

Profiling Tools for FPGA-Based Embedded Systems: Survey and Quantitative Comparison

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Abstract—Profiling tools are computer-aided design (CAD) tools that help in determining the computationally intensive portions in software. Embedded systems consist of hardware and software components that execute concurrently and efficiently to execute a specific task or application. Profiling tools are used by embedded system designers to choose computationally intensive functions for hardware implementation and acceleration. In this paper we review and compare various existing profiling tools for FPGA-based embedded systems. We then describe *Airwolf*, an FPGA-based profiling tool. We present a quantitative comparison of *Airwolf* and a well known software-based profiling tool, GNU *gprof*. Four software benchmarks were used to obtain profiling results using *Airwolf* and *gprof*. We show that *Airwolf* provides up to 66.2% improvement in accuracy of profiled results and reduces the run time performance overhead, caused by software-based profiling tools, by up to 41.3%. The results show that *Airwolf* provides accurate profiling results with minimal overhead and it can help the designers of FPGA-based embedded systems in identifying the computationally intensive portions of software code for hardware implementation and acceleration.

Index Terms—Profiling Tools, FPGA, Embedded Systems, co-design

I. INTRODUCTION

Over the years embedded computing systems have grown in popularity due to their increased processing power and hardware circuit density while sustaining a compact size. They are prevalent in our modern society, where these systems are used in a wide variety of applications ranging from performing simple everyday tasks to manufacturing a product. Typical end users make use of these devices for communication and entertainment with examples such as cell phones, electronic pagers, television remote controls, digital cameras, personal data assistants and much more. In large industrial companies, embedded systems are used as programmable controllers for manufacturing, nuclear power generation, transportation and medical instrumentation.

The continuing advancement and innovation of embedded systems, along with their increasing complexity, has led designers to intensify their development efforts during the design stages. In addition, consumer demands for these devices continue to rise, which leads to shorter design cycles and tighter time-to-market deadlines. The design of embedded systems is becoming difficult without the use of computer-aided design (CAD) tools that can

effectively partition the components into the hardware or software domains. There are other additional constraints that designers must consider such as smaller area and size and lower power consumption of the embedded system while sustaining maximum performance [1].

The hardware-software co-design methodology is one of the methods used for the design of embedded systems. There are other methodologies, including platform-based design [2] and functional architecture co-design [3]. In this paper, we focus on using the hardware-software co-design methodology of embedded systems by employing reconfigurable technologies such as Field Programmable Gate Arrays (FPGAs).

FPGAs are user programmable integrated circuits that offer reasonably high level of integration, negligible prototyping cost and instantaneous manufacturing capability. Riding on Moore's law [4], FPGAs have grown in logic capacity while maintaining affordable cost for many applications [5]. Embedded development kits that utilize FPGAs contain an abundance of on-board resources such as clock multipliers, fast memory chips, math co-processors, etc. Hence, this makes them an attractive alternative for rapid prototyping of large embedded system designs due to their reconfigurability and flexibility.

Previous work on using FPGAs for hardware-software co-design has led to a proposed co-design methodology for implementing a H.264 video encoder [6]. In addition, using the co-design methodology on FPGAs also allowed designers to implement computationally intensive digital signal processing algorithms onto the FPGA for hardware acceleration [7]. Furthermore, FPGAs are used as a co-verification environment for multimedia-based applications [8], [9]. It is evident that FPGAs are becoming popular for the design of embedded systems [10], [11].

The main objective in hardware-software co-design is to find an optimized partition and a balanced configuration of the hardware and software components of a system. The quality of the final product is dependent on the effectiveness of the hardware-software partition. Automated hardware-software partitioning algorithms require information about the systems performance prior to partitioning of these components [12]. This is where profiling tools become vital since they determine which component is the bottleneck while others are meeting timing requirements.

Profiling tools are CAD tools that measure the performance of a system based on the time needed to perform certain functions in software. They also help in detecting problems such as communication bottlenecks in a system, cache misses and other important measurable performance metrics. They allow early detection of performance bottlenecks and help the embedded system designers to optimize their designs in order to meet system performance constraints [13], [14].

Previous researchers have taken advantage of FPGAs by creating FPGA-based profiling tools that are used for measuring the performance of a software code running on an embedded soft-core processor. Soft-core processors are packaged Hardware Description Language (HDL) files which describe the behaviour of a microprocessor and can be implemented on several FPGA platforms [15]. Popular FPGA vendors such as Altera [16] and Xilinx [17] provide embedded soft-core processors with software-based profiling tools. This requires the designer to compile their software with instrumentation code at the binary level. Shannon *et al* [13] and Vahid *et al* [14], [18] proposed FPGA-based profiling tools that were implemented using the MicroBlaze [19] soft-core processor and have attained significant improvement over the profiled results provided by software-based profilers.

In this paper we first describe existing profiling tools and present a qualitative comparison of the various profiling tools that have been proposed to date. In our earlier paper [20], we compared two existing profiling tools, namely *gprof* [21] and *Altera Performance Counters* [22]. Then we describe *Airwolf*, an FPGA-based profiling tool developed for Altera Nios II [23] based embedded systems. Nios II is Altera's flagship soft-core processor that is used in embedded systems based on Altera FPGAs [24]. We present a quantitative comparison of *Airwolf* and a well known software-based profiling tool, GNU *gprof*. Four software benchmarks were used to obtain profiling results using *Airwolf* and *gprof*. We show that *Airwolf* provides improvement in accuracy of profiled results and reduces the run time performance overhead. To our knowledge, this is the first time quantitative performance overhead results for profilers used in FPGA-based embedded systems have been presented and compared.

The remainder of this paper is organized as follows: Section 2 gives a detailed discussion and classification of current profiling tools. Section 3 introduces The *Airwolf* Profiler and describes its profiling architecture and operations. Section 4 discusses the profiling and CAD tools used and the experimental framework, the *Nios II Profiling Environment*. Experimental results obtained using the GNU profiling tool *Nios2-gprof* and The *Airwolf* Profiler on selected software benchmarks are presented in Section 5. We conclude the paper in Section 6 with suggestions for future work.

