HIGH CAPACITY OPTICAL DATA STORAGE AND RETRIEVAL SYSTEMS

RICHARD H. NELSON and THOMAS H. OTTEN
HARRIS Corporation
Melbourne, Florida

Introduction. Recording of digital data on photographic film is the practical solution to a broad spectrum of computer memory and data storage and retrieval requirements. Mass memory systems with bulk storage capacities between 10^{11} and 10^{13} bits with multi-second access times are currently being built. Development effort is also continuing in the specialized area of ultra-high speed transfer of data into and out of large intermediate bulk stores. Systems currently being produced by Harris Electronic Systems Division take advantage of holographic principals: (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) reconstruction of the data into parallel non-skewed channels, and (3) insensitivity of the recording medium placement relative to the detector array, greatly reducing mechanical tolerances necessary for rapid access and ultra-high speed data transfers.

The purpose of this paper is to present a synopsis of the current status of each of two storage and retrieval systems under development for the U. S. Air Force. The first system we describe (HRMR Microfilm Mass Memory System) uses photographic film in the form of microfiche to provide a mass storage capability with automatic, computer-controlled, random access to stored records. The second system we consider (Wideband Holographic Recorder) uses multichannel recording on roll film for storage and retrieval of large unit records at hundreds of megabits per second.

Mass Memory System. The HRMR Microfilm Mass Memory System is an information recording, storage, and retrieval system utilizing 4"x6" microfiche as the storage media. Both human readable (HR) and machine readable (MR) recordings (or a combination of each) can be generated. The human readable fiche containing 98 reduced text images conforms to the NMA, ANSI, and military DIAR 59-3 microfiche format standards for on-line recording of alpha numeric text or graphic arts scanned and digitized text. The machine readable format consists of 30 million bits of binary data storage recorded on seventy tracks with random access to any track during readout. Figure 1 depicts the combined HRMR microfiche format. Ten MR tracks can be exchanged for each HR row

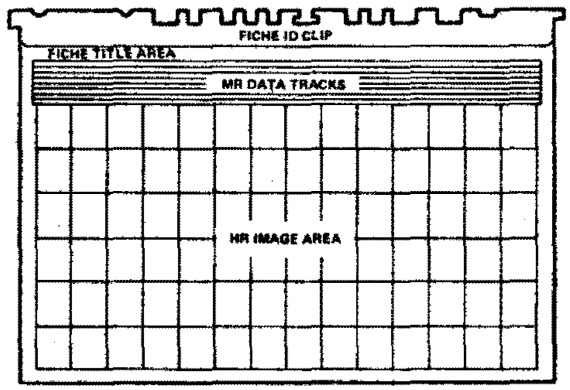

Fig. 1 - HRMR Microfiche Format

of 14 images. In this paper we will stress the features of the all machine read microfiche format.

The system components include a Controller unit (DEC PDP 11/45) with I/O peripherals; a recorder unit (RPV) to record, with automatic film processing and fiche verification (MR data validation); and a storage and retrieval unit (S&R) which can provide less than 15 seconds access to any one of 6750 microfiche for on-line access to a $2x10^{11}$ bit data base. Figure 2 presents the system block diagram.

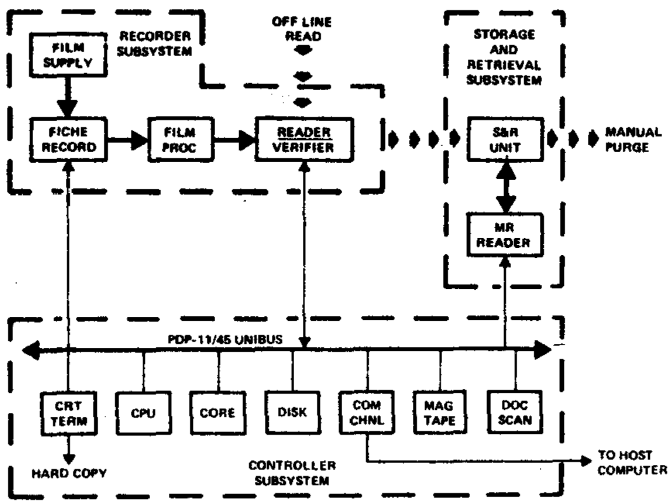

Fig. 2 - HRMR System Block Diagram

Mass storage and retrieval of fiche is accomplished by the attachment of an address coded metal clip affixed to the top of each microfiche (see Figure 1) and microfiche placement into the S&R unit. The S&R unit consists of readout electronics and nine carousel levels; each carousel (Figure 3) housing a maximum of 750 microfiche. To readout a particular fiche, the Controller provides the carousel level and fiche address for fiche extraction and subsequent readout.

