OUTPUT PROTOCOLS FOR ANGLE AND LINEAR POSITION SENSORS

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INTRODUCTION

Allegro angle and linear position sensors can output data through a wide variety of different protocols. Depending on the application, certain protocols are preferred over others. This application note describes working principles, lists advantages and limitations, outlines communication rates/delays, and defines error reporting tactics for digital and analog protocols used in angle and linear position sensing.

SPI PROTOCOL

Many Allegro linear and angular position sensors use the SPI (Serial Peripheral Interface) protocol. SPI is a synchronous serial communication interface for short distance communication. Most SPI devices communicate in full duplex mode using a master-slave architecture.

Advantages

SPI offers many advantages due to its structure:

- Flexible communication that allows read/write (full duplex) to/from the device's memory map.
- High throughput: All Allegro SPI devices support clock frequencies up to 10 MHz.
- Easy to use and integrate with microcontrollers.
- Flexibility for the number of bits transferred.
- Multiple slave devices can be connected on one SPI bus.

Limitations

- Requires four data signal wires.
- Only handles short distances compared to other protocols.
- Supports just one master device.

Table of Contents

SPI Interface and Timing

Devices that use the SPI interface require four signal lines to communicate. Communication lines are illustrated in Figure 2 and defined below:

- SCLK: serial clock. The master needs to provide the clock on this line.
- MOSI: master-out-slave-in. This line is for data sent from the master to the slave. Microcontrollers frequently call this line DOUT (Data Out).
- MISO: master-in-slave-out. Data that the master receives from the slave. Microcontrollers also call this line DIN (Data In).
- $\overline{CS}$/$\overline{SS}$: Chip-Select or Slave-Select.
- The master pulls down this line to select and initiate slave communication.

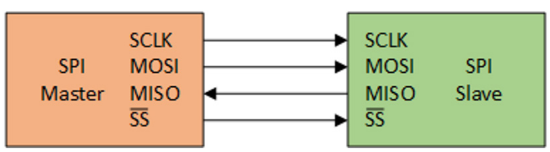

Figure 1: Basic SPI Bus Example

In Allegro sensors, the SPI interfaces operate in pure Slave mode, with the Master controlling the SCLK, MOSI, and $\overline{CS}$ lines.

The period in which $\overline{CS}$ is low (active) is called a “frame”. The communication is out of frame. This means that when a command is sent to the sensor in one frame, the sensor response, usually requested data, will be transmitted with the next write or read request from the master.

Clock Polarity and Phase

All Allegro sensors use SPI-mode 3 (CPOL = 1 and CPHA = 1). CPOL determines the polarity of the clock. If CPOL = 1, the clock idles at HIGH. If SCLK switches to LOW, this counts as a rising edge. CPHA determines the phase of the clock.

If CPHA = 1, the data will be read at the falling edge and changes at the rising edge. In conclusion, the SPI-mode 3 means that the clock idles at HIGH and will be read at the rising edge of SCLK.

SPI Message Frame Size

The SPI message frame size varies from sensor to sensor and this information can be found in each sensor’s datasheet. “SPI message frame size” is also referred to as “SPI packet size” in some documentation. Most sensors at Allegro use an SPI transaction with a length of 16 bits. Other sensors offer an optional extended SPI communication, which adds a 4-bit CRC making the message frame size 20 bits in total. Figure 2 shows an example of an SPI transmission.

Read Cycle Overview

Read cycles have two stages: a Read command, selecting a serial register address, followed by another SPI command. During this second SPI command, the data from the selected register, are transmitted from the part to the host.

Write Cycle Overview

Write cycles consist of a 1-bit sync bit (low), a 1-bit R/W set to high, 6 address bits (corresponding to the primary serial register), 8 data bits, and 4 optional CRC bits. To write a full 16-bit serial register, two write commands are required (even and odd byte addresses).

