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A Tale of Three Actuators: How Mechanics, Business Models and Position Sensing Affect Different Mechatronic Servo Problems

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Abstract— **Students studying control problems often learn a lot of wondrous algorithms that impart near mythical properties to the systems that they are applied to. At least this is how it works in theory and simulation. In practice, however, a thorough understanding of the system, the use model, and the market is often far more important than the differences between any two optimization algorithms. Knowing when and where a particular algorithm is useful is typically at the heart of real control problems.**

This paper will focus on three servo systems with which the author has had considerable experience: hard disks, optical disks, and atomic force microscopes. By examining how the particulars of these three systems affect the use of control algorithms, the author will try to extract some general lessons.

I. A PHILOSOPHY FOR INDUSTRIAL RESEARCH

An understanding of industrial research is not something that happens instantaneously, but over years of practice. My first job at HP Labs was to do MIMO control on an optical disk system. Having been weaned on Matlab throughout graduate school, I decided that I wanted to be able to dump MIMO designs from Matlab direction into my real time DSP system. It took 15 months of tool building to make this work, so that I could start really doing my original job. At the time, it seemed as if this tool building time might have been wasted, but it resulted in a sophisticated real time system that was I used for research over the next seven years. The difficulty of having to implement a system to translate my algorithmic work into something useful was a first insight into the differences between the academic and industrial worlds. This insight was broadened when I was about seven years out of graduate school. In about 1994, two events happened that led me to a much fuller understanding of the *philosophical differences* between academic and industrial research.

During that year, I was doing research on the control of hard disk drives at Hewlett-Packard Labs. I got a phone call from a Ph.D. student at an East Coast school. (If I ever find out who it was, I will apologize for what happened next.) The graduate student told me they were finishing their Ph.D. on this and that subject and then said, "I am very interested in working on optimal control." Almost reflexively, the words leaped out of my mouth, "Me, too, pal."

While I feel bad that this might have sounded callous, the difference in points of view was right on. The graduate student had a tool that they wanted to apply to do whatever amazing things the tool could do. I, as an industrial researcher, had a tool bucket and a problem to solve. While it would have been nice to be able to concentrate on one particular tool, I have found that it is more important to understand how to select the right tool to make headway on the physical problem. While successful academic researchers often chase a particular algorithm, successful industrial researchers rarely have that luxury. The student is stuck following *Hanlon's Razor*, "When all you have is a hammer, every problem looks like a nail." The industrial guy is handed something that with high probability, bears no resemblance to a nail.

The second thing that happened is that some friends and I attended a martial arts seminar on Brazilian Jiu Jitsu taught by Rickson Gracie. Those who know about mixed martial arts competition know him as one of the all time greats in that sport. In person, he is physically imposing. And yet, techniques aside, he made two philosophical statements about competition against an opponent [1]:

- "You can't do what you want. You must do what they give you."
- "The more you want to use this stuff for the real thing, the more you need your opponent's reaction to help you."

Now, coming from such a physically imposing person, this made us all think, "Well if he has to react to each situation, what do the rest of us have to do?" For me, though, I realized that those same thoughts could be rewritten for industrial engineering research:

- You can't do what you want. You must solve the problem they give you.
- The more you want to use this stuff (e.g. control theory) for the real thing, the more you need your problem's characteristics to help you.

Furthermore, it is important to look up from our algorithms and realize the truth in the words of Star Trek's Lt. Montgomery Scott (Scotty) "I can't change the laws of physics![2]" This fundamental realization that no algorithm can make the physics of the problem disappear, is key to making progress on applying control to physical problems. Whenever anyone says, "You don't need to understand the problem; X will take care of it," alarms should go off in the listener's head. *Hogwarts* [3], *The Force* [4], perpetual motion machines, warp speed [5], etc. are not in evidence on this planet. More importantly, knowing when someone is relying on one of those is useful.

So, what use are algorithms in real problems? Well, like a surfer on a big wave, good algorithms ride the physics of the problem, rather than trying to change them. The problems

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determine the control algorithm. No one “hammer” can solve them all. However, the prepared engineer is most likely to find the right tool, especially if they are agnostic in their selection. By taking this philosophy, they are more likely to find the fracture points in a real problem: those hidden places where significant progress can be made. One of the hardest lessons for a highly skilled controls person to learn and accept is that often, the best solution to the servo problem often has nothing to do with control. Like Han Solo, we are not looking for a mystical energy field, but applying our simple tricks and nonsense [6][1] . And like Pope John Paul I, once we realize what algorithm can help with a particular problem, we always wish we had studied it harder [7][2].

The rest of this paper will show how this view, when applied to three separate mechatronic control problems, allows us to see both their fundamental differences and the commonality. The reader will see how the physics of the problem, the use model, even the selling price, will determine what control algorithms can be applied. Furthermore, the choice of the right method to suit the overall problem will have a much more significant effect than the particular optimality of a given algorithm.

The paper is organized as follows: Sections II, III, and IV go through the basics of the hard disk, optical disk and atomic force microscope (AFM) control problems, respectively. Section V describes what moves on these different systems and at what frequencies. Section VI describes the electromechanical actuators used in the different systems and how they affect the respective control problems. Sections VII and VIII describe the generation of servo signals and the noise sources for the different problems. Section IX describes how the sample rates and use models affect the use of extra sensors, multirate, and auxiliary loops. Sections X and XI describe how the intellectual property (IP) and business model issues affect the control systems.

II. HARD DISK 101

Referring to Figure 1, we see that the hard disk system starts with a stack of rotating media holding user data. The data written on concentric tracks in the media. The spindle spins media so that read/write heads are mounted in a slider that “flies” over the surface on an air bearing. The vertical position (flying height) is controlled via passive loop between mechanical springiness of actuator and air bearing. The radial position is controlled via an active feedback loop. For hard disks, the actuators have been rotary since the 1970s [8]. The position information almost always multiplexed with user data on the track – a practice known as sectored servo.

Figure 2 shows a pictorial block diagram of a hard disk control loop. For this loop, the main sources of noise are shock and vibration (both external and internal), Position Sensing Noise (a.k.a. PES noise), windage (air flow from spinning disks buffeting the mechanics), disk flutter (driven by windage), and spectral noise usually related to orders of the spindle rotation frequency. The spindle rotation adds both spectral and non spectral disturbance components. The impact of air on the head and actuator provides a lot of “process noise,” while the “measurement noise” comes from media, head, and demodulation errors.

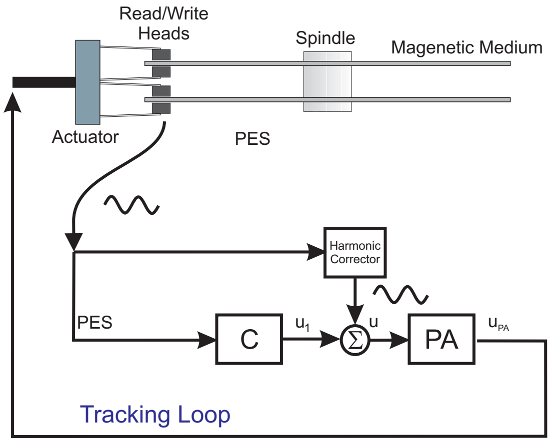

Fig. 1. Pictorial diagram of a hard disk system. The read/write heads float on an air bearing over a spinning surface coated with magnetic medium. The main servo loop involves controlling the radial position of the heads via a rotary actuator.

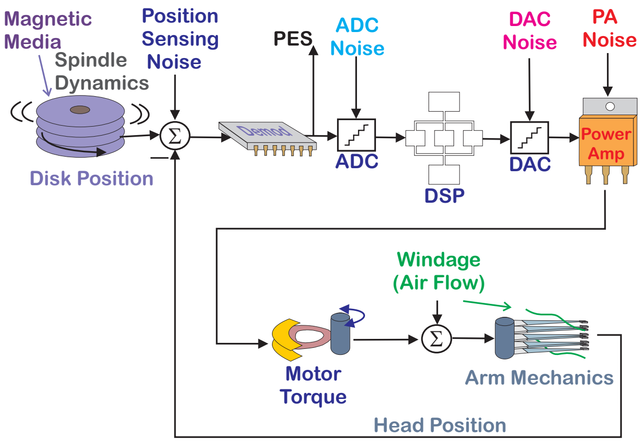

Fig. 2. For a hard disk loop, the control starts with concentric tracks of user data on stacks of spinning media. The read/write heads float on air bearing and read position from magnetically written servo information. The Position Error Signal (PES) is demodulated from magnetic domains, then digitized. The control output passes through DAC and power amplifier to drive voice coil actuator.

The hard disk control loop features excellent actuators, but limited access to the Position Error Signal (PES). Furthermore, the increasingly pervasive use of hard disks means that they are used in increasingly harsh environments. Furthermore, the limits on PES spawn a need for extra sensors. This is despite the severe cost limits due to market needs.

