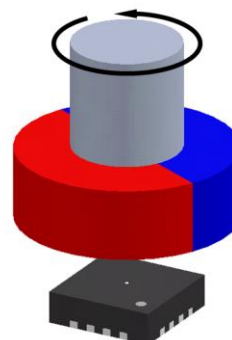# MagAlpha
MA700

Angular Sensor for Position Control with Side-Shaft Positioning Capability

Key features

11 bit resolution absolute angle encoder

500 kHz refresh rate

Ultra low latency: 3 µs

Serial interface for data readout and settings

10 bit incremental output (A,B,Z)

Built-in linearization for side-shaft mounting

7.5 mA supply current

QFN-16 3x3mm Package

General Description

The MagAlpha MA 700 is a robust contactless angle encoder. The IC detects the absolute angular position of a permanent magnet, typically a diametrically magnetized cylinder attached to the rotor. The MagAlpha is an extremely fast acquisition and processing sensor, allowing accurate angle measurement at speeds from 0 to 120'000 RPM.

Since the measurement is spatially confined, the user has flexibility in terms of magnet shapes and configurations. This can help relaxing mechanical tolerances and, in case the end of shaft position is not available, the MagAlpha 700 can also operate away from the axis of rotation ("side-shaft" mounting).
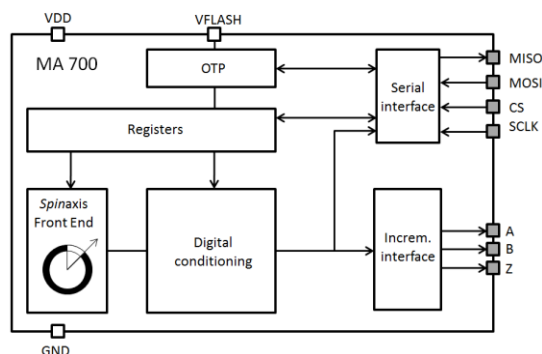

Figure 1: Functional Block Diagram

1. Specifications

TABLE 1 OPERATING CONDITIONS

Parameters	Symbol	Min	Typ	Max	Unit
Supply voltage	VDD	3.0	3.3	3.6	V
Supply current	Isup	5.7	6.6	8.0	mA
Supply voltage for OTP flashing	Vflash	3.6		3.8	V
Supply current for OTP flashing[1]	Iflash	50		100	mA
Operating temperature	Top	-40		125	°C
Applied magnetic field	B	30	75	150	mT

(1) See section 11 for more details about the supply circuit for OTP flashing.

TABLE 2 SENSOR OUTPUT SPECIFICATIONS

Measurement conditions: VDD = 3.3 V, 50 mT < B < 100 mT, Temp = -40 .. +125°C, unless otherwise noted

Parameters	Min	Typ	Max	Unit	Remark
Power up time		2	3	ms	
INL	+/- 0.7	+/- 1.5	+/-2.5	deg	
Output drift					
Temperature induced	+/-0.005	+/-0.008	+/-0.05	deg/°C	
Magnetic field induced	-0.005	-0.01	-0.025	deg/mT	
Voltage supply induced	0.0007	0.001	0.005	deg/mV	
Absolute output - serial					
Data output length	16		16	bit	
Refresh rate	500	520	550	kHz	
Latency	2	3	4	µs	
Resolution (3σ noise level)	10.5	11.0	11.5	bit	
Incremental output					
Resolution	1024		1024	edge/revol.	
Jitter		10		% of a period	
Hysteresis			0.35	deg	
Digital I/O					
Threshold voltage High		1.75		V	
Threshold voltage Low		1.05		V	
Rising edge slew rate		0.7		V/ns	CL = 50 pF
Falling edge slew rate		0.7		V/ns	CL = 50 pF

