Fast LZW compression using a GPU

Abstract—**The LZW compression is a well known patented lossless compression method used in Unix file compression utility "compress" and in GIF and TIFF image formats. It converts an input string of characters into a string of codes using a code table (or dictionary) that maps strings into codes. It is Since the code table is generated by adding newly appeared substrings during the conversion, it is very hard to parallelize it. The main purpose of this paper is to develop accelerate LZW compression for TIFF images using a CUDA-enabled GPU. We have implemented LZW compression algorithm using several acceleration techniques using CUDA. Suppose that a GPU generates a resulting image generated by a computer graphics or image processing program and we want to store it as a LZW-compressed TIFF image in the SSD connected to the host PC. We focused on two scenarios: Scenario 1: the resulting image is compressed using a GPU and written in the SSD through the host PC, and Scenario 2: it is transferred to the host PC, and compressed and written in the SSD using a CPU. The experimental results using GeForce GTX 980 and Intel Corei7 4790 show that Scenario 1 using our LZW compression implemented in a GPU is about 3 times faster than Scenario 2. From this fact, it makes sense to compress images using a GPU to archive them in the SSD.** ***Keywords—ata compression, big data, parallel algorithm, GPU, CUDAata compression, big data, parallel algorithm, GPU, CUDAD***

I. Introduction

A GPU (Graphics Processing Unit) is a specialized circuit designed to accelerate computation for building and manipulating images [1]. Latest GPUs are designed for general purpose computing and can perform computation in applications traditionally handled by the CPU. Hence, GPUs have recently attracted the attention of many application developers. NVIDIA provides a parallel computing architecture called *CUDA* (Compute Unified Device Architecture) [2], the computing engine for NVIDIA GPUs. CUDA gives developers access to the virtual instruction set and memory of the parallel computational elements in NVIDIA GPUs.

CUDA uses two types of memories in the NVIDIA GPUs: *the shared memory* and *the global memory* [2]. The shared memory is an extremely fast on-chip memory with lower capacity, say, 16-64K bytes. The global memory is implemented as an off-chip DRAM, and thus, it has large capacity, say, 1.5-12 Gbytes, but its access latency is very long. The efficient usage of the shared memory and the global memory is a key for CUDA developers to accelerate applications using GPUs. In particular, we need to consider *bank conflicts* of the shared memory access and *coalescing* of the global memory access [3]–[5]. The address space of the shared memory is mapped into several physical memory banks. If two or more threads access the same memory banks at the same time, the access requests are processed in turn. Hence, to maximize the shared memory access performance, threads of CUDA should access distinct memory banks to avoid the bank conflicts of the memory accesses. To maximize the throughput between the GPU and the DRAM chips, the consecutive addresses of the global memory must be accessed at the same time. Thus, CUDA threads should perform coalesced access when they access the global memory. Also, the latency of the global memory access is several hundred clock cycles, while that of the shared memory access is quite small [2]. Hence, we should minimize the memory access to the global memory to maximize the performance.

There is no doubt that data compression is one of the most important tasks in the area of computer engineering. In particular, almost all image data are stored in files as compressed data formats. There are basically two types of image compression methods: *lossy* and *lossless* [6]. Lossy compression can generate smaller files, but some information in original files are discarded. Hence, decompression of lossy compressed images does not generate files identical to the original images. On the other hand, lossless compression creates compressed files, from which we can obtain the exactly same original files by decompression. Hence, lossless compression can be used far more than images. In this paper, we focus on LZW (Lempel-Ziv & Welch) [7] compression, which is one of the most well known patented lossless compression method [8] used in Unix file compression utility "compress" and in GIF image format. Also, LZW compression option is included in TIFF file format standard [9], which is commonly used in the area of commercial digital printing.

The LZW compression algorithm converts an input string of characters into a string of codes using a code table (or a dictionary) that maps strings into codes. In LZW compression in TIFF file format, characters are 8-bit unsigned integers representing intensity levels of gray-scale images, and codes are 12-bit unsigned integers. During the conversion, the code table is generated by adding new substrings. Hence, it is very had to parallelize the LZW compression, because the addition of new substrings is performed sequentially. However, LZW compression and decompression are hard to parallelize, because they use dictionary tables created by reading input data one by once. In [10], a CUDA implementation of LZW compression has been mentioned, but the paper is very poorly written and it is not possible to understand their results. Also, several GPU implementations of some dictionary based compression methods have been presented [11], [12]. As far as we know, no paper has presented the details of LZW implementations for GPUs.