III. OPTICAL DISK 101

Referring to Figure 3, the typical optical disk system starts with a single piece of removable rotating media holding user data. There have been attempts at fixed optical disks (as

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[1] “There’s no mystical energy field that controls my destiny. It’s all a bunch of simple tricks and nonsense. – Han Solo

[2] “If someone had told me I would be Pope one day, I would have studied harder.” – Pope John Paul I

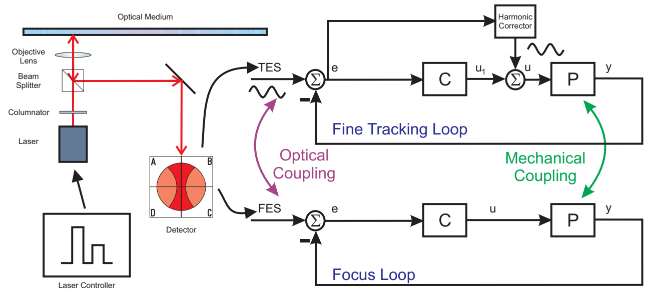

Fig. 3. Pictorial diagram of an optical disk system. The single read/write head is suspended above the removable storage medium. There are three main control loops: the focus, coarse tracking, and fine tracking loops. The main actuator (not shown) holds a lens assembly that does the focus and fine tracking.

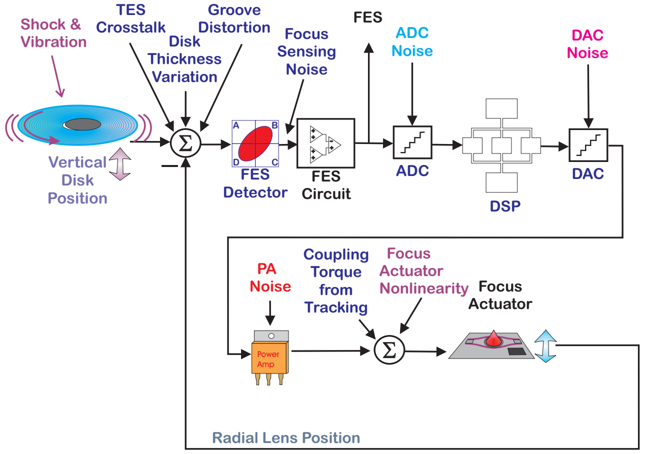

Fig. 4. The focus control loop for an optical drive. The lens structure must focus a beam on the spinning disk which has vertical excitation due to its movement. The Focus Error Signal (FES) is digitized and processed by a digital controller. The amplified output of the DAC moves the lens assembly in the Z direction to result in a focused spot.

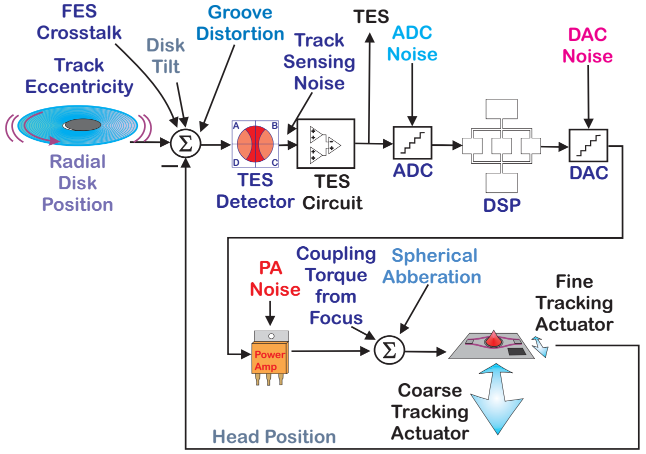

Fig. 5. The fine tracking control loop for an optical drive. Once the spot is focused, the tracks form a diffraction pattern on the detector. The first orders of this change in intensity with the offtrack position, resulting in an error signal that can be used to drive the fine tracking actuator.

hard disk replacements), but none have made it to market. For a standard optical disk, the data is written on tracks on a single piece of removable media. Typically, these tracks are spiral, but occasionally they are concentric circles. Since most removable optical disks are used with streaming media, either audio files, video files, or software installation disks, spiral tracks have the advantage that long files can be read without many track jumps.

The spindle spins the media but – unlike the hard disk – the read/write head is in the far field; far enough away from the disk that it is relatively unaffected by air flow. Because of the distance from the surface, the vertical position of lens (and therefore the focus of the laser spot) must be controlled via an active focus loop. The radial position of the laser spot is controlled via two active tracking feedback loops: a coarse position loop for large linear actuator that holds the focus and fine tracking actuators and a fine tracking loop using the latter. The fine tracking actuator is usually a small voice coil, mounted on leaf springs, that is used to actively follow the track position. The coarse tracking actuators are almost always linear. The tracking information is in parallel user data along the track. Sometimes the radial position is obtained from the track walls, sometimes it is from the data itself.

The main optical disk servo loops, focus and fine tracking, are shown pictorially in Figures 4 and 5, respectively. In the case of an optical disk, there are also low bandwidth loops such as the spindle and the coarse tracking control (mentioned above), but these will not be discussed in this paper. For this paper, the loops described will be those used when the drive is following a data track.

For both focus and fine tracking there are several ways of generating a push pull error signal. For example, focus error can be generated using an astigmatic lens. When the lens is too far from the disk, the optical spot shows up as an oval with the major axis across one diagonal of the detector. When the lens is too close, the major axis is on the opposite diagonal. Only when the lens is at the right focal distance does the oval become circular. However, there are other focus detection methods as described in [9].

The focus loop moves the objective lens in the Z axis. The signal from the reflected spot is always available, so that sampling can occur at any frequency. While the focus error signal is only linear in a region about the focus point, the lens can be be moved until the zero crossing is found and so the focus loop can be initialized independently of the tracking loop.

Once focus has been achieved, then the data and (if they are present) grooves are imaged on the detector. This allows a tracking error signal to be generated off of the virtual grooves caused by the average around the track signal from the data pits (most typical for CD-ROM or DVD-ROM media) or the grooves (used in rewritable optical drives). The diffraction pattern caused by the laser beam reflected from the grooves (virtual or real) produces the classic “baseball” pattern, shown later in Figure 24. In this, the intensity of the diffraction orders varies with the radial track position, thus allowing the push-pull signal.

The fine tracking loop moves the light beam sideways across a track using a small actuator, e.g. a galvanometer or by moving the lens. In order for the tracking error signal to be available, the focus loop has to be locked, so the minimum bandwidth requirements for the tracking loop often form a lower bound for bandwidth requirements for the focus loop.

For both of these loops the main noise sources include shock and vibration (mostly external), spectral noise usually related to orders of the spindle rotation frequency, optical noise and distortion (which usually becomes worse with a higher numerical aperture (NA) of the lens, and coupling between the two loops. As with the hard disk, the rotation of the media on the spindle adds both spectral and non spectral components. Unlike the hard disk, in which the tracks are written on media fixed to a spindle, the optical disk has a lot of eccentricity cause by the removable media. The tracks themselves are very clean, and so once the main disturbance due to the eccentricity is handled there are few other harmonics due to track writing as happens in hard drives. Most of the “process noise” comes from poor mechanics of system and there is very low “measurement noise.”

IV. AFM 101

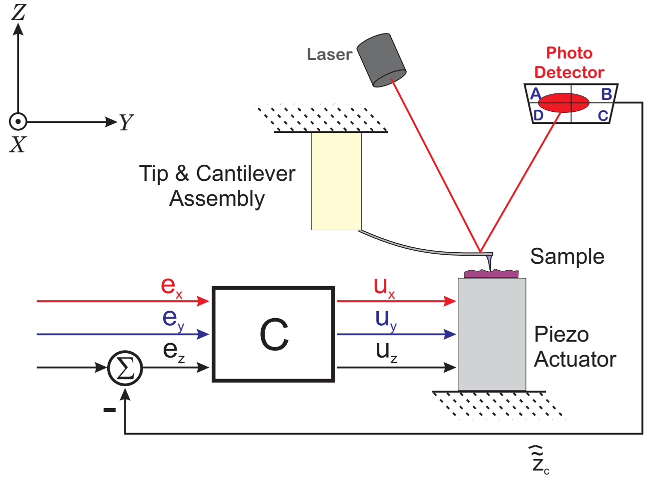

Fig. 6. Pictorial diagram of an atomic force microscope system. This diagram shows a scanning sample design, in which the sample is actuated in three dimensions by a piezo tube actuator. With the tip in close interaction with the sample surface, the sample is scanned in X and Y dimensions. This results in a deflection in the Z dimension of the cantilever which is detected optically and used as the error in a feedback loop. The control of the X and Y scans can be done in open or closed-loop, depending upon the needs of the system.

Referring to Figure 6, we see that the AFM system doesn’t start with spinning media, but with a sample surface to measure. The properties of the surface determine type of AFM measurement. To do the measurement, the tip is brought into proximity with surface until surface interaction is detected, via a laser spot reflected off the back of the cantilever and back into an optical quad detector. The deflection signal is compared to a reference deflection to form an error signal that is passed to a feedback controller which adjusts the height of the cantilever or sample via the use of an actuator.