2. Timing of the Serial Interface

The data link is a 4-wire serial bus, conmplying to the Serial Peripheral Interface (SPI) usual convention shown in Table 3 and Table 4.The MagAlpha sensor operates as slave. During one transmission a 16 bit word can be simultaneously sent to the sensor (MOSI pin) and received from the sensor (MISO pin). Note that it is possible to receive 24 bits of data (16 bits for the angle and 8 bits for a time index). See section 10 "Output Signals" for details.
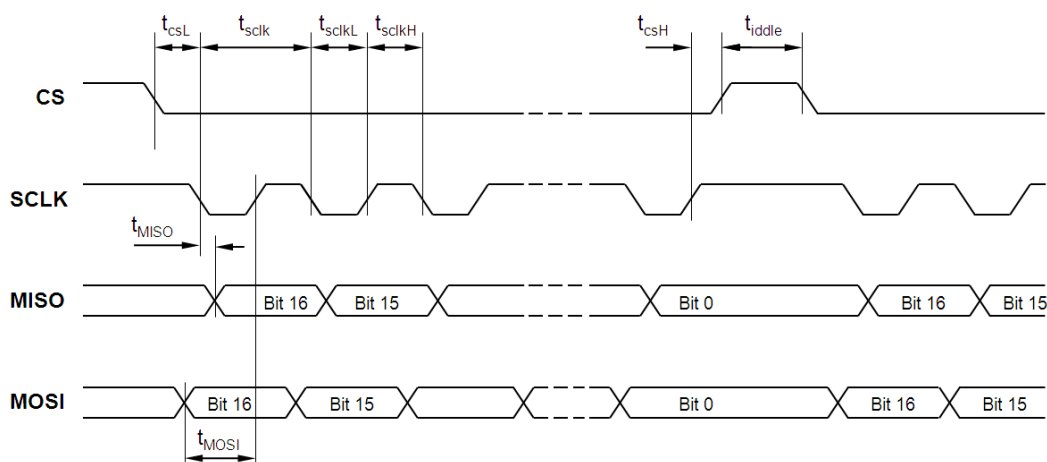

Figure 2: SPI Timing Diagram

TABLE 3 SPI SPECIFICATION	
SCLK idle state	High
SCLK readout edge	Rising
CS idle state	High
Data order	MSB first

TABLE 4 SPI STANDARD	
CPOL	1
CPHA	1
MODE	3
DORD	0

TABLE 5 SPI TIMING

Parameter	Description	Min	Max	Unit
t_{idle}	Time between two subsequent transmissions	20		ns
t_{csL}	Time between CS falling edge and SCLK falling edge	25		ns
t_{sclk}	SCLK period	40		ns
t_{sclkL}	Low level of SCLK signal	20		ns
t_{sclkH}	High level of SCLK signal	20		ns
t_{csH}	Time between SCLK rising edge and CS rising edge	25		ns
t_{MOSI}	Data input valid to SCLK reading edge	15		ns
t_{MISO}	SCLK setting edge to data output valid		15	ns

3. Registers

TABLE 6 REGISTER MAP

No	Hex	Bin	Bit 7 MSB	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0 LSB
		Register address								
3	0x3	0011	BCT(7:0)							
4	0x4	0100	Z(11:4)							
5	0x5	0101	0	0	ETY	ETX	Z(3:0)			
9	0x9	1001	-	-	F5	F4	F3	-	-	-

TABLE 7 PROGRAMMING PARAMETERS

| Parameters	Symbol	Number of bit	Brief description	See table
Bias Current Trimming	**BCT**	8	For side-shaft configuration: reduce the Hall device bias current of X- and/or Y-axis	9
Zero setting	**Z**	12	Set the zero position	11
Enable Trimming X	**ETX**	1	When enabled, the X-axis bias current is trimmed by the quantity BCT	10
Enable Trimming Y	**ETY**	1	When enabled, the Y-axis bias current is trimmed by the quantity BCT	10
Flash register *n*	**F*n***	1	Flash the content of register number *n*	

4. Pin Configuration
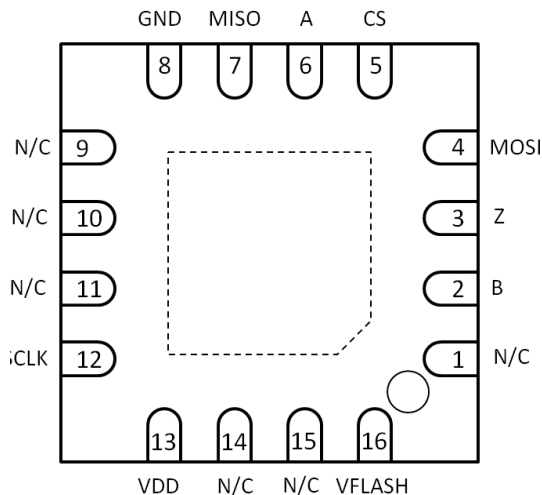
Figure 3: QFN-16 Top View

TABLE 8 PIN FUNCTIONS

No	Name	Function
1	N/C	-
2	B	B (incremental output)
3	Z	Z (incremental output)
4	MOSI	Data in (serial)
5	CS	Chip Select (serial)
6	A	A (incremental output)
7	MISO	Data out (serial)
8	GND	Ground
9	N/C	-
10	N/C	-
11	N/C	-
12	SCLK	Clock (serial)
13	VDD	3.3 V supply
14	N/C	-
15	N/C	-
16	VFLASH	3.6 V supply for OTP flashing

