2.2 Tape Transport Technology

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2.2.1 Introduction

The mechanical transport area encompasses all technology associated with moving and tensioning the tape in a linear tape drive, including the technology for keeping the read/write head registered to the desired tracks on the tape. Modern data storage tape decks must guide the tape accurately while holding tension steady as the drive accelerates and decelerates the tape. Concurrently, they must precisely position recording heads containing multiple read/write elements over the corresponding data tracks on the tape. Significant transport challenges lie ahead with higher areal density, thinner tapes, and higher tape velocities.

Modern linear tape drives are highly evolved, efficient devices for storing and retrieving vast amounts of data. Across several different formats, half-inch wide tape has emerged as the de-facto standard. The tape is partitioned into alternating servo and data bands with a recording head with its multiple read/write elements spanning a single data band. Depending on the format, there may be anywhere between four and eight data bands and between five and nine servo bands across the width of the tape. Servo elements sense the position of the head within the data band and enable precise control of the head tracking. Within a data band, there are typically many more tracks than head elements, so each head element will write to or read from a subset of the total tracks in a band called a sub-band. Data is read and written in a bi-directional fashion with sequential down and back passes of the media across the head.

The Tape Technology Roadmap goals laid out in Section 2.1.1 (see Table 1 of that section) have several ramifications for tape guiding and motion control. The primary impact will be felt with increasing the track density to nearly 53,000 tracks per inch (TPI), which is equivalent to 0.48 μm track pitch. With multiple head elements reading and writing simultaneously, each read/write element must be accurately positioned over its respective track within a given data band. Many factors come into play in ensuring good tracking, including variation in the element pitch, tape expansion or contraction, lateral tape motion, and reader width. As track width shrinks and tracks are crowded closer together, each of these factors must be carefully controlled or compensated for. The consequences of not budgeting for all of the tracking tolerance contributors could be writing off track, longer store/restore times due to having to re-read or re-write data, or inability to recover customer data.

As in any engineering problem, there are multiple ways to achieve the same goal. The Transport section will detail many solutions that could be implemented to reach 53,000 TPI, although not all may be required. However, many of the following improvements will be needed. Reducing tape expansion and contraction (or compensating for it) has the largest effect on improving tracking margin. A smaller, but still significant factor is lateral tape motion. Last, in terms of tracking impact, is reducing the variation in head element pitch, the distance from one head element to another within the recording head.

The Roadmap goals show tape thickness dropping from 6.0 µm in 2012 to 3.99 µm in 2022. Thinner tapes are more prone to edge buckling, so guides that rely on edge stiffness may not control lateral tape position accurately enough and may also damage fragile tape edges. With higher tape velocity and increasing number of passes to fill a cartridge, cartridge life and reliability will drop unless these effects can be understood and controlled. Reels will have to accommodate increasing numbers of wraps; therefore to keep pack stress from increasing unacceptably, tension will likely have to be reduced. Better methods of managing reel deformation under increasing stress will be needed. Media dimensional changes as the tape is packed, stored, and then unpacked will either need to be minimized or compensated for.

Data channel considerations will mandate lower head-tape spacing, which in turn will dictate a reduction in the roughness of the magnetic surface. Backcoats will also become smoother to reduce imprinting through the thinner tapes. A possible result of this is sticking between head and tape, between guides and tape, and between tape layers in the pack. These problems may manifest themselves as debris on guides, media dropouts, tape sticking to the head when stopped, tension transients caused by stick/slip between head and tape at low speeds, or tension transients emanating from the supply pack.

In the reliability area, the mechanical components of the drive will likely have to tolerate increased length of tape rubbing across them with the increased number of passes per cartridge predicted by the Roadmap.

Tape speed will increase from 6.4 m/s to 7.5 m/s in the ten years covered by the Roadmap. Higher tape speeds increase the frequencies at which servo tracking variation appears, and may also increase the magnitude of lateral tape motion (LTM) due to dynamic interactions with tape path reels and guides. Actuator bandwidth must increase to compensate for this. Mid-range products will likely follow the lead of enterprise products in implementing dual stage actuators to achieve higher bandwidth. Written-in servo variation on the tape and position sensing noise must also be reduced.

For cutting-edge enterprise products, costly media substrates, multiple actuators, and high channel counts can be considered. But for mid-range products, the desire to keep the cost per unit of data storage steadily dropping as the technology advances is especially important. For a mid-range library with many cartridges, it may make sense to increase drive cost if that helps to avoid increasing cartridge cost.

This Tape Transport Technology section of the Roadmap identifies the major challenges in track misregistration and tribology at the areal densities required in 2022 and highlights the needed improvements in head and media technologies. Areas of research are identified and elucidated, aimed at advancing scientific understanding of tape motion and enabling the technical progress required by the Roadmap.

2.2.2 Archival Readback

Overview

For the transport, the archival readback problem boils down to being able to recover data from tape, in some cases months or even years after it was written. The tape could have changed dimensionally due to temperature, creep, or humidity and it is likely that it would be read with a different drive from the one that wrote it. Therefore, this model would have to include expansion/contraction of the media, head geometry and tolerances, and tape lateral motion during writing and readback. It is assumed that the write bump of the head provides the servo feedback during writing, as this has been widely adopted by the major developers of linear tape drives. The following model was first introduced in the 2005 INSIC Roadmap [1] and has been refined for the 2008 INSIC Roadmap [2] as well as this one.

Model

Developing a tolerance budget for track misregistration is a straightforward matter of considering all of the sources of variation between writing at one time and reading back at another time, maybe even years later, and then describing them with an equation. The statistical model, first developed for the 2005 INSIC Roadmap [1] and shown in Figure 1, describes the major items in the analysis, assuming that the head servos on the write bump during writing and the read bump during reading. The operation in the left half of Figure 1 generates the written track while the operation shown in the right half of Figure 1 is the readback process which may occur long after the tape has been written.