II. PROFILING TOOLS

Profiling tools are used during the design process of embedded systems whereby they measure the perfor-

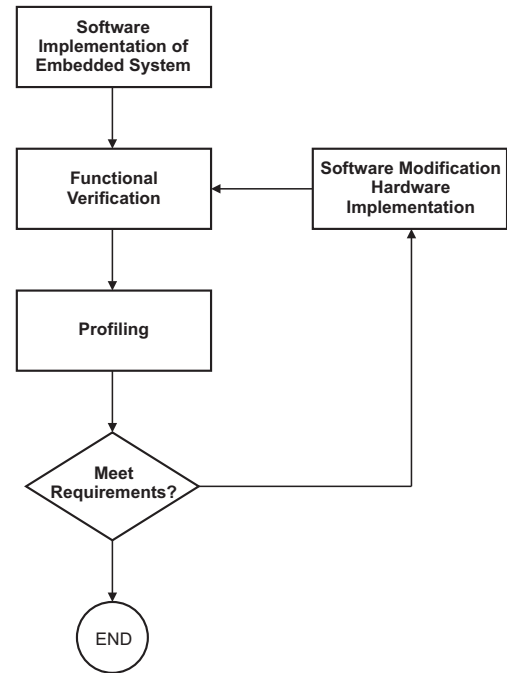


Figure 1. Software Profiling Methodology

mance of the application code running on the target processor of an embedded system. Embedded designers have two options for the initial implementation of their design. First, the embedded system can be implemented entirely in hardware then moving certain components to the software domain, depending on the execution performance of those functions [25]. Second, the embedded system design can be implemented entirely in software [26] and then the software code is profiled using a profiler. It is used to detect any computational intensive portions in the code and other performance bottlenecks. The information provided by the profiler is used by designers to help them choose which software functions are more desirable for hardware implementation and acceleration. The goal is to find an optimized partition of the embedded system based on the accurate profiled information such that it creates a proper balance between the hardware and software components in order to attain a speed-up in the overall system performance. This latter approach has led to a proposed *Software Profiling Methodology* (SPM) as shown in Figure 1 [13].

The design flow is similar to the hardware-software co-design methodology of embedded systems [27]. The SPM begins at the software specification stage. The complete embedded system is written in a high level language such as C or C++ and then the software is functionally verified. Next a profiler is invoked in order to measure the runtime performance of the program and eventually return feedback and performance statistics to the designer. The designer will analyze the results and determine if the software code meets the specified performance constraints. If the system fails to meet the requirements, the designer will try to optimize the code or move certain computationally intensive functions into the hardware

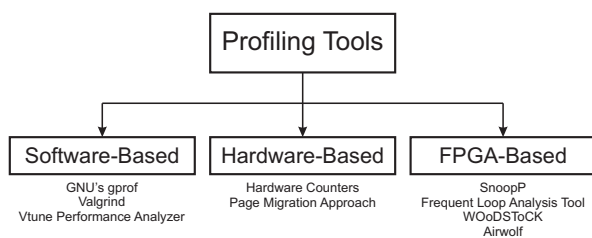


Figure 2. Classification of Profiling Tools

domain as a hardware accelerator. If necessary, the entire methodology starts again until the designer is satisfied with the performance.

Existing profiling tools offer different types of profiling capabilities and support different programming languages. C/C++ profiling tools are common, but there are also tools available that can profile programs written in *Java* [28]. Currently, there are many different kinds of profiling tools that are used to retrieve a variety of profiled information about a program. The most common is function-level profiling which measures the amount of time needed for a function to execute on the processor. Another type is memory profiling, provided by *Rational Purify* [29] and *Valgrind* [30]. These memory profiling tools determine which function, data variable type or instruction is causing memory related problems: excessive memory references, cache misses, heavy pointer dereferencing, branching and looping instructions. Figure 2 shows a proposed classification of the existing profiling tools [31].

There are three main categories of profiling tools: software-based, hardware-based and FPGA-based. In this paper we discuss these categories.

A. Software-Based Profiling Tools

Software-Based Profiling (SBP) is the most common technique for measuring the performance of application code written in a programming language. There are two approaches to profiling the software code when using these tools: simulation and the insertion of instrumentation code. Simulations take place in virtual environments that simulate the behaviour of a microprocessor as the software code is running in a virtual environment. The insertion of instrumentation code allows an SBP tool to attach itself to the binary file and collect performance information during the execution of a program on the processor. In this section, a description of the ISS and GNU's *gprof* is given.

Instruction Set Simulators (ISS) are one of the SBP tools used for profiling software code running in a simulated environment. One popular ISS is the *SimpleScalar Toolset* which simulates application code running on the *SimpleScalar* computer architecture [32]. The advantages of using an ISS for profiling is that the designer is able to view the entire data flow movement inside the microprocessor's registers during the simulation. It keeps track of all of the execution processes, the current instruction in execution, data manipulations, cache accesses and other reportable events. This does not require the software code

to be modified, therefore intrusiveness to the binary file is non-existent.

The use of an ISS may not be feasible for larger software programs or with system-on-a-chip designs since they can be very slow to simulate [33]. This could lead to very inaccurate profiles of the execution times of each function. Simulations can have varying times to complete depending on the complexity of the software code. It may take several hours to run an entire simulation which may only cover a few seconds of real-time, thus misrepresenting the entire execution time. Due to the increasing complexity of embedded systems designs, constructing complex models of the system's components and other external environments may not be possible.

gprof [21] is an open-source profiling tool that is used on Linux [34] and Unix [35] workstations to profile C and C++ application code. It provides two types of profiled outputs: the flat profile and the call graph. The flat profile is a report of how much time the program is spent on each function and the number of times that function was called. The call graph displays each function, its calling function and other functions called within that function. To utilize this profiler, the designer is required to compile code with the default debug instrumentation setting. This option inserts additional instrumentation code into the binary executable file, as required by *gprof*.

During program execution, *gprof* utilizes the inserted instrumentation code to monitor the performance of the program running on the CPU. The instrumentation code allows *gprof* to count the precise number of function calls and generate the appropriate number of interrupts to sample the program counter (PC) of the CPU. It is capable of generating a profile that accurately counts the number of functions that have been called, however, the reported execution time of each function may be somewhat inaccurate.

gprof collects information on the execution time of a program by reading the value of the PC at specified intervals. The PC value determines which function is being executed on the processor. Based on this value, *gprof* increments the execution time counter of the function that is currently executing by its sampling period. This can create inaccurate timing results for each function called and the execution time of the entire program [36]. The accuracy of the profiled execution time is entirely dependent on the sampling frequency of the PC.

The use of the sampling technique in common SBP tools helps to reduce the run-time overhead during profiling. Nevertheless, this can produce inaccurate profiled results which can potentially create a sub-optimal partition of the embedded system. The use of an ISS can also produce inaccurate results since simulations are only as good as the system model that is being simulated. Also, the simulation time may not accurately match the actual run-time execution of the program. Certain SBP tools require the designer to link their program with instrumentation code which is inserted at the binary level. This can lead to an excessive number of interrupt calls which may cause

unpredictable behaviour of the software code running on the embedded hardware platform. Additionally, the instrumentation code can lead to an increase in code size and may potentially change the behaviour and the performance of the software system.