5. Sensor – Magnet Mounting

The sensitive volume of the MA 700 is confined in a region less than 100 μm wide and consists of multiple integrated Hall devices. This volume is located, with a precision of 50 μm in the center of the QFN package, both horizontally and vertically. The sensor detects the angle of the magnetic field projected in a plane parallel to the package upper surface. It means that the only magnetic field that matters is the *in-plane* component (X and Y components) in the package middle point.
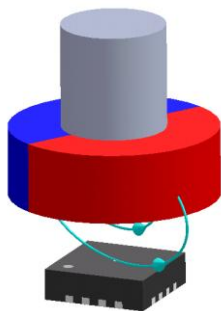
This detection mode gives flexibility for the design of an angular encoder: all the sensor needs is that the magnetic vector lies essentially within the sensor plane and that its amplitude is comprised between 30 and 150 mT. Note that the MA 700 does work with smaller than 30 mT fields, but the linearity and resolution performance may deviate from the specifications (table 2). The straightforward solution is to place the MA 700 sensor on the rotation axis of a permanent magnet for instance a cylinder diametrically magnetized (see Figure 4).

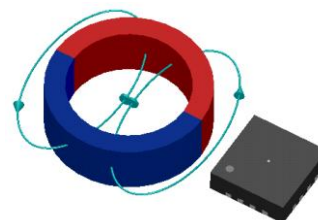
Figure 4: End-of-Shaft Mounting

Figure 5: Side-Shaft Mounting

When the end-of-shaft position is not available the sensor can be positioned away from the rotation axis of a cylinder or ring magnet (see Figure 5). In this case the magnetic field angle is not directly proportional to the mechanical angle anymore. The MA 700 can be adjusted to compensate this effect and recover the linear relation between the mechanical angle and the sensor output. With multiple pole pairs, the MA 700

will indicate multiple rotations for each mechanical turn.

6. Power Supply Decoupling

For most applications, a single 100 nF bypass capacitor placed close to the supply pins sufficiently decouples the MA 700 from noise of the power supply. If better decoupling is required, a larger capacitor (10 µF) can be added in parallel with the 100 nF, and/or a resistor (10Ω) can be added between the supply line and the capacitor node.

In any case, make sure that the connection between the MA 700 ground and the power supply ground has a low impedance, in order to avoid noise transmitted from the ground.

VFLASH needs to be supplied only when flashing the memory. Otherwise the VFLASH pin can remain unconnected or grounded (see Figure 6).
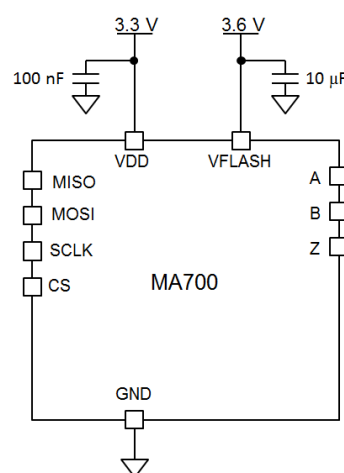
Figure 6: Connection for Supply Decoupling

7. Sensor Front-End

The magnetic field is detected with integrated Hall devices located in the package center. The particularity of this sensor is that the angle is measured using the *spin*axis method which directly digitizes the direction of the field without any ATAN computation or any feedback loop based circuit (interpolators, etc.).

The *spin*axis method is based on *phase detection*. It requires a sensitive circuitry generating a sinusoidal signal whose *phase* represents the angle of the magnetic field. The angle is then retrieved by a time-to-digital converter, which counts the time between the zero crossing of the sinusoidal signal and the edge of a constant waveform (see Figure 7). The digitized time is the front-end output.
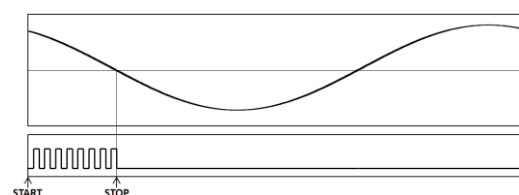
Figure 7: Phase Detection Method. Top: Sine Waveform. Bottom: Clock of Time-to-Digital Converter.