Since it is not possible to actually measure the tip position, the surface measurement – from which an image will be formed – is typically estimated using the control signal, u, in Figure 6. This surface estimate produces a Z axis value. By scanning the surface a map is produced relating the Z measurements for each X-Y value. Other signals in the system can be used to estimate different surface properties.

Depending upon the precision needed, entire system can be put in isolation (optical table, controlled temperature and humidity, air flow control). Actuators which can achieve excellent DC precision often have poor dynamic properties at high frequencies.

A. Control of Contact Mode in AFMs

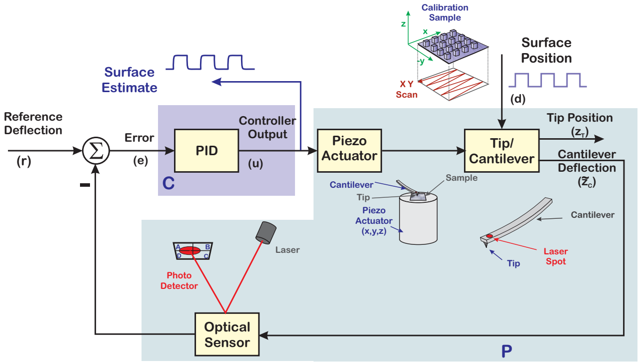

Fig. 7. A nominal AFM control loop. This one shows a scanning sample design, where the sample is scanned in the horizontal plane (X and Y axes), and the Z-axis feedback loop controls the vertical position of the piezo actuator in response to the deflection of the cantilever.

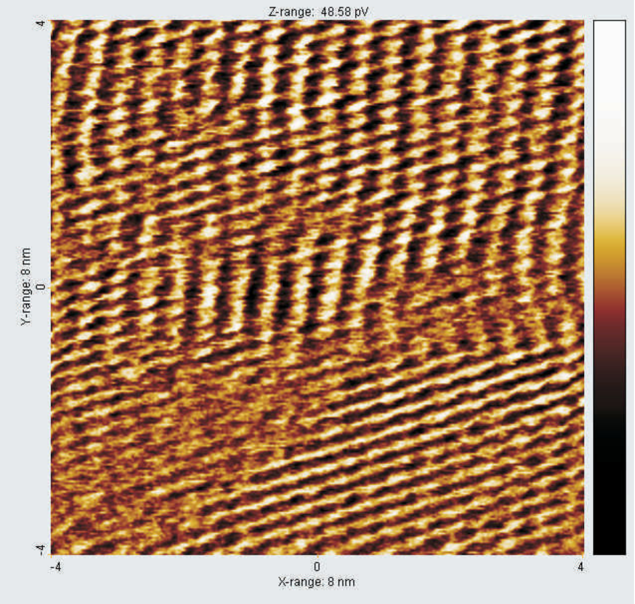

Fig. 8. A contact mode image of C10 Thiol Monolayer. C10 Thiol is a hydrocarbon molecule ($HS(CH_2)_9CH_3$) with a methyl group (CH_3) on one end and a thiol group (SH) on the other. The thiol group binds to a gold (Au(111)) surface resulting in a group of molecules that are standing on end akin to a shag carpet. The light areas of this topography image show the tops of the terminal methyl groups, while the dark areas indicate the gaps between molecules. (Courtesy Agilent Technologies.)

No matter what the design, an image generating scan starts with the surface and the tip being moved in the horizontal plane relative to each other. This is done either by scanning the sample or scanning the tip. The tip on the end of a flexible cantilever interacts with the surface. While the tip surface interaction cannot be measured directly, it can be inferred cantilever deflection. By shining an optical beam off the back of the cantilever and onto a detector, a significant amplification of the tip/surface motion is achieved. In contact mode, the surface and the tip are moved relative to each other with the tip in constant interaction with the surface. In effect, the tip is dragged over the surface and the deflection is measured. For such modes, cantilevers with relatively soft spring constants are used, which minimizes damage to the surface[10].

The control loops in an AFM differ from those of the hard and optical disk drives first in that there is no data to read or write. There is simply a surface to measure. Furthermore, for many of the AFM measurement modes, there are actually three active loops, corresponding to the X, Y, and Z axes (where Z is the normal to the plane of the sample). Depending upon the AFM design, the X and Y loops may be open or closed-loop. However, for most use models, the Z-axis is controlled in closed-loop. This loop will be the focus of the AFM discussion.

A typical AFM system is a low speed device. That is, images take something on the order of minutes to achieve. There are considerable efforts in industry and academia to speed up the imaging process [11], [12], [13], [14], [15], [16], [17], [18], but it is worth understanding the assumptions of a low bandwidth AFM. These will be discussed in more detail in Section VI-C. There we will see that for most low bandwidth AFM systems, the controller output, u, is effectively proportional to the surface topology. A PID or a state-space controller that provides lead can broaden the bandwidth, but this requires more accurate modeling of the system. The images themselves come from coordinating the Z deflection information with the X and Y positions.

An AFM is susceptible to shock and vibration. Because these are test instruments, considerable effort can be made to isolate the system. However, the distances to be measured are so small that even small perturbations can provide significant errors. Furthermore, as the measurement is made optically, noise from the laser and detector can provide a significant source of error.

B. Control of AC Mode in AFMs

Contact mode AFM measurements can be made on surfaces that can tolerate sheer forces, but a lot of surfaces do not fall into this category. Examples of the latter include cell membranes and other biological samples. These surfaces are stronger in compression than in sheer and so a dynamic mode measurement works here.

In dynamic or AC mode, the tip must be oscillated in some way. This is well beyond the bandwidth of the standard piezo actuators. However, the cantilevers can be oscillated using acoustic, magnetic, or micro-piezo actuators acting directly on the actuator [15], [18], [19]. The optical return signal is now modulated with a sinusoidal signal altered by the tip interaction with the surface. The return signal has to be demodulated to extract the information from the signals. The modulation of the signal amplitude can be extracted using a RMS to DC circuit [20], although this is a non-coherent analog method which tends to be slow. The use of lock-in detectors, both external to the AFM and more recently internal to the AFM can be used for both amplitude and phase modulation. Demodulated signals can be used for the servo loop and for surface characterization.

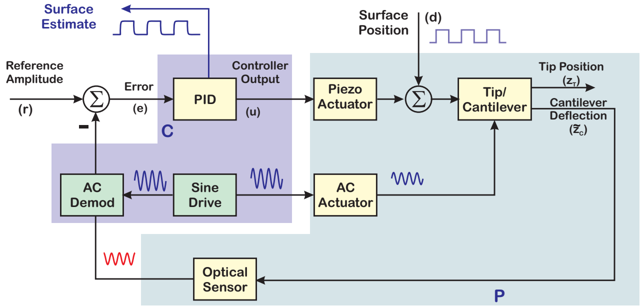

Fig. 9. The AFM control loop in dynamic (or AC) mode. Note the addition of a sine generator, which generates signals both to drive the cantilever/tip and to be used in demodulating the oscillatory return signal.

V. MOVEMENTS AND FREQUENCIES

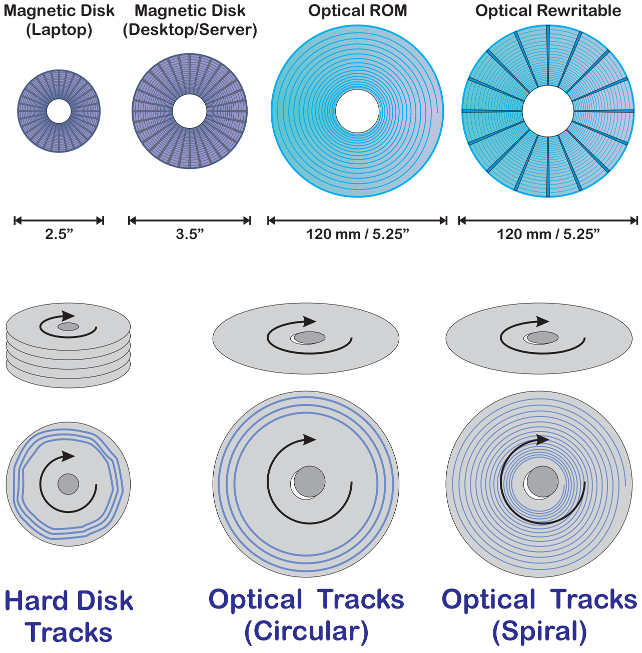

Fig. 10. For disk drives, everything starts with spinning media.

