Esami di Stato per l'abilitazione alla professione di Ingegnere
Sessione I - Giugno/Luglio 2006
Nuovo Ordinamento - Sez. A
Settore Informazione - Classe 29/S Ingegneria Meccatronica
Prova Pratica

1 Problema

II candidato deve sviluppare un progetto di fattibiltà per un sistema di auto-localizzazione e navigazione, da installarsi su un robot mobile, per la sorveglianza interna di una struttura industriale, priva di guide ottiche o altri landmark specifici. Il robot deve poter fare uso solo dei sensori seguenti: gli encoder presenti sulle ruote, un accelerometro bi-assiale e una bussola a stato solido.

A bordo sono tuttavia presenti sensori a ultrasuoni (o altro) che permettono al rover di evitare gli ostacoli.

La mappa della struttura è nota; il punto di partenza e l'assetto iniziale del rover sono noti.

2 Ipotesi per il progetto

II candidato sviluppi il progetto considerando le seguenti ipotesi semplificative:

- II robot mobile (per brevità chiamato *rover)* si muove liberamente all'interno di edifici *(indoor motion)* su una superficie sostanzialmente piana e priva di asperità, tale per cui è sufficiente un accelerometro bi-assiale.
- H rover si muove entro il campo magnetico terrestre, che è misurabile e costante nel tempo.
- II tempo è da considerarsi discreto, con un periodo di campionamento costante pari a $T = 10\,\text{ms}$.
- H rover è modellizzabile come un "uniciclo", ossia un corpo quasi puntiforme dotato di tre gradi di libertà: $x(k), y(k), \theta(k)$; si veda lo schema di Figura 1.
- II rover è dotato di due motori cc; il primo (motore 1) aziona l'unica ruota e fornisce la velocità di avanzamento $v(k)$, il secondo (motore 2) aziona lo sterzo e fornisce la velocità di rotazione w(fc) intorno all'asse verticale. Ciascun motore è fornito di un motoriduttore ideale. Le caratteristiche dei motoriduttori possono essere anche diverse tra loro e sono lasciate alla scelta del candidato.
- Ciascun motore è dotato di un encoder incrementale, posto a monte del motoriduttore;

- U rover possiede massa totale m (telaio + ruota + motori + motoriduttori, ecc), un momento d'inerzia intorno all'asse orizzontale *J* e un momento d'inerzia intorno all'asse verticale J2, entrambi costanti nel tempo.
- D contatto tra ruota è terreno è ideale (puntiforme) e il moto avviene senza strisciamento tra ruota e terreno;
- Gli attriti interni sono modellizzabili con i coefficienti *fa* (motore 1 + motoriduttore 1) e /?2 (motore 2 + motoriduttore 2)
- Si assume una coppia di disturbo *Ar(k)* che in ogni istante *k* genera un disturbo di assetto *A6(k)* G [-2°,2°], uniformemente distribuito

3 Punti da sviluppare

D candidato deve sviluppare i seguenti punti:

1. Fornire i requisiti funzionali del sistema di auto-localizzazione e navigazione. Discutere se sono necessari altri sensori dì posizione assoluta (come landmark ottici, a radiofrequenza ecc.) oppure i sensori di bordo sono sufficienti alla auto-localizzazione e navigazione.
2. Ricavare il modello cinematico del robot, ossia come si ottengono *x(k),y(k),9(k)* a partire daw(Jfe),w(fc).
3. Ricavare le equazioni dinamiche del robot; considerare come comandi *v(k),u>(k),* come uscite *x(k),y(k),9(k),* e come disturbo A0(fc).
4. Poiché si vogliono utilizzare gli encoder, l'accelerometro e la bussola per migliorare le prestazioni di autolocalizzazione del rover, il candidato deve presentare un progetto a livello di sistema (con l'ausilio di schemi a blocchi funzionali, diagrammi ecc.) dove risulti come si possono integrare reciprocamente le misure dei sensori per fornire le uscite *x(k),y(k),6(k).*
5. Discutere la relazione tra le prestazioni dei sensori e la precisione ottenibile dalla autolocalizzazione (soprattutto a bassa velocità, quando gli encoder tendono a fornire misure affette da maggiore errore).

   H candidato deve decidere se montare l'encoder a valle 0 a monte del motoriduttore (misura l'angolo ruota oppure l'angolo motore?), e motivare la scelta anche in funzione della precisione a bassa velocità.

4 Materiale di supporto

In allegato vengono fornite:

a) Estratto specifiche del Low-Cost ±2 g Dual-Axis Accelerometer ADXL202E della Analog Device.

b) Estratto Application Note AN-602 per l'uso dell'accelerometro come pedometro in applicazioni di navigazione personale.

e) Estratto Application Note AN00022 relative a bussole a stato solido Philips KMZ51 e KMZ52.

Figure

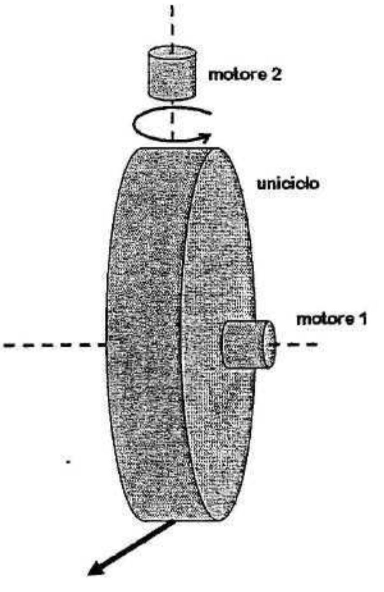


Figura 1: Schema dell'uniciclo.

ANALOG DEVICES

AN-602
APPLICATION NOTE

One Technology Way • P.O. Box 9106 • Norwood, MA 02062-9106 • Tei: 781/329-4700 • Fax: 781/326-8703 • www.analog.com

Using thè ADXL202 in Pedometer and Personal Navigation Applications

by Harvey Weinberg

INTRODUCTION

iMEMS® accelerometers have sparked thè interest of many designers looking for ways to build accurate pedometers. The personal navigation system is an extension of thè pedometer with an electronic compass integrated to thè pedometer to allow a user to de'termine their position relative to some starting point. This application note will discuss thè issues that designers will face in these applications and describe some strategies for thè implementation of personal navigation systems.

THE CLASSICA!. IMPLEMENTATION

Accelerometers have been used as position sensors in inertial navigation systems for many years. Inertial navigation systems use a combination of accelerometers and gyroscopes to determine position by means of "dead reckoning," where thè deviation of position from a known reference (or starting point) is determined by integration of acceleration in each axis over time. The math is fairly straightforward:

$$Position = Starting\,Position + \frac{A \times t^2}{2}$$

However for low speed movement, thè accuracy of such a system over any reasonable length of time is poor because small de errors accumulate and eventually amount to very large errors. This is most easily **illustrateci** with an example of a person walking at 5 km/h (1.39 m/s) over a five minute period. The average acceleration for thè 416 m traveled would be:

$$A_{avg} = \frac{2 \times Displacement}{r^2} = \frac{833}{300^2} =$$

$$0.00926\ \boldsymbol{m/s^2} = \mathbf{0.944\ mg}$$

Since thè temperature coefficient of thè ADXL202 is approximately 2 mg/°C, a temperature deviation of even 0.5°C over thè five minutes would add 1 mg of error—more than thè desired signal itself! In fact, a change in inclination of thè accelerometer of just 0.06°C would be greaterthan 1 mg.