Looking further down the treatment chain, it is crucial that the signal treatment does not add unwanted phase shifts. For this purpose the MagAlpha incorporates an architecture where these shifts are automatically compensated, resulting in the stability displayed in

Table 2. In short, the front-end delivers in a straightforward and open loop manner a digital number proportional to the angle of the magnetic field at the rate of 500 kHz.

Side-Shaft

The default current biasing of the Hall devices can be adjusted by programming in order to accommodate low field or compensate non-linearities inherent to side-shaft configurations.
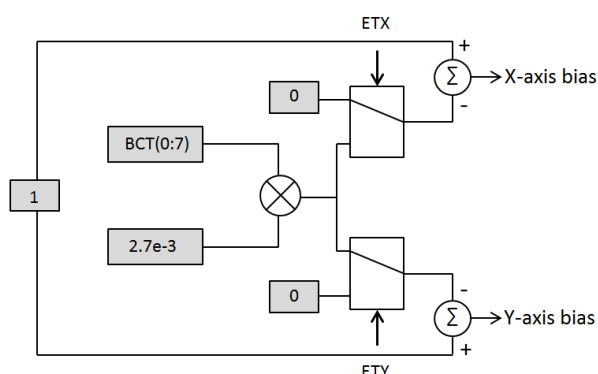

Figure 8: Hall Devices Biasing Diagram

In case the MA700 gets mounted in side-shaft configuration, the relation between the field angle and the mechanical angle is not directly linear anymore. This effect is related to the fact that the tangential magnetic field is usually smaller than the radial field. We define the field ratio k as:

$$k = B_{rad}/B_{tan},$$

where B_{rad}, respectively B_{tan}, is the maximum radial, respectively tangential, magnetic field (see Figure 9).
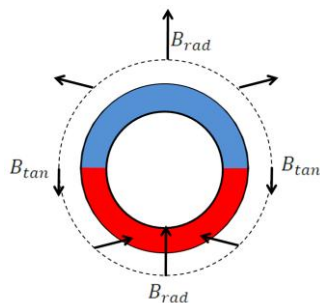

Figure 9: Side-Shaft Field

The ratio k depends on the magnet geometry and the distance to the sensor.

The X-axis or the Y-axis bias current can be reduced in order to recover an equal Hall signal for all angles and therefore suppress the non-linearity. The current reduction is set by the parameter Bias Current Trimming BCT(7:0), which is an integer from 0 to 255. For an optimum compensation the radial axis should be reduced by the quantity:

$$BCT(7:0) = \frac{255}{0.667}\left(1 - \frac{1}{k}\right)$$

TABLE 9 EXAMPLE OF OPTIMUM BCT SETTING

BCT(7:0)	Magnet ratio k
0	1
1	1.003
…	…
128	1.50
…	…
255	3.00

From the dot printed on the package it is possible to know whether the radial field is detected by the sensor X or Y component (see Figure 10).
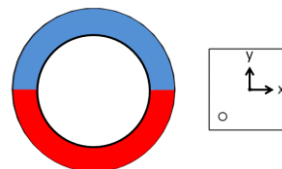

Figure 10: Package Top View with X and Y Axes

First the user must determine which axis needs to be reduced (see the qualitative field distribution around a ring in Figure 9). For instance, with the arrangement depicted in Figure 8, the X-axis should be reduced. Then the parameter ETX or ETY can be set. Note that if both ETX and ETY are set to 1 the current bias will be reduced in both directions the same way, i.e. without side-shaft correction.

TABLE 10 ETX AND ETY

ETX	Enable trimming the X axis
0	Disabled
1	Enabled
ETY	**Enable trimming the Y axis**
0	Disabled
1	Enabled

8. Digital Signal Conditioning

Digital Filtering

Advanced digital filtering allows improving the resolution without adding latency. The principle is to measure the rotation *speed* over the last 512 data points in addition to the angular position to provide an evaluation of the present position with the best possible accuracy. This principle gives a lag-free position at constant speed.

Zero setting

The zero position of the MagAlpha, α_0, can be programmed with 12 bit of resolution. The angle streamed out, α_{out}, is given by:

$$\alpha_{out} = \alpha_{fe} - \alpha_0,$$

where α_{fe} is the raw angle, out of the front-end. The parameter Z(11:0), which is 0 by default, determines α_0 (see Table 18). This setting is valid for all output formats: SPI, ABZ and UVW.