B. Hardware-Counter Based Profiling (HCBP) Tools

Hardware-Counter Based Profiling (HCBP) tools utilize on-chip hardware counters that are available on advanced processors such as *Sun Ultrasparc* [37], *Intel Pentium Processors* [38] and *Advanced Micro Device (AMD) Processors* [39]. These hardware counters are dedicated to monitoring specific events that occur during runtime execution of an application. The types of events which can be monitored are: memory accesses, cache misses, pipeline stalls, types of instructions executed and etc. HCBP tools do not require the use of instrumentation code since these counters are designed to collect performance information of the software program. In addition, very little performance overhead is introduced during runtime execution.

Accessing these counters requires a unique instruction. The *Performance Advanced Programming Interface (PAPI)* [40] provides users with a high level interface to access these counters and can supports many different processors [41]. *Intel's VTune* counter monitor provides an interface for accessing and utilizing the hardware counters to profile application code executing on Pentium-based processors [38].

Itzkowitz et al from *Sun Microsystems* have described a software profiling tool that utilizes the hardware counters in an *Ultrasparc-III* microprocessor [42]. Originally this profiling tool was built as an extension of the *Sun One Studio* [43] compilers and performance tools, which are used for measuring the performance of software code. These hardware counters are included in the architecture and contain different types of event counters such as, *Instructions Completed*, *Instruction-cache (I\$) Misses*, *Data-cache (D\$) Read Misses*, *Data-translation-lookaside-buffer (DTLB) Misses*, *External-cache (E\$) References*, *E\$ Read Misses*, *E\$ Stall Cycles*, and many others.

There are some limitations to using this tool. One such limitation is counter-skidding [42]. The tool uses hardware-counter overflows to obtain profiled information. When a counter overflow occurs, the tool does not execute a precisely timed trapping mechanism to obtain the correct value of the counter. The second problem is the backtracking mechanism of instructions which was implemented as a solution to solve the trapping mechanism flaw. The backtracking technique is used to find the instruction address that caused the overflow event to occur, however the instruction immediately preceding the current one in the processor's PC may not have the correct address value, due to the possibility that the previous instruction was a branch call. Instead of relying on the value of the PC, the profiling tool tries to find the proper values in other registers to calculate the effective address

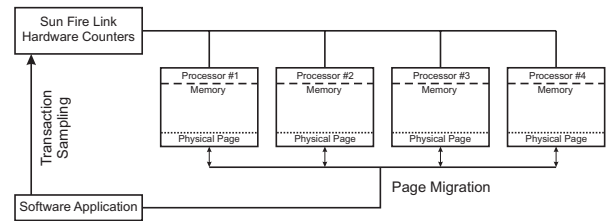


Figure 3. Page Migration Approach

of the instruction that caused the overflow event. It is not guaranteed success in finding the address since the value of the registers may have changed once other overflow signals have been delivered to other hardware counters. Despite with these drawbacks, the tool has managed to find the proper instruction 99% of the time. The MCF benchmark was profiled and the feedback provided enabled a 20% performance improvement.

The *Page Migration Approach (PMA)*, developed by *Tikir et al* utilizes hardware-counters for profiling memory with memory page-migrating capabilities [44]. The profiler was used on a multi-processor system based on *Sun's SunFire Server* as shown in Figure 3. Each system board contained several processors and memory. The *Sun Fire Link* hardware counters are used to sample the frequency with which each processor "touches" a page of memory that is remote from the on-board local memory hardware. At a certain number of counts specified by the user for remote touching of memory pages, the profiler halts the execution. It then migrates that particular memory page to the processor that accesses it most frequently for read and write operations. PMA has demonstrated 90% speed improvement when certain memory pages are placed closest to the processor that requires data from that page.

There are consumer desktop processors today that contain hardware counters which monitor the performance of application code in the CPU. *AMD Athlon* microprocessors [39] contain four 48-bit performance hardware counters that can be used as event driven or timing driven counters. These counters can monitor the number of times a certain event occurs or they can measure the duration of an event that is currently taking place on the processor. *Intel Pentium* microprocessors also contain a set of performance hardware counters [38]. They are also event or timing driven and are accessible through *Intel's VTune* [45] profiling tool.

Using hardware counters for profiling software code is beneficial since it does not introduce any instrumentation code, leaving the compiled application source code untouched. Additionally, they do not add any performance overhead since the data collection of these counters occurs during runtime execution of the software. However, there are drawbacks when using HCBP tools. First, some HCBP tools may require the user to reconfigure and reprogram the counters to detect different events, which can lead to the addition of certain functions at the source code level. Secondly, they use the sampling method to sample

the hardware counters which leads back to the problems that were introduced with SBP tools. Thirdly, handling of interrupts affect the gathered data since the interrupt service routines (ISR) used add to the number of events. Lastly, there is a limited number of hardware counters available. The programmer must run the application many times to obtain data for different monitoring events [41].

C. FPGA-Based Profiling Tools

FPGA embedded development kits are a popular re-configurable design platform for synthesizing and rapid-prototyping of embedded systems. This is due to the continuing advancement of FPGAs by providing increased logic capacity and other on-chip resources. FPGA-based embedded systems usually consist of a soft-core processor which is used as the target processor to execute software programs. The two major FPGA vendors, Altera [16] and Xilinx [17], provide embedded system development kits that uses Nios II [23] and MicroBlaze [19] soft-core processors respectively. These processors are instantiated in the embedded system design, in which they are used as basic building blocks for the design of embedded systems [10], [15].

FPGA-based profiling (FPGA-BP) tools also utilize these soft-core processors for profiling. In FPGA-BP tools, the designer executes the software on the soft-core processor and collects the performance data provided by the on-chip profiling hardware. These tools have provided improved results compared to the previous profiling tools described earlier. They keep latency and performance overhead at a minimum, because they are non-intrusive and require negligible instrumentation. They do not use the sampling technique and require very minimal processor computation. These features are highly desirable for profiling tools used in embedded systems. In this section, a detailed discussion of the proposed FPGA-based profiling tools to date is provided.

SnoopP [13] is an on-chip function level profiler that was implemented on the Xilinx Virtex-II 2000 FPGA board. This board is used to implement designs based on the Xilinx MicroBlaze soft processor [19]. The on-chip profiler utilizes the MicroBlaze as a target processor. *SnoopP* uses a hardware profiling architecture that is non-intrusive to the code, such that any additional instructions, commands or other flags are not necessary. Figure 4 depicts the hardware architecture for the *SnoopP* profiler.

