

Application Note – AN219

Digital Compass Reference Design with the SiRFstar2t GPS Chipset

ABSTRACT

Until recently, combining a GPS chipset with magnetic sensors for a digital compass (heading) feature was pretty much a separate circuit affair. Today with the introduction of the SiRFstar2t digital processor integrated circuit (IC), closer circuit integration is now possible. This application note shall describe the latest available Honeywell magnetic sensor products combined with SiRF Technologies SiRFstar2t architecture to create GPS-based navigation engines that can point and even locate when short-term GPS availability is missing.

APPLICATIONS

Two popular applications that combine GPS position location and compassing are pedestrian navigation systems and vehicle telematics systems. Pedestrian navigation systems are used in handheld GPS receivers and wireless phones to perform Location Based Services (LBS) and indoor navigation, where GPS satellite reception is intermittent. Vehicle telematics systems use pointing with the vehicle direction, plus location information to harvest provider information. Generally driving maps that are destination driven will include current LBS updates for weather, construction detours, and traffic predictions for time of arrival prediction.

PEDESTRIAN NAVIGATION

Pedestrian navigation circuits are primarily focused on running on low voltage battery power, and are designed for utmost compactness for handheld form factors. By using the SiRFstar2t chipset, the onboard 14-bit ADC channels provide a handy digital insertion pointing for magnetic sensor signals to implement the point and compassing features. Figure 1 shows the basic block diagram for pedestrian navigation systems.

At the heart of the Pedestrian Navigation System is the host microprocessor. This processor gathers the GPS receiver latitude and longitude, the magnetic sensor vector amplitudes, the MEMS accelerometer vector amplitudes, and any system status data. The GPS receiver typically consists of the antenna, Radio Frequency (RF) front-end circuits, and the demodulator section create a data stream of waypoints and receiver acquisition status. Most receivers use two chips to convert the 1227.6 MHz signals (L2 downlink) from the dozens of GPS satellites orbiting the earth.

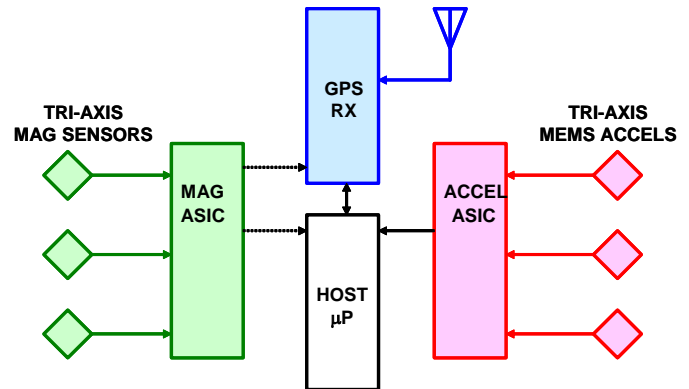


Figure 1
Pedestrian Navigation System

The three axis of magnetic sensors break the external earth's magnetic field down into X, Y and Z vector components. This three-dimensional representation of the field needs to be flattened to two dimensions to create a compass heading ($\text{heading} = \arctan Y/X$). By using the pitch and roll angle inputs from the 3-axis MEMS accelerometers, the tilt-compensated (flattened) X' and Y' values can be converted into a heading. Both the magnetic sensors and the MEMS accelerometers require signal conditioning by their Application Specific Integrated Circuits (ASICs) before being sent to the host microprocessor.

The magnetic sensor ASIC outputs are usually analog representations of the X, Y and Z magnetic measurements, and require high resolution digitization to derive precision heading output. To accommodate this digitization, 10 to 16-bit Analog-to-Digital Converter (ADC) circuits are incorporated in either the GPS demodulator IC or the host microprocessor to keep the integration high and the costs low. In this specific application note, the SiRFstar2t demodulator IC provides two 14-bit inputs for external sensor signal inputs. In other wireless phone chipsets, the phone's RF demodulator may combine the GPS demodulator plus the sensor ADC inputs.