TABLE 11 ZERO POSITION

Z(11:0)	Zero position α_0(deg)
0	0
1	0.088
…	…
4095	359.912

Rotation direction

Looking at the MagAlpha top, the angle increases when the magnetic field rotates clockwise.

9. Programming the MA700

The MA700 incorporates 3 programmable registers. Each register has 8 bit of memory. When the MA700 is powered up, each of these 3 x 8 bit of memory are set to zero, unless the register was previously stored in the One-Time-Programmable (OTP) memory. It means that during startup, the content of the OTP memory is copied to the registers. Once flashed the register content cannot be modified anymore.

In order to set the content of a register, the user must send a digital stream composed of the 4-bit REGISTER WRITE command (0010), followed by a 4-bit register address and the 8-bit value to be sent to the register. The data stream, sent through the MOSI wire, is therefore 16 bits long:

command				reg. address				MSB			value				LSB
0	0	1	0												

Once the command is sent, it will immediately be effective and will affect the next data sent from the MagAlpha.

Read back the register content

It might be helpful to check the content of a register, for instance to verify that the programming was successful. The user must send the REGISTER READ command: 0001, then the 4-bit address of the register under test. The last 8-bit of the stream will be ignored. The user can send for instance 0000 0000:

command				reg. address				MSB			value				LSB
0	0	0	1	x	x	x	x	0	0	0	0	0	0	0	0

The MagAlpha response is *within the same transmission*. In the first byte (simultaneous to the 4-bit READ command and the 4-bit address), the MagAlpha

sends the 8 MSB of the measured angle A(15:8). The second byte is the content of the register under test. After this transmission the MagAlpha will continue delivering the usual 16-bit angles A (15:0).

Example

To check the content of the register 4 (0100), which contains the 8 MSB's of the zero setting, send the data:

command				reg. address				MSB	value						LSB
0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
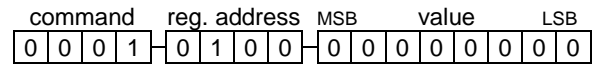
Simultaneously the MagAlpha replies:

Angle out		MSB	value		LSB
A(15:12)	A(11:8)		Z(11:4)		
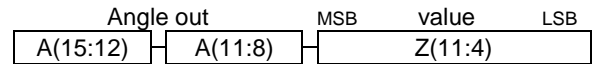
10. Output Signals

The raw data coming out of the conditioning blocks is an absolute angle, between 0 and 360 deg. This angle is coded on 16 bits, depending on the value of AF. The absolute output is sent out digitally as serial data. The other outputs, ABZ or UVW, are constructed from the absolute angles.

Absolute - Serial

The bit order of the transmitted data is MSB first, LSB last. The timing requirements are indicated in section 3. Every 2μs a new data is transferred into the output buffer. The master device connected to the MagAlpha triggers the reading by pulling the CS down. When a falling edge of the CS signal occurs, the data remains in the output buffer until the CS signal returns to logic 1. As the CS is low, the master can read the data by sending clock pulses with a maximum frequency of 25 MHz. There is not any minimum frequency or timeout. See Figure 11 for a simple reading of 16 bit data.
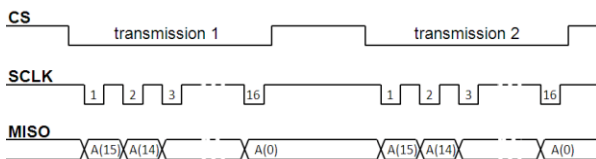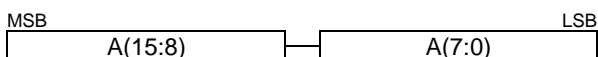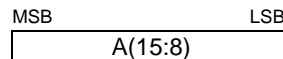

Figure 11: Timing Diagram for Simple SPI Readout

A full reading requires 16 clock pulses. The MA700 delivers:

MSB		LSB
A(15:8)	A(7:0)	

In case the user needs less resolution, since the MSB is sent first, he can read the angle by sending less than 16 pulses. For instance by sending only 8 pulses, the

MagAlpha provides an 8-bit angle without ambiguity over 360 deg.

MSB	LSB
A(15:8)	

If the master triggers the reading faster than the refresh rate the MagAlpha may send several times the same data point.

