FUTURE TRENDS IN HARD DISK DRIVES

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ABSTRACT—Magnetic hard disk drives have significantly improved in size, performance and cost due to many technological innovations; including magnetoresistive heads, low noise thin film disks, PRML channels and advanced mechanical actuators and motors. By analyzing specification trends of each new disk drive design, a perspective of this evolution can be developed and design characteristics of future disk drives can be estimated.

I. INTRODUCTION

The rapid evolution of magnetic hard disk drives in form factor, performance, and cost during the past 15 years has been the direct result of many technological innovations applied to these products. These include magnetoresistive heads for areal densities approaching 1 Gbit/sq.in., PRML data channels for media data rates exceeding 14 Mbytes/sec, mechanical improvements for 3.5 inch, 2.5 inch and smaller form factor designs, spindle speeds exceeding 7000 RPM, reliabilities as measured in MTBF approaching 1M POH, and finally OEM price/MB less than $0.20. Analysis of specifications and parameters for disk drives allows a quantification of these trends to be developed so that extrapolation of progress to the year 2000 and beyond results in a projection of future disk drive characteristics. A basic assumption here is that relatively continuous progress will be made, i.e., no major redirection of the technologies will occur throughout the useful lifetime of magnetic hard disk drives.

II. AREAL DENSITY

The areal density of information stored in hard disk drive products is currently advancing rapidly (Fig. 1). As shown, the compound growth rate is an astounding 60%, driven by technical progress in producing advanced magnetic sensors as magnetoresistive heads as well as through the use of smaller form factor drives. Prior to 1991, development of thin film inductive heads continued areal density growth at about 40% CGR. Merging of small form factor drives with key technical advances such as thin film magnetoresistive heads, thin film metal media, and digital PRML channels dramatically changed the slope of areal density growth in products after 1991. As this trend presently continues, one may expect that areal densities approaching 10 Gbits/sq.in. to be realized by the year 2000, based on an extrapolation of the data. Laboratory demonstrations of MR heads which achieved areal densities of 1, 2, and 3 Gbits/sq.in. [1], [2] indicate that disk drives with capacities much larger than those available today are very likely. Progress beyond these areal densities will require head advances such as the spin valve or giant MR structure which maintains sufficient signal amplitude at very small geometries [3]. Beyond the year 2000, disk drives will enter a regime bounded by the superparamagnetic limit, estimated to be nearly 100 Gbits/sq.in. At this point, magnetic domains within the disk's magnetic film become too small to remain stable at room temperature. At this point a new, non-magnetic recording technology may be required [4].

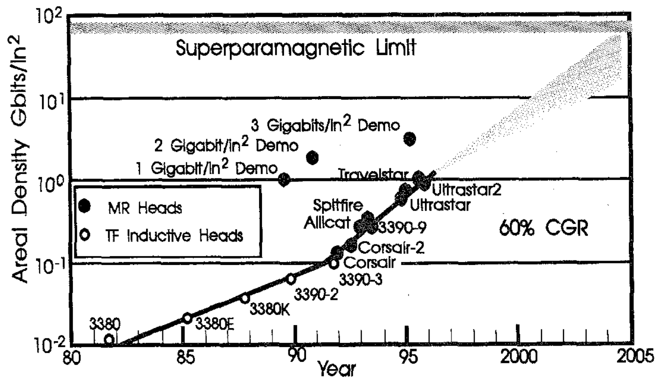

Fig. 1. Areal density trends with MR heads attaining a 60 % CGR

III. FORM FACTOR EVOLUTION

Since the early 1980's, the disk drive industry has adopted a progression of smaller form factors based on scaling. This has resulted in products with disk diameters of 130 mm, 95 mm, 65 mm, 48 mm, and 34 mm. While the primary reason behind this evolution has been space constraints of desktop personal computer systems, workstations, laptop, and handheld computers, other significant advantages in smaller form factors have been very evident. In addition, advances in head, disk, interface, and channel technologies, combined with these novel design concepts have allowed miniaturization to go forward while simultaneously improving storage capacity and performance. With continued progress in magnetics, mechanics, and electronics, one can envision the path to even more compact and efficient disk-based storage devices continuing into the next decade [5].

