Design and simulation of high performance computer architecture using holographic data storage system for database and multimedia workloads

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Abstract—The performance of modern mainframe computers keeps increasing due to the advances in the semiconductor technology. However, the quest for the faster computer has never been satisfied. To overcome the discrepancy in the supply and demand, we studied a high performance computer architecture utilizing a three-dimensional Holographic Data Storage Systems (HDSS) as a secondary storage system. The HDSS can achieve a high storage density by utilizing the third dimension. Furthermore, the HDSS can exploit the parallelism by processing the two-dimensional data in a single step. To compare the performance of the HDSS with the conventional hard disk based storage system, we modeled the HDSS using the DiskSim simulation engine and performed the simulation study. Results showed that the HDSS can improve the access time by 1.7 times.

Index Terms—Simulation, modeling, holographic data storage system, spatial light modulator, DiskSim, access time.

I. INTRODUCTION

The rapid developments in computer technology and the wired/wireless communication technology triggered the demands for the high-performance data processing computers. Particularly, in the multimedia service applications, the size of the data became too large to be handled efficiently. Few years ago, the fastest supercomputer announced was for the scientific and military applications. Now, the supercomputer customers are not the scientists but the businessman of the multi-national corporations such as VISA and American Express. The data processing and transaction processing became an integral part of problems to solve for the major mainframe computer companies. In fact, Figure 1 illustrates that the demand for the mainframe computers from the commercial sectors such as financial companies and distribution industries is now four times greater than the demands from the universities and scientific research organizations.

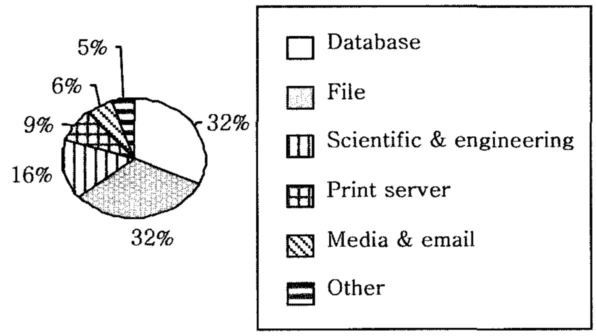

Fig. 1 Market distribution for the server computer

The computers used in the commercial sectors utilize the computer hardware such as the Symmetrical multiprocessors (SMP) and Redundant Array of Independent Disks (RAID) running Oracle database software or application software.[3] The users and manufactures of the mainframe computers discovered the facts illustrated in figure 2. The hardware processing requirements increase two times per every 9 months,[4] while the performance of the processor and storage capacities increase two times per every 18 months according to the Moore's law. Therefore, we can conclude that the supply cannot exceed the demand. Here the supply means the computer hardware or the manufacturers and the demand implies the application software or the users.[5] Furthermore, this gap is destined to increase in the foreseeable future.[6]

In order to reduce this performance gap, parallel high-performance database computer architectures as well as various kinds of database accelerators have been researched. In the case of the parallel high-performance database computer architecture research, novel architectures using parallel computer architectures such as the share-nothing multiprocessor for the parallel and high-performance database processing has been proposed. The storage system research was more active than the architecture research. For example, smart disk systems such as the Active Disk[8] and Intelligent Disk[9] were announced.

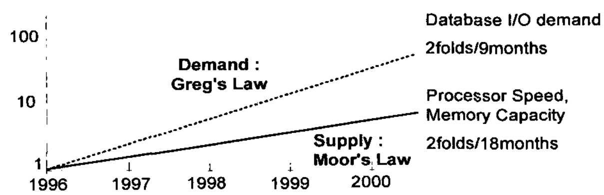

Fig. 2 The supply (Hardware) and demand (Applications) graph

In the smart disks, the storage devices were re-enforced with the microprocessors and DRAMs at the device level.