Quite recently, we have presented a GPU implementation for LZW decompression [13]. The LZW decompression algorithm converts an input string of codes into a string of characters, that is, it is the inverse of the LZW compression.

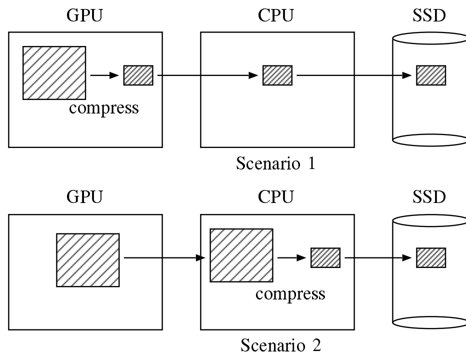

Fig. 1. Two scenarios to store the LZW-compressed image in the SSD

Similarly, during the conversion, the code table is generated one by one. However, unlike the LZW compression, the LZW decompression can be highly parallelized. The idea of parallel LZW decompression is to generate the code table from the input string of codes in parallel. After that, the input string of codes are converted into the output string of characters. These two steps can be done in parallel using one thread to each code. On the other hand, it is not possible to generate the code table from the input string of characters in parallel. Hence, it is very hard to parallelize LZW compression.

Our idea for LZW compression is to use an idea of bulk execution of the same sequential computation that have been show in our previous papers [14], [15]. In Tiff LZW compression, an input image to be LZW compressed is partitioned into stripes, each of which consists of one or more rows. Since each strip is LZW compressed in dependently, we assign one thread to each strip for this task. For the coalesced memory access, we have transposed the image. Since the memory access is

To show the benefit of LZW compression using the GPU, we have compared two scenarios: Scenario 1: An image is stored

II. LZW COMPRESSION

The main purpose of this section is to review LZW compression/decompression algorithms. Please see Section 13 in [9] for the details.

The LZW compression algorithm converts an input string of characters into a string of codes using a code table (or a dictionary) that maps strings into codes. If the input is an image or plain ASCII text, characters may be 8-bit unsigned integers. It reads characters in an input string one by one and adds an entry in a code table. In the same time, it writes an output string of codes by looking up the code table. Let $X = x_0 x_1 \cdots x_{n-1}$ be an input string of characters and $Y = y_0 y_1 \cdots y_{m-1}$ be an output string of codes. When we show examples of LZW compression, we use an input string with 4 characters a, b, c, and d, which can be mapped to 2-bit unsigned integers, 0, 1, 2, and 3. Let C be a code table, which determines a mapping of a code to a string, where codes are non-negative integers. Initially, $C(0) = a$, $C(1) = b$, $C(2) = c$, and $C(3) = d$. By procedure AddTable, new code is assigned to a string. For example, if AddTable(cb) is executed after initialization of C, we have $C(4) = cb$. We also use symbol C to denote a set of codes in a code table C, that is, $C = \{C(0), C(1), \cdots\}$ if it is clear from the context.

The LZW compression algorithm finds the longest prefix Ω of the current input that is in the code table, and outputs the code of Ω. Let x be the following character of Ω in the current input. Since $\Omega{\cdot}x$ is not in the table, it is added to the code table, where "·" denotes the concatenation of strings/characters. The same procedure is repeated from x. The LZW compression algorithm is formally described as follows:

[LZW compression algorithm]
1 $\Omega \leftarrow x_0$;
2 for $i \leftarrow 1$ to $n-1$ do
3 　if($\Omega \cdot x_i$ is in C)
4 　　$\Omega \leftarrow \Omega \cdot x_i$;
5 　else
6 　　Output($C^{-1}(\Omega)$); AddTable($\Omega \cdot x_i$); $\Omega \leftarrow x_i$;
7 Output($C^{-1}(\Omega)$);

Table I shows the compression process and the code table C for an input string $cbcbcbcda$. First, $\Omega \leftarrow x_0 (= c)$ is performed. Next, since $\Omega{\cdot}x_1 = cb$ is not in C, Output($C^{-1}(c)$) and AddTable(cb) are performed. More specifically, $C^{-1}(c) = 2$ is output and we have $C(4) = cb$. Also, $\Omega \leftarrow x_1 (= b)$ is performed. By repeating the same procedure, we can confirm that 214630 is output by this algorithm.