As shown in Figure 4, *SnoopP* consists of a variable number of segment counters that are user specified and define the address of instructions to be analyzed. The number of segment counters is dependent on the number of functions the user wishes to profile and the area available on the FPGA.

The comparators inside *SnoopP*'s profiling counters, shown in Figure 5, determine if the value of the PC address is in the range of memory addresses in which the binary code corresponding to the function resides. This is determined by the comparators inside each segment counter. If this condition is true, the comparator sends an

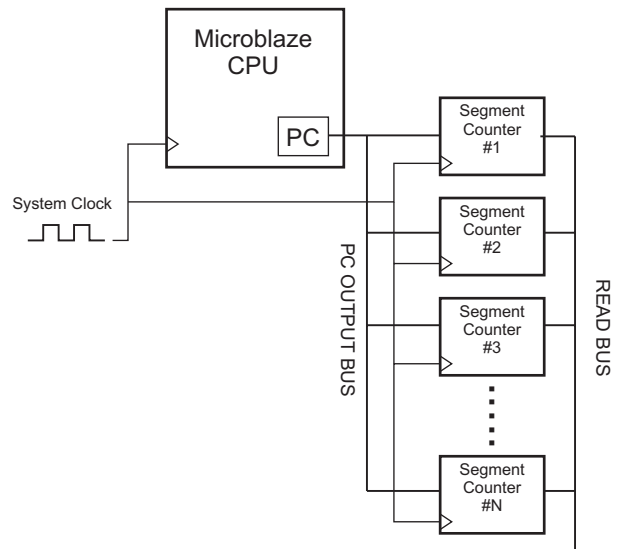


Figure 4. SnoopP Profiler

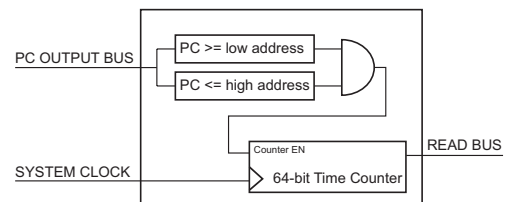


Figure 5. SnoopP's Profiling Counter

enable signal to the hardware counter which utilizes the processor's system clock to count the number of clock cycles the function has used. This gives the designer the precise number of clock cycles that the particular function needs to execute on the processor. *SnoopP*'s and *gprof*'s results were compared, and it was shown that *SnoopP* was significantly more accurate. Additionally, *SnoopP* does not slow down the performance of either the software or the profiling process.

Frequent Loop Analysis Tool (FLAT) is a tool that detects functions in software that heavily use loops [46]. In most cases, loops use 90% of the execution time while constituting only 10% of the entire software code. FLAT searches for these critical regions and records the execution frequency of each loop-intensive function into a cache-like hardware architecture that is implemented on an FPGA. A block diagram of the FLAT architecture is shown in Figure 6.

Usually a loop instruction is typically denoted as a short backwards branch (SBB), when the program jumps back to the first instruction of that loop. The value of the SBB is a negative address offset. The *Frequent Loop Cache* (FLC) stores the execution frequency of each loop function at the index memory location that is based on the SBB value. A cache controller, called the Frequent Loop Cache Controller, keeps the data updated with the latest values. FLAT does not require the use of instrumentation code or any sampling techniques. Nonetheless, the accuracy of the loop detection relies on the size of the on-chip cache in the FPGA.

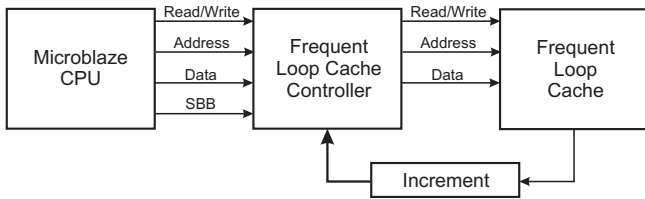


Figure 6. Frequent Loop Analysis Toop

WOoDSTOCK [47] (*Watches Over Data Streaming On Computing element linKs*), is a profiling tool that monitors the communication dataflow between Computing Processor Elements (CPEs). It helps determine the components that cause communication bottlenecks in the entire system.

WOoDSTOCK monitors the data flow between each CPE by adding monitors to the circuit which run in real time. The data link between each element of the system is created by *Fast Simplex Links* (FSLs) [48], available in Xilinx's MicroBlaze [19] soft-core processor. FSLs allow streaming and buffering of data between the hardware components of the system. The profiler utilizes the links to measure the stream of data between each CPE. It measures the number of run-time execution clock cycles to see which CPE is stalled or starved for data.

A stalled CPE occurs when a stream of data is at the input but little or no output data is coming out. A starved computing element occurs when little data is coming in or going out of the CPE, but it is still running. The results obtained showed that the tool was able to detect bottlenecks using a pipelined system and a branching system benchmark.

D. Qualitative Comparison of Profiling Tools

There are a variety of profiling tools available today that can measure the performance of software code by collecting information about different performance metrics. The majority of these tools have one or more drawbacks related to accuracy, runtime overhead and extended execution time. Table I shows a comparison of the profiling tools discussed in this paper.

The SBP tools have functional and memory profiling capabilities. They do require the insertion of code that is needed to interrupt the processor at specific intervals to sample the data stored in the hardware registers in the system. This can cause inaccurate profiled results reported along with the introduction of performance overhead during execution and an increase in file size. This is not desirable in the design of embedded systems.

One of the advantages of using simulators is that the original program does not require any insertion of code. This is beneficial since this does not modify the behaviour of the software program, although simulating large programs is very slow and is therefore an impractical option for profiling large embedded system designs.

HCBP tools are mostly used for profiling memory systems, however, they do use techniques that are similar to those used by software-based profiling tools, such as

sampling, which can affect the accuracy of the performance information retrieved. The accuracy of the profiled results is dependent on the frequency of the sampling rate.

FPGA-BP tools are clock-cycle accurate and do not introduce overhead during software execution. The software program may require minimal code disturbance or can be left alone, thus reducing the effect of unpredictable execution behaviour. We can observe from the table that FPGA-BP tools are not as restricted as functional or memory profilers. They also have the ability to detect communication bottlenecks between CPEs.