Another aspect of pedestrian navigation is that the MEMS accelerometers and the accelerometer ASIC serve a second function besides compass tilt compensation. This second function is a pedometer for both raw step count, and applied pedometer calculations such as stride length and stride direction.

While step count is handy for customer health concerns, indoor navigation relies on statistical prediction of stride length based on step rate (walking or running or stair-

stepping). This prediction is done when GPS is actively tracking the steps/strides per change in distance (via GPS waypoints). As part of this statistical pedometry data, the kinds of stride directions must be cataloged. Forward steps, backward steps, side steps, and even stair steps may be needed to accurately track a person's change in position per step taken.

Since the wireless phone may be worn in many orientations such as in the shirt pocket, belt-mount, or carried in a purse; these stride directions must be constantly updated as the handset to customer orientation changes. And with each step or stride, a corresponding compass heading is associated so that distance and direction are used from the last good GPS waypoint to navigate via dead reckoning indoors. Figure 2 shows a typical pedestrian with a shirt-pocket mounted phone walking indoors.

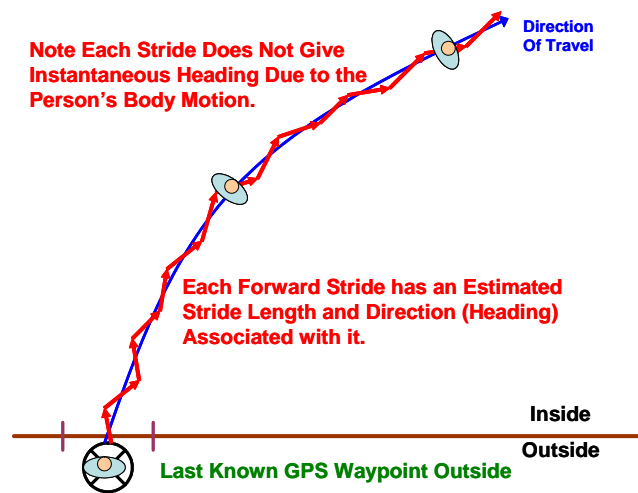


Figure 2
Indoor Pedestrian Navigation

As you can see above, each step is a piece-wise change in direction and location. Simple algorithms will use a fixed stride length derived from recent outdoor strides between waypoints. More sophisticated algorithms will also track stride per time, and adjust stride length on step rate for slow walk, fast walk, and running.

VEHICLE TELEMATICS

Telematics is the fusion of wireless communications with navigation aids to provide location and direction of the vehicle for the benefit of the vehicle's occupants. While turn-by-turn mapping and navigation is the "killer application", the pointing aspect permits proper map orientation and additional data flow with both push and pull methods. Pull data for telematics are driver/passenger inquires for information up ahead that the person has interest in. Classic pull examples are fuel and restaurant brand locations, points of historic interest, and web content "data mining".

Push data is location based content that you have voluntarily or involuntarily chosen to be sent as the direction and location changes. Classic push data is location-based advertising in which local businesses buy space on your dashboard Liquid Crystal Display (LCD). By knowing your direction and brand preferences, product or service providers are cued to upload banner ads on your LCD.

These ads subsidize your telematics service provider to allow customers free or low cost subscription of telematics services for your vehicle. A good example is a pop-up banner ad that advertises your preferred brand of fuel service station (e.g. a BP station) based on the reading of your gas gauge (via CAN-bus), and tells you the up-ahead station address and distance, and provides the current fuel price plus in-store sale items. Figure 3 shows a typical telematics system flow diagram.