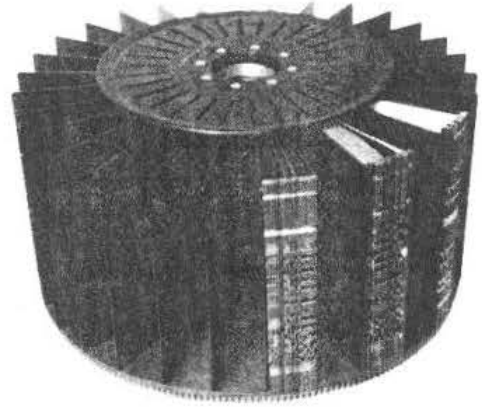

Fig. 3 - Fiche Carousel Module

Each system unit interfaces with the Controller via a standard DEC DRIIB and DRIIC interface and interacts with the Controller as a stand-alone peripheral operating in a responsive mode. Operational software developed for the system is file oriented and was patterned after tape and disc peripheral handlers. Existing DEC software is used to a maximum extent so that a minimum orientation is required to operate the system.

MR Record/Readout Description. The machine read (MR) data is recorded as a series of synthetically generated holograms (9000 per track along the 6 inch dimension) with each 1.3mm by 13μm hologram containing the Fourier transformation of 48 user bits. The Fourier transformation coefficients amplitude modulate a raster scanned spot to record each two-Rayleigh synthetic hologram. The components of the recorder are shown functionally in Figure 4. At computer data transfer rates, it is practical to perform the recording using this synthetic hologram generating technique. This approach is simpler and circumvents the stability and complexity of the two beam optical system required for interferometric hologram generation.

On readout, each hologram is illuminated with a coherent laser beam which is diffracted as a function of the recorded frequencies in the hologram. The diffracted beam illuminates particular photodetector diodes with a one-to-one correspondence to the recorded data bits. This is shown schematically in Figure 5. The spatial invariance property exhibited by the Fourier transform holograms significantly relaxes the mechanical positional tolerances required to accurately readout the densely stored data.

System Features. The HRMR System utilizes film as the storage medium which is characterized by low cost, archival life, and a minimum storage environment requirement. It features optical non-destructive readout of data. This results in virtually permanent records and contrasts with magnetic media which suffers from signal loss and deterioration due to readout and long term storage. Digital data recorded sequentially onto the fiche may be accessed in blocks of approximately 430 Kb and at data transfer rates