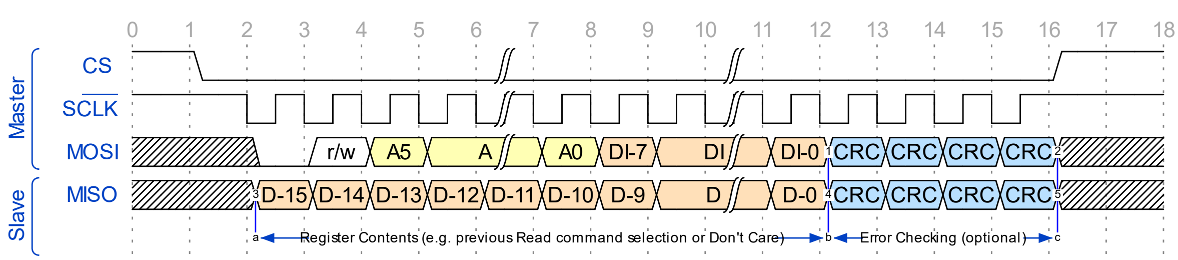

Figure 2: SPI Communication Example

I²C PROTOCOL

I²C is used with some Allegro sensors. I²C is a synchronous bus which provides a full duplex interface between two or more devices. Only two communication wires with respective pull-up resistors are required for this protocol. Typical voltages used are 3.3 V or 5 V, but other voltages are permitted. Some Allegro sensors supports voltages down to 1.8 V.

Advantages

- Flexible communication to read and write (full duplex).
- Can handle multiple slave and multiple master devices on one I²C bus.
- Only requires two signal wires.
- Easy to use/integrate. Most microcontrollers support I²C in hardware and/or via software.

Limitations

- Throughput is lower than SPI.
- I²C supports up to 5 Mbit/s (only unidirectional) but most devices support just 0.4 or 1 Mbit/s (bidirectional).
- Only handles shorter distances compared to other protocols.
- Slave number can be limited by address conflicts.
- Communication is not as stable as other protocols, especially in noisy environments.

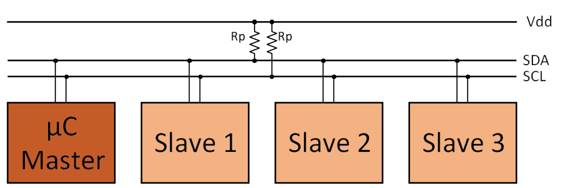

Figure 3: Basic I²C Bus Example

I²C communication is composed of several steps outlined in the following sequence as shown in Figure 4.

1. Start Condition: Defined by a negative edge of the SDA line, initiated by the Master, while SCL is high.
2. Address Cycle: 7-bit Slave address, plus 1 bit to indicate write (0) or read (1), followed by an Acknowledge bit.
3. Data Cycles: Reading or writing 8 bits of data, followed by an Acknowledge (ACK) bit. This cycle can be repeated for multiple bytes of data transfer. The first data byte on a write could be the register address. See the following sections for further information.
4. Stop Condition: defined by a positive edge on the SDA line, while SCL is high.

Except to indicate Start or Stop conditions, SDA must remain stable while the clock signal is high. SDA may only change states while SCL is low. It is acceptable for a Start or Stop condition to occur at any time during the data transfer.

The state of the Read/Write bit is set to 0 to indicate a write cycle and set to 1 to indicate a read cycle.

The Master monitors for an Acknowledge bit to confirm the Slave device is responding to the address byte. When the Slave decodes the 7-bit Slave address as valid, it responds by pulling SDA low during the ninth clock cycle. When a data write is requested by the Master, the slave device pulls SDA low during the clock cycle following the data byte to indicate that the data has been successfully received. After sending either an address byte or a data byte, the Master must release the SDA line before the ninth clock cycle, allowing the handshake process to occur.

CRC

Some sensors (e.g. ALS31313, an Allegro 3D sensor) also support a CRC calculation to verify the data. If the CRC feature is enabled, the read transaction returns one extra byte corresponding to the CRC calculation of that read. The bytes of the I²C read sequence used for CRC calculations can be found in the sensor's datasheet.