The top row of Figure 10 shows disk drive layouts for common magnetic and optical drive formats. On the left are typical 2.5” and 3.5” drive layouts. On the right are optical ROM and typical optical rewritable drives. However, the rewritable optical disk formats of the far right (with edit

TABLE I
COMPARISON OF HARD DISK, OPTICAL DISK AND AFM

	Hard Disk	**Optical Disk**	**AFM**
Typical Cost	\$50 – \$300	\$20 – \$300	\$20K – \$200K
Media	Multiple Fixed Disks	Single Removable Disk	Surface to Image
What Moves	• Disks Rotate (θ) • Rotary Voice Coil Actuator (r)	• Disk Rotates (θ) • Linear Voice Coil Actuator (coarse r) • Focus Actuator (z) • Fine Tracking Actuator (r)	Cantilever (X, Y, Z) OR Sample (X, Y, Z) OR Sample (X, Y) & Cantilever/tip (Z)
Operating Environment	Desktop computers, laptop computers, servers, set top boxes (e.g. HDRs), mobile applications, PDAs and IPods	Desktop computers, laptop computers, set top boxes, automotive systems	Lab benches, isolation tables, factory inspection systems
Control Loops	• Passive (z) • Active (r)	• Active (z) • 2 Active (r)	• Active (X & Y – open or closed-loop) • Active Z (usually closed-loop)
Media Loop	Low Frequency Spindle Loop	Low Frequency Spindle Loop	X & Y positioning at lower bandwidth than Z
Position Info	Multiplexed with user data	Optical – in parallel with user data	Optical (z), sensors for X,Y (e.g. capacitive)
Sampling	Limited by MUX with user data	Samples always available, but disk must be in focus to see tracks	Always available if interacting with surface
SNR	Mediocre to Good	Excellent	Mediocre to excellent
Mechanics	Excellent	Mediocre	Mediocre to excellent
Signal Processing Hardware	μC, μP, DSP (fixed point)	μC, μP, DSP (fixed point)	DSP (floating point), FPGA
Sample Rates	8 – 20 kHz	10 – 50 kHz	50 – 500 kHz

gaps in between data sectors) have been largely replaced by formats that attempt to be fully compatible with the DVD-ROM format. The most compatible is the DVD+R/RW format, although the DVD-R/RW format is able to use error correction to approximate this compatibility [21].

The lower half drawings of Figure 10 show the typical eccentricities of drive movement. Tracks and eccentricity for magnetic and optical disk drives are determined by mastering (optical) or servo-writing (magnetic). Almost all hard disks have sectored servos, that is, user data and servo information multiplexed together. This servo information is generated through servo-writing, where blank disks are mounted on spindle and then tracks are written into the disks by encoding track information. On the other hand, optical disks are formatted using mastering in which a pattern is masked onto a master disk. All other disks are stamped from this master, making the groove/data pit structure very clean.

Generally speaking, servo-written disks have multiple harmonics of the spindle frequency, but they are generally of smaller amplitude than the one found in optical disks. Mastered optical disks have near perfect tracks, but removability means that the media is misregistered on the spindle, leading to a large disturbance at the fundamental spindle frequency.

Figure 11 shows the X-Y scanning of a sample area that is typical in generating an image. X-Y scanning leads to multiple problems. First of all, it is impossible to have perfect zig-zag motion with finite bandwidth. This means that pixels at edges of scan are crossed over differently than pixels in center of an image. If the X and Y motion are accomplished in open loop, then any correction is through dead reckoning. Not only are their issues in the generation of the X-Y motion itself, but this motion can couple into the Z axis. For example, if the X-Y scanning is actuated with piezo tube, there is an additional bowing of the image. Furthermore, even separate X-Y motion stages have some out of plane motion, resulting in a Z axis displacement that can couple into the deflection signal.

The thing to realize is that because of the sectored servo

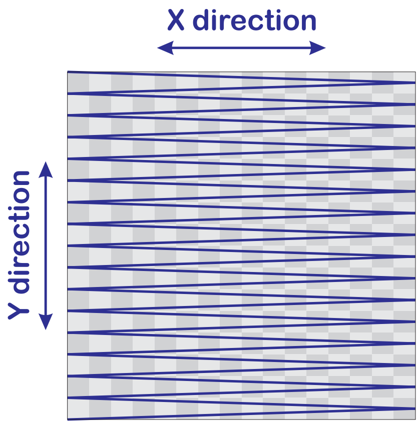

Fig. 11. A raster scan generates the initial movements in an AFM. The blue line represents the scan, which is generally faster in one direction – commonly denoted as the X axis. The checkerboard pattern underneath schematically shows pixels that might be formed from such a scan pattern. Each direction of scanning along the X axis is used to form a separate image. For each scan, the sampling of data along the Y axis will be considerably slower than the sampling of data along the X axis. Typically, some sort of decimation or averaging is done to reduce the X data samples to the pixel rate in the X direction.

TABLE II
SPATIAL FREQUENCIES BECOME TEMPORAL FREQUENCIES

Rate	Definition
sample rate	frequency of data sampling
spindle frequency (disks)	frequency of 1 rotation of media
sectors per track (hard disks)	number of servo sectors in one rotation
scan rate (AFM)	frequency of 1 line scan in each direction
frame rate (AFM)	scan rate/lines per frame
pixel rate (AFM)	scan rate $\cdot$ pixels per line
samples per pixel (AFM)	sample rate/pixel rate
scan speed (AFM)	scan line width (μm/line) $\cdot$ scan rate (lines/s)

nature of hard disks, their sample rate is simply the spindle frequency times the number of servo sectors per track. For the optical disk and the AFM, the sample rate is independent of the fundamental motion.

VI. ACTUATORS

A. Actuators for Hard Drives

Hard disks feature multiple spinning flat platters covered in media with magnetic read/write heads for each surface. In order to keep the volumetric density high, the heads are small and contained in "flying" sliders which move over the surface on an air bearing, as diagrammed in Figure 12. This provides a passive feedback loop for the vertical distance of the head to the recording surface, with the actuator spring pushing the head toward the surface and and the air bearing pushing the head away. In recent years, a slow active Z loop has involved moving the heads down from the slider so as to more closely control the Z spacing beyond what the passive loop can do. The actuators themselves have been rotary for the past three decades as this design has more mechanical stiffness and simplicity [8], [22], [23].

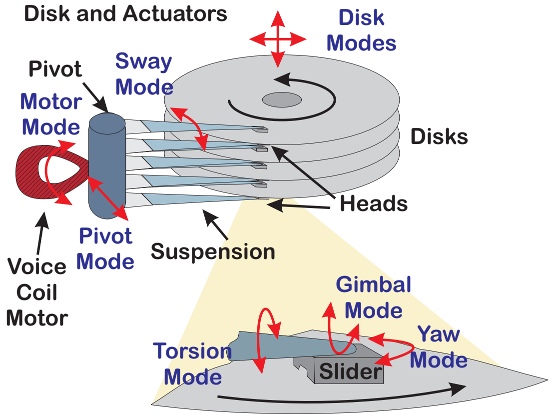

Fig. 12. The actuators and resulting modes for hard disks.

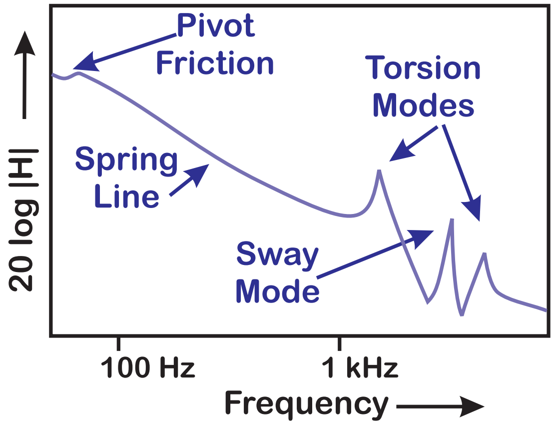

Fig. 13. Schematic Bode plot of hard disk actuator modes. By damping the resonances and minimizing the effect of pivot friction, the hard drive servo loop can be closed with the open loop crossover corresponding to the mass line.

A single rotary voice coil motor moves all heads together but only one at a time provides servo information. This is discussed further in Section VII-A. There are multiple resonant modes in the actuators and they often have a high Q (low damping factor), as diagrammed in Figure 13. These resonances vary over time, from drive to drive, and with environmental variations. These resonant modes are typically notched, so the notches must either be broad enough to handle a whole class of drive actuators or must be adjusted during the production process or on-line. The goal is to close the loop on the mass line, between the apparent "spring line" due to pivot friction and the resonances.

