Holographic memories—Fantasy or reality?

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INTRODUCTION

Twelve years have passed since Leith’s historic paper which opened the era of modern holography. Although initially investigated for its unusual imaging properties, we have seen about five years of intensive research on the application of holography to digital data storage. Because of its unique properties, it is not surprising that attempts have been made to apply holography to such a broad range of memory and storage hierarchy. Activity has ranged from developing small-capacity, high-speed memories to large-capacity, read-only storage in the multi-terabit range. Additionally, significant activity has been directed toward solving the highly specialized problems associated with ultra-high data rate recorders and reproducers. Memory systems are now, and will continue to be, the highest single cost item in the computer hardware structure. This, at least in part, accounts for the intensive research activity in optical alternatives to computer memory and storage.

What is the current status of our research and in what segments of the memory hierarchy are holographic techniques likely to play a significant role? Although research continues across the broad spectrum of memory hierarchy, some strong indicators point to very specific areas where the technology has a reasonable chance of success.

Before we consider the specific nature of holographic memories, we review the current state-of-memory technology and identify the targets at which holographic memories have been aimed. Perhaps the two most widely used performance measures for memories are capacity and access time. Clearly there are many other factors such as transfer rate, size, power consumption, interface ease, reliability and reproducibility which may play equally important roles in characterizing memory performance. Similarly, memory cost or more commonly, cost per bit, forms one of the important criteria for memory selection. For purposes of this discussion, capacity and access time will be sufficient factors if we remember that even the ultimate in memory performance is unacceptable if the eventual costs are not consistent with what the marketplace can afford.

Figure 1 shows the present state-of-the-art in so-called conventional memory technology, in terms of capacity and access time. The technology ranges from the relatively small but fast semiconductor memory through moving head disc memory to the larger and slower bulk storage devices such as magnetic tape. Clearly most memory and storage technology is confined to magnetic phenomena. The exceptions to the magnetic dominance have been at the low-capacity, high-speed end with semiconductor technology and at the large capacity slow access end with the IBM 1360 and Precision Instrument Model 190 bit-by-bit optical technology.

The trends in memory and storage technology indicate a gradual (although sometimes rapid) trend up and to the left, i.e., toward larger and faster devices. Consequently, the aim of early holographic memory researchers was toward those areas where the payoff would be largest, i.e., 10^7-10^9 bit capacities with 1-10μsec access time for disc replacement. Similarly, the promise of extremely high data packing density afforded by holographic encoding encouraged research activity at the upper end of the spectrum to achieve terabit capacity.

Before we discuss the progress made to date, we shall review some of the basic concepts and components used in almost all holographic memory and storage devices. The holographic approach does not record individual bits but rather the optical interference pattern produced by two coherent light beams, one of which contains the information about the data to be recorded. This is shown in Figure 2. In general, the holographic approach requires that several unique components be arranged to produce a memory device. These are a source of coherent light, such as a laser, some rather conventional, but sophisticated, optical elements, a page composer to transduce electrical data into a form which can spatially modulate a light beam, a recording medium which records the information as a hologram, an array of detectors to transduce the reconstructed light pattern back into electrical signals and finally light deflectors or moving recording media to address various hologram positions on the recording media.

The principal advantages of recording data in holographic form include: (1) a natural distributive encoding by recording the information over the entire hologram rather than at discrete points, thereby reducing susceptibility to dust, scratches and recording media imperfections, (2) the data reconstructed during readout is projected directly onto a fixed photodetector array with 10^8 to 10^9 bits appearing simultaneously (i.e., a page-oriented parallel access) and (3) insensitivity of the recording medium placement relative to the detector array.
A logical distinction between various holographic memories can be made by first considering those which are truly read/write memories and are aimed at existing mainframe and peripheral technology and those which are directed at mass storage applications. While the basic technology in both applications is somewhat similar, the approaches to solutions require emphasis on different components.