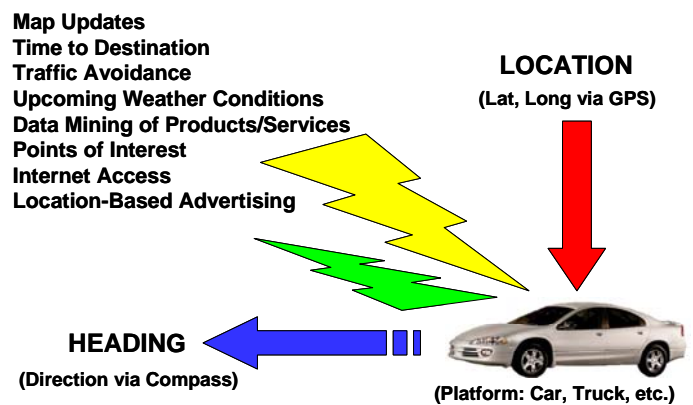


Figure 3
Telematics System Flow

The telematics electrical block diagram is nearly identical to pedestrian navigation, except the accelerometers can be removed. Instead a wheel speed sensor or sensors are used to count rotations and estimate distance per rotation correlating to the current location. While GPS availability is generally better for vehicles than indoor wireless phones, there are times when dense foliage, covered bridges, tunnels, and urban environments (tall buildings) obscure GPS signal reception.

CIRCUIT DESIGN

Getting down to the circuit details; for best integration for telematics applications, a Honeywell HMC6042 2-axis sensor and ASIC is recommended. Figure 4 shows the basic circuit schematic diagram; with the SiRF GSP2t tracker engine IC connected normally between the GRF2i radio frequency front-end IC and the host processor. Spare GSP2t ADC pins (ADC2 and ADC3) interface with the HMC6042 X and Y axis output pins. Besides the IC packages, two low-ESR ceramic capacitors of 2.2 and 0.22 micro-farads are required to create set and reset pulses to drive the set/reset straps