To minimize thè error, we must know thè orientation of thè accelerometer and have some method of "resetting" thè integrator to known reference positions fairly often. Many systems use GPS receivers or position switches to provide this periodic reference position information. If this absolute positional information was available fairly often (say every 10 seconds), we could greatly reduce thè error.

In 10 seconds, thè average acceleration would be 28.4 mg. Assuming we could hold ali de errors to 1 mg over 10 seconds and fix thè orientation of thè accelerometer, we would have a positional error of approximately 0.5 m—much better than a GPS system alone could do. So, using dead reckoning as an adjunct to an existing positioning system may be very useful, but it is not very accurate when used alone.

As an example of where dead reckoning works well, consider an elevator. Magnetic position switches are placed on its track every meter. However, we wish to control thè positioning of thè elevator to 10 mm. The classic solution is to use an optical encoder on a wheel coupled to thè track as a "fine position" sensor. Since mechanical sensors are prone to wear, we wish to replace thè encoder wheel with an accelerometer to improve long term reliability.

Assuming we can hold thè de errors stable to 1 mgover a few seconds and thè elevator travels at 1 m/s, we can find thè positional error as:

$$E_{pos} = \frac{A \times t^2}{2} = \frac{1\ mg \times 9.8\ m/s \times 1}{2} = 4.9\ mm$$

well within our target.

PEDOMETERS

When trying to determine how far a person has walked, there is other information available to us. When people walk, there is Z-axis (vertical) movement of thè body with each step. A simple but inaccurate way to measure distance walked is to use this Z-axis movement to determine how many steps have been taken and then multiply thè number of steps taken by thè average stride length.

A common algorithm for step counting uses some manner of peak detection. Generally, sampling is performed at 10 Hzto20Hzand then averaged downto2 Hzto3Hz to remove noise. The step detection routine then looks for a change in slope of thè Z-axis acceleration. These changes in slope indicate a step.

Only looking for thè change in slope at appropriate times can improve step counting accuracy. Stride frequency tends to change no more than ±15% per step during steady state walking. Looking for thè peak only during a time window as predicted by thè last few steps ±15% will result in more accurate step counting.

IMPROVING THE ACCURACY

Unfortunately, using a fixed value for stride length will always result in a low accuracy System. Stride length (at a given walking speed) can vary as much as ±40% from person to person and depends largely on leg length. Some pedometers ask thè user to program their stride length to eliminate most of this error. However, each individual's stride length will vary by up to ±50% depending on how fast one is walking (at low speeds, people tend to take short steps while at high speeds, their stride is much longer). Knowledge of leg length cannot eliminate this error. But by looking closely at thè application, we can find ways to improve thè situation.

While walking, thè knee is bent only when thè foot is off thè ground. Therefore we can look at thè leg as being a lever of fixed length while thè foot is on thè ground. Figure 1 illustrates how thè hip and, by extension, thè upper body move vertically when walking. By geometry of similar angles we know that:

$$\alpha = \theta$$

So we can show that:

$$Stride \approx \frac{2 \times Bounce}{\alpha}$$

Where *Bounce* is thè vertical displacement (Z axis) of thè hip (or upper body).

Bounce (Z-axis displacement) can be calculated as thè second integrai of thè Z-axis acceleration. a is a small angle and is difficult to measure since there is a lot of shock present in ali axes while walking. We have demonstrated empirically that we can simply use a Constant for a without a large accuracy penalty. In fact, we can approximate distance traveled by:

$$Distance \approx \sqrt[4]{A_{max} - A_{min}} \times n \times K$$

where:

- A™ is thè minimum acceleration measured in thè Z axis in a single stride.
- A_{mBX} is thè maximum acceleration measured in thè Z axis in a single stride.
- *n* is thè numberof steps walked.
- *K'\s a* Constant for unit conversion (i.e., feet or meters traveled).

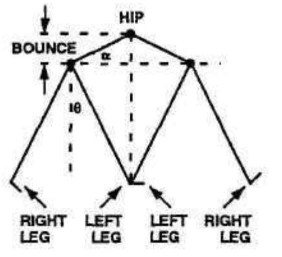


Figure 1. Vertical Movement of Hip while Walking

This technique has been shown to measure distance walked to within ±8% across a variety of subjects of **dif**ferent leg lengths. Close coupling of thè accelerometer to thè body is important to maintain accuracy. An adaptive algorithm that "learns" thè user's stride characteristics could improve thè accuracy significantly.

A BASIC program listing for thè Parallax BASIC Stamp® (BS2) processor that performs step counting and distance calculation and displays distance and steps walked on a standard 16X2 LCD display is included in thè Appendix of this application note.

ADDING DIRECTION SENSING

To fully implement a personal navigation System, some method of direction sensing is required. An electronic compass normally handles this task. Honeywell and Phillips (among others) manufacture low cost electronic compass sensor components and modules that are suitable for personal navigation applications. A microcontroller is used to keep track of where you are (relative to thè starting position) by vector addition using thè distance information derived from thè accelerometer along with directional information from thè electronic compass.

The accelerometer and microcontroller may also be used to improve thè accuracy of thè electronic compass by implementing a compass tilt correction algorithm (consult electronic compass manufacturer's application notes regarding tilt correction techniques).

CONCLUSION

While dead reckoning can be used to improve thè posizionai resolution of a System where thè dead reckoning time is short, it is not very useful for long-term position measurement. Careful examination of thè application can often reveal surprisingly simple solutions. In this case, a single simple mathematical equation along with a simple step counting routine outperforms traditional dead reckoning techniques.

BASIC Stamp is a registered trademark of Parallax, Inc.

ANALOG DEVICES

Low-Cost ±2 *g* Dual-Axis Accelerometer with Duty Cycle Output

ADXL202E*

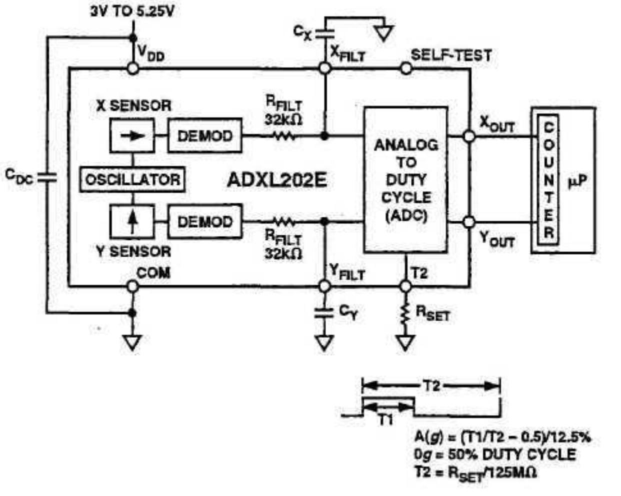
FEATURES

- 2-Axis Acceleration Sensor on a Single IC Chip
- 5 mm x 5 mm x 2 mm Ultrasmall Chip Scale Package
- 2 mg Resolution at 60 Hz
- Low-Power < 0.6 mA
- Direct Interface to Low-Cost Microcontrollers via Duty Cycle Output
- BW Adjustment with a Single Capacitor
- 3 V to 5.25 V Single Supply Operation
- 1000 g Shock Survival

APPLICATIONS

- 2-Axis Tilt Sensing with Faster Response than Electrolytic, Mercury, or Thermal Sensors
- Computer Peripherals
- Information Appliances
- Alarms and Motion Detectors
- Disk Drives
- Vehicle Security

FUNCTIONAL BLOCK DIAGRAM



GENERAL DESCRIPTION

The ADXL202E is a low-cost, low-power, complete 2-axis accelerometer with a digitai output, ali on a single monolithic IC. It is an improved version of thè ADXL202AQC/JQC. The ADXL202E will measure accelerations with a full-scale range of ±2 *g*. The ADXL202E can measure both dynamic acceleration (e.g., vibration) and static acceleration (e.g., gravity).

