

# Toward Fine-grained GPU Resource Management using Microcontrollers

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**Abstract**—Recent graphics processing units (GPUs) integrate wimpy microcontrollers on a chip. These microcontrollers are highly available to extend the functionality of GPU resource management, launching firmware code to control GPU executions and data transfers without accessing the host CPUs at all. In this paper, we develop a compiler and debugging environment for NVIDIA’s GPU microcontrollers in order to enhance the productivity of GPU firmware development. Our compiler is implemented using the well-known portable LLVM compiler infrastructure, while together providing a debugging subsystem that can individually execute firmware on the microcontroller. As a proof of concept, we develop fully-functional firmware using our compiler and debugging environment, and evaluate it using an NVIDIA’s graphics card. Experimental results demonstrate that the overhead of introducing our firmware is suppressed to within 2.3%, as compared to the native proprietary firmware. It is also identified that the impact of overhead is no greater than 0.01% of the total execution time of microbenchmark programs.

**Keywords**—GPGPU; LLVM; Microcontrollers

## I. INTRODUCTION

Graphics processing units (GPUs) are becoming more and more commonplace to support compute-intensive and data-parallel computing. In many application domains, GPU-accelerated systems provide significant performance gains over traditional multi-core CPU-based systems. As shown in Table I, the peak performance of the state-of-the-art GPUs exceeds 3,000 GFLOPS, integrating more than 1,500 cores on a chip, which is nearly equivalent of 19 times that of traditional microprocessors, such as Intel Core i7 series. Such a rapid growth of GPUs is due to recent advances in programming support, such as CUDA [1] and OpenCL [2], for general-purpose computing on GPUs, also known as GPGPU.

In recent years, real-time systems have been augmented with the GPU [3]–[8]. The motivation of using the GPU in real-time systems is mainly found in emerging applications of cyber-physical systems [9]–[11], where a large amount of data acquired from the physical world needs to be processed in real-time. Given that the workload of such applications is highly compute-intensive and data-parallel, many-core computing on the GPU is best suited to meet the real-fast requirements of computation. What is challenging in this line of work is to control the GPU under real-time constraints. The GPU is a coprocessor independent of the CPU, and

hence two different pieces of code are running concurrently on the GPU and the CPU, respectively. This heterogeneity poses a core challenge in resource management. Since the GPU is designed to accelerate particular workload, resource management functions are often performed on the CPU. In other words, the GPU and the CPU must be synchronized in some way to ensure timeliness. Unfortunately, this could be a major source of latency that makes real-time systems unpredictable [3], though the previous work are forced to take this approach due to a lack of functionality that enables resource management functions to offload on to the GPU. While compute cores or shaders on the GPU are not available to perform resource management, recent GPUs integrate microcontrollers on a chip where firmware code is launched to control the functional units of the GPU. These microcontrollers are highly available to extend the functionality of GPU resource management, launching special pieces of firmware code to control GPU executions and data transfers.

This paper presents a compiler and debugging environment for NVIDIA’s GPU microcontrollers based on the well-known portable LLVM compiler infrastructure. The main purpose of this environment is to enhance the productivity of GPU firmware development so that the community can facilitate future research on fine-grained GPU resource management using microcontrollers. Firmware is self-contained within the GPU, and there will be interference from background jobs running on the CPU, once it is uploaded by the device driver. Therefore, we believe that GPU computing would be more timely and reliable for real-time systems, if the firmware can support GPU resource management by itself. In this paper, we develop an initial stage of the firmware, and evaluate its basic performance.

The rest of this paper is organized as follows. Section I introduces the underlying platform technology. Section II describes the design and implementation of our compiler and debugging environment for NVIDIA’s GPU microcontrollers, and Section IV evaluates its basic performance. Related work are discussed in Section V. This paper is concluded in Section VI.

## II. PLATFORM TECHNOLOGY

First of all, we describe the platform technology underlying our development. We intensively focus on NVIDIA’s

Table I  
COMPARISON OF THE INTEL CPU ARCHITECTURES AND THE NVIDIA GPU ARCHITECTURES

	Core i7 980XE	Core i7 3960X	GeForce GTX285	GeForce GTX480	GeForce GTX680
# of processing cores	6	6	240	480	1536
Single-precision performance (GFLOPS)	108.0	158.4	933.0	1350.0	3090.0
Memory bandwidth (GB/sec)	37.55	51.2	159.0	177.0	192.2
Power consumption (watt)	130	278	183	250	195
Release date	2010/03	2011/11	2009/01	2010/04	2012/03

GPU architectures, while the idea of integrating GPU resource management into on-chip microcontrollers is not limited to these specific architectures. All pieces of technology presented herein are open-source, and may be downloaded from the corresponding websites, respectively.

