March 14, 2011(http://blogs.freescale.com/sensors/2011/03/hard-and-soft-iron-magnetic-compensation-explained/)

Hard and soft iron magnetic compensation explained

By Mike Stanley — My last couple of posts have explored options and technologies for measuring magnetic fields (see "Magnetometers Come in Multiple Flavors (http://blogs.freescale.com/sensors/2011/03/magnetometers-come-in-multiple-flavors/)" and "Magnetic Sensor makes Electronic Compass Design Easy(http://blogs.freescale.com/sensors/2011/01/magnetic-sensor-makes-electronic-compass-design-easy/)"). Today, we'll explore issues that you may encounter when using *any* magnetic sensor in consumer applications. To keep things simple, let's consider the case where you're

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integrating a magnetic sensor into a smart phone. Nominally, you would like to use your magnetic sensor to implement compass and navigation features. In a pristine environment, free from interference, we could take measurements directly from our sensor. The real world is not that simple.

Problem #1: Distortion of the magnetic field due to the presence of soft iron.

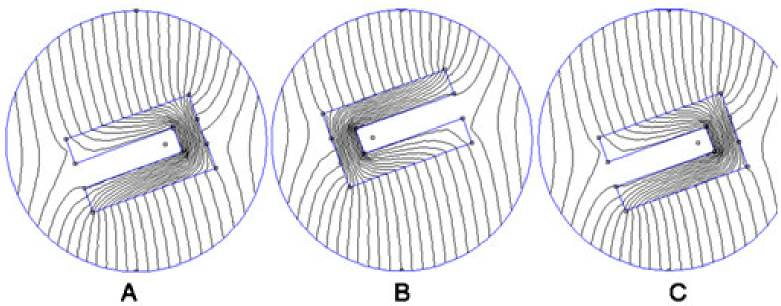

Figure 1: Soft Iron Distortion in a Uniform Field

(http://blogs.freescale.com/wp-content/uploads/2014/12/post-3726-2-animatedsteelbar1.gif)

Soft iron, you say? What's that? Think steel. Think EMI shields, screws and battery contacts. To illustrate the point, I performed a finite elements simulation of a U-shaped piece of steel sitting in a uniform magnetic field. Figure '1A' shows how the magnetic field (which would otherwise be shown as vertical lines) is distorted by the presence of our "U-bar". Steel provides a "lower resistance" path to the magnetic field than does the surrounding air. So it's natural for the field to be diverted.

Figure "1B" takes that same U-bar and rotates it exactly 180 degrees in the same ambient field. You can see similarities in the field distortion. We can see just how similar "1A" and "1B" are by taking "1B", and flipping it, first about one axis and then the other, to obtain "1C", **which is identical in form to Figure "1A".**

This makes a lot of sense when you realize that *from the steel's perspective*, "1A" and "1B" are identical except for the polarity of the ambient magnetic field. We *should* get symmetrical results.

More importantly, we're going to be able to use this simple observation to remove the distortion caused by soft iron from our measurement of the ambient magnetic field.

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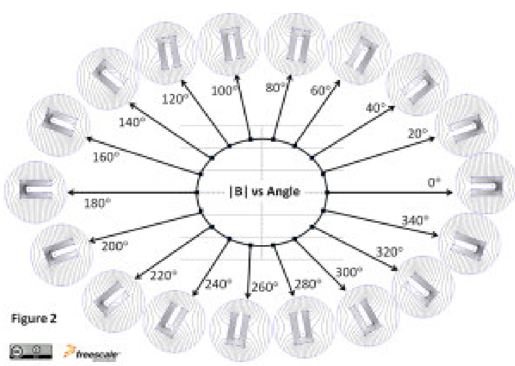
What's next for your wearables design? WaRP 7 (http://blogs.freescale.com/io

To see how, let's take this same U-bar and rotate it in 20 degree increments in the same field. At the same time, let's measure and plot the magnetic field at the "dot" you see nestled near the base of the "U". It's important to note that this point is fixed relative to the disturbing metal. They rotate together.

The symmetry seen above continues to hold as we rotate our soft iron. The field distortion at each angle of rotation matches (after the "flips" noted above) the distortion seen at that angle + 180 degrees. More importantly, the field magnitude measured at each angle matches the field magnitude measured at that angle + 180 degrees.

If we plot the x/y sensor readings for all of our points, we will get an ellipse (you can click on Figure 2 to see a larger image). This is a function of the basic physics, and always holds true, regardless of the sensor type used to make the measurement.



