Advanced control technologies for magnetic tape data storage

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IBM Research – Zurich, Rüschlikon, Switzerland

IEEE CCTA 2018, Aug 21-24, Copenhagen, Denmark

IBM Research – Zurich

- Established in 1956
- 45+ different nationalities
- Open Collaboration:
  - Horizon2020: 50+ funded projects and 500+ partners
- Two Nobel Prizes:
  - 1986: Nobel Prize in Physics for the invention of the scanning tunneling microscope by Heinrich Rohrer and Gerd K. Binnig
  - 1987: Nobel Prize in Physics for the discovery of high-temperature superconductivity by K. Alex Müller and J. Georg Bednorz
- 2017: European Physical Society Historic Site
- Binnig and Rohrer Nanotechnology Centre opened in 2011 (Public Private Partnership with ETH Zürich and EMPA)
- 7 European Research Council Grants

Scientific Departments

Cognitive Computing & Industry Solutions

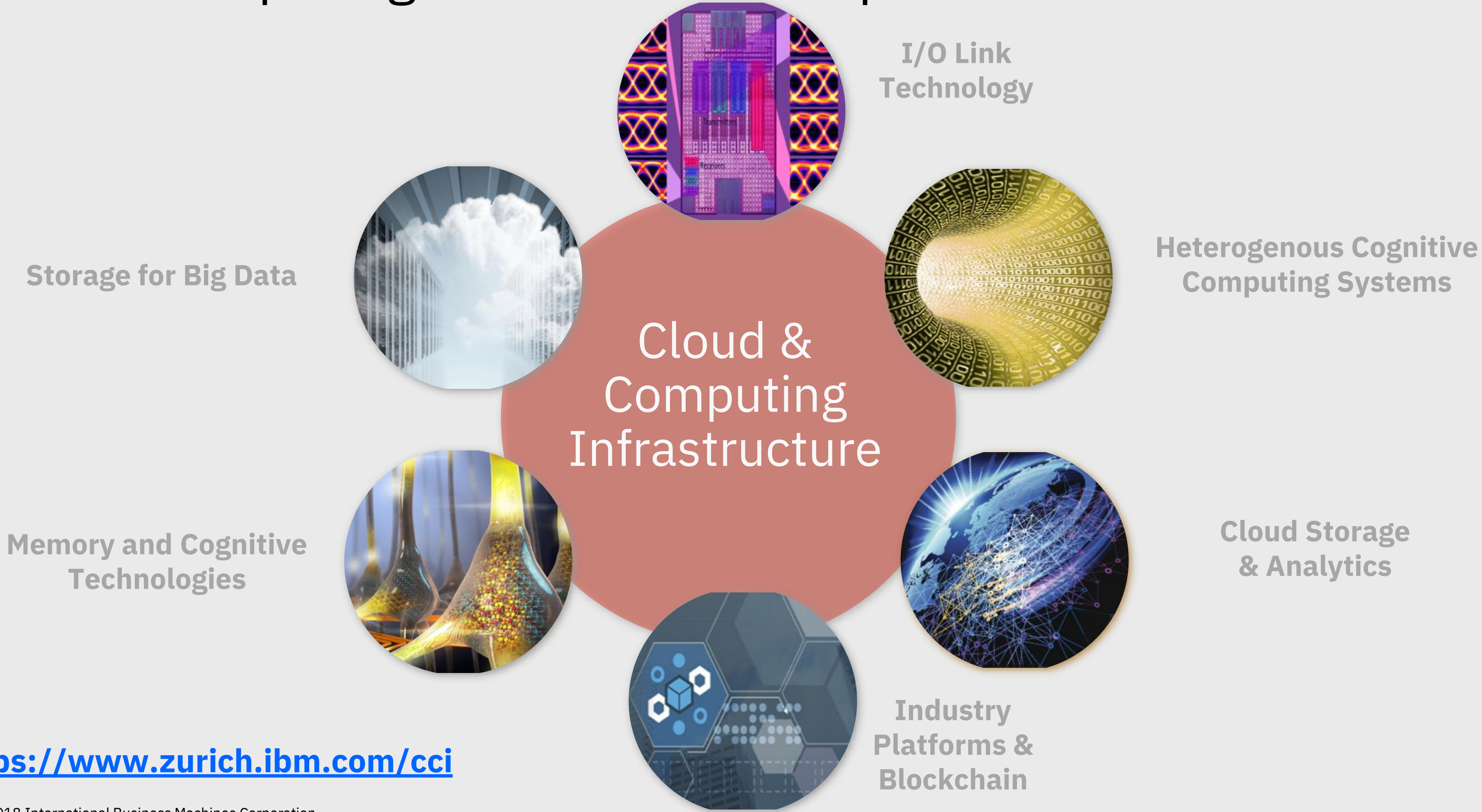
Cloud & Computing Infrastructure

Science & Technology

Big Data Analytics

Atoms

Cloud & Computing Infrastructure Department



https://www.zurich.ibm.com/cci

Outline

Introduction

- **The role of tape in the era of big data**

Tape storage system

- Position sensing and head actuation
- Disturbances and noise

Advanced control technologies

- Tape transport control
- Track-follow control

The future of tape

- World record tape areal density demo of 123 Gb/in^2
- Technologies enabling the 123 Gb/in^2 demo

Conclusions

2.5 exabytes
of data created
every day.

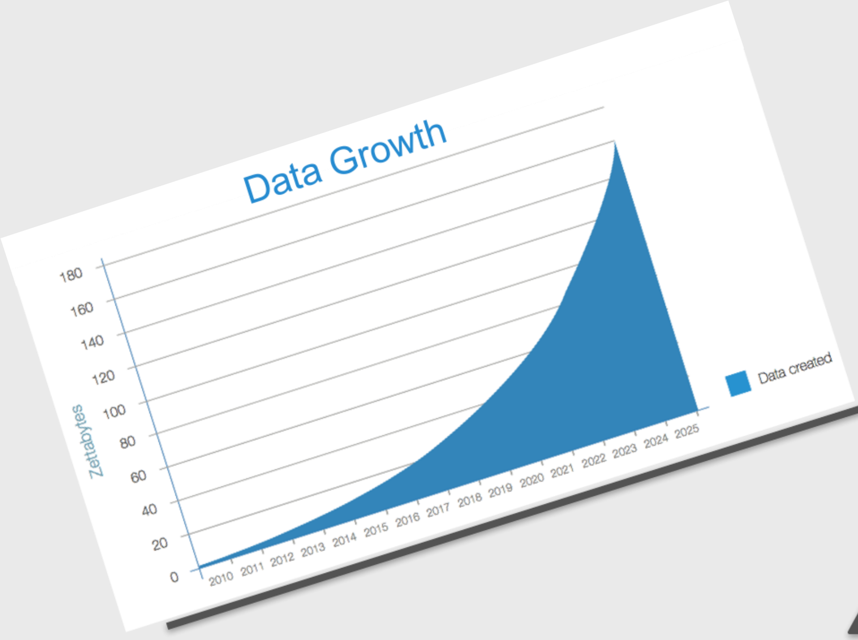
1 exabyte is 1,000,000,000,000,000,000 or 10^{18} Bytes

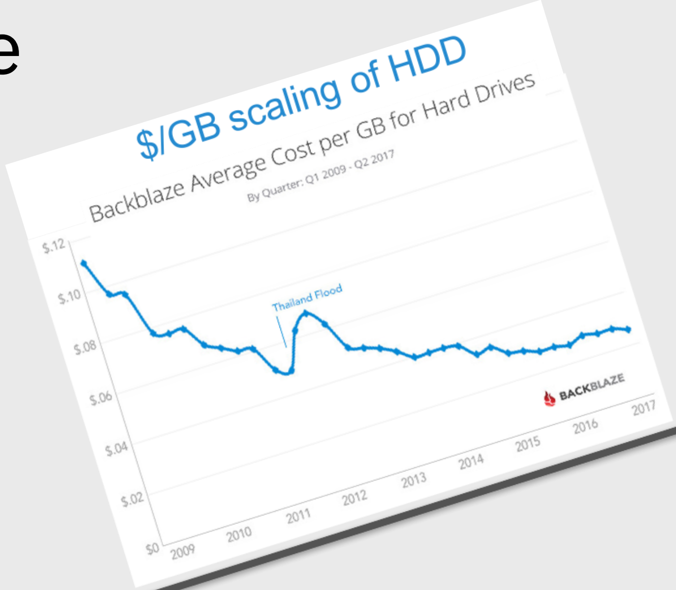
The digital universe will approximately **double every two years**

Global scientific output **doubles every nine years**

>2.5 million papers per year
>300,000 US Patents annually
>100 million substances in CAS Registry, growing exponentially

The Data Center is Out of Balance





BUT.....
80% of all files created are inactive – no access in at least 3 months!

https://www.backblaze.com/blog/hard-drive-cost-per-gigabyte/

Tape’s Renaissance

2006

*”Tape is **dead**, Disk is Tape, Flash is Disk, RAM locality is king”*

Microsoft

2015

*”All cloud vendors will be using tape and will be using it at a **level never seen before**”*

Microsoft

Cloud has changed the economics of storage completely

http://research.microsoft.com/en-us/um/people/gray/talks/flash_is_good.ppt

http://www.infostor.com/disk-arrays/how-do-you-store-a-zettabyte.html

Tape advantages

High storage capacity

- ✓ Up to 15TB per cartridge (uncompressed)

Energy efficiency

- ✓ No power needed after data has been recorded

Security

- ✓ Drive-level encryption
- ✓ Data inaccessible when drive is not loaded

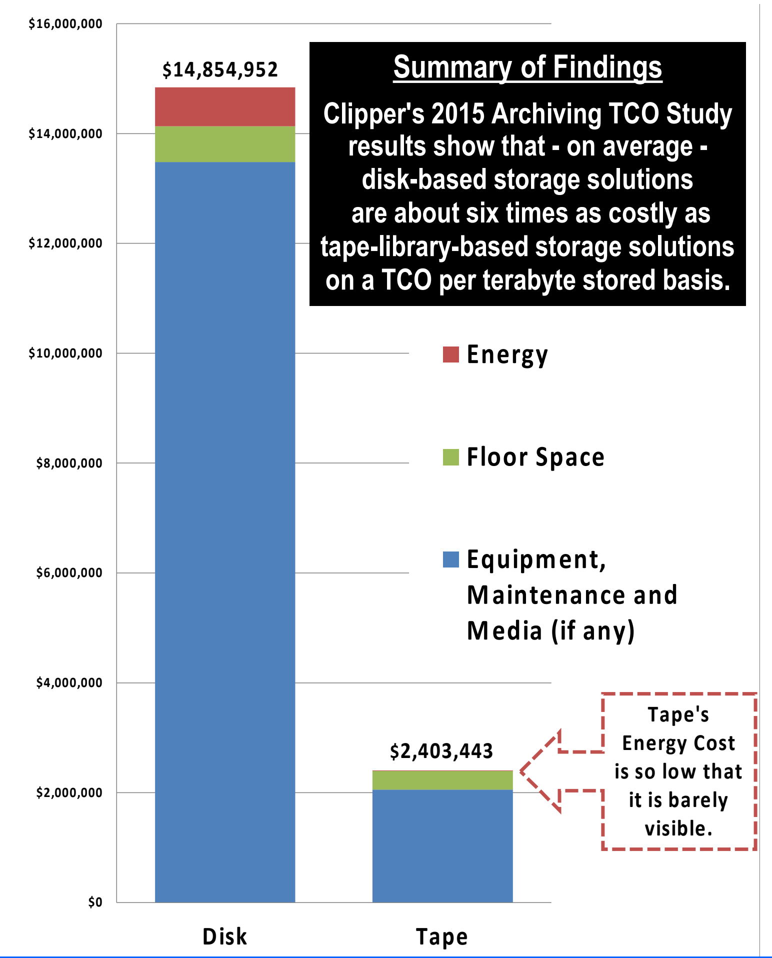
Long media lifetime

- ✓ 30+ years

Reliability

- ✓ Orders of magnitude better error protection than disk
- ✓ Typically, no data loss in case of drive failure

The main net advantage of tape is low cost: 6.7x TCO advantage of LTO Tape over Disk!