#### A. Assembler for GPU microcontrollers

The assembler is comprised in package of the Envytools suite [12]. The Envytools suite is a rich set of open-source tools to compile or decompile GPU shader code, firmware code, macro code, and so on. It is also used to generate header files of GPU command definitions used by the device driver and the runtime library. There are many other useful tools and documentations for NVIDIA's GPU architectures enclosed in the Envytools suite.

#### B. GPU Device Driver

In general, the application programming interface (API) for the GPU is provided by the runtime library. GPU resource management, on the other hand, is often supported by the device driver and the operating system (OS) module [3], [13], [14]. As part of resource management, the device driver communicates with microcontrollers integrated on the GPU. The communication is typically managed by specific commands, which can be handled by firmware running on each microcontroller.

The firmware is built into the device driver by a shape of byte code, and is uploaded on to the GPU at boot time. To do so, we require open-source software, because we have to build the firmware into the device driver. In this paper, we use Gdev [13], an open-source module of the GPGPU device driver and runtime library.

#### C. LLVM Infrastructure

The LLVM (Low Level Virtual Machine) project is a collection of open-source modular and reusable compiler tool sets. Since the microcontroller has its own instruction set architecture, we develop an architecture-dependent backend of LLVM so that we can make use of all the front-end modules of LLVM.

Figure 1 illustrates the structure of LLVM. It first generates the LLVM IR (Intermediate Representation) from the source code. This IR code is assembled by the LLVM backend. The assembly code is finally translated to the object code for the target machine.

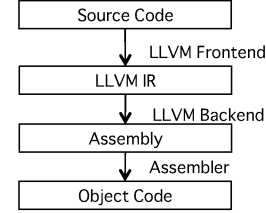


Figure 1. Compilation stages of LLVM.

1) *LLVM IR*: The LLVM IR is an intermediate language used in LLVM, also called bitcode or LLVM assembly languages. This intermediate language is very powerful, scalable, light-weight, and low-level enough to underlie many languages on top of many architectures. LLVM uses an expression of SSA (Static Single Assignment), which is suitable for a lot of compiler optimization algorithms.

2) *LLVM frontend*: The LLVM frontend generates an intermediate language from a high-level language in LLVM. It is mainly used for code generation and its optimization. In particular, we use Clang for our development, which is an open-source compiler for the C family of programming languages provided by LLVM.

3) *LLVM backend*: The LLVM backend generates target code from an intermediate language in LLVM. The backend of LLVM features a target-independent code generator that may create output for several types of target processors including X86, PowerPC, ARM, and SPARC. This backend framework may also be used to generate code targeted at accelerators such as Cell B/E and GPUs. In fact, NVIDIA has announced recently that they use LLVM for the basis of their CUDA compiler. The backend of LLVM is composed of the LLC (LLVM static Compiler) and the LLI (LLVM Interpreter). LLI is an interpreter of the LLVM IR, also available as a JIT compiler, while LLC is a static compiler to generate code. We use this backend part of LLVM to generate code targeted at NVIDIA's GPU microcontrollers.

### III. COMPILER AND DEBUGGING ENVIRONMENT

This section describes the design and implementation of our compiler and debugging environment for NVIDIA's GPU microcontrollers.

Table II  
SPECIFICATION OF GF100 MICROCONTROLLER.

Name	HUB	GPC
Number of units	1	4
Bit	32bit	32bit
Code size	16,384 byte	8,192 byte
Data size	4,096 byte	2,048 byte

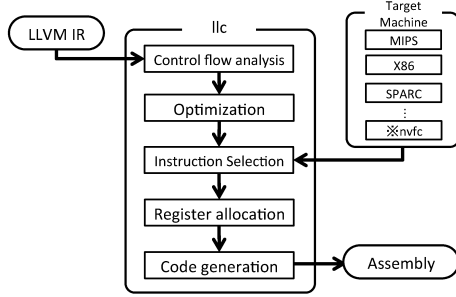


Figure 3. Code generation stages of LLVM.

