Holographic Storage: Overcoming Limitations of the Optical Disk Medium for Applications in Libraries, Archives, and Information Centers

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Abstract

Imaging, the application of digital technology to the management and manipulation of information in non-digital format (paper, etc.) is an attractive possibility for offices. However, directors of libraries, archives, and information centers have been reluctant to fully embrace imaging because it consumes voluminous quantities of expensive storage space, and because of unsatisfactory retrieval times. Holographic technology, in which date is stored in three dimensions and is returned simultaneously, will make large scale digital conversion projects practical.

Limitations of two-dimensional optical storage media are contrasted with the holographic medium. Also described is how data is written to and read from a crystal.

Imaging Large Databases: Optical Disk Limitations

Imaging is the application of digital (i.e., computer) technology to the management and manipulation of non-digital media such as paper, photographs, pictures, microforms, and voice. Imaging provides secure electronic storage (albeit for a period less than archival), multiple access points to identify and rapidly retrieve documents from its electronic database, and document dissemination to external users. For archivists, digitization allows usage and even circulation of brittle or rare materials.

Not surprisingly, several libraries and information centers are engaging in pilot imaging projects. These include imaging of some 50,000 law books at Columbia University, the black and white photograph file at the Denver Public Library, color slides for classrooms and learning labs at USC, and fragile sources at Yale. (1)

However, storing large-scale images poses severe problems for the WORM (Write Once, Read Many times) optical disk commonly employed for data storage. "Digitalization of images creates enormous problems of storage space and [consequent] costs...Storage capacity has increased and cost has decreased by more than 20% per year and seems to be continuing in that direction. But this may still not be enough to make digital storage a [financially] viable alternative for a large collection." (2)

Unfortunately, many applications require high resolution and even color pictures, which voraciously consumes memory space. "Because image quality is so important, images [must] be stored at fairly high resolutions creating a mammoth storage problem."(3) Text scanned at 200 dots per inch (dpi) is acceptable for reading. However, to reveal details with sufficient clarity, images in pictorial databases must be minimally scanned at 400 dpi. That requires storing exponentially greater quantities of data (200 x 200 = 40,000 bits per square inch; but 400 x 400 = 160,000 bits per square inch). Consequently, even after compression, a process whereby the computer stores white space according to a code rather than accepting each space, "A high quality picture in colour may contain 160 Mbits -- that is 20 Mbytes -- or more, of data." (4)

In fact, compression may not help at all. "... continuous tone images do not compress well compared to line drawings or text. Lossless compression will typically give reductions of no more than 3:1. Compressions that involve loss will give greater storage savings, but because they involve a loss of quality they may yield unacceptably bad images.." (5)

Therefore, authorities caution that "Integrated picture databases -- where one can search data records and display picture images on the same screen -- are not practical for most uses due to their extensive memory and storage requirements." (6) Storage space is not the only problem. Intolerable response times are common when retrieving voluminous data quantities. "One problem with such disks is their slow read rate (around 150KB/s). (7) "...Vendors have realized that the optical disk is very poor in its ability to deliver high-speed transfer of images." (8)

Analog videodisc is no alternative. "For some applications where...high quality detail must be maintained, such as pages of text, or technical images...analog video disk storage is clearly not suitable." (9) The reason is that "The standard American video signal (NTSC) does not contain enough information to adequately display an overview of a base 50 cm high. The figures are blurred and many of the lines of paint which define details are completely lost." (10)

Finally, large databases require multiple optical disks, which necessitate a jukebox to exchange automatically and load disks into the optical drive. Exchange cycles range from five seconds to three minutes in cases where multiple users are waiting in queue. Furthermore, "Jukeboxes are often the single most expensive device in an imaging system." (11)

Density is thus a crucial issue in mass storage applications, some of which may require capacities ranging from 100 gigabytes (one gigabyte = one billion bytes) to multiple terabytes (one terabyte = one trillion bytes). Fortunately, a new storage medium is close to perfection, which will permit storage capacities and retrieval speeds required for large scale image/picture database applications. This is the holographic medium.

