, the SPU presents another option. With the SPU option the processor can continue executing other code while the sensor monitoring responsibility is relinquished to the SPU. The rest of the processor could even be put into a low power state, and woken up only when specific conditions are met. In this context it might be worth looking into ways to reduce the context switching overhead in embedded microprocessors in order to allow for better response times (e.g. as in [25]).

VI. CONCLUSION AND FUTURE WORK

In this paper we have 1) described a set of common sensor processing tasks, 2) proposed a sensor processing architectural extension for executing these common task, and 3) prototyped and evaluated the performance of this extension. Our evaluations show an average speed up of 2.48 fold in processing these kernels on our sensor processing unit (SPU), as compared to executing these kernels purely in software over a standard peripheral bus. We still show an average speed up of 1.38 fold over executing these kernels purely in software, and using a low latency coprocessor interface. Considering many applications might require a large number of sensors, a next step in this work is to further explore a scalable

architecture for the SPU. The scalability could be not only in terms of additional sensors but also support for more than one equation at a time.

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