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The role of the smart disk is performing the subtasks of a database queries such as scan, join, project, search, and sorting at the storage device in advance so that the processing elements are relieved from the burden of the complex and demanding database query. In the database computer architecture, the systems achieve the good scalablity. However, they suffer from the complex interconnection network problems, distributed system administration problem, as well as the packaging problems.[7] On the other hand, in the smart disk systems, we may reduce the latency problem. However, they also suffer from the fact that the legacy software must be rewritten and the standardization effort has not been addressed.[8,9]

In this paper, we propose an smart holographic disk system and evaluate the impact of the system. In the following section, the holographic storage system is explained. Then we evaluate the proposed system using simulation.

II. THE ARCHITECTURE OF THE OPTICAL STORAGE SYSTEM

A. Overview

The market of the storage device is expected to exceed over 10billion dollar in 2000. Thus the major vendors as well as research institutes make an enormous efforts to preoccupy the storage system market by developing a next-generation storage systems. In the optical storage system, we can achieve not only the increased storage density but also the faster data transfer rate. The one of the major optical storage system is three-dimensional holographic data storage system (HDSS). The 3-D HDSS research consortium including IBM, Kodak, University of Stanford, and University of Arizona is supported by the Defense Department Advanced Research Project Agency. Utilizing these research, the Silos co. is supposed to design and construct a prototype HDSS.[10] The Holostore, supported by Polaroid and Syracuse University also is planning to announce the waveguide holographic storage system.[18] Finally, the Call/Recall co. is going to announce the two-photon optical storage system that can store 100 Gbytes at the data rate of 100 Gbps.[16]

B. Optical Storage-based Computer System

Figure 3 illustrates a computer system utilizing an optical storage system. The proposed system uses the 3-D optical storage so that the data transfer at the bus I/O level reaches at the Giga-bit rate. In the case of the relatively new Ultra SCSI-2 has a data bus width of two bytes, while the 3-D HDSS can transfer the 10^4 or 10^6 data at one clock cycle. So if the 3-D HDSS can sustain only KHz rate, one can easily achieve Giga-bit data transfer rate.[15] In the computer architecture, the cache memory is used to reduce the speed gap between the processor and the memory. Assuming the rate of the data readout of 1 MHz from the photodiode, the buffer becomes saturated rather early. Thus, the size of the buffer should be reasonably larger than the size of the traditional buffer in the storage system. Also, the traditional processors assume the size of the data bus of 4bytes, 8bytes, 16bytes, and 32bytes. Since the data bus of the optical storage is 10^4 or 10^6, the need of a fairly large size of buffer in the system is obvious. If there are no buffering tasks in the system, the data bus of the system becomes saturated so that the performance of the system will be degraded.

Figure 3 illustrates the buffer to control the flow of data between the optical storage and the data bus. It is our goal to investigate the relationship between the performance parameters and the system design parameters such as the size of the buffer, data rate, the size of the bus. From this analysis, we will find the optimal value of those design parameters. The Application Specific Integrated Circuit (ASIC) in the interface block is designed to execute the operation of the database. For the compound operations of the database transactions, the role of the ASIC in the interface block is to preprocess the sub-operations of the complex database operations. In this way, the absolute amount of data to be transferred to the processor can be reduced.