If there were no soft iron present, and we simply rotated our sensor, the ellipse would collapse into a simple circle. Since the field remains the same regardless of the angle of measurement, this must be the case. So we see that the effect of soft iron is to distort a circle whose radius is equal to the magnitude of the ambient magnetic field into an ellipse.

This result can be extended to 3 dimensions. Measurements taken while rotating a sensor in free space undisturbed by hard or soft iron can be visualized as a sphere with fixed radius equal to the magnitude of the ambient magnetic field. Adding soft iron to the mix will distort that sphere into a 3D ellipsoid(http://en.wikipedia.org/wiki/Ellipsoid) (Figure 3).

The equation for a 3D sphere is:

$$x^2 + y^2 + z^2 = r^2.$$

In matrix form, if we have X = [x y z], then

$$XX^T = r^2.$$

For an ellipsoid, it is:

t/2015/11/whats-next-for-your-wearables-design-warp-7/)

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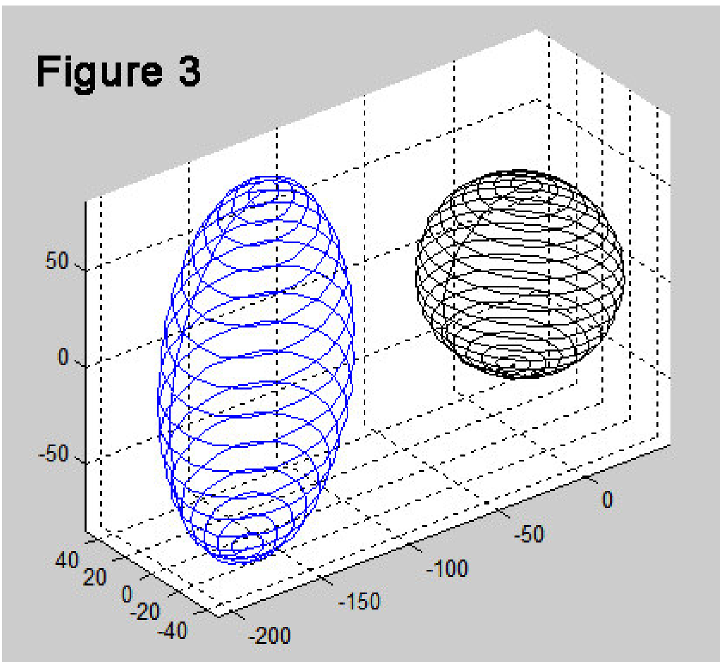
$$x^2/a + y^2/b + z^2/c = 1.$$

In matrix form this is

$$A = \begin{pmatrix} 1/a & 0 & 0 \\ 0 & 1/b & 0 \\ 0 & 0 & 1/c \end{pmatrix}$$

$XAX^T = 1$, where



You can see that the equation of the sphere can be linearly derived from that of the ellipsoid, and vice versa. If we take a representative set of samples on the surface of our ellipsoid, we can, through a variety of methods, determine the reverse mapping from distorted to undistorted magnetic field readings. Essentially, we're curve fitting in 3 dimensions. Now on to…

Problem #2: Distortion of the magnetic field due to the presence of hard iron

"Hard iron" is just a physicist's way of saying "permanent magnet". "Why," you might ask, "am I worried about permanent magnets?" Well, that smart phone we mentioned must have a speaker. And speakers have magnets. And a lot of phone holsters have magnets to secure the device. So it turns out that yes, we DO have to deal with them. The good news is that (compared to soft iron effects), compensating for hard iron offsets is relatively simple. If a magnet is fixed in location and orientation with respect to our sensor, then there is an additional constant field value added to the value that would otherwise be measured. If only soft iron effects are present, the ellipsoid mentioned above should be centered at [x,y,z] = [0,0,0]. A permanent magnet fixed relative to the measurement point simply adds an offset to the origin of the ellipsoid. If we have a large enough data set, we can determine that offset as

$$\text{hard iron offset} = [x_{max}\text{-}x_{min},\ y_{max}\text{-}y_{min},\ z_{max}\text{-}z_{min}]/2$$

This technique will NOT work for magnets that move with respect to the sensor. The magnet on the phone holster flap can't be permanently canceled out. But that's good news! A sudden shift in offset/magnitude of our calculated field probably implies that the phone has been inserted or removed from its holster. That can be a useful thing to know.

Implications

The techniques discussed generally employ some form of curve fitting, which raises subtle issues that don't get discussed much: How many data points do we need in our constellation of sample points? How often does that constellation need to be updated? How do we decide to add or drop points to/from the constellation? What should we do when a sudden change in ambient field magnitude is detected? What numerical method(s) should be used to calculate the trim parameters? How do you deal with uncorrelated magnetic disturbances that occur around us every day? How do you deal with field variations over time and temperature? The answers to these questions make up much of the "secret sauce" used by various vendors in their calibration algorithms.