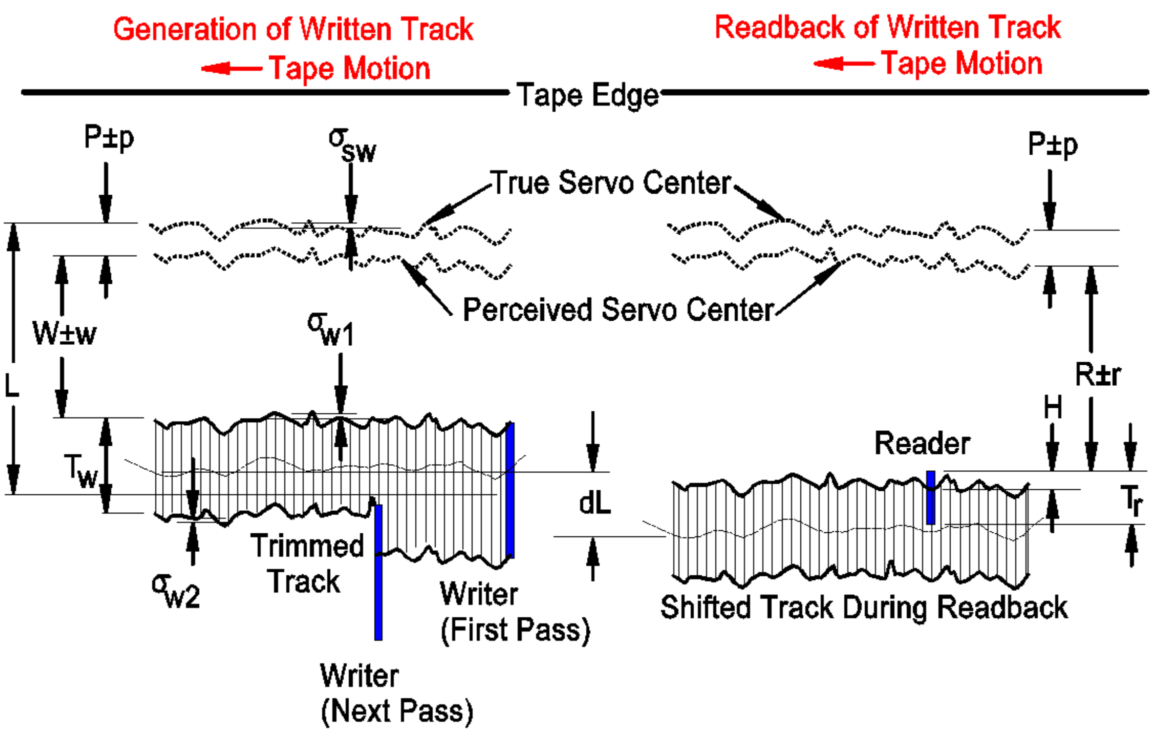

Figure 1: Archival Readback Factors.

To understand the archival process, the steps that a tape goes through from media factory to data writing and then to data retrieval can be followed chronologically. This analysis assumes that tolerances and tape motions are normally distributed and that the servo center is established by two servo elements spanning the read and write elements, thus establishing the middle of the head as the servo center.

1. $\boldsymbol{\sigma}_{SW}$ is the standard deviation of the servo track position on the tape. It is written-in at the media factory and is statistically averaged with the in-drive portion of tape lateral motion to derive the final PES. In timing-based patterns, it can consist of a cross-track term and an along-track term.

2. **P** is the distance between the true servo track location and the perceived servo track location and is assumed nominally to be zero. Due to instabilities in the head, this value changes from time to time and its 3σ variation is described by p.

3. **L** is the distance between the servo center and the centerline of the outermost writer on the head. Current linear tape drives typically derive a servo position from two individual servo elements that span the head writers; the servo center is generally at the mid-position of the head elements. Thus, L is one-half of the writer element span.

4. **W** is the distance from the servo center (the imaginary point between the two servo readers) and the edge of the write element. The nominal value is of less importance than the 3σ variation in write pole position, **w**, that occurs due to photolithography tolerances during the head manufacturing process. **w** consists of two parts: one from the alignment tolerance from one layer to another in the head manufacturing and another from the variation in write pole width.

5. $\boldsymbol{\sigma}_{LTM}$ is the standard deviation of the drive's contribution to the tape lateral motion.

6. $\boldsymbol{\sigma}_{n}$ is the broadband position sensing noise primarily due to peak jitter arising from media noise, which creates random variations in the demodulated lateral position.

7. $\boldsymbol{\sigma}_{w1}$ is the standard deviation of the position error signal from the first write pass and is written-in to the top edge of the track as shown in Figure 1. It is common in the industry to write much wider than the final track width to preserve the ability to write tracks that are compatible with the wide tracks of the previous generation's format. The final track width is determined by the overwrite process from the next pass of the media over the head. $\boldsymbol{\sigma}_{w1}$ is the statistical sum of the drive's contribution to lateral tape motion (σ_{LTM}) and the written-in variation of the tape's servo track (σ_{SW}).

$$\sigma_{\mathrm{w1}} \equiv \sqrt{\sigma_{LTM}^2 + \sigma_{SW}^2 + \sigma_n^2}$$

8. $\boldsymbol{\sigma}_{w2}$ is the standard deviation of the lateral tape motion from the second write pass and is shown only for completeness. It is written-in to the bottom edge of the track shown in Figure 1. This is the pass that determines the final track width. Assuming that the trimmed track width is larger than the reader width, the reader can never hang off of both sides of the track at one time, so the variation in track width is not of significance. For this analysis it is assumed that the reader overhangs the top edge of the track.

9. $\mathbf{T}_w$ is the nominal written track width resulting from the initial wide write and the subsequent trim pass. By definition, this is the track pitch since there is no guard band between written tracks.

10. **S** is the tape dimensional stability (TDS) expressed either as µm/µm or ppm.

11. **dL** is the distance that the track shifts between being written and subsequently readback. This shift results from tape creep due to packing stresses, humidity changes between writing and reading, thermal tape and head expansion, and tension variation.

dL = L * S

12. $\boldsymbol{\sigma}_r$ is the standard deviation of the position error signal during reading, and is not shown in Figure 1, since it describes the variation in head position during readback and does not become a feature of a track written on the media. Previous Roadmaps have assumed $\boldsymbol{\sigma}_r$ to be the same as $\boldsymbol{\sigma}_{w,}$ but in cases where a servo pattern is written to the media concurrently with data writing, $\boldsymbol{\sigma}_w$ could be much smaller than $\boldsymbol{\sigma}_r$.

13. **R** is the distance from the servo center (the imaginary point between the two servo readers) and the edge of the read element. The nominal value is of less importance than the 3σ variation in reader position, **r**, which occurs due to photolithography tolerances during the head manufacturing process. **r** consists of two parts: one from the alignment tolerance from one feature to another feature within the same layer of the thin-film process and another from the variation in effective reader width.

14. $\mathbf{T}_r$ is the reader width. The tolerance of this dimension is $\mathbf{t}_r$.

15. **F** (not shown in Figure 1) is the ratio of reader width to written (trimmed) track width.

16. **H** is the allowable overhang of the reader beyond the track edge. Generally, this is expressed as a fraction, **h**, of the reader width.

17. **D** (not shown in figure 1) is the allowable number of standard deviations that the position error signal is multiplied by. This product must fit into the gross track margin determined by the nominal distance between the reader edge and the track edge. To stay on track 99.9% of the time, D must be 3.3 or greater. To stay on track 99.96% of the time, D must be 3.5 or greater. Due to the derivation of this term from the normal probability variable, z, this term is also referred to as "Z-Score."

$$TPI = \frac{25{,}400\,\mu m / in}{\left(\sqrt{\sigma_r^2 + \sigma_w^2} * D + L * S + \sqrt{w^2 + r^2 + 2p^2}\right) * \left(\frac{2}{(1 - F + 2 * h * F)}\right)}$$

PES * Z-Score | Head Span * TDS | Head Tolerances | Gross Read Margin

Equation 1: Contributors to TPI.

Analysis

The nature of the above equation is pretty obvious. In order to increase track density, the denominator must be minimized. In the last four years, head tolerances and tracking (PES * Z-Score) have advanced more quickly than head span and tape dimensional stability (Head Span

* TDS). This has created a situation where the TDS and head span dominate the tracking budget, making TDS solutions, reduced head span, or compensation a high priority for future track density advancement. Better understanding of error rate degradation with how much the reader overhangs the track edge has eliminated excess margin and enabled some of the higher tracking since 2008.

2.2.3 Progress Since the 2008 Roadmap

Overview

Table 1 compares the individual components of the tracking budget in 2012 with the values in 2008. The values used herein reflect a consensus of the transport team members across multiple formats and technologies of linear tape. Table 2 combines the terms into the four main categories previously discussed.