Optical Disk Medium Contrasted with Holographic Medium

Summarizing how the optical disk medium functions will illuminate its limitations for large-scale databases. On the surface of the WORM (Write Once, Read Many times) disk, the kind most commonly used in imaging applications, the write head, which is a laser beam, burns a pit to indicate a one, or it skips a space (e.g., a land) to indicate a zero. The ones and zeros constitute digitalized data, combinations of which represent alphanumeric characters. Data are interpreted by the read head, a laser beam of lesser power, passing over the surface of the spinning disk and reporting to the computer that it has encountered either a pit or a land. Differences in reflectivity between pits and lands triggers an appropriate electrical signal to the computer causing it to reconstitute the data into human-readable information. Information is encoded on a flat surface and is retrieved sequentially. These are sources of inherent limitations overcome by holographic storage:

Holography outperforms optical in the following areas:

1. Density. Optical disks store data in two dimensions -- on the flat surface of tracks or grooves. Disk technology is reaching its physical storage limits because discrete data bits cannot be crammed substantially closer than they are now. "The limiting factor for the amount of storage in both magnetic and optical processes is the closeness of the spacing of bits on the discs. The closer the spacing the more difficult it is to detect discrete bits." (12)

Holography stores data in three dimensions, thus creating exponentially greater storage space. This difference is analogous to storing file cabinets not only on the floor, but also to the ceiling of a warehouse.

[Figure 1]

2. Speed. Disks are slow because data are written to and retrieved from them one bit at a time. Whenever one thing must wait upon the processing of another, delays are inevitable. Holography avoids this logical impasse by storing and retrieving whole images at one time, even though each image may consist of millions of bits.

Slow retrieval also occurs as a result of read-write heads waiting several thousandths of a second for data to arrive on the spinning optical disk. That may sound negligible, but waiting for millions of bits to return can become intolerable. Holographic retrieval does not depend on moving parts. Laser beams manage entire blocks of data in a millionth of a second, thus allowing massive data storage or retrieval virtually at once.

For these reasons, in the same time required by disk technology to store or retrieve one bit, i.e., one pit or one land, "...all one million bits of data stored in a layered "page" within a holographic memory crystal could be retrieved or written at the same instant." (13) Incredibly, more information can be retrieved from a holograph tile in one second than could be retrieved from a computer's disk drive in five hours. (14)

3. Resolution. Because holographically stored data is retrieved instantly, trade offs between storage density and scanning resolutions will cease to be an issue in pictorial databases. Image clarity will be excellent.

4. Portability. Like CD-ROM systems, the WORM and erasable optical disk media require high power consumption and because they have delicate moving parts, their drives are impractical for portable computers. Conversely because it has no moving parts, holographic technology is transportable.

In summation, holographic storage overcomes the density limitations of disks by utilizing three dimensional storage rather than two. It overcomes limitations on retrieval speeds by returning entire images simultaneously rather than sequentially, and without the delays inherent in moving parts. Holography will permit highly detailed resolution. As a side benefit, it is portable. Knowing the components of a holographic system and how they function will develop an appreciation of its potential.

Holographic Imaging Components and Functions

Holographic systems are ingenious combinations of components and techniques from the fields of computer and laser technologies, optics, crystallography, and solid state chemistry. Four major components each fulfill specific functions: the tile, lasers, optics, and detectors.

1. The tile. Data are stored within a tile. Each tile consists of a glass substrate and a photosensitive medium. The latter is a photorefractive crystal for rewritable applications or a polymer film for write-once applications. A tile is organized by, is made up of, "pages" and stacks. These stacks, which constitute the Read/Write storage medium, are crystals. They are what makes holographic storage unique; it is a crystal based technology. Rather than a single crystal, the Tamarack Laboratory, a leader pioneering in holographic technology, utilizes an array of small crystallites.

The crystals are referred to as stacks because within each crystal, data are layered, or stacked to form "pages." Approximately 30 vertically arranged pages constitute one of the 4,096 stacks embedded within the photosensitive medium. Vertical arrangement enables data storage across three dimensions of width, length, and depth. Each pages contains 8 KB of storage. Thirty pages contain 240 KB.