1) Continuing the Search for the Right Mix of Long-Term Storage Infrastructure – A TCO Analysis of Disk and Tape Solutions (15 July 2015)
2) The Impact of LTO-7 on The TCO of Long-Term Storage (15 Sept. 2015)

Magnetic tape (r)evolution

Product Year	IBM 726 1952	LTO8 2017	TS1155 2017	**Demo 2015 BaFe Tape**	**Demo 2017 Sputtered Tape**
Capacity	2.3 MB	12 TB	15 TB	220 TB	330 TBytes
Areal Density	1400 bit/in^2	8.6 Gbit/in^2	9.6 Gbit/in^2	123 Gbit/in^2	201 Gbit/in^2
Linear Density	100 bit/in	525 kbit/in	510 kbit/in	680 kbit/in	818 kbit/in
Track Density	14 tracks/in	16.3 ktracks/in	18.9 ktracks/in	181 ktracks/in	246 ktracks/in

1952

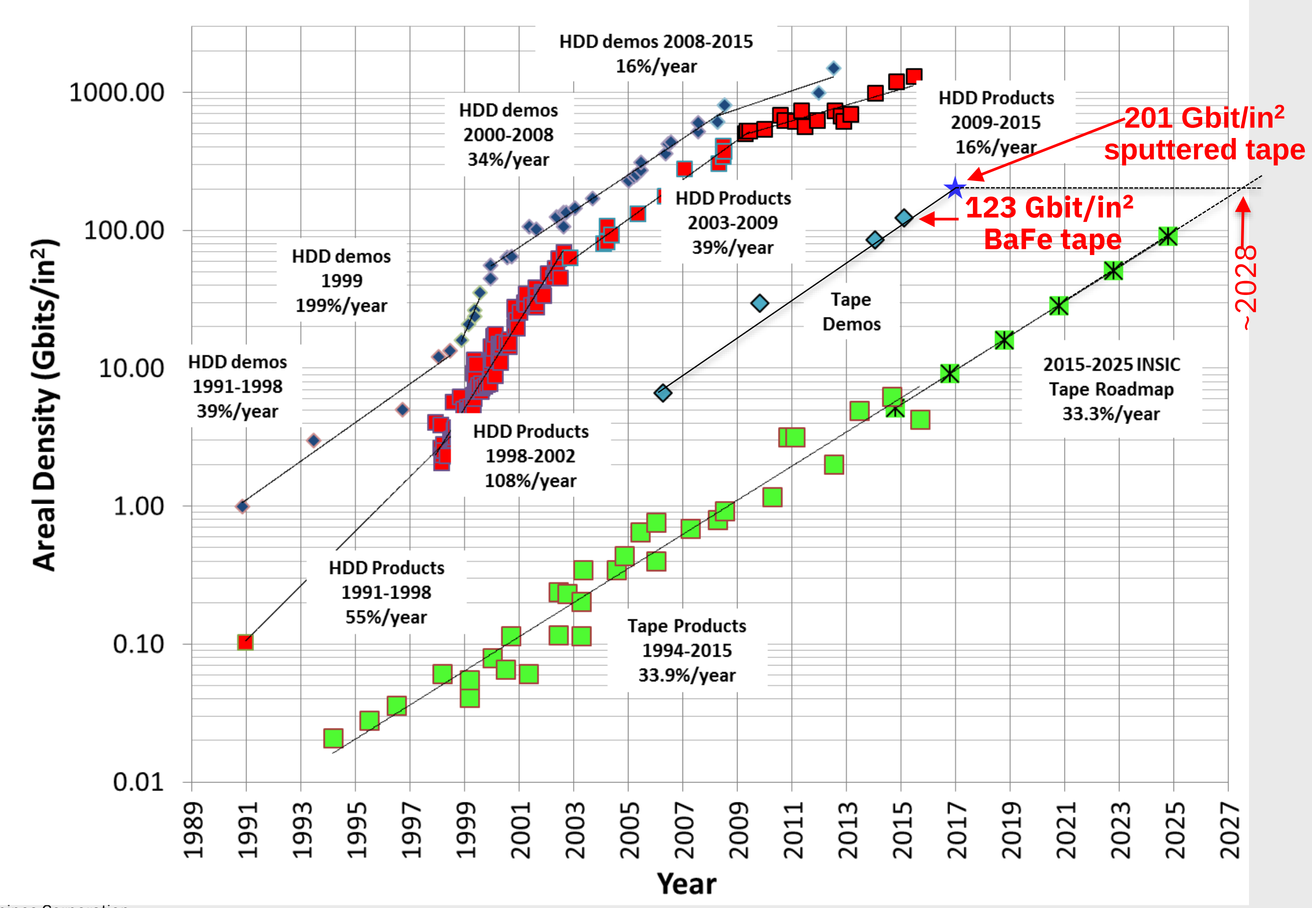
IBM 726

Areal Density >6.8M x

2017

TS1155

Areal density scaling

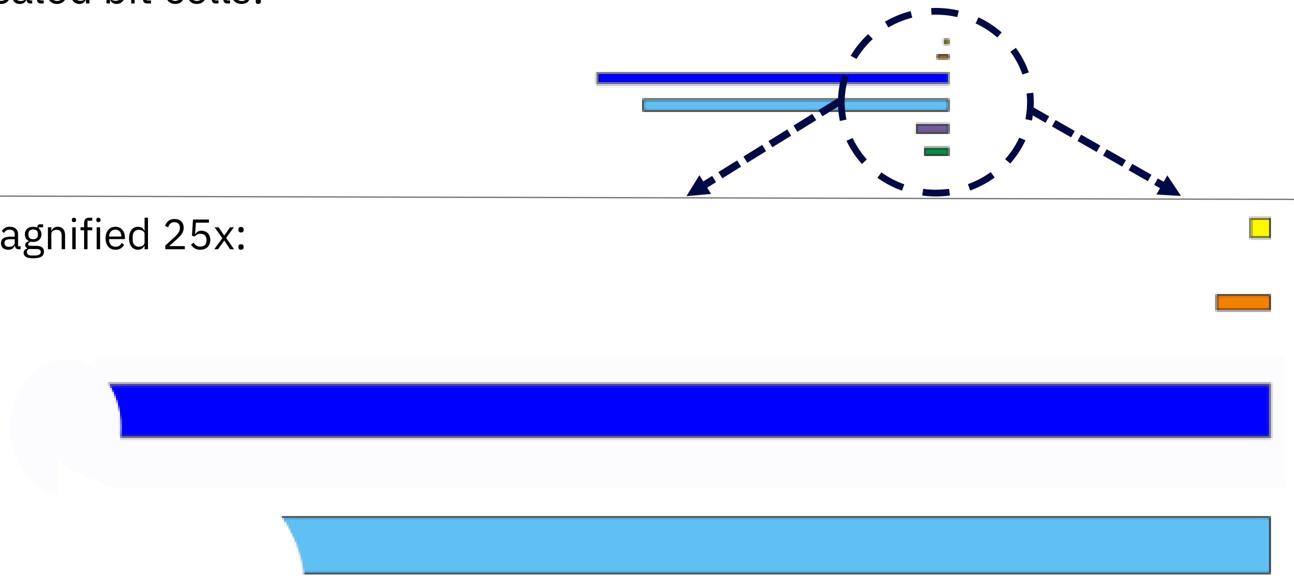


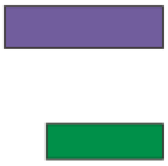
INSIC 2012-2022 International Magnetic Tape Storage Roadmap

2018 Storage Bit Cells and Extendibility

Scaled bit cells:

Magnified 25x:





NAND Flash (3 bits) 2150 Gb/in^2
17.3 nm x 17.3 nm

HDD 1000 Gb/in^2
47 nm x 13 nm

LTO8 Tape ~8.6 Gb/in^2
1560 nm x 48.4 nm

Jag5A Tape ~9.6 Gb/in^2
1347 nm x 50 nm

BaFe Demo 123 Gb/in^2
140 nm x 37 nm

Sputtered Demo 201 Gb/in^2
103 nm x 31 nm

Track density increase *is key for increasing areal density of future tape systems*

Tight control of tension *is key for moving to thinner tape, thereby increasing volumetric density*

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- **Disturbances and noise**

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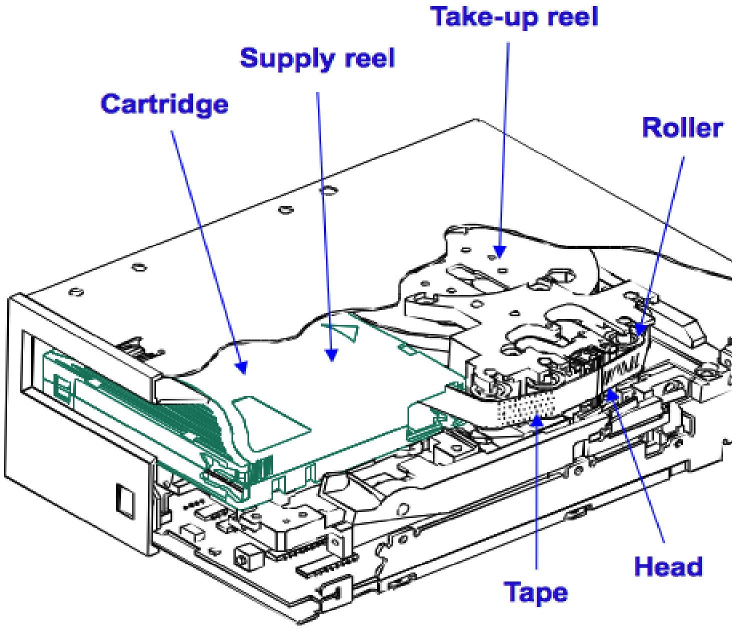
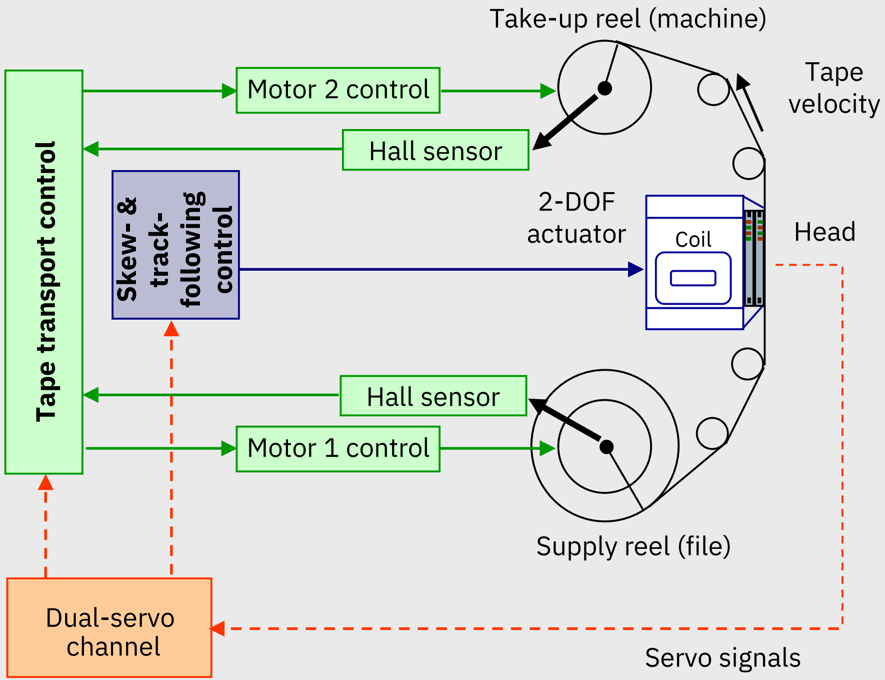
Tape storage system





- **Tape transport** system moving tape from supply reel to take-up reel
  - Velocity control: target velocities of ~1 to 10 m/s
  - Tension control: maintain nominal tape tension
- **Skew- and track-following system** used to position the head for writing/reading data on magnetic tape media and to compensate for the lateral tape motion (LTM) disturbance

Tape layout and position sensing

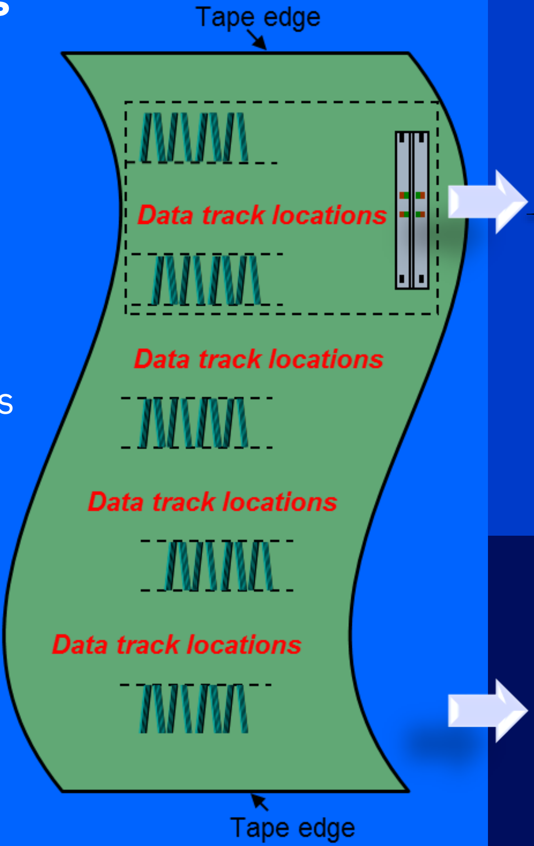
Servo and data bands

Five servo bands are pre-recorded on the tape

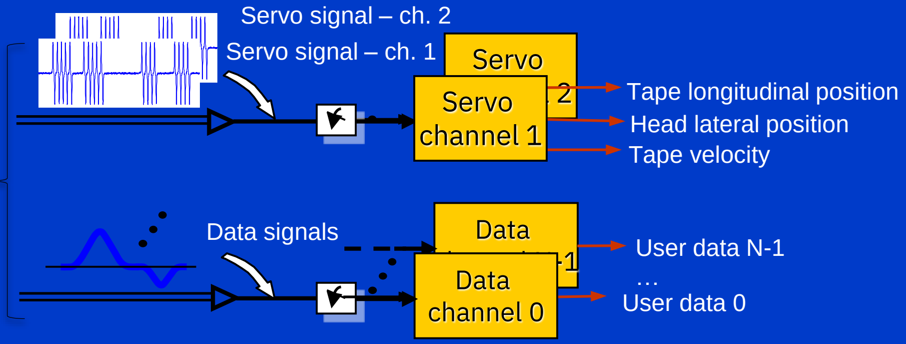
Data tracks are placed between pairs of servo bands

Each servo frame consists of 18 servo stripes arranged in four bursts (A, B, C and D)

Lateral position derived from the relative timing of pulses generated by the head while reading the pattern