The impact of the rapid areal density increase is to correspondingly increase storage capacity per disk, allowing smaller disk diameters and smaller form factors while still maintaining high capacities. Fig. 2 indicates that 3.5 inch form factor drives, originally developed for personal computer applications, have sufficient gigabyte capacity to be used for large system storage. In fact, this 3.5 inch form factor is a basic disk drive design for RAID subsystems which have storage capacities in the hundreds of gigabyte and use over 60 drives per box. Smaller form factor drives such as 2.5 inch and 1.8 inch

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are expected to increase in capacity based on areal density increases, and it is possible to predict 2.5 inch drives with greater than a 10 GB capacity will be available by the year 2000. At a similar rate of progress, a 3.5 inch drive could store up to 90 GB; and system performance as well as architectural considerations will be necessary to determine the value of having 90 GB under one actuator.

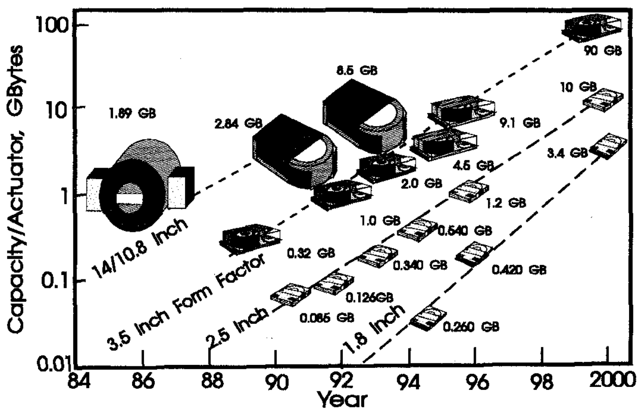

Fig. 2. Disk drive form factor evolution

Considering the evolution of the storage industry and its technical progress, it is an open question whether a substantial market will develop for every form factor. Experience has shown a number of products have developed around each of the 5.25″, 3.5″, and 2.5″ form factors, with a wide spectrum of capacities and performance available in each. The achievable capacity, performance and cost must be attractive for the required application. The smaller 3.5″ and 2.5″ form factor disk drives are now finding broad use in portable, desktop, workstation, and server environments, as well as becoming the building blocks for large (mainframe) storage systems in array configurations, as was previously discussed. These reliable units are enabling novel applications such as digital libraries, and on-demand systems of video servers and printing.

Fig. 3 indicates the evolution of disk drive capacities with time and is determined by the areal density increase as shown in Fig. 1. Several examples of disk drive form factors, each with the most probable numbers of disks per drive, are indicated as increasing in drive capacity. The lower bound in this case is an arbitrary region in which a minimum in useful disk drive capacity is allowable. Lower capacities are not of interest as a storage device, and the limit continuously increases with time as the demand for more storage develops with new operating systems and raw capacity requirements for data storage. An upper bound is predicted based on increasing areal density and corresponding linear density, that is, a limit in the fundamental ability of the electronic channel to operate at very high media data rates is reached. A discussion of data rate effects of disk drive design will follow in a subsequent section.