Presently, a tile can store 983,040,000 bytes, or nearly one gigabyte of data. Increasing the pages per stack increases capacity. Tamarack already has achieved 50 pages per stack, which approximates 1.6 gigabytes per tile. Before long, "Advanced versions...will be able to store more than ten gigabytes...of data...in a volume smaller than a sugar cube." (15)

Each stack contains about 30 pages or 240 kilobytes of data, which totals to 914 megabytes of raw data. Tens of thousands of such pages can be stored in one system.

Pages are created by changing the angle of light (see below) as it passes through the crystal. As many as 30 such pages can be created in this manner. Each page consists of millions of bits, and as many as 100,000 pages are stored in a crystal.

[Figure 2]

2. Lasers, and

3. Optics. As with optical disk media, laser beams write data to the medium and read data from it, but in holographic systems, it is done to/from a crystal medium. To record an image, a laser beam is divided into two parts by a beam splitter. One ray, the data beam, then passes through an optic device or separator that, acting like a photographic negative, blocks out part of the light, which travels on angle to a "reference beam positioner." The remainder passes through on its way through a "page composer," which contains the data in the form of thousands of opaque and transparent squares that in the aggregate looks like a crossword puzzle. These dark and light squares represent, of course, information encoded in binary form. As the light passes through, it picks up the patterns on its way to entering the crystal.

Meanwhile, the second beam, known after splitting as the "reference beam," bounces off a beam positioner and is steered into the crystal storage medium, which in the Tamarack system is strontium barium niobate (SBN). The two beams meet at a precise angle and create events at the molecular level (see below).

Passing through a spatial light modulator, the data beam picks up digital information as a pattern of dark and light spots. The data beam intersects with the reference beam in the crystal to form a hologram (like the hologram on a credit card), which is recorded as a page of information. In other words, the intersection of the two beams creates an interference pattern of light and dark areas, i.e., ones and zeros, at which point the crystal's optical properties change, thereby allowing data to be encoded into the crystal by the action of the light.

Understanding why the crystal's optical properties change requires recourse to the principles of solid state chemistry. At the atomic level, when two separated light beams meet at the crystal, their energy excites electrons within the crystal. As the excited electrons move about, they refashion the crystal's lattice, resulting in a change in the crystal's light bending characteristics, that is, in its optical properties. The holographic scientists are taking advantage of the fact that optical properties change as a result of interactions between the incoming photons and the electrons bound within the crystal.

Additional pages are recorded onto the same crystal but with the reference beam set at a slightly different angle. Only a fractional change in the angle at which the laser beam meets the crystal is sufficient to alter its light bending characteristics. This allows for the crystal to be re-shaped in numerous ways. Re-shaping is accomplished by stacking the two-dimensional pages (that contain the dark and light areas) one on top of the other. Stacking forms the hologram, which allows multiple data to be stored at the same location, thus creating a vast third dimension of storage space at the sub-microscopic level.

4. Detector. For data retrieval, the reference beam alone is shone through the crystal. It is aimed at the crystal at exactly the same angle used to write the information. Consequently, its light is bent in such a way that the original image of the page is located and reconstructed. The detector is a CCD (charged-coupled device) that reads information from the laser when it focuses on a stack and converts the light pattern back into digital electronic signals useful to the computer. Note that entire images are stored or retrieved simultaneously, bypassing the bit-by-bit processes of the hard disk or WORM media.

Different pages are retrieved by pointing the reference beam at different angles. This is the source of a serious, but not insurmountable obstacle. Steering a single reference beam is inherently difficult. One solution announced by Bellcore, a consortium owned by the seven Bell regional operating companies, is to use a chip containing 10,000 microscopic lasers. Each laser points at the chip at a different angle. Retrieval requires turning on the correct laser, which is faster than trying to steer a single reference beam. (16)

To repeat for clarification, a laser beam is split into a data beam and a read beam. One picks up data, and then they intersect to set up an interference pattern, which becomes a hologram within a crystal to store information in three dimensions. Retrieval is essentially a matter of re-focusing on the desired hologram.