As the size of drives shrink, the pivot friction of the

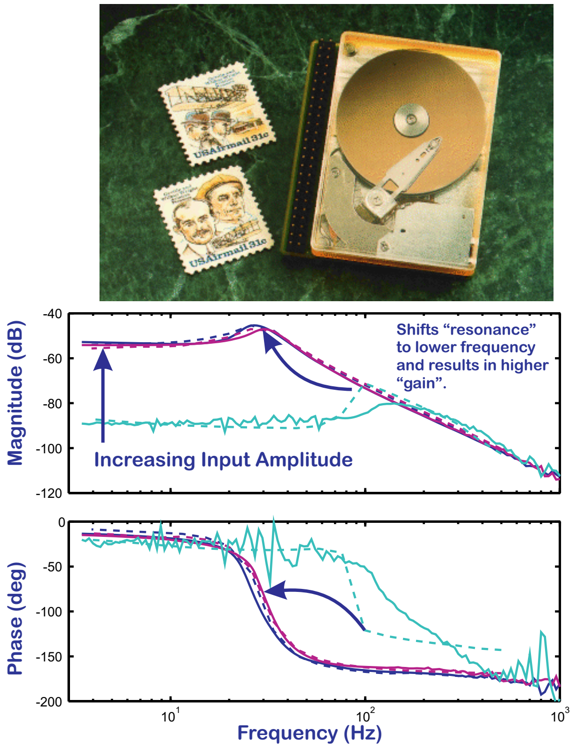

Fig. 14. The top picture shows HP’s 1.3” KittyHawk disk drive, 1994. The bottom two plots show bode plots of the response from the voice coil motor to the head. Notice that the frequency responses functions change with varying input amplitude, a sure sign of nonlinearity. This is a consequence of the friction becoming more prominent as the actuator inertia changes. (Solid Curves: Lab Meas. Dashed Curves: Simulink Meas)

rotary actuator bearing becomes a big issue. An example of this from the 1990s is shown in Figure 14, where HP’s 1.3” KittyHawk disk drive exhibited varying behavior with different input amplitude levels. This was due to friction in the pivot bearing, the effects of which became far more pronounced as the actuator’s rotational inertia was shrunk. While nonlinearity cannot fully be characterized with frequency domain methods, the Swept-Sine/Describing Function Method [24], [25] was able to show that this was mostly a low frequency phenomenon. For small pivot motion, the pre-rolling behavior of the ball bearings had a significant effect [26], [27], [28]. One proposed fix to pivot friction problems has been to add a secondary actuator, as is done in optical drives [29], [30], [30], [31]. However, these have been very difficult to get into mass production.

Shrinking drives considerably simplify some design problems. It is easier to make disk substrates out of glass if the surfaces are smaller. Glass disks in turn are smoother, which leads to less air flow variation and less power dissipation. Furthermore, the smaller disk actuator has resonances at higher frequencies, which results in higher bandwidth behavior [23].

From a business perspective, smaller drives can go into a lot more applications, from notebook and hand held computers to music players such as the iPod, and digital cameras. The lower mass of the disks and smaller actuators result in lower airflow and so far less power dissipation [32].

B. Actuators for Optical Drives

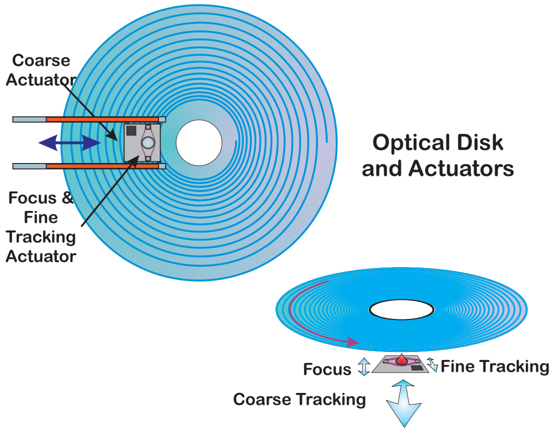

Fig. 15. A picture of the disks and actuators for an optical disk

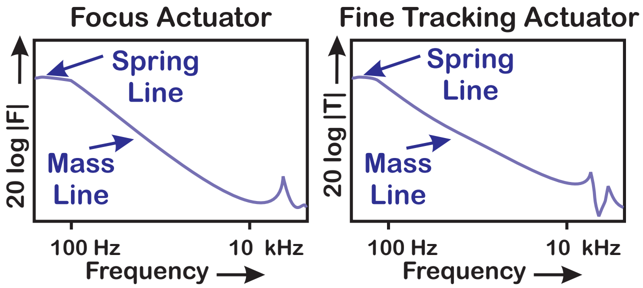

Fig. 16. The typical modes for optical disks. The focus and fine tracking actuators have similar qualitative responses. The goal is to close the loop as far down the mass line as reasonable which means that the high frequency structural resonances need to be damped with notches.

In contrast to the hard disk drives, optical disk drives – being designed for removable media – feature a single platter of data and a large read/write head. The head is large because of the optics needed to read and write data to the disk and to read the position information. The optics are used to focus the laser beam (Z-axis servo), while a combination of coarse linear actuator and fine actuator are used for tracking, as shown in Figure 15. Typically, the two tracking loops are run in a master/slave fashion with the fine actuator following the grooves and the coarse actuator trying to zero out the position of the fine actuator. Because both the focus actuator and the fine tracking actuator are on spring structures, the friction in the coarse actuator response is bypassed. As can be seen in the schematic Bode diagram of Figure 16, both the fine tracking and the focus actuator have a low frequency spring behavior and a high frequency resonance. The loop is typically closed on the mass line before the high frequency resonance [9].

C. Actuators for AFMs

The most typical actuators for AFMs are diagrammed in Figure 17. The 3 degree of freedom piezo tube (on the left

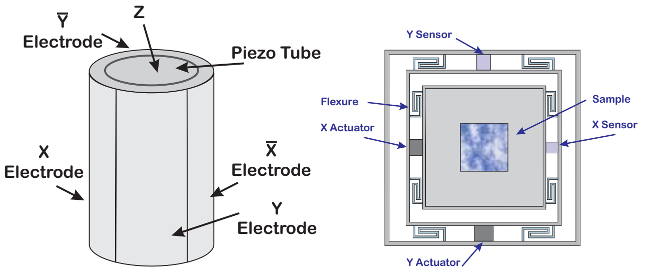

Fig. 17. AFM actuators: On the left is a diagram of the 3 degree of freedom piezo tube, which can actuate in the X, Y, and Z directions. On the right is a diagram of an X-Y scan stage which can decouple the X-Y motion from that of the Z and allow for larger scan ranges.

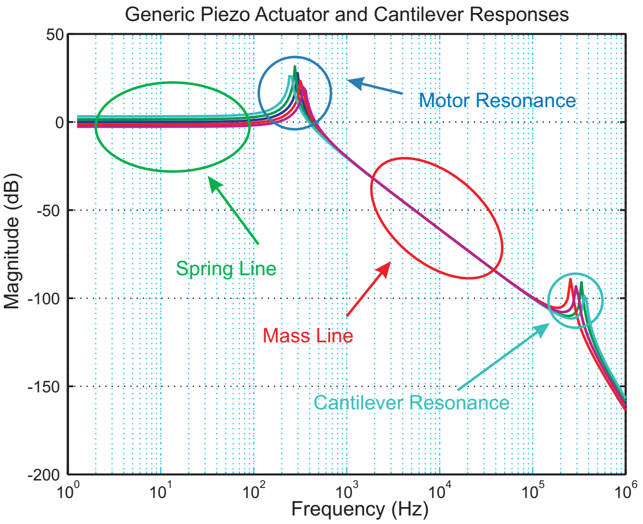

Fig. 18. AFM Z axis control ranges. In the low performance region, closed-loop bandwidth falls well below the peizo actuator resonance. This requires the least knowledge of the actuator model. In the medium performance region, closed-loop bandwidth falls in between the piezo actuator and cantilever resonances. This requires accurate modeling of the piezo. The bandwidth falls off fast enough so that cantilever resonances don't destabilize the control loop. The cantilever oscillation only enters the loop after the signal has been demodulated (in AC mode). This requires a good model of the actuator, but not the cantilever. The highest performance bandwidth requires control through both the piezo actuator and the cantilever, which implies extremely fast sampling rates.

of Figure 17) is cost effective and compact, and allows for actuation in X, Y, and Z dimensions. Often only Z axis is run in closed-loop. Because of the mechanical structure of the piezo tube, X-Y actuation results in bowing of the image which can be corrected with image processing.

Separate X-Y actuation decouples dynamics of X-Y scan with dynamics of Z surface measurement (to first order). Furthermore, separate X-Y stages (diagrammed on the right of Figure 17) are most likely to have sensors and feedback loops on them. This results in a more linear scan over larger distances. Finally, stacked piezo actuators can be used to speed both the Z axis response and the X-Y responses of the system [11].

Piezo actuators are very accurate, but have some nonlinear behavior that makes it harder to run them at higher frequencies. Considerable effort is made to operate these actuators in their linear regime. Some typical Bode plots of Z actuators for AFMs are shown in Figure 18. Note that with this system, we see the spring-mass-damper behavior of the main actuator in the 1-10 kHz range and the resonance of the cantilever in the range of 80 kHz to 2 MHz. Most commercial AFMs are controlled so that the loop is closed far below the first resonance, on the spring line.

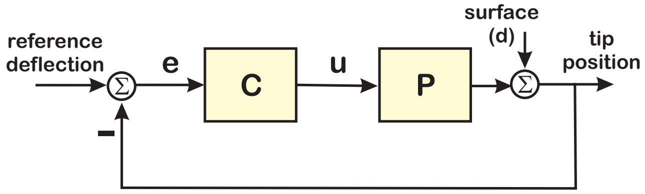

Fig. 19. A simple view of the AFM control loop. The surface position comes in as a disturbance. The control signal, u, is often used as a substitute for the surface itself, particularly when a PI loop is run with low bandwidth.