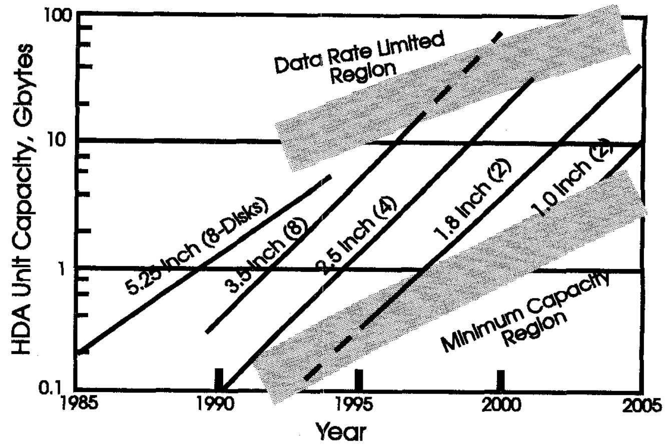

Fig. 3. Disk drive unit capacity evolution

IV. PRICE DECLINE

The rapid reduction in OEM price/MB for disk drive storage is shown in Fig. 4. For comparison, recently available expectations for the OEM price of semiconductor storage is shown as well. It is expected that by the end of the year 2000 the OEM price of 64MB DRAM will be below \$10/MB, falling at a decrement rate of 24% per year. In contrast, one can predict on the basis of current cost trends, that the price gap between semiconductor and disk drive storage may widen [6]. Disk drive prices can be expected to be well below \$0.01/MB, falling at at rate of 40% per year. The basic unit cost of a disk drive is decreasing slightly, due to improved manufacturing of the simpler, smaller form factor drives. Moreover, as areal density progressively increases at 60% CGR, each drive will retain a higher storage capacity thereby reducing price per MB. The near 40% decrease in prices as shown can be mathematically linked to the areal density CGR, as the factor $\{(1/1.60)\ -\ 1.0\}$, assuming a constant relationship between price and unit cost. At this price decline, disk drive storage will continue to be attractive for a broader range of applications than have previously been imagined.

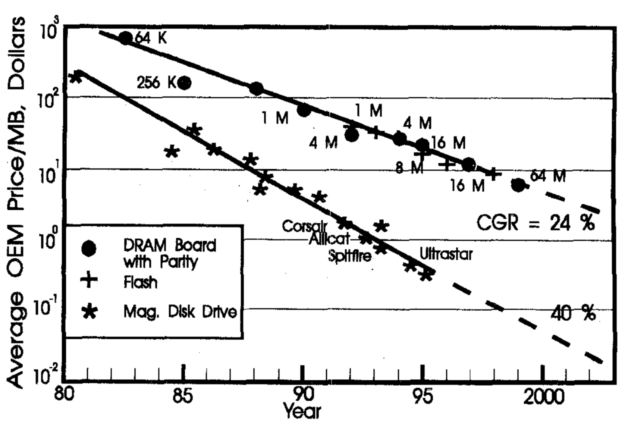

Fig. 4. Disk drive price decline compared with DRAM

V. MEDIA DATA RATE AND SPINDLE SPEED

The recent evolution of media data rate is illustrated in Fig. 5. Currently the compound growth rate is about 40%, and expectations are that data rates in the range of 50 MB/sec will be realized by the end of the decade. This progress will come as a result of advances in head and disk technology which will allow higher linear density, and disk drive design which will enable higher disk rotation. The ability of electronics to support the higher data rates will also be vital, with the constraint of raw silicon performance as well as power dissipation playing major roles in influencing designs.

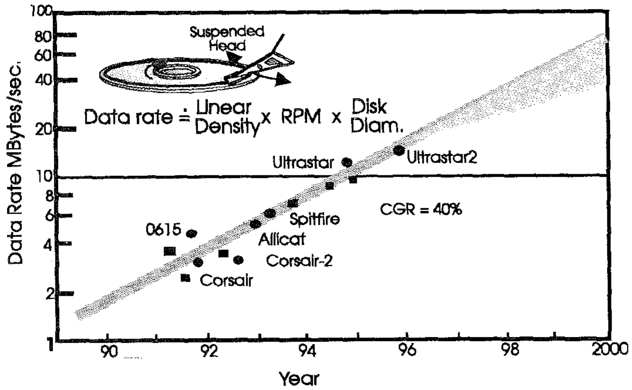

Fig. 5. Media data rate trend

As shown in Fig. 5, achievable data rate is the product of disk diameter, linear density, and disk rotation speed. With disk diameter either remaining constant in a given form factor or decreasing as the momentum to smaller sizes continues, higher media data rates will thus be critically dependent on advances in linear density and disk RPM. Linear density improvements will be realized through advances in heads, media, and flying height. Scaling to smaller head geometries to achieve higher linear density will undoubtedly be important. Efforts on improvement in linear density will also be focussed on enhancing base signal to noise of a head. This may be realized by increasing head sensitivity through efforts such as the recent "spin valve" heads.