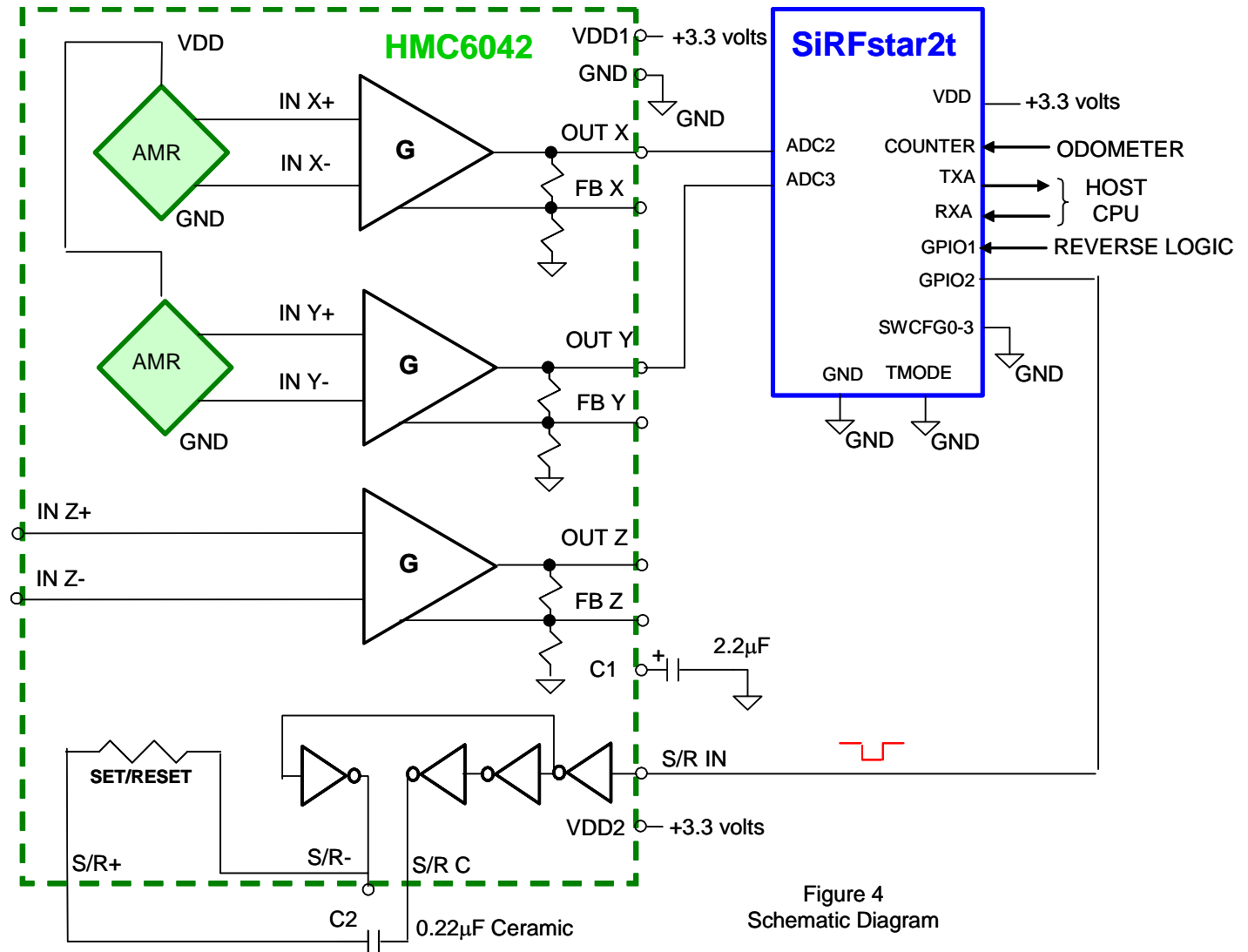


Figure 4
Schematic Diagram

on the sensors for periodic de-gaussing and offset compensation.

The Honeywell HMC6042 2-axis Magnetic Sensor IC is an integrated circuit chip containing two silicon die for sensing and signal conditioning. The HMC1042 2-axis sensor die and an ASIC die are included in the HMC6042 IC, with a linear low-field pair of magnetic sensors capable of handling magnetic fields up to ± 6 gauss with an amplified linear voltage output. The sensors can handle up to ± 20 gauss of external magnetic fields before becoming partially saturated. Since the earth's natural magnetic field is measured around ± 0.6 gauss, field strengths beyond 20 gauss typically are encountered by proximity to magnetized hand tools (screwdrivers, pliers, etc.), speaker magnets, TVs or video monitors, test equipment power transformers, or high current wires from welding equipment or electrical supply wiring.

Should the sensors and whole circuit assembly be intimately exposed to these high magnetic field sources, most instances the sensor set and reset pulses will restore magnetic sensor function, and the compass

headings will be back to factory specifications. Extreme high field exposure could build magnetism on the nickel-plating of electronic components and cause compass heading errors; as the component magnetic flux emissions could buck or boost the external earth's fields. By using a commercial degaussing wand (magnetic tape eraser), residual component magnetism can be removed.

Also within the HMR6042 Magnetic Sensor IC, the signal conditioning ASIC takes the milli-volt output signals from the sensors and amplifies the signals about 225 times and centers the signals at a zero gauss level of half-supply (e.g. 1.65 volts for a 3.3 volt supply). Three of these amplification sections are included, with the third input signal connections brought out for an external Z-axis magnetic sensor.

The HMR5003 ASIC also needs to generate 1 to 2 microsecond length set and reset pulses at 400 milli-ampere or higher currents per set/reset strap. Since most applications have current limited battery supplies, these pulses are created by trickle charging the 2.2 micro-farad C1 capacitor. This capacitor serves as a low

energy reservoir for the H-bridge MOSFET strap driver sub-circuit that applies several volts across the set/reset strap of the sensors. Capacitor C2 at 0.22 microfarad sets the pulse time constant at around 1 micro-second and prevents direct current from passing through the driver output nodes into the strap. In three-axis applications, the set/reset strap connections are brought out for paralleling the Z-axis magnetic sensor's set/reset strap to the internal strap. Capacitors C1 and C2 should be doubled in value (4.7uF and 0.47uF) when the external strap is added.