#### A. Microcontroller

This paper presumes the microcontroller of NVIDIA’s Fermi architecture. In particular, we target the GeForce GTX 480 graphics card designed based on the GF100 architecture. In this architecture, a streaming multiprocessor (SM) consists of 32 CUDA cores, while a graphics processing cluster (GPC) consists of 4 SM’s. There are four GPC’s in total equipped in the GF100 architecture, and hence the maximum number of CUDA cores is 512.

Table II illustrates the specification of the GF100 microcontroller. There are two types of microcontrollers, HUB and GPC, relevant to CUDA engines. HUB is broadcasting the access to all GPC’s, while the GPC represents a specific microcontroller for each GPC engine. Since the maximum code size is limited to 16KB as indicated in Table II, developers should carefully design the firmware.

#### B. Compiler Implementation

Figure 2 shows an overview of our compiler implementation. The main flow of compilation is done by Clang. It generates the LLVM IR from the C source file. The LLVM next generates assembly code, which contains code and data in separate files. Finally, the Envytools outputs an executable file. This executable file can be launched by the device driver, and can also be tested by our debugging tool described in the later section. To summarize, our compiler takes the following stages:

- (1) Clang  
This is a frontend of C language that generates LLVM IR code from the source file.
- (2) LLVM with nvuc  
This is a backend of LLVM that compiles LLVM

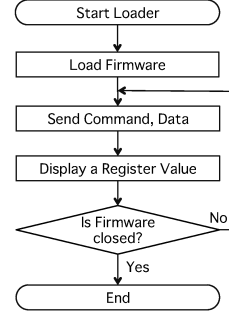


Figure 4. Flowchart of our debugging tool.

IR code into assembly code. As shown in Figure 3, there are five steps to exploit compilation: (i) flow analysis, (ii) optimization, (iii) instruction selection, (iv) register allocation, and (v) code generation. This flow is not dependent on the target machine. The LLVM reads a configuration of the target machine at the time of instruction selection, and selects a set of the instruction and register to meet the specifications of each machine. Our implementation adds a new configuration called nvuc (NVIDIA Micro-Controller) to support NVIDIA’s GPU microcontrollers under LLVM.

#### (3) LLVM to envyas

This stage divides the generated assembly code into code and data sections so that we can create binary images using “envyas”, which is a microcontroller assembler provided by the Envytools suite. The bootstrap code is also unified into the binary images in this stage.

#### (4) envyas

This is a final assembly stage for the microcontroller, which generates the byte code of the firmware.

#### (5) hex to bin

This stage translates the hexadecimal byte code to the binary format so that the firmware can execute on the microcontroller.

#### (6) Running the microcontroller

The compiled firmware is loaded on the microcontroller by the device driver. We also support a debugging tool that launches the firmware in the same way as the device driver for development purposes.

#### C. Debugging Support

We support a debugging tool to load the firmware, send commands and data, monitor the status, and display register and memory values of the microcontroller. Figure 4 shows control flow of our debugging tool. The following are the details of each block in the flow:

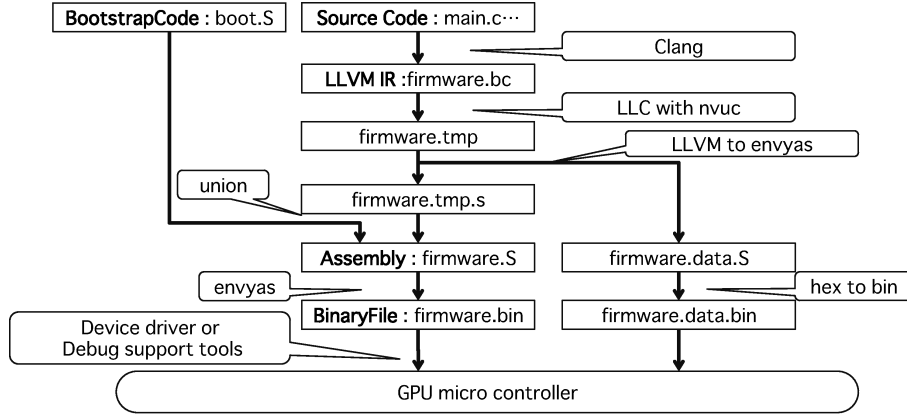


Figure 2. Overview of Compiler Implementation.

#### (1) Load Firmware

Our debugging tool uploads a set of firmware programs on to the HUB and the GPC micro-controllers. The uploaded firmware programs start execution when a flag is set in the specified register.