In some applications it is helpful to know how many data updates occurred between two successive readouts or if the same data points was read more than once. For this purpose the user can read an 8-bit index attached to the data .It allows keeping track of the precise time of measurement without the need of precisely controlling the readout time. This index runs from 0 to 255 and is incremented by 1 each time the output buffer is refreshed. Using the index the user can detect a double reading of the same data (same index), or how many data points were skipped.

For reading the 8-bit index the master has to send 16 + 8 = 24 clock pulses (see Figure 12).
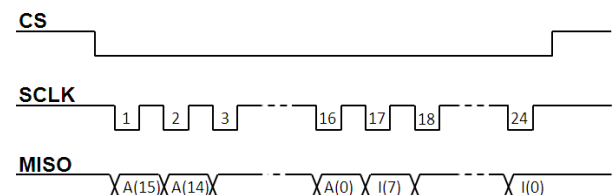

Figure 12: Timing Diagram for SPI Angle + Index Readout

Incremental - ABZ

With the ABZ output the MA700 emulates a 10-bit incremental encoder, such as an optical encoder, providing logic pulses in quadrature (see Figure 13). Compared to A, the signal B is shifted by a quarter of pulse period. Over one revolution the A signal pulses 256 times. It makes 1024 edges per revolution. The signal Z ("Zero" or "Index") raises only once per turn, at the zero angle position.
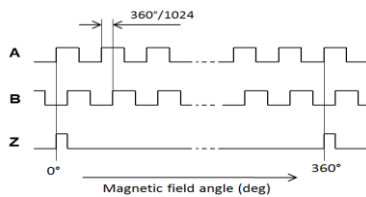

Figure 13 : ABZ Output during Rotation

11. OTP Programming

The One-Time-Programmable (OTP) memory can permanently store the content of the programmable registers. The OTP memory is made of poly-silicon fuses. By activating the "flash" command the content of the entire register will be stored in the OTP memory. The flash command consists in setting some bits (named F*n*, where *n* is the register number) in the register 9. When the bit F*n* is set, the register *n* is stored permanently. **Important: the user can flash only one register at the time.** It is possible to operate the MagAlpha without flashing the registers.
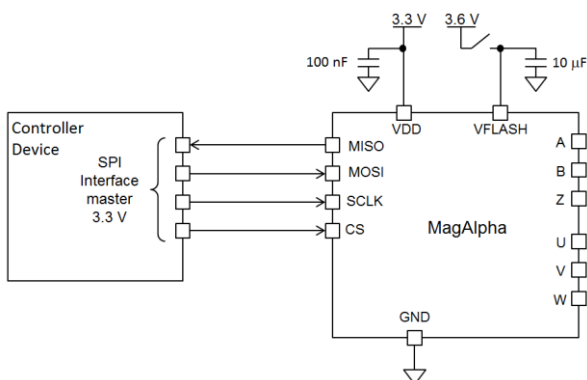

Figure 14: Circuit for Flashing

The burning of the fuses during the flash process is irreversible: once a register is flashed the default values

at power up will always be the same. After flashing the registers content cannot be modified anymore.

Flashing procedure

Prior to flashing, it is recommended to test the MagAlpha with the new settings and verify the performance of the sensor.

Once satisfied, the user can proceed with the flashing:

- Send the parameter to the register, and read back for verification.
- Tie the VFLASH pin to 3.6 V. Note: it is possible to supply both VDD and VFLASH with the same 3.6 V source.
- In the register 9, set the bit corresponding to the register to be flashed.
- Untie the VFLASH pin

Then switch off and on and check by reading back the register content.

Example: set & flash the zero position at 50 deg

Note: permanently storing the zero position requires to burn two registers, 4 and the 5.

1. Convert into binary: within a resolution of 12 bits, 50 deg is the binary number 001000111000 (≈49.92 deg).

2. Store the 8 MSB (00100011) of the zero position into register 4:

command				reg. address				MSB		value					LSB
0	0	1	0	0	1	0	0	0	0	1	0	0	0	1	1

3. Read back the register 4

command				reg. address				MSB		value					LSB
0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0

If the programming was correct the MagAlpha replies with the register 4 content:

Angle out		MSB		value					LSB
A(15:12)	A(11:8)	0	0	1	0	0	0	1	1

4. Then store the 4 LSB (1000) of the zero position into the 4 LSB of register 5:

command				reg. address				MSB		value					LSB
0	0	1	0	0	1	0	1	0	0	0	0	1	0	0	0

5. Read back the register 5:

command				reg. address				MSB		value					LSB
0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0