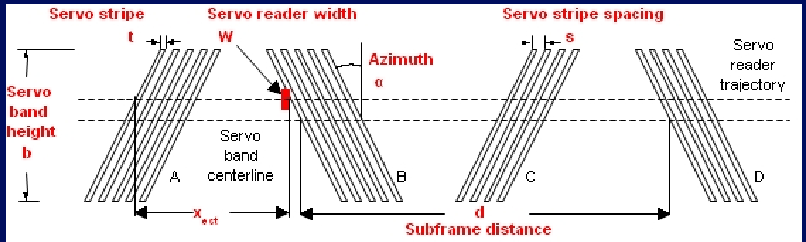
Position and velocity information



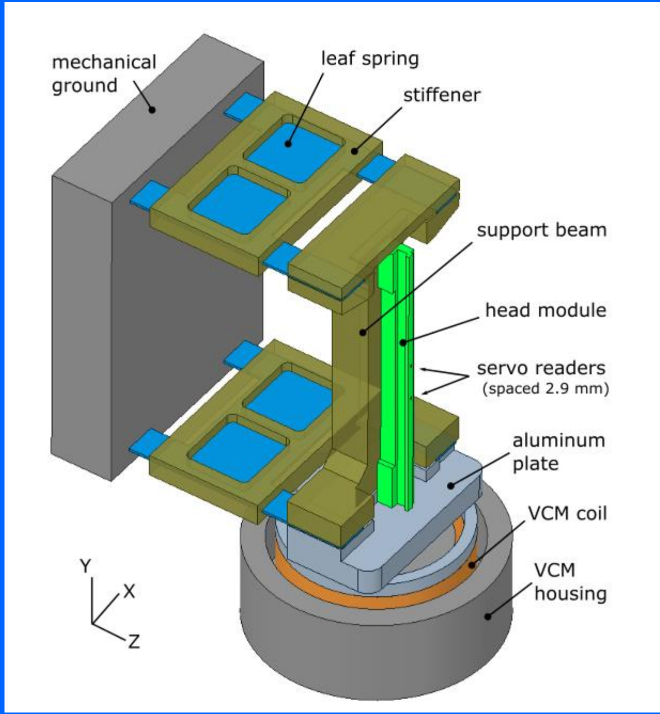
$$y_{est} = \left(\frac{1}{2} - \frac{\Sigma A_i}{\Sigma B_i} \right) \cdot \frac{d}{2 \cdot \tan(\alpha)}$$

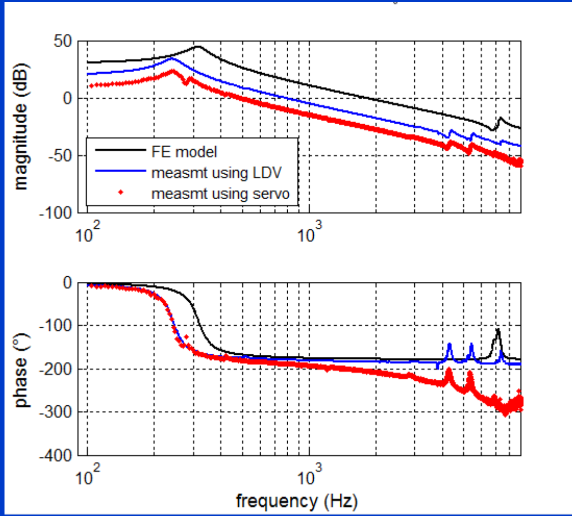
$$v_{est} = \frac{4d \cdot f_s}{\Sigma B_i}$$

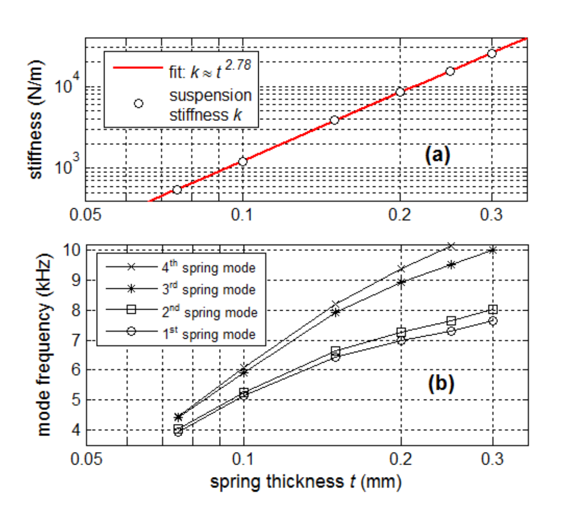
Servo pattern



Head actuation

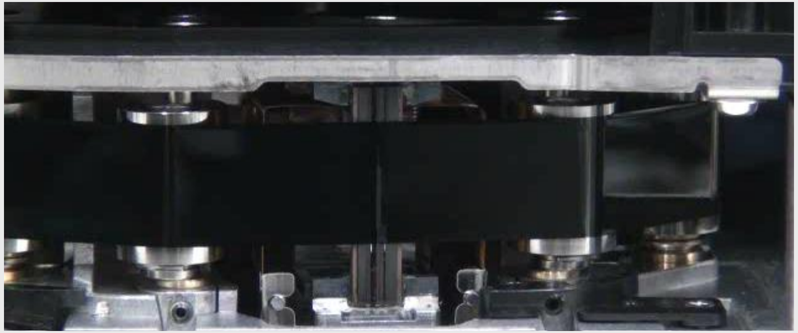






VCM actuator maintains track-following during read/write operations

Lateral tape motion disturbances

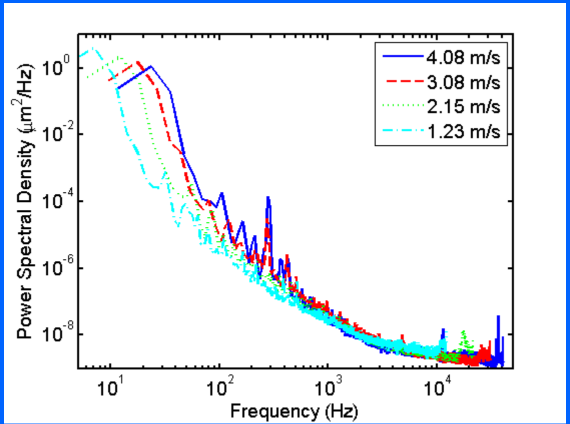


Tape speed determines the update rate of the position estimates

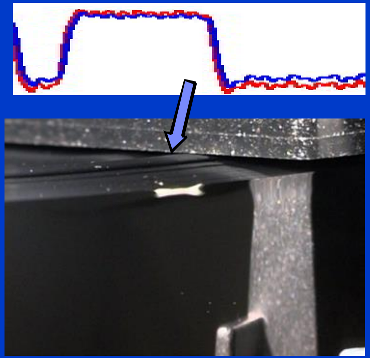
Tape-to-head skew errors are present in drives with flangeless rollers

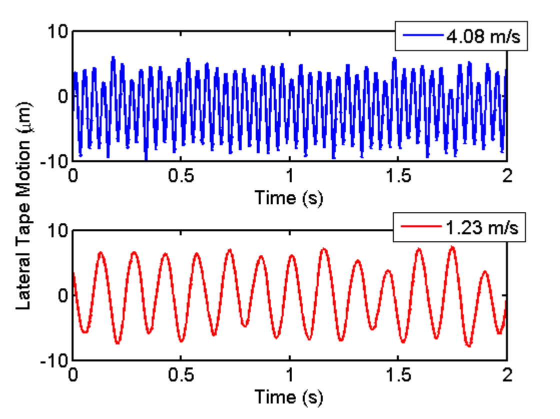
High-amplitude LTM appears at low frequencies

LTM disturbances shift to higher frequency with increasing tape speed



Effects are mainly due to stack shifts and periodic reel disturbances





Measurement noise

Resolution of the position estimate is important for achieving nanoscale track-following performance

– Noise floor in the high-frequency part of the LTM measurement is due to estimation noise

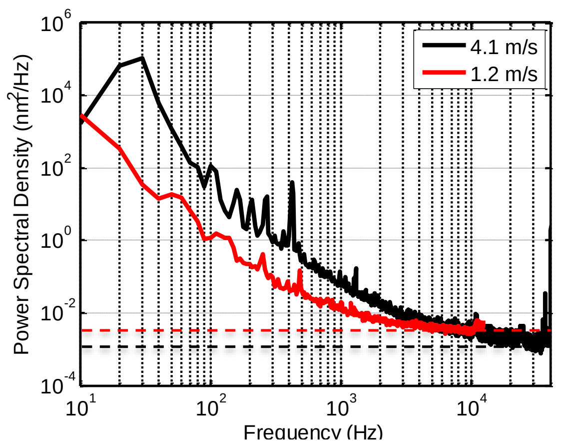
– Resolution estimate by extrapolation & integration over full bandwidth

Noise floor decreases with increasing tape speed due to increased sampling rate

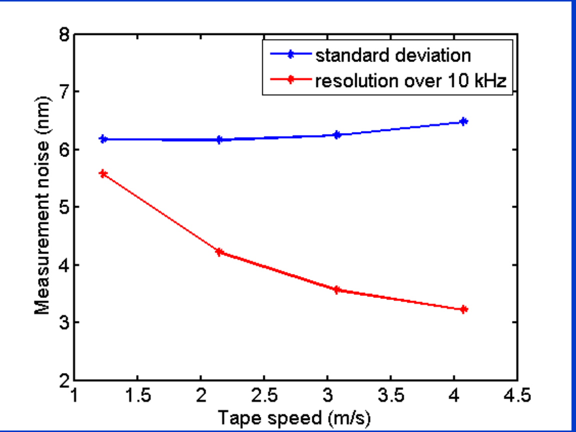
– Noise in 10 kHz bandwidth decreases with increasing tape speed

A. Pantazi, et. al., American Control Conference, 2015

PSD of the position estimate at two speeds



Resolution of the position estimate



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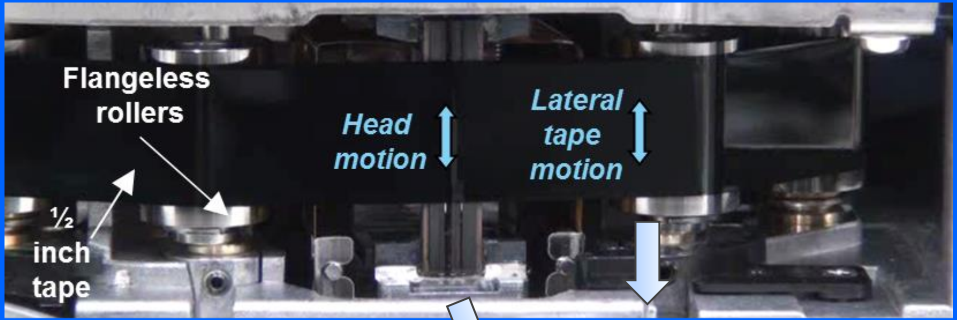
Tape drive track-follow control system

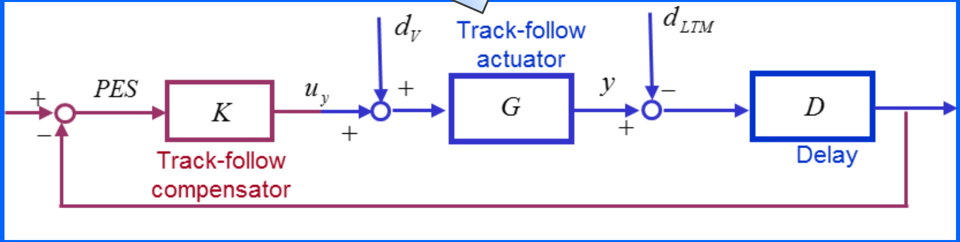
Main disturbances in the track-follow system

- LTM arising primarily from imperfections in tape guide rollers and reels
- Vibration disturbances that follow standard vibration profiles

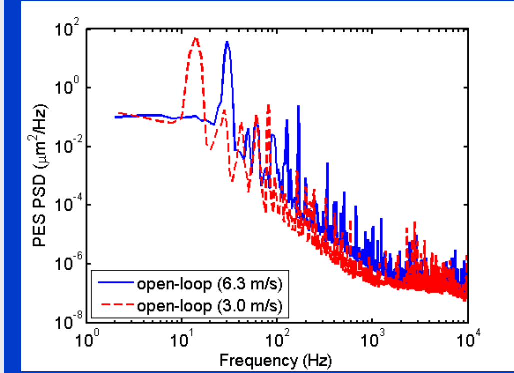
Main sources affecting the tracking error

- Lateral tape motion at low/high speed
- System delay / sampling time
- Mechanical coupling
- Operation under vibration environment

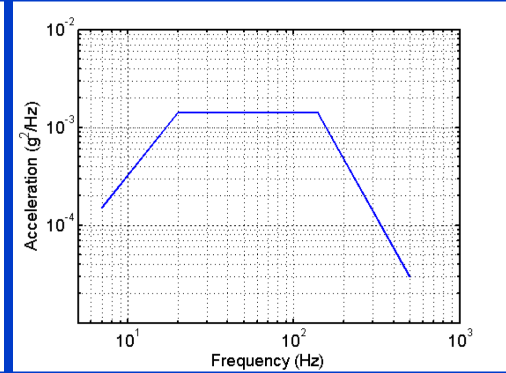




Lateral tape motion



Typical vibration profile



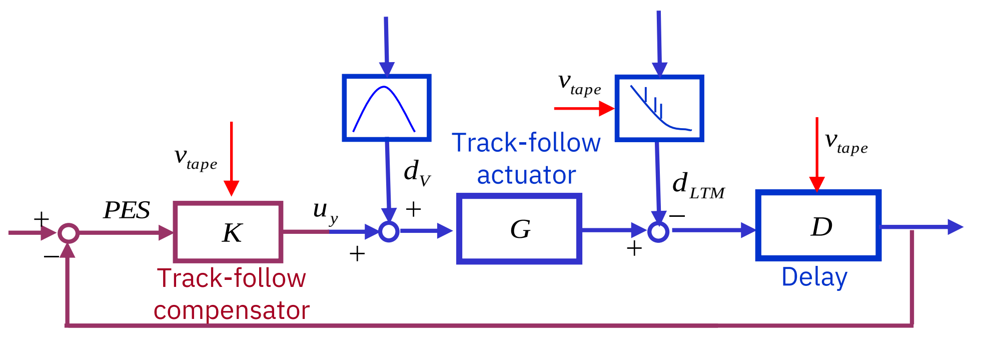
Tape drive track-follow control system

Main features

- The operating tape speed is used as a parameter to select the controller coefficients
- Disturbance rejection is enhanced at frequencies corresponding to roller rotation frequency and harmonics
- A speed dependent model of the system delay is used for control design
- A vibration frequency domain profile is used for the control design
- Support for tape skew-following control

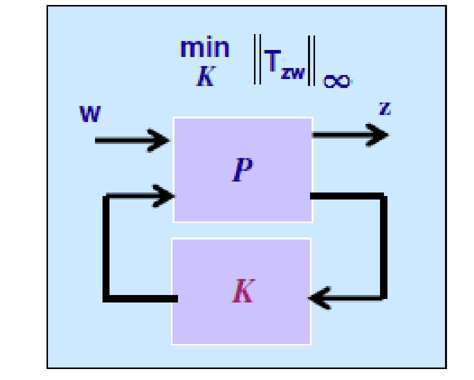
H∞ control framework essential in capturing the multiple control objectives

