Welcome to Embedded Unveiled! I'm excited about sharing with you an exploration into the inner workings of real systems. I'll be tearing apart perfectly good products to see, in great detail, how they work. This won't be anything like the static teardowns you may have seen elsewhere. I'll be showing the product in operation and discussing the theory behind some interesting aspect of its design. I'll be on the lookout for particularly clever or unusual technologies.

Much of what I learned about electronics when I was younger came from opening up off-the-shelf products and trying to figure out how they worked. It really helped me when it came time for a formal engineering education, since I found it much easier to understand the theory when I had already had some exposure to the practice. I hope this column can continue that journey for me and will inspire you to learn something new from an in-depth look at what others have designed.

This first column provides a detailed look at linear positioners. I'll be exploring the innards of removable media drives and how their magnetic or optical heads follow the data tracks on the media. Then I'll focus on a linear electromagnetic actuator that's used in a CD player. I'll cover the player's entire tracking system and show it in operation during various normal and adverse conditions. If you're wondering how I happened to choose this topic, read on!

I recently noticed that my home CD player wasn't working too well. It would occasionally skip when playing the higher numbered tracks on a disc. I shouldn't have been too surprised, given its age, since I had bought it more than 25 years ago in the days when CDs were still competing with vinyl records. But, the player seemed like it was built sturdily enough to last a long time, so I figured it was time to take a look inside and see if I could fix the problem. I took off the cover and realized it

This column presents the inner workings of linear positioners—specifically media drives. Here you learn how exploring the linear electromagnetic actuator of a removable media drive breathed new life into an aging CD player.

### Linear Positioners

Table 1—Track geometries and positioning methods for some common removable media. The RPM ranges are for constant linear velocity (CLV) operation, where the drive starts at the maximum speed and gradually slows down as it progresses. Although the RPM and run times are for 1× speed, most optical disk drives run considerably faster.

<table>
<thead>
<tr>
<th>Media</th>
<th>Tracks per inch</th>
<th>RPM (1× speed)</th>
<th>Run time (1× speed)</th>
<th>Tracking method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phonograph record</td>
<td>150–300</td>
<td>33 1/3</td>
<td>15–30 minutes</td>
<td>Groove</td>
</tr>
<tr>
<td>Floppy disk</td>
<td>48–135</td>
<td>300 or 360</td>
<td></td>
<td>Stepper motor</td>
</tr>
<tr>
<td>CD</td>
<td>15,875</td>
<td>480–210</td>
<td>74 minutes</td>
<td>Linear actuator and voice coil positioner</td>
</tr>
<tr>
<td>DVD</td>
<td>34,325</td>
<td>1,530–630</td>
<td>60 minutes</td>
<td></td>
</tr>
<tr>
<td>Blu-ray disk</td>
<td>79,375</td>
<td>1,957–810</td>
<td>90 minutes</td>
<td></td>
</tr>
</tbody>
</table>

---

2011-9-007_Wotiz_Layout 1  08/09/11  5:02 PM  Page 56
had been a while since I had worked on anything so mechanically complex. As I tried to understand where the problem was, I became intrigued with how the tracking mechanism worked.

A HISTORY OF MEDIA

I was curious about how linear head-tracking systems for removable media have evolved over the years as data density has increased. Table 1 shows parameters for some of the more common media, and Photo 1 shows the head positioning mechanisms for several different drives. Floppy drives use an open-loop stepper motor to navigate between tracks. Their low track density doesn’t require much precision, and a simple leadscrew or cam does the job. Photo 1a shows the mechanism of a 5 ¼” drive from the early 1980s. If you look closely, you can see a spiral track on the large white gear that converts the stepper’s rotary motion to a linear position to move the head.

The much higher track density of optical disks required a change from open-loop steppers to a closed-loop servo tracking system. A typical CD or DVD drive has two different head positioning systems. The first is a coarse positioner that moves a carriage or sled containing the entire optical pickup assembly. This is similar to the mechanism in a floppy drive. It isn’t accurate enough to zero in on a particular track, but it can move from one end of the disk to the other. Different drives implement this positioner in different ways. It can be a linear voice coil actuator, or it can be a DC or stepper motor. Photo 1b shows a stepper motor with a worm drive. The tiny motor is almost hidden under four solder blobs at the top left above the much larger spindle motor. You can see the angled threads of the shiny worm gear just below the upper printed circuit board (PCB). The mechanism in Photo 1c uses an ordinary DC motor at the upper right driving several gears. There’s a position encoder sandwiched between the motor and the first gear that’s barely visible in the photo.