Table 1: Transport Progress 2008 to 2012.

Transport Progress			
Parameter	**2008**	**2012**	**% Improvement**
Allowable Number of Standard Deviations	3.5	3.0	14.3%
Media Written-in PES	0.154 µm	.0482 µm	68.7%
Drive PES	0.270 µm	.079 µm	70.7%
PES Due to Wear	0.108 µm	.0273 µm	74.7%
PES Noise	0.049 µm	0.0179 µm	63.5%
Total PES Standard Deviation	0.333 µm	0.09813 µm	70.5%
Head Span	1250 µm	1086 µm	13.1%
Tape Dimensional Stability	900 ppm	550 ppm	38.9%
3-sigma Layer-to-layer Head Tolerance (Servo center to writer edge)	0.548 µm	0.1792 µm	67.3%
3-sigma Within Layer Head Tolerance (Servo center to reader edge)	0.202 µm	0.1254 µm	37.9%
Servo Reader Variability	0.137 µm	0.07 µm	48.9%
Ratio of Reader Width to Track Width	0.435	0.416	3.4%
Allowable Reader Overhang	2.5%	7%	180%

Table 2: Transport Progress Summary.

Transport Progress Summary			
Parameter	**2008**	**2012**	**% per Year Improvement**
PES * Z-Score	1.166 μm	0.294 μm	29%
TDS * Head Span	1.125 μm	0.597 μm	14.6%
Head Tolerances	0.615 μm	0.240 μm	20.1%
Overhang & Reader Width Ratio	3.409 μm	3.13 μm	2.1%

Table 2 shows that the biggest improvements in the last four years have occurred in tracking and head tolerances, while tape dimensional stability and head span have lagged. Gross read margin, characterized by reader overhang and ratio of reader width to track pitch, has only improved slightly. The TDS term now consumes more than half of the total tracking budget.

All of the components of PES * Z-Score have been improved in lockstep. The media written-in component has benefited from the separation of speed variation at the servowriter from actual physical tape lateral motion. All linear tape products for computers now utilize a timing-based servo scheme whereby magnetic transitions are written in a herringbone fashion at a steep angle relative to the tape edge. Lateral head position is sensed by measuring the timing of pulses from the servo elements on the head. Any variations in tape speed during the servowriting process will get written into the tape and subsequently be perceived as lateral tape motion as the cartridge is read or written. The realization that tape speed variation during servowriting can contribute to PES even if it doesn't physically increase lateral tape motion has allowed servowriter engineers to focus on more precisely controlling tape speed. In addition, improvements in tape guiding during the servowriting process have reduced the amount of servo track wander written onto the tape.

The drive contribution to lateral tape motion has also improved dramatically since 2008. This has come through continued engineering of the tape path components to reduce their cumulative impact. Reducing flange impacts from guides and reels, improving guide and reel alignment, improving reel cylindricity, controlling and damping resonances, and tuning the servo compensator have all contributed. Surface guiding and improved guide coatings have reduced the amount of PES degradation attributed to wear.

Z-Score relates to the probability that the head is technically off track assuming a normal distribution of track position. Thus a Z-Score of 3 standard deviations means that the head will be on track 99.7% of the time, as can be confirmed by consulting a table of normal probabilities [3]. Since 2008, Z-Score has dropped from 3.5 to 3.0, indicating that drives can tolerate a slightly increased off-track value.

In the tape stability/head span category, the average head span has decreased slightly due to the introduction of an eight band format in one enterprise-class product. Other enterprise products and the mid-range LTO format have maintained head spans in the 2800 μm range, equivalent to four data bands. The primary improvement in this portion of the budget has come about from substrates with increased dimensional stability. At least one product now shipping has adopted aramid substrates [4] to reduce dimensional change during humidity fluctuations. Other products have benefited from metallized substrates and tensilization.

Improvements in head tolerances have come about from various wafer fab improvements in layer alignment and imaging. A major improvement in this category has also come about from the realization that most of the write to read misregistration is due to mask shift during patterning, meaning that the average alignment across all of the tracks can be measured and calibrated out. Servo track wander originating in the servo elements has improved due to improved head stability and the transition to GMR servo elements, although these advances have lagged those of the other budget contributors.

Gross tracking margin has improved slightly with the introduction of GMR heads as the allowable reader overhang has increased and the reader to trimmed track width ratio has decreased.

2.2.4 The Path to 53,000 Tracks Per Inch (0.48 µm Track Pitch)

Equation 1, above, provides the means to study various scenarios for reaching 53,000 tracks per inch. One approach could be to focus entirely on the TDS and head span term. Another might be to drive lateral tape motion to zero. Alternatively, the reader width to track pitch ratio could be reduced below its historical value of approximately 0.45. Figure 2 shows the expected improvement in track density that could be expected by only improving one component of the tracking budget. Relatively aggressive rates of improvement of 20% per year in the three major terms and 10% per year in reader overhang were chosen to illustrate what happens. The baseline 2012 values used to achieve the starting point of 6506 TPI are taken from the 2012 column of Table 1.

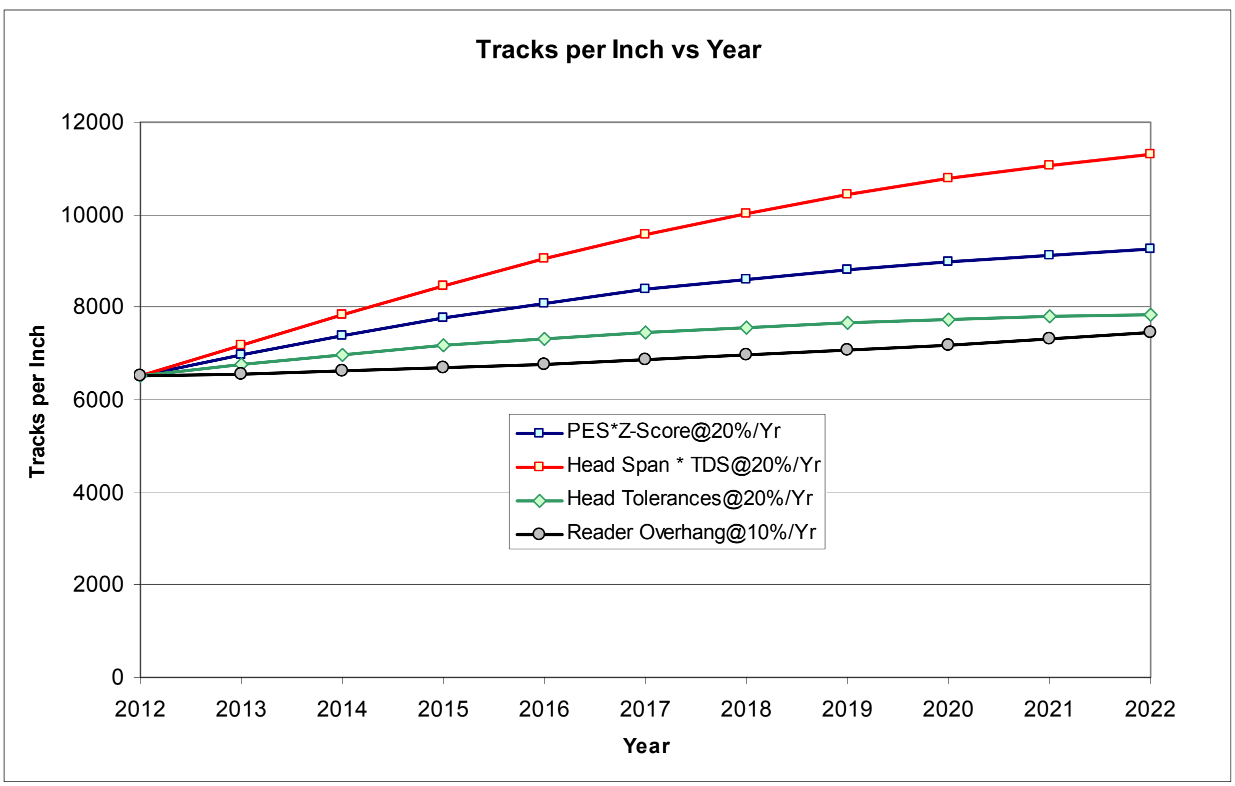

Figure 2: Result of Improving One Tracking Factor at a Time.