Track-follow control system



H∞ formulation

- ***P*:** plant used to formulate the design problem
  - includes system model and weighting functions
- ***K*:** controller to be designed



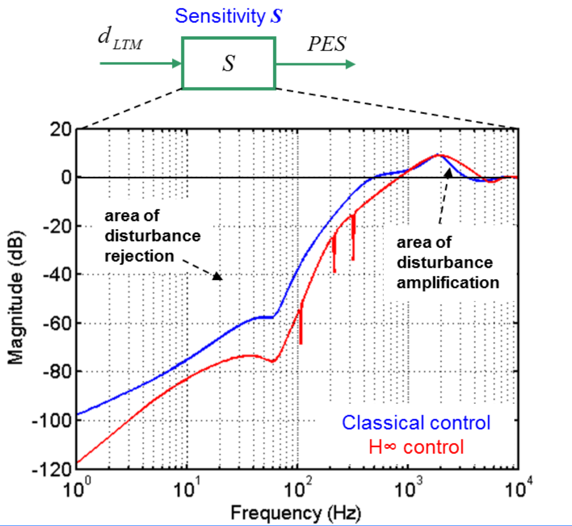
Experimental results using H∞ track-follow controller

Experimental results using H∞ controller show better performance compared to the classical controller both in normal and vibration conditions

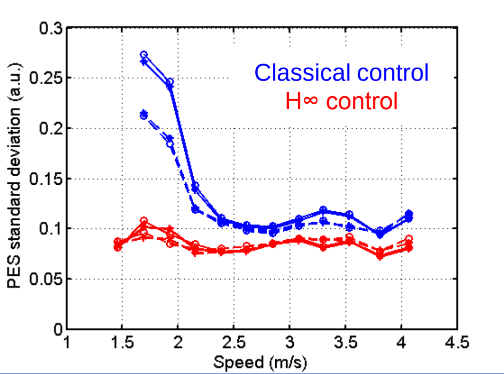
PES performance is uniform across tape speeds

H∞ track-follow controller provides ~2.5x better track-follow performance

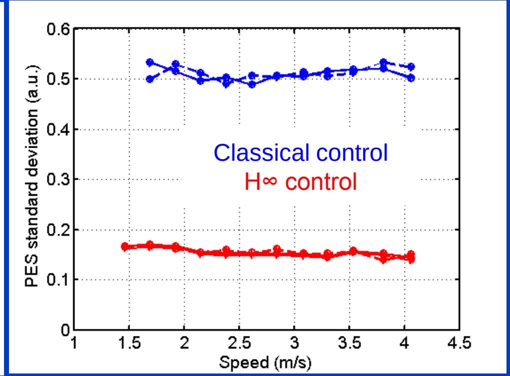
Sensitivity closed-loop transfer function



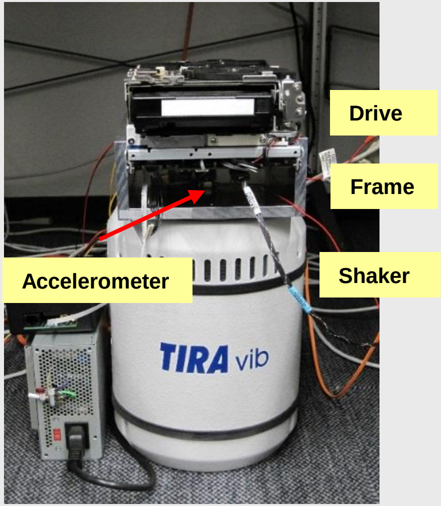
Track-following without vibrations

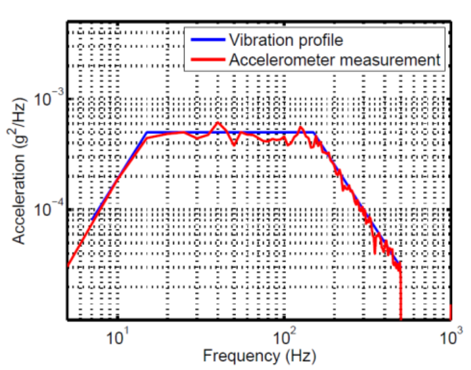


Track-following with vibrations



Tape drive operation under vibration conditions



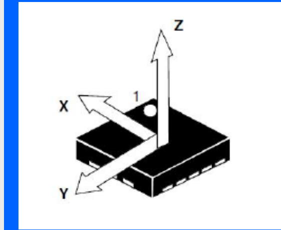


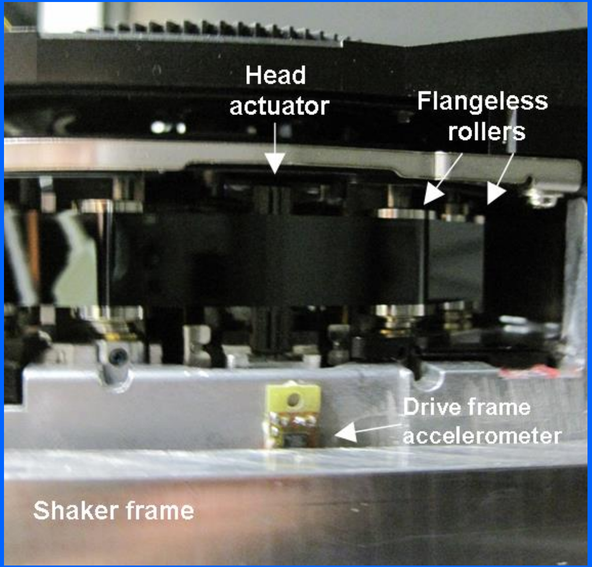
A vibration test system is used to create external disturbances in the lateral direction according to the acceleration profile

Vibration compensation using multiple MEMS accelerometers

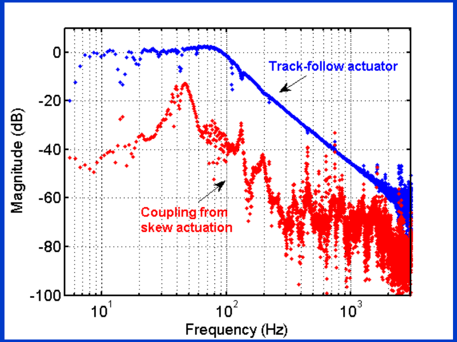
Experiments demonstrate 20% improvement in track-follow performance during vibrations

A. Pantazi and M. Lantz, IFAC Symposium on Mechatronic Systems, 2013

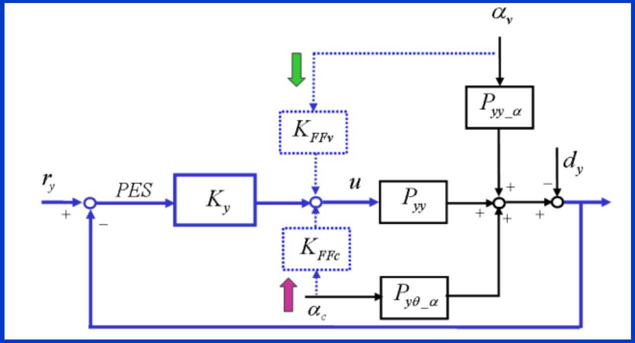




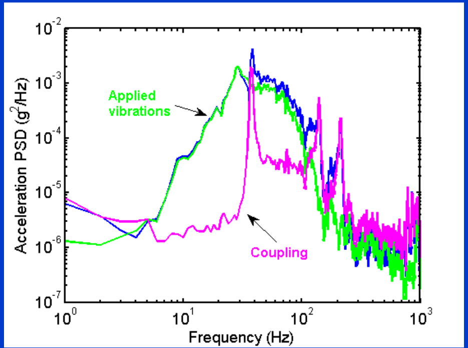
2DOF actuator exhibits coupling between the translational and rotational directions



Feedforward control based on acceleration measurements can substantially improve track-following under vibration conditions



Vibration coupling estimated by the difference between two accelerometer measurements



Track-following using external GMR sensor and cascade control

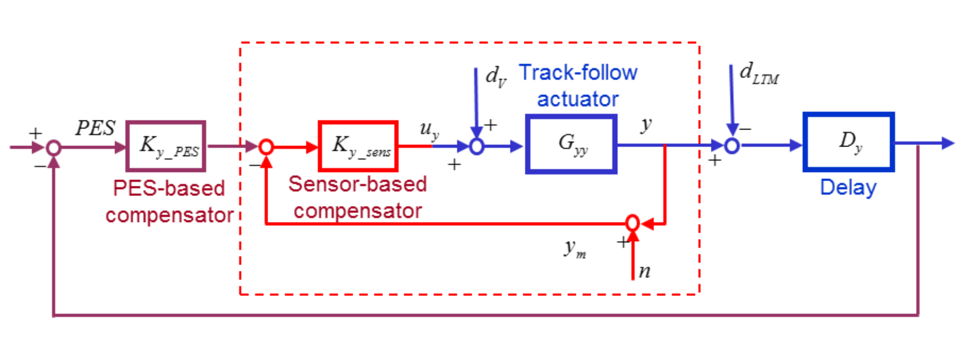
A position sensor measures the position of the actuator with respect to the tape frame

An inner loop is designed based on the position measurement

- to increase the track-follow actuator bandwidth
- to minimize the effects of external vibrations

A PES-based controller is designed to compensate for the LTM disturbances and is connected in a cascade control configuration

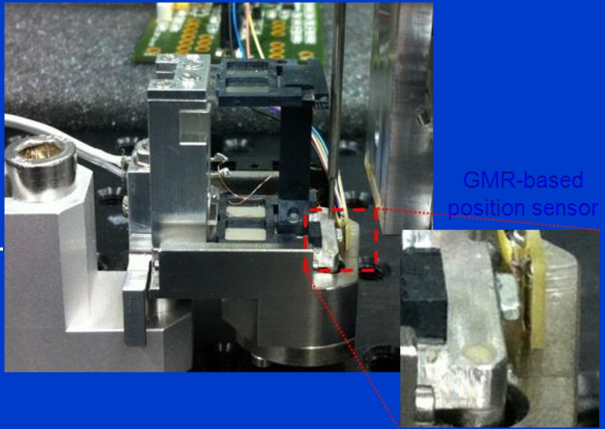
Cascade control architecture



External position sensor

Requirements:
High bandwidth,
low noise

Examples:
Optical position sensor,
giant magnetoresistance-(GMR) position sensor



GMR-based position sensor: Concept

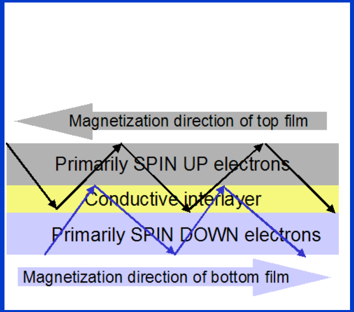
Translate the motion to a change in magnetic field as seen by a GMR sensing element

Motion of the actuator body → Motion of the magnet → Change of the magnetic field → Change in sensor resistance

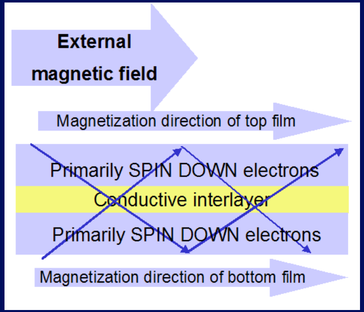
Key advantages

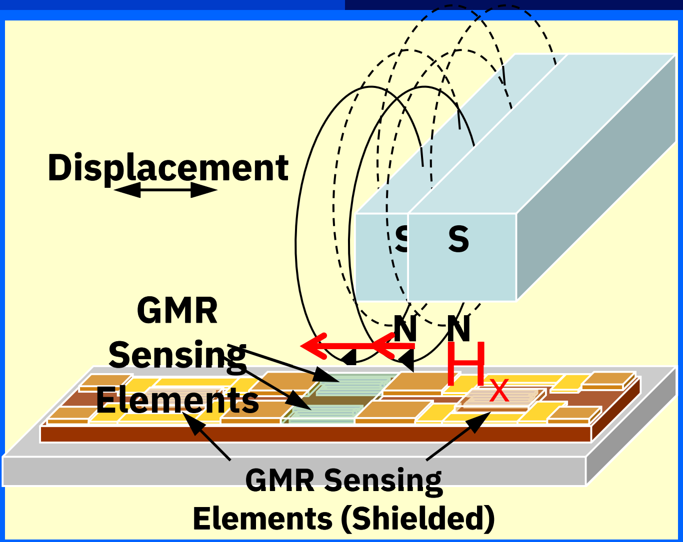
– Non-contact sensing
– Small form factor
– Simple read-out circuitry
– Very high bandwidth (> MHz)
– Extremely low cost

MORE SCATTERING:
HIGH RESISTANCE



LESS SCATTERING:
LOW RESISTANCE





GMR-based position sensor: Resolution

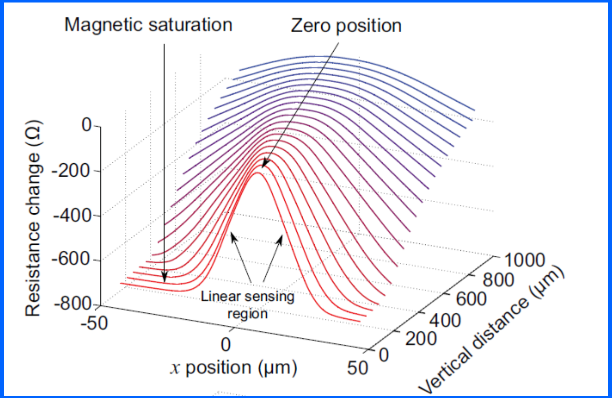
Lower sensitivity / longer range for larger vertical distance