In addition to the sled positioner, the optical pickup head always contains two miniature electromagnetic voice coil actuators. One controls the laser beam’s focus and the other is the fine-tracking positioner. Both have springs so they will return to center when current is removed. The tracking positioner can move the optical pickup to the exact location of a particular track. It’s much faster than the sled mechanism and can easily follow any slight variation in the track position as the disk rotates. But, its range is limited, so the sled first has to get the pickup head reasonably close to the desired track.

MAGNETIC FORCE

My CD player’s drive mechanism uses a linear voice coil actuator as a sled positioner (see Photo 2). Figure 1 shows its operation in more detail. The actuator consists of a ferrous metal frame holding a pair of permanent magnets. The magnets create a magnetic field, known as a B field, with flux lines that exit at the North Pole,
He determined the formula that represents the force on a charged particle due to electric and magnetic fields: $F = q (E + v \times B)$, where $F$ is the force vector in newtons, $q$ is the particle's electric charge in coulombs, $E$ is the electric field vector in volts per meter, $v$ is the particle velocity in meters per second, $B$ is the magnetic field vector in teslas, and $\times$ is the vector cross product. When applying the formula to a coil in a magnetic field, it can be simplified to: $F = NI (I \times B)$, where $N$ is the number of turns of wire, $L$ is the wire length in meters, and $I$ is the current vector in amps.

Linear actuators that depend on this force have been around for more than a century.\[3\]

**TRACKING CONTROL**

Figure 2 shows a block diagram of the tracking servo loop. A pair of

---

**Figure 1**—Top view of the linear actuator. The solid arrows are magnetic flux lines, which point from north to south. The dashed arrows show the force exerted on the coil. The direction of the force is determined by the polarity of the coil current.

---

**Figure 2**—The CD player’s tracking control loop. Any difference in illumination of the two photodiodes causes the drive coils to push the optical pickup to minimize the difference. The concept is remarkably simple for such a precision system. Some more recent players use a DSP in the sled control loop, but the operating theory is still the same.
photodiodes on either side of the optical pickup head's centerline will produce a voltage with a polarity and amplitude that depend on how far off the head is from the center of the track. This error signal is amplified, filtered, and fed back to both positioners to keep the head centered on the track. The sled mechanism has enough friction that any small corrections are handled exclusively by the tracking voice coil. But, when the tracking coil approaches the end of its travel, the error signal will become large enough that the sled will start to move as well.

Once the sled is in motion, it takes very little force to keep it going. If a constant force were applied, it would continue to accelerate. However, when the sled needs to slow down, the system still has to slow down the rate of acceleration. The CD player prevents this by measuring the sled speed and applying it to a feedback loop that controls the current fed to the drive coil. The physical configuration of the speed sensor is much like the actuator, but it uses only one single magnet (see Photo 2). As the sensor coil moves through a magnetic field, Faraday’s law of induction tells us that a voltage will be induced in the coil that’s proportional to its velocity.

The track is one continuous spiral, so the positioners are in constant motion to follow the track. However, when the player needs to skip to a different section of the disk, the tracking system switches to an open-loop seek mode. The tracking voice coil is disabled, and the player’s control logic feed a constant voltage to the sled positioner’s driver. Photo 3 shows the signals involved in this process. I had the CD player jump from the beginning of the disk to a point about halfway through. The top trace shows the control signal from the player’s microcontroller. You can see the sled coil’s drive signal [middle trace] immediately jump up to its positive clipping limit. As the sled starts to accelerate, the bottom trace shows the sense coil voltage start to rise. When it reaches the same level as the control voltage, the drive signal starts to drop. The system eventually stabilizes with the drive signal barely above zero. That’s just enough to compensate for friction while keeping the sled at a constant speed.

When it’s time for the sled to stop, the same process happens in reverse. But you can see that it takes less time to slow down than to speed up, since friction helps with the process.