The HMC6042 has two positive voltage supply pins (VDD1 and VDD2) for separating the supplies for the sensors and amplifiers (VDD1) and the set/reset strap drivers (VDD2). Typically the set/reset strap drivers can be left permanently connected to the battery supply as it draws virtually no current shortly after the pulses have been applied. The set/reset logic input pin (S/R IN) creates a reset pulse on the high to low logic transition, and then creates a set pulse on the low to high logic return. These logic changes typically are spaced milliseconds apart to accommodate ADC measurements at least 500 micro-seconds after each pulse for sensor bridge offset voltage computation. See application notes AN212 and AN213 on offset and set/reset strap functions.

To save battery energy, connection VDD1 may be powered down between magnetic sensor measurement

periods to drop many milli-amperes of supply draw. This may save immense amounts of energy for handheld devices, but not necessarily a priority in telematics applications.

CIRCUITS FOR WIRELESS HANDSETS

For wireless handsets and personal GPS receivers, the indoor/pedestrian navigation function can also be accommodated with the combination of the SiRF GSP2t and Honeywell HMC6042 ICs. However, the arbitrary positioning of handheld products requires that compass design involves three-axis of magnetic sensors plus at least two-axis of MEMS accelerometers. To make this happen, the Honeywell HMC1041Z z-axis magnetic sensor is added to the HMC6042 IC to complete the third axis. Figure 5 shows the complete system schematic for handheld navigation system.

Because the SiRF GSP2t tracker engine only has two ADC inputs, an external micro-analog switch IC is used to multiplex the Y-Z input axis from the HMC6042 sensor IC. Choosing the Toshiba TC7W66FK dual analog switch in the SSOP-8 package, provides a low cost, small size multiplex function. While not shown in Figure 5, a MEMS accelerometer like the MEMSIC MXD6020G can be integrated to the host microprocessor, through the accelerometer's two Pulse Width Modulated (PWM) output pins. These PWM outputs typically run at 100Hz

