10-bit Absolute Magnetic Rotary Encoder

1 Introduction

TMR3101 is a contactless absolute magnetic rotary encoder. It is designed for measuring single-turn absolute angular position from 0 - 360 °, or it can be used as an incremental encoder with pulse output signals.

TMR3101 is designed with Tunneling Magnetoresistance (TMR) angle sensors and integrated with digital signal processing circuitry. Paired with a magnet that is magnetized along the radial direction, it can measure 0-360 °angular position in 10-bit (1024-line) resolution, with the angular resolution at 0.35 °. It supports multiple output interfaces, including PWM, SPI, dual-pulse with zero position, single-pulse with zero position and direction output, or UVW output.

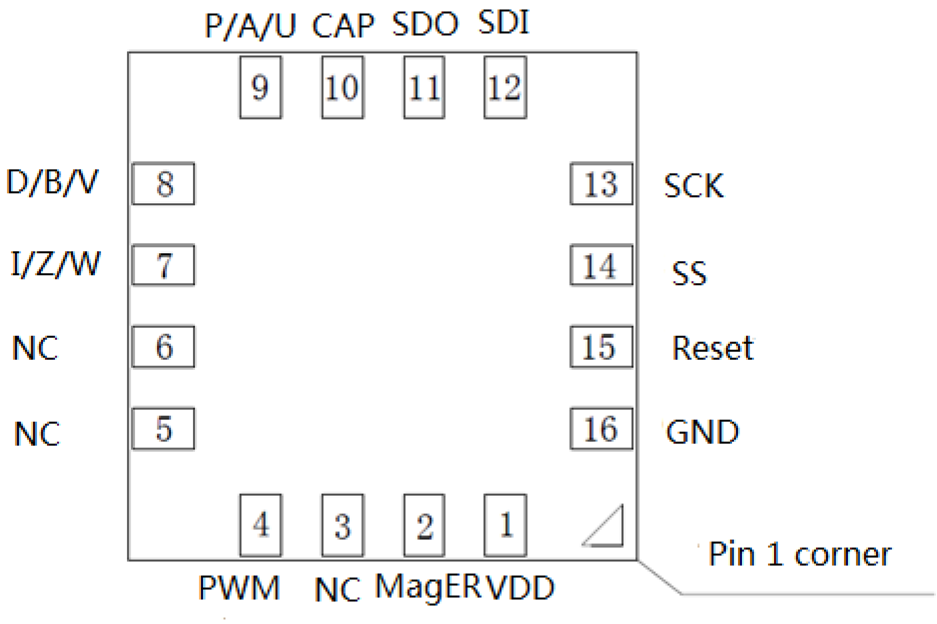
1.1 Features

- 360 °angular position measurement
- Contactless measurement suitable for complicated operating environment
- Wide operating magnetic field range, allowing exceptional jitter tolerance
- Magnetic sensor operates in saturation range, providing enhanced noise immunity
- Angular resolution up to 0.35 °
- Multiple output interfaces including SPI/PWM/ABZ/UVW/PDI
- High-speed SPI bus at 5MHz
- Fast PWM refresh rate
- 10-bit continuous angular position output @3000RPM in real-time
- 1024-line incremental output @10000RPM
- Pulse width variation < 10%
- Operating temperature range: -40℃~125℃
- Compact LGA package in 5mm*5mm*0.9mm
- Single-turn/multi-turn absolute rotary encoder
- Contactless angular position measurement
- Steering wheel position detection
- Gas pedal position detection
- Rotary position knobs

1.2 Applications

- Single-turn/multi-turn absolute rotary encoder
- Contactless angular position measurement
- Steering wheel position detection
- Gas pedal position detection
- Rotary position knobs

2 Pinout



Pin Definition

Pin No.	Symbol	Type	Description
1	VDD	S	3.3V voltage supply
2	MagER	DO	Magnet position indicator, high-voltage indicating incorrect magnet mounting position (400~900 Gauss)
3	NC		Keep unconnected
4	PWM	DO	PWM output for angular position
5	NC		Keep unconnected
6	NC		Keep unconnected
7	I/Z/W	DO	Mode1: zero-position signal; Mode2: Z; Mode3: W
8	D/B/V	DO	Mode1: rotation direction signal; Mode2: B; Mode3: V
9	P/A/U	DO	Mode1: angular position pulse output; Mode2: A; Mode3: U
10	CAP		Shall be connected with a 10uf capacitor
11	SDO	DO	SPI master input / slave output
12	SDI	DI	SPI master output / slave input
13	SCK	DI	SPI clock
14	SS	DI	SPI slave enable, low-voltage to enable
15	Reset		Shall be connected with a 10KOhm pull-up resistor
16	VSS	S	GND