III. THE AIRWOLF PROFILER

The *Airwolf* Profiler is an on-chip FPGA-BP tool used to profile software programs running on the Nios II [23] Processor in real-time. This is done by determining the run-time of each software function by accurately counting the number of system clock cycles. The modification of the interface of the *Airwolf* Profiler can also be instantiated on other embedded soft-core processors such as Tensilica *Xtensa* Soft-Core Processor [49] and the Xilinx *MicroBlaze* Soft-Core Processor [19]. *Airwolf* does not require any instrumentation code added to the binary file. A pair of software drivers needs to be placed in between a software function block in the source code in order to activate and deactivate a particular profiling counter contained in *Airwolf*. This approach minimally disturbs the program and the software behaviour during execution. The goal of the *Airwolf* Profiler is to provide accurate results while minimally modifying the software code. Figure 7 depicts the *Airwolf* Profiler Architecture.

A. Airwolf Profiling Architecture

As shown in the figure, the *Airwolf* Profiler contains the *Time Counter Enable* (TCE) module and 20 profiling counters. This is sufficient for profiling large programs that consist of a large number of software functions. Instantiating the *Airwolf* Profiler onto the Stratix EP1S40F780C5 FPGA [50] consumes 3,345 logic elements. The maximum operating frequency of this profiler is 120 MHz. Hence, this can be used for high-speed Nios II Processor systems [23].

The TCE module contains 20 *Counter Enable* (CE) registers which are used to activate the appropriate profiling counter. The logic circuit in the TCE module is dependent on the *Address* and *Data_In* bus inputs that are being fed from the *Avalon Interface Bus* (AIB) [51]. The AIB contains all of the necessary control logic signals that are used to manipulate the CE registers in the TCE module. The accompanying software drivers of the *Airwolf* Profiler are programmed to access the appropriate CE register by sending a unique address onto the interfacing bus. The output of each CE register is fed into the input enable of the assigned profiling counter (shown as the *Time Counter Enabling Lines* (TCELs) in the figure).

The *Hits Counter Enable Lines* (HCEL) are the output control lines coming from the TCE module. Their purpose

TABLE I.
COMPARISON OF PROFILING TOOLS

Feature	gprof	ISS	VTune	Valgrind	Purify	HWC	PMA	SnoopP	Woodstock	FLAT
Instrumentation Code	X		X	X	X					
Sampling	X		X	X	X	X	X			
Clock Cycle Accurate								X	X	X
Performance Overhead	X	X	X	X	X		X			
Simulation		X	X	X						
Software-Based	X	X	X	X	X					
Hardware-Based						X	X			
FPGA-Based								X	X	X
Functional Profiler	X	X	X					X	X	X
Memory Profiler				X	X	X	X			
Other Profiler									CPEs	

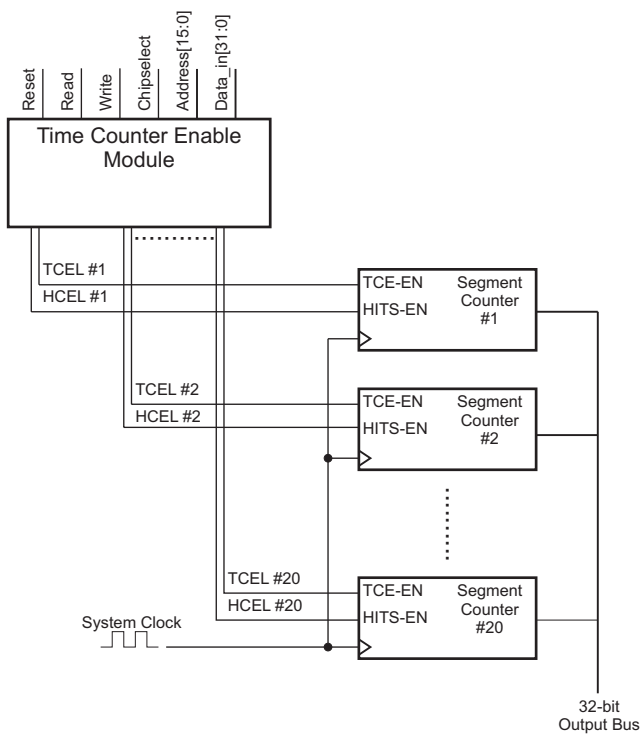


Figure 7. The Airwolf Profiler

is to indicate when a function has been called as the program is executing on the processor.

The *Data_In* and *Address* input buses are also used to extract the profiling data stored in the profiling counters. These data are sent out to a host computer through the *Data_Out* bus. A set of control signals provided by the AIB, namely the *chipselect*, *write_enable* and *read_enable* signals, are used to prevent any illegal input or output accesses of the CE registers and the profiling counters.

B. Airwolf Profiling Counter

The *Airwolf* Profiler contains 20 profiling counters which allow for up to 20 functions to be profiled at a time. Figure 8 depicts the contents of each profiling counter.

Each profiling counter actually consists of two counters, a 32-bit *hits counter* and a 64-bit *time counter*. The hits counter counts the number of positive edges of the input HCEL control signal. When the appropriate profiling software driver activates the profiling counter,

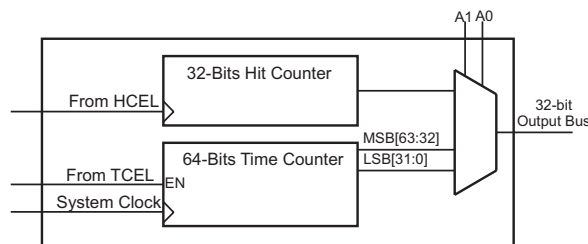


Figure 8. Airwolf Profiling Counter

the HCEL control signal becomes high for one clock cycle. This signifies that the assigned function has been activated and the hits counter is incremented by 1.

The 64-bit time counter is used to count the number of clock cycles of the currently executing function. Each 64-bit time counter is capable of measuring over 100 million hours of profiling time when using a 50 MHz system clock. This ensures that the overflow of the register will effectively never occur. There are two distinct inputs to each of the 64-bit time counters, which are the time counter enable and the system clock inputs. The time counter enable input is fed by the appropriate TCEL control line, which controls the counting sequence of the counter. If the TCEL signal becomes high and remains at that state, the counter begins to count the number of positive edges of the system clock. If the TCEL signal becomes low, counting of the clock ticks is disabled. This concept is of great importance since *Airwolf* accurately counts the number of clock ticks a function has taken. This helps to provide accurate performance feedback which can be beneficial for embedded system designers.

A multiplexer component that is controlled by the address bits from the *Address* input bus exists in every profiling counter. This mandates which data is assigned to the AIB. In the end, the profiled data stored in these counters is extracted by calling the appropriate software driver and displayed for the designer.

IV. PROFILING ENVIRONMENT AND BENCHMARKS

In this section, the profiling and design CAD tools, the experimental profiling environment and the software benchmark descriptions are presented.