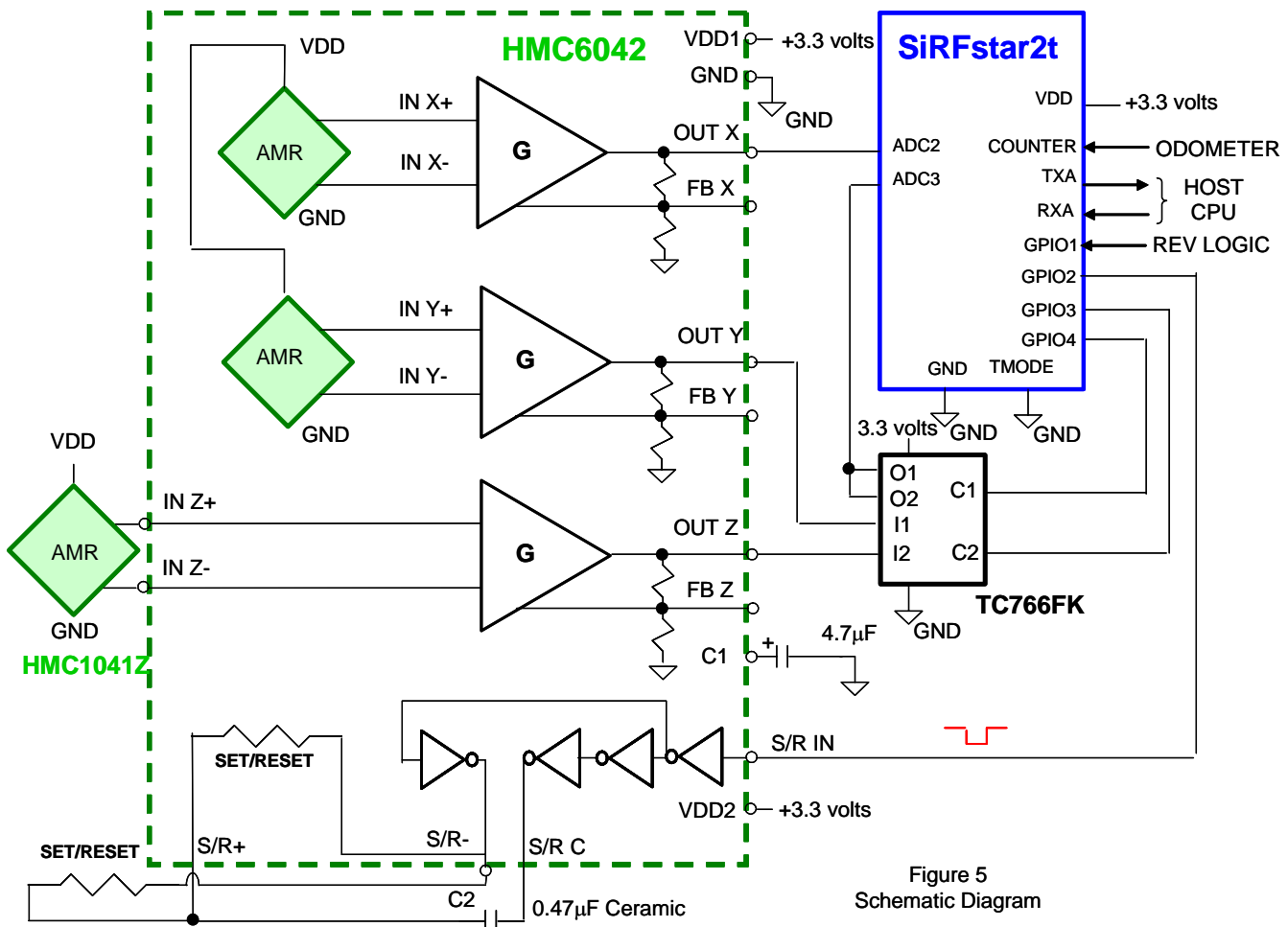


Figure 5
Schematic Diagram

with a level output at 50% duty cycle (handset horizontal) and range from 30 to 70% duty cycle as the handset pitch and roll angles rotate to ± 90 degrees. If the handset needs an upright forward direction through the back of the handset, then a 3-axis accelerometer is required. This would permit the automatic selection of XY or YZ forward directions depending on horizontal or vertical handset attitude.

Footstep or pedometry detection with an accelerometer is non-trivial, but can either be accomplished by dedicated circuitry within the accelerometer, or by digital algorithms in the host processor to discern sudden changes in acceleration while keeping accurate values of pitch and roll for compass tilt compensation. Honeywell has proprietary algorithms for processor-based step/stride-length pedometry and can be contacted for licensing.

SYSTEM AND FIRMWARE DESIGN

As described in the early sections of this application note, dead reckoning for indoor navigation is a complex amalgamation of digital compassing, GPS, and pedometry functions. The main sources of location prediction error occur in compass heading (75% of error) and in stride length estimation (25% of error). So to create reasonable location prediction for consumer electronics products, a 5% error of distance traveled from last good GPS waypoint is considered reasonable.

To achieve this goodness of location prediction, the compass system should approach 1 degree of accuracy under modest tilt conditions of normal usage. Since a compasses' error budget falls heavily on the pitch and roll angle accuracy, the chosen MEMS accelerometer must have sufficient tilt accuracy to not eat up the entire 1 degree heading accuracy error budget. A prudent goal of less than 0.25 degrees of either pitch or roll error can create up to ± 0.5 degrees of compass heading error at North American latitudes. While competitive dead reckoning system designers skimp with piezo accelerometers and cheaper magnetic sensor elements; the resulting compass accuracy is worse than a couple of degrees, and would make an indoor navigation system useless. Especially when in tight building floor plans with no chance of getting GPS waypoint updates.