Type definition:

S: power supply, DI: digital input, DO: digital output

3 Electrical Characteristics

3.1 Absolute Maximum Ratings (non-operating condition)

Parameter	Symbol	Condition	Limit	Unit
Supply Voltage	VCC	TJ=25 ℃	4	V
Input Current	Iscr	TJ=25 ℃	60	mA
Magnetic Field	Hext	TJ=25 ℃	2000	Oe
ESD Voltage	VESD		2	KV
Storage Temperature	Tstg		-40~125	℃

3.2 Operating Condition

Parameter	Symbol	Min	Typical	Max	Unit
Operating Temperature	T	-40		125	℃
Supply Current	Icc		5	60	mA
Supply Voltage	Vcc	3	3.3	3.6	V

3.3 DC Characteristics of Digital Input / Output

3.3.1 CMOS Schmitt Trigger Input: SCK, SS, SDI

Parameter	Symbol	Min	Typical	Max	Unit
Vih	Input voltage high	0.8*VDD			V
Vil	Input voltage low			0.3*VDD	V
Ileak	Input leakage current	-1		1	uA
Iil	Low-voltage pull-up input current	150	250	550	uA

3.3.2 CMOS Open-drain Output: SDO, Index, Direction, Plus, MagER

Parameter	Symbol	Min	Typical	Max	Unit
Vol	Output voltage low			0.3*VDD	V
Io	Output current			8	mA
Ioz	Open-drain leakage current	-1		1	uA

3.3.3 CMOS Output (PWM)

Parameter	Symbol	Min	Typical	Max	Unit
Voh	Output voltage high	0.8*VDD			V
Vol	Output voltage low			0.3*VDD	V
Io	Output current			8	mA

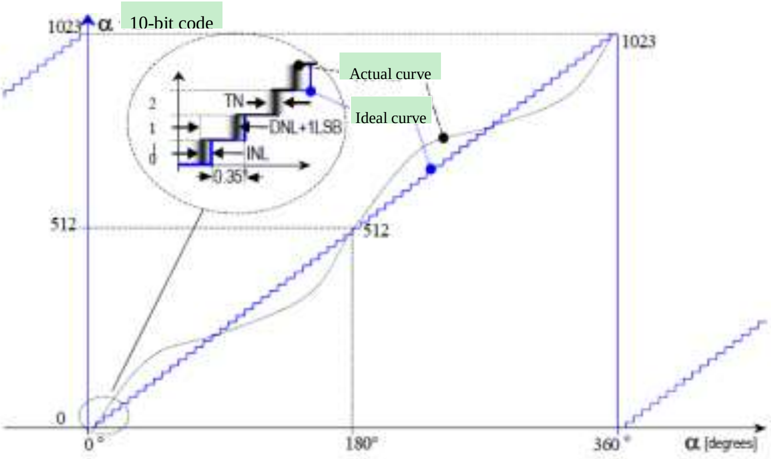
3.4 Magnetic Characteristics (operating condition: -40~125 ℃, VCC=3.3V, two-pole cylindrical magnet with radial magnetization)

Parameter	Symbol	Min	Typical	Max	Unit	Notes
Diameter	dmag	6	8	10	mm	Recommended: Ø 8mm x 2.5mm cylindrical magnet
Thickness	tmag		2.5		mm	
Magnetic field	Bpk	400	700	900	Gauss	Magnetic flux in parallel to sensor surface
Magnetic offset	Boffset	-100		100	Gauss	Constant magnetic stray field
Non-linearity				5	%	Including deviation of gradient
Input frequency	Fmag_abs			50	Hz	Absolute mode at 3000rpm
	Fmag_inc			83	Hz	Incremental mode at 10000rpm
Misalignment radius	Disp			0.25	mm	
Recommended magnetic material and temperature drift			-0.12		%/K	NdFeB