In such a system, the Z axis control loop is most often a proportional plus integral (PI) loop. This type of controller has no phase lead [10]. In combination with the fact that the AFM actuator is often modeled reasonably by a simple resonance, we realize that the use of a PI controller limits this loop to very low bandwidth, so that the lag of the PI is only active on the spring line of the mechanism.

As we can see in Figure 19, the surface is viewed as a disturbance, and the transfer function from the surface, d, to the control input, u, is

$$\frac{U(s)}{D(s)} = \frac{C(s)}{1 + P(s)C(s)} \tag{1}$$

Remembering that at frequencies far below the resonance of the plant, ω_P, $P(j\omega) \approx k$, where k is the spring constant of the plant. So we get

$$\frac{U(j\omega)}{D(j\omega)} = \frac{C(j\omega)}{1 + kC(j\omega)}, \text{ for } \omega << \omega_P. \tag{2}$$

However, at low frequency a PI controller has very high gain due to the integrator, so $kC(j\omega) >> 1$ which leads us to the relationship often used by non-control engineer AFM users:

$$\frac{U(j\omega)}{D(j\omega)} \approx \frac{1}{k}, \text{ for } \omega << \omega_P. \tag{3}$$

Thus, we see that the transfer function from the surface to the control signal being reasonably approximated by the inverse of the actuator spring constant [10]. To close the loop on the mass line as is done with hard disks and optical disks requires being able to control through the main resonance [33]. The issue is often the knowledge of the actuator resonance and the frequency separation between the actuator and cantilever resonances. This can be seen in Figures 20 and 21. Figure 20 shows the identification of a simple model for the AFM actuator resonance, from which a set of PID parameters can be generated. These in turn allow us to close the loop on the mass line as would be done in hard disks and optical disks. The projected closed-loop response is shown in Figure 21.

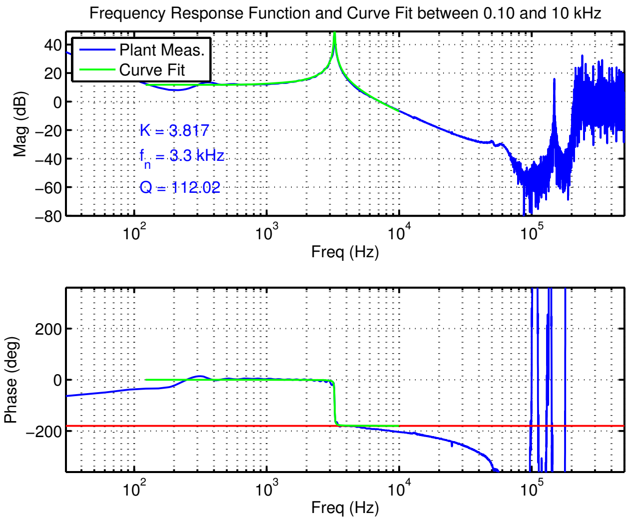

Fig. 20. Plant response and 2nd order curve fit model. From the curve fit, the parameters of a simple resonance can be immediately extracted: $K = 2.817$, $f_n = 3.3$ kHz, and $Q = \frac{1}{2\zeta} = 112.02$. Note that the resonance around 150 kHz is due to the cantilever. It is notched with a separate notch that is not part of the PID design in this paper.

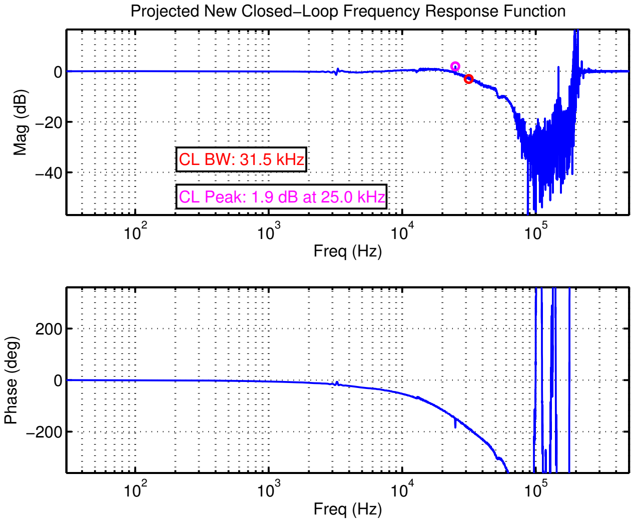

Fig. 21. Projected closed-loop response of AFM system with loop closed on the mass line.

The cantilever resonances are typically in the range from 80 – 1200 kHz. Damping of the cantilever oscillation using digital filtering or control and/or demodulation of AC mode signals with a digital lock in amplifier, require extremely high sample rates. The typical control factor of sampling 10 to 20 times the frequency of interest means that for 300 kHz cantilevers, the data will be sampled at 6 MHz.

There are some fairly large commonalities between all these problems. Each of their electromechanical plant response look like a system with a low frequency spring line, a middle frequency mass line, and some high frequency resonances. However, the origins of these vary by system. In the case of the hard drive, the spring line is due to the pivot friction. In the case of the optical disk it's due to the leaf springs holding the focus and fine tracking actuator. For the AFM, it is a consequence of the piezo actuator itself. The major differences from a mechatronic control perspective are in the ease or difficulty in closing the loop on the mass line. Typically for AFMs, the separation between the actuator and cantilever resonances are not large enough to easily ignore, as they are on the optical and hard disks.

VII. SERVO SIGNALS

In order to understand the behavior of any control loop, it is necessary to understand the error signals for those loops.

A. Servo Signals: Hard Disks

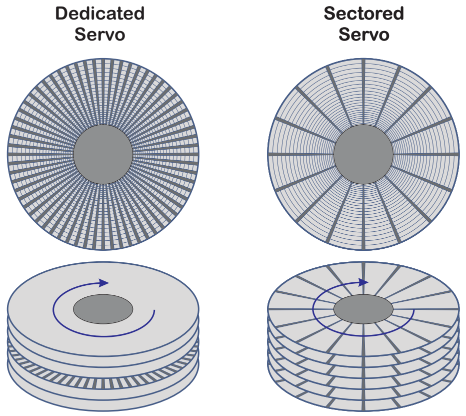

Fig. 22. Dedicated and sectored servo patterns for hard disks. Note that radial position information is encoded magnetically either way, rather than being obtained from physical features of the substrate.

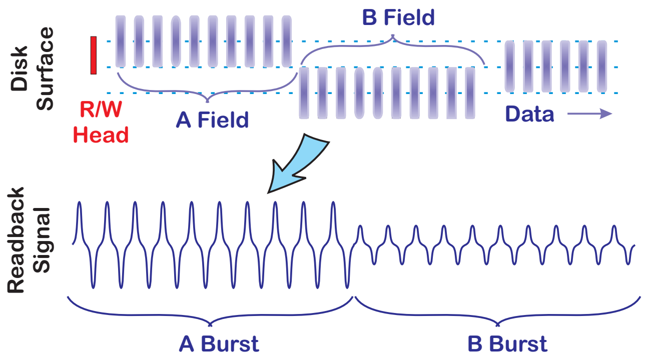

Fig. 23. Split field servo patterns, typical in a sectored disk drives. These magnetically encoded position patterns result in a high frequency signal that needs to be demodulated to extract the radial position of the read/write head relative to the track.

Even though there are multiple heads and actuators, only one is typically active for control and one is active for reading and writing. In a dedicated servo design, one surface is entirely filled with servo information, as shown in the left of Figure 22. The servo read head is always active, while a separate head on a separate surface is used to do reading and writing of data. In this method the mechanical offsets between the servo head and the read/write head is the critical limitation. As track widths have shrunk, this mechanical difference has made a second method, shown in the right of Figure 22, called sectored servo the preferred choice. In this case, every track on every surface contains servo information multiplexed with the user data. The same head used for reading data is used for reading the position information.

In either case, the servo signals are encoded within alternating magnetic domains. This means that the radial position information must be demodulated from the readback signal over these domains, as seen in the simplified diagram of Figure 23. When the head is more centered over one field than the other, it will produce a larger amplitude readback signal. The amplitude is demodulated to extract a position error signal (PES).

B. Servo Signals: Optical Disks

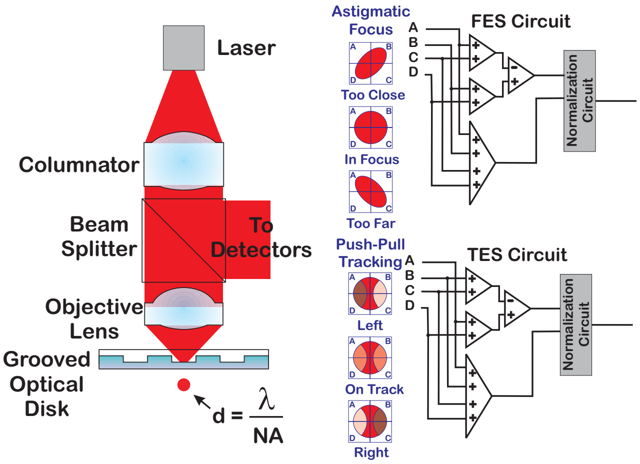

Fig. 24. Generation of servo signals in an optical drive. Note that the signals are generated from features on the substrate and therefore are always available. Generally, no demodulation of optical disk servo signals is needed.