To enhance disk capacity a technique known as zoned recording is now employed throughout the industry. By attempting to maintain a nearly constant linear density from inner to outer diameter tracks on a disk, less unused surface area results and disk capacity increases can approach the theoretical limit of 50%. The penalty for this is increased media data rate which can vary as much as 2X from inner to outer tracks. Besides increasing the complexity of the electronic data channel, which now must function over a range of data rates, new and higher data rate requirements are to be met by the electronics.

Spindle rotation speed can be increased through improved motor and bearing design, although power dissipation may provide a constraint due to battery or thermal limits. The available torque for a given motor design may be limited by the volume available for the motor in a small form factor drive, particularly in one designed for rotation speeds of 10,000 RPM or higher. Power dissipation due to air shear is known to be dependent on nearly the third power (2.8) of the disk rotation speed [5]. This factor alone can provide a critical limit to the performance of a given drive design, particularly for systems in which battery life is critical. The uses of 3.5 inch form factors, or smaller, are allowing higher RPM's, decreasing rotational delay, or latency, as shown in Fig. 6. The significantly reduced air drag for the smaller diameters, as well as smaller moment of inertia and ease of balance, all make the smaller diameter disks suitable for high RPM. With rotation rates well above 10K RPM on the horizon, rotational latencies of disk drives approaching a several milliseconds can be expected. These higher speeds will place a greater emphasis on spindle motor and bearing designs for low power and less heating, improved precision in rotation with no distortions, and higher reliability.

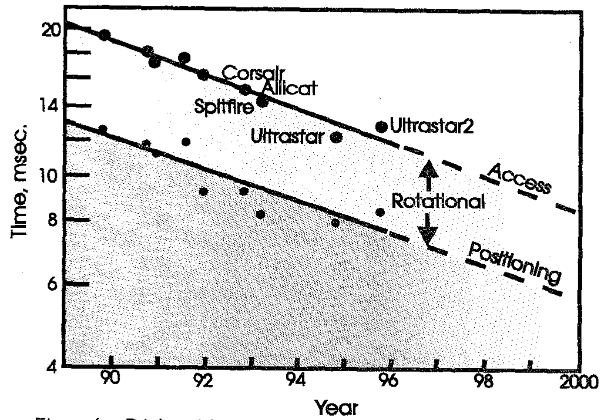

Fig. 6. Disk drive position, rotation and access times improvements

Fig. 6 also indicates that positioning times, based on the mechanical motion of the actuator, is significantly decreasing and that this trend is continuing throughout this decade. High speed actuator motion combined with the shorter data bands of smaller diameter disks is responsible for this improvement. Positioning or seek times approaching 6 ms. or less are achievable with low mass actuator designs as well as highly efficient voice coil motors.

The electronics ability to support much higher media data rates will also be critical for progression of storage technology. Current advanced channels operate at data rates up to 14 MB/sec using electronics clock rates well over 100 MHz, with signal to noise ratios high enough to support on-track error rates of 1E-9. The electronics system includes high performance write circuitry, broadband low noise input amplifier, efficient digital filter and equalizer, high speed A/D converter, clocking circuitry for timing and gain recovery, high speed digital detection, and error correction. We can expect in the future that clock rates for data encoding and detection circuitry for disk drive channels well above 200 MHz will be available at voltages below 3V [6]. This *progress* will originate from device development in the semiconductor industry for logic and processors using 0.2 um and smaller lithography. With power limits due to heating and battery life, analog circuitry may continue to find ongoing use in some portions of disk drive channels.

VI. HEAD-MEDIA SPACING

Fig.7 illustrates the evolution of head-media spacing, or physical spacing, and magnetic spacing for disk drives since 1990. Magnetic recording is a near-field technology, and the head-media spacing required is determined by the exponential Wallace spacing formula. It is estimated, based on Fig. 7, that a 10X decrease in spacing will be necessary from 1990 to 2000 and this is an indicator of the progress which has been and must be achieved in mechanical tolerances, design, and air bearing technology to attain an areal density of 10 Gbits/sq.in. The technical hurdles to bring head disk clearance into the range of 10nm and below (regime of "contact recording") on a reliable basis will continue to drive innovative design and engineering.