3.5 Electrical Properties

Parameter	Symbol	Min	Typical	Max	Unit	Notes
Resolution	RES			10	bit	0.352 °
Integral non-linearity	INL			±1.4	deg	Best-fit curve =(ERRmax-ERRmin)/2, using 8mm diameter magnet, temperature from -40~125℃
Hysteresis	Hyst		0.704		deg	Incremental mode only
Transition noise	TN			0.12	deg	
Power-up time	tpwup		110		ms	
Incremental mode output latency				50	Us	> 2-point sampling
Sampling rate of absolute output	fs		50		KHz	
Read frequency	SCK			5	MHz	Maximum clock frequency for reading serial data

Notes:



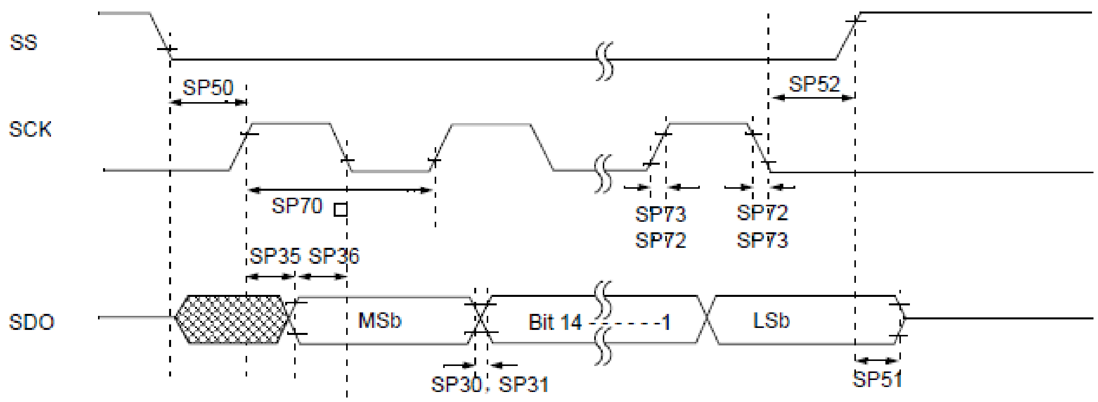
Integral non-linearity（INL）is the maximum difference between the actual position and the measured position.

Differential non-linearity is the maximum different from one position to its adjacent position.

Transition noise (TN) indicates the repeatability of a position.

3.6 Timing Characteristics

SPI Output



Parameter	Symbol	Min	Typical	Max	Unit	Notes
SP70	FscP			5	MHz	Maximum SCK input frequency
SP72/SP73	TscF/TscR		5	10	ns	SCK rise/fall time
SP30/SP31	TdoF/TdoR		5	10	ns	SDO rise/fall time
SP35	TscHdoV		6	20	ns	Time between edge of SCK and SDO output valid
SP36	TdoVscH	30			ns	Time between SDO output data

						establishment and first edge of SCK
SP50	TssLscH	120			ns	Time between SS (low-voltage) and rising edge of CLK
SP51	TssHdoZ	10		50	ns	Time between SS (high-voltage) and SDO reaching high impedance

PWM Output

Parameter	Symbol	Min	Typical	Max	Unit	Notes
PWM frequency	f		32.3		KHz	
Min pulse width	PW min		30.1		ns	Digital position 0, angular position 0°
Max pulse width	PW max		30.9		us	Digital position 1023, angular position 359.65°

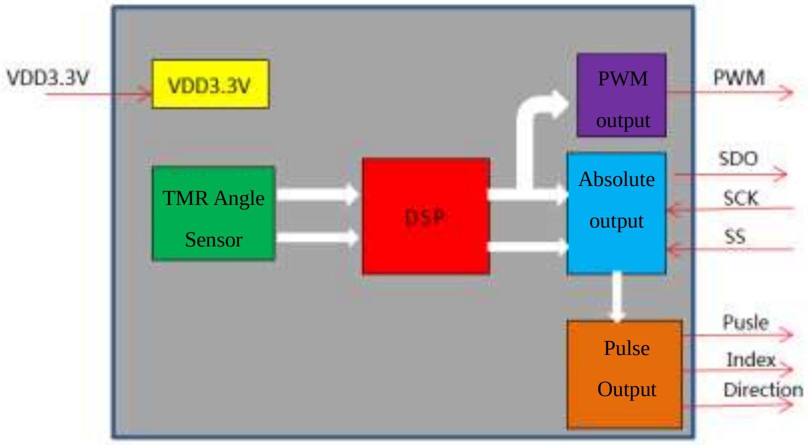
Pulse Output

Parameter	Symbol	Min	Typical	Max	Unit	Notes
Pulse frequency	f	16	17	18	KHz	Rotation speed at 1000RPM
Pulse output uniformity	Duty	0	5	7	%	2*(tmax-tmin) / (tmax+tmin)