READ/WRITE HOLOGRAPHIC MEMORIES

The major effort to date on read/write holographic memories has addressed capacities between $10^6$ and $10^9$ bits with access times measured in microseconds. Several domestic companies, including Harris Corporation, Bell Labs, IBM, and RCA, as well as several foreign laboratories at Siemens, Nippon, Hitachi and Thomson-CSF, have either developed breadboard memories or are actively pursuing development of major components which are required in holographic memories. It is beyond the scope of this paper to discuss in detail the work of each laboratory and to dwell on the progress made in developing individual components. It is sufficient to say that although progress on each holographic memory component has been significant over the past decade, a truly viable cost competitive memory has not emerged from the breadboard stage into the marketplace. Because of the interactive nature of all holographic memory components, a major advance in one area may produce only minor improvement in system performance.

Perhaps the two components which have received the greatest attention are the input page composer and the holographic recording media. In both cases, the performance limitation has been dictated by the availability of suitable materials. The page composer should contain between 4000 and one million elements. Various materials have been or are being considered, including PLZT, liquid crystals, thin deformable membrane mirror arrays and cadmium sulfide. All currently suffer from one or more shortcomings including uniformity, speed, contrast ratio and stability. The holographic recording materials have also received considerable attention and all candidates fall short of the desired properties of high efficiency, high sensitivity and long lifetime. Significant progress has been made in developing beam deflectors and photodetector arrays, stimulated in part by the requirements imposed on these devices by holographic memory researchers. The performance of beam deflectors has nearly doubled in the past ten years and sophisticated multielement two dimensional photodetector arrays were essentially unavailable ten years ago. Research in all component areas is continuing. We can expect significant breakthroughs only by application of new materials or through better understanding and perfection of existing materials.

Until recently, heavy emphasis was placed on preserving high speed access with no moving parts while increasing capacity. Clearly the target was disc replacement. Analyses of the constraints imposed on common optical components such as lenses as well as a better appreciation of physical limitations imposed on the electro-optical components has led most investigators to revise their pre-
This area has recently been improved enough to allow system applications. Since a one-dimensional (instead of a two-dimensional) page composer is typically required, device capability in this area is characterized by high cost per bit. Only in highly specialized applications where technical performance plays an over-riding part will we see this memory used. Even so, it is not likely to emerge from the research laboratory before the end of this decade.

**READ-ONLY MEMORIES**

Read-only holographic memories typically use film as the recording media. Once exposed, the film record is removed from the recorder, developed by normal techniques, and placed in a holding area until data retrieval is required. If any portion of the recorded data must be changed or updated, the entire record must be re-recorded and replaced within the memory. Read-only memories, therefore, are best suited for archival, non-dynamic memory applications or applications where updating is relatively infrequent.

Other than the recording media, the holographic exposure and data readout processes are similar to those used in a read/write memory. Similar devices are required to implement a read-only memory as are required to implement a read/write memory; hence, read-only memories are therefore constrained by similar device limitations. Possibly the most critical device limitation in read-only memory implementation has been the page composer. Since a one-dimensional (instead of a two-dimensional page composer) is typically required, device capability in this area has recently been improved enough to allow system applications.

One way to overcome the page composer limitation in holographic recording is to use a synthetic hologram approach. In this approach, a film intensity function is calculated by a special purpose digital processor and scanned onto the film by a scanning device. The resulting film exposure has nearly the same reconstruction properties as does an interferometrically generated hologram.

The recent advances in materials and components have allowed production of a few prototype holographic memories. For example, let us discuss some specific hardware systems being developed by Harris Corporation, Electronic Systems Division.

Synthetic holography has been successfully applied to the recording and storage of digital data in the Human Read/Machine Read (HRMR) System developed by Harris Electronic Systems Division under contract with the Rome Air Development Center. A research prototype, shown in Figure 3, was delivered in May, 1973 and an engineering prototype is currently under development.