TABLE II.
NIOS DEVELOPMENT BOARD COMPONENTS

Nios Development Board	
Stratix Professional Edition	41250 Logic Elements
Static RAM (Off-Chip) Module	1MB
Flash Ram (Off-Chip) Module	8MB

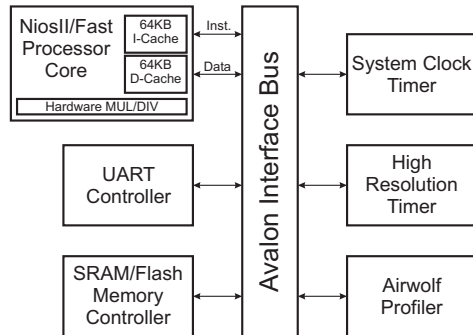


Figure 9. Nios II Profiling Environment

A. Profiling and Design CAD Tools

The two profiling tools, *Nios2-gprof* and the *Airwolf Profiler* were utilized in measuring the performance of the software code running on the soft-core processor, Nios II. A Nios II Processor System was built as the target hardware platform that was used for running and profiling software programs. We refer this as the *Nios II Profiling Environment* (Nios-II-PE). *Nios2-gprof* is Altera's implementation of the GNU's *gprof* profiler. The *Airwolf Profiler* is the FPGA-based profiler that is a component of the Nios-II-PE. The following design tools were used for this experiment: Altera's Quartus II Version 5.0 SP2 [52], Nios II IDE Version 5.0 [53] and SOPC Builder Version 5.0 [54].

B. FPGA Development Board

The Nios Development Kit [24] was used to implement the Nios-II-PE. This kit contains a Nios Development Board, Stratix Professional Edition, featuring a Stratix EP1S40F780C5 FPGA chip. The chip features 41,250 logic elements, 3,423,744 memory bits and 14 Digital Signal Processing (DSP) blocks, [50]. There are available off-chip memory modules that can be used, which include the 8MB flash memory, the 1MB SRAM and the 16MB SDRAM modules. In this experiment, the 1MB SRAM was used for the program, stack and data memories for each benchmark. All of the components on the development board utilized the 50MHz clock oscillator as the system clock of the Nios-II-PE.

C. Nios II Profiling Environment

Figure IV-C shows the diagram of the profiling environment, namely the Nios-II-PE, and Table IV lists the instantiated Intellectual Property (IP) cores. The Nios-II-PE consists of the fast version of the Nios II Processor core, which is a soft-core processor that is optimized

TABLE IV.
NIOS II PROFILING ENVIRONMENT COMPONENTS

Nios II Profiling Environment
Nios II Fast-Core Processor (with Hardware Multiply/Divide)
1MB SRAM Controller
System Clock and High Resolution Timers
UART Controller
The Airwolf Profiler

for high performance in computationally-intensive applications at the expense of consuming more logic elements on an FPGA [23]. This processor is suitable for executing the benchmarks used in this experiment. The core contains multiply and divide hardware accelerators which allow multiplication and division operations to be executed in hardware. In addition, it contains separate instruction and data cache memories, each having 64KB. For the program, stack and data memories, the Nios-II-PE utilizes the 1 MB static Random Access Memory (RAM) module which is located off-chip. Software benchmarks are downloaded onto this memory module. There are two timers in this system, namely the system clock and high performance timers. They are required for *Nios2-gprof* in order to measure the run-time of the software functions and by some of the software benchmarks as well. An instance of the *Airwolf Profiler* is used in the Nios-II-PE, consisting of all 20 profiling counters. Each of these counters is assigned a specific software function to profile. The Universal Asynchronous Receiver and Transmitter (UART) controller is used to communicate with the Nios-II-PE and to transfer streaming messages back to the host computer. All of the instantiated components in the Nios-II-PE are connected using the *Avalon Interface Bus* (AIB) [51] which provides all of the necessary control logic and data signals that are used to communicate between each instantiated component.

D. Software Benchmarks

The profiling software benchmarks used in this experiment are listed in Table III, along with a brief description of each. These benchmarks were obtained from *MiBench* [55], [56] and the *UTNiosbenchmarks* [57]. Each benchmark was compiled using the *Nios II GCC* compiler applying the highest optimal compilation (-O3) setting. The compiler generates the executable binary by optimizing the code for fast performance at the expense of a slightly larger file size [58].

Each benchmark was slightly modified for each of the profile runs so that no function calls any other function in the program. The reported execution time is dedicated to the assigned function, and not to any other function that may be called.

There are additional settings and code modifications for each of the benchmarks when we use the two different profilers. For instance, *Nios2-gprof* requires the default debug (-g) setting which causes the GCC compiler to add instrumentation code at the binary level. The *Airwolf Profiler* required a pair of software drivers [59] to be

TABLE III.
BENCHMARK DESCRIPTIONS

Profiling Software Benchmarks	
BitCount	Performs several bit manipulations (10,000,000 iterations)
Dhrystone	Tests the integer performance of a microprocessor (100,000,000 iterations)
Dijkstra	Computes the shortest path between 160 distinct nodes
Fibo_Matrix_Mult	First computes the 40th Fibonacci term and then multiplies two 250x250 matrices

inserted in between each function. One driver is used to activate and the other to deactivate the assigned function's profiling counter.

V. EXPERIMENTAL RESULTS

Each benchmark was executed with *Nios2-gprof* and the *Airwolf* Profiler with their respective software compilation settings. In the subsequent paragraphs, we present an analysis of the profiled results for each of the benchmarks listed in Table III.

A. Dijkstra

Table V shows the profiled results for the *Dijkstra* benchmark. The first four columns show the results obtained by *Nios2-gprof* and the latter four columns show the results obtained with *Airwolf* profilers. The first column gives the function name. The second column shows the execution time of each function. The third column shows the function's execution as a percentage of total execution time of the benchmark. The number of function calls is displayed in the fourth column. The same explanation applies for the remaining columns in the table and for all subsequent tables.

Each profiler's results are alike, having similar execution times and rankings of computationally intensive functions. The *Dijkstra* function is reported to run for 41.56 seconds by *Nios2-gprof* whereas the *Airwolf* Profiler reported 42.27 seconds.

There are very minor differences in the reported execution times of the remaining software functions. This implies that *Nios2-gprof* reports results with comparable accuracy to those of the *Airwolf* profiler for smaller, less computationally intensive benchmarks. *Airwolf* attained an improvement in accuracy of 1.67%.