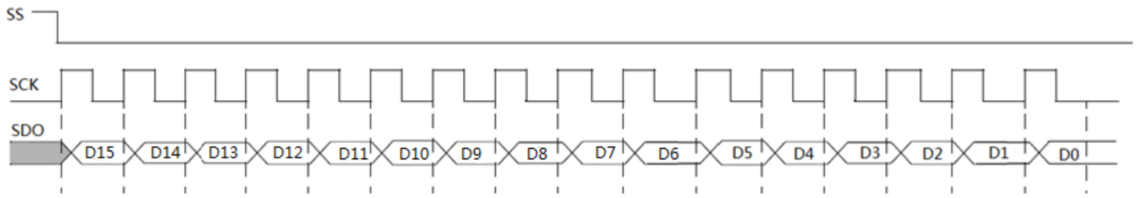
4 Functional Description

The TMR3101 applies TMR sensor technology to measure the angle of the magnetic field on the sensor’s surface. Paired with a small, low-cost and 2-pole magnet that is magnetized at the radial direction, the TMR elements generate a voltage value corresponding to the angle of the magnetic field, through ADCs and digital signal processing circuitry, the high-resolution angular position value can be accurately calculated.

By detecting the angular position of the magnetic field, the TMR3101 computes the 10-bit angular position value in a digital format that can be accessed by the serial interface. In addition, the absolute angular position value can also be accessed by the PWM signal and analog voltage output, as well as incremental output interfaces.

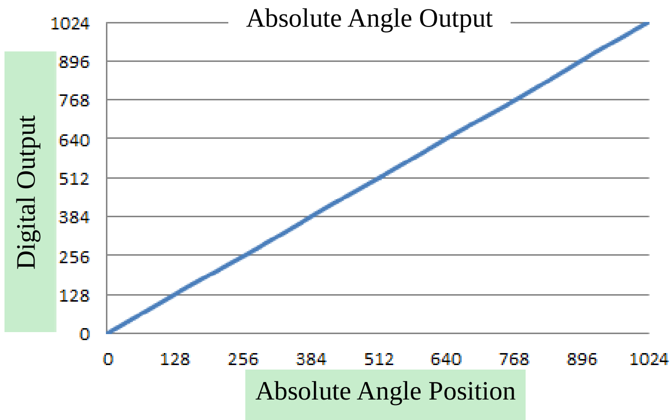


4.1 10-bit Absolute Angular Position Output through SPI



- If SS becomes logical low-voltage, SDO will turn to high-voltage from the high-impedance state (tri-state), and initiate the read operation.
- Each rising edge of succeeding SCK signals will output one bit at a time.
- The serial code of the angular position contains 10 bits, with the highest significant bit becoming available first and the lowest significate bit at last.

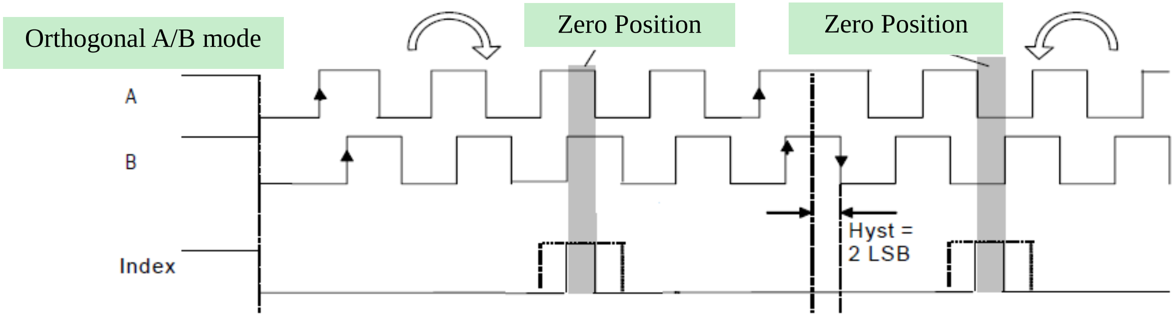
The sampling rate of each absolute position code is 50kHz. As a result, all possible codes of 1024 positions can be read within each 0.02 second (~50Hz), and the maximum rotation speed is 3000RPM accordingly.