The HRMR System addresses the document storage, retrieval and dissemination problem which is impacting both government and industrial complexes having large document data bases. The HRMR concept is based upon annotating a standard microfiche with the digital equivalent of the associated images. Optical readout of the digital data directly from the microfiche facilitates storage, retrieval and dissemination of data to both local and remote locations.

A direct extension of the concept is the full utilization of the microfiche film chip for digital data recording. Thirty megabits of user data per film chip is presently being realized at a packing density exceeding one megabit per square inch. Since this packing density is significantly below theoretical limitations, considerable improvement can be anticipated as components and techniques are further refined.

Utilization of holography as the digital data recording technique in the HRMR System provides an inherent immunity to dust, scratches, and film imperfections associated with practical hardware which is capable of functioning in an operational environment. Only normal microfilm storage environmental conditions are required. The recorded data is archival and optical readout of data is nondestructive. This results in a virtually permanent record and contrasts with magnetic media which suffers from signal loss and deterioration due to readout and long term storage. Of further benefit, the positional invariance property of holography facilitates readout and allows relatively simple and economical hardware configurations.

Microfiche generation in the HRMR System is accomplished by means of a laser recorder which scans onto a film chip both the human readable images and the synthetically generated machine readable holograms containing digital data. Digital data is recorded sequentially onto the fiche in 500 kilobit blocks and at data rates compatible with magnetic tape drives. Fiche are automatically developed and all digital data is verified by means of parity bits which are appended during the recording process.

**Figure 3—HRMR research prototype system**
Since the HRMR System storage media is oriented around the standard microfiche film chip, there is a maximum compatibility with commercially available microfiche handling equipment. It has been a straightforward development to configure a medium scale microfiche storage and retrieval device capable of handling approximately 7000 microfiche. Total digital store of this device is $2(10^{11})$ bits.

In the present HRMR System configuration, the mass memory is on-line to a PDP-11/45 computer. Random fetch of any 500 kilobit data block stored within the memory is provided with a maximum access time of less than 15 seconds. Transfer rates are compatible with DEC Unibus cycle times, but can be tailored to any host computer's channel characteristics and data absorption rates.

Because the holographic technique used in the HRMR mass memory is read-only, utilization of the system is projected to be oriented primarily toward archival data store applications in which the data placed in the memory is non-dynamic. Such data bases are quite common in both governmental and industrial organizations and are typically characterized by large magnetic tape libraries. A magnetic tape, having typical block sizes and utilizations, can be holographically recorded on one to two fiche. The 7000 fiche storage capacity of the holographic memory provides on-line access to approximately 3500 magnetic tapes with access times a fraction of manual retrieval, mount and read times. Based upon user requirements, additional holographic memory modules can be added to increase this capacity at least an order of magnitude.

Possibly the most significant characteristic associated with the HRMR System's holographic memory is simplicity of operation. The HRMR configuration has integrated into a mini-computer system, a $2(10^{11})$ bit memory and has made this data store available at a media cost of approximately $2.5 \times 10^{-4}$ cents per bit. In contrast to many other conventional mass memory approaches, which record sequential blocks and must retrieve blocks sequentially, the HRMR approach provides random access to data blocks without a sacrifice in overall access time.

While the use of the synthetic holography for storage and retrieval of digital data on microfiche provides a solution to document-oriented mass memory requirements, different recording techniques and physical record formats are more suitable to other types of applications. For example, the storage and retrieval of digital data in very large data records at extremely fast recording and readout data rates can be best handled using roll film and interferometric holography.

As with magnetic tape recorders, the large supply of continuously moving recording media allows very large (i.e., tens to hundreds of megabits) data records to be recorded and played back with little interface buffering. Roll-film formats also allow sustained data processing at hundreds of megabits per second. Thus, holographic recording on roll-film offers an extension of the large data buffer capabilities now offered by high speed instrumentation-type magnetic tape recorders. Currently, single transport magnetic tape recorders can operate at recording and playback speeds of up to 80 or 90 Mb/s and can store data at a linear density of about 600Kb/inch on one-inch wide tape. In comparison, holographic techniques can be used to record and reproduce digital data on single transport devices at several hundred megabits per second at linear packing densities that are at least six times greater than now practical with magnetic tape.