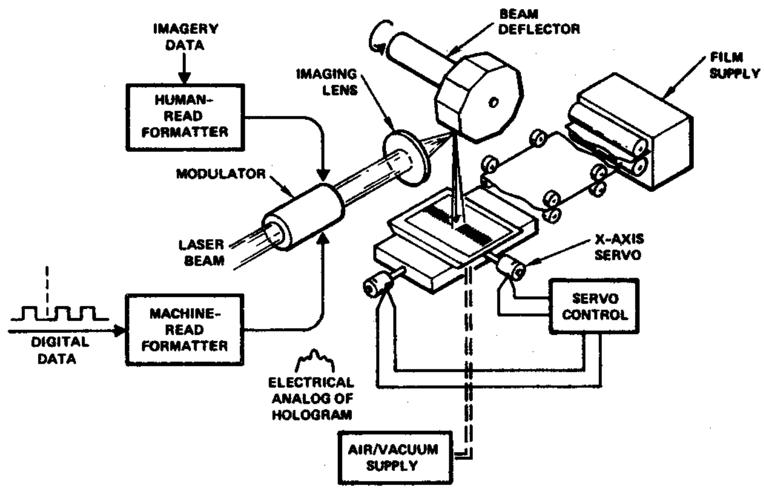

Fig. 4 - Record Conceptual Diagram

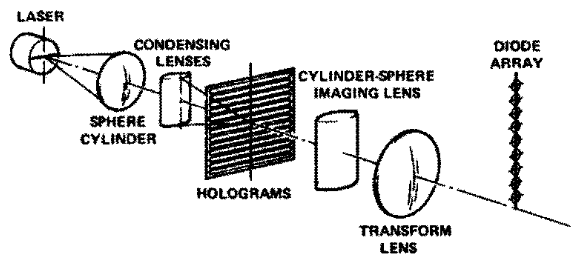

Fig. 5 - Hologram Reader Optics

compatible with magnetic tape drives. Based upon the concept of annotating a standard microfiche with the digital equivalent of the associated images, the HRMR system uniquely addresses the document storage, retrieval and dissemination problem which is impacting both government and industrial complexes. Optical readout of the digital data directly from the microfiche facilitates storage, retrieval and dissemination of data to both local and remote locations. The characteristics of the System make it most applicable to large archival, non-dynamic memories or to information storage where updating is relatively infrequent.

The system can be separated to provide an off-line recording facility and an on-line S&R facility interfacing directly with a host computer. The mass-store capacity is limited only to the number of S&R units installed at any facility and by the interface capability of the host computer.

Figure 6 is a table of the major system performance parameters for a minimum configuration.

Storage Medium:	4" x 6" Microfiche
Storage Density:	30 Megabits/Fiche MR 98 Images at 24X
Storage Capacity:	6750 Fiche (2 x 10^{11} Bits in MR Mode)
Record/Read Rate:	500 Kb/s
Transfer Rates:	Computer Compatible
Total Record/Process/Verify Time:	10 Minutes/Fiche
Throughput Rate:	2 Minutes/Fiche
Random Access to Fiche:	15 Seconds
Total Read Time:	2 Minute s/Fiche
Error Rate:	10^{-7} Maximum

Fig. 6 - HRMR Performance

Wideband Digital Recording System. To perform some special data handling functions, the recording and playback of large unit records of digital data at rates up to 1,000 Mb/s may be necessary. In anticipation of such needs, Harris has been developing and demonstrating a Wideband Holographic Recorder Exploratory Development Model. At this writing, recording and playback of digital data at rates up to 600 Mb/s have been demonstrated. The key to storage and retrieval of large unit records at hundreds of megabits per second is multichannel recording on rolls of photographic film using holographic techniques. The techniques that have been demonstrated can be extended to recording and readout rates exceeding a gigabit per second, and they readily enable us to slow down the data during playback.

System Approach. The holographic recorder/reproducer system has fundamental attributes that make high data rate recording and data reconstruction possible. First, the high rate digital data to be recorded is demultiplexed into several lower-rate data channels, each of which is clocked into the optical system in parallel. This procedure places the high speed requirements of the system upon the input electronics subsystem and reduces the dynamics of the optomechanisms, for example, light modulators and deflectors. The parallel data channels, at the demultiplexed clock rate, are simultaneously recorded into a single Fourier transform holograms The holograms are sequentially recorded adjacent to one another in roster-scan format across a continuously moving film strip. A significant feature of the rows of Fourier transform holograms is that the holograms can be sequentially addressed in the readout process by a scanning loser beam with a relatively relaxed degree of accuracy, due to the spatial invariance property and the larger dimensions of the holograms. The distributive nature of the Fourier transform coding provides some immunity to localized recording media imperfections.

As shown in Figure 7, the recording medium is in roll form; the EDM currently uses 35mm photographic film. Incoming data is demultiplexed into 128 parallel channels. One bit from each channel is stored in parallel in a one-dimensional hologram. Holograms are recorded across the 35mm film in rows that are on lmm centers, with 800µm devoted to hologram length and 200µm to inter-row guard bonds. With 1512 data carrying holograms per row, a linear packing density of greater than 4.9 Mb/in on 35mm wide film is achieve. For 16µm by 1mm hologram centers, the average packing density is $0.8x10^6$ b/cm^2.