4.2 Incremental Output

4.2.1 Orthogonal A/B Output

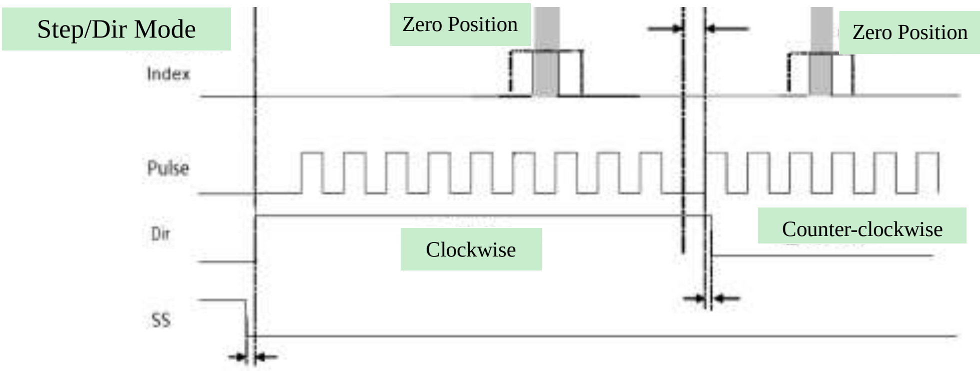
The phase shift between channel A and channel B indicates the rotation direction of the magnet. When the magnet rotates clockwise (from top view), the phase of channel A leads channel B by 90°; when the magnet rotates counter-clockwise, the phase of channel A lags by 90°.



4.2.2 Pulse/Dir Output

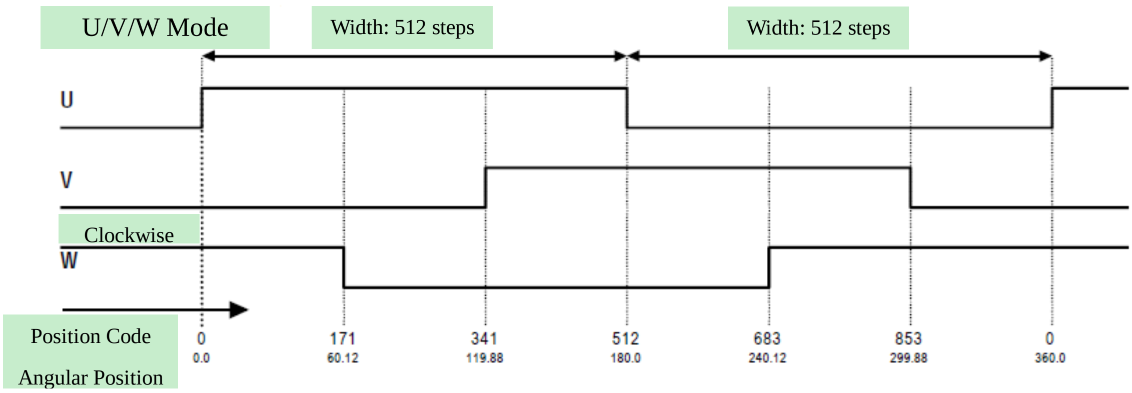
Dir output indicates the rotation direction of the magnet, with high-voltage meaning clockwise rotation, and low-voltage for counter-clockwise rotation (top view when the magnet is mounted above the device). The magnet can be mounted below the device as well.

The Index pulse signal indicates the zero position. Its pulse width equals the period of each position code.



4.2.3 BLDC Motor Commutation Mode

In BLDC motor control, the angular position is needed to control the commutation of the stator. The TMR3101 can provide the U/V/W signal for commutation control in BLDC motors with a two-pole magnet.



4.2.4 Switching between Different Incremental Output Modes

All output modes ABZ/PDI/UVW can be programmed by writing internal registers through the 4-wire SPI interface. When the device is powered up, the initial mode is ABZ. The mode switching can be initialed by the following operations.