Even though the TDS term dominates the tracking budget in 2012, improving it at a rate of 20% per year, while showing the greatest improvement in TPI, only reaches 11,300 TPI in 2022. Likewise, improving only one of the other terms at a time leads to TPI values in 2022 that fall far short of our 53,000 TPI goal. Once one individual term is minimized, the other terms dominate and the rate of improvement in TPI levels out. This leads to the conclusion that **all** of the contributors to tracking must be improved or compensated for simultaneously to reach the 53,000 TPI goal. Figure 3 illustrates one way in which all factors can be improved together to achieve this.

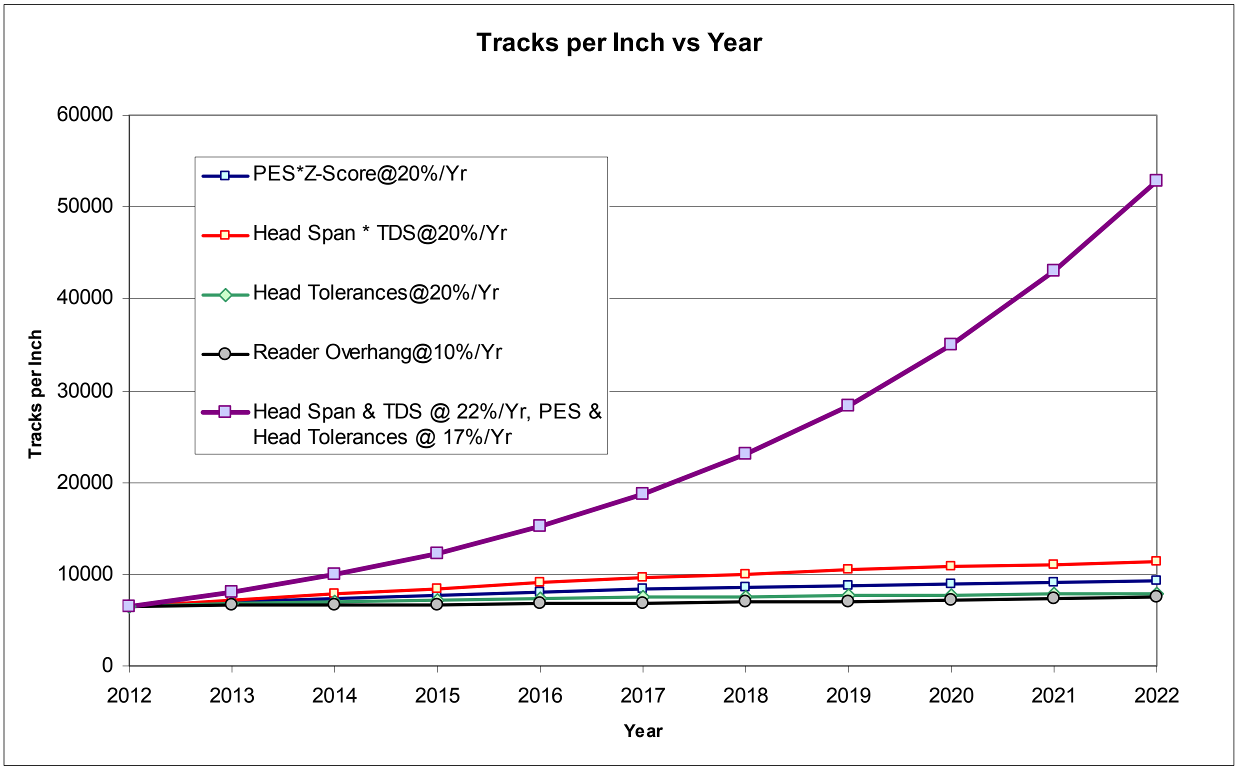

Figure 3: Result of Improving all Contributors Simultaneously

Here the TDS term improves at a faster rate than the other terms, simply due to the fact that its impact is greater than that of the other factors. The next few portions of the Transport section will explore how the individual contributors could be improved to meet the Roadmap goals.

Gross Margin

Current linear tape backup/archive products utilize read elements that are roughly half the width of the track pitch. The track width margin has to accommodate tape lateral motion, media dimensional changes, and head variation. One method to take the pressure off of head, media, and the transport mechanism, is just to reduce the reader width relative to the track pitch. But this would require the media SNR to increase at a higher rate than the track density, even as bit density also increases. So, for the purposes of this Roadmap, the ratio of reader width to track pitch will remain constant at 0.42. In addition, reader overhang will remain at 7%. While reader overhang could be increased to provide more tracking margin, significant drop-off in read signal limits the usefulness of that approach.

Improving Tape Dimensional Stability and Head Span

The bulk of lateral dimensional change in tape results from the media substrate's propensity to absorb or release moisture. Increasing moisture content swells the media, increasing the tape width and the track pitch of previously-written data. Drying the media out has the opposite effect. Thermal expansion also plays a role in media dimensional change, although to a lesser extent as the head material is carefully matched to the media for thermal expansion rate. From a control system standpoint, this is a very low frequency process, as the tape media may take days or weeks to absorb or desorb moisture and change width. Nevertheless, it has the effect of changing the pitch of the written tracks from the time of writing and must be factored in.

From a layman's perspective, it might seem a simple matter to just make the media more stable. Aramid substrates absorb less moisture and thus change width less when subjected to environmental extremes. This is one way to reduce the TDS term which has been utilized in helical scan products and high-end linear tape [4]. However, the specialized casting process required to manufacture aramid makes it 3 to 5 times more expensive than PET or PEN. With the increasing cost-sensitivity of mid-range tape products, this is an option of last resort for mid-range tape.

Limiting the environmental range that tapes are subjected to can limit the tape dimensional change, but this is difficult to enforce when the product is in a customer's hands, especially if time spans of years or decades are involved. However, some specification relief has been found recently by assuming that customers will write at a nominal environmental condition and readback at an extreme or write at an extreme and readback at nominal. This effectively halves the budgeted dimensional change compared to writing at one extreme and reading back at the other extreme.

Thin metallic coatings have been applied to polymer substrates with some success in improving the media stability. They act to reduce substrate moisture absorption and counteract the substrate swelling by sandwiching the substrate between two high elastic modulus layers. But making the coatings thick enough to eliminate all moisture absorption and counter all expansion drives up cost and reduces throughput.