Unlike the magnetic disk drive, the main business of optical disk drives has been in the area of removable media. This has meant that the recording surfaces would be covered with a protective coating, and the read/write heads would be in the far field. Because of this, focusing of the optical beam and following the track position has been done with information obtained from features in the substrate, either the distance to the surface itself for focus or grooves in the surface for tracking. In some optical drives, tracking information is obtained from the data, but in this mode, the data features flying by at a rapid pace form a virtual groove from which tracking information can be extracted. The key aspect of this is that unlike hard disks, the position information is always available and doesn't take away from user data. From a control perspective, this means that the sample rate on an optical disk is limited only by our ability to process the sampled data.

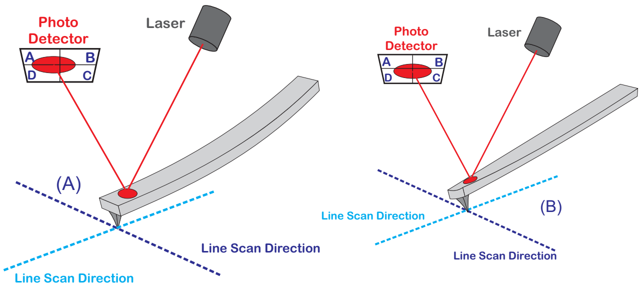

Fig. 25. Servo signals for the Z axis of an AFM are generated optically.

C. Servo Signals: AFMs

In many respects, the generation of position signals for the Z axis loop is very similar to that of an optical disk. An optical beam is reflected off the back of the cantilever to produce a deflection signal on an optical detector. This deflection signal is used to generate an error for use with the Z axis servo. As with the optical disk, there is no multiplexing of servo information with user data and so the only limiting factors for sample rate is the ability to process signals and the noise in the optical signals.

Because AFMs are not standardized yet, there is a lot of variability in the X-Y position control methodology. It is not uncommon to run the X-Y position of a piezo tube as an open loop operation. In this case, there is no error signal for these axes. In other designs, both with piezo tubes and separate X-Y stages, the motion is sensed (e.g. with capacitive sensors) so that error signals can be generated.

VIII. NOISE SOURCES

A major aspect of servo systems is understanding where noise and disturbances enter into the system. These noise sources determine what needs to be addressed by the control system and limit what it can do.

A. Noise Sources: Hard Disks

Hard disk drives generate a lot of disturbances simply by spinning the disks past the read/write heads and the actuator arms. The motion of the disks on the spindles generate spectral disturbances in the motion of the disk at frequencies that are harmonics of the spindle frequencies. There are also a lot of non-spectral disturbances caused by the motion of the disk. The same entrainment of air that generates an air bearing for the heads to fly over also generates air flow that buffets the read/write heads and actuator arms. On top of that, there is position sensing noise (often called by the misnomer, "PES Noise"). An example of the breakdown in non-spectral noise in a hard disk from about 1995 is shown in Figure 26 [34], [35], [36], [37], [38]. At that point, the dominant baseline noise was caused by the generation of servo signals from the magnetic domains.

Another issue is that of reaction forces caused by the movement of the radial actuator, especially in large seeks.

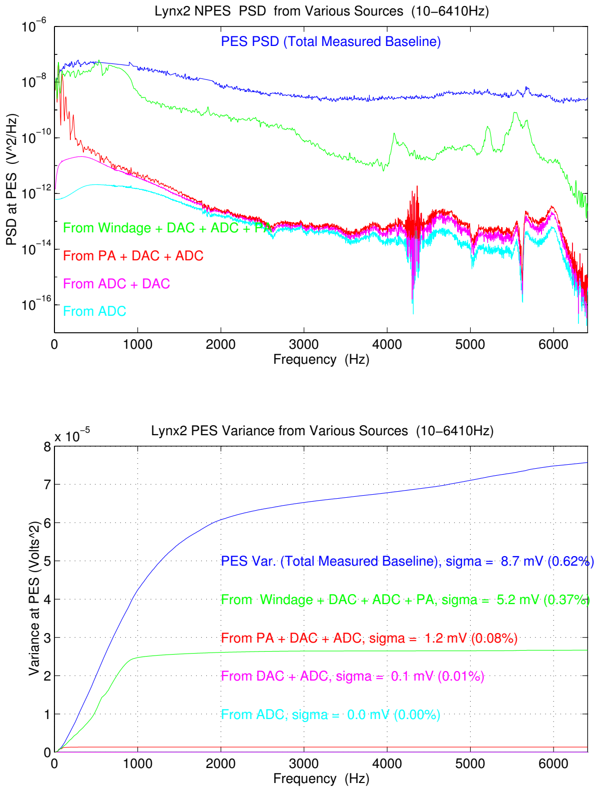

Fig. 26. Decomposition of baseline noise sources in a hard disk.

The effect of this is similar to that of external shock and vibration, and will be discussed in Section IX.

B. *Noise Sources: Optical Disks*

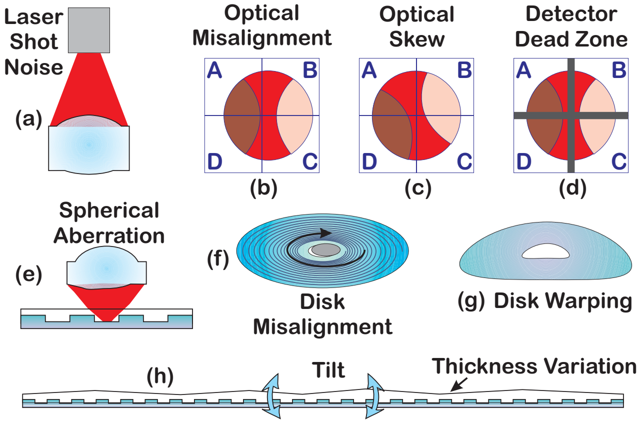

Fig. 27. Sources of optical noise in an optical disk drive

Apart from the large harmonic due to disk misalignment, most problems in optical drives are due to imperfections in the optical signal. The former is characterized by a large eccentricity at the main spindle frequency, but relatively few higher order harmonics of this frequency. Many of the optical effects that lead to noise are shown in Figure 27. These problems get much worse with higher numerical aperture and lower wavelength (which is exactly what is used in high density optical drives such as Blu-Ray and HD-DVD).

External disturbances can also be a factor for optical disks, especially in in mobile applications. This is discussed in Section IX.

C. *Noise Sources: AFMs*

Unlike the hard disk and optical disk, the AFM is not a consumer application. AFMs are generally used in laboratories. As such, isolation chambers and optical tables can be used to isolate the instrument from external disturbances. However, mechanical disturbances have dramatic effect when the measurement resolution is on the order of a nanometer. Even the optical beam can be affected by air flow and temperature variations.

Laser and detector noise also drive the sensing noise and limit the bandwidth of the system. Even imperfections in the cantilever can result in sensor noise.

The movement of the sample relative to the tip in the X and Y dimensions can result in coupling – often nonlinear – in the Z dimension. As attempts are made to speed up AFM measurements, this coupling becomes more severe, resulting in the need for better mechanical and electrical isolation.

That being said, because the use model for AFMs is that of a specialized instrument, a lot of time and hand tuning can be employed to generate a single publication quality measurement.

IX. SAMPLE RATES, EXTRA LOOPS, & EXTRA SENSORS

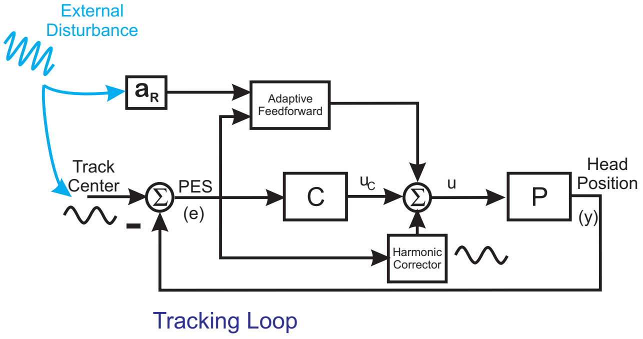

Fig. 28. Disk drive servo loop showing auxiliary loops.

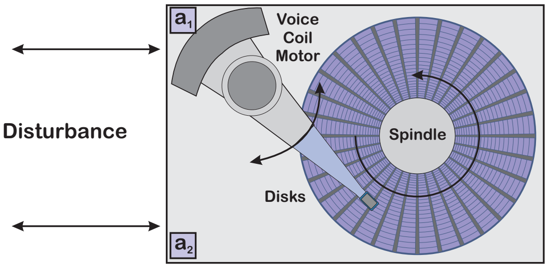

Fig. 29. Head disk assembly under effects of external acceleration.