When SDI input word is 0xaa13, mode 1 is selected, and SDO will return 0xaa13. The device will operate in Step/Dir mode, in which Index outputs the zero position, Dir indicates the rotation direction, and Pulse give a pulse signal for each angular position.

When SDI input word is 0xaa11, mode 2 is selected, and SDO will return 0xaa11. The device will operate in orthogonal A/B mode, in which Index outputs Z signal, Dir and Pulse give phase A and phase B signal respectively.

When SDI input word is 0xaa12, mode 3 is selected, and SDO will return 0xaa12. The device will operate in U/V/W mode, in which Index/Dir/Pulse become U/V/W signals, respectively.

An SDI input word of 0xaa5a finalizes the mode selection, and SDO will return 0x005a. The setting will be saved to internal registers and will be kept after the device is powered up next time.

Output Mode	Pin 7	Pin 8	Pin 9
1 Orthogonal A/B/Z	Index	B	A
2 Step/Dir	Index	Direction	Pulse
3 Commutation	W	V	U

4.2.5 User Programmable Zero Position

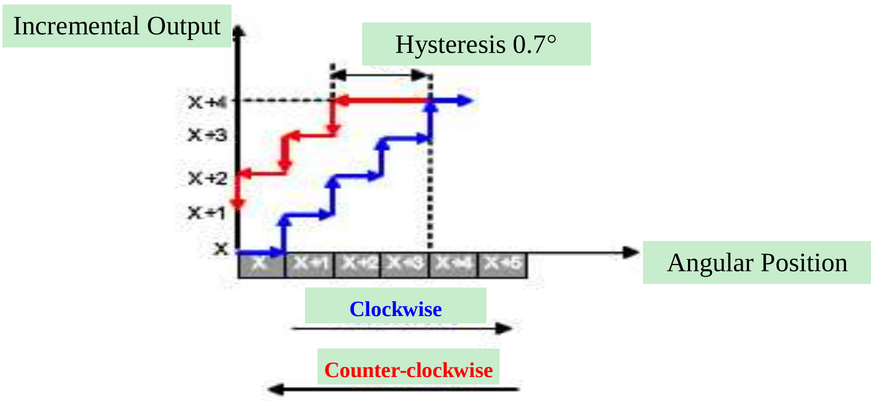
The zero position can be programmed to simplify the assembly process, without requiring the magnet to be mechanically adjusted to a specific position. After assembly, the mechanical zero position and the electrical zero position can be logically matched by user programming. Any position can be defined as the zero position permanently.

When performing zero position programming, the magnet can be rotated to a given mechanical zero position. The actual angular value can be recorded and save to the internal register through the following procedure.

When SDI input word is 0x0000, the actual angular position will be computed in real-time, and the angular value code will be outputted to SDO. The following SDI input word of 0xaa55 will define the current position as the zero position, and the SDO will return 0x0055. This completes the zero position programming, with the current position permanently defined as the zero position, where the Index pulse signal will take place on every rotation of the magnet.

4.2.6 Incremental Output Hysteresis

A hysteresis mechanism is designed to avoid incremental output glitches when the magnet remains stationary. When the rotation direction changes, the incremental output will cover a hysteresis that is equal to 2 LSB. 2LSB corresponds to the highest resolution in 10-bit, which is equal to 0.704°