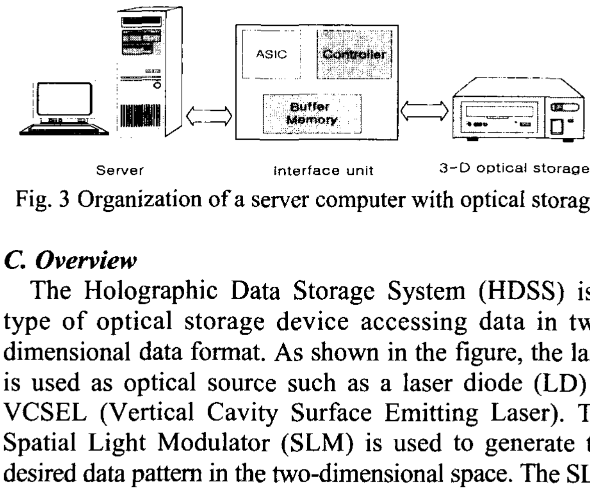


Fig. 3 Organization of a server computer with optical storage

C. Overview

The Holographic Data Storage System (HDSS) is a type of optical storage device accessing data in two-dimensional data format. As shown in the figure, the laser is used as optical source such as a laser diode (LD) or VCSEL (Vertical Cavity Surface Emitting Laser). The Spatial Light Modulator (SLM) is used to generate the desired data pattern in the two-dimensional space. The SLM could be one of the electro-optical SLM, magneto-optical SLM, micro-mechanical SLM, or deformographic SLM with varying size 128x128, 640x480 or 1024x1024 at the modulation clock cycle time from a few milliseconds to microseconds depending upon the characteristics of the device. The Detector array converts the optical signals into the electrical signal. The Charge coupled device (CCD), CMOS image sensor chip, or opto-electronic IC (OEIC) can be used in the system. In the case of the CCD, one can achieve the data rate of 1 Gbit/sec.

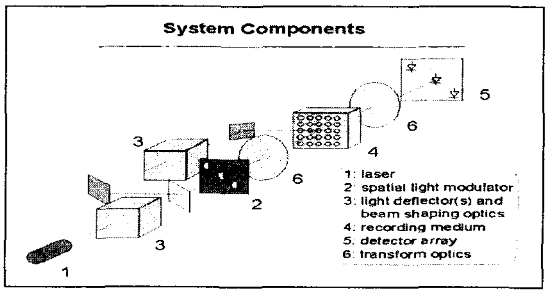


Fig. 4 Block diagram of the 3-D Holographic Data Storage System

HDSS stores data as follows: First, the processor decides the contents of the data to be stored. Then the electro-optical conversion process is initiated so that the data contents are represented in the two-dimensional space. We will refer this two-dimensional optical data plane as a page. The conversion can be realized by the SLM at the modulator level or by the VCSEL array at the source level. Figure 5 illustrates the system using the SLM for the electro-optical conversion process. Then the two-dimensional optical signals from the SLM and the reference beam from a optical source creates an interference pattern which are recorded at one plane of the three-dimensional holographic media. In this way a page of data is recorded in the media. For the next page, the SLM creates the corresponding optical data plane. Then the references beam of different incident angle are used to generate the next interference pattern of the second page so that the system can record the second page at the holographic media. Therefore, by controlling the incidence angle, the media can record an independent two-dimensional data plane which can be up to 5000 pages using today's technology.

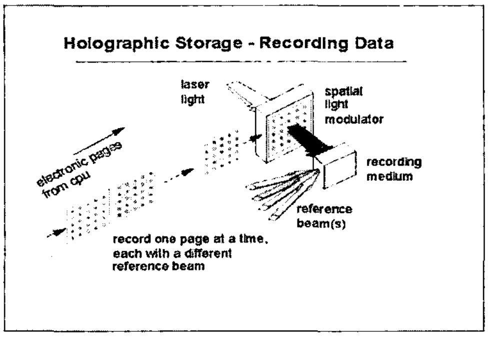


Fig. 5 Recording a page in the Holographic Data Storage System

Now we explain the data readout scheme. In order to read a page from the holographic media, the page must use the reference angle used to record. Thus using the reference beam of the 'correct' incidence angel, the recording media outputs the recorded page at the output data plane. These pages are detected at the two-dimensional detector plane which performing the opto-electrical data conversion. The two-dimensional detector plane then transfers the electrical data to the processor or memory of the computer.

