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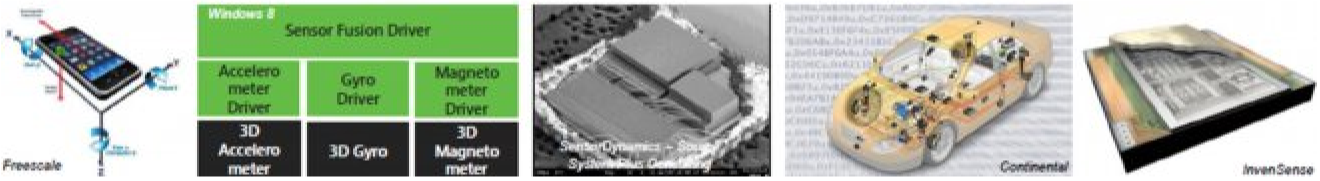

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Dynamic Analysis of Wireless Sensor Network Programs Based on Binary Tool and Simulator

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Abstract: Software quality of sensor network programs has become one of the major concerns during the adoption of WSN technology. Program analysis plays an important role in the software quality assurance. We present a general approach for dynamic program analysis of TinyOS programs before deployment. The approach first utilizes binary dump tool to obtain the disassemble code for the target program under analysis, and then analyzes the dumped file to create associations between concerned instructions and their corresponding memory addresses. Based on those associations, the approach executes the program and analyzes the interested program behaviors at instruction level by utilizing the simulation and analysis infrastructure of Avrora. The examples illustrated in this paper have been implemented in our experiments. *Copyright © 2012 IFSA.*

Keywords: WSN, Program analysis, TinyOS programs, Dump tools, Avrora.

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1. Introduction

Wireless Sensor Networks (WSNs) attract increasing interest in a number of domains concerned with monitoring of physical environment. However, application development is still one of the main hurdles to a wide adoption of WSN technology [1]. WSN applications are error prone and many software bugs have been reported [2, 3]. It is often difficult or even impossible to debug and fix WSN applications after deployment, for instance, when the sensors are deployed in human-inaccessible places. Therefore, it is very important to develop pre-deployment program analysis and testing techniques for WSN programs.

The de facto standard programming language for sensor nodes is nesC [4] and the underlying operating system is TinyOS [5]. The nesC tool chain (e.g., make system) pre-processes a TinyOS application into a single C file, and then compiles the C code into the target machine code [6]. In this paper, we focus on the analysis of WSN programs over TinyOS operating system and AVR [7] target platform.

To discover WSN program problems before deploying it onto the target sensor node, we can utilize WSN simulator to run the program and analyze its behaviors. Avrora is a WSN simulator with cycle accurate execution times. Avrora provides a framework for simulating and analyzing assembly codes written for AVR microcontrollers on sensor nodes [8, 9]. The framework allows users to add monitoring code to the simulation to collect information on program execution, which information can be used for program analysis. Because the collection is at instruction level, the information can be very precise and detailed. Although Avrora has provided a few profiling utilities that can be directly used to study program behaviors, more profiling tools have to be developed to achieve various profiling goals.

This paper presents a general program analysis approach for TinyOS applications. The approach first identifies the features of user-concerned instructions in the disassemble code. Next, based on the identified features, the approach observes and analyzes the instructions' executions over Avrora. In the first phase, the approach uses GNU Binutils [10] package to obtain the disassemble information of object files, which are performed over AVR target platform. The package contains such binary tools as avr-objdump for manipulating object files.

The rest of this paper is organized as follows: Section 2 outlines the dynamic analysis approach. Section 3 illustrates how to analyze dumped files. Section 4 shows how to investigate the execution of the program under analysis. The final section concludes our argument.

2. Outline of Approach

We propose a general program analysis approach based on the binary dump tool, avr-objdump [11], and the instruction-level simulator, Avrora. By utilizing avr-objdump, we can generate the assembler mnemonics for the machine instructions from the object file of a TinyOS program. By utilizing Avrora, we can run the assembler code and analyze the program behaviors at instruction-level. The approach consists of three steps as below.

(1) Use AVR-objdump tool to obtain the disassemble code for the target program under analysis.

The target binary code of the TinyOS program under analysis can be generated using nesC make system or using avr-gcc. The binary code is executable on the AVR target platform including the simulated ones. However, binary code is difficult for us to understand and to analyze. To inspect the contents of binary-code files, disassemblers can be invaluable. The simulator Avrora allows us to run and analyze the object program with disassembly information. Therefore, the first step of our program analysis is to generate the disassemble code from the target binary code of the TinyOS program under analysis. Because we focus on the AVR target platform, we utilize the binary tool, avr-objdump, to achieve this goal.

The file extension of the standard ELF object file format is .elf. The avr-objdump tool can be applied to ELF files. Assume that the object file is demo.elf, we can use the avr-objdump tool with the option –D to generate a file named demo.od. The file demo.od is executable over Avrora and contains the disassembly information dumped from the object file demo.elf.

(2) Analyze the dumped file (.od file) to identify the user-concerned instructions, and then create association between those instructions and their corresponding memory addresses.

Because a user is always concerned with multiple types of instructions, the identified information for each instruction involves both instruction type and such particular instruction information as instruction name.

(3) Investigate the execution of the dumped file.

Inspect the execution of the concerned instructions to perform program analysis, by utilizing Avrora instrumentation framework (API).

Next, we will present the approach with details and examples. Because first step above is easy to implement, we will dwell on the last two steps.

3. Analyze Dumped File

3.1. Identify User-concerned Instructions

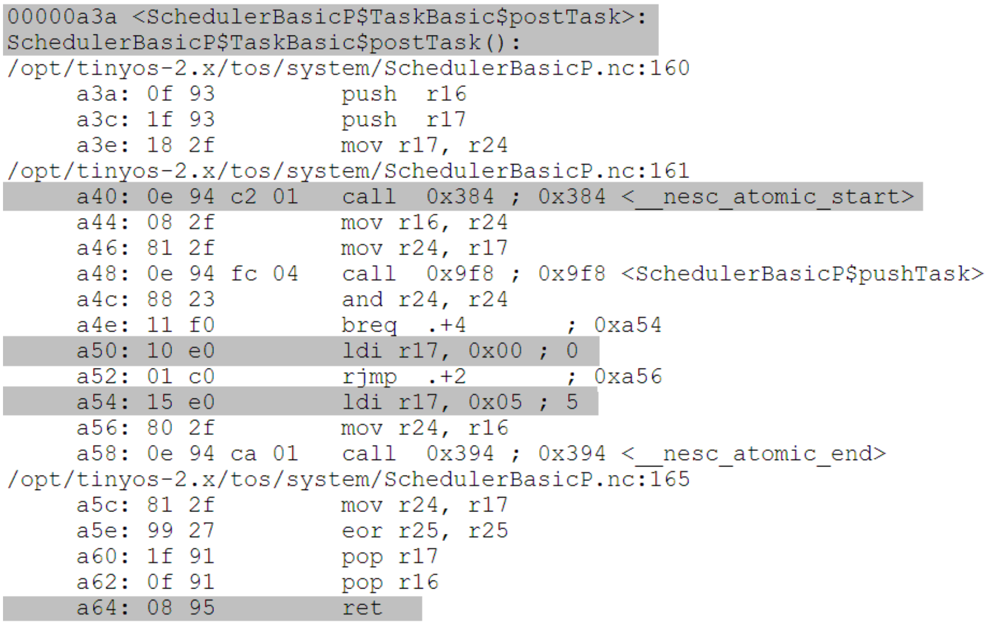
As in a standard ELF object file, in a dumped .od file, .text section contains the machine code of the compiled program. To identify all the user-concerned instructions, we need scan the whole .text section.

In the .text section of the dumped file, instructions are grouped in functions or in interrupt handlers. Because the code segments of two functions (or interrupt handlers) can never be overlapped, the segment of a function (or an interrupt handler) can be identified by finding its initial line and its final line. The lines mentioned above have the following characteristics, which enable us to make them out when scanning the dumped file.

(1) The initial line of a function (or an interrupt handler) starts with *00* and ends with *a pair of angle brackets*. The function name (or the interrupt number) is available both in the brackets and in the second line of the function (or the interrupt handler). For example, Fig. 1 illustrates the disassembly segment of the TinyOS postTask function in a dumped file (e.g. demo.od). The complete function name is *SchedulerBasicP.TaskBasic.postTask(),* where *SchedulerBasicP*, *TaskBasic* and *postTask* are TinyOS system component name, interface name and function name, respectively. Recall that when a nesC function is compiled to a C function, a function name and its corresponding component name and interface name are separated by the *$* character, as shown in the first line in Fig. 1. The OS postTask function attempts to put (i.e., post) a task into the system task queue. Fig. 2 shows the nesC source code of the OS postTask function.

(2) The last line of a function (or an interrupt handler) is actually its last instruction. For a function, the last instruction is *ret*, as the last line shows in Fig. 1. For an interrupt handler, the last instruction is *reti*.

In the .text section, each line containing machine code represents an instruction's information. Each such line is in the form of '*address: machine_instruction assembly_instruction ; comment*', where *address* is the memory address of the instruction, *machine_instruction* is the machine code in the form of a sequence of bytes, *assembly_instruction* is the text representation of the instruction generated by the disassemble tool (i.e., avr-objdump with option -D), and comment makes the disassemble code even more human-readable.



```
00000a3a <SchedulerBasicP$TaskBasic$postTask>:
SchedulerBasicP$TaskBasic$postTask():
/opt/tinyos-2.x/tos/system/SchedulerBasicP.nc:160
     a3a: 0f 93          push  r16
     a3c: 1f 93          push  r17
     a3e: 18 2f          mov r17, r24
/opt/tinyos-2.x/tos/system/SchedulerBasicP.nc:161
     a40: 0e 94 c2 01    call  0x384 ; 0x384 <__nesc_atomic_start>
     a44: 08 2f          mov r16, r24
     a46: 81 2f          mov r24, r17
     a48: 0e 94 fc 04    call  0x9f8 ; 0x9f8 <SchedulerBasicP$pushTask>
     a4c: 88 23          and r24, r24
     a4e: 11 f0          breq  .+4        ; 0xa54
     a50: 10 e0          ldi r17, 0x00 ; 0
     a52: 01 c0          rjmp  .+2        ; 0xa56
     a54: 15 e0          ldi r17, 0x05 ; 5
     a56: 80 2f          mov r24, r16
     a58: 0e 94 ca 01    call  0x394 ; 0x394 <__nesc_atomic_end>
/opt/tinyos-2.x/tos/system/SchedulerBasicP.nc:165
     a5c: 81 2f          mov r24, r17
     a5e: 99 27          eor r25, r25
     a60: 1f 91          pop r17
     a62: 0f 91          pop r16
     a64: 08 95          ret
```

Fig. 1. Disassembly code of TinyOS postTask function.

```
/*Return SUCCESS (0) if the post succeeded, EBUSY (5) if it was already posted. */
async command error_t TaskBasic.postTask[uint8_t id]() {
atomic {
return pushTask(id) ? SUCCESS : EBUSY;
}
}
```

Fig. 2. NesC source code of TinyOS postTask function.

The given goal of a user's program-analysis determines which instructions are concerned by the user. Therefore, the user-concerned instructions are different in various program-analyses. Sometimes, it is easy to identify the instructions, while in other cases, it is not.

(1) Some instructions are easy to identify because the disassembly information associates the instruction to its corresponding source explicitly. For example, in the third highlighted line of Fig. 1, the disassembled text string is '*call 0x384; 0x384 <__nesc_atomic_start>*'. It is easy to parse this string and get the following results: the instruction mentioned above is a call instruction and the invoked function's name is *__nesc_atomic_start()*.

(2) However, not all the disassembly information can directly associate an instruction in the object file to its exact source, especially when a source statement corresponds to multiple lines of object instructions. In this case, program-analysis requires more in-depth investigation of both the source code and the disassembly information. Next, we will illustrate it with an example.

Recall that a TinyOS program posts a task via a *post* statement. After compilation, the statement is converted into a C function *taskName$postTask()*, which calls the OS postTask function mentioned above. During program analysis, a user may concern whether or not a task-posting is successful. However, we cannot always get such information by tracing the return value of the function *taskName$postTask()*, because it is also valid to use *post()* without a return value. Our solution is to identify the key instructions in the OS postTask function and trace their executions, which instructions indicate a successful posting or a failed one. As Fig. 2 shows, OS postTask function attempts to push the task id to OS task queue by calling *pushTask()*: the return value of the invocation is *SUCCESS* (i.e., *0*) if the posting is successful, and *BUSY* (i.e., *5*) otherwise. By studying the disassembly code of the OS postTask function, we found the key instructions that can distinguish those two cases, namely the fourth and the fifth highlighted lines, respectively, shown in Fig. 1. Both key instructions above have fixed relative offsets in the OS postTask function. As shown in Fig. 1, within the OS postTask function, the relative offset of the instruction that denotes a successful posting is *0x16*, and the relative offset of the one that denotes a failed posting is *0x1a*. Therefore, based on identifying the entry of the OS postTask function, we can identify the key instructions that indicate whether or not a posting is successful.

3.2. Create Instruction-Address Association

When a user-concerned instruction is identified, the association between the instruction and its memory address need to be established. During the dynamic program-analysis, the program is executed instruction by instruction, and we monitor each instruction's execution. By utilizing the created association mentioned above, we can retrieve the current instruction's information from the current instruction's address. Because a user is always concerned with multiple types of instructions, the instruction's information retrieved contains both instruction type and particular information such as instruction name. For example, in Fig. 1, line 4 is a function-entry instruction, the instruction's information always involves the instruction type (e.g., *FuncEntry*) and the function name (i.e., *SchedulerBasicP.TaskBasic.postTask*).

To implement association between the concerned instructions and their corresponding addresses, a direct way is to utilize a list structure as below: to represent each concerned instruction, create a structure-type which consists of several fields for denoting instruction information and one field for instruction address; create a list-type whose elements are of this structure-type. During the identification process, as presented in Section 3.1, we put each identified instruction's information and address to the above list. To retrieve the instruction's information from an instruction's address, we need search the list mentioned above. This way to create and use associations is traditional and direct.

A more concise and more efficient way to the implementation is to utilize the *map* type. In a map, the *key-value* is generally used to uniquely identify the element, where the *mapped value* is some sort of value associated to this *key*. Therefore, the association between an instruction's address and its information can be created by mapping the instruction information (i.e., value) to the instruction address (i.e., key). Many popular programming languages, such as Java and C++, support the map type [12, 13]. For instance, in Java, we can utilize the class of *java.util.HashMap* for the implementation: use the method *put*(*instructionAdr, instructionInfo*) to associate the specified instruction information with the specified instruction address in a map, and use the method *get*(*instructionAdr*) to retrieve the instruction information to which the specified address is mapped.

4. Investigate the Execution

By utilizing the simulator Avrora, we can run a TinyOS program and investigate the execution at instruction-level. Although Avrora has provided several profiling options for basic profiling purpose, in most cases, we need develop our own tool for various program analyses, which are always complicated due to the particular user concerns. To serve this role, we need utilize the Avrora infrastructure [9] to develop our own tool to monitor and profile the execution of the program. The development of such a tool consists of two steps:

(1) Create a monitor and add it to the Avrora simulation. With the infrastructure of Avrora [9], we can write a subclass of the *avrora.monitors.MonitorFactory* class and Avrora can attach instrumentations to the Monitor.

(2) Add instrumentation to the program to collect user-concerned information during the simulation run and generate a resultant report. We can utilize such Avrora mechanisms as probes and watches to implement the instrumentation: Probes are used to observe specific instructions when they are fired; Watches are used to monitor specific data memory-addresses when they are accessed [9].

Suppose that we want to trace the execution of some types of instructions (e.g., function entry, function exit, successful posting and failed posting) and extract some concerned information from the instruction (e.g., the function name, the task name, and the instruction type), we can override the method *fireBefore()* or *fireAfter()* of the interface *Probe* exposed by Avrora. We can add a probe before (or after) the concerned types of instructions. The probe will fire before (or after) this instruction's execution and collect the concerned information from the instruction. If we want to trace the executions of several types of instructions at the same time, we can also insert a probe before (or after) every instruction, and perform the analysis as below:

(1) Get the instruction's type by utilizing the mapping from the instruction's address, which mapping has been created during the analysis of the dumped file, as described in Section 3.

(2) If the instruction type is not user-interested, we do nothing; otherwise, we get the concerned instruction information from the instruction's address, also by utilizing the previously-created mapping, as presented in Section 3.

5. Conclusions

We present a general framework for dynamic analysis of TinyOS programs. Based on a binary dump tool, we get the disassembly code of the program under analysis. By analyzing the dumped code, we create the associations between the concerned instructions and their memory addresses. By utilizing the instruction-level simulator Avrora, we run the program and study the program behaviors. The observation and analysis of the program execution is based on the associations created previously. The framework presented in this paper is promising to implement many program-analysis tools for sensor network programs.

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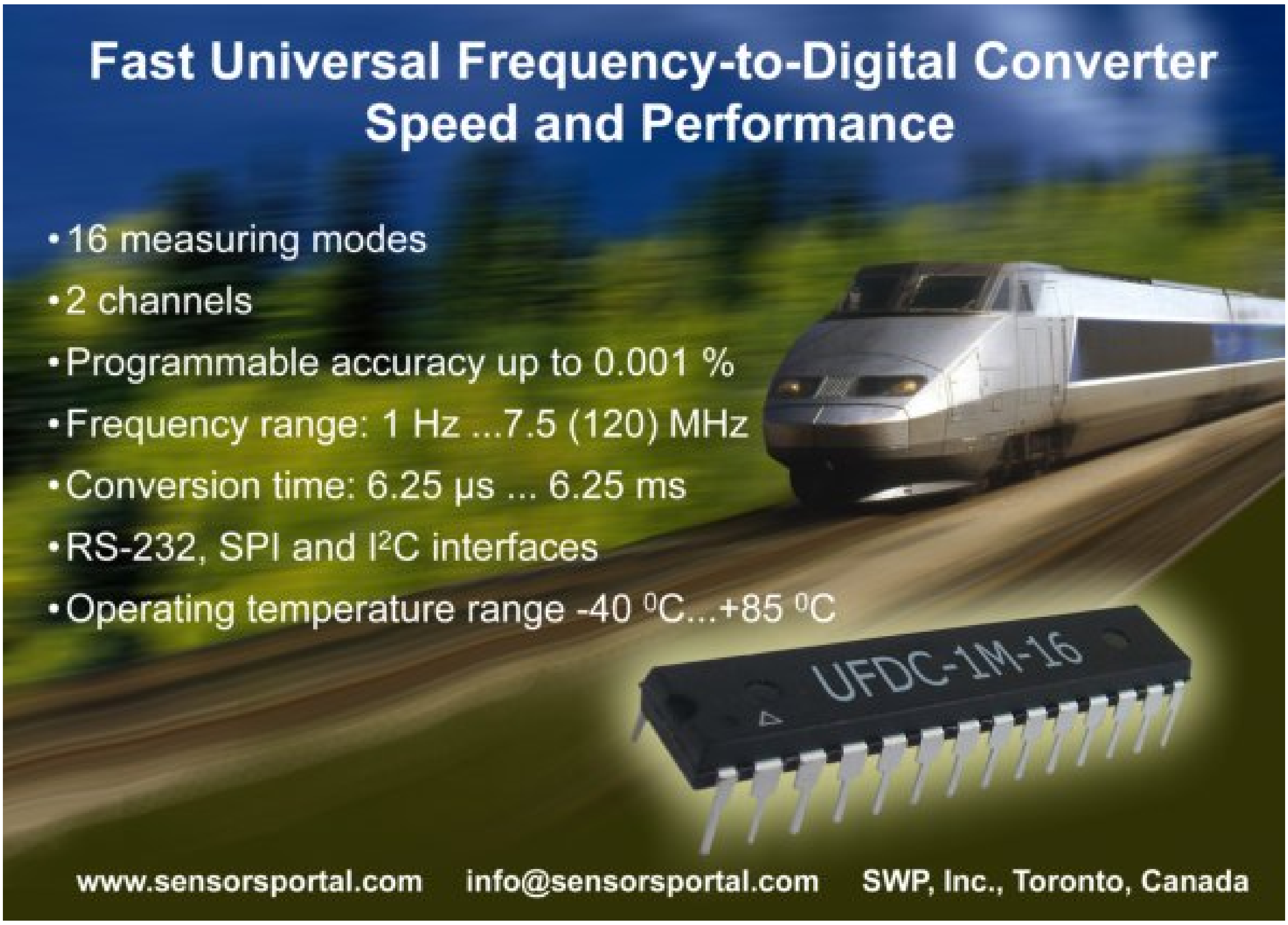

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