Other improvements have been made in the substrate tensilization process, whereby the lateral elasticity modulus is traded off against the machine direction modulus by stretching the substrate as it is manufactured.

A review of the patent literature finds literally dozens of inventions aimed at compensating for media expansion and contraction [5, 6, 7]. If tracks are written onto the tape with the head at a small initial azimuth angle, then subsequent head azimuthal rotation can increase or decrease the track pitch as the media expands or contracts. But until track widths shrink to submicron values and the bit aspect ratio approaches one, there will be a problem with amplitude loss and bit stretching as the head gaps no longer align with the transitions on the tape.

Heads with element pitch slightly larger or smaller than nominal have been envisioned. Heads that combine dual bump reading with azimuthing have been proposed to eliminate up to half of the dimensional change. To implement this requires multiple head bumps with dedicated sets of elements, preamps, and interconnects all of which increase the head cost and hurt yields. A simpler, but less effective variant on this idea is to reduce the reader width on the outermost elements as described in a 2009 patent [8] awarded to IBM. This would degrade the error rate on the narrower elements, but presumably this could be made up for with enhanced error correction.

Reducing head span is one way of mitigating the impact of media expansion. By using multiple heads, each spanning half of a data band, the effective media dimensional change can be halved. The downside is increased cost for a second actuator and head, increased number of preamps and write drivers, a larger circuit board, and more power consumption/heat dissipation.

Another means of reducing head span is to shrink the width of the data bands and the span of the head. This has the added benefit of slightly reducing the width of tape dedicated to servo code, as 2n+1 half-width servo bands will be required if data band width is halved, where n is the current number of data bands. Unfortunately, this greatly complicates readback of prior generation cartridges written with the larger data band width. The newer format will have servo code in locations that the older format had data tracks. This necessitates a much more complicated head with additional elements to read earlier formats.

Adding head modules with elements on slightly larger or smaller than nominal pitch enables a head to improve the likelihood of being able to read tapes that have expanded or shrunk. The best recovery will occur if the media shrinkage or expansion matches one of the preset head pitches. Not knowing beforehand how much media dimensional change will occur makes this method subject to the head designer making a good guess as to what pitch to use. It also significantly increases the head cost and complexity with additional readers, interconnects, and preamps.

Heads that are capable of expanding or contracting have been envisioned, but a practical implementation remains elusive. Piezo elements could conceivably expand or contract portions of a head relative to the remaining elements. Alternatively, heating elements could achieve the same thing. However, it may take 10mm or more of piezo material in a head to stretch its span by 5-10 µm when actuated. Higher voltages could reduce the required length of PZT material, but this risks damaging the sensitive GMR elements with electrical overstress. Heating elements could be employed, but their role in stain formation and media damage remains largely unknown.

Tension compensation has been considered to oppose the media dimensional change. If the tape has expanded laterally, higher tension can bring the track pitch partially back to its nominal value through the Poisson effect. This may become even more effective if tape substrates are optimized to enhance the ratio of lateral width change per unit of machine direction change. Generally, this technique would only be used in a retrieval mode and not while writing data. Nevertheless, it may necessitate a packing step where the media is repacked at nominal tension to reduce the issue of media creep under high stress. It may also require a tension sensor to improve tension control.

Adjacent track recording, in which adjacent data tracks are recorded side-by-side in the same pass, rather than in the current configuration using successive passes, has been shown to be feasible with a novel head design [9, 10, 11, 12]. It also offers the possibility of being able to write supplementary servo code during the data writing process that effectively eliminates the write portion of position error signal. Due to the format changes required, however, products based on adjacent track recording would most likely not provide the backward compatibility to read prior tape formats recorded in a serpentine fashion, which could be a significant disadvantage for the customer.

Whether by improving media substrates, reducing head span, or compensating for tape shrinkage/expansion, the net contribution of media TDS and head span must be reduced from the 2012 value of 0.597 µm to 0.053 µm in 2022 in order to reach the 53,000 TPI goal.

Improving and Compensating for Lateral Tape Motion (LTM)

The challenge in LTM will be to sustain the progress of the last few years, where we have seen improvements of 29% per year. Non-periodic disturbances will increasingly dominate the spectrum of LTM as reel, guide, and resonance-related sources are minimized. These new factors likely will originate from the smoother, thinner tape anticipated in 2022. Traditional contact tape recording systems have relied on tiny wear-resistant particles embedded in the pigment layer of the coating to control the head-tape spacing. Higher linear bit density requires the head elements to be closer to the media magnetic layer to maintain SNR. In turn, this forces the wear particle size to be reduced, thus making the media surface smoother. At current linear densities of 467 KFCI, the tape industry is just now crossing the physical spacing threshold of about 20 nm where stiction begins to dominate the interface physics. Stiction is a result of high real area of contact between surfaces, moisture absorption, wear of surface asperities, and surface smoothness and is expected to become more problematic as tape roughness is reduced. Tape sticking to heads, tape instantaneous speed variation, head-tape coupling, tape tension waves, tape sticking to guides, broken tapes, and layer to layer adhesion in tape packs will all need engineering effort to solve. Hard disk drive developers have used disk texture, lubricants, and head unloading to counter stiction, and some of their experience may benefit tape. Tape-head stiction can be alleviated by lifting the tape off of the head surface at turnarounds or by minimizing the head surface in contact with the tape. But the other factors are complete unknowns. Not only are the tribology phenomena and possible solutions poorly understood, so also are the numerous ways that handling of sticky tape can cascade through the transport.

From a servo standpoint, one of the more challenging problems will be head-tape coupling. This is the propensity of smooth tape to move laterally in response to lateral head motion. In mild cases, this phenomenon reduces phase margin. In severe cases, it can cause servo system instability. Likely solution paths include reducing the surface area of the head's contact region, head coatings, head surface ion implantation, and media lubricants.

Of utmost concern is the initiation and propagation of tension waves that instantaneously stretch the tape as it sticks to a head, a guide, or a pack layer and then release, launching a longitudinal pulse into the tape path. How these waves propagate through the tape path, couple into out of plane and lateral tape motion, are attenuated by tape path components, and ultimately dissipate will determine whether the sought-after LTM improvements can be achieved.

The Roadmap envisions tape thickness dropping to 4 µm in 2022 as areal density alone is unable to keep pace with the required increase in capacity per cartridge. Thinner tapes will lead to other problems which must be overcome. It is expected that thinner tapes will ultimately make edge guiding untenable as the edge stiffness drops and the ease of damaging tape edges increases. Surface guides utilizing grooves or texture to control tape position are the logical choice, but they introduce other problems, namely poorer control of tape tilt. This will drive the adoption of multiple actuators or multiple-degree-of-freedom actuators to follow the increased tape tilt.

The task of the servo system is to move the head so it follows the high-amplitude, low-frequency motion of the tape. In reality, the servo can never completely remove the low-frequency components and because the Bode Sensitivity Integral must equal zero, it actually amplifies some high frequency components. As the tape velocity increases, LTM disturbances from rotating transport elements and spatial variations in the tape edge and servo pattern will increase in frequency, and thus will be more transparent to the servo system. To keep pace with the higher tape velocity predicted by the Roadmap, servo system bandwidth must increase. While the details are product specific, it is likely that bandwidth improvements will come about from dual stage actuators that combine a long-range low bandwidth primary stage with a low mass, short range, secondary stage. Recent INSIC-sponsored research [13] has shown the benefit of servo controllers that can sense transport resonances and adapt to product differences, as well as to differences in behavior from beginning to end of pack and beginning to end of life.