The outputs are analog voltage or digitai signals whose duty cycles (ratio of pulsewidth to period) are proportional to acceleration. The duty cycle outputs can be directly measured by a microprocessor counter, without an A/D converter or glue logic. The duty cycle period is adjustable from 0.5 ms to 10 ms via a single resistor (R_{SET}).

The typical noise floor is 200 (JL^N/HZ, allowing signals below 2 *mg* (at 60 Hz bandwidth) to be resolved.

The bandwidth of thè accelerometer is set with capacitors Cx and Cy at thè XFILT and YFILT pins. An analog output can be reconstructed by filtering thè duty cycle output.

The ADXL202E is available in 5 mm X 5 mm X 2 mm 8-lead hermetic LCC package.

*Patents Pending

REV.A

One Technology Way, P.O. Box9106,Norwood, MA 02062-9106, U.S.A.
Tei: 781/329-4700 World Wide Web Site: http://www.analog.com
Fax: 781/326-8703

ADXL202E–SPECIFICATIONS ($T_A = T_{MIN}$ to T_{MAX}, $T_A = 25°C$ for J Grade only, $V_{DD} = 5$ V, $R_{SET} = 125$ kΩ, Acceleration = 0 *g*, unless otherwise noted.)

Parameter	Conditions	TPC[1] Graph	ADXL202JE Min	Typ	Max	ADXL202AE Min	Typ	Max	Unit
SENSOR INPUT	Each Axis								
Measurement Range[2]			±2			±2			*g*
Nonlinearity	Best Fit Straight Line			0.2			0.2		% of FS
Alignment Error[3]		X		±1			±1		Degrees
Alignment Error	X Sensor to Y Sensor			0.01			0.01		Degrees
Cross-Axis Sensitivity[4]		X		±2			±2		%
SENSITIVITY	Each Axis								
Duty Cycle per *g*	T1/T2, $V_{DD} = 5$ V	X	10.5	12.5	14.5	10	12.5	15	%/*g*
Duty Cycle per *g*	T1/T2, $V_{DD} = 3$ V	X	9.0	11	13.0	8.5	11	13.5	%/*g*
Sensitivity X_{FILT}, Y_{FILT}	$V_{DD} = 5$ V	X	265	312	360	250	312	375	mV/*g*
Sensitivity X_{FILT}, Y_{FILT}	$V_{DD} = 3$ V	X	140	167	195	140	167	200	mV/*g*
Temperature Drift[5]	Delta from 25°C	X		±0.5			±0.5		%
ZERO *g* BIAS LEVEL	Each Axis								
0 *g* Duty Cycle	T1/T2, $V_{DD} = 5$ V	X	34	50	66	30	50	70	%
0 *g* Duty Cycle	T1/T2, $V_{DD} = 3$ V	X	31	50	69	31	50	69	%
0 *g* Voltage X_{FILT}, Y_{FILT}	$V_{DD} = 5$ V	X	2.1	2.5	2.9	2.0	2.5	3.0	V
0 *g* Voltage X_{FILT}, Y_{FILT}	$V_{DD} = 3$ V	X	1.2	1.5	1.8	1.2	1.5	1.8	V
0 *g* Duty Cycle vs. Supply		X		1.0	4.0		1.0	4.0	%/V
0 *g* Offset vs. Temperature[5]	Delta from 25°C	X		2.0			2.0		m*g*/°C
NOISE PERFORMANCE									
Noise Density	@ 25°C	X		200			200	1000	μ*g*/√Hz rms
FREQUENCY RESPONSE									
3 dB Bandwidth	At Pins X_{FILT}, Y_{FILT}			6			6		kHz
Sensor Resonant Frequency				10			10		kHz
FILTER									
R_{FILT} Tolerance	32 kΩ Nominal			±15			±15		%
Minimum Capacitance	At Pins X_{FILT}, Y_{FILT}		1000			1000			pF
SELF-TEST									
Duty Cycle Change	Self-Test "0" to "1"			10			10		%
DUTY CYCLE OUTPUT STAGE									
F_{SET}	$R_{SET} = 125$ kΩ		0.7		1.3	0.7		1.3	kHz
Output High Voltage	I = 25 μA		V_S – 200 mV			V_S – 200 mV			V
Output Low Voltage	I = 25 μA				200			200	mV
T2 Drift vs. Temperature				50			50		ppm/°C
Rise/Fall Time				200			200		ns
POWER SUPPLY									
Operating Voltage Range			3		5.25	3.0		5.25	V
Quiescent Supply Current				0.6	1.0		0.6	1.0	mA
Turn-On Time	C_{FILT} in μF			160 × C_{FILT} + 0.3			160 × C_{FILT} + 0.3		ms
TEMPERATURE RANGE									
Specified Performance AE						–40		+85	°C
Operating Range			0		70	–40		+85	°C

NOTES
[1]Typical Performance Characteristics.
[2]Guaranteed by measurement of initial offset and sensitivity.
[3]Alignment error is specified as the angle between the true and indicated axis of sensitivity (see TPC 15).
[4]Cross-axis sensitivity is the algebraic sum of the alignment and the inherent sensitivity errors.
[5]Defined as the output change from ambient to maximum temperature or ambient to minimum temperature.
Specifications subject to change without notice.

ABSOLUTE MAXIMUM RATINGS*

Acceleration (Any Axis, Unpowered for 0.5 ms) . . . . . . 1000 *g*
Acceleration (Any Axis, Powered for 0.5 ms) . . . . 500 *g*
$+V_S$ . . . . -0.3 V to +6.0 V
Output Short Circuit Duration, (Any Pin to Common)
. . . . Indefinite
Operating Temperature . . . . -55°C to +125°C
Storage Temperature . . . . -65°C to +150°C

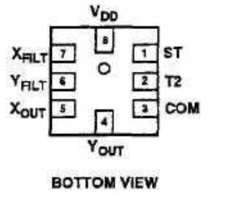
*Stresses above those listed under Absolute Maximum Ratings may cause permanent damage to thè device. This is a stress rating only; functional operation of thè device at these or any other conditions above those indicate in thè operational sections of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

Drops onto hard surfaces can cause shocks of greater than 1000 *g* and exceed thè absolute maximum rating of thè device. Care should be exercised in handling to avoid damage.