Additional Applications

In addition to what it will do for the imaging industry, holographic technology has other exciting applications. "The ability to transfer large numbers of bits could make systems useful for new types of ultra-fast computers that harness thousands of processors working in parallel. Such memories might also work well with neural networks, which are computers modeled on the brain. And the ability to store or retrieve an image at once could also allow computers to display video more easily. You could see it as a replacement for VCRs..." (17)

Indeed, "Bellcore is studying holographic storage as a way to deliver movies on demand to homes over optical fibers or cable television. Currently, a two-hour movie takes two hours to transmit. In the future, a movie might be transmitted over fiber with extreme rapidly to be captured by a holographic storage system, then played back at regular speed." (18)

Holographic technology may eliminate hard disks. According to one report, a "...prototype holographic memory device is planned as a replacement for hard-disk drives in personal computers, although military or supercomputer applications may come first." (19)

Durability

Testing is being conducted to determine the effects of heat, light, and humidity in a variety of environments. One positive finding is that "long term exposure to Ultra-Violet rays actually helps solidify data." (20)

Cost

What will be the per unit cost of holographic storage? Although figures have not yet been made available, price indications are encouraging. Industry observers report that Tamarack aims to make the optical disk "obsolete" as an imaging medium. "Its technology is seen as a potential replacement for ...CD-ROMs in applications that require storage and quick access to large amounts of information." (21) That demonstrates that the company intends to financially compete against it.

Conclusion

Tamarack is a spinoff of the Microelectronics & Computer Technology Corporation (MCC), a 103 member electronics industry research group. As an information management professor and as a participant in the imaging industry, this author enthusiastically agrees with the industry executive who recently predicted, "If there's anything that MCC will do that will change the world, it will be holographic storage." (22)

Notes

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[16] Pollack, "The Hologram Computers of Tomorrow," F9.

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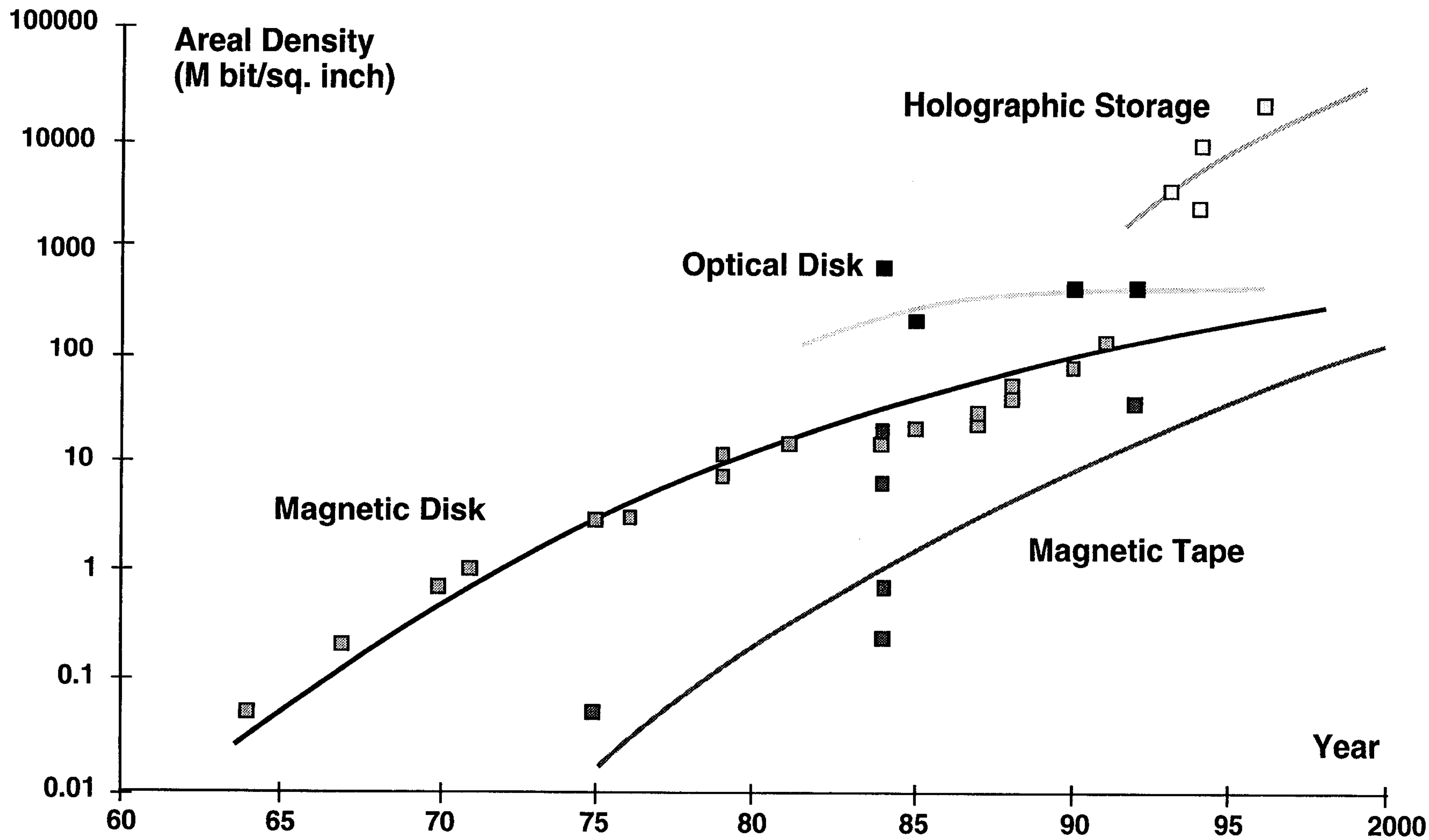
Storage Capacity Curves