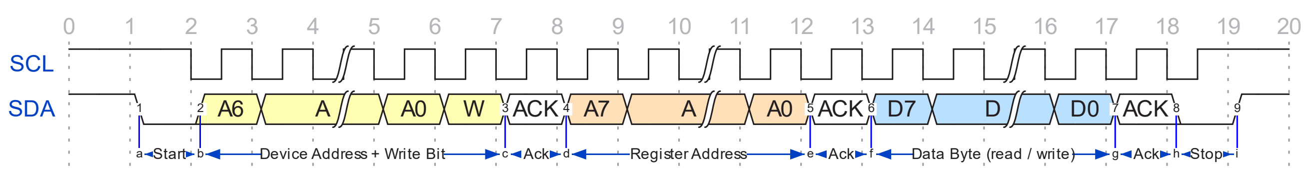

Figure 4: I2C Transmission Example

MANCHESTER CODE

Nearly all Allegros linear and angular sensors can be programmed using a Manchester-based communication protocol (as per G.E. Thomas). It allows an external controller to read and write registers, including EEPROM, using a point-to-point command/acknowledge protocol.

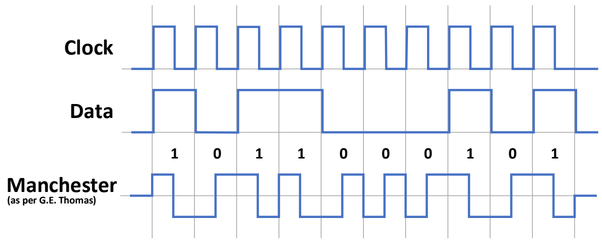

Figure 5: Manchester Code as per G.E. Thomas

Advantages

- Only requires one or two data wires for communication, depending on the implementation.
- Clock and data line combined.
- DC component of the encoded signal is not dependent on the data.
- Self-synchronized.

Limitations

- Low throughput (1B2B encoding).
  Two bits are required for the transmission of one data bit.
- Not as easy to implement compared to other protocols.

Encoding and Decoding

Table 1: Encoding data using XNOR logic

Original Data	Operator	Clock		Manchester Value
0	XNOR or XAND	0	=	1
		1		0
1		0		0
		1		1

To encode data using Manchester Code, a XNOR or XAND calculation must be performed on the desired data and clock to be transmitted (Table 1). The result is a Manchester value, which is used in communication. See Figure 5 for an example. Each bit is transmitted in a fixed time (or period) in which a '0' is expressed by a low to high transition and a '1' is expressed by a high to low transition. These transitions occur at the midpoint of a period. The transitions at the start of a period are overhead and don't contain data.

Implementations

Depending on the Allegro sensor used, there are different methods for initializing Manchester communication. Different Manchester communication methods are outlined below

Enable Over V_{CC}, Data Over V_{OUT}

As for the A1342, the Manchester communication will start with a high voltage level of 8 V on the V_{CC} line, which will stay high until the Manchester communication is done.

During this time, the V_{OUT} line will transmit the data. The high level on V_{OUT} is also set to 8 V while transmitting data via Manchester for this method.

Data Over V_{CC} and V_{OUT}

With the A1363, the method different. While V_{CC} is normally at 5 V, the controller will start transmitting data over the V_{CC} line. The low level is 3.3 V and the high level is 5.6 V. The sensor will respond over the V_{OUT} line instead, with a low level of 0 V and high level of 5 V.

Enable and Data Over V_{OUT}

For some sensors, it is also possible to enable the Manchester transmission over V_{OUT}. To enable Manchester communication, the controller has to pull down the V_{OUT} line for a specific time. This is often called "stomp". After, the V_{OUT} line will be at a High-Z state and will wait for the Manchester command. To finish Manchester communication, it is required to reset a register in the sensor e.g. MANCH_COMM_E for the A31313.

PWM PROTOCOL

PWM is an output protocol option for a multitude of Allegro linear and angular sensors. It converts the output voltage amplitude to a sequence of constant-frequency binary pulses, with a duty cycle directly proportional to the applied magnetic field. The duty cycle for some sensors has limits at 5% and 95% DC corresponding to 0° and 360° respectively. Figure 6 displays the PWM output waveform and corresponding magnetic field angle. For each PWM period, the output is high for the first 5% and low for the last 5%. The middle 90% segment of the wave is a linear interpolation of the desirable signal output, depending on whether it is an angle or linear sