TINYHIVE: DYNAMIC VIRTUAL MACHINE FOR SENSOR NETWORKS

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TINYHIVE: DYNAMIC VIRTUAL MACHINE FOR

SENSOR NETWORKS

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TABLE OF CONTENTS

Chapter Page

I. INTRODUCTION 1

1.1 OUR CONTRIBUTIONS 4
1.2 OUTLINE OF THE THESIS 4

II. REVIEW OF LITERATURE 4

2.1 DELUGE 4
2.2 TINYDB 4
2.3 MATE 6
2.4 SWISSQM 7
2.5 SOS 8

III. METHODOLOGY 11

3.1 ARCHITECTURE 11
3.2 DATA STRUCTURES 16
3.3 MEMORY MANAGEMENT 18
3.4 INSTRUCTION SET ARCHITECTURE 19
3.5 VIRTUAL CODE INTERPRETER 26
3.6 DYNAMIC INSTRUCTIONS 26

IV. FINDINGS 30

4.1 INTRODUCTION 30
4.2 CASE STUDY 1: SIMPLE VIRTUAL APPLICATION 31
4.3 CASE STUDY 2: DYNAMIC INSTRUCTION 34
4.3 CASE STUDY 3: REAL WORLD EXAMPLE 35
4.5 ENERGY USAGE ANALYSIS 36

Chapter Page

V. CONCLUSION AND FUTURE WORK 38

REFERENCES 40

APPENDIX A: MANUAL 44

APPENDIX B: SOURCE CODES 46

LIST OF TABLES

Table Page

Table 1: List of instructions and its details 25

Table 2: List of instructions and its details 25

Table 3: Cost versus Flexibility 31

Table 4: Code and data footprint 32

Table 5: Native execution versus emulation 33

Table 6: TinyHive fetch decode overhead 33

Table 7: Dynamic instruction overhead 35

Table 8: Power Usage Comparison..37

LIST OF FIGURES

Figure Page

Fig 1: Transfer of queries and results 5

Fig 2: Mate architecture 6

Fig 3: SwissQM architecture 8

Fig 4: Linking and jump table layout in SOS 9

Fig 5: Architecture of TinyHive 12

Fig 6: Flowchart TinyHive 13

Fig 7: Flowchart of flow of code in TinyHive 14

Fig 8: Program memory layout 18

Fig 9: Instruction types and their sizes 19

Fig 11: Sample virtual program 20

Fig 12: Sample virtual program with dynamic instruction 27

Fig 13: Dynamic instruction Flow 28

CHAPTER I

INTRODUCTION

Sensor Networks are the collection of infrastructures that allow us to sense, record, analyze and respond to any natural or artificial phenomena. The sensor networks usually consists of electronic devices called motes. Those motes are usually tiny computer system typically consisting of processing, storing and some sensing capability. Their primary function is to sense the phenomena like temperature, soil composition etc. and storing the data and communicating. They usually work in a group and communicate using radio or other form of communication. Sensor networks are one of the important technologies for the future. They have a wide variety of implementations from military, medical, surveillance, robotics, industrial control etc.

Sensor networks run a small embedded operating system of their own. There are several of them like TinyOS [1], Contiki [12], SOS [11] etc. but among them TinyOS is the most popular and one of the first specifically designed for sensor networks. TinyOS was designed at University of California at Berkeley [1]. It was programmed using a programming language called Nesc which is an extension of C programming language. The user then writes an application for some special purpose and uploads the program in the mote. The program can be uploaded by writing on the ROM inside a mote which is

very expensive power wise. That means it uses a lot of power and if we update the program every now and then, its battery will be dead very soon. Another problem is sometimes the motes are at unreachable places like inside the wall of the building. In such cases, there is no easy way to update the software.

Virtual machine is a software representation of a computer system. It emulates all the functionalities of a specific hardware. Virtual machine is an efficient and isolated duplicate of a real machine [13]. They are very much popular today as they isolate the underlying hardware from the system software running on it. There are basically two types of virtual machine. They are system virtual machine and process virtual machine. The system virtual machine virtualizes the whole computer system like its I/O devices, memory, processors etc eg. Vmware [14]. The process virtual machine only virtualizes the process. eg. JAVA.

The virtual machines stated above are too resource hungry to run on motes. So, the researchers have come up with virtual machines for sensor networks. The idea is to write a middleware application which virtualizes the hardware and enables to write applications in a virtual code. Those virtual codes can be easily uploaded using the wireless network. They are all stored in memory instead of ROM which is expensive to write to. The virtual machine software is deployed to the motes by writing the entire code to the ROM. Now the application is written in a virtual code. Then it is deployed by either radio or connecting serially to the base station.

Several solutions has been provided so far including Mate [8], SwissQM [2]. But the problem with them is they cannot be easily extended when the need arises. So, this

research tries to make a virtual machine which is extendible. This enables the applications to extend the functionality without having to redeploy the whole system.

So, the finding of this research could be very helpful for the development of sensor network applications and its deployment.

1. OUR CONTRIBUTIONS

- The User will be able to define his own instruction and implement his own handler code for his instruction.
- It will make the applications more flexible and will be able to do things the traditional virtual machines could not.
- It will consume less power than deluge because it writes only a portion of code memory.

2. OUTLINE OF THE THESIS

- The introduction part introduces in brief the idea about sensor networks, virtual machines and its relationship.
- In the review of literature, we talk about the various systems that were created to make mote reprogramming more convenient. Those systems include Deluge, TinyDB, Mate, SwissQM and SOS.

- In the Methodology section, we talk about how the TinyHIve system is designed. It describes about architecture, data structures, memory management, instruction set architecture, virtual code interpreter and dynamic instructions.
- In the Findings section, we describe the three test cases we used to test the TinyHive system. We also present some code performance analysis.
- In the conclusion and future work section, we talk about the contributions of the TinyHive and also talk about how it can be improved.

CHAPTER II

REVIEW OF LITERATURE

The virtual machine for sensor network is a very promising topic. So, several works has been done in the field of virtual machine for sensor networks.

2.1. DELUGE

One of the earlier implementation was Deluge [5]. It is not a virtual machine but a middleware application that allows sending binaries using a wireless network. The deluge middleware receives the incoming network data and writes the new program to memory. Though this technique does not require us to be physically present for reprogramming, the overhead of reprogramming is still there. It just sends the application binary over the network but the reprogramming still has to be done. And that process takes a lot of power.

2.2. TINYDB

Another implementation that is designed to overcome the shortcoming mentioned above is TinyDB[7]. TinyDB makes possible to write a sensor network application in a form

SQL like queries. It views the sensor network as a big relational table. By using the queries, we can extract the sensor data as an output of the query. As the diagram below shows the query is done using a PC which is known as base-station. The query is first parsed and optimized so that the network transfer is minimal. The resulting query is then processed by the motes and the results are routed back to the base-station. This technique addresses the problem of reprogramming and physical presence. This technique is not dynamic. If we need to add a new query or feature, it has to be done in whole TinyDB. The figure below shows the flow of queries and data in the TinyDB.

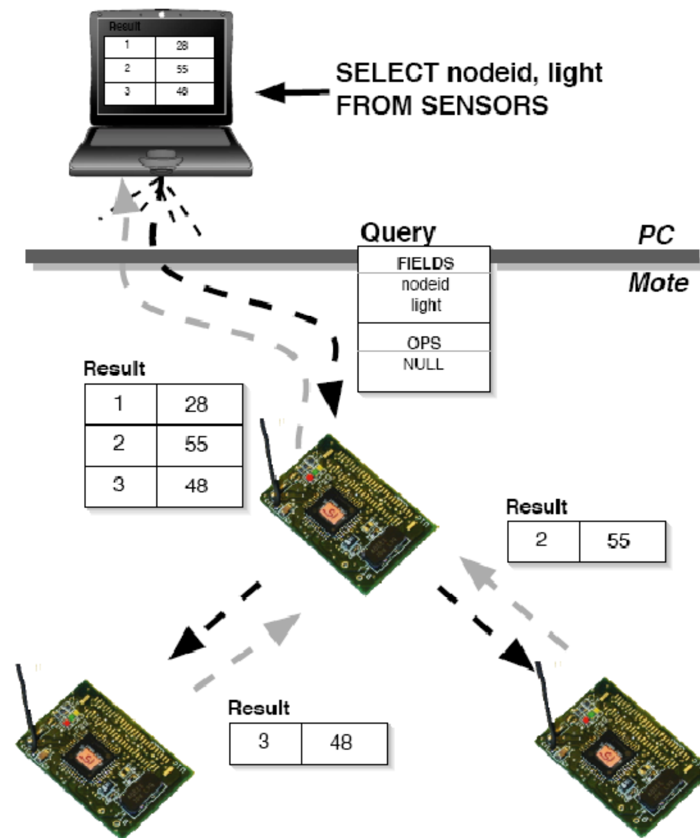


Fig 1: Transfer of queries and results [9]

2.3. MATE

One of the early virtual machines designed for sensor networks is mate [8]. Mate is a tiny Virtual machine designed especially for sensor networks. It's a ByteCode interpreter and runs on a top of TinyOS. It runs a special form of code called ByteCode. The virtual instructions are fed in fixed sized chunks called capsules which are 24 instructions in size. If any of the programs is larger, then it is divided into several capsules.

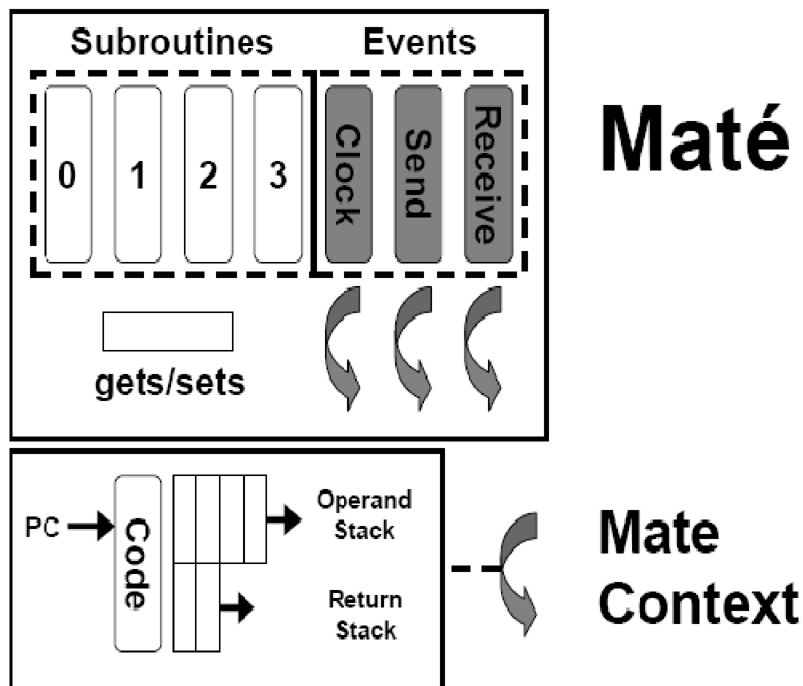


Fig 2: Mate architecture [8].

2.4. SWISSQM

Another important virtual machine for sensor networks is SwissQM [10]. SwissQM is a virtual machine that interprets the virtual code which is written in SwissQM ByteCode. The sensor nodes run the SwissQM program called Query machine. The query machine is a ByteCode interpreter that interprets the program written for SwissQm. The figure below shows the SwissQM architecture. SwissQM is a stack based virtual machine. It means all the operations are performed on the stack. There are no registers to store intermediate data. Besides the code interpreter, the SwissQM also contains the transmission buffer and the synopsis. The transmission buffer is the buffer used for transmission and reception of data. The synopsis is also a buffer but have two different modes of access.

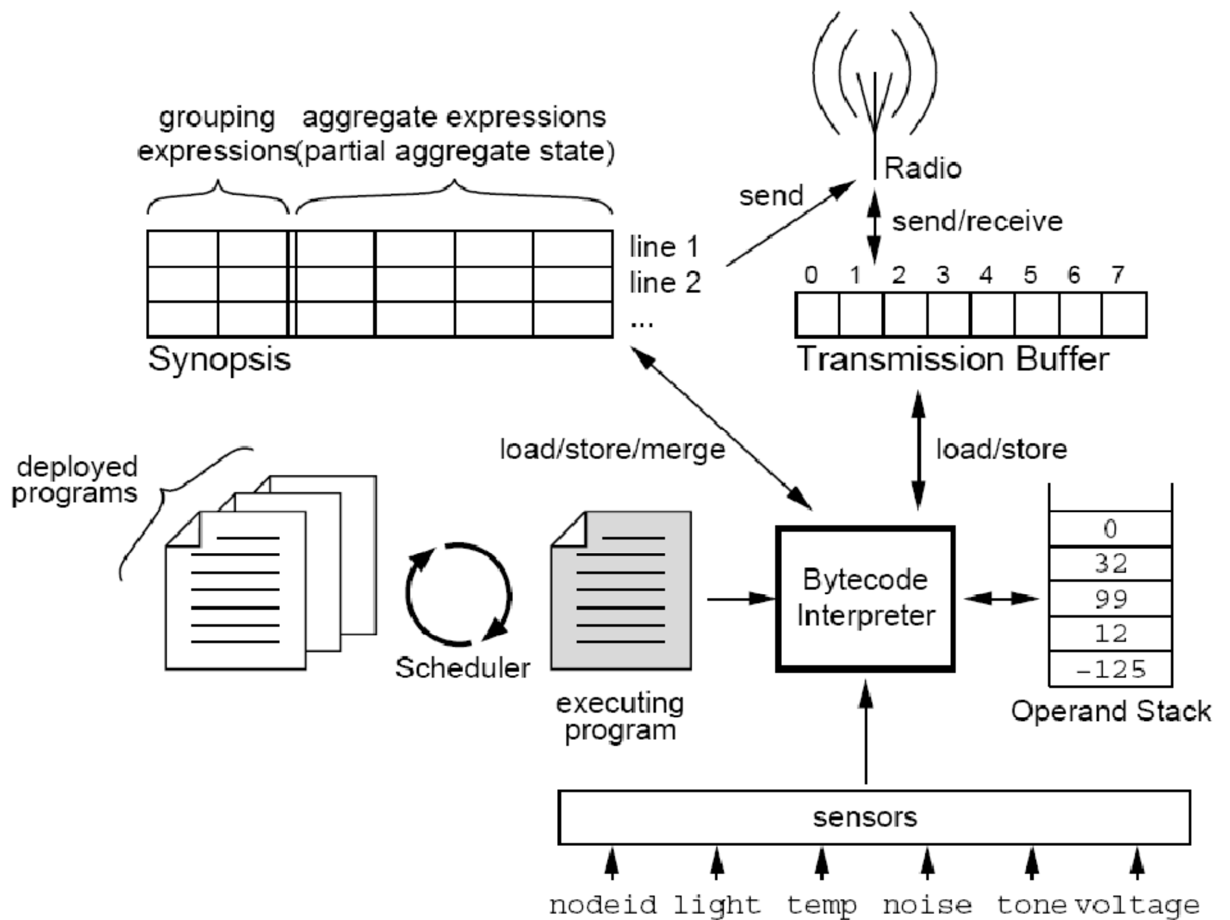


Fig 3: SwissQM architecture [10]

The SwissQM virtual machine also contains the gateway program. It runs on a base station and is also used to generate the ByteCode and feed the ByteCode to the motes.

2.5. SOS

SOS [11] is an operating system designed for sensor networks. It was written in C programming language. The main distinction of SOS from other sensor network based operating system is that it is dynamic in nature. It means the functionality of the operating system can be increased by using pluggable modules. The modules, which are written by users, can be deployed at runtime. This implementation closely resembles Microkernel architecture [15].

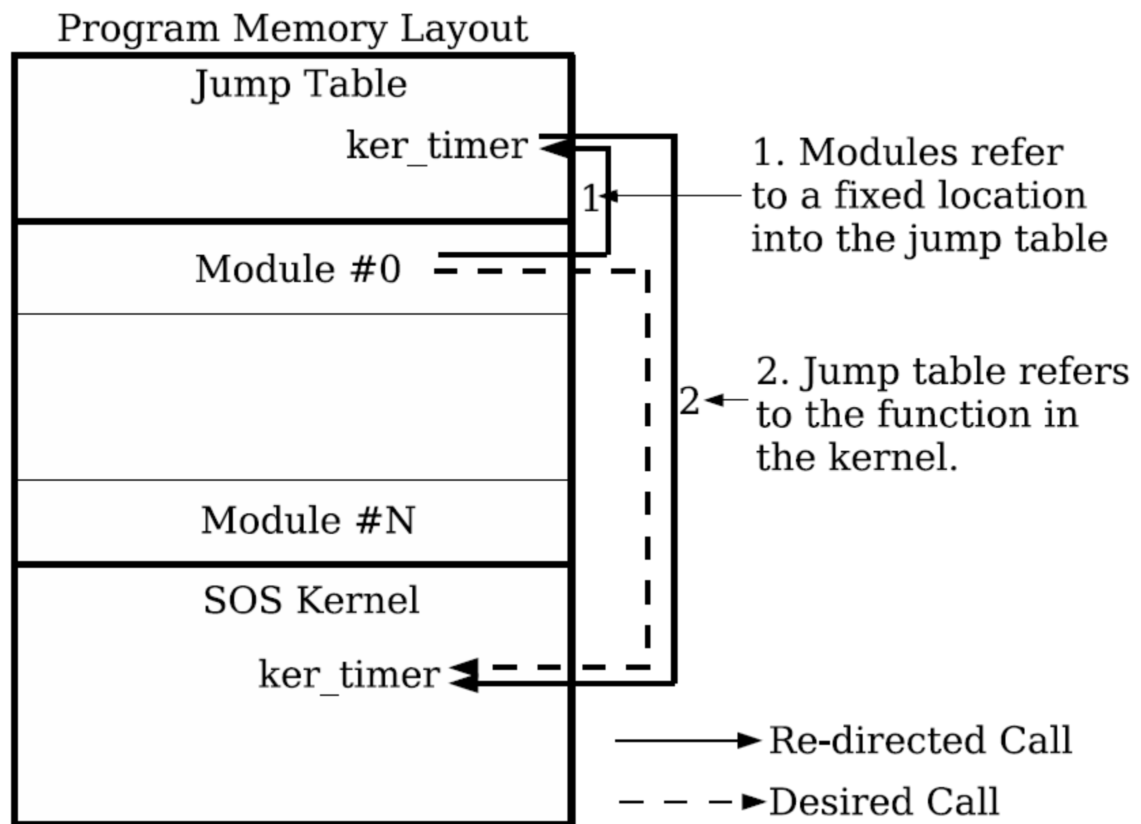


Fig 4: Linking and jump table layout in SOS [11]

Modules are the most important entity of the SOS system. They resembles component in tinyos but they are pluggable at runtime. Most of the operating system functionality is provided by the modules which are loaded later. The SOS operating system only provides the bare minimum functionality like low level resource management. The SOS only needs redeployment if there is a need to change in those low level codes. The modules interact with each other to achieve the functionality of an application.

CHAPTER III

METHODOLOGY

Virtual machine for sensor networks is becoming a very popular research topic these days. The research was started first by designing a very simple virtual machine. It was then further extended by implementing a feature of dynamic instructions where users can define and implement their own instruction set. This project shall now be referred as TinyHive. The main components of the TinyHive are Instruction sets, virtual code interpreter and memory manager.

3.1 ARCHITECTURE

The TinyHive Virtual machine consists of four basic components. They are Memory manager, virtual code interpreter, instruction set architecture and I/O manager. Those components interact with the TinyOS to use its services. The TinyOS further interacts with the hardware to achieve the functionality.

The Virtual program written in virtual code interacts with TinyHive through the instruction set architecture. The virtual instructions are then emulated or interpreted by the virtual code interpreter subsystem. The basic working of TinyHive can be demonstrated in the following figure.

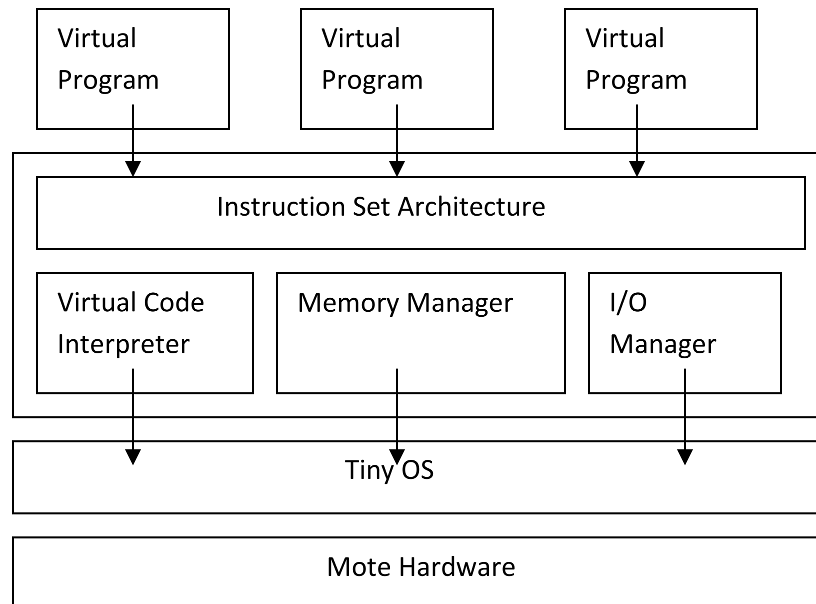


Fig 5: Architecture of TinyHive

As the above figure shows, the virtual program interacts with TinyHive which interacts with TinyOS and which interacts with the underlying hardware.

There are several ways to implement a virtual machine. One technique is to use the intermediate registers to hold the intermediate data and the other is to use the stack for the operands and intermediate data. The latter is called stack based virtual machine. TinyHive is a stack based virtual machine. All the operations are done in stack. There are no intermediate registers to store the results. For example to do a simple addition of

a = b + c, we do

Push b

Push c

Add

Pop a

The reason for using the stack based virtual machine is that it makes the code compact and we don't have to use separate instructions to move data to register and so on. So, the implementation of TinyHive consists of a dedicated stack space for instruction execution.

The flowchart below shows the flow of program in TinyHive.

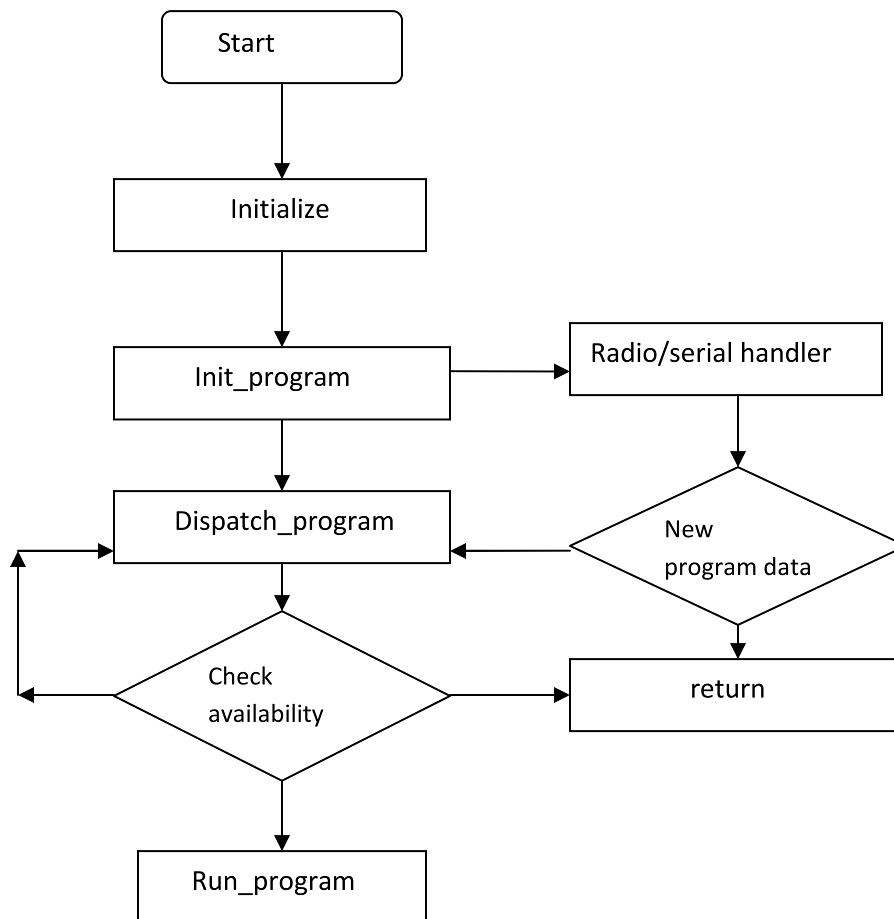


Fig 6: Flowchart TinyHive

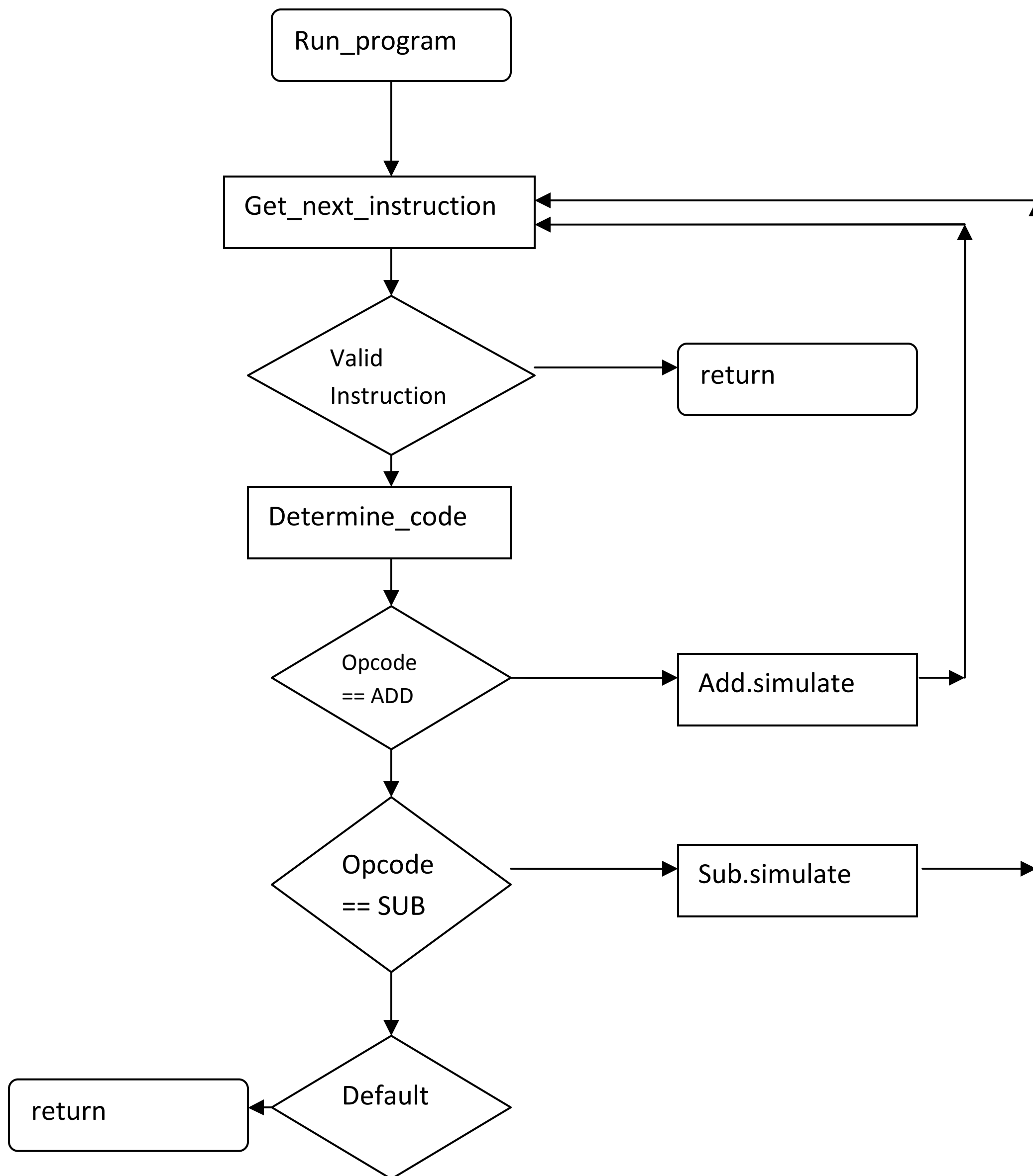


Fig 7: Flowchart of flow of code in TinyHive

The flow of the program starts from the initialize function. The handle is given to the TinyHive after the usual TinyOS Bootstrap. That function is called “initialize”. That function initialized all the global data into 0. Then it calls init_program which initializes

the stack and memory for program. Then dispatch_program is called, which checks if there are any virtual program loaded in memory. If it finds the program, then it calls the run_program function. It gets the virtual instruction one by one and executes it. The instruction with opcode 0x00 is considered as the end of program. If it encounters instruction not defined it is considered illegal instruction and is terminated. The program waits in the loop until another program is found. The programs are uploaded using radio or serial communication. The handler for radio and serial loads the incoming program into the memory and its returns. The dispatch_program detects it and runs the new program.

Besides the normal instructions, there a special instruction called the “dyninst”. It’s a dynamic instruction. The purpose of the instruction is to create a new user defined instruction which can later be used by other applications. A typical example of this is a customized mote hardware which is customized to get soil sensor data. If the user application has to run in a virtual machine environment, there is no virtual instruction to read the sensor data. In TinyHive, the developer can add a new instruction that reads the sensor data. All other applications can then use that instruction. To accomplish this behavior, the “dyninst” instruction should be able to upload the machine instruction to accomplish that behavior and store it in program memory so that in can be run. So the handler of the instruction should be able to find the free space in the program memory and write the handler code to that space. TinyHive should also keep track of the new virtual instructions added and its location, size, etc.

Now when the newly created instruction is used by the virtual application, the tinyhive interpreter determines it as a dynamic instruction and jumps the program to the location

where its code was written in program memory. After the code is executed it returns back.

3.2 DATA STRUCTURES

There are some important data structures used in TinyHive. All the structures are statically allocated. There is no dynamic allocation. The first structure is the stack structure. It is used to store the runtime stack values of the program. The size of stack is fixed. It is implemented as

```
typedef struct stack {
        nx_uint8_t top;
        nx_uint16_t data[16];
} stack_t;
```

Another important structure is the context structure. It is used to store the context of currently running virtual program. It is implemented as

```
typedef struct context {
        stack_t stk;
        nx_uint16_t PC;
        bool zflag;
        struct program *pg;
```

```
} context_t;
```

Another important structure is the program structure. It holds all the virtual code of the virtual program together with context and all necessary flags. Each program has its own program structure. It is implemented as

```
typedef struct program {
        nx_uint8_t isfree;
        context_t ctx;
        nx_uint8_t pdata[MAX_PROGRAM_SIZE];
}program_t;
```

Besides these data structures, there are few global flags and variables that is used to control the program flow.

```
typedef struct dyn_instr {
        nx_uint8_t opcode, size;
        bool free;
        handler_t handler;
} dyn_instr_t;
typedef struct dyn_table {
        struct dyn_instr dyn_instr[MAX_DYN];
```

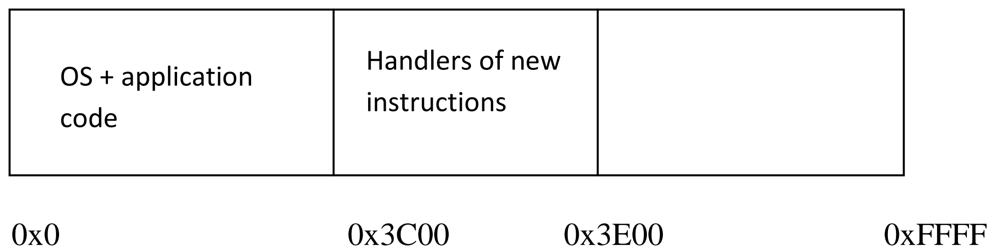
} dyn_table_t;

The dyn_table data structure is used to store the information about the new instructions that are dynamically loaded. The total number of new instructions supported is determined by MAX_DYN. Each new instruction has its opcode, handler size and the function pointer to the handler of the function.

3.3 MEMORY MANAGEMENT

Memory management is a very important component of any program. It is further important in sensor networks which have limited memory. The dynamic memory management is not available in TinyOS so all memory is statically allocated and managed. All the data structures mentioned above are stored in ram. So, it has a dedicated memory of holding 4 different virtual programs which has a maximum size of 128 bytes.

The dynamic instruction uses the flash memory to store the data structure and program memory to store the hander binary.



0x0 0x3C00 0x3E00 0xFFFF

Fig 8: Program memory layout

3.4 INSTRUCTION SET ARCHITECTURE

Instruction sets are the bases of all computer systems. The virtual machine also resembles a physical computer system. So it must have its own instruction set.

The instructions in instruction set architecture of TinyHive are variable in length. There are basically three types. They are:

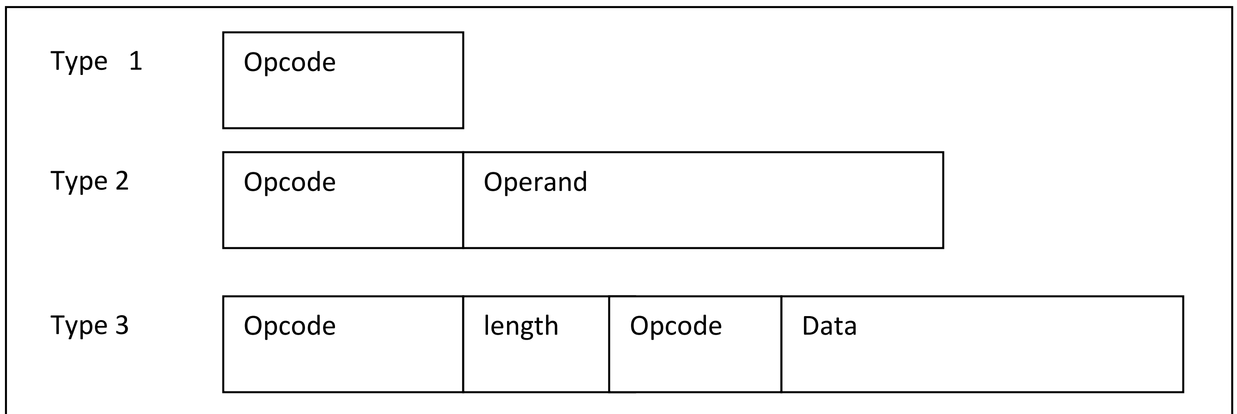


Fig 9: Instruction types and their sizes

Type 1: They are single byte in length and do not require an operand. Most of the instructions fall in this category. The instructions like add, sub, mul etc. are in this category.

Type 2: They are 3 bytes in length and have a 2 byte operand. The instructions like push and pop fall under this category.

Type 3: This is a special type and is only used for dynamic instruction. They are multiple bytes in length and is of variable length. The first byte is opcode. The second byte is the length of the data and the third byte is the opcode of the new instruction to be created.

The rest of the bytes are the machine codes that are to be executed as the microcode of the newly created instruction.

There are only a couple of instructions that have operands and they are push, pop and dyninst. Other instructions do not require the operands because all the operands are available in the stack through the push and pop instructions. The instruction set and thus the program is fed to the interpreter in its binary form. This makes the program compact and easy to process. The current implement encodes the instruction in an 8 bit (1 byte) value and the operand as a 16 bit value except for dyninst for which operand is multibyte. So the binary program consists of an array of 1 byte and 3 bytes data. The interpreter determines whether the next byte is an instruction or operand by looking at the instruction. The instructions have specific numbers it matches the numbers and finds out if it has an operand or not. The typical program for the instruction below is

Push 4

Push 5

Add

Pop a (a is a variable so in a program it's a location, say 100)

1	0	4	1	0	5	15	2	0	100

Fig 10: Sample virtual program

The instructions can further be divided into several types. They are divided according to what they do and what type of instructions they are. They are:

- Arithmetic Instructions:

This class of instructions does the arithmetic operations like addition, subtraction, logical or, etc. All the instructions that fall in this category are type 1 i.e. they don't have operands.

The instructions that fall in this category are:

  - Add: It adds two values in the top of the stack. The result is then stored at the top of the stack. It is identified by the opcode binary value of 0x0F.
  - Sub: It subtracts two values in the top of the stack. The second value on the top is subtracted from the first value. The result is then stored at the top of the stack. It is identified by the binary value of 0x10.
  - Mul: It multiplies two values in the top of the stack. The result is then stored at the top of the stack. It is identified by the binary value of 0x11.
  - Div: It divides the second value on the top of the stack with the top value. The result is then stored at the top of the stack. It is identified by the binary value of 0x12.
  - Inc: It increments the value in the top of the stack. It is identified by the binary value of 0x15.
  - Dec: It decrements the value in the top of the stack. It is identified by the binary value of 0x16.

- Logical Instructions:

This category of instructions do the logical operations like “and” and “or”. These instructions also don’t need operands as the operands are taken from stack. The instructions that fall in this category are:

    - And: It does the logical and between the two values in the top of the stack. The result is then stored at the top of the stack. It is identified by the binary value of 0x13.
    - Or: It does the logical or between the two values in the top of the stack. The result is then stored at the top of the stack. It is identified by the binary value of 0x14.

- Stack Instructions:

This category of instructions does the stack operations like push and pop. They fall under the type 2 instruction set i.e. they have a 16 bit operand. The instructions in this category are:

    - Push: This instruction has an operand. It pushes the value in the operand to the top of the stack. It is identified by the binary value of 0x01.
    - Pop: This instruction also has an operand. It pops the value in the top of the stack to the location determined by the operand. It is identified by the binary value of 0x02.

- I/O Instructions

This class of instruction does the Input/ output operations. Currently there is only one instruction which is the sense instruction. This category does not have operands. The instructions are:

- Sense: This instruction is used to read the sensor data. The sensor to read is determined by the value on the top of the stack. The result is then stored at the top of the stack. It is identified by the binary value of 0x17.

- Dynamic Instruction

This is a special instruction which enable the dynamic feature on the TinyHive. This instruction has multibyte operand. The first byte is opcode. The second byte is the length of the data and the third byte is the opcode of the new instruction to be created. The rest of the bytes are the machine codes that are to be executed as the microcode of the newly created instruction. The maximum length of the handler instruction can be 128 bytes. The following table shows the list of instructions in TinyHive and its opcode values:

	Opcode Value	Operand length (if available)	description
Nop	0x00	N/A	Null instruction; end of program
push	0x01	2 bytes	Push the operand into the stack
pop	0x02	2 bytes	Pop the data from the stack
add	0x0F	N/A	Add the contents of the stack

sub	0x10	N/A	Subtract the contents of stack
mul	0x11	N/A	Multiply the contents of the stack
div	0x12	N/A	Divide the contents of the stack
and	0x13	N/A	Logical and of the contents of the stack
or	0x14	N/A	Logical or of the contents of the stack
inc	0x15	N/A	Increment of the value of the topmost stack
dec	0x16	N/A	Decrement the value of the topmost stack
sense	0x17	N/A	Read the sensor value defined by the topmost stack value. Another table defines those values
cmp	0x18	2 bytes	Compare the values in operand and stack top and set the zero flag accordingly.
jmp	0x19	2 bytes	Jump to the code location pointed by operand
jz	0x1A	2 bytes	Jump to the code location

			pointed by operand if Zero flag is set.
dinst	0x1B	variable	The instruction to load the user defined instruction and its handler
(other user created instructions)	0xF0-0xFF	N/A	User defined instructions

Table 1: List of instructions and its details

The “sense” instruction depends on a value to determine what sensor to read from. It is first pushed to the stack. The following table shows those values.

Sense Values	Sensor to read from
0x01	Light Sensor
0x02	Temperature
0x03	Humidity
0x04	Voltage

Table 2: List of values for “sense” instruction

3.5 VIRTUAL CODE INTERPRETER

This is the important component of the TinyHive system. This component does the work of interpretation and emulation of all the instructions. When the program runs the opcode is interpreted by it one by one. By seeing the value of the opcode it determines which emulation function to run. For eg: If it finds the opcode as 0x0F, it determines that the function to run is the add.simulate(). The detection is done by the switch statement.

The scheduling of the task is non-preemptive. So, the virtual program runs until the task is over. The scheduling is on a first come first served (FCFS) basis. The VM just waits on a loop until a virtual task is available to run.

3.6 DYNAMIC INSTRUCTION

The purpose of the research is to make the virtual machine dynamic. Using this technique, the user can add a custom instruction or procedure and deploy it at runtime. This addition can then be later used by other virtual programs.

A similar type of feature has been implemented in an Operating system for Sensor network called SOS [11]. In this operating system a module can be deployed at runtime and other tasks can use its functions. This has made the SOS operating system very dynamic. The idea is to use the similar feature for a TinyHive virtual machine.

The idea is to implement an instruction that uploads a procedure or a set of instructions into the code memory. Now when the virtual program tries to execute the opcode of the newly added virtual instruction, the code block is executed. The virtual machine stores a

set of function pointers (location of added code). So when that virtual code is encountered, the code block is run. We call that instruction dyninst. For the gateway program, the program which is responsible for loading of virtual instructions to mote, its operand is a memory location of the procedure in the binary form. So, the loader program (gateway) just sends the opcode for dyninst followed by length in bytes of the procedure followed by the binary code.

The sequence of binaries for the “dyninst” instruction is similar to the fig below.

25	8	0xF0	23	21	12	54	8	6	0

Opcode length new opcode binary codes in machine language

Fig 11: Sample virtual program with dynamic instruction

The implementation of the dynamic instruction capability involved writing a little portion of the code in the program memory and storing each new instructions code handler location. TinyHive reserves a small portion of code memory to store the new instructions code. The total number of new instruction supported by tinyHive is fixed and is determined by the MAX_DYN macro. When the virtual code interpreter finds the dyninst instruction, it looks if the max number of new instruction is reached. If there is a slot available, it stores the information like start address, opcode and size and uploads the data to the program memory. The following flowchart describes how

Now when the new instruction is encountered in the virtual code, it searches the table to see if the instruction is new instruction or an invalid instruction. If it finds the instruction in the table, it jumps to the handler of that new instruction. The handler of the instruction must contain the machine instruction that returns to the caller. The typical example in

most architecture is the ret instruction. The following flow shows the working of the dynamic instruction.

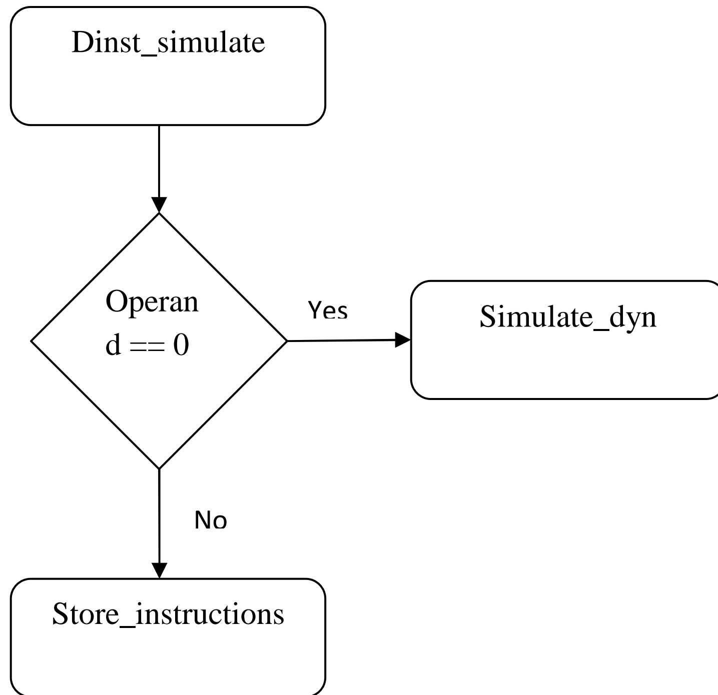


Fig 13: Dynamic instruction Flow

The implementation includes a small portion of an architecture dependent code. The use of the architecture dependent code could not be avoided because of the flowing reasons. Firstly, TinyOS did does not have any interfaces to write to the program flash. So, the architecture dependent code to write in the program flash was written. Secondly, there was no architecture independent way to call the program memory address without using the assembly. For now dynamic instruction is only implemented for the motes that uses

the AVR cpu. Those motes include micaZ, mica2 and IRIS motes. All the architecture dependent codes are written in a file called avr.c. There are two functions, one to write in the flash memory and another to jump to flash memory location where the handler is stored.

CHAPTER IV

FINDINGS

4.1 INTRODUCTION

The purpose of the research is to make the virtual machine dynamic. Using this technique, the user can add a custom instruction or procedure and deploy it at runtime. This addition can than be later used by other virtual programs.

A similar type of feature has been implemented in an Operating system for Sensor network called SOS [11]. In this operating system a module can be deployed at runtime and other tasks can use its functions. This has made the SOS operating system very dynamic. The idea is to use the similar feature for a TinyHive virtual machine.

The idea is to implement a instruction that uploads a procedure or a set of instructions into the code memory. Now when the virtual program tries to execute the opcode of the newly added virtual instruction, the code block is executed. The virtual machine stores a set of function pointers (location of added code). So when that virtual code is encountered, the code block is run. For now I have called that instruction dyninst. For the gateway program, the program which is responsible for loading of virtual instructions to mote, its operand is a memory location of the procedure in the binary form. So, the loader

program (gateway) just sends the opcode for dyninst followed by length in bytes of the procedure followed by the binary code.

So, this technique will make the sensor platform more dynamic. This will enable the user to write a new instruction and load it so that other applications can easily use it. So this means that the feature has added flexibility to the platform. The table below shows the cost versus flexibility comparisons.

Method	**Flexibility**	**Cost**
Bytecode	Medium	Low
New Binary	Very High	Very High
TinyHive	High	Medium

Table 3: Cost versus Flexibility

To demonstrate the flexibility and to do the performance analysis, two test cases have been created.

4.2 CASE STUDY 1

The first case study is created to show the simple working of a virtual machine. The results from this case study are used to analyze the performance of the virtual machine without the use of dynamic instruction.

For this case study, a very simple virtual application is written. It uses some of the simple instructions implemented by TinyHive. The program is written as:

Push 0x05

Push 0x04

Add

Push 0x02

Mul

Sense 0x01

The instructions above just do some additions, multiplications and get the light sensor data. The table below shows the size of the overall TinyHive code and compares it with other virtual machines.

	Code (ROM) bytes	Data (RAM) bytes
Mate	16044	849
SwissQM	33000	3000
SOS	20464	2699
TinyOS with Deluge	21132	597
TinyHive	12084	1242

Table 4: Code and data footprint [11]

One of the side effects of a virtual machine is that the instruction is always slower than the native instructions. Let us take an example of a simple and instruction, in micaz hardware, it is just few cycles. But in a virtual machine, it needs to be emulated and needs several memory access. So, it takes far more cycles in virtual machine. The table below shows the comparison of the clock cycle taken for native execution and interpretation by TinyHive. It does not take into consideration the fetching and decoding of instruction in TinyHive.

	TinyHive	Native
Add	314	1
Push	174	2

Table 5: Native execution versus emulation

Another overhead in a virtual machine is that it needs to do a lot of work for fetch and decode cycles. In order to fetch the code, the program needs to access the memory where the virtual program is stored. In order to decode the instruction, it needs to check the instructions it supports and compare it. The table below shows the clock cycle needed for the fetch and decodes cycles in TinyHive.

	Clock Cycles
Fetch	28
Decode	37

Table 6: TinyHive fetch decode overhead

4.3 CASE STUDY 2

The next case study is a simple test program to demonstrate how to use the dynamic instruction and how to write a handler. In this test case the handler contains a minimal code which must be present in every handler. That code is the “ret” instruction. This instruction is used to return to code which called this handler. In case of TinyHive, the execution is returned to the interpreter which interpreted the new user created instruction.

In this simple test, a few mandatory instructions were only used. They are:

(i) dyninst: the dynamic instruction used to define the new instruction.

(ii) New instruction: the newly defined instruction itself.

(iii) Ret: the return instruction which is in the data section of the dyninst instruction.

Eg. Code:

```
Dyninst 0x02F09508

// here 0x02 = length of handler

// 0xF0 = opcode of the newly created instruction

// 0x95 0x08 = machine instruction for AVR instruction ret

0xF0

// execute the instruction
```

Firstly, the dyninst instruction loads the handler in the program memory and later the newly created instruction is executed.

4.4 CASE STUDY 3

In the next case study, we implement a test program which is used get the soil moisture sensor data. In this case study we demonstrate how we can use other customized sensors which are not supported by other virtual machines. This is a real world example where the TinyHive could be used.

A small program is written to get the sensor data from a soil moisture sensor. In order to get a soil moisture data, we create a new instruction called "get_moist". We first upload the handler to that instruction and then later call that instruction to get the data. The handler is written in a native code to the AVR processor. The virtual application is written using a TinyHive instruction set.

The initial part of the code dynamically installs the code into the TinyHive system. And the latter part executes that newly created instruction. The result will be in the stack. The following table shows the total cycles required for upload. The numbers are dependent on the size of the handler code.

	Load (cycles)	Execution (cycles)
Case study 2 application	2600	162

Table 7: Dynamic instruction overhead

4.4 ENERGY USAGE ANALYSIS

One of the other most important benefits of virtual machine is the energy usage while reprogramming. On a system without virtual machine there are only two ways to reprogram the mot. One is to physically access the mote which might not be feasible. Another option is to use middleware application like Deluge. The Deluge middleware application receives the whole binary through radio and writes the whole program in the flash. Writing in a flash memory is expensive as it used a lot of power.

On a system with a virtual machine it does not need to write in program memory but it not flexible. In TinyHIve, a new instructed can be added whose handler in written in program memory. Since the handler is very small compared to the whole binary, it consumes less power than deluge. In ATMega128, we can only write one page at a time which is 256 bytes. The energy required to write 1 page is 0.31 mJ [11]. In this analysis, the power used to transmit the code and execute the code is not taken into consideration. The power only required to write the program memory is considered because the design of TinyHive improves power usage while handler is written in program memory.

The following table shows the energy usage while writing to the program memory.

System	Bytes to load (typical program size)	Write cost per page (mJ)	Total cost (mJ)
SwissQM	46	0	0
Mate	46	0	0
Tinyos (through deluge)	21132	0.31	25.58
TinyHive	128	0.31	0.31

Table 8: Power Usage Comparison

CHAPTER V

CONCLUSION

Virtual machine for sensor network is becoming a very popular topic these days. One of the main benefits of a virtual machine is the flexibility it provides. Though, this flexibility comes with a tradeoff of execution cost. But the flexibility it provides is far more than the execution cost.

The developers started thinking about making sensor network application more flexible by first designing systems like deluge. Deluge made the system flexible but it had major power cost involved. Later, the virtual machines were developed for sensor networks. The virtual machines like Mate and SwissQM had the ability to send a new program through radio. But those programs's functionality was limited by the instruction set they provided.

So, this research has come up with a technique which enables the expansion of functionality of a virtual machine. This is achieved by adding the ability to add a user defined instruction. The user can write the handler according to the needs of his application. The handler is written in a native code executed by the underlying micro-controller. This makes the virtual machine very dynamic. The working of this functionality is shown by two use cases described in results section.

The first test case shows how one can write an application using TinyHive instructions. The second test case shows how one can define his own instruction which does a specific job which is not possible without that feature. As an example soil moisture sensor is used for this purpose. The results show that though the virtual programs take more CPU cycles than native instructions, they are much more flexible. From the results we can see that, TinyHive is more flexible than regular virtual machines like mate and SwissQM. It can also be seen from the results section that it consumes less power than having to write the whole program in flash.

So we can conclude that TinyHive is very flexible and dynamic. And it consumes less power even though it needs some program memory writes. There are also few problems with this system. One problem is that program memory can only be written 10,000 times. So this loading of new instruction has to be rare. Secondly, TinyHive is in the infant age of its development. So there is no easy way to write a handler function than to use a native instruction. Thus, TinyHive can help in creating more dynamic applications for sensor networks.

The TinyHive in currently in the infant stage and needs a lot of work. The following are the future work that can be either improved or implemented in TinyHive.

- A new GUI based gateway program can be implemented. It could load the TinyHive virtual application. In addition, it could also enable the user to write virtual applications in simple English.
- Another efficient way could be developed to write the handler of the new user created instruction.

- We can implement the radio code where there virtual applications can be transmitted through the radio.
- The size of the program can currently be as big as the maximum size of the packet. This can be extended by implementing the feature where 1 application can be sent using multiple packets.
- The instructions related to the use of radio and serial can be added. we can have send and receive instructions for both radio and serial.

These are some of the things that can be implemented in TinyHive as future work.

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APPPENDIX A: MANUAL

The Source code of the TinyHive is stored in a SVN server. We have created a repository for TinyHive project in SVN. The path to the project is https://www.cs.okstate.edu/svn/s3lab/tinyhive/. In order to check out the code, the user should use the command:

svn checkout https://www.cs.okstate.edu/svn/s3lab/tinyhive --username <your cs server username>

After checking out you can make the changes to the files. If you wish to commit the changes do svn commit -m "put your comment on what changes you made in short". Please make sure you fix all compile errors before committing.

Currently, the access is for Oklahoma State University Computer science students only.

In order to compile the code, the architecture dependent code needs to be compiled separately. It is written in C. It can be compiled as follows for MicaZ platforms (or any other platform that used AVR).

avr-gcc -c –mmcu=atmega128 avr.c

Then the remaining code can be compiled as:

Make micaz

Then it can be written to the mote as:

Make micaz reinstall mib520, <serial port>

where, serial port is the serial port name. In Linux, it is usually /dev/TTYUSB0. Mib520 is the board we used.

The files in the TinyOS code directory are:

S3vm.h

Avr.c

Arith.nc

Control.nc

Dyninst.nc

Makefile

S3vm.nc

S3vmapp.nc

S3vmc.nc

S3vmisa.nc

Sensor.nc

Serialcomm.nc

Stack.nc

Stackc.nc

Stackops.nc

APPENDIX B: SOME SOURCE CODES

1 Makefile:

```
COMPONENT=S3vmApp

CFLAGS += -I$(TOSDIR)/lib/printf

CFLAGS += -Wl,--section-start=.bootloader=0xF000

LDFLAGS += avr.o

include $(MAKERULES)
```

2. s3vm.h

```
#ifndef S3VM_H__

#define S3VM_H__

#define MAX_PROGRAM_SIZE     128

#define MAX_PROGRAMS         2

#define MAX_STACK            16

#define S3VM_BUSY            1

#define S3VM_FREE       0

#define PROTOCOL_ID_SER           9

#define INST_NULL 0
```

```
#define INST_PUSH 1
#define INST_POP 2
#define INST_LOAD 3
#define INST_STORE 4

#define INST_ADD 15
#define INST_SUB 16
#define INST_MUL 17
#define INST_DIV 18
#define INST_AND 19
#define INST_OR 20
#define INST_INC 21
#define INST_DEC 22

#define INST_SENSE 23
#define INST_CMP 24
#define INST_JMP 25
#define INST_JZ      26
#define INST_DYN 27
#define SENSOR_LIGHT            1
#define SENSOR_TEMPERATURE 2
#define SENSOR_HUMIDITY             3
#define SENSOR_VOLTAGE              4
#define MAX_DYN                 5
#define TOSBOOT_START           0x1E000
```

```
#define DYN_START                    (TOSBOOT_START - 1024)

typedef struct stack {
        nx_int8_t top;
        nx_uint16_t data[MAX_STACK];
} stack_t;
typedef struct context {
        stack_t stk;
        nx_uint16_t PC;
        bool zflag;
        struct program *pg;
} context_t;

typedef struct program {
        nx_uint8_t isfree;
        context_t ctx;
        nx_uint8_t pdata[MAX_PROGRAM_SIZE];
}program_t;

typedef struct dyn_instr {
        nx_uint8_t opcode, size;
        bool free;
        nx_uint32_t start;
} dyn_instr_t;
typedef struct dyn_table {
```

```
        struct dyn_instr dyn_instr[MAX_DYN];
} dyn_table_t;
extern int copy_to_flash(nx_uint32_t addr, nx_uint8_t *data, nx_uint8_t len);

#endif // S3VM_H__
```

3. avr.c

```
int BOOTLOADER_SECTION copy_to_flash(uint32_t addr, uint8_t *data, uint8_t len)
{
                uint16_t* instr = (uint16_t*)data;
                uint32_t i;
                uint8_t pgmdata, sreg;

                if ( addr + len > 0x1f000 )
                return 0;



                sreg = SREG;
                eeprom_busy_wait ();

                boot_page_erase( addr );

                while( boot_rww_busy() )
                        boot_rww_enable();
```

```
        for (i=0; i<SPM_PAGESIZE; i+=2)
    {
            boot_page_fill(addr + i, *instr++);
    }

        boot_page_write (addr);     // Store buffer in flash page.

        while ( boot_rww_busy() )
          boot_rww_enable();

        SREG = sreg;
        return 1;
    }
```

4. s3vmapp.nc

```
#include "printf.h"

#include "s3vm.h"



configuration S3vmApp {
    provides interface S3vmC;
}

implementation {
```

```
components MainC, s3vm, LedsC, StackC;
components new TimerMilliC() as Timer;
components new TimerMilliC() as Timer0;
components StackOps, arith, dyninst;
components SerialComm;
components SerialActiveMessageC as AM;

S3vmC = s3vm.S3vmC;
s3vm.Boot -> MainC;
s3vm.Stack -> StackC.Stack;

// Instructions
s3vm.S3vmISA[INST_PUSH] -> StackOps.push;
s3vm.S3vmISA[INST_POP] -> StackOps.pop;

s3vm.S3vmISA[INST_ADD] -> arith.add;
s3vm.S3vmISA[INST_SUB] -> arith.sub;
s3vm.S3vmISA[INST_MUL] -> arith.mul;
s3vm.S3vmISA[INST_DIV] -> arith.div;
s3vm.S3vmISA[INST_INC] -> arith.inc;
s3vm.S3vmISA[INST_DEC] -> arith.dec;
s3vm.S3vmISA[INST_AND] -> arith.and;
s3vm.S3vmISA[INST_OR] -> arith.or;

s3vm.S3vmISA[INST_DYN] -> dyninst.dinst;
```

```
    dyninst.Leds -> LedsC;
    StackOps.Stack -> StackC.Stack;
    arith.Stack -> StackC.Stack;
    SerialComm.Control -> AM;
    SerialComm.Receive -> AM.Receive[PROTOCOL_ID_SER];
    SerialComm.Timer -> Timer0;
    SerialComm.Packet -> AM;


    SerialComm.S3vmC -> s3vm.S3vmC;
}
```

VITA

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Scope and Method of Study: The scope of this study is to design and analyze a dynamic virtual machine. Virtual machines are becoming a popular area of research. One of the most important benefits from virtual machine is flexibility for redeployment. Though, this flexibility comes at a cost of slightly slow code. So far researchers have tried to create a static virtual machine. But they all have a common problem, dynamicity. This project creates a dynamic virtual machine called TinyHive. It enables the user to define his instruction and its handler. The user can write the handler according to the needs of his application. The handler is written in a native code executed by the underlying micro-controller. This makes the virtual machine very dynamic.

Findings and Conclusions: Through the use of test cases, we show that TinyHive can enable a virtual application to achieve which was not possible in traditional virtual machines. The user can define his instruction and its handler extending the scope of a virtual machine application. The study also shows that it is much cheaper power wise to write a handler in program memory than other systems like deluge. Thus TinyHive virtual machine can be used to create an application which is more dynamic and flexible than other virtual applications.

ADVISER’S APPROVAL: Dr. Xiaolin Li