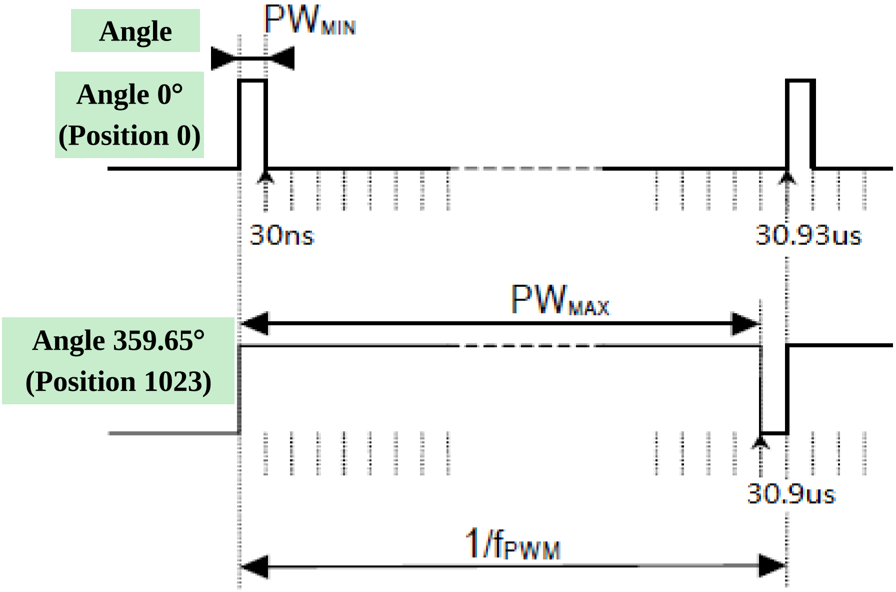


Hysteresis Window of Incremental Output

4.3 PWM Output

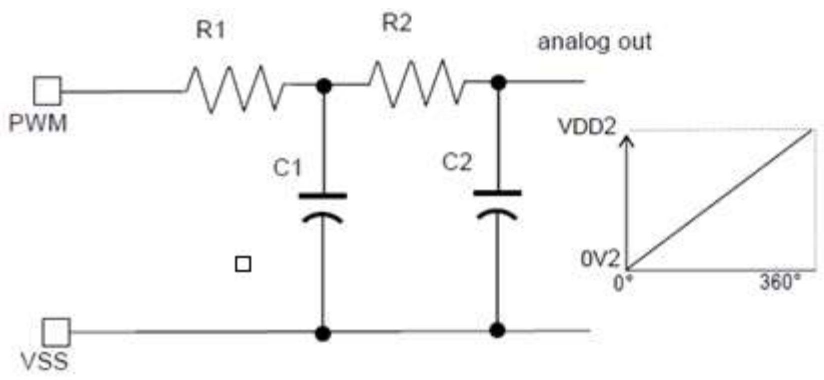
PWM Output

This device provides a single PWM output signal, with its duty cycle proportional to the absolute angular position value.



PWM Conversion to Analog Output

Through an external active or passive low-pass filter circuit, the PWM output can be averaged to generate an analog output signal, with its voltage value in proportion to the angular position values, for example, in a linear voltage range between 0 ≒0V and 360 ≒VDD3.3V. This method will implement the function of a potentiometer. A sample circuit is shown as the following:



Using large resistance and capacitance values on Rx and Cx shall improve filter performance and ripple rejection, but it may extend the response time of the circuit.

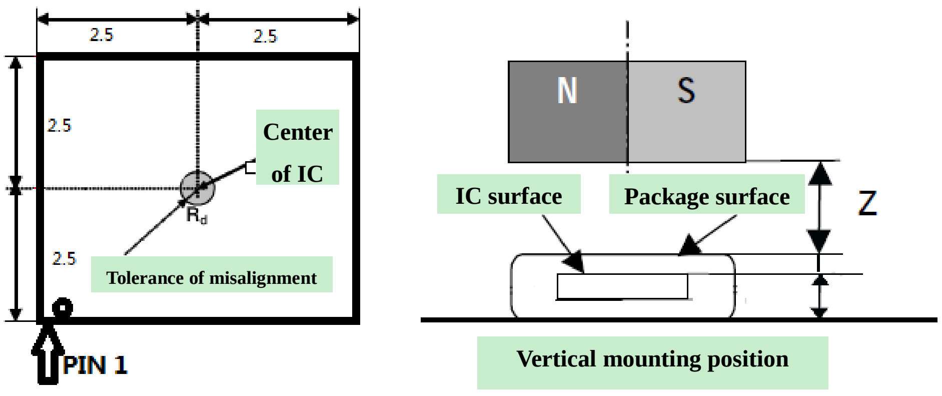
5 Selection and Assembly of the Magnet

5.1 Selection of the Magnet

Under normal condition, the diameter of the magnet should be 8mm, with the thickness >= 2.5mm. The recommended materials are AlNiCo, SmCo5, or NdFeB. A Gauss meter should be used to verify that the magnetic field at the device surface is between 400 Gauss and 900 Gauss.