Package Characteristics

Package Weight	θ_{JA}	θ_{JC}	Device
8-Lead LCC	120°C/W	tbd°C/W	<1.0 grams

PIN CONFIGURATION



PIN FUNCTION DESCRIPTIONS

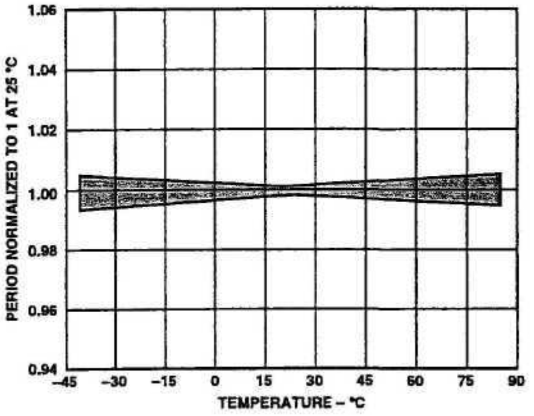
Pin No.	Mnemonic	Description
1	ST	Self-Test
2	T2	Connect R_{SET} to Set T2 Period
3	COM	Common
4	YOUT	Y-Channel Duty Cycle Output
5	XOUT	X-Channel Duty Cycle Output
6	YFILT	Y-Channel Filter Pin
7	XFILT	X-Channel Filter Pin
8	VDD	3 V to 5.25 V

ORDERING GUIDE

Model	No. of Axes	Specified Voltage	Temperature Range	Package Description	Package Option
ADXL202JE	2	**3 V** to **5 V**	0 to 70°C	8-Lead LCC	**E-8**
ADXL202AE	2	**3 V** to **5 V**	-40°C to +85°C	8-Lead LCC	**E-8**

CAUTION.

ESD (electrostatic discharge) sensitive device. Electrostatic charges as high as 4000 V readily accumulate on thè human body and test equipment and can discharge without detection. Although thè ADXL202E features proprietary ESD protection circuitry, permanent damage may occur on devices subjected to high-energy electrostatic discharges. Therefore, proper ESD precautions are recommended to avoid performance degradation or loss of functionality.



TPC 25. Normalized DCM Period (T2) vs. Temperature

DEFINITIONS

TI Length of thè "on"portion of thè cycle.

T2 Length of thè total cycle.

Duty Cycle Ratio of thè "on" tìme (TI) of thè cycle to thè total cycle (T2). Defined as T1AT2 for thè ADXL202E/ ADXL210.

Pulsewidth Time period of thè "on" pulse. Defined as TI for thè ADXL202E/ADXL210.

THEORY OF OPERATION

The ADXL202E is a complete, dual-axis acceleration measurement system on a single monolithic IC. It contains a polysilicon surface-micromachined sensor and signal condMoning circuitry to implement an open loop acceleration measurement architecture. For each axiSj an output circuit converts thè analog signal to a duty cycle modulated (DCM) digitai signal that can be decoded with a counter/timer port on a microprocessor. The ADXL202E is capable of measuring both positive and negative accelerations to at least ±2 *g*. The accelerometer can measure static acceleration forces such as gravity, allowing it to be used as a tilt sensor.

The sensor is a surface micromachined polysilicon structure built on top of thè silicon wafer. Polysilicon springs suspend thè structure over thè surface of thè wafer and provide a resistance against acceleration forces. Deflection of thè structure is measured using a differential capacitor that consists of independent fixed plates and centrai plates attached to thè moving mass. The fixed plates are driven by 180° out of phase square waves. An acceleration will deflect thè beam and unbalance thè differential capacitar, resulting in an output square wave whose amplitude is proportional to acceleration. Phase sensitive demodulation techniques are then used to rectify thè signal and determine thè direction of thè acceleration.

The output of thè demodulator drives a duty cycle modulator (DCM) stage through a 32 kQ resistor. At this point a pin is available on each channel to allow thè user to set thè signal bandwidth of thè device by adding a capacitor. This filtering improves measurement resolution and helps prevent aliasing.

After being low-pass filtered, thè analog signal is converted to a duty cycle modulated signal by thè DCM stage. A single resistor sets thè period for a complete cycle (T2), which can be set between 0.5 ms and 10 ms (see Figure 12). A 0 *g* acceleration produces a nominally 50% duty cycle. The acceleration signal can be determined by measuring thè length of thè TI and T2 pulses with a counter/timer or with a polling loop using a low cost microcontroller.

An analog output voltage can be obtained either by buffering thè signal from thè XFILT and YFILT *P*^m> ^or by passing thè duty cycle signal through an RC filter to reconstruct thè de value.

The ADXL202E will operate with supply voltages as low as 3.0 V or as highas 5.25 V.

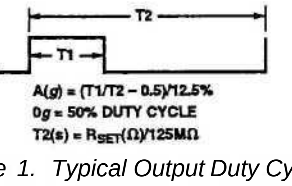


Figure 1. Typical Output Duty Cycle

APPLICATIONS

POWER SUPPLY DECOUPLING

For most applications a single 0.1 uF capacitor, CDC> will adequately decouple thè accelerometer from signal and noise on thè power supply. However, in some cases, especially where digitai devices such as microcontrollers share thè same power supply, digitai noise on thè supply may cause interference on thè ADXL202E output. This may be observed as a slowly undulating fluctuatdon of voltage at XFILT ^sn^ *Ymr-* If additional decoupling is needed, a 100 *D.* (or smaller) resistor or ferrite beads, may be inserted in thè supply line of thè ADXL202R

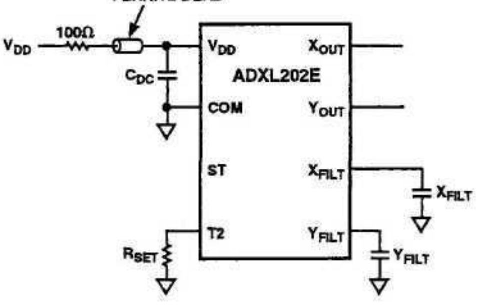


Figure 2.

DESIGN PROCEDURE FOR THE ADXL202E

The design procedure for using thè ADXL202E with a duty cycle output involves selecting a duty cycle period and a filter capacitor. A proper design will take into account thè application requirements for bandwidth, signal resolution and acquisition time, as discussed in thè following sections.

Decoupling **Capacitor** C_{DC}

A 0.1 uF capacitor is recommended from V_{DD} to COM for power supply decoupling.

ST

The ST pin controls thè self-test feature. When this pin is set to V_{DD}, an electrostatic force is exerted on thè beam of thè accelerometer. The resulting movement of thè beam allows thè user to test if thè accelerometer is functional. The typical change in output will be 10% at thè duty cycle outputs (corresponding to 800 m^). This pin may be left open circuit or connected to common in normal use.

Duty Cycle Decoding

The ADXL202E's digitai output is a duty cycle mpdulator. Acceleration is proportional to thè ratio T1/T2. The nominai output of thè ADXL202E is:

0 *g* = 50% *Duty Cycle*

Scale factor is 12.5% Duty Cycle Change per *g*

These nominai values are affected by thè initial tolerance of thè device including zero *g* offset error and sensitivity error.

T2 does not have to be measured for every measurement cycle. It need only be updated to account for changes due to temperature, (a relatively slow process). Since thè T2 time period is shared by both X and Y channels, it is necessary only to measure it on one channel of thè ADXL202E. Decoding algorithms for various microcontroUers have been developed. Consult thè appropriate Application Note.