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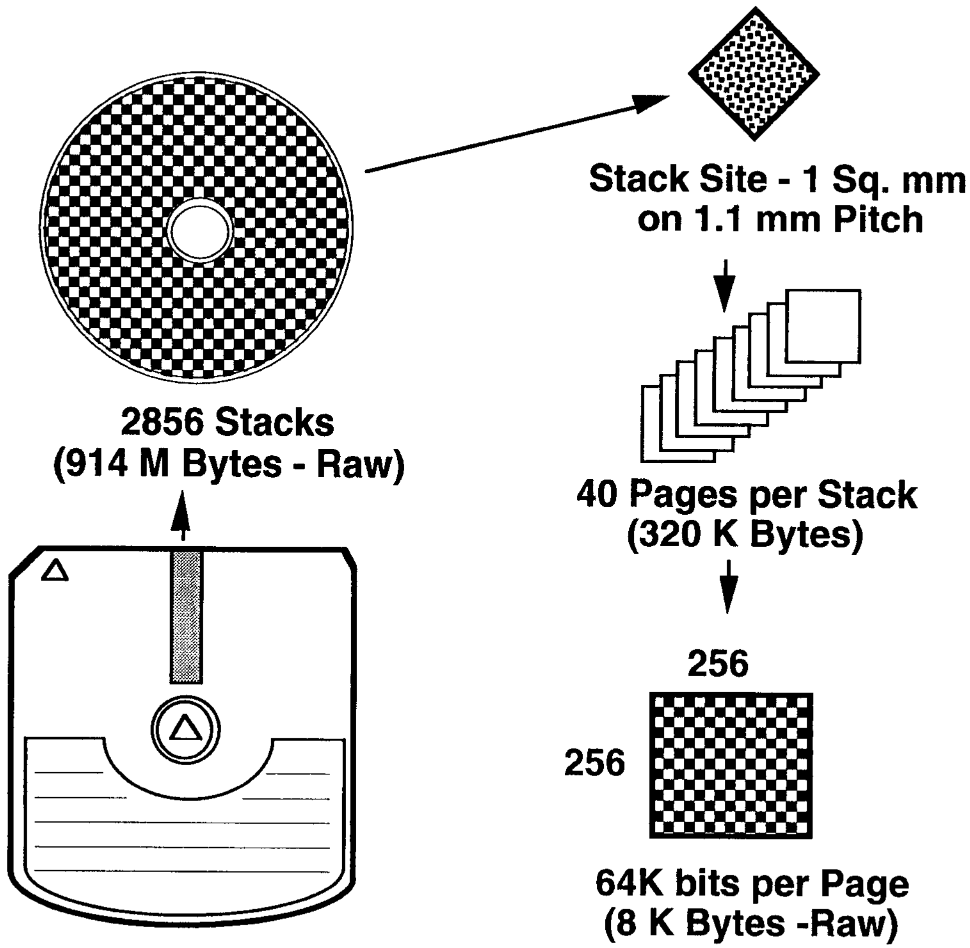

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