The herringbone servo pattern written onto the tape has served linear tape very well for multiple generations and classes of products. But as track density increases, several limitations are becoming apparent. Foremost is the error which occurs during pattern writing when tape speed variation causes the reference spacing of servo pulses to change. Lateral position is sensed by dividing the timing between pulses originating from non-parallel stripes (A in Figure 4) by the timing between pulses originating from parallel stripes (B in Figure 4). The non-parallel stripes are written concurrently, but the parallel stripes are written with a very short time delay, leading to pattern sensitivity to tape speed. Recent generations of linear tape drives have been able to measure the speed variation using multiple servo elements on one servo track, but the distance between the servo elements prevents full characterization of this timing jitter. However, a good portion of the jitter can be filtered out of the PES signal. Media manufacturers will be expected to continue to reduce speed variation during servowriting, but there is only so much that can be practically done. Once these limits are reached, further improvement will only come by writing the non-parallel and parallel stripes concurrently to effectively eliminate this frame spacing error [14].

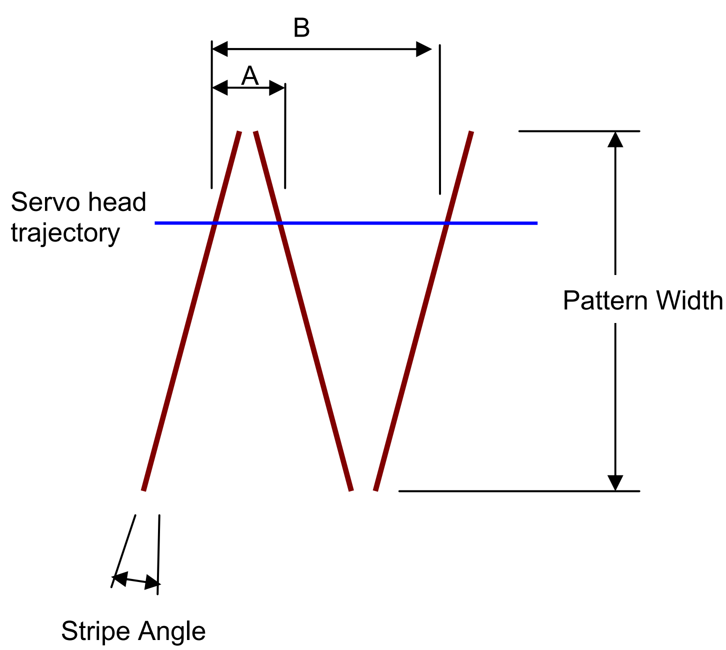

Figure 4: Servo Pattern Nomenclature.

Increased track density reduces the timing difference used to resolve a given percent off-track. To regain resolution, stripe angle must be increased to maintain adequate timing differences to resolve lateral position as a percentage of track width. However, increasing the stripe angle drops the frame rate unless the width of the servo pattern can be reduced. Fortunately, this is feasible with more channels in the head or with smaller data band width. Servo frame spacing will need to decrease, not so much to keep up with actuator bandwidth, but more likely to provide adequate update rate at low tape speeds. While the Roadmap projects an increase in maximum tape speed through 2022, it is likely that the minimum tape speed will drop when channel counts increase in order to maintain the ability to stream data from a slow host with a minimum of back hitching. Low tape speed reduces the servo frame rate, since the servo pattern spacing is a fixed distance on the tape.

Written-in servo pattern straightness is crucial to minimizing lateral tape motion and PES. Minimizing tape width variation and edge weave in the slitting process and keeping the servo pattern parallel to this ultra-straight edge with precision guiding during servowriting will be needed to enable high track densities.

Reduced media magnetic layer thickness, which is required to support high linear bit density, leads to lower servo signal amplitude, which complicates what is effectively a peak detect channel. Heads and servo channels must accommodate this. Increasing tape speed will necessitate higher bandwidth servos and will require faster servo processors. More efficient algorithms may be required to keep up with the higher tape speed and higher order control systems.

Another concern is measurement noise in the servo control system. This can originate from media noise or signal timing quantization error. However, other improvements may mitigate the adverse impacts of increased noise. For one, media noise must improve to achieve the required bit densities and this improvement will translate into lower servo noise. Secondly, while servo reader width will likely decrease, it will not decrease as much as data reader width. This will boost relative servo performance. Lastly, narrower servo readers will enable optimization of timing-based servo patterns to reduce the effects of detection errors

As tape thickness decreases, the number of wraps on each reel will increase. Unless tension is reduced, packing pressure will increase. This increased packing pressure will lead to lateral dimensional changes in the media due to the Poisson effect. It will also increase pressure exerted against the reel hub and reel flanges. Distortion of reels due to packing stresses can lead to flange scuffing against tape edges and tape path misalignment. To counteract these effects, stiffer reel hubs and flanges will be required.

Air entrainment increases with higher tape velocity and this increases the number of floating wraps and thus the length of unconstrained tape [15]. Combined with variations in tape curvature, this leads to the tape packing inconsistently and alternately packing against one flange and then the other. Packing rollers squeeze air out at the nip and, while they are used in the tape manufacturing process, their practicality for use in current form factor tape drives is doubtful. More achievable may be the development of tape cartridge systems that always pack against one flange. Steerable guides may also be required to guide the tape between the takeup reel flanges. Reducing flange run out and tape width variation will enable tighter flange spacing and reduced flange taper, which will improve tape alignment within the tape path.

Z-Score relates to how often the head can be off-track. Assuming that tape lateral motion is normally distributed, a Z-Score of 3.0 implies that the head will be off-track 0.3% of the time.

For the purposes of this Roadmap, Z-Score will remain at the baseline value of 3.0, as any reduction will just increase the number of retries and back-hitches.

Whether by improving mechanics, increasing servo bandwidth, changing servo patterns, reducing tape bearing surface area, or utilizing steering guides, the net contribution of tape lateral motion and Z-Score must be reduced from the 2012 value of 0.2944 μm to 0.0457 μm in 2022 in order to reach the 53,000 TPI goal.

Head Tolerances

Head element cross-track variation is the third broad category that must be improved in lockstep with PES and tape dimensional stability in order to meet the Roadmap goals. In terms of tracking performance, the critical tolerances that are RSS (root sum of squares) summed are the tolerances of reader width, read center to servo center, write width, and write center to servo center. Of these, the largest contributor to the RSS sum is the write center to servo center. This comes about since the write structures are defined at different steps in the head wafer process than the servo structures, and thus are subject to mask alignment errors, which are usually larger than variation within a mask. The result is that all of the write elements will be shifted relative to the servo elements and this average shift can be measured and calibrated out. Process variation that produces inconsistent reader and writer widths will need to be minimized. Masks must be produced on a 0.05 μm or better snap grid to reduce the variation in element to servo distance, and mask aligners must be increasingly more precise.

To meet the Roadmap's goal of 53,000 TPI in 2022, the RSS total for reader width, writer width, read to servo, and write to servo distances must improve from 0.24 μm in 2012 to 0.037 μm in 2022.