Let us discuss implementations of code table C. The following operations for a string Ω of characters must be supported for LZW compression.

- determine if $\Omega \cdot x_i$ is in C,
- return the value of $C^{-1}(\Omega)$,
- perform AddTable($\Omega \cdot x_i$).

A straightforward implementation of a code table C, which uses an array such that each i-th ($i \geq 0$) element stores $C(i)$, is not efficient. All values of $C(i)$ may be accessed to compute $C^{-1}(\Omega)$. We may use an associative array with keys $C(i)$ and values i, which can be implemented by a balanced binary tree or a hash table. However, these operations takes more than $O(|\Omega|)$ time. If the compression ratio is high, Ω may be a long string. Hence, it is not a good idea to use a conventional associative array to implement C.

We will use a pointer-character table shown in Table II to implement a code table C. In the pointer-character table, a pointer $p(j)$ and a character $c(j)$ are stored for each code j. Also, a back-pointer $q(j, x)$ for every code j and character x is used. Back-pointer table q can be implemented using an associative array. We will discuss implementations of a back-pointer later. We can obtain a string $C(j)$ by traversing p until we reach NULL . More specifically, $C(j)$ can be obtained from p and c by the following definition:

$$
\begin{aligned}
C(j) &= c(j) \quad \text{if } p(j) = \text{NULL} \\
&= C(p(j)) \cdot c(j) \quad \text{otherwise.}
\end{aligned}
$$

For example, in Table II, we have $C(6) = C(4) \cdot c = C(2) \cdot bc = cbc$. A back-pointer $q(j, x)$ takes value k if $p(k) = j$ and $c(k) = x$. If there exists no k such that $p(k) = j$, then

TABLE I. CODE TABLE C, STRING STORED IN Ω, AND OUTPUT STRING Y FOR $X = cbcbcbcda$

i	0	1	2	3	4	5	6	7	8	-
x_i	c	b	c	b	c	b	c	d	a	
Ω	-	c	b	c	cb	c	cb	cbc	d	a
C	-	$4 : cb$	$5 : bc$	-	$6 : cbc$	-	-	$7 : cbcd$	$8 : da$	-
Y	-	2	1	-	4	-	-	6	3	0

TABLE II. A POINTER-CHARACTER TABLE AND A BACK-POINTER TABLE TO IMPLEMENT CODE TABLE C

j	0	1	2	3	4	5	6	7	8	9
$p(j)$	NULL	NULL	NULL	NULL	2	1	4	6	3	0
$c(j)$	a	b	c	d	b	c	c	d	a	-
$q(j,a)$	NULL	NULL	NULL	8	NULL	NULL	NULL	NULL	NULL	NULL
$q(j,b)$	NULL	NULL	4	NULL	NULL	NULL	NULL	NULL	NULL	NULL
$q(j,c)$	NULL	5	NULL	NULL	6	NULL	NULL	NULL	NULL	NULL
$q(j,d)$	NULL	NULL	NULL	NULL	NULL	7	NULL	NULL	NULL	NULL
$C(j)$	a	b	c	d	cb	bc	cbc	$cbcd$	da	-

$q(j,k) =$ NULL. It is used to perform the three operations above efficiently.