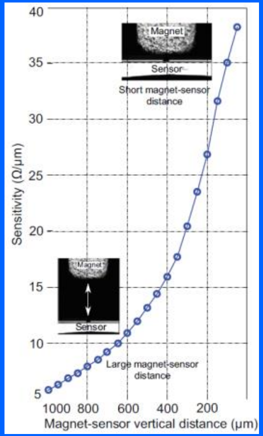
Higher sensitivity / shorter range for shorter vertical distance

Noise: 610 pm over 1 MHz

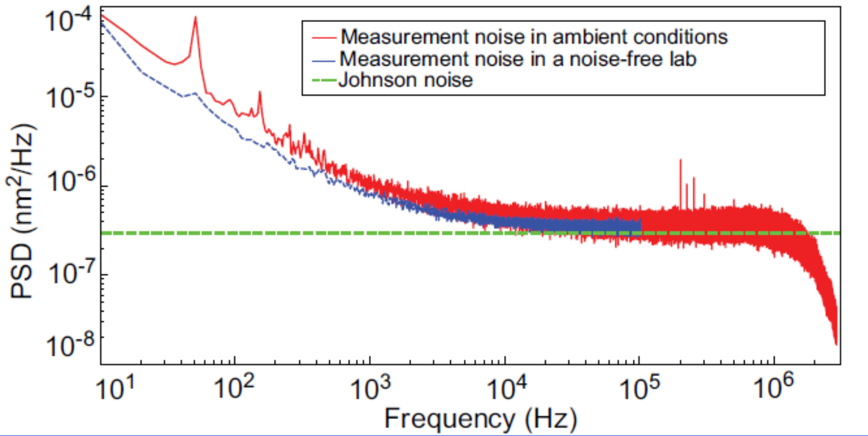
T. Tuma et. al, Nanotechnology, 2014

Sensitivity

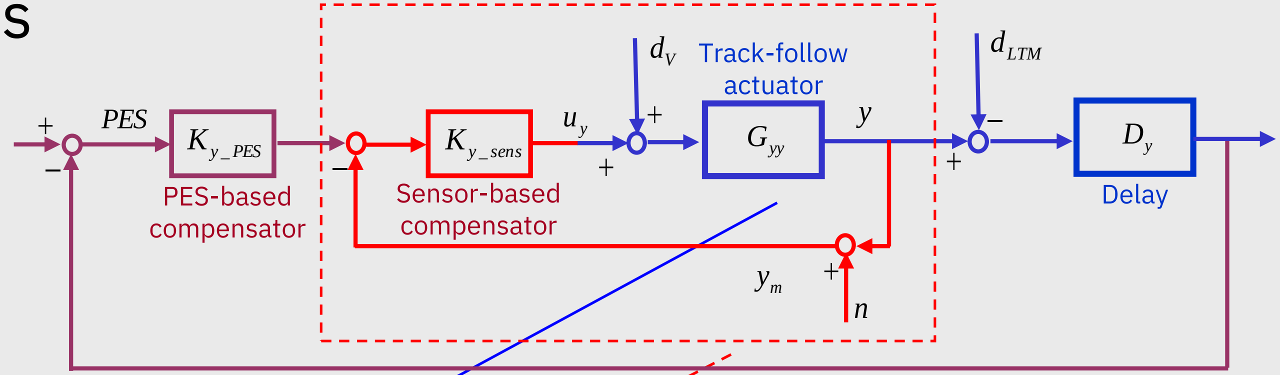


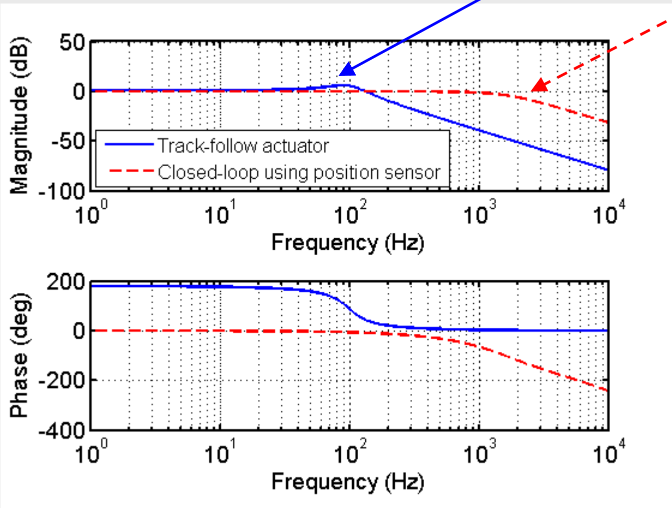


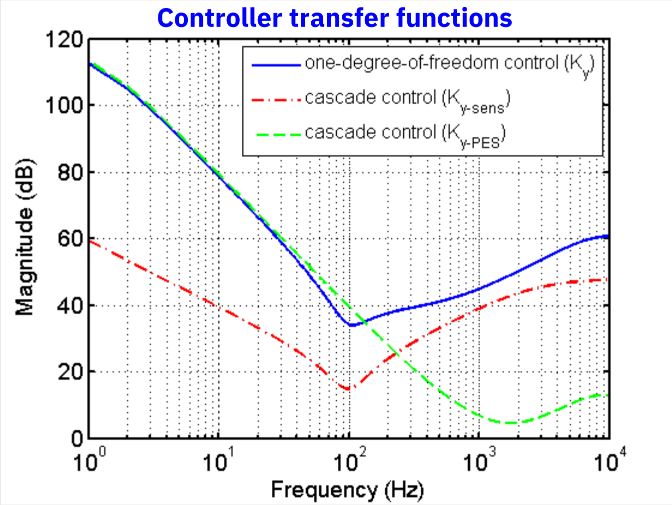
Noise



Control design: Transfer functions







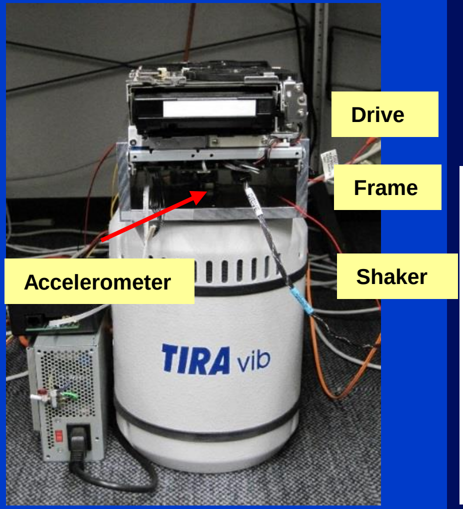
PES performance under vibration conditions

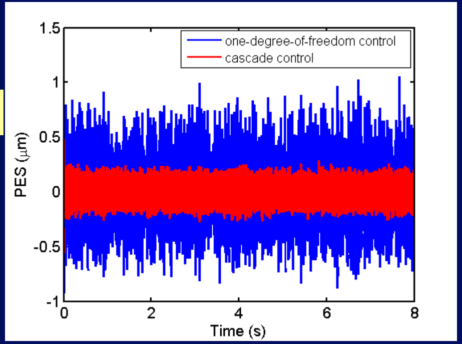
Simulation results show improved performance (in terms of 1 σ PES) in the presence of vibrations

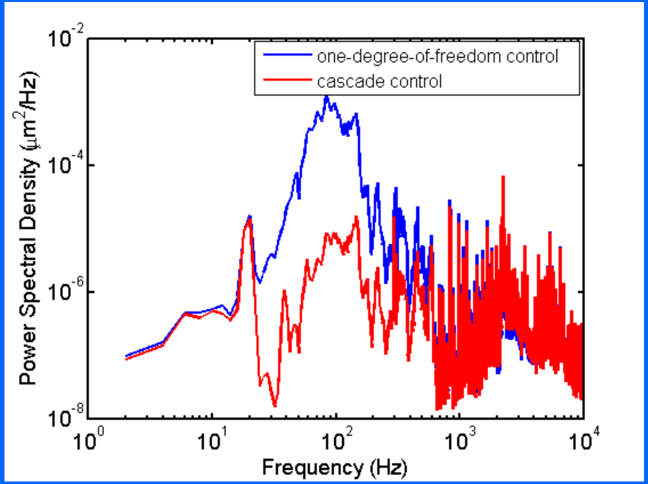
PES-based control: 250 nm

Cascade control: 63 nm

A. Pantazi and M. Lantz, IFAC World Congress, 2014







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Position sensing and head actuation

Disturbances and noise

Advanced control technologies

Track-follow control

Tape transport control

The future of tape

World record tape areal density demo of 123 Gb/in^2

Technologies enabling the 123 Gb/in^2 demo

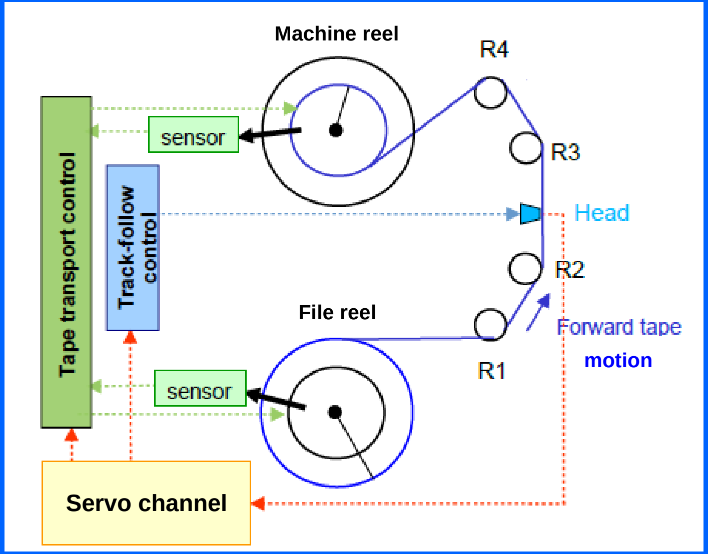
Conclusions

Tape transport system

Motivation

Improved tape transport is essential in achieving larger volumetric recording densities

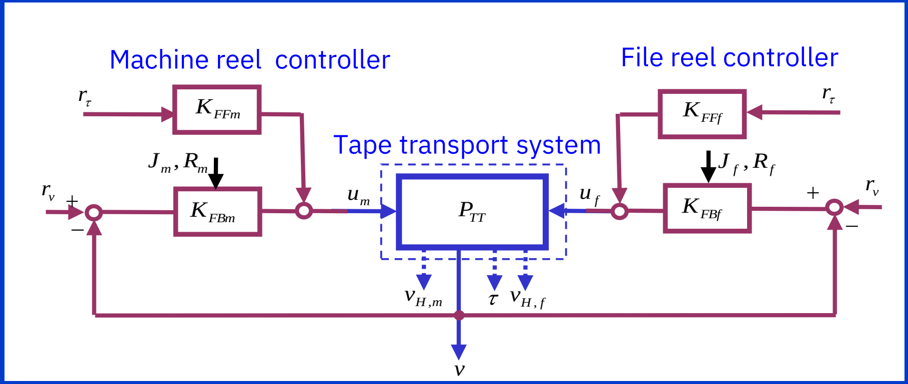
- Enables tape drive operation with thinner tape
- Supports higher areal data densities by minimizing: tape speed variations, tape deformation, lateral tape motion



Tape transport velocity control

Primary velocity: Measures tape velocity at the head using pre- formatted servo information

Secondary velocity: Measures the individual reel velocity based on Hall sensors



Tape transport model

Tape transport state-space model

$$\dot{\mathbf{x}}(t) = \mathbf{F}\,\mathbf{x}(t) + \mathbf{G}\,\mathbf{u}(t)$$

$$\mathbf{y}(t) = \begin{bmatrix} v_m(t) \\ v_f(t) \\ \tau \end{bmatrix} = \mathbf{H}\,\mathbf{x}(t),$$

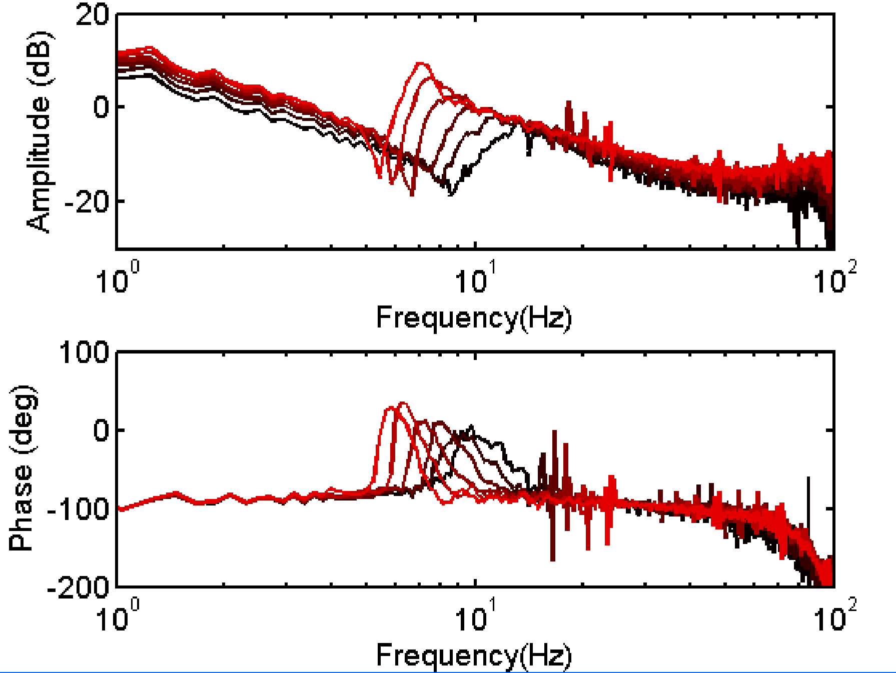
$$\mathbf{x}(t) = \begin{bmatrix} x_m(t) \\ v_m(t) \\ x_f(t) \\ v_f(t) \end{bmatrix} = \begin{bmatrix} \text{tape position at machine reel} \\ \text{tape velocity at machine reel} \\ \text{tape position at file reel} \\ \text{tape velocity at file reel} \end{bmatrix}$$

$$\mathbf{F} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \dfrac{-(1+\mu)R_m^2 K_T}{J_m} & \dfrac{-(1+\mu)R_m^2 D_T - \beta_m}{J_m} & \dfrac{(1+\mu)R_m^2 K_T}{J_m} & \dfrac{(1+\mu)R_m^2 D_T}{J_m} \\ 0 & 0 & 0 & 1 \\ \dfrac{R_f^2 K_T}{J_f} & \dfrac{R_f^2 D_T}{J_f} & \dfrac{-R_f^2 K_T}{J_f} & \dfrac{-R_f^2 D_T - \beta_f}{J_f} \end{bmatrix}$$

$$\mathbf{G} = \begin{bmatrix} 0 & 0 \\ \dfrac{R_m K_m}{J_m} & 0 \\ 0 & 0 \\ 0 & \dfrac{R_f K_f}{J_f} \end{bmatrix} \qquad \mathbf{H} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ K_T & D_T & -K_T & -D_T \end{bmatrix},$$