The Wideband Holographic Recorder Exploratory Development Model, also developed by Harris Corporation, Electronic Systems Division under contract with the Rome Air Development Center, uses roll-film format and an interferometric approach. This system has demonstrated the recording of data at 400 Mb/s and the readout of data at 40 Mb/s—a 10:1 slow down. Using interferometric Fourier transform holography, data is recorded in one dimensional holograms spaced on 15 micron centers across the film. Over 1500 such holograms, each containing 128 data bits, are recorded across the film which is continuously moving at approximately 2 meters per second. Figure 4 is a functional diagram of the system showing both the recorder and reader components.

About $3(10^{14})$ bits of data can be recorded on a 5000 foot roll of 35 mm film. Using recording rates of up to 500 Mb/s, non-stop recording could be sustained for a period of up to 9.5 minutes. Readout rates reduced by 10:1 or 100:1 from record rates are easily implemented and current development activities promise that readout speeds equivalent to record rates will soon be possible. Although recording is readily accomplished using roll-film supplies, once recorded, the film can be segmented and cassette mounted when faster, more random data access or distribution of duplicate data packs is desired.
In some applications, both the automatic storage and retrieval features offered by the microfiche recording format and the higher speed recording and readout capability provided by roll-film formats are desirable. Under contract to NASA Marshall Space Flight Center, Harris Electronic Systems Division is developing a Holographic Memory that incorporates some of the features of both HRMR and the Wideband Holographic Recorder. One of the goals of this system development is to record up to 80 Mb of data on a microfiche which is formatted into randomly addressable files.

CONCLUSIONS

During the past several years we have witnessed a considerable effort which was and still is being undertaken by many research laboratories to apply the principles of holography to a broad spectrum of memory and storage applications. The research is directed toward both the intermediate-capacity, fast access time read/write memory market as well as the large-capacity, longer access time read-only storage devices. Effort is also continuing in the specialized area of ultra-high speed transfer of data into and out of large intermediary bulk stores.

Read/write memories have not yet emerged from the research laboratory into the commercial marketplace. Efforts have been hampered primarily by the unavailability of suitable materials which are needed to configure several key memory components. Even if we assume that material and other technological problems are overcome, the prospects that holographic memories will seriously challenge other existing and emerging technologies before the end of this decade, indeed if ever, is unlikely. The inertia of magnetic technology coupled with remarkable yearly improvements in packing density, access time and transfer rates presents a formidable challenge to those who desire to penetrate that particular segment of the market.

The prospects for read-only holographic memories which have multi-microsecond access time and $10^6$ to $10^8$ bit capacity appear to be better because problems associated with high-speed page composers and reusable storage media are obviated. Unfortunately, the read-only property will limit its usefulness to special applications where data volatility, extreme environments and data security overshadow cost considerations.

The prospects for application of holographic techniques to read-only bulk storage appear to be much better. Systems with capacity between $10^4$ and $10^5$ bits and with multi-second access time are currently being built as engineering developmental units. At these capacities, costly electro-optical components can be justified. On a more modest scale, $10^7$ bit capacity, 1.5 second access time read-only storage units are already commercially available for application to the point-of-sale credit card verification problem.

To date, archival read-only optical memories using bit-by-bit recording techniques have penetrated a portion of the large capacity storage market. This market will grow as demand for larger common data bases increases. Although today's market penetration is being made by magnetic and bit-by-bit optical techniques, holographic techniques offer the most promising cost-effective approach for achieving high transfer speeds and large capacity. We believe that holographic storage devices will become commercially attractive well before the end of the decade.

REFERENCE