Digital compass firmware is not a task to be attempted by novice designers with quick design times in mind. In most cases, hundreds to over a thousand hours of firmware development and testing are expended to create a successful compass routine. Then tack on a similar effort for dead reckoning data fusion, Kalman filtering of GPS and dead reckoning locations, and the pedometry stride database routines. Figure 6 depicts a flow chart of compass firmware routines.

The process of compass firmware starts with the prime routines of magnetic sensor data acquisition, data correction, and heading computation. To offer the best

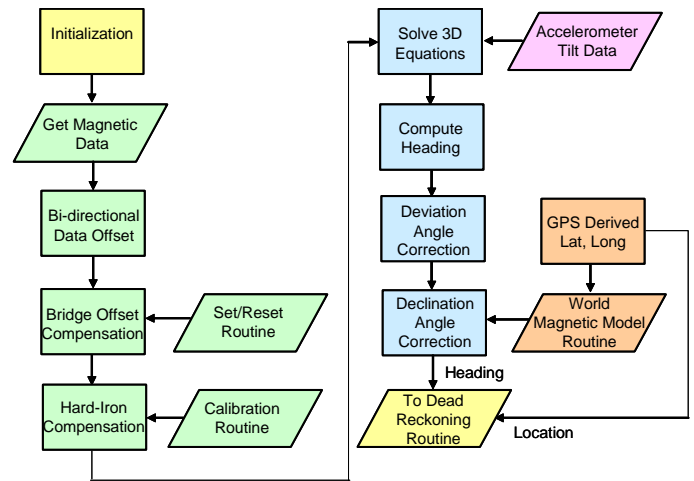


Figure 6
Compass Firmware Flow Chart

compass accuracy, each axis of magnetic sensor data must be quickly digitized, for both power saving reasons, and for near simultaneous attitude sensing (snap-shot) of the moving person. At nearly the same time, the best pitch and roll angles are to be acquired for the same snap-shot reasons.

Since magnetic field measurements are bi-directional in magnitude, each magnetic sensor axis ADC value must subtract its "zero-gauss" ADC counts so that negative values can be represented in two's-complement form. Typically the zero-gauss ADC count offset is about half the ADC range or at the half-supply voltage point.

A second offset for each magnetic sensor axis, is the bridge offset voltage. While this value is consistent for each sensor bridge, there is a noticeable drift of bridge offset voltage with temperature. As a result, a periodic bridge offset recomputation must be made and the bridge offset in ADC counts subtracted from the magnetic sensor data. This bridge offset voltage measurement is explained in detail in application note AN212, but usually entails making measurements after reset and set pulses to null out the earth's magnetic field, leaving only the bridge offset counts when the measurements are summed together.

The last magnetic sensor offset routine is for hard-iron calibration. While most handheld applications do not require much calibration beyond factory values; by placing a telematics receiver in-dash or mounting a handset in a vehicle cradle, the vehicle chassis and motor may emit a gauss or two of field that will combine with the earth's magnetic field and bend the compass headings. To remove these nearby hard-iron emissions from the earth's far-field stimulus, a firmware routine is written to correct for hard-iron offsets on each sensor's sensitive axis.

For 2-axis telematics applications, the hard-iron calibration routine would prompt the driver to drive in a

circular fashion to collect minimum and maximum values of each axis. At the completion of the circle, the mean value of each axis is computed and used as the offset to re-center the incoming data about the zero gauss points. In handheld, 3-axis applications, the same circular turn is required, plus upside-down positions to get a z-axis mean value.