G. Cherubini, A. Pantazi, M. Lantz, Proc. IFAC Symp. Mechatronic Systems, 2016

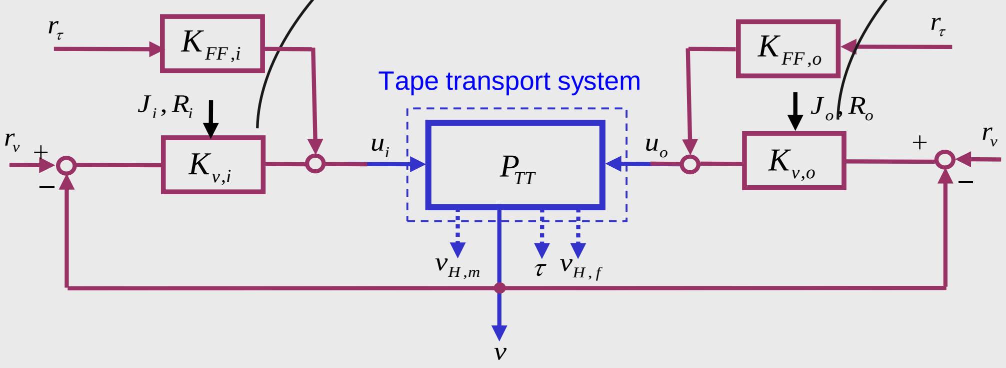
Identified transfer functions: File reel motor current to velocity (BOT → EOT)



Tape transport characteristics are time-varying

Tape transport velocity control

$$K_{v,i} = g_v \frac{J_i}{r_i K_i} \qquad K_{v,o} = g_v \frac{J_o}{r_o K_o}$$

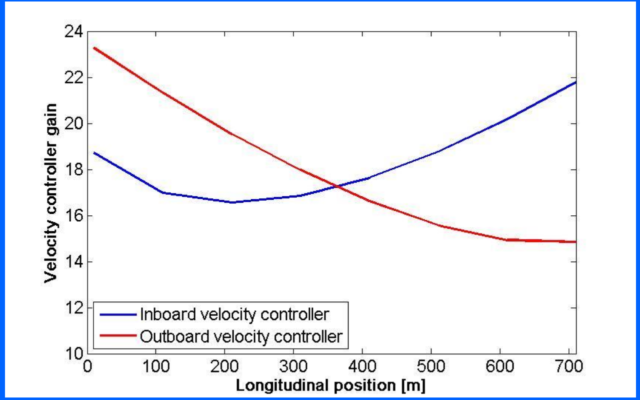


Time-varying p-type controllers are designed such that the closed-loop transfer functions for the file reel velocity match the corresponding transfer functions for the machine reel velocity

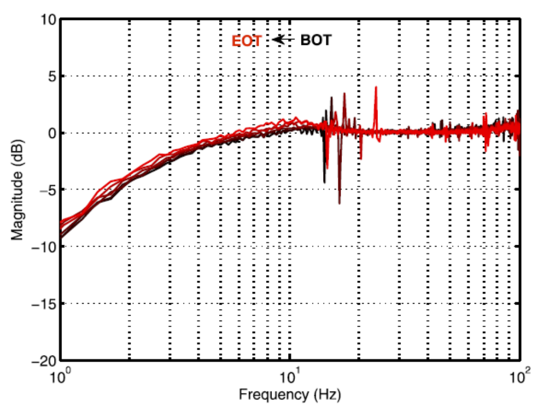
All functions become **essentially independent of the longitudinal position**

G. Cherubini, A. Pantazi, M. Lantz, Proc. IFAC Symp. Mechatronic Systems, 2016

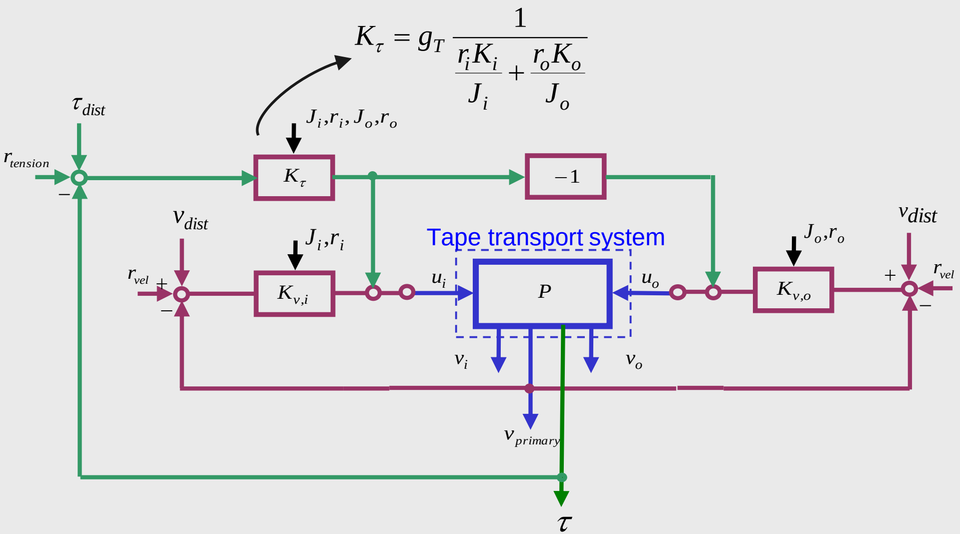
p-type velocity controllers



Experimental frequency response of velocity disturbance to velocity error



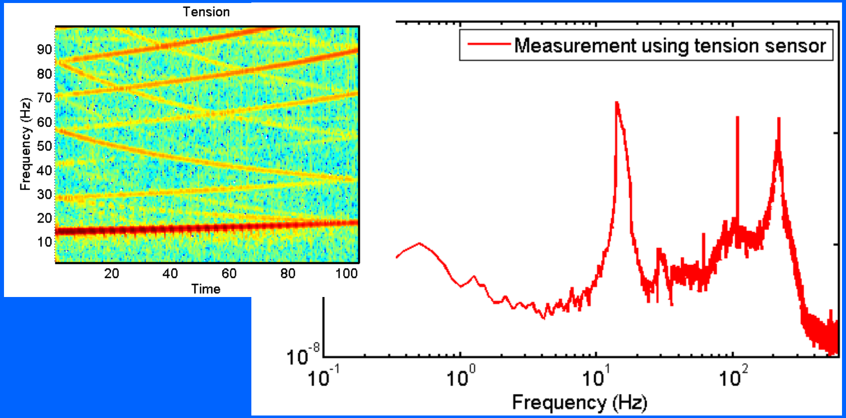
Tape transport tension control



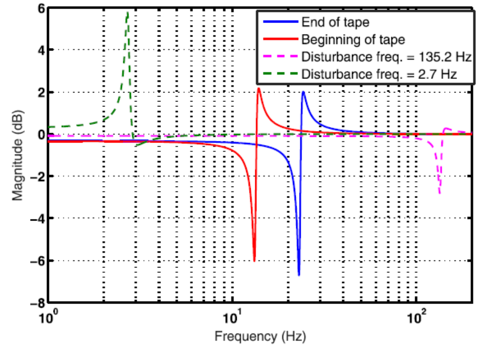
Time-varying p-type controllers were proposed to achieve a tension control system essentially independent of the tape longitudinal position

However, p-type controller can't provide enhanced disturbance rejection at the periodic tension disturbances → Control system **enhanced by an H∞ narrow-band filter**

Tension variations are mainly induced by reel eccentricities that lead to time-varying tension disturbances

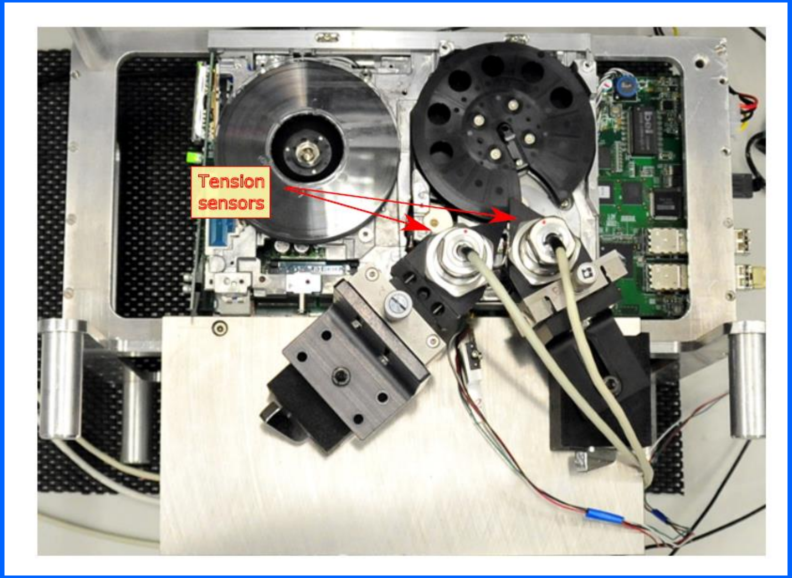


The transfer function of the H∞ narrow-band filter can vary significantly depending on the disturbance frequency



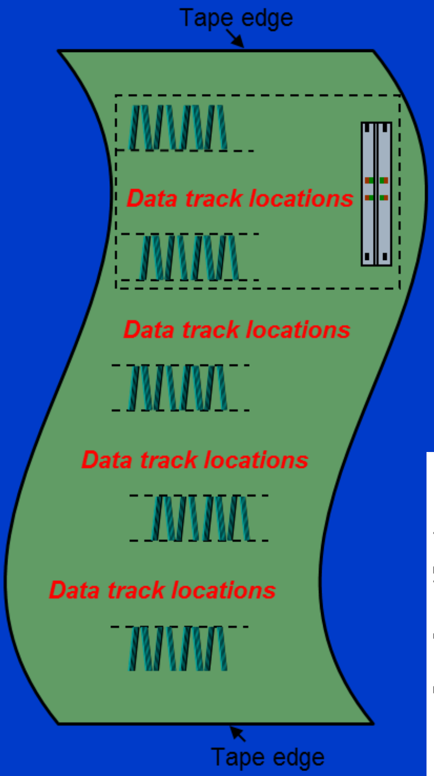
Tension measurements

Experimental tape transport



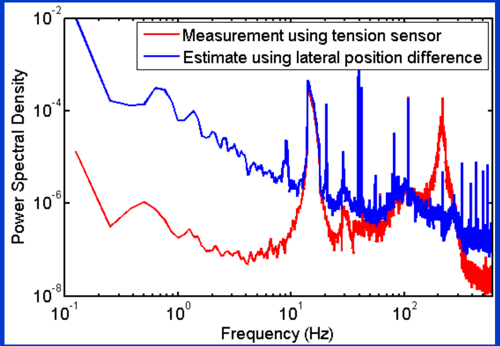
Tension is measured by two strain gauges mounted on two of the tape guide rollers in the tape path

Tape layout



Tension is estimated based on the difference of lateral position estimated from two adjacent servo channels

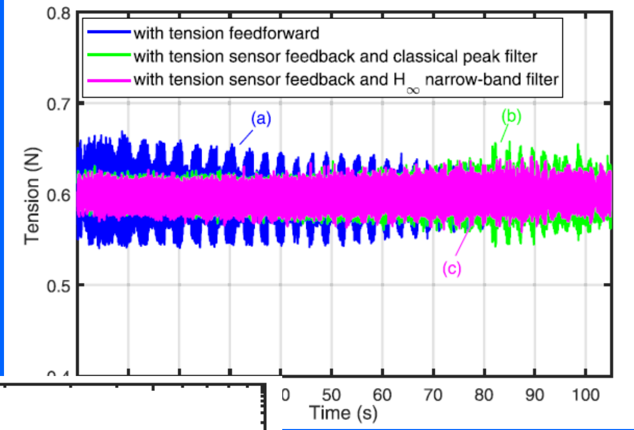
$$\Delta T \approx -\frac{4uE}{\nu}(y_{ch1} - y_{ch0})$$