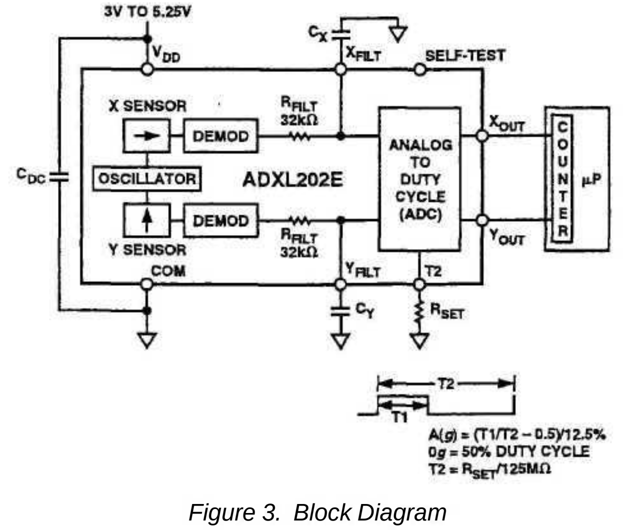


Figure 3. Block Diagram

Setting the Bandwidth Using C_X and C_Y

The ADXL202E has provisions for bandlimiting the X_{FILT} and Y_{FILT} pins. Capacitors must be added at these pins to implement low-pass filtering for antialiasing and noise reduction. The equation for the 3 dB bandwidth is:

$$F_{-3\,dB} = \frac{1}{\left(2\pi(32\ k\Omega)\times C(x,y)\right)}$$

or, more simply, $F_{-3\,dB} = \dfrac{5\,\mu F}{C_{(X,Y)}}$

The tolerance of thè internai resistor (RFILT)J canv&ry typically as much as ±15% of its nominai value of 32 kQ; so thè bandwidth will vary accordingly. A minimum capacitance of 1000 pF for C(x, Y) is required in ali cases.

Table I. Filter Capacitor Selection, C_x and C_y

Bandwidth	Capacitor Value
10 Hz	0.47 µF
50 Hz	0.10 µF
100 Hz	0.05 µF
200 Hz	0.027 µF
500 Hz	0.01 µF
5 kHz	0.001 µF

Setting thè DCM Period with R_{SET}

The period of thè DCM output is set for both channels by a single resistor from RSET to ground. The equation for thè period is:

$$T2 = \frac{R_{SET}\ (\Omega)}{125\ M\Omega}$$

A 125 kQ resistor will set thè duty cycle repetition rate to approximately 1 kHz, or 1 ms. The device is designed to operate at duty cycle periods between 0.5 ms and 10 ms.

Table II. Resistor Values to Set T2

T2	R_{SET}
1 ms	125 kΩ
2 ms	250 kΩ
5 ms	625 kΩ
10 ms	1.25 MΩ

Note that thè RSET should always be included, even if only an analog output is desired. Use an RSET value between 500 kQ and 2 MQ when takdng thè output from XHLT or YFILT- The RSET resistor should be piace dose to thè T2 Pin to minimize parasitic capacitance at this node.

Selecting **thè** Right Accelerometer

For most tilt sensing applications thè ADXL202E is thè most appropriate accelerometer. Its higher sensitivity *(12.5%/g)* allows thè user to use a lower speed counter for PWM decoding while maintaining high resolution. The ADXL210 should be used in applications where accelerations of greater than ±2 *g* are expected.

MICROCOMPUTERINTERFACES

The ADXL202E is specifically designed to work with low-cost microcontrollers. Specific code sets, reference designs, and application notes are available from thè factory. This section will outline a generai design procedure and discuss thè various trade-offs that need to be considered.

The designer should have some idea of thè required performance of thè system in terms of:

Resolution: thè smallest signal change that needs to be detected.

Bandwidth: thè highest frequency that needs to be detected.

Acquisìtion Time, thè time that will be available to acquire thè signal on each axis.

These requirements will help to determine thè accelerometer bandwidth, thè speed of thè microcontroller clock and thè length of thè T2 period.

When selecting a microcontroller it is helpful to have a counter timer port available. The microcontroller should have provisions for software calibration. While thè ADXL202E is a highly accurate accelerometer, it has a wide tolerance for initial offset. The easiest way to nuli this offset is with a calibration factor saved oh thè microcontroller or by a user calibration for zero *g*. In thè case where thè offset is calibrated during manufacture, there are several options, including esternai EEPROM and microcontrollers with "one-time programmable" features.

DESIGN TRADE-OFFS FOR SELECTING FDLTER CHARACTERISTICS: THE NOISE/BW TRADE-OFF

The accelerometer bandwidth selected will determine thè measurement resolution (smallest detectable acceleration). Filtering canbe used to lower thè noise floor and improve thè resolution of thè accelerometer. Resolution is dependent on both thè analog filter bandwidth at XFILT *an*^ YHLT **&&* on thè speed of thè microcontroller counter.

The analog output of thè ADXL202E has a typical bandwidth of 5 kHz, while thè duty cycle modulators' bandwidth is 500 Hz. The user must filter thè signal at this point to limit aliasing errors. To minimize DCM errors thè analog bandwidth should be less than 1/10 thè DCM frequency. Analog bandwidth may be increased to up to 1/2 thè DCM frequency in many applications. This will result in greater dynamic error generated at thè DCM.

The analog bandwidth may be further decreased to reduce noise and improve resolution. The ADXL202E noise has thè characteristics of white Gaussian noise that contributes equally at ali frequencies and is described in terms of Ụ£ per root Hz; i.e., thè noise is proportional to thè square root of thè bandwidth of thè accelerometer. It is recommended that thè user limit bandwidth to thè lowest frequency needed by thè application$_5$ to maximize thè resolution and dynamic range of thè accelerometer.

With thè single pole roll-off characteristic, thè typical noise of thè ADXL202E is determined by thè following equatión:

$$Noise\,(rms) = \left(200\ \mu g/\sqrt{Hz}\right) \times \left(\sqrt{BW \times 1.6}\right)$$

At 100 Hz the noise will be:

$$Noise\,(rms) = \left(200\ \mu g/\sqrt{Hz}\right) \times \left(\sqrt{100 \times (1.6)}\right) = 2.53\ mg$$

Often thè peak value of thè noise is desired. Peak-to-peak noise can only be estimated by statistica! methods. Table IH is useful for estimating thè probabilities of exceeding various peak values, given thè nns value.

Table DI. Estimation of Peak-to-Peak Noise

Nominai Peak-to-Peak Value	% of Time that Noise Will Exceed Nominai Peak-to-Peak Value
2.0 **x** rms	32%
4.0 x rms	4.6%
6.0 x rms	0.27%
8.0 x rms	0.006%

The peak-to-peak noise value will give thè best estimate of thè uncertainty in a single measurement.

Table IV gives typical noise output of thè ADXL202E for various Cx and Cy values.

Table IV. Filter Capacitor Selection, C_x and C_Y

Bandwidth	CXJ Cy	rms Noise	Peak-to-Peak Noise Estimate 95% Probabflity (rms x 4)
lOHz	0.47 µF	**0.8 m^**	**3.2** *mg*
50 Hz	0.10 µF	**1.8** *mg*	**7.2** *mg*
100 Hz	0.05 pF	*2.5 mg*	**10.1** *mg*
200 Hz	0.027 µF	*3.6 mg*	**14.3 m^**
500 Hz	0.01 µF	*5.1 mg*	**22.6** *mg*

CHOOSING T2 AND COUNTER FREQUENCY: DESIGN TRADE-OFFS

The noise level is one determinant of accelerometer resolution. The second relates to thè measurement resolution of thè counter when decoding thè duty cycle output.

The ADXL202E's duty cycle converter has a resolution of approximately 14 bits; better resolution than thè accelerometer itself. The actual resolution of thè acceleration signal is, however, limited by thè time resolution of thè counting devices used to decode thè duty cycle. The faster thè counter clock, thè higher thè resolution of thè duty cycle and thè shorter thè T2 period can be for a given resolution. The following table shows some of thè trade-offs. It is important to note that this is thè resolution due to thè microprocessors' counter. It is probable that thè accelerometer's noise floor may set thè lower limit on thè resolution, as discussed in thè previous section.