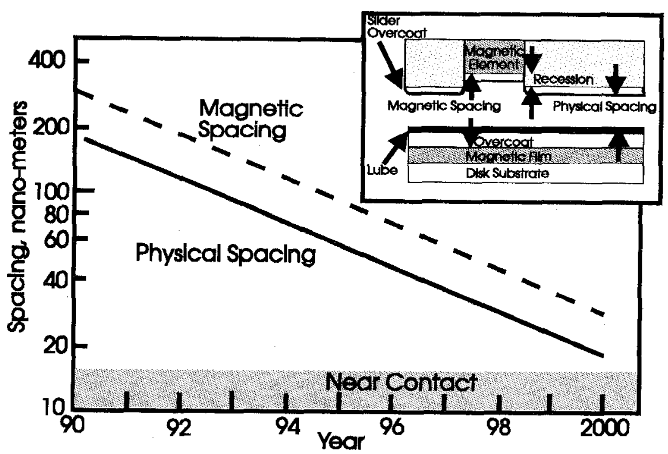

Fig. 7. Magnetic/physical spacing evolution

Fig.8 [7] shows that magnetic spacing requirements for head technologies such as thin film inductive and magnetoresistive differ as areal density increases. Inductive heads based on disk noise limitations require closer spacings than do MR heads based on the MR head's advantages in resolution, signal amplitude and the valuable write wide/read narrow phenomenon. The trend towards low head/disk spacings required for high areal densities, 1 Gbit/sq.in. or higher, could be slowed by the application of MR heads resulting in potentially improved disk drive reliabilities.

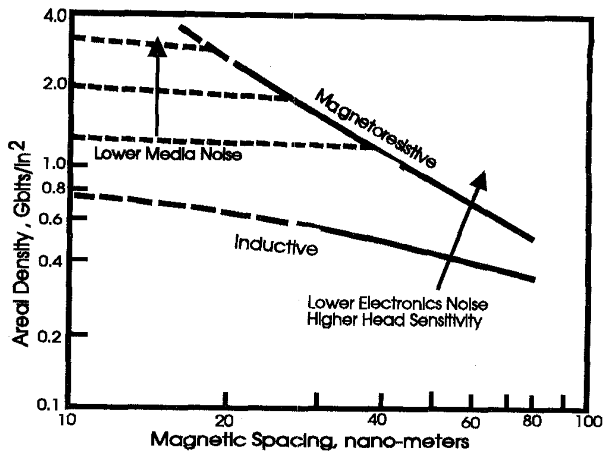

Fig. 8. Head/media spacings for magnetic head technologies.

VII. RELIABILITY AND MTBF

A basic issue in the application of disk drives is how reliable are they as storage devices, particularly when their use involves retention of valuable data not easily replaced without back-up. Reliability of disk drives, as measured in MTBF, has been progressively improving to a value of 1 million hours, and there are indications that additional engineering attention will further improve this reliability. Minimization of parts count within the disk drive (including heads and disks), more integrated electronics, more attention to tolerance controls and limiting operating temperature rise have all increased reliability of disk drives by 5X since 1990 and this trend is expected to continue. Additionally, using multiple disk drives in an array architecture in which a parity function is included either in one drive or distributed over all drives improves storage reliability to a significant extent.

VIII. CONCLUSION

The evolution of disk drives is expected to advance throughout this decade at a pace equivalent to prior progress. Areal density is the principal driver of this progress, and drive capacity can increase even when combined with form factor miniaturization. The latter has generated improved performances such as rotation speed and seek time while allowing a substantial reduction in power dissipation. The importance of magnetic hard disk drives to data processing, and the absence of any alternative competing technology, assures that magnetic hard disk drive products will continue with rapid advances, well into the next decade.

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