The method in which error signals are generated in these problems determines the limits on sampling rate. The most

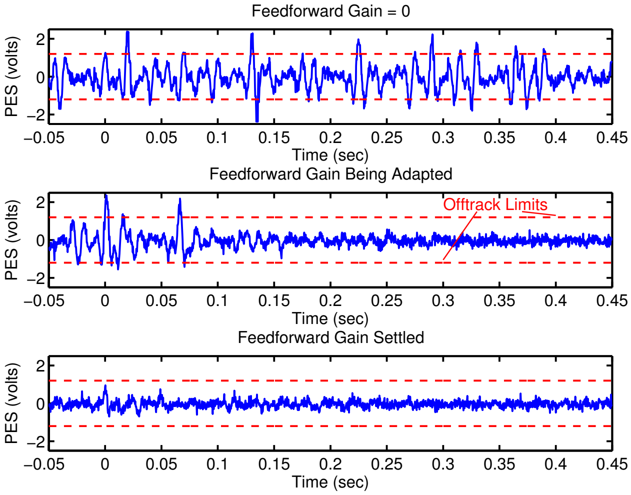

Fig. 30. Adaptive feedforward accelerometer compensation of rotary vibration on a KittyHawk disk drive. The top plot shows the effects of rotary disturbance with no feedforward. The red dashed lines are the offtrack limits. When adaptive feedforward is turned on in the middle plot, the effects of the disturbance are quickly minimize. In the lower plot, the drive stays within the offtrack limits, despite the external rotary disturbance.

limited of these is the hard disk drive, which multiplexes user data with position information. Because of this, there is a natural tendancy to want to push sample rates down so as to maximize data capacity. Optical disks and AFMs lack this multiplexing of position information with user data and as such their sample rates are only limited by the ability to cleanly sample and process that data. As noted in Table I, the sample rates for hard disks tend to be lower than those of optical disks and significantly lower than those of AFMs. Because hard disks and optical disks are inexpensive commodities, the signal processing hardware is relegated to micro-controllers, micro-processors, and DSPs (for the high end drives). On the other hand, the instrumentation nature and higher selling price of an AFM means that it is perfectly reasonable for these devices to have high end floating point DSP chips, field programmable gate arrays (FPGAs), or Field Programmable Analog Arrays (FPAAs) [39].

Because of the limited sample rates in the main loops of hard disks, there have been several attempts at multirate control. In this case, multirate refers to controllers where outputs are sent to the DACs much faster than inputs come in from the sampled PES on the ADC [40], [41], [42]. In most of these, the main advantage is to be able to produce sharper digital notches.

Likewise, the limited sample rate has caused another unique problem for hard disks. Hard disks used in mobile environments have to deal with severe shock and vibration. Server drives encounter disturbances from mechanical interaction with other hard disks in the same server. Because the drives use balanced rotary actuators, the most signficant disturbances are those that are rotational in the plane of the disk. One would expect the main feedback loop to reject these disturbances, but the sample rate restrictions due to the tradeoff between servo information and user data limit this capability.

This has created market for external sensors, particularly accelerometers, in feedforward. Essentially, extra loops using extra sensors are added to the basic drive control problem as shown in Figure 28. Furthermore, these sensors have no effect on user data and so they can be sampled faster than the main loop.

These loops are adaptive [43], [44], [45]. Early on, it was thought that rotary accelerometers would be the best choice for these problems, since they would pass only the rotary disturbances and not the translational ones. However, rotary accelerometers are expensive, so two linear accelerometers are differenced, as shown in Figure 29. The linear accelerometers are quite inexpensive, but that comes at the price of mismatch between the two, which can be in the range of ±15%. This often limits the benefits of such a feedforward system [46].

In contrast, optical disks – even when used in automotive applications – rarely have accelerometer feedforward loops associated with them. Certainly, the higher sample rates help the main loops stay in focus and on track, but another major contributor is the use model. Since most optical disks contain streaming media (audio or video) it is simpler and cheaper to buffer a stream of data in solid state memory than to use an auxiliary loop. As long as the drive can keep the buffer mostly full of data, intermittent shocks and vibrations that cause the servo loops to have to reaquire lock do not affect the user's listening or viewing experience.

The use of auxiliary loops in AFMs is not at all determined because the systems themselves are not very standardized and the application space is also not standardized. AFMs typically reside in laboratories, but even the isolation systems vary dramatically based on what they will be measuring. What is clear is that the addition of extra sensors or auxiliary loops is not driven by cost or sample rate constraints.

X. IP ISSUES

The use of intellecutal property (IP), specifically the utility of patent protection, is vastly different in the different markets.

The big differentiator in the use of IP between hard disks and optical disks comes from the hard disk being a fixed device inside the computer, versus the optical media being removable. Because the hard disk remains inside the computer, the only standardization that needs to be done is on the interface to the computer. Thus, inside the hard disk, designers have complete freedom. The main standardizing force is the consolidation of component vendors. That is, a handful of vendors push standard components to the disk drive manufacturers. The use of those components in the system design is completely open. Furthermore, most disk drive companies have cross licenses with other disk drive companies. Becasue of this, patents have limited value to disk drive companies.

In contrast, optical disk formats are based on standards and interchangeability. The company that has the IP on the enabling technology for an accepted standard is able to generate considerable royalties from licensing of the right to use their patented format. Philips and Sony made considerable revenue on CDs as a license fee had to be paid to them for every player and recorder, as well as for every piece of media sold. Even companies that manufacture no media or optical drives of their own can still make money based on the licensing of IP as HP does with the DVD+R/RW optical disk format[47]. The recent format battle between the two competing high density optical formats, Blue-Ray and HD-DVD, can be seen not as a fight over technology, but over licensing fees[48].

And while hard disk drives are often distinguished by their performance, there is little advantage to a super fast optical drive if the primary use is to play back movies. Computers may be able to use data that arrives twice as fast, but humans still watch movies and listen to music at a fixed rate. Thus, as an optical disk format becomes common, the manufacture of the drives and the media is often outsourced, leaving only the IP as the main revenue stream for the companies that invented the technology.

IP can be very valuable to a component vendor. These are generally not cross licensed with the drive manufacturers or each other, so IP that helps them distinguish their products can be very valuable.

XI. Business Model

As different as the physical circumstances are, the business models for each of these systems have a major effect on the system in general and the control system in particular.

First, the business model determines how much processing will be done in the system. The cost of a typical hard disk drive (as of January 2009) is about $100 for a 1 TB SATA drive. A drive manufacturer has to sell millions of units to recoup the technology investments. Furthermore, the constant push to lower costs means a low cost DSP or even a microcontroller is used for servo system. Even then, 85–95% of what processor does is not implementing the control law, but all the other functions needed to run the real time system. A similar situation exists for optical disks. The typical cost (as of January 2009) for a dual layer 4.7GB multiformat drive which can read and write media is under $40. In either of these situations, the amount of DSP power available is directly limited by the low cost of the drives. Nobody is going to put a $200 FPGA in a $40 drive. More likely, the budget for processing will be down in the neighborhood of $1 or less.

The AFM presents a significantly different situation. With a unit cost between $20K and $200K, the AFM vendors are unlikely to sell millions of units. However, with these sales prices, the manufacturers are able to spend a lot more money on computational power. This budget freedom, combined with the high sample rates and need for lots of processing, means that either floating point DSP or FPGAs are used in AFMs.

It is worth mentioning one more example of how the business model trumps the engineering solution. For many years, the mechanical and servo engineers working on hard disks wanted to replace the ball bearing spindles with fluid bearing spindles. They reasoned that the drive would have much smoother behavior, much fewer disturbances caused by the spindle orders. While the technology was available, this never came to pass. However, these days most hard disks have fluid bearing spindles on them. The reason for this is that hard drives have migrated from the office to the living room, and the audible noise caused by the ball bearings was no longer tolerable. A user may not mind their office computer being noisy, but they do not want their DVR to make noise when they are trying to watch a movie. Thus, what the engineers wanted to do for years was finally brought about by TiVo and its cousins.

XII. Conclusions

This paper has tried to show, through the use of three real mechatronic control system examples that the physical problem drives the control system, not the other way around. Most of the work involved in working on real control involves thoroughly understanding the system ("What your opponent is giving you…") No real problem "starts with a third order transfer function."

Furthermore, I have tried to illustrate how the business model often drives the problem.

- How much someone is willing to pay often determines what will go into the system.
- Where there are standards, there is the licensing of IP.
- How the product will be used determines which physical problems have to be solved.

Finally, I have tried to show how despite all of this, if someone pays attention and understand the physical and business constraints, it is still possible to see parallels in these systems. It is my opinion that this is why the same mechatronics folks go to all the same disk drive and AFM talks at controls conferences, irrespective of which system they actually work on. It's not just about how to use a particular algorithm it's about when to use a particular algorithm.

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