Table V. Trade-Ofis Between Microcontroller Counter Rate, T2 Period, and Resolution of Duty Cycle Modulator

T2(ms)	RSET (MI)	ADXL202E Sample Rate	Counter-Clock Rate (MHz)	Counts perT2 Cycle	Counts per^	Resolution (mg)
1.0	124	1000	2.0	2000	250	**4.0**
1.0	124	1000	1.0	1000	125	8.0
LO	124	1000	0.5	500	62.5	16.0
5.0	625	200	2.0	10000	1250	0.8
5.0	625	200	1.0	5000	625	1.6
5.0	625	200	0.5	2500	312.5	3.2
10.0	1250	100	2.0	20000	2500	0.4
10.0	1250	100	1.0	10000	1250	0.8
10.0	1250	100	0.5	5000	625	1.6

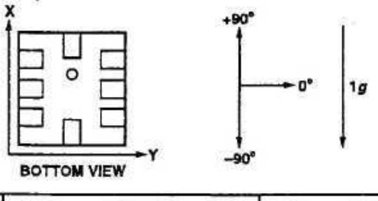
STRATEGBES FOR USING THE DUTY CYCLE OUTPUT WTIH MICROCONTROLLERS

Application notes outlining various strategies for using thè duty cycle output with low cost microcontrollers are available firom thè factory.

USING THE ADXL202E AS A DUAL-AXIS TILT SENSOR

One of thè most popular applicatìons of thè ADXL202E is tilt measurement. An accelerometer uses thè force of gravity as an input vector to determine orientation of an objea in space.

An accelerometer is most sensitive to tilt when its sensitive axis is perpendicular to thè force of gravity, Le., parallel to thè earth's surface. At this orientation its sensitivity to changes in tilt is highest. When thè accelerometer is oriented on axis to gravity, i.e., near its +1 *g* or -1 *g* reading, thè change in output acceleration per degree of tilt is negligjble. When thè accelerometer is perpendicular to gravity, its output will change nearly 17.5 rn^per degree of tilt, but at 45° degrees it is changing only at 12.2 *mg* per degree and resolution declines. The following table illustrates thè changes in thè X and Y axes as thè device is tilted ±90° through gravity.



«Axis Orientation to Horizon *Ci*	X Output		Y Output <g)	
	X Output (g)	A per Degree of Tllt(mg)	Y Output (g)	Aper Degree of Tilt (mg)
-90	-1.000	-0.2	0.000	17.5
-75	-0.966	4.4	0.259	16.9
-60	-0.866	8.6	0.500	15.2
-45	-O.7O7	*112*	0.707	12.4
-30	-0.500	15X1	0.866	8.9
-15	-0.259	16.8	0.966	4.7
0	0.000	175	1.000	0.2
15	0.259	16.9	0.96E	-4.4
30	0.500	155	0.866	-8.6
45	0.707	12.4	0.707	-12.2
60	0.866	*es*	0.500	-15.0
75	0.966	4.7	0.259	-16.8
90	1.000	0.2	0.000	-17.5

Figure 4. How thè X and Y Axes Respond to Changes in Tilt

A DUAL AXIS TILT SENSOR: CONVERTING ACCELERATION TO TILT

When thè accelerometer is oriented so both its X and Y axes are parallel to thè earth's surface it can be used as a two axis tilt sensor with a roll and a pitch axis. Once thè output signal from thè accelerometer has been converted to an acceleration that varies between -1 *g* and +1 *g*, thè output tilt in degrees is calculated as follows:

Pitch = ASIN (4x11 g)
Roti. = ASIN {Ayll g)

Be sure to account for overranges. It is possible for thè accelerometers to output a signal greater than ± 1 *g* due to vibration, shock or other accelerations.

MEASURING 360° OF TILT

It is possible to measure a full 360° of orientation through gravity by using two accelerometers oriented perpendicular to one another (see Figure 5). When one sensor is reading a maximum change in output per degree, thè other is at its minimum.

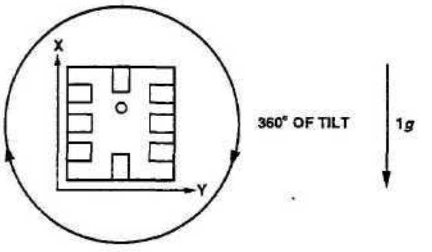


Figure 5. Using a Two-Axis Accelerometer to Measure 360° of Tilt

USING THE ANALOG OUTPUT

The ADXL202E was specifically designed for use with its digitai outputs, but has provisions to provide analog outputs as well.

Duty Cycle Filtering

An analog output can be reconstrueted by filtering thè duty cycle output. This technique requires only passive components. The duty cycle period (T2) should be set to <1 ms. An RC filter with a 3 dB point at least a factor of > 10 less than thè duty cycle frequency is connected to thè duty cycle output. The filter resistor should be no less than 100 kQ to prevent loading of thè output stage. The analog output signal will be ratiometric to thè supply voltage. The advantage of this method is an output scale factor of approximately doublé thè analog output. Its disadvantage is that thè frequency response will be lower than when using thè X_{FILT}, YFILT output.

X_{FILT}, Y_{ITLT} Output

The second method is to use thè analog output present at thè XHLT and YFILT P*11- Unfortunately, these pins have a 32 kQ output impedance and are not designed to drive a load directly. An op amp follower may be required to buffer this pin. The advantage of this method is that thè full 5 kHz bandwidth of thè accelerometer is available to thè user. A capacitor stili must be added at this point for filtering. The duty cycle converter should be kept running by using R_{SET} <10 *MD.*. Note that thè accelerometer offset and sensitivity are ratiometric to thè supply voltage. The offset and sensitivity are nominally:

0 *g* Offset = $V_{DD}/2$

ADXL202E Sensitivity = (60 mV x V_s)/*g*

Magnetic Field Sensor KMZ52

FEATURES

- High sensitivity
- Integrated compensation coil
- Integrated set/reset coil.

APPLICATIONS

- Navigation
- Current and earth magnetic field measurement
- Traffio detection.

DESCRIPTION

The KMZ52 is an extremely sensitive magnetic field sensor, employing thè magnetoresistive effect of ìhin-film permalloy. The sensor contains two magnetoresistive Wheatstone bridges physically offset from one another by 90° and integrated compensation and set/reset coils. The integrated compensation coils allow magnetic field measurement with current feedback loops to generate outputs that are independent of drift in sensitivity. The orientation of sensitivity may be set or changed (flipped) by means of thè integrated set/reset coils. A short current pulse should be applied to thè compensation coils to recover (set) thè sensor after exposure to strong disturbing magnetic fields. A negative current pulse will reset thè sensor to reversed sensitivity. By use of periodically alternated flipping pulses and a lock-in amplifier, thè output is made independent of sensor and amplifier offset.