We implement procedure AddTable($\Omega \cdot x_i$) for code table C as a procedure AddTable(j, x_i) for the pointer-code table. If AddTable(j, x_i) is performed, new available entry k with $p(k) = q$ and $c(k) = x_i$ is added to the pointer-character table. Also, the value k is written in $q(j, x_i)$. Using the pointer-character table, we can rewrite LZW compression algorithm as follows:

```
[LZW compression algorithm]
1  j ← c^{-1}(x_0);
2  for i ← 1 to n − 1 do
3      if(q(j, x_i) ≠ NULL)
4          j ← q(j, x_i);
5      else
6          Output(j); AddTable(j, x_i); j ← c^{-1}(x_i);
7  Output(j);
```

Note that, $c^{-1}(x)$ for a character x can be computed very easily. Usually, a set of all 8-bit unsigned integer are used, and $c^{-1}(x) = x$ holds for every character x. Let us see how a table II is created by this algorithm. First, $j \leftarrow C^{-1}(x_0) = 2$ is performed. Next, since $q(j, x_1) = q(2, b)$ is NULL, Output(2) and AddTable(2,b) are performed. The pointer-character table has new entry $p(4) = 2$ and $c(4) = b$. Also, 4 is stored in $q(2, b)$. Continuing similarly, we can confirm that the algorithm creates the pointer-character table and outputs 214630.

III. GPU IMPLEMENTATION FOR LZW COMPRESSION FOR TIFF IMAGES

We focus on LZW compression of an image into a TIFF image file. We assume a gray scale image with 8-bit depth, that is, each pixel has intensity represented by an 8-bit unsigned integer. Since each of RGB or CMYK color planes can be handled as a gray scale image, it is obvious to modify gray scale LZW compression for color image compression.

As illustrated in Figure 2, a TIFF file has *an image header* containing miscellaneous information such as ImageLength (the number of rows), ImageWidth (the number of columns), compression method, depth of pixels, etc [9]. It also has *an image directory* containing pointers to the actual image data. For LZW compression, an original 8-bit gray-scale image is partitioned into *strips*, each of which has one or several consecutive rows. The number of rows per strip is stored in the image file header with tag RowsPerStrip. Each Strip is compressed independently, and stored as the image data. The image directory has pointers to the image data for all strips.

Next, we will show how each strip is compressed. Since every pixel has an 8-bit intensity level, we can think that an input string of an integer in the range $[0, 255]$. Hence, codes from 0 to 255 are assigned to these integers. Code 256 (ClearCode) is reserved to clear the code table. Also, code 257 (EndOfInformation) is used to specify the end of the data. Thus, AddTable operations assign codes to strings from code 258. While the entry of the code table is less than 512, codes are represented as 9-bit integer. After adding code table entry 511, we switch to 10-bit codes. Similarly, after adding code table entry 1023 and 2037, 11-bit codes and 12-bit codes are used, respectively. As soon as code table entry 4094 is added, ClearCode is output. After that, the code table is re-initialized and AddTable operations use codes from 258 again. The same procedure is repeated until all pixels in a strip are converted into codes. After the code for the last pixel in a strip is output, EndOfInformation is written out. We can think that a code string for a particular strip is separated by ClearCode. We call each of them *a code segment*. Except the last one, each code segment has $4094 - 511 + 1 = 3584$ codes. The last code segment for a strip may have codes less than that.

Let us discuss the implementation of back-pointer q for TIFF LZW compression. Since codes have up to 12 bits and characters are 8 bits, we can implement q as a table wit has $2^{12} \times 2^8 = 2^{20}$ entries. Since the value of back-pointer $q(i, x)$ takes value up to 12 bits, each entry can be be 2 bytes. Hence, a back pointer can be implemented in $2^{21} =$ 2Mbytes. However, this straightforward implementation has large overhead due to the cache miss. Hence we will use a hash table to implement back-pointer q.

Let $h(i, x)$ be a hash function returning a 14-bit number, where i and x are 12 bits and 8 bits respectively. In the experiment that we will show later, we have used the following hash function h to specify a 14-bit number.

$$h(i,x) \quad = \quad (i \oplus (x << 10) \oplus (x >> 4)) \wedge \text{0x3FFF},$$

We use an array of 2^{14} elements with 2 bytes each to store the 14-bit values of back pointers $q(i, x)$. When we write the value of back pointer in address $h(i, x)$, it may already be used. If this is the case, the current value of each address $(h(i, x) +$