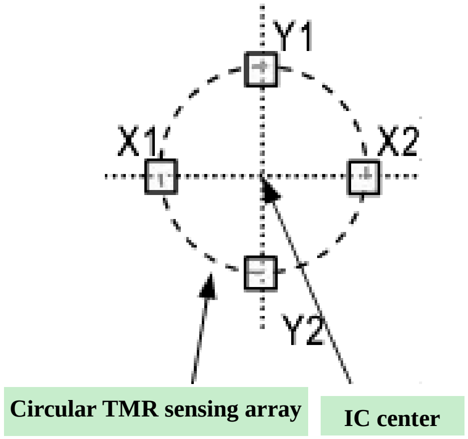
5.2 Assembly of the Magnet

As illustrated below, when the center of the magnet is precisely mounted on top of the center of the IC package, the optimal performance will be achieved.



The central axis of the magnet should be aligned with the center of the IC package. The maximum amount of misalignment should be controlled within a perimeter of Rd=0.25mm. The vertical clearance can be adjusted such that the magnetic field along the IC surface falls between 400 and 900 Gauss. When using the recommended magnet (8mm*2.5mm), the distance Z is between 1.3mm and 2.5mm.

6 Emulation Modeling



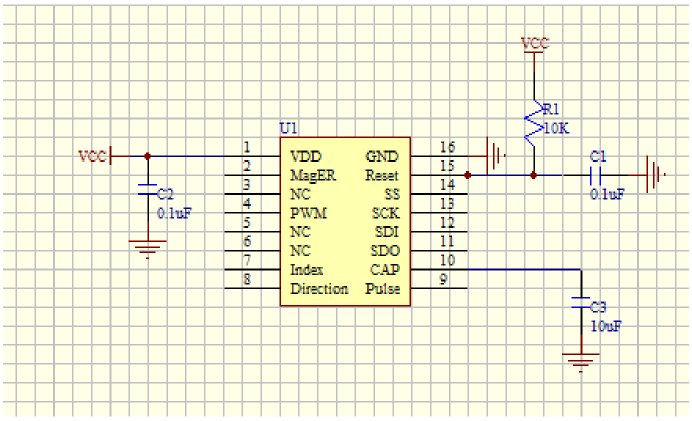
As shown in the figure above, the sensing mechanism can be modeled by a TMR sensor element array that measures the magnetic field in parallel to the IC surface. The four TMR sensor elements are centered at the IC's center, and placed around a circle with a 1.2mm radius. They are paired by two X sensors and two Y sensors with different output of each pair representing the Sine and Cosine component of the magnetic field vector in the X-Y plane. The differential signal Y1-Y2 is the Sine component, and X1-X2 represents the Cosine component. The angular position of the magnetic field vector α can be modeled as:

$$\alpha = \tan^{-1}(Y2 - Y1)/(X2 - X1)$$

In order to suppress the impact of the magnetic field interference, a robust differential sample and ratiometric calculation algorithm is applied. The differential sample on Sine and Cosine components cancels out the stray field or common-mode error from the magnet or the environment. The ratiometric calculation between the Sine and Cosine components eliminates the need for measuring the absolute magnitude of the magnet field.

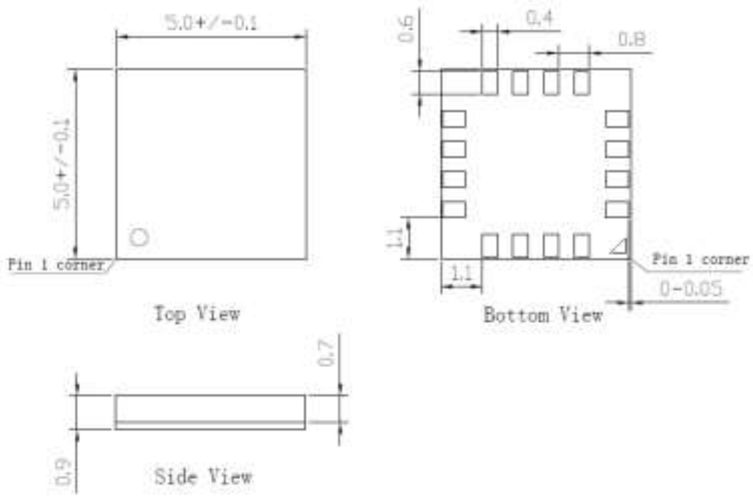
7 Application Guide

An example of the application circuit is illustrated below. When the device is powered up, users should rotate the magnet slowly for two full turns to allow the internal calibration before the device enters the operation mode.



8 Package Dimension and Position of the Sensing Device

Package Dimension



Sensing Element Position