PINNING

SYMBOL	PIN	DESCRIPTION
+Ifiip2	1	flip coil
VcC2	2	bridge supply voltage
GND2	3	ground
+'comp2	4	compensation coi!
GND1	5	ground
+'comp1	6	compensation coil
"'compì	7	compensation coil
-Voi	8	bridge output voltage
$+V_{o1}$	9	bridge output voltage
-Iflipi	10	flip coil
+'fiip1	11	flip coil
Veci	12	bridge supply voltage
~'comp2	13	compensation coil
$-V_O2$	14	bridge output voltage
$+V_02$	15	bridge output voltage
-Iflip2	16	flip coil

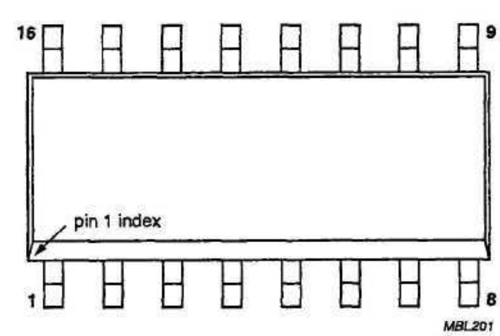


Fig.1 SimplifiedoutlineSOT109-1.

QUICK REFERENCE DATA

SYMBOL	PARAMETER	MIN.	TYP.	MAX.	UNIT
V_{CC}	bridge supply voltage	–	5	8	V
S	sensitivity (uncompensated)	12	16	–	$\frac{mV/V}{kA/m}$
V_{offset}	offset voltage per supply voltage	−1.5	0	+1.5	mV/V
R_{bridge}	bridge resistance	1	2	3	kΩ
R_{comp}	compensation coil resistance	100	170	300	Ω
A_{comp}	field factor of compensation coil; note 1	19	22	25	$\frac{A/m}{mA}$
R_{flip}	resistance of set/reset coil	1	2	3	Ω
I_{flip}	recommended flipping current for stable operation; note 2	±800	±1000	±1200	mA
t_{flip}	flip pulse duration; note 2	1	3	100	µs

Notes

1. The compensation coi) generates a field $H_{comp} = A_{comp} \times I_{comp}$ in addition to thè extemal field H_{ex}t- Sensor output will become zero if H_{ex}t = Hco_{m}p.
2. Average power consumption of thè flipping coil, defined by current, pulse duration and pulse repetition rate may not exceed thè specified limit, see Chapter "Limiting values".

LIMITING VALUES

In accordance with thè Absolute Maximum System (IEC 60134).

SYMBOL	PARAMETER	MIN.	MAX.	UNIT
Vcc	bridge supply voltage	-	8	**V**
Ptot	total power dissipation	-	130	**mW**
Tstg	Storage temperature	-65	+150	**°C**
T_{amb}	maximum operating temperature	-40	-125	**°C**
I_{comp}	maximum compensation current	-	15	**mA**
Iflip (max)	maximum flipping current	-	1500	**mA**
Pflip (max)	maximum flipping power dissipation	-	50	**mW**
V_{is}o.	voltage between isolated systems: flip coil and Wheatstone bridge; compensation coil and Wheatsone bridge; flip coil and compensation coil	–	60	**V**

THERMAL CHARACTERISTICS

SYMBOL	PARAMETER	VALUE	UNIT
Rthj-a	terminal resistance from junction to ambient	105	**K/W**

CHARACTERISTICS

T_{bridge} = 25 °C; V_{CC1} = V_{CC2} = 5 V; unless otherwise specified.

SYMBOL	PARAMETER	CONDITIONS	MIN.	TYP.	MAX.	UNIT
V_{CC}	bridge supply voltage	note 1	–	5	8	V
H	field strength operating range in sensor plane		−0.2	–	+0.2	kA/m
S	sensitivity	open circuit	12	16	–	$\frac{mV/V}{kA/m}$
TCS	temperature coefficient of sensitivity	T_s = −25 to +125 °C	–	0.31	–	%/K
k_{SX}	sensitivity synchronism	note 2	92	100	108	%
TCV_O	temperature coefficient of output voltage	V_{CC} = 5 V; T_{bridge} = −25 to +125 °C	–	−0.4	–	%/K
R_{bridge}	bridge resistance	note 3	1	2	3	kΩ
TCR_{bridge}	temperature coefficient of bridge resistance	T_{bridge} = −25 to +125 °C; note 4	–	0.3	–	%/K
V_{offset}	offset voltage per supply voltage		−1.5	0	+1.5	mV/V
TCV_{offset}	temperature coefficient of offset voltage	T_{bridge} = −25 to +125 °C; note 5	−3	0	+3	$\frac{\mu V/V}{K}$
FH	hysteresis of output voltage		–	–	2	%FS
R_{comp}	resistance of compensation coil	note 6	100	170	300	Ω
A_{comp}	field factor of compensation coil		19	22	25	$\frac{A/m}{mA}$
R_{flip}	resistance of set/reset coil	note 7	1	2	3	Ω
TCR_{flip}	temperature coefficient of resistance of set/reset coil	T_{flip} = −25 to +125 °C	–	0.39	–	%/K
I_{flip}	recommended flipping current for stable operation		±800	±1000	±1200	mA
t_{flip}	flip pulse duration		1	3	100	µs
R_{isol}	isolating resistance	note 8	1	–	–	MΩ
V_{isol}	voltage between isolated systems	note 8	–	–	50	V
R_{isol_dice}	isolating resistance between dice	die 1 to die 2	1	–	–	MΩ
f	operating frequency		0	–	1	MHz
α	angle die-to-die	note 9	88	90	92	deg
β	angle dice-to-package	note 9	−5	0	+5	deg

Notes

1. Due to the ratiometric output, the same supply voltage (V_{CC}) must be applied to both dice in one KMZ52 device.
2. $k_{SX} = 100 \times \frac{A_{comp1} \times S_1}{A_{comp2} \times S_2}\%$
3. Bridge resistance die 1: between pins 5 and 12; bridge resistance die 2: between pins 2 and 3.
4. $TCR_{bridge} = 100\,\frac{R_{bridge(T_2)} - R_{bridge(T_1)}}{R_{bridge(T_1)}\,(T_2 - T_1)}$ Where T_1 = −25°C; T_2 = 125°C.

5. $TCV_{offset} = \frac{V_{offset(T_2)} - V_{offset(T_1)}}{(T_2 - T_1)}$ Where T_1 = −25°C; T_2 = 125°C.
6. Resistance of compensation coil die 1: between pins 6 and 7; resistance of compensation coil die 2: between pins 4 to 13.
7. Resistance of set/reset coil die 1: between pins 10 and 11; resistance of set/reset coil die 2: between pins 1 to 16.
8. Isolating resistance die 1: pins 7 and 8, 7 and 10 and 8 to 10; isolating resistance die 2: pins 1 to 2, 1 to 4 and 2 to 4.
9. Angle die-to-die: die 2 is turned by 90 ±2 degrees in anticlockwise direction with respect to die 1; angle dice-to-package: both dice in their fixed die-to-die position are tilted towards the package edges by 0 ±5 degrees.