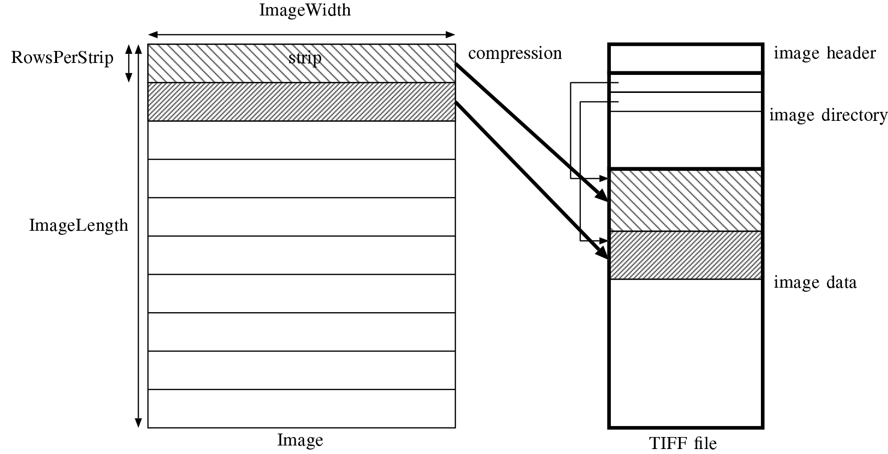

Fig. 2. An image and TIFF image file

$501i) \wedge$0x3FFF is read for $i = 1, 2, \ldots$ until an unused address is found. Since at most 3584 elements are added, the hash table of size $2^{14} = 16384$ is good enough.

After ClearCode is output, we need to initialize the hash table. However, it is too costly to clear all elements in the hash table. Hence, we use the time-stamp technique as follows: Since the value of each $q(i, x)$ has 12 bits is stored in 2 byte element, the remaining 4 bits are used as a time stamp. The time stamp takes value from 0 to $2^4 - 1 = 15$. Initially, the time stamp is 0 and incremented after ClearCode is output. When the new entry is added to and some value is written in $q(i, x)$, the current time stamp is written with it. Using the time stamp, one can determine if the value stored in each $q(i, x)$ is valid. When the time stamp is incremented 16 times, it is set to 0 and the values of all addresses are initialized by 0. Note that the size of the hash table is $2^{14} \cdot 2 = 32$K bytes, which is much smaller than the straightforward implementation.

We are now in a position of our implementation of LZW compression using a CUDA-enabled GPU. We assume that an 8-bit gray scale image to be LZW-compressed is stored in the global memory of the GPU. Our implementation performs LZW compression and the resulting image is stored in the global memory using a TIFF format. To maximize parallelism, we set RowsPerStrip= 1, that is, each strip has one row of the gray-scale image. We assign each thread to one strip, which perform LZW compression of it independently. Each thread uses the local memory, which is mapped in the global memory of the GPU, to store the pointer-character table and the hash table. The details of our implementation is spelled out as follows: [LZW compression using a CUDA-enabled GPU]
Step 1: Transpose the gray-scale image such that each row of the image is in a column.
Step 2: Each thread performs the LZW compression and the resulting sequence of LZW codes are written in the global memory.
Step 3: The prefix-sums of the lengths of the resulting sequences of LZW codes.
Step 4: The resulting LZW codes are concatenated into one to fit a TIFF format using the prefix-sums.

One CUDA kernel is invoked for each of the three steps. Step 1 can be done by an algorithm for matrix transposition [16]. After the transposing, each row of the image is arranged in a column. Since every thread access to the same position of a column, access to the image performed in Step 2 is coalesced. After Step 2, the resulting sequences of LZW codes generated by all threads are separated. To convert it in a TIFF format, they must be concatenated. For concatenation, the prefix-sums of the lengths of all resulting sequences of LZW codes are computed in Step 3. More specifically, let $l_0, l_1, l_2, \ldots$ be the lengths of all resulting sequences. The prefix-sums $l_0, l_0+l_1, l_0+l_1+l_2, \ldots$ are computed. The prefix-sums can be computed by a GPU very efficiently [17], [18] From the prefix-sums, we can determine the position in the TIFF format where each resulting sequence must be copied. Step 4 performs this copy operation in an obvious way.

IV. EXPERIMENTAL RESULTS

We have used Nvidia GeForce GTX 980 which has 16 streaming multiprocessors with 128 processor cores each to implement parallel LZW decompression algorithm. We also use Intel Corei7 4790 (3.6GHz) to evaluate the running time of sequential LZW decompression.