B. Fibo_Matrix_Mult

Table VI depicts the profiled results of the *Fibo_Matrix_Mult* benchmark. *Nios2-gprof* reported that the *Fibonacci* function was called only once. The call-graph, however, displays that the function was recursively called 204,668,308 times. This explains the "+" in between the two values. Similarly, *Airwolf* reported that the number of calls to *Fibonacci* was 204,668,309. In terms of the run-time, *Nios2-gprof* and *Airwolf* reported that the function was running for 172.14 and 195.17 seconds respectively. This implies that the sampling technique used in *Nios2-gprof* has produced an inaccurate report of the execution time when profiling recursive function calls. In contrast, the

clock-cycle counting method that *Airwolf* utilizes shows an 11.79% accuracy improvement in the reported time for that function.

The *Matrix_Mult* function had very minor difference in the reported time between the two profilers. The percentage difference is 0.36%.

C. BitCount

Table VII shows the profiled results for the *BitCount* benchmark. There is a significant difference in the reported execution time of each function when the results from each profiler are compared. Not only do the execution times differ, but *Nios2-gprof* also ranked the most time consuming functions differently than *Airwolf*. *Nios2-gprof* listed the *ntbl_bitcnt*, *bit_shifter* and *bit_count* as the most time consuming functions, whereas the *Airwolf* Profiler reported that the *bit_shifter*, *bit_count* and *ntbl_bitcnt* functions contributed the most toward the total execution time of the benchmark.

Nios2-gprof reported that *bit_shifter* ran for 66.27 seconds whereas *Airwolf* Profiler has measured that function to take 196.64 seconds on the processor. Once again, due to the sampling technique used by *Nios2-gprof*, the profiler provided an inaccurate reporting of the execution time. *Airwolf* Profiler provided up to 66.2% improvement in accuracy in some of the functions.

As for the *ntbl_bitcnt* function, which was called recursively, *Nios2-gprof* and *Airwolf* reported that the function was running for 71.88 and 51.34 seconds respectively. This shows that *Nios2-gprof* reports inaccurate execution times when profiling recursive functions.

Nios2-gprof reported that the *ntbl_bitcnt* and *Flipbit* functions were called during the execution of the benchmark. However, the *Airwolf* Profiler did not detect calls to those functions. The insertion of instrumentation code not only generates additional function calls and interrupts, but it can also cause unpredictable behaviour of the executing program.

D. Dhrystone

Table VIII shows the profiled results for the *Dhrystone* benchmark. Both profilers have similarly ranked the most time consuming functions. However, the reported execution times of each function were quite different. *Proc_1* was reported to take 131.84 and 106.53 seconds by *Nios2-gprof* and the *Airwolf* Profiler respectively. This amounts to a 19.19% improvement in accuracy when using the *Airwolf* Profiler. Another observation is with regards to the reported times of *Func_1* and *Proc_3*. *Nios2-gprof*

TABLE V.
PROFILED RESULTS OF DIJKSTRA

Nios2-gprof				Airwolf Profiler			
Function Name	Time (Sec)	% Time	Number of calls	Function Name	Time (Sec)	% Time	Number of Calls
Dijkstra	41.56	71.43	160	Dijkstra	42.27	70.98	160
Enqueue	16.27	27.96	192739	Enqueue	16.61	27.89	192739
Dequeue	0.25	0.43	192739	Dequeue	0.52	0.88	192739
Read_Lint	0.05	0.09	25600	Read_int	0.12	0.20	25600
Qcount	0.05	0.09	192899	Qcount	0.03	0.05	192899

TABLE VI.
PROFILED RESULTS OF FIBO_MATRIX_MULT

Nios2-gprof				Airwolf Profiler			
Function Name	Time (Sec)	% Time	Number of calls	Function Name	Time (Sec)	% Time	Number of Calls
Fibonacci	172.14	82.69	1+204668308	Fibonacci	195.17	84.46	204668309
Matrix_Mult	36.03	17.31	1	Matrix_Mult	35.90	15.54	1

TABLE VII.
PROFILED RESULTS OF BITCOUNT

Nios2-gprof				Airwolf Profiler			
Function Name	Time (Sec)	% Time	Number of calls	Function Name	Time (Sec)	% Time	Number of Calls
ntbl_bitcnt	71.88	22.35	80000000	bit_shifter	196.64	54.40	10000000
bit_shifter	66.27	20.60	10000000	bit_count	61.98	17.15	10000000
bit_count	63.55	19.76	10000000	ntbl_bitcnt	51.34	14.20	80000000
main	47.10	14.64	1	ntbl_bitcount	22.26	6.16	10000000
ntbl_bitcount	24.51	7.62	10000000	ar_bt看l_bitcount	15.04	4.16	10000000
ar_bt看l_bitcount	19.76	6.14	10000000	bitcount	12.63	3.49	10000000
bitcount	17.41	5.41	10000000	bw_bt看l_bitcount	4.40	0.44	10000000
bt看l_bitcnt	6.47	2.01		main	0.01	0.00	1
bw_bt看l_bitcount	4.40	1.37	10000000	bt看l_bitcnt	0.00	0.000	
Flipbit	0.28	0.09		Flipbit	0.00	0.00	

TABLE VIII.
PROFILED RESULTS OF DHRYSTONE

Nios2-gprof				Airwolf Profiler			
Function Name	Time (Sec)	% Time	Number of calls	Function Name	Time (Sec)	% Time	Number of Calls
Func_2	240.02	30.02	100000000	Func_2	253.64	38.32	100000000
Proc_1	131.84	16.49	100000000	Proc_1	106.53	16.01	100000000
Proc_8	100.52	12.57	100000000	Proc_8	78.26	11.83	100000000
Proc_6	80.52	10.07	100000000	Proc_6	62.28	9.41	100000000
Func_1	67.69	8.47	300000000	Proc_2	36.00	5.44	100000000
Proc_3	49.19	6.15	100000000	Func_1	34.69	5.24	300000000
Proc_7	38.13	4.77	300000000	Proc_7	30.14	4.55	300000000
Proc_2	36.91	4.62	100000000	Proc_3	22.13	3.34	100000000
Proc_4	30.01	3.75	100000000	Proc_4	18.00	2.72	100000000
Proc_5	15.11	1.89	100000000	Func_3	10.14	1.53	100000000
Func_3	9.69	1.21	100000000	Proc_5	10.00	1.51	100000000

reported that Func_1 took 67.69 seconds to execute and Proc_3 ran for 49.19 seconds. However, the results obtained with the *Airwolf* Profiler showed that Func_1 had an execution time of 34.69 and that Proc_3 executed for 22.13 seconds. Again, a 55% improvement in accuracy was obtained using the *Airwolf* profiler.