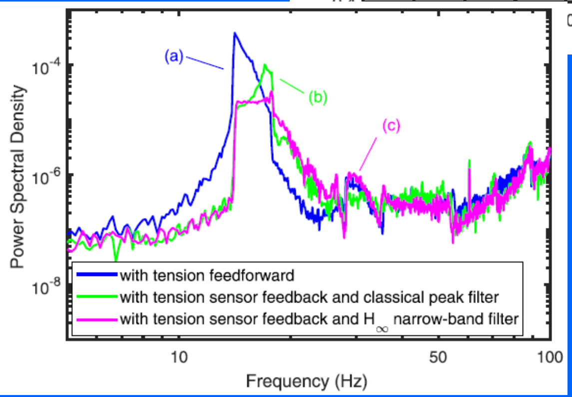


Experimental results: Tension control

External tension sensor used for tension feedback

H∞ optimized narrow-band filter improves performance





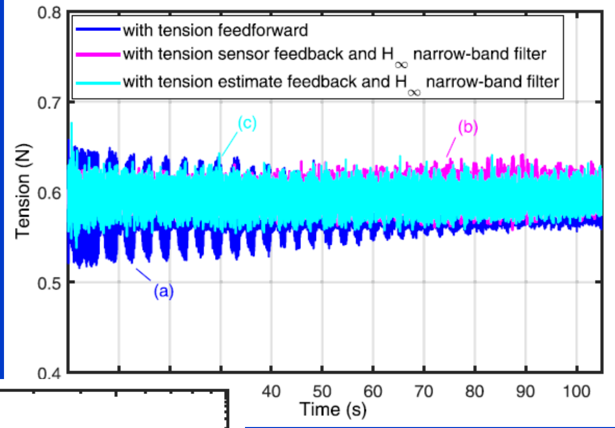
1σ tension
with feedforward: 0.022 N

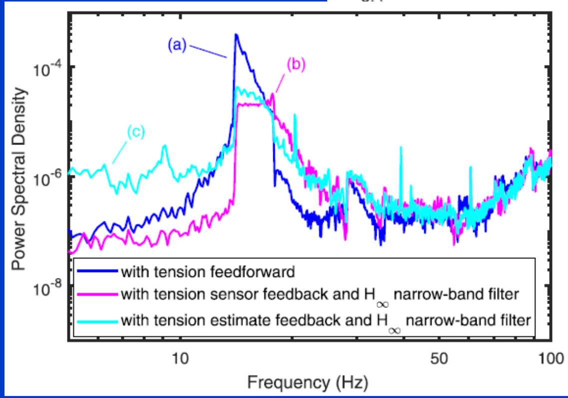
with classical peak filter: 0.014 N

with H_∞ narrow-band filter: 0.011 N

Ypos difference estimate used for tension feedback

Improved performance without requiring additional sensors in the tape path





1σ tension
with feedforward: 0.022 N

with H_∞ narrow-band filter: 0.013 N

G. Cherubini, A. Pantazi, M. Lantz, Mechatronics, 2018

Outline

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Disturbances and noise

Advanced control technologies

Track-follow control

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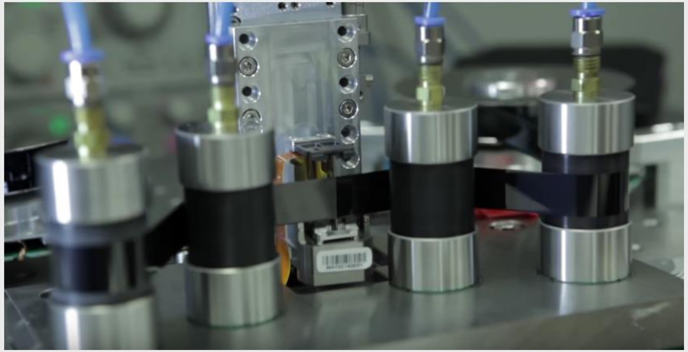
World record tape areal density demo of 123 Gb/in^2

Technologies enabling the 123 Gb/in^2 demo

Conclusions

Demo technologies



Focus on aggressive track density scaling

Require:

– **dramatic improvement in track following → enables track width reduction**

– reduce reader width from a few microns to 90 nm

Ultra narrow reader results in a dramatic loss in read back signal that must be compensated for with

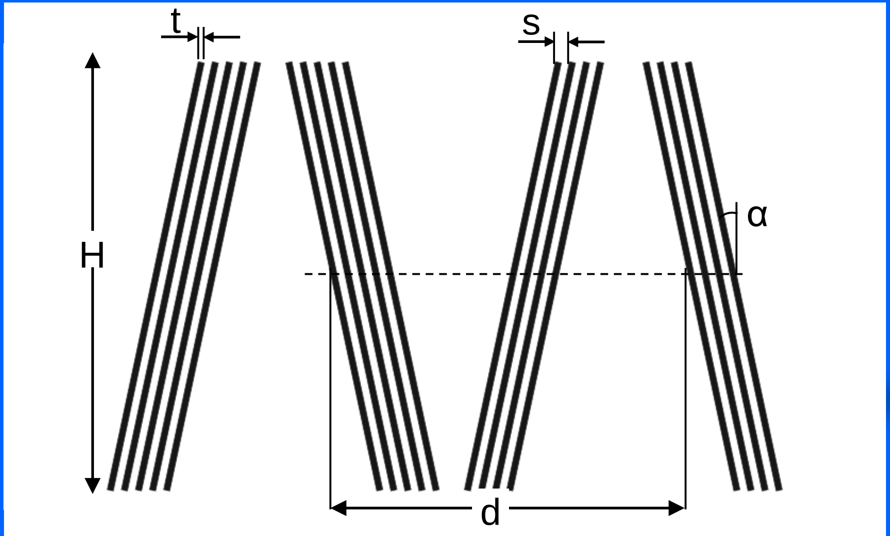
– improved media technology → require improved writer technology

– improved signal processing and coding

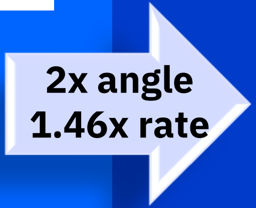
– improved reader technology

Servo pattern design for high areal density demo

Standard LTO7 / 8 / Jag4 / 5 / 5A Pattern



H = 93 µm, t = 1.25 µm, s = 3 µm
α = 12°, d = 76 µm



Demo Pattern

Main design goal: nm-scale head position resolution

Increased azimuth angle → increased resolution

Increased pattern density → increased servo bandwidth and resolution

H = 23.25 µm, t = 1.0 µm, s = 2.4 µm
α = 24°, d = 52 µm

Synchronous servo channel

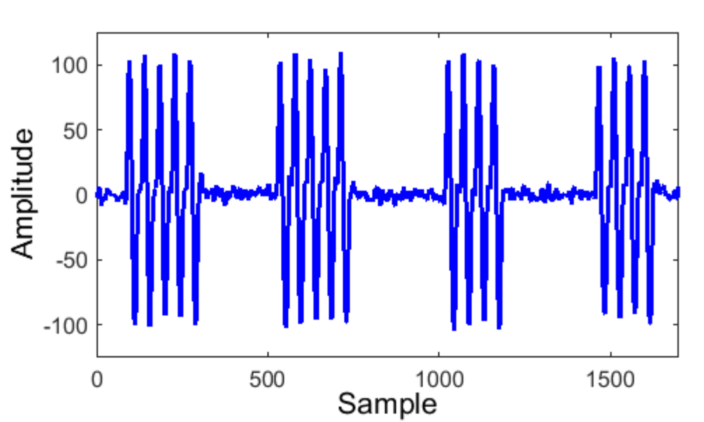
Servo channel decodes the readback signal from the servo pattern and provides position information to the track-following control system

Servo channel optimized for p-BaFe → improved resolution

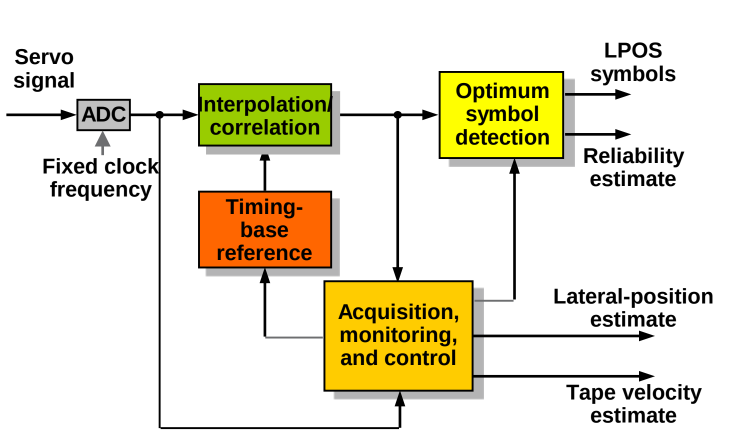
Optimized servo channel in combination with advanced BaFe media formatted with the 24°demo servo pattern provides nanoscale position information

G. Cherubini et. al., IEEE/ASME Tran. Mech., 2016

Servo readback signal



Servo channel



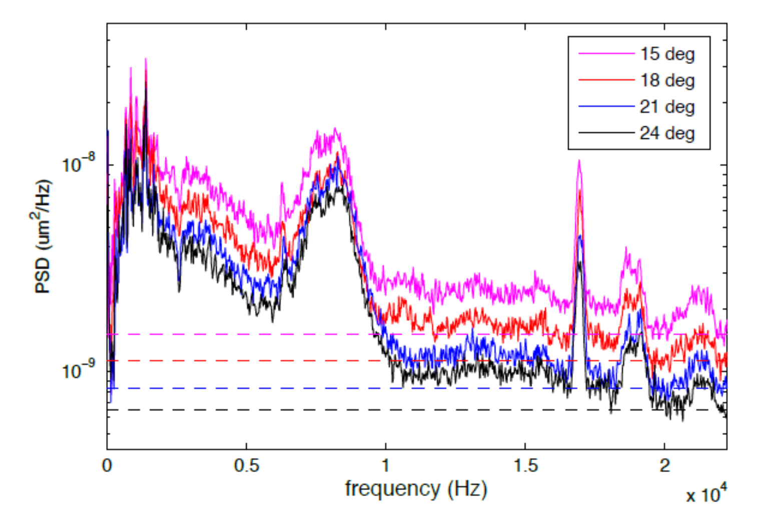
Resolution limits

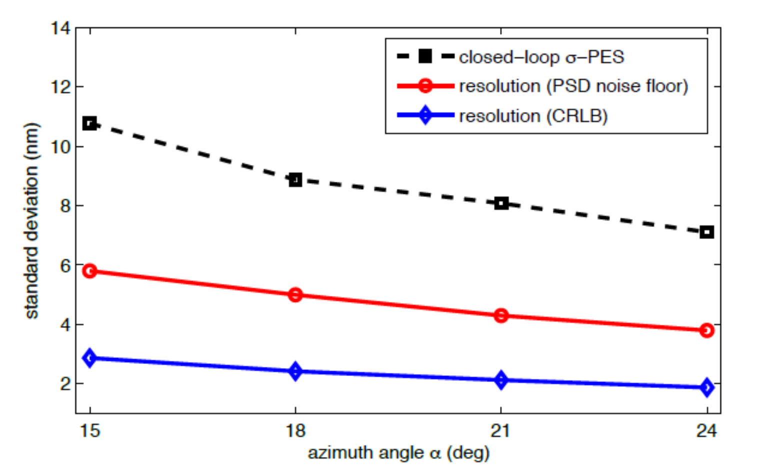
Resolution was estimated by two methods

– The noise floor of the PSD of the LTM measured from the servo pattern

– An analytical lower bound derived from the readback signal characteristics

The 24°pattern provides the highest performance with a resolution better than 3.8 nm for a single channel and better than 2.6 nm when two channels are combined





S. Furrer, A. Pantazi, G. Cherubini, and M. Lantz , IEEE Trans. Magn., 2015

New H∞ track-follow control system

Key features

– Prototype high bandwidth head actuator

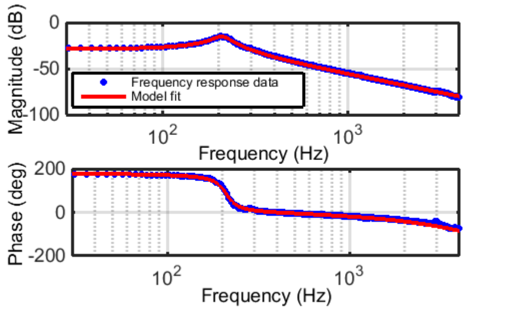
– A speed dependent model of the system delay is used for control design

– The tape speed is used as a parameter to select the controller coefficients

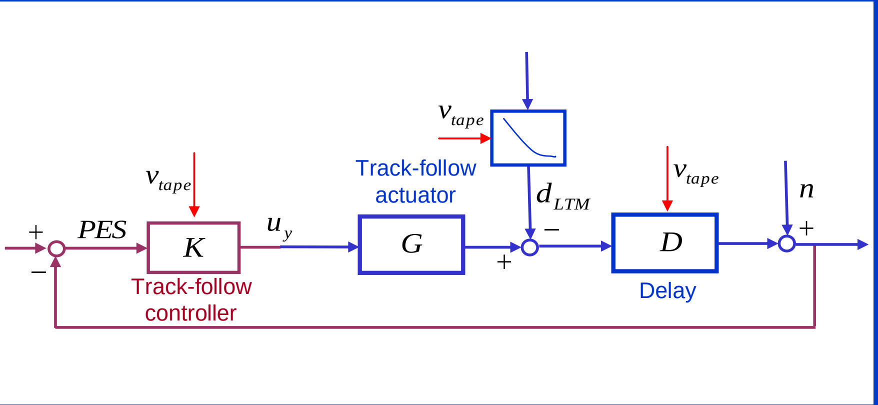
– Disturbance rejection is enhanced at the frequencies of the tape path disturbances

A. Pantazi, et. al., American Control Conference, 2015

High Bandwidth Actuator



Track-follow control system



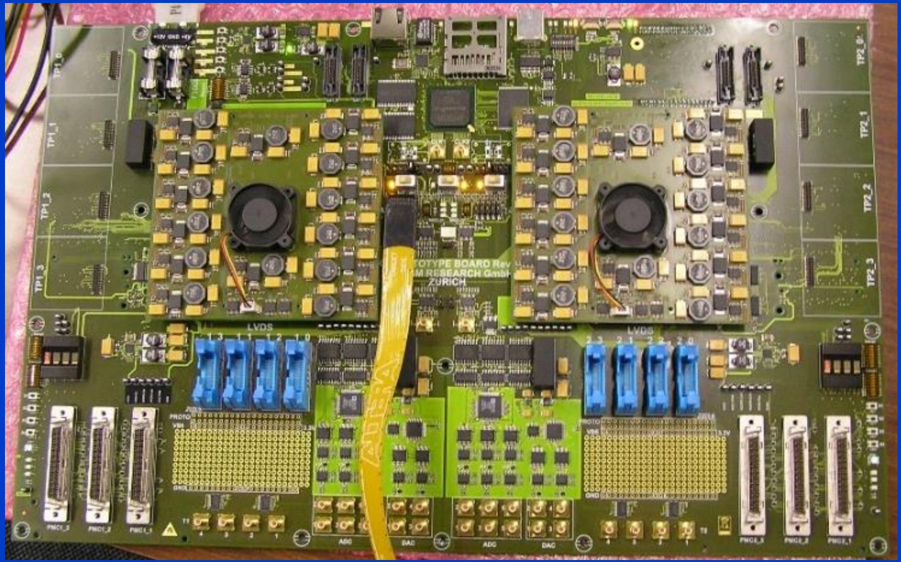
Prototype tape transport & hardware platform