Earth ambient magnetic field as a function of zip code can be obtained from the online National Geophysical Data Center magnetic field calculator (http://www.ngdc.noaa.gov/geomagmodels/IGRFWMM.jsp). But for some applications, you may not even care what the local value is. The important point to take from the discussion above is that we are leveraging the symmetry of the data set to drive a solution. Compass orientation is determined by ratios of the 3 dimensions calculated. If those values are off from the expected values by a multiplicative constant, the ratios still hold.

I purposely didn't talk about the specific curve fitting procedures used to perform the reverse mapping described above. This area continues to be the subject of much research. I've listed a few papers in the references at the end of this post. Although often intense, don't let the math scare you. Almost all have the basic assumptions discussed above at the heart of their approach. Some solve the problem only in the X/Y plane, others address all three dimensions. Tradeoffs include program and variable memory space, CPU cycles required, and ease of implementation. If your sensor vendor is serious about servicing this market, they should be able to supply pre-packaged routines to bootstrap your product development efforts.

A basic requirement of these approaches is that the sensor output data vary linearly with magnetic field. If your sensor is non-linear, correction factors must be applied prior to applying the techniques discussed. Linear scale factor differences *between* axes can be automatically resolved by a number of algorithms.

More fun to be had

If you click on Figure 1, you'll be taken to an animated GIF that rotates through the various positions shown in Figure 2. You can also download the original PowerPoint file (http://freescalehome.files.wordpress.com/2011/03/soft_iron_rotations.pptx)for both Figure 1 and Figure 2, which have been released under a Creative Commons Attribution-NonCommercial 3.0 Unported License (http://creativecommons.org/licenses/by-nc/3.0/).

My FE simulations were done with the free FEMM 4.2 simulation tool (http://www.femm.info/wiki/HomePage) by Dr. David Meeker, who graciously offered examples and hints about the best way to run the simulations. I've used a lot of free engineering tools from the web. This one is more robust and easier to use than many others I've tried.

References

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2) National Geophysical Data Center magnetic field calculator at http://www.ngdc.noaa.gov/geomagmodels/IGRFWMM.jsp (http://www.ngdc.noaa.gov/geomagmodels/IGRFWMM.jsp).

3) A Geometric Approach to Strapdown Magnetometer Calibration in Sensor Frame (http://users.soe.ucsc.edu/~elkaim/Documents/ReimmanTAES08.pdf), Vasconcelos, Elkaim, Oliveira & Cardeira

4) A Non-Linear, Two-Step Estimation Algorithm for Calibrating Solid-State Strapdown Magnetometer(http://www.google.com/url?sa=t&source=web&cd=1&ved=0CCgQFjAA&url=http%3A%2F%2Fciteseerx.ist.psu.edu%2Fviewdoc%2Fdownload%3Fdoi%3D10.1.1.153.7485%26rep%3Drep1%26type%3Dpdf&ei=42txTbyQJIm-sAP9k_XICw&usg=AFQjCNGKN5Bak8TLue88k02s63YDpvl88g), Gebre-Egziabher, Elkaim, Power & Parkinson.

5) Iterative calibration method for inertial and magnetic sensors (http://www.google.com/url?

sa=t&source=web&cd=1&ved=0CCcQFjAA&url=http%3A%2F%2Fcas.ensmp.fr%2F~petit%2Fpapers%2Fcdc09%2FED.pdf&ei=GGxxTaizJoqssAO5pYzLCw&usg=AFQjCNFH_LdQ9P5D5CPnl-B2qRNfV_nN4w), Dec. 2009, Dorveaux, Vissiere, Martin & Petit

6) A Research of an Improved Ellipse Method in Magnetoresistive Sensors Error Compensation(http://www.google.com/url?sa=t&source=web&cd=1&ved=0CCMQFjAA&url=http%3A%2F%2Fen.cnki.com.cn%2FArticle_en%2FCJFDTOTAL-XDYX201002002.htm&ei=S2xxTbHML4rksQOH0KHPDw&usg=AFQjCNGBD811MJMntD_Yb831hW6jrbe_Eg), Aug. 2009, Lian-yan, Qing & Wen-yuan

7) **Free tool!** Finite Element Method Magnetics (http://www.femm.info/wiki/HomePage), FEMM 4.2.