Servo and Track Layout Overhead

The Roadmap goals from Section 2.1.1 predict that servo and track layout overhead will decrease from roughly 18.5% of the tape width to 11.5% in 2022. It is expected that this will result primarily from less total tape width allocated to servo bands, which becomes possible with more data bands and higher head channel counts. Additional benefit could be gained by servoing on the backside of the tape or reducing the tape edge margin. However, as discussed in the 2008 Roadmap [2], this only provides a small step towards the 2022 goal of 53,000 TPI.

Write Verification

Issues with write verification were covered extensively in the 2008 Roadmap [2]. That analysis predicted a reduction in bump to bump spacing as track density increased, but then acknowledged the difficulty in head manufacturing and anticipated additional servo systems to track tape tilt if such head changes proved impossible. Those predictions have come true in 2012 with the widespread adoption of azimuthing actuators and dual head drives for the sole purpose of compensating for tape tilt. The new control systems have effectively eliminated tape tilt concerns, therefore no write verification analysis will be done for this 2012 Roadmap.

2.2.5 Transport Summary of Requirements to Meet Roadmap Goals

The following table summarizes the cascading requirements for transport, heads, and media to achieve the Roadmap goals.

Table 3: Detailed Breakdown of Transport Improvements.

Year	2012 (Baseline)	2014	2016	2018	2020	2022
Media Written-in PES (σ_{SW} Std. Dev. - nm)	48.2	33.2	22.9	15.8	10.9	7.5
Drive PES (Std. Dev. - nm)	79	54.4	37.5	25.8	17.8	12.3
PES due to Usage (Std. Dev. - nm)	27.3	18.8	13.0	8.9	6.1	4.2
PES Noise (Std. Dev. - nm)	17.9	12.3	8.5	5.9	4.0	2.8
PES [σ - RSS Sum of Media + Drive + Noise + Wear] (nm)	98.1	67.6	46.6	32.1	22.1	15.2
Head Bump-to-Bump Spacing (B - µm)	1250	882	622	439	310	219
Head Span - Center to Furthest Element (L - µm)	1086	911	765	642	539	452
Media Dimensional Stability (S - ppm)	550	403	296	217	159	116
Head Layer-to-Layer Tolerances (w - 3 Std. Dev. - µm)	0.1792	0.123	0.085	0.059	0.040	0.028
Head Within Layer Tolerances (r - 3 Std. Dev. - µm)	0.1254	0.086	0.060	0.041	0.028	0.019
Media Servo Track Variability (µm)	0.07	0.048	0.033	0.023	0.016	0.011
Total Head Tolerances plus Servo Track Variability (µm)	0.2401	0.1654	0.1139	0.0785	0.0541	0.0373
Servo and Layout Overhead	18.46%	16.59%	15.02%	13.67%	12.50%	11.49%
Modeled TPI	6506	9951	15171	23060	34942	52791
Roadmap TPI	6,506	9,773	14,787	22,498	34,393	52,791

2.2.6 Unresolved Issues

While the details of how track density will increase are unknown, the transport team has identified numerous promising technologies to reach the Roadmap goal. Many unknowns remain, but the components of the tracking budget are consistent with current track width and the progression over time is consistent with the overall Roadmap. Therefore, there are no remaining unresolved consistency issues.

2.2.7 Dependencies

Heads

As Table 3 shows, the 3-sigma within-layer tolerance for distance between servo element and edge of read element in the head must improve to 0.019 µm in 2022. Similarly, the 3-sigma layer-to-layer tolerance for distance between servo element and edge of write pole in the head must improve to 0.028 µm. The half-span of the read/write elements must be reduced to 452 µm. Contours must be capable of maintaining spacing with thinner tape, at higher velocities, and at lower tensions than currently used.

The transport is extremely sensitive to characteristics of the head that influence head-tape tribology. Smoother tapes will necessitate changes to the head such as tape bearing surface coatings, implantations, or surface area reductions.

Media

Referring to Table 3, written-in PES must improve to less than 7.5 nm by 2022. Also, total tape dimensional stability must be either reduced to 100 ppm or compensated for to reduce its effect to less than 100 ppm.

Media changes to mitigate the adverse consequences of smoother tape will be needed. The most likely path here is improved lubricants that counter head and guide stiction.

2.2.8 Suggested Areas for Future Research

Background

The analysis of transport technology has identified several gaps that will need to be closed to meet the Roadmap goals for 2022. The research projects below are targeted toward those areas expected to be most problematic at the end of the period covered by the Roadmap and are thus deemed to be pre-competitive. The topics are prioritized based on the urgency of the need and the applicability to university research faculty and facilities.

1. **Tribology of Smooth Surfaces**

   This INSIC Roadmap predicts that head-tape spacing will be reduced from the current value of about 36 nm to 17 nm in 2022. This reduced spacing is necessary to provide magnetic recording improvements required to meet future capacity targets. Unfortunately, such spacing will likely require modification of the mechanics of the head-tape interface and possibly other components within the tape path.

   Possible Areas of Research

   Longitudinal Tape Vibration: Smooth tape running on smooth heads can cause longitudinal vibration (scrape flutter). Possible solutions include textured head designs or modified head contours (flat contours with small area of contact).

   Static Friction: Disk drives long ago required heads to disengage (park) off of the disk due to high static friction when relative speeds drop to zero. Tape drives of the future will likely face the same issue. Possible solutions involve engineered surface roughness of the head or media, contour changes, or mechanisms to lift the tape off of the head when stopped.

   Pack Stability: Smooth tape has a tendency to bleed air more slowly when winding on a reel. This results in pack instability and/or poorly formed packs. Also, air entrainment can be detrimental to reel-to-reel servo control systems because the dynamics of the system changes when layers of tape start to fly on the take-up reel. Possible solutions include engineered backcoat surfaces that both fly low and allow air to bleed, or packing mechanisms that produce well-formed packs.

   Head Wear: Head-tape spacing must be reduced without compromising head wear. Surface materials/coatings that provide low friction and low wear are required.

2. **Tape Path Physics and Modeling**

   Early generation linear tape products with track widths of 20 μm or more could tolerate a relatively large amount of lateral tape motion before the head would be positioned too far off track to read or write. Thus, tape path designers primarily had to be concerned with guide flange hits and reel hub quality. As track widths approach sub-micron widths envisioned by 2020 in the Roadmap and first order effects are characterized and eliminated, a whole new set of physical phenomena, some resulting from the requirements for smoother tape, will dominate the tracking budget. Some examples of factors that may dominate tape path mechanics are tape cupping and/or curling, longitudinal tension waves, out-of-plane tape motion, unspooling of tape from reels, air bleed/entrainment into tape packs as tape surfaces become smoother, lateral tension gradients, lateral tension waves, rolling guide traction, and head or guide stick/slip. The objective of research in this area would be to provide insight into how these effects contribute to lateral tape motion, what possible methods could be employed to reduce their impact, and which factors will dominate the system. It is envisioned that this will primarily be a model development project, but experimental work will be important to validate the model and the various sources of lateral tape motion. A possible related project could be a feasibility demonstration of 10 nm one-sigma position error signal as anticipated by the Roadmap by 2022.

The INSIC-sponsored LTMSim software package [15] is primarily intended to model the lateral tape motion (LTM) resulting from various excitations, such as pack run-out, tape weave, and various forms of impulse events. Earlier versions of LTMSim considered the guides and the heads as point-wise entities, thus had limited ability to model the physics of coupling the tape to guides. The frictional and hydrodynamic nature of this interface is critical to understanding tape-to-guide coupling and has a significant effect on LTM, as well as longitudinal and cross-width tape tension.