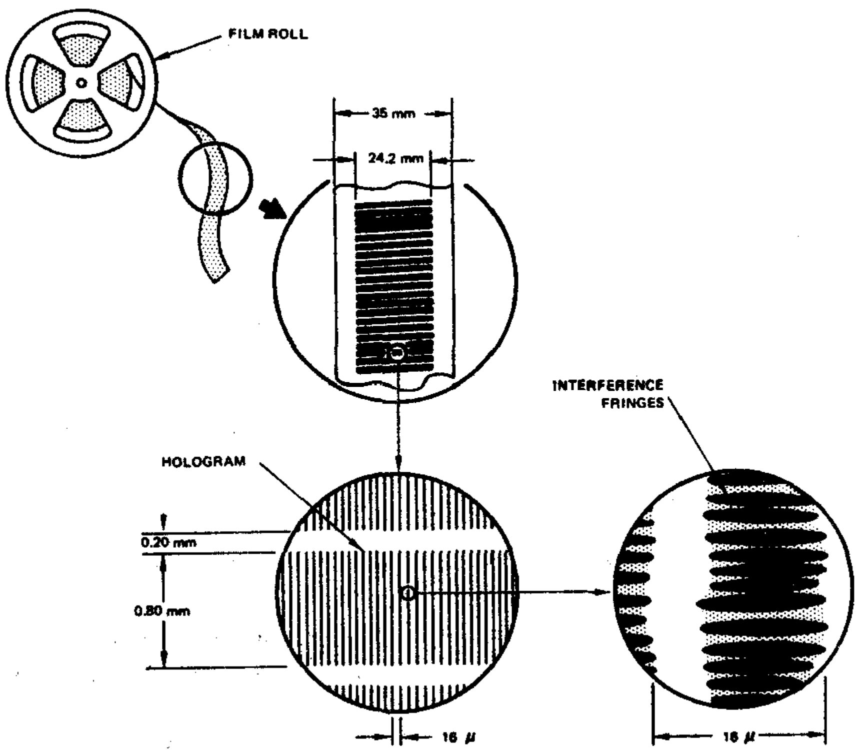

Fig. 7 - Wideband Recorder Film Format

Figure 8 depicts with much simplification the configuration of a Wideband Holographic Recorder like the EDM. This figure shows the externally modulated CW laser used for recording and readout illumination. The beam-forming optics split the loser beam and shape the two resultant beams into a signal beam and a reference beam. These two beams pass through the page composer, consisting of an acousto-optic device (Figure 9), to generate a 128-bit spatial pattern in parallel and a single-bit reference beam. The scanner sweeps these beams across the 35mm direction of the film through a transform lens. The transform lens forms the Fourier transform of the data along with the transform of the reference source. The interference pattern between the coherent signal wave and reference