1. INTRODUCTION

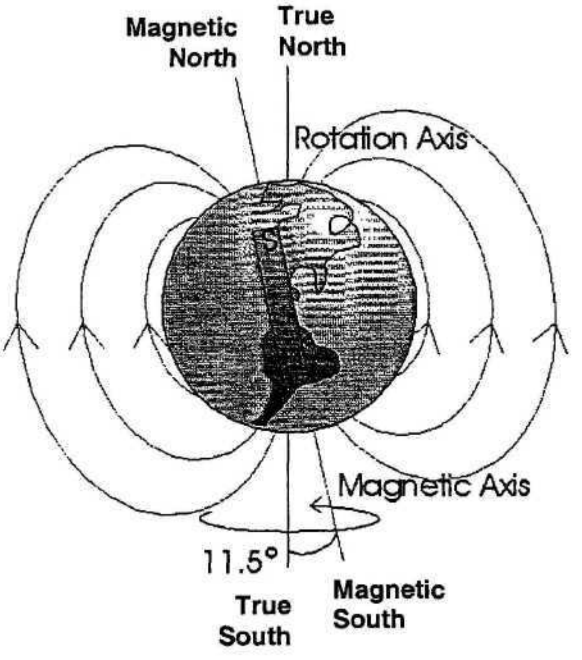
The magnetic compass is a cruciai navigation tool in many areas, even in times of thè globai positioning System (GPS). Replacing the "old" magnetic needle compass or the gyrocompass by an electronic solution offers advantages like having a solid-state component without moving parts and thè ease of interfacing with other electronic systems.

For the magnetic field sensors within a compass System, thè magnetoresistive (MR) technology is thè preferable solution. Compared to flux-gate sensors, which could be found in most electronic compasses until now, the MR technology offers a much more cost effective solution, as it requires no coils to be wound and can be fabricated in an IC-like process. Due to their higher sensitivity, MR sensors are also superior to Hall elements in this application field.

The intention of this paper is to give a generai introduction of electronic compass design with MR sensors and also to give detailed realization hints. Therefore, the basic characteristics of thè earth's magnetic field are explained and an overview of thè building blocks of an electronic compass is given. Following a description of Philips' magnetoresistive sensors for compass applications, the design of each building block is covered in detail. Here, both hardware and software realisations are shown. Further sections are dedicated to special items like interference field calibration, true north calibration, tilt compensation and System accuracy. Finally, examples for complete compass systems are given, consisting of previously described building blocks.

2. EARTH'S MAGNETIC FIELD

The magnetic field of the earth is the physical quantity to be evaluated by a compass. Thus, an understanding of its basic properties is required, when designing a compass. Figure 1 gives an illustration of thè field shape.



EARTHFLD.GIF

Figure 1 Earth´s magnetic field

The magnetic field strength on the earth varies with location and covers the range from about 20 to 50 A/m. An understanding of thè earth's field shape can be gained, if it is assumed to be generated by a bar magnet within thè earth, as pointed out in Figure 1. The magnetic field lines point from thè earth's south pole to its north pole. Fig. 1 indicates, that this is opposite to the physical convention for thè poles of a bar magnet (thè background is a historical one, in that a bar magnet's north pole has been defined as that pole, that points towards north in thè earth's magnetic field). The field lines are perpendicular to thè earth surface at thè poles and parallel at thè equator. Thus, thè earth field points downwards in thè northern hemisphere and upwards in thè southern hemisphere. An important fact is, that thè magnetic poles do not coincide with thè geographical poles, which are defined by thè earth's axis of rotation. The angle between thè magnetic and thè rotation axis is about 11.5°. As a consequence, thè magnetic field lines do not exactly point to geographic or Ime" north.

Figure 2 gives a 3-D representation of thè earth field vector He at some point on thè earth. This illustration allows to define thè quantities, which are of importance for a compass. Here, thè x- and y-coordinates are parallel to thè earth's surface, whereas thè z-coordinate points vertically downwards.

- **Azimuth** a
  The angle between magnetic north and thè heading direction. Magnetic north is thè direction of Heh, thè earth's field component perpendicular to gravity. Throughout this paper, Heh will be referred to as "horizontal" component of thè earth's field. Figure 2 shows, that:

$$\alpha = arctan\frac{Hey}{Hex} \qquad (1)$$

The azimuth is thè reading quantity of a compass. Throughout this paper, a is counted clockwise from magnetic north, i.e. north is 360° or 0°, east ìs 90°, south is 180°, west is 270°.

- **Inclination or dip** 5
  The angle between thè earth's field vector and thè horizontal piane. As already pointed out, thè inclination varies with thè actual location on earth, being zero at thè equator and approaching ±90° near thè poles. If a compass is tilt, then inclination has to be considered, as explained in section 9.
- **Declination** *X*
  The angle between geographic or true north and magnetic north. Declination is dependent on thè actual position on earth. It also has a long term drift. Declination can be to thè east or to thè west and can reach values of about ±25°. The azimuth measured by a compass has to be corrected by thè declination in order to find thè heading direction with respeet to geographic north. This is pointed out in section 8.

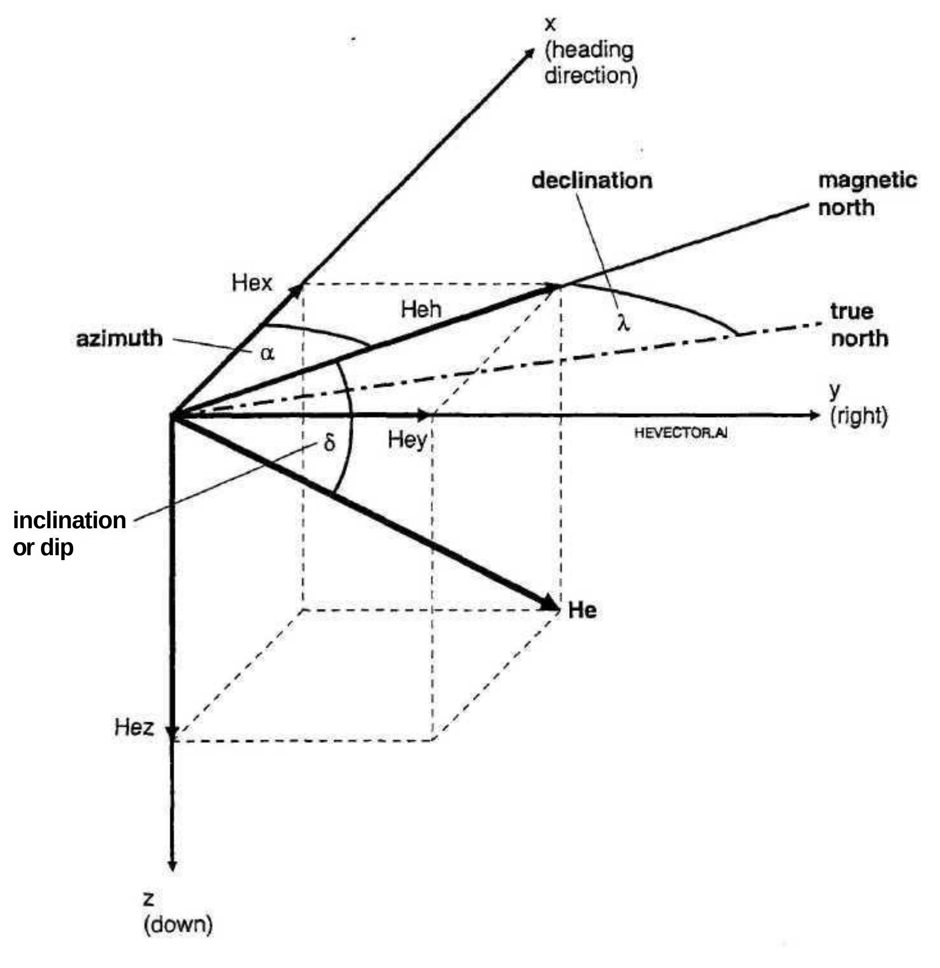


Figure 2 Earth field vector