The MagAlpha returns:

Angle out		MSB		value					LSB
A(15:12)	A(11:8)	0	0	0	0	1	0	0	0

6. Connect the VFLASH pin to 3.6 V

7. Flash register 4:

command				reg. address				MSB		value					LSB
0	0	1	0	1	0	0	1	0	0	0	1	0	0	0	0

8. Flash register 5:

command				reg. address				MSB		value					LSB
0	0	1	0	1	0	0	1	0	0	1	0	0	0	0	0

9. Disconnect the VFLASH pin from 3.6 V.

10. Turn the MagAlpha off and on, and read back the registers 4 and 5 to verify that the flashing was successfully accomplished (steps 3 & 5).

12.   Typical Characteristics

Measurement conditions: VDD = 3.3V, Temp = 25°C, unless otherwise noted.
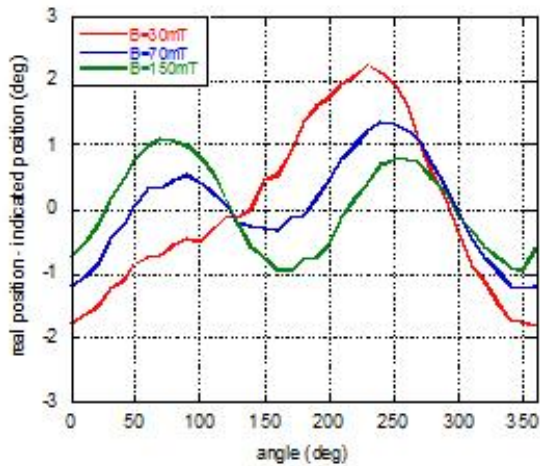

Figure 15: Error Curve at Different Magnetic Fields. The INL is the Maximum Value of this Curve.
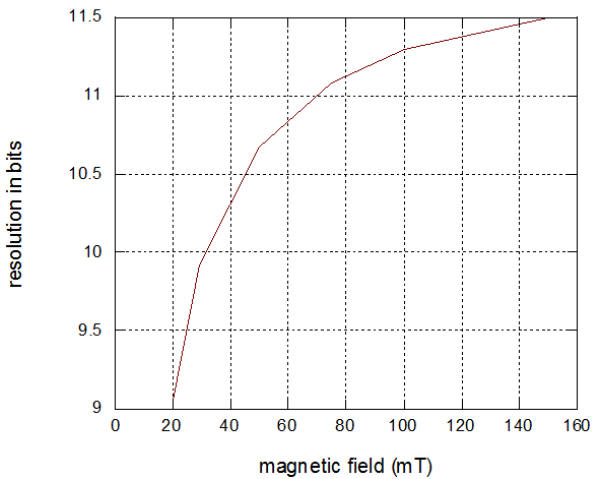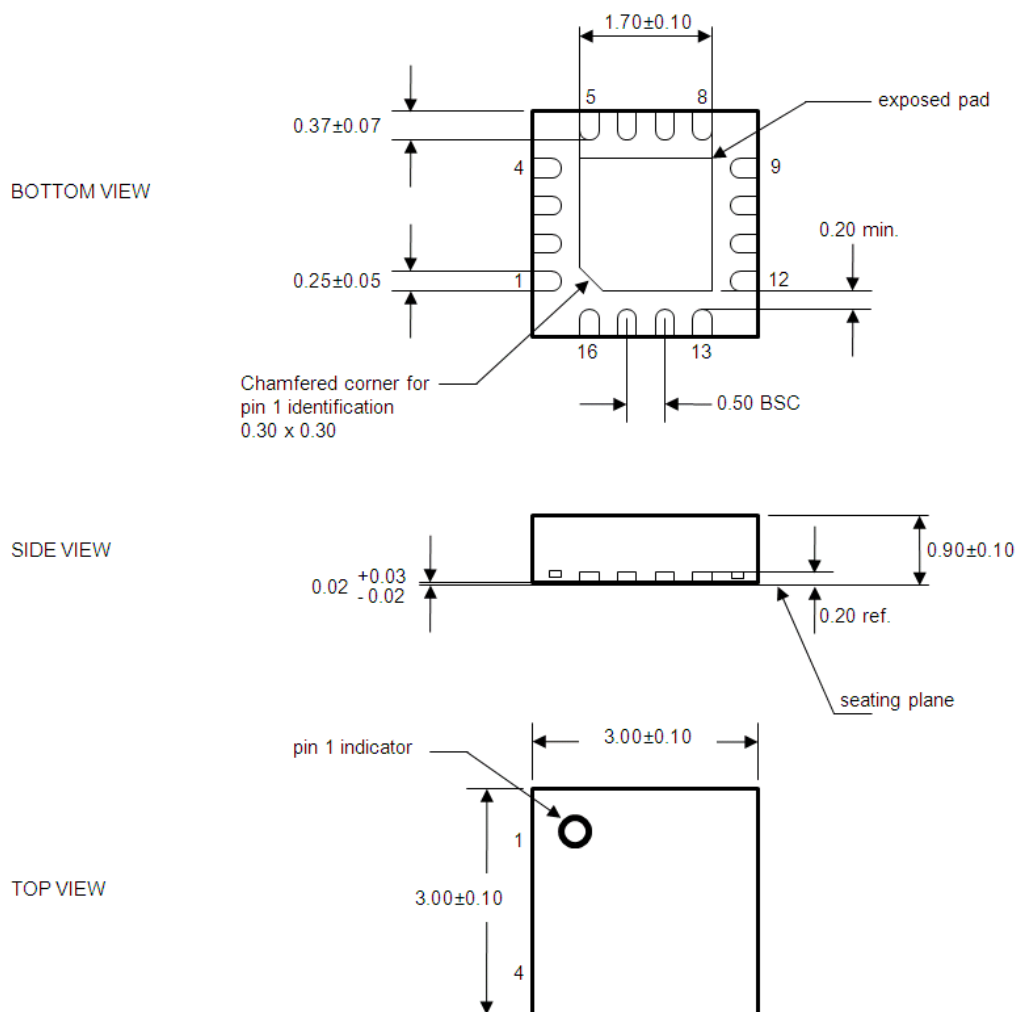