After the three offsets are applied to each axis of the magnetic sensors, the new corrected magnetic values plus the corrected values for pitch and roll angles are inserted into a heading computation routine. For two-axis design the equation is simply the arctan (Y/X) function and floating-point processors can directly compute the arctangent of the quotient. For microcontrollers without floating-point engines, the arctangent must be memory mapped in the controller.

Fortunately the arctangent memory map needs only to be mapped for 90 degrees, as the function repeats each 90 degree quadrant for 360 degrees. By noting the sign of the X and Y magnetic data, the 90 degree map can be offset for the correct quadrant. To size the memory map, the resolution will drive the number of arctangent solutions for the mapped quadrant. For a one degree resolution compass, then about 90 memory locations have arctangent values for matching up to the (Y/X) quotient. Thus about 900 memory locations are needed for 0.1 degree resolution, or about 180 locations for 0.5 degree heading resolution. A reasonable expectation would be 0.1 degree heading resolution with a 1 degree accurate compass for indoor navigation.

With three axis applications, the two flattening equations must be solved to convert the XYZ magnetic values and pitch and roll angles into tilt compensated X' and Y' values for final arctangent computation. These equations are:

$$X' = X * \cos(\phi) + Y * \sin(\theta) * \sin(\phi) - Z * \cos(\theta) * \sin(\phi)$$

$$Y' = Y * \cos(\theta) + Z * \sin(\theta)$$

The good news is that the accelerometers provide the pitch (ϕ) and roll (θ) angles directly in numeric cosine phi and cosine theta format, so no further trigonometric memory maps are required. Knowing that the sine value is one minus the cosine value, provides all the values for the flattening (3D to 2D) equations.

The detail so far unmentioned, is the accelerometer calibration problem to create accurate pitch and roll angles. Calibrating accelerometers is mostly a factory test problem, and procuring accelerometers of good angle linearity is very important. While end-users can re-

zero (level) pitch and roll by placing the handset or vehicle on a known level surface, non-linearity correction values must be provided within the accelerometer.

If tilt calibration is not provided with the accelerometer, a factory test must run through a robotic sequence of tilt angle tests, to correlate stimulated verses measured pitch and roll angles to fill in the non-linear correction values. This becomes crucial when one degree accurate compassing demands better than 0.5 degree accurate pitch and roll angle measurement.

CONCLUSIONS

Magnetic sensors and GPS functions do work well together in simple to complex navigation tasks. While GPS receivers alone can derive heading for platforms in motion, as soon as the motion slows (like in traffic) the heading prediction from waypoint differences becomes too coarse for utilization. Also a compass heading becomes necessary in handheld products, as a stationary person rotates around.

To best describe various levels of magnetic sensor and GPS utility, Figure 7 shows three tiers of accuracy. A low grade of magnetic field sensing can be called a "direction sensor", and can be used for basic map orientation and basic 4 to 8-point cardinal directions (north, south, east, and west). Moderate grades of accuracy enable "pointing" for LBS and Telematics plus true compassing from 16-point cardinal directions degrees heading displays. Precision grade navigation is better than ± 2 degrees heading accuracy and required dead reckoning, airborne and seaborne navigation applications. While precision navigation once meant hundred of dollars for compassing and GPS reception features, this application note shows circuits with ICs that are just a couple dollars each.

Magnetic Sensor Accuracy	GPS and Magnetic Sensor Applications
Low (> \pm 5 degrees)	Direction Sensing (Not a Compass). Map Orientation for right reading legends.
Moderate (\pm 2 to \pm 5 degrees)	Basic Cardinal Point Compassing (N, S, E, W), and Pointing Functions like Simple Location-Based Services and Telematics.
Precision (< \pm 2 degrees)	Navigation-Grade Applications such as Dead-Reckoning, Ship, and Aircraft Navigation.

Figure 7
Tiers of Accuracy

For further questions, please call for applications support at 800-323-8295 (USA toll free) or 763-954-2474 or visit our website at www.magneticsensors.com.