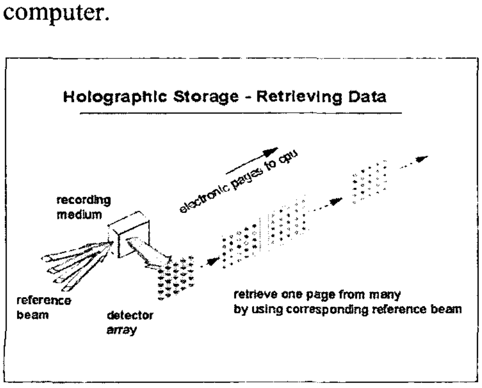


Fig. 6 Readout of a page from the Holographic Data Storage System

III. THE SIMULATION AND ANALYSIS OF THE HDSS

In this section, we discuss the effect of the three-dimensional HDSS on the computer system. For this purpose, we used the DiskSim which is a well known storage system simulation tool.[19] DiskSim is developed from the researchers at the University of Michigan in the mid 90's to compare the various kinds of storage system. In the DiskSim, the bus, controller, adapter, and the disk are modeled and tested. Therefore, given the external or internal trace data, one can characterize the performance of the disk system and perform comparative study. The goal of this simulation study is to find out whether HDSS can fit into the memory hierarchy as a sub-memory system. We compare the disk system by observing the access time. The access time is an useful performance parameter that can measure the disk seek time, data transfer delay, controller overhead, and rotational delay. In the DiskSim, we plug in the value of the disk seek time, various kinds of delay data, overheads, and the rotational delay to create a simulation model file. Then the workload data are send to the simulation program to generate the resulting output file. The disk access service time is $T_{service}$ is represented as follows:

$$T_{service} = T_{seek} + T_{rotate} + T_{transfer} \qquad (1)$$

The disk seek time $T_{readout}$ represents the time to move the arm to the target cylinder. The rotational delay T_{rotate} is the time to move to the target sector. The media transfer time $T_{transfer}$ can be represented by the product of the disk rotation time by the number of sectors accessed. In the case of the 3-D HDSS, the readout methods are different than that of the conventional disk storage system. Thus, the disk service time of the HDSS $T_{service}$ becomes $T_{readout}$ since there are no moving mechanical units in the system. In order to simulate the 3-D HDSS, we created a simulation model using the simpledisk[19]. The detailed description about the simpledisk is explained in Ref. [20]. The design parameters such as disk seek time, transfer delay, controller overhead, rotational delay are included in the simulation model to calculate the simulated access time. We created a HDSS simulation model for this study using the simpledisk simulation model. The readout time of the HDSS $T_{readout}$ can be represented as follows:

$$T_{readout} = T_{laser} + T_{SLM} + T_{detector} \qquad (2)$$

Here, the laser can be modulated at the GHz data rate, the detector array can be modulated at the MHz data rate. However typical SLMs such as liquid crystal SLM can be modulated only at the KHz rate.

$$T_{laser} << T_{detector} << T_{SLM} \qquad (3)$$

The SLM modulation time is three orders of magnitude slower than the detector. Thus it can be safely assumed as follows:

$$T_{readout} \approx T_{SLM} \quad (4)$$

In the same way, the recording time can be represented as follows;

$$T_{store} = T_{laser} + T_{SLM} + T_{detector} \quad (5)$$

Thus, SLM switching time is the dominating term in the Eq. (5). Therefore we can also represent the followings:

$$T_{store} = T_{laser} + T_{SLM} \approx T_{SLM} \quad (6)$$

If we plug in T_{SLM}= 1 msec, the $T_{readout}$= $T_{store} \approx$ 1 msec, we obtain the simulation results as follows: We plug in theses results into the HDSS simulation file. The simulation results are reported as follows[20]:

HDSS Access time average = 6.065118

To compare the HDSS with the conventional disk storage system, consider the "Segate ST32171W" hard disk model which was supplied from the DiskSim. The simulated access time of the Segate hard disk is reported as follows:

Segate Disk Access time average = 10.476667

A. Discussions

The simulation result indicates that the access time of the HDSS is 1.7 times faster than the conventional storage system. The biggest problem in the hard disk storage system was found to be the average rotational delay. Unfortunately, the rotational delay is an architectural problem which can not be reduced easily in the foreseeable future. In the case of HDSS, we can find the SLM with the modulation rate of few tens of microseconds. This modulation speed can goes up to the Giga hertz rate if we use laser system based on such as VCSEL based Smart Pixel Array. Furthermore, the HDSS handles the data of the size of 128 x 128, 512 x 512, 1024 x 1024 instead of the 32 bits, 64bits or 128 bits of conventional computer systems that the increase in the performance is obvious.