Figure 16: Resolution in Bits vs. Angle at Different Magnetic Fields.

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13. Package Dimensions

Package: Plastic Quad Flatpack No-lead QFN-16 3x3mm

NOTES:
1. All dimensions are in mm
2. Package dimensions does not include mold flash, protrusions, burrs or metal smearing
3. Coplanarity shall be 0.08
4. Compliant with JEDEC MO-220

14. Ordering Information

Part Number	Package	Free Air Temperature (T_A)
MA700GQ	**QFN 3x3mm**	**-40° to 125°**

* For Tape & Reel, add suffix –Z (e.g. MA700GQ–Z).

Appendix A: Definitions

|	
Resolution (3σ noise level)	The smallest angle increment distinguishable from the noise. Here the resolution is defined as 3 times σ, the standard deviation in degrees, taken over 1000 data points at a constant position. The resolution in bits is obtained with: $\log_2(360/6\sigma)$.
Refresh rate	Rate at which new data points are stored in the output buffer.
Latency	The time between the data ready at the output and the instant at which the shaft passes that position. The lag in degrees is $lag = latency \cdot v$, where v is the angular velocity in deg/s.
Power up time	Starting at power up, time until the sensor delivers valid data.
Integral Non-Linearity (INL)	Maximum deviation between the sensor output and the best line fit.
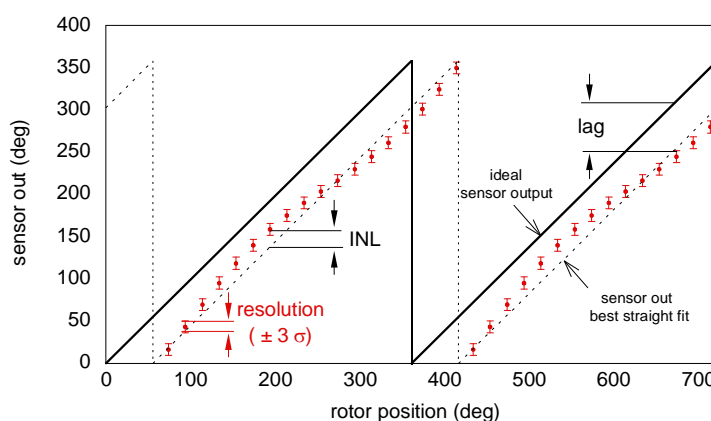
Figure A1: Absolute Angle Errors

Jitter   For the incremental output maximum fluctuation of the angular position of the raising edges.

Overall reproducibility   Maximum variation between two readings, successive or not, of the same shaft position at a fixed magnetic field over the complete temperature range.

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