8) Freescale Semiconductor Magnetic Sensors Page (http://www.freescale.com/webapp/sps/site/taxonomy.jsp?code=MGNTCSNS)

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Georges Khouzam

March 16, 2011 at 3:00 pm (http://blogs.freescale.com/sensors/2011/03/hard-and-soft-iron-magnetic-compensation-explained/#comment-37236)

Thanks for the analysis.
I appreciated very much reading your article.
G.K.

Reply(/sensors/2011/03/hard-and-soft-iron-magnetic-compensation-explained/?replytocom=37237#respond)

Djan Rosario (http://poderdaspontas.blogspot.com)

March 17, 2011 at 7:11 am (http://blogs.freescale.com/sensors/2011/03/hard-and-soft-iron-magnetic-compensation-explained/#comment-37237)

I really appreciated your article that I’ll sum up, translate to Portuguese and post it in my blog. I would especially thank if you could send me another suggestions of free engineering tools as FEMM cited on your article. I teach Electromagnetism, Waves & Antennas and this kind of tool is a valuable contribution to my work.

Reply(/sensors/2011/03/hard-and-soft-iron-magnetic-compensation-explained/?replytocom=37239#respond)

Mike Stanley

March 22, 2011 at 10:26 am (http://blogs.freescale.com/sensors/2011/03/hard-and-soft-iron-magnetic-compensation-explained/#comment-37239)

Djan,
You might also try the trial versions of infolytica's MAGNET and ELECNET tools at http://www.infolytica.com/en/products/trial/ (http://www.infolytica.com/en/products/trial/).
Best regards,
Mike

Reply(/sensors/2011/03/hard-and-soft-iron-magnetic-compensation-explained/?replytocom=37250#respond)

Ashoi

May 29, 2012 at 2:24 am (http://blogs.freescale.com/sensors/2011/03/hard-and-soft-iron-magnetic-compensation-explained/#comment-37250)

Could you help me to describe hard iron and soft iron please?

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Pingback: Sensor Fusion with the MMA8451 Accelerometer and MAG3110 Magnetometer « The Embedded Beat: Freescale Blog Community(http://blogs.freescale.com/2011/05/18/sensor-fusion-with-the-mma8451-accelerometer-and-mag3110-magnetometer/)

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kalyan subbu

July 11, 2011 at 4:44 pm (http://blogs.freescale.com/sensors/2011/03/hard-and-soft-iron-magnetic-compensation-explained/#comment-37242)

I am using magnetic field sensors built in mobile phones to collect ambient magnetic fields inside buildings. I observed that certain pillars have low magnitudes of magnetic fields compared to others. In other words, although the pillars are made of steel, some showed strong magnetic fields and some weak. What is the cause for this?

Also I understood that the data collected is a combination of the Earth's magnetic field and the field from these pillars. In that case, if the earth's magnetic field is around 50microT (obtained using the IGRF model), why do I see this? is it because there is some vector addition or subtraction between the components of the Earth's magnetic field and fields from the pillars?

Pingback: Distorsione campo magnetico: spiegata la compensazione del metallo duro e morbido | Kimblo (http://www.kimblo.com/distorsione-campo-magnetico-spiegata-la-compensazione-del-metallo-duro-e-morbido/)

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Kevin Ding

February 16, 2012 at 9:17 pm (http://blogs.freescale.com/sensors/2011/03/hard-and-soft-iron-magnetic-compensation-explained/#comment-37245)

great! very detailed and clear

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jeniusj

September 21, 2012 at 6:07 am (http://blogs.freescale.com/sensors/2011/03/hard-and-soft-iron-magnetic-compensation-explained/#comment-37251)

Hi,

What I am getting from your method for soft iron compensation is that it is only valid for two dimensional compass. If we want to calibrate a 3 axis compass then we should have to apply the same procedure over YZ plane by taking Z as major axis instead of X axis and then we can calculate theta and scale values as we are calculating for XY ellipse plane.

i.e. first calculate the theta and scale for soft f

Reply(/sensors/2011/03/hard-and-soft-iron-magnetic-compensation-explained/?replytocom=37252#respond)

Mike Stanley

September 24, 2012 at 11:25 am (http://blogs.freescale.com/sensors/2011/03/hard-and-soft-iron-magnetic-compensation-explained/#comment-37252)

Sorry, your interpretation is wrong. My Figure 1 and Figure 2 examples are, for the sake of clarity, 2 dimensional. But the mathematics that follow are valid for 3 dimensions. 3-dimensional magnetic calibration should be performed before any eCompass calculations, which commonly place emphasis on the horizontal components of the field.

Pingback: Magnetometer placement – where and why « The Embedded Beat: Freescale Blog Community (http://blogs.freescale.com/2012/10/03/magnetometer-placement-where-and-why/)

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