IV. CONCLUSION AND FUTURE RESEARCH

The rapid increase in the amount of data will definitely require the massive amount of data to be stored and processed. Thus, the current RAID or Jukebox-based magnetic storage systems will soon become a bottleneck in the near future. The Holographic Data Storage System will become an alternative that can substitute the tape storage in the memory hierarchy of the conventional virtual memory management system. In this initial study, the role of the 3-D HDSS is investigated using a DiskSim simulator. Simulation results suggest that the 3-D HDSS can exhibit about 1.7 times performance increase over the current disk based systems. Note that the key system performance parameter is not the capacity but the access time. Currently, the size of the hard disk storage system increases very rapidly, but the disk access rate has never seen a daylight since it is the architectural problem. The proposed 3-D HDSS can be an alternative solution to the access time problem by using a new architecture. The future study includes the more comprehensive simulation study to compare the 3-D HDSS with the robot-based tape storage system. Then we will constructs the prototype HDSS system that can execute the conventional software to demonstrate the 3-D HDSS memory system.

REFERENCES

[1] "PC Server Market Growth Restrained But Rebound Expected For 1999 : Gap Narrows Between Compaq and HP", http://www.idc.com.

[2] P. Stenstrom, et al. "Trends in shard memory multiprocessing", IEEE computer, pp. 44-50, Dec. 1997.

[3] Press Release, "Clarion Joins Forces with Oracle and NEC to build Multi-terabyte Data warehouse", http://www.oracle.com.

[4] G. Papadopoulos, "Future of computing", NOW Workshop, Lake Tahoe, CA USA, July 1997.

[5] Processor hall of fame, "What is Moore's Law", http://www.intel.com/research/silicon/mooreslaw.htm.

[6] R. Winter and K. Auerbach, "The big time: the 1998 VLDB servery", Database programming and design, vol. 11, no. 8, August 1998.

[7] C. Mohan, et al. "Parallelism in relational database management systems", IBM systems journal, vol. 33, no. 2, 1994.

[8] E. Riedel, G. Gibson, C. Faloutsos, "Active storage for large-scale data mining and multimedia", Proceedings of the 24th VLDB Conference, New York, USA, 1998.

[9] K. Keeton, et al., "A case for intelligent disks", SIGMOD, August 1998.

[10] "Optotek becomes siros; company focusing upon the development of 3-D storage technology", Mass storage News.

[11] U.S. Paik, "3-D Holographic Data Storage Device", High Density Storage Device Development for the new millenium, University, Research Institute, and Industry Research Exchange Program, KOSEF, 1999.

[12] C.W. Lee, "The current research trends in the near field optical recording technology", High Density Storage Device Development for the new millenium, University, Research Institute, and Industry Research Exchange Program, KOSEF, 1999.

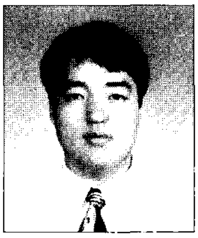
[13] K.C. Noh, "The performance comparison between the next generation storage medium", High Density Storage Device Development for the new millenium, University, Research Institute, and Industry Research Exchange Program, KOSEF, 1999.

[14] B. Olson,et al, "Biorthogonally accessed three-dim. two-photon memory for elational database operations", applied optics, vol. 36, no. 17, 10 June,1997.

[15] P. Mitkas, L Irakliotis, "Three-dimensional optical storage for database processing", in Optical memory and neural networks, vol.3, no. 2, 1994.

[16] H. Urey, et al., "Two-photon three-dimensional optical memories: Resolution and crosstalk issues", OSA Spring topical meeting 1997.

[17] K. Keeton, et al, "Performance characterization of a quad pentium pro SMP using OLTP workloads", Proceedings of the 25th international symposium on computer architecture, Barcelona, Spain, June 1998.
[18] Holographic Media Technology, http://www.mhtx.com/technology/holographic_storage/.
[19] DiskSim Homepage, http://www.ece.cmu.edu/~ganger/disksim/.
[20] Jongwhoa Na, "Design and simulation of high performance computer architecture using holographic data storage system for database and multimedia workloads", Internal Report, 2000.



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