Recent work at Northeastern University [16] made significant progress in this area. To date, a distributed roller model (allowing roller tilt), a 1D grooved roller model, and a 2D smooth guide traction module have been implemented into LTMSim to incorporate frictional and hydrodynamic effects in the tape-to-guide interface. Continuing work is needed to model grooved rollers: first, with a 2D model, and ultimately as a full 3D coupled interface. A 3D model is important in simulating how the tape "dips" into the grooves and the frictional traction on the groove edges.

3. Possible Material for Low TDS Substrate

To meet the track density requirement of 53,000 TPI in 2022, uncompensated tape dimensional change must be improved at a rate of 15.7% per year to less than 100 ppm in the next ten years.

Possibilities for compensating for tape expansion/contraction include heads that have extra elements to read tracks at non-nominal pitches, azimuthing heads that can effectively increase or decrease head channel pitch, heads with narrower readers on the outer elements, drives with enhanced error correction for the outer elements, and tension control that uses the Poisson effect to change the track spacing. None of these methods offers complete cancellation of tape track pitch change, so ongoing improvements in tape substrate stability will be required. Efforts to improve tape substrates will be complicated by thinner tapes and higher packing stresses resulting from more cartridge wraps.

Currently, the only material that seems possible to reach the 100 ppm dimensional stability target is aramid, otherwise known as aromatic polyamide. The manufacturing process for aramid requires costly raw materials and a non-conventional casting process, instead of the high-volume extrusion process typically used for other substrate materials. The net result to the end user is a cost penalty of roughly 3-5X over conventional PET/PEN substrates. Improving dimensional stability of existing substrates and/or developing new low-cost dimensionally stable substrate materials are vital to the future success of tape-based storage.

The source of tape dimensional change results from the substrate's propensity to absorb and desorb moisture. Therefore, this project would like to focus on research on the mechanisms of hygro-expansion phenomena, on alternative polymeric materials with suppressed hygroscopicity, and/or on the addition of a new compensation layer capable of mass-production.

4. Servo Technologies for Sub-10nm Track-Following Performance

Historically, areal density increases in tape systems have been achieved by scaling linear density and track density at roughly the same rate (e.g., LTO-1 through LTO-4). In the future, however, areal density increases will likely be achieved primarily through track density scaling. This increased emphasis on track density puts more stringent requirements on the performance of the track-following control system and the rate at which this performance must be improved with each generation of tape drive. For example, in 2012, tape drives will need to achieve a track-following performance with a standard deviation of the position error signal (PES) on the order of 100 nm. By 2022, this will have to be reduced to below 15 nm. Over the same period, tape speeds are expected to scale to up to 7.5 m/s, increasing the amount of high frequency disturbance that the controller will have to deal with. Achieving this level of track-following fidelity at increasing tape speeds will require the optimization of the entire track-follow servo system, including the servo pattern, the servo channel, the servo controller and the head actuator. In addition, it will also be necessary to reduce the amount of high frequency lateral tape motion that the track-follow controller needs to compensate for through the optimization of the tape path and the development of low-noise tape guides. The objective of research in this area is to develop technologies that will improve upon the 23.4 nm one-sigma performance already demonstrated [17, 18]. Examples of such technologies include an optimized servo pattern for enhanced resolution and increased update rate, high bandwidth track-follow actuation and/or dual stage actuation, low noise tape guides, advanced control techniques such as periodic disturbance rejection, adaptive control and control design for dual stage actuation. A potential goal could be a demonstration of track-follow control with a 10nm or less one-sigma position error signal.

5. Tape Transport LTM Improvements

As described in the Roadmap (see Section 2.1.1), in 2022 the track width will be close to 0.5 µm, and the expected tracking performance should achieve PES sigma close to 10 nm. This imposes challenges in many aspects, including tape guiding, tracking servo, and the media's written-in PES. In the aspect of improving tape guiding to reduce lateral tape motion (LTM), the design of the tape transport will also need to work well with the thinner media (thickness of 4 µm), smoother media (head-tape spacing of 20 nm), longer media life (50,000 passes), and sustaining more tape guide wear from green tapes (tape market shift to increasing archive use means that drives will see mostly green tapes). Tape drive designers are familiar with these issues, and have tackled them continuously. Much engineering innovation has been devoted to reducing the source of the disturbances (e.g., better tape path alignment and tighter reel flange tolerances), and attenuating the LTM such that the head actuator can follow it (e.g., edge guiding using flanged rollers or surface guiding using grooved rollers). Future research projects in tape transport will be needed to further improve tape tracking performance beyond the 23 nm demonstrated in [18] with thinner/smoother tape while reducing the wear to media and tape guides.

Possible Related Areas of Research

Identify the Issues of Using Smoother/Thinner Tapes and Green Tapes: Possible issues include tape edge damage/wear due to thinner tape rubbing the guide flanges and reel flanges, tape packing quality due to smoother tape with air entrainment, LTM due to the peel-off during unwinding, tape vibration due to stiction between tape and guides, and tape guide wear/contamination due to running green tapes.

Improve Tape Guiding Performance: The goal is to prevent/attenuate high frequency LTM, while the low frequency LTM can be corrected by the head actuator servo. Currently, the tape industry uses both surface guiding and edge guiding methodology to achieve this goal. In surface guiding, possible issues are stick-slip in the lateral direction, tape surface wear, and guide surface contamination. Related projects can include surface texture design, coating, and wrap angle arrangement. In edge guiding, possible issues are tape edge wear, and guide flange wear. Related projects can include tape guide flange design, coating, and wrap angle arrangement. In terms of preventing high frequency LTM, related projects can include identifying sources of high frequency LTM, reducing motor cogging, and reducing tension variation.

Investigate the Benefit and Feasibility of Active Tape Guiding and Other Alternatives: Intuitively speaking, the benefit of active tape guiding is that it attenuates the high frequency LTM, limits the amplitude of LTM, and doesn't wear the tape edge. However, the complexity of the system makes it less attractive to product designers and the performance has not yet been demonstrated to be better than that of existing tape guides. Related projects can include a feasibility study of active tape guiding, and exploration of new ideas for tape guiding that can meet the stringent requirements mentioned above.

6. Characterization of Head Tolerances

As mentioned previously (see, for example, Section 2.2.4), head tolerances are one of the three main contributors to track misregistration. A tape written in one tape drive must be readable when the cartridge is used in another drive. This not only applies to drives from the same manufacturer, but often will include a drive from a different manufacturer. Therefore, any variation in the positions of the writer or the reader relative to the servo elements will reduce the tracking margin and limit the achievable track density. Today, the cumulative head tolerances are approximately 0.24 μm. To achieve a track pitch of 0.48 μm in 2012, this tolerance must be reduced to near 0.037 μm.

One of the challenges to improving these tolerances is the difficulty in measuring the actual tolerances. What is important to the tracking budget is the location of the magnetic edges of the readers and the writers. Unfortunately, the magnetic edges aren't necessarily aligned with the optical features on the head. Developing an effective measurement system that can easily characterize all the variations of large numbers of heads will be very important. Once a good measurement system is in place, it will facilitate process improvements to reduce manufacturing variations.

Incremental or revolutionary changes in the head manufacturing process will be required to address the root cause of manufacturing variations to reduce these tolerances to acceptable levels.

2.2.9 References

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