VI. PERFORMANCE OVERHEAD ANALYSIS

Nios2-gprof requires the C/C++ file to be compiled with instrumentation code which generates additional software interrupts and counter variables in the original program. This can lead to a large increase in the execution time of the benchmark and can cause an inconvenience to the embedded system designer who has to wait to retrieve the profiled results. This becomes a major impediment as the software code size grows larger.

In this section, an analysis of the performance overhead is presented for the software benchmarks discussed above. Each software program was compiled with the default debug (-g) setting while the same assigned functions were profiled with the *Airwolf* Profiler. The performance overhead was determined by summing the execution time of each profile run, with and without instrumentation code.

Table IX shows the performance overhead analysis for *Dijkstra*. Column 1 lists the function names. Columns 2 and 3 show the execution times when the program was executing with and without instrumentation code respectively. The last column shows the time difference between the two compilation runs.

As evident from the table, there is very minor time difference when instrumentation code is added, at most 1.04 seconds. This implies that profiling with *Nios2-gprof*

TABLE IX.
PERFORMANCE OVERHEAD ANALYSIS OF DIJKSTRA

Function Name	Execution Time (Sec)	Execution Time (Sec) with Instrumentation	Difference (Sec)
Dijkstra	42.20	43.24	1.04
Enqueue	16.60	17.22	0.62
Dequeue	0.52	0.92	0.4
Read_int	0.12	0.12	0
Qcount	0.031	0.031	0
Performance Overhead: 3.35%			

TABLE X.
PERFORMANCE OVERHEAD ANALYSIS OF FIBO_MATRIX_MULT

Function Name	Execution Time (Sec)	Execution Time (Sec) with Instrumentation	Difference (Sec)
Fibonacci	195.17	357.90	162.74
Matrix_Mult	35.90	36.00	0.10
Performance Overhead: 41.34%			

TABLE XI.
PERFORMANCE OVERHEAD ANALYSIS OF BITCOUNT

Function Name	Execution Time (Sec)	Execution Time (Sec) with Instrumentation	Difference (Sec)
bit_shifter	196.64	197.31	0.67
bit_count	61.98	62.18	0.20
ntbl_bitcnt	51.34	99.77	48.43
ntbl_bitcount	22.26	22.31	0.05
AR_btbl_bitcount	15.04	15.09	0.05
bitcount	12.63	12.66	0.03
BW_btbl_bitcount	1.60	1.60	0.00
btbl_bitcnt	0.00	0.00	0
Performance Overhead: 12.10%			

TABLE XII.
PERFORMANCE OVERHEAD ANALYSIS OF DHRYSTONE

Function Name	Execution Time (Sec)	Execution Time (Sec) with Instrumentation	Difference (Sec)
Func_2	253.64	361.23	107.59
Proc_1	106.53	106.00	-0.53
Proc_8	78.26	83.00	4.74
Proc_6	62.28	130.00	67.72
Proc_2	36.00	37.59	1.59
Func_1	34.69	33.00	-1.69
Proc_7	30.14	30.00	-0.14
Proc_3	22.13	25.00	2.87
Proc_4	18.00	18.25	0.25
Func_3	10.14	10.00	-0.14
Proc_5	10.00	10.00	0.000
Performance Overhead: 21.59%			

on smaller benchmarks, such as *Dijkstra*, contributes minimal performance overhead. In this case, only 3.35% of additional execution time was contributed by the instrumentation code.

Table X depicts the performance overhead analysis for the *Fibo_Matrix_Mult* benchmark. Notice that the Fibonacci function has taken 162.74 seconds of additional execution time. The added instrumentation code changed the behaviour of the software benchmark. Since the Fibonacci function was called recursively, this implies that instrumentation code adds significant performance overhead when profiling recursive functions with *Nios2-gprof*. This has caused the entire benchmark to have a performance overhead of 41.34%

Table XI demonstrates the performance overhead analysis for the *BitCount* benchmark. The instrumentation code added an additional 48.43 seconds in execution time to the recursively called function *ntbl_bitcount*. This strongly supports the idea that profiling recursive func-

tions with *Nios2-gprof* can cause a significant increase in run-time execution. The other functions listed in this table show minor differences in the execution time. This has resulted an overall performance overhead of 12.10%.

Table XII depicts the execution time differences of each software function in *Dhrystone*. Some of the functions showed a slight decrease in execution time, resulting in the negative time differences shown in the table. This is probably caused by the inserted instrumentation code that changes the normal behaviour of those functions during execution. This could potentially give inaccurate reporting from *Nios2-gprof*. Since those negative values are diminutive however, it minimally affects the entire benchmark's execution time. The software functions *Func_2* and *Proc_6* show a significant increase in run-time, adding 107.59 and 67.72 seconds respectively. The overall performance overhead for *Dhrystone* is 21.59% when using *Nios2-gprof*.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, we presented a detailed discussion and comparison of different profiling tools for FPGA-based embedded systems. We described *Airwolf*, an FPGA-based profiling tool developed for Altera Nios II [23] based embedded systems. We described an experimental framework, called the *Nios II Profiling Environment* (Nios-II-PE), that was used for profiling a set of software benchmarks using software-based and FPGA-based profilers, namely *Nios2-gprof* and the *Airwolf* Profiler respectively. Experimental results show that the *Airwolf* Profiler provides up to a 66.2% accuracy improvement. This is beneficial to embedded system designers since they rely on accurate performance information to implement the appropriate software functions in the hardware domain. *Nios2-gprof* uses the sample technique which has a tendency to report inaccurate timing of each function in the software code. The *Airwolf* Profiler counts the number of clock ticks that each function uses which provides an accurate report of the execution time of each function.

The performance overhead analysis has also shown further disadvantages when profiling with SBP tools. Adding instrumentation code at the binary level not only is intrusive but has caused computationally intensive functions to run longer than normal. In some of the software benchmarks, the instrumentation code has caused a performance overhead of up to 41.3%. This added time and overhead is unnecessary since it causes *Nios2-gprof* to report inaccurate execution times of each function and longer delays for the designer to retrieve the profiled results.

The *Airwolf* Profiler was designed for research purposes to profile software applications running on an Altera Nios II processor implemented on an Altera FPGA. It can easily be modified to become an instruction address-based profiler that has the capability to monitor the current instruction in execution on the processor. This concept can provide an improvement in the profiled results compared to the current software driver strategy. In future work, the *Airwolf* Profiler can be enhanced to cover memory profiling as well, which monitors memory related events such as the number of off-chip memory accesses, cache misses and memory leaks. This can further benefit embedded system designers and help in improving certain portions of the software code that cause memory related performance issues. The *Airwolf* profiler can also be easily modified to work with other FPGA-based soft core processors such as Xilinx's MicroBlaze [19].

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