#### (2) Send Command and Data

The microcontroller is event-driven. It is totally suspended in an idle state. When it receives a command from the debugging tool through the PCI bus, the interrupt handler is invoked and its execution is resumed.

#### (3) Display Register Value

The microcontroller has a set of registers that may be used by the debugging tool for any purpose. There are also several important registers relevant to firmware execution. The debugging tool hence displays the values of these registers to notify what is happening.

### D. Firmware Development

In this paper, we present the most basic firmware program for NVIDIA's GPU microcontrollers. We develop this firmware entirely using our compiler and debugging environment. This is indeed the initial step toward fine-grained GPU resource management using microcontrollers, and enhanced functions could build upon this work.

Figure 5 shows control flow of the basic firmware developed in this paper. The following are the details of each block in the flow.

#### (1) initialize

The firmware configures the interrupt handler, and receives the default set of data when started.

#### (2) sleep

The firmware enters the standby mode in the main event loop, waiting for the next command issued by the device driver or the debugging tool. Upon every arrival of the command, an interrupt is generated on the microcontroller, awakening the firmware in

Table III  
EVALUATE ENVIRONMENT

CPU	Intel core i7 2600
GPU	NVIDIA GeForce GTX480
Memory	8GB
Kernel	Linux 2.6.42.12-1.fc15.x86_64
Device driver	PSCNV

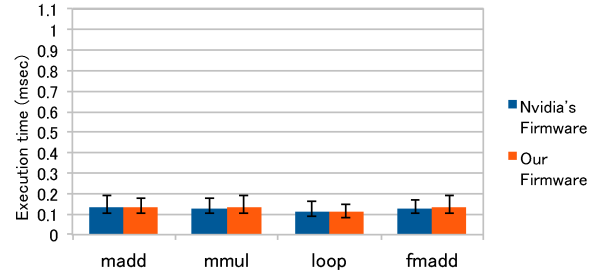


Figure 6. Execution Time of Gdev Sample Program : Case A

the “ihbody” function.

#### (3) ihbody

This is an interrupt handler invoked by the command. All we have to do here is to enqueue the corresponding command, and releases the standby mode to resume firmware execution.

#### (4) work

This is a main body of the firmware. It is called when the firmware is released from the standby mode. The basic procedure of this function is to dequeue a pending command one by one, and call the function corresponding to the command. If the specified flag is cleared, we destroy the firmware.

### IV. EVALUATION

The evaluation compare the performance of the NVIDIA's standard firmware and we developed firmware used FARM. Table III shows the evaluation environment. This evaluation

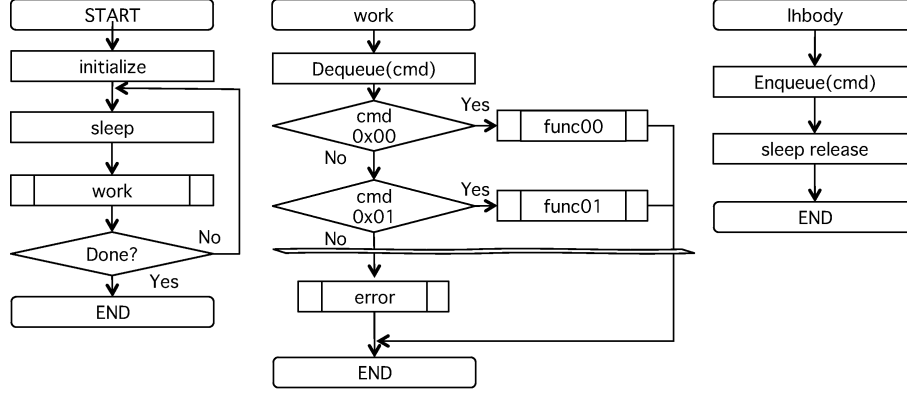


Figure 5. Flowchart of our basic firmware.

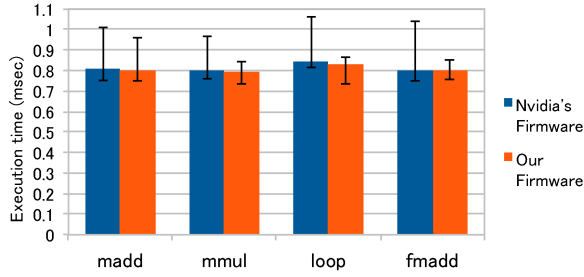


Figure 7. Execution Time of Gdev Sample Program : Case B

measure the overhead of measuring the execution time in the NVIDIA's firmware and the we developed firmware on Gdev [15] [16] of GPGPU runtime and resource management engine set. This execution time is the time to copy of the data into device, the process execution, the copy of the data into host.