Now that I had measured what the sled was doing, I wanted to see if I could apply Lorentz’s formula to the system. I don’t have a magnetic field strength meter, but I was able to measure all of the other parameters to varying degrees of accuracy. Then I made a rough estimate of the field strength. First, I needed to find a value for F. My rusty memory from high school physics recalled a couple of useful formulas: F = ma and v = at. I measured the sled position before and after the seek shown in Photo 3 and
found it had moved 17 mm in 265 ms, or a velocity of 0.064 m/s. Then, I zoomed in on the leading edge of the waveforms, and measured 13.5 ms for the acceleration from standstill to the steady-state velocity (prior to the initial overshoot). That’s an acceleration of 4.74 m/s². To find the sled’s mass, I precariously perched the CD player on its side and managed to press a small postal scale against the sled. The measurement varied from about 70 to 130 g, so I chose 100 g as an approximate value. That means we have a force of 0.474 N. Phew!

Measuring the coil was much easier. The wire diameter (with insulation) is just under 8 mils, which would be AWG 33. At 206 Ω per 1,000’, the coil, which I measured at 200 Ω, would have 971’ of wire. I measured the coil’s circumference to be approximately 2.4”, which would yield 4,855 turns. The I vector from the Lorentz formula corresponds only to the vertical wire segments, which I estimated at 20 mm on each side, or 40 mm/turn. That gives a value of NL of 194 m. A close look at Photo 3 shows that the drive current during initial acceleration is about 40 mA. Now we have all the numbers we need! Plugging them all into the original formula and solving for B = F/(NLI) yields a value of 0.061 tesla, or 610 gauss. That’s a little smaller than I thought I’d see, but still within an order of magnitude of what I’d expect for a ferrite bar magnet.

After all that work, I was curious to see how the player would handle a slight bump. Photo 4 shows the tracking and sled coil drive signals when I hit the table that the player was sitting on. The cyclical pattern follows the rotation of the disk, a result of the disk’s center hole being slightly off center. The sudden increase in noise after one rotation is where the positioners are compensating for the bump. In this case, the system maintained tracking without any difficulty. Photo 5 shows a more severe impact that causes the player to momentarily lose tracking. You can see the sled bouncing around until it settles back down after about 1½ rotations. The player’s audio dropped out for a short time during this process. Most newer players, especially portable ones, will buffer enough data to cover several rotations. They will also spin the disk at a faster speed, so it’s possible to catch up after a short tracking loss without any dropouts.

PUTTING IT BACK TOGETHER

I’m happy to report that I was able to fix the CD player’s skipping problem. As I moved the sled along its track by hand, it was obvious that one end was noticeably more stiff than the other. I carefully cleaned off all of the long-since-expired lubricant from the entire track and replaced it with a small amount of white lithium grease. That seemed to make more of a difference than I had planned. Now, even some CDs that wouldn’t play at all—ones that I had assumed must have used some format incompatible with a 25-year-old player—play just fine.

I hope you’ve enjoyed this journey into the inner workings of a real embedded system as much as I have. I’ll be taking a look at both conventional and exotic products in future columns. I’d also welcome suggestions for unusual products or technologies I may not be aware of. There will be a lot more to explore in upcoming months. I hope you can come along for the ride!

Richard Wotiz has been taking products apart ever since he was old enough to pick up a soldering iron. He’s been helping others put them together since 1991, when he started his design consulting business. Richard specializes in hardware and software for consumer products and children’s toys. He can be reached at rw601@spiraltap.com.

REFERENCES


Find the Right Development Tool, Compare it to Other Tools, Evaluate It, and Buy It from Digi-Key Tools Xpress -- Without Leaving Our Site.

The Digi-Key Tools Xpress intuitive research engines are used by engineers worldwide to locate, compare and evaluate hardware or software development tools.

Compare before you buy: tools are listed side-by-side, with features and performance specs, availability, and prices, so you can make an educated decision!

Digi-Key Tools Xpress, engineered by Embedded Developer, is the only site in the industry where engineers can quickly find, compare and buy the leading development tools.

Join the thousands of engineers worldwide who use Digi-Key Tools Xpress for their development tool needs.