We have used three gray scale images with 4096×3072 pixels (Figure 3), which are converted from JIS X 9204-2004 standard color image data. We set RowsPerStrip= 1, and so each image has 3072 strips with 4096 pixels each. We invoked a CUDA kernel with $\frac{4096}{32} = 128$ CUDA blocks of 32 threads each for decompression. the compression ratio, that is, "original image size: compressed image size." We can see that "Graph" has high compression ratio because it has large areas with constant intensity levels. On the other hand, the compression ratio of "Crafts" is small because of the small details. Table III also shows the running time of LZW decompression using a CPU and a GPU. In the table, T_1 and T are the time for constructing tables and the total computing time, respectively. To evaluate time T_1 of sequential LZW decompression, OUTPUT in lines 4 and 6 are removed. Also, to evaluate time T_1 of parallel LZW decompression on the GPU, the CUDA kernel call is terminated without computing the prefix-sums and writing resulting characters in the global memory. Hence, we can think that $T - T_1$ corresponds to the

time for for generating the original string using the tables. Clearly, sequential/parallel LZW decompression algorithms take more time to create tables for images with small compression ratio because they have many segments and need to create tables many times. Also, the time for creating tables dominates the computing time of sequential LZW decompression, while that for writing out characters dominates in parallel LZW decompression. This is because the overhead of the parallel prefix-sums computation is not small. From the table, we can see that LZW decompression for "Flowers" using GPU is 69.4 times faster than that using CPU.

We have evaluated the running time of two scenarios that may be used in real life applications. Suppose that, some GPU computation generated a gray-scale image in the global memory of the GPU. What we want to do is to store it using LZW-compressed TIFF format in the SSD (Solid State Drive) connected to the host PC. We compare the following two scenarios:
Scenario 1: The gray-scale image is compressed and converted into an TIFF image by our implementation on the GPU. After that, the resulting LZW-compressed TIFF image is transferred to the host PC and written in the SSD.
Scenario 1: The gray-scale image is transferred to the host PC and compressed using a CPU. After that, the resulting LZW-compressed TIFF image is written in the SSD.
Table **??**

V. Conclusion

In this paper, we have presented a parallel LZW decompression algorithm and implemented in the GPU. The experimental results show that, it achieves a speedup factor up to 69.4. Also, LZW decompression in the GPU can be used to accelerate the query processing for a lot of compressed images in the storage.

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“Crafts” “Flowers” “Graph”

Fig. 3. Three gray scale image with 4096×3072 pixels used for experiments

TABLE III. THE RUNNING TIME (IN MILLISECONDS) OF LZW COMPRESSION USING A GPU AND A CPU FOR THREE IMAGES

Images	compression ratio	GPU Step 1	GPU Step 2	GPU Step 3	GPU Step 4	GPU All	CPU Our	Speed-up
“Crafts”	$1.23:1$	0.32	29.3	0.015	0.17	29.3	92.8	3.2
“Flowers”	$1.44:1$	0.40	23.8	0.015	0.16	22.2	65.4	2.9
“Graph”	$10.8:1$	0.36	11.0	0.017	0.14	11.0	33.3	3.0

TABLE IV. THE RUNNING TIME (IN MILLISECONDS) OF TWO SCENARIOS USING OUR GPU AND CPU IMPLEMENTATIONS AND LIBTIFF LIBRARY FOR THREE IMAGES

Images	Scenario 1 Compress on GPU	Scenario 1 Transfer GPU→ CPU	Scenario 1 Writing CPU→SSD	Scenario 1 All	Scenario 2 Transfer GPU→ CPU	Scenario 2 Compress on CPU	Scenario 2 Writing CPU→SSD	Scenario 2 All	Scenario 2 libTiff
“Crafts”	29.3	2.34	3.85	35.2	3.84	92.8	3.84	100.4	118.6
“Flowers”	22.23	1.44	2.80	26.0	3.82	65.4	2.74	71.9	105.0
“Graph”	10.99	0.40	0.38	11.3	3.88	33.3	0.28	37.5	46.1