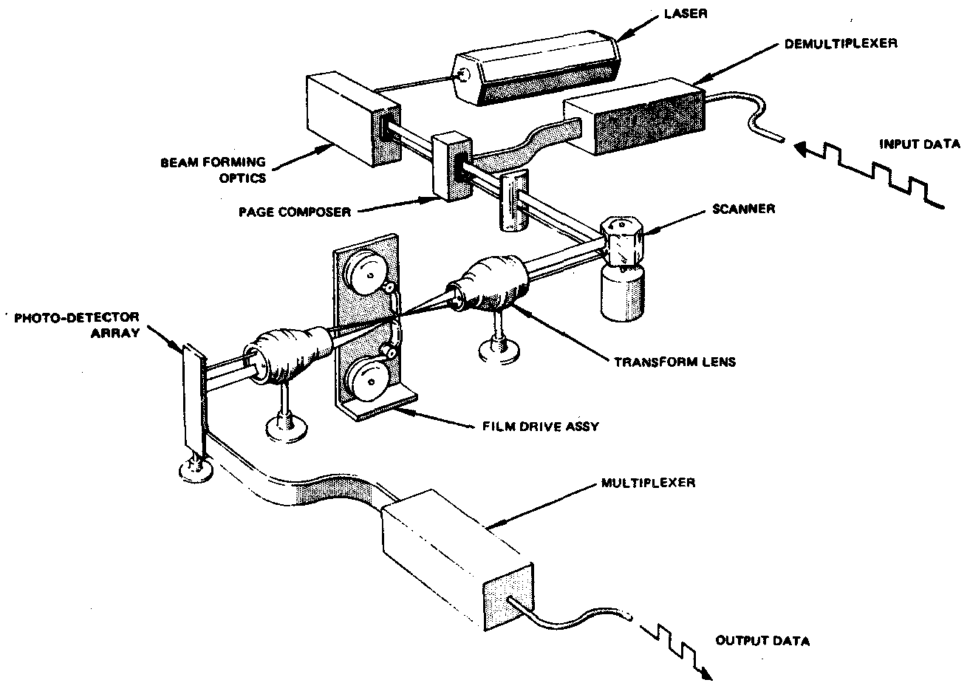

Fig. 8 - Widebond Holographic Recorder

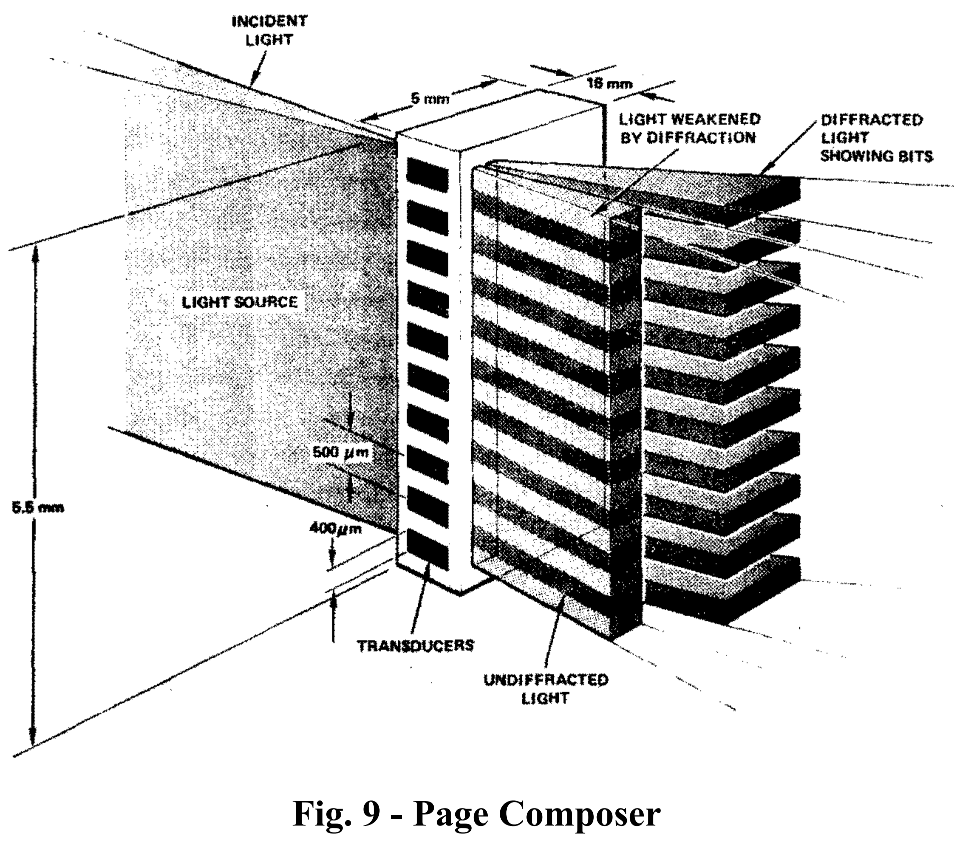

Fig. 9 - Page Composer

wave at the surface of the film forms the Fourier transform hologram. With the 128-bit data blocks recorded in the form of Fourier transform holograms, the information necessary to produce the individual bits is recorded throughout the relatively large area of each hologram. Hence, the hologram rows are much easier to address during the readout process than are the much narrower lines that are produced by a spot recorder. Also, since the light from each of the 128 input bits is distributed over the entire region of the hologram, this redundant recording technique makes it possible to read out the bits even if part of the hologram is destroyed.