Precision flangeless tape path

Precision flangeless tape path with grooved rollers & pressured air bearings to minimize disturbances

TS1140 electronics card for reel-to-reel control and analog front end

Hardware platform



FPGA Board: System-on-Chip (SoC)

- Servo channels
- Microprocessor for synchronous track-follow (TF) servo controller

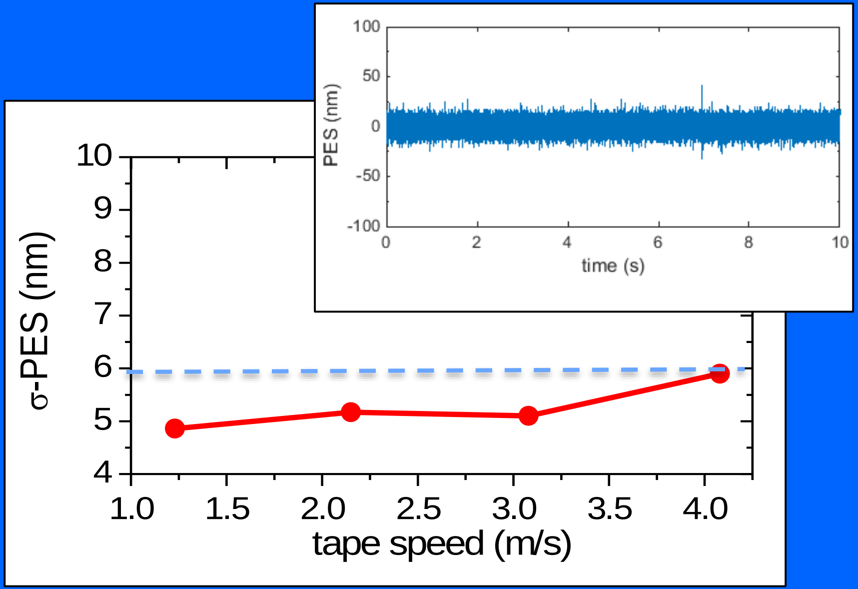
Track-follow performance on BaFe tape

Track width computation based on measured PES (INSIC method)

σPES : measure of track following fidelity

Track width = 2*√2 * 3*σPES + Reader Width
(Reader Width = 90nm)

σ-PES ≤ 5.9 nm over TS1140 speed range



Reader Width = 90nm
σ-PES ≤ 5.9 nm

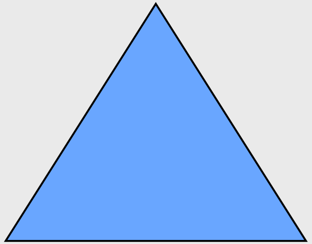
Track width = 140 nm
Track density = 181 ktpi

Enhanced Write Field Head Technology

Magnetic Media “Trilemma”:

Small particles (V)

$$SNR \propto V$$



Thermal Stability

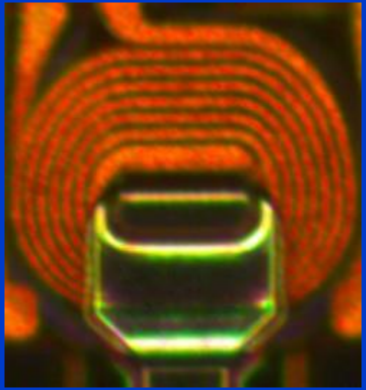
$$E_B \propto K_u \cdot V$$

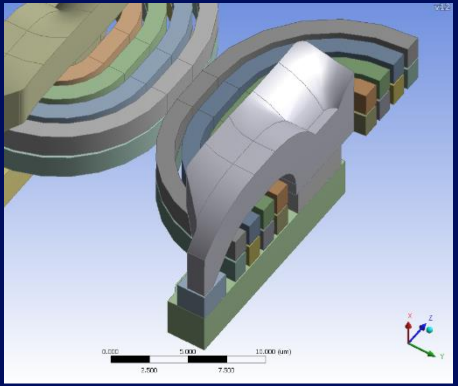
Writability

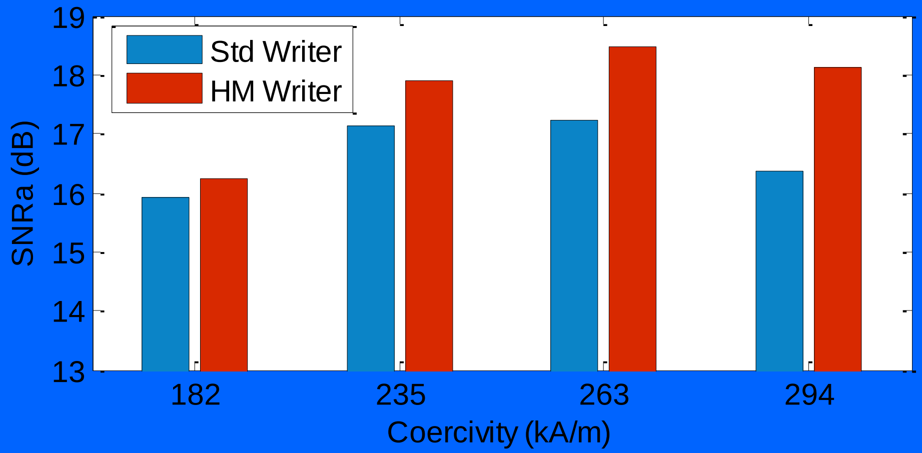
$$H_0 \propto K_u$$

$$H_0 < Head\ Field$$

IBM developed a new high moment (HM) layered pole write head that produces much larger magnetic fields enabling the use of smaller magnetic particles







Increasing media coercivity

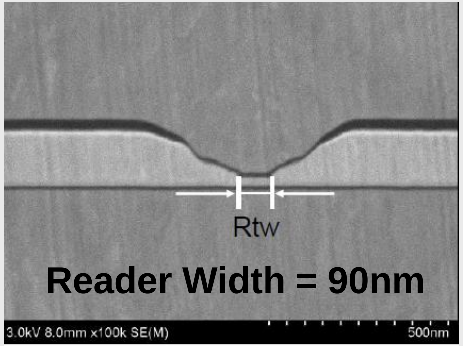
Recording performance

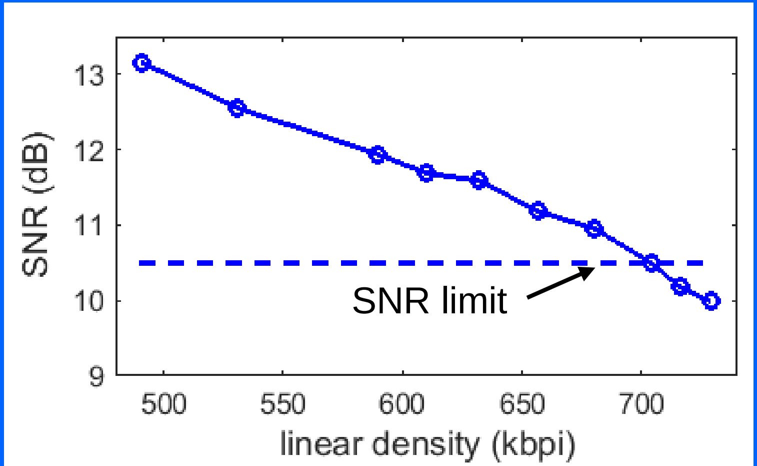
New data channel combines

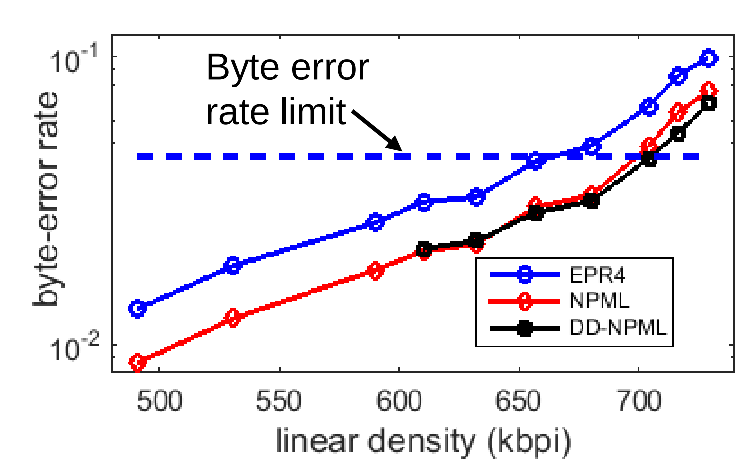
- Advanced NPML detection schemes
- New iterative decoding scheme

Advanced BaFe supports a linear density of **680kbpi** with a 90nm reader and provides an operating margin of ~ 0.5dB SNR

SEM image of GMR reader







Summary of demo results

Advanced Perpendicular BaFe medium

Linear density = 680 kbpi w/ 90 nm reader (single-channel recording)

1-sigma PES = 5.9 nm,

Track density = 181 ktpi (track width = 140 nm)

Areal recording density : 123 Gb/in^2

12.8x TS1155 areal density

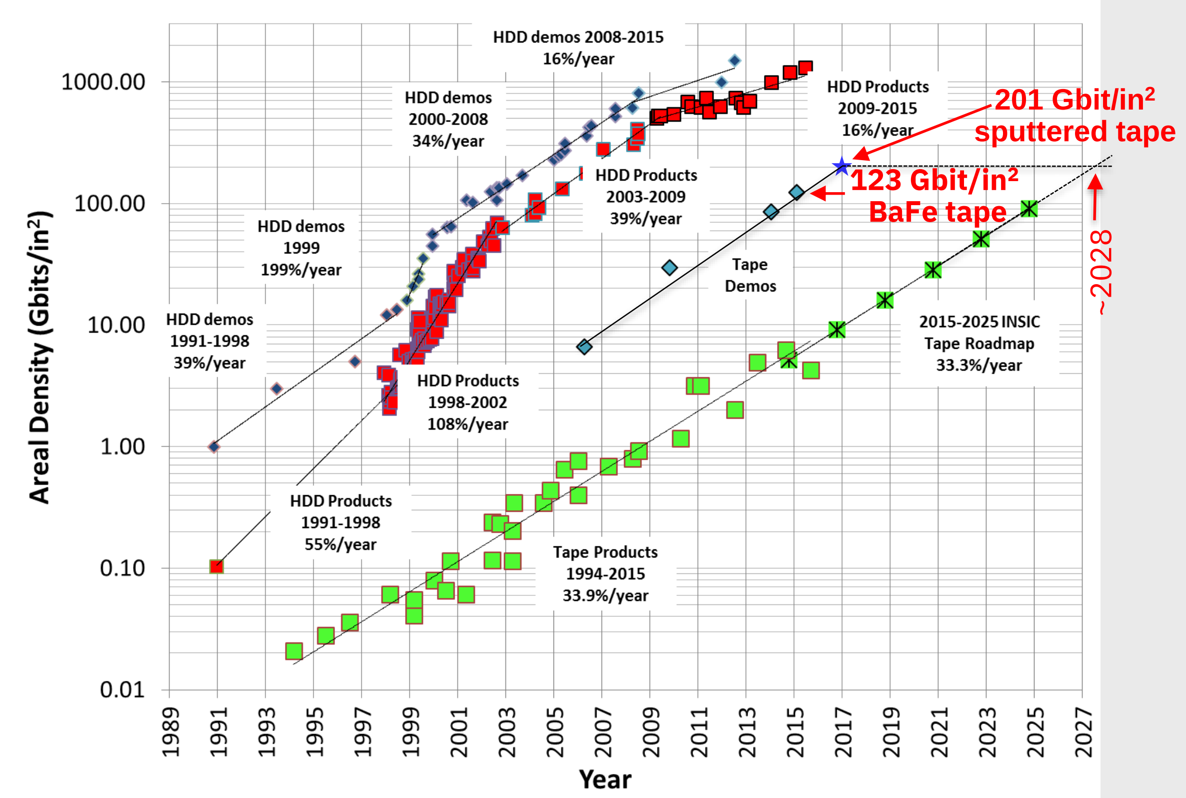
→ 220 TB cartridge capacity (*)

This demonstration shows that tape technology has the potential for significant capacity increase for years to come!

(*) 220 TB cartridge capacity, assuming LTO6 format overheads and taking into account the 48% increase in tape length enabled by the thinner Aramid tape substrate used

M. Lantz et. al., IEEE Trans. Magn., 2015

Areal density scaling



Tape has a sustainable roadmap for at least another decade

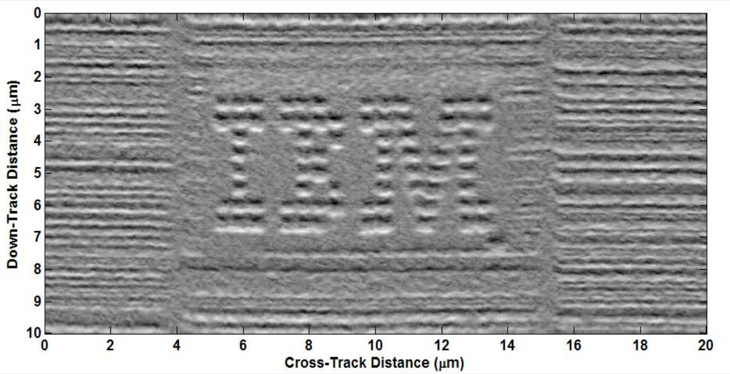
INSIC 2012-2022 International Magnetic Tape Storage Roadmap

Summary

The era of big data is creating demand for cost effective storage solutions

- Tape remains the most cost-efficient and greenest technology for archival storage and active archive applications
- 123 Gbit/in^2 and 201 Gbit/in^2 areal density demos show feasibility of multiple future tape generations
- Potential exists for the continued of scaling of tape beyond 201 Gbit/in^2

Advanced control technologies are crucial for achieving these ultra-high areal densities and thereby ultra-large storage capacities.



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