Measurement results were concentrated in the following over 7msec and less 2msec. This phenomenon occurred both firmware. That because GPU's program are many things influence compared to the CPU Program. Specifically, these are device memory, device driver, GPU cache and GPU memory. Thus we divide over 7 msec are "case A", and less 2 msec are "case B". We compare the average each case A and case B. Figure 6 shows result of case A. Also figure 7 shows result of case B. The abscissa axis is Sample program name. The vertical axis is Execution time (msec). The blue is the NVIDIA's standard firmware, also the red is the we developed firmware. Figure 6, 7 can be as seen almost no overheads. It is the largest overhead, the case A is 0.003msec of madd, it was 2.31%. also it was the lowest overhead, the case B is -0.002msec, it was -1.74%. In this way, result has been increased execution time and decreased execution time. Thus, it is within the range of error at execution time from a range of numbers that was measured is wide. In

addition, if you want to use the GPU application, there will be less affected because the processor core for processing time increases. For example, The total time of madd in NVIDIA'S standard firmware is 21.842msec, this total time is between finished program from the start program by host. The execution time overhead occupy relatively small 0.01% of the total time Thus, the overhead of firmware developed by our development environment is within the allowable range. It follows from what has been said that developing firmware by this our development environment is a valid one.

The total time includes the time required to generate GPU context, Memory allocation and Memory release time. madd by the running NVIDIA's standard firmware The total time is 214 msec at the madd first execution times by the NVIDIA standard firmware. The second total time is 20 msec, this result is a big gap to the first execution time. Further, the our developing firmware get the same results to NVIDIA standard firmware. Because the firmware generate the GPU context when the first run, and then, the firmware secondly running use GPU context generated by the first run. Thus, it takes a long time to generate the GPU context. This problem findings obtained by firmware development and evaluate.

## V. RELATED WORK

This Section introduce related work and draw a comparison between our works and related work.

### A. Helios: Heterogeneous Multiprocessing with Satellite Kernels

A study on Helios [17] was made by Edmoud at the Microsoft Research, and it revealed that is an operating system designed to simplify the task of writing, deploying, and tuning applications for heterogeneous platforms. There says required the using programmable devices such as GPU and NIC for the high-performance vector processing and high-speed communications. GPU and NIC leveraging its capabilities via the device driver, in this form, the amount of

data that can be transferred is limited by the communication between the CPU and the device. Further more, the problem has complexity of the device driver and not provided interface of runs a task. Approach is providing OS called Helios. The Helios has micro kernel called satellite kernels. The satellite kernels has the scheduler, memory manager, name space manager, and communication between the kernel. The same direction that the Helios is our aim. Helios approach to NIC, but our approach to GPU. The above problems be able to solve by the implement firmware on GPU microcontroller.

### B. Design of Direct Communication Facility for Manycore based Accelerators

A study on DCFA [18] was made by Si at the Tokyo university, and it revealed that the DCFA avoid the trouble of having to the communication latency of between devices by direct communication between devices without going through the host. Currently, the DCFA can not adapt to the GPU, because the device address isn't known GPU. We think that communication is done between the GPU devices by issuing to direct communication by the firmware.

## VI. CONCLUSION

It has been presented FARM, a new GPU firmware development environment. We advance the approaches by firmware for this problem, however, we pointed the problem of the productivity on firmware development. Then, we proposed the implementation of GPU microcontroller firmware development environment to solve. Then, we evaluated the overhead to run the Gdev sample program on developing firmware by the our development environment. The results of evaluated were less than 2.31%, and result looked cases that were completed earlier than NVIDIA standard firmware. Further we confirmed the within an acceptable range of the application was less affected by microcotroller overheads. Finally, for reasons mentioned above, our development environment is a valid one. Further more, we found the overhead of generate GPU context.

Our development environment is all open-source, and can be download from our web site [19], [20], [15].

Our future, we pursue a new direction for GPU resource management. In particular, we think the CPU load reduce by we shifts firmware on the microcontroller from the device driver works. Further, the scheduling of GPU processing can not be preempted because scheduling performed in the device driver and the runtime engine. However, the microcontroller has scheduling, it can be preempt, Available resource effectively of the GPU. On the other hand, we expect getting improvement result in Section IV of the overhead of generate the GPU context.

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