After the film is developed and placed back on the drive assembly, the signal wave is regenerated from the hologram when it is illuminated by only the reference beam. An image of the original data record is formed and detected with an array of photodetectors.

Performance of the Exploratory Development Model. To make performance evaluations, we constructed coder/decoder electronics for error correction for several data channels of the 128 channels per hologram. The coder generates a 63 bit code word for each sequential group of 51 user data bits. Each hologram row contains 24 code words (per coded channel) storing a total of 1224 user bits. The decoder accomplishes error correction by outputting the most likely 51 bit sequence for each 63 bit code word that is reconstructed from the holograms. This coding/decoding technique is totally independent of user data content. Successive pairs of code words are interleaved to scramble burst errors.

The current Exploratory Development Model is capable of recording and reproducing data at row rates up to 750 Mb/s. With error correction coding as implemented, recording and playback of corrected data occurs at rates up to 600 Mb/s. We have recorded numerous rolls of film at 600 Mb/s and have been conducting diagnostic evaluation of data reconstructed at 60 Mb/s and 600 Mb/s. During this evaluation, we have operated the EDM at readout rates of 600 Mb/s and successfully produced error-free readouts on single channels reconstructed over approximately 200 feet of film. Typically, error rates on the order of 10^{-6} have been measured. Further component evaluation will provide us with information necessary to optimize the performance of the system.

System Capabilities. Figure 10 provides a chart indicating the capabilities of two Wideband Loser Recorder Systems compared with an IRIG wideband magnetic tape recorder. This chart is derived using the data packing density and film thickness from the EDM. Note that the data packing density in the laser recorder is independent of recording speed and is about five times greater than that of the magnetic recorder. Furthermore, even at 600 Mb/s the film speed is only a fraction of the 80 Mb/s magnetic tape speed. We predict that even more significant performance will be achieved with further development of the laser recorder. Potentially, a factor of two improvement in data packing density will be possible. This will enable the recording of data at a rate of 600 Mb/s for 25 minutes on a single reel of recording medium with no mechanical or temporal skew of the data upon full or reduced speed readout.

DESIGN PARAMETERS	LASER RECORDING		MAGNETIC
	600 Mb/s	300 Mb/s	80 Mb/s
CHANNEL PACKING DENSITY	60.96 kb/IN	60.96 kb/IN	24.8 kb/IN
NUMBER OF CHANNELS	128	128	24
TOTAL LINEAR PACKING DENSITY	7.8 Mb/IN	7.8 Mb/IN	0.6 Mb/IN
FILM OR TAPE WIDTH	2.76 IN (70 mm)	2.76 IN (70 mm)	1 IN (25.4 mm)
PACKING DENSITY	2.83 Mb/IN^2	2.83 Mb/IN^2	0.6 Mb/IN^2
FILM OR TAPE SPEED	79 IPS	39 IPS	135 IPS
RECORDING MEDIA REEL	5000 FT OF 0.004 IN ON 18 IN REEL	5000 FT OF 0.004 IN ON 18 IN REEL	10,800 FT OF 0.001 IN ON 15 IN REEL
RECORD TIME (APPROX)	12.5 MIN	25 MIN	16 MIN
TOTAL DATA CAPACITY	450 Gb	450 Gb	76.8 Gb

Fig. 10 - Comparison of Loser and Magnetic Recorders

Conclusions. Mass memories capable of storing 10^{11} to 10^{13} bits of information on line with computer controlled random access to data records can now be produced. With the successful demonstration of 600 Mb/s recording and read rates on roll film, we can now produce engineering prototype wideband recorders. Such recorders offer significantly greater capability as a large, high-speed data buffer than available magnetic-tape systems.

Acknowledgements. The HRMR Microfilm Mass Memory System is presently under development for Rome Air Development Center under the guidance of Mr. F. Haritatos.

Continuing support for wideband holographic digital recording is being provided by the Defense Advanced Research Projects Agency and the Air Force Systems Command, Rome Air Development Center, under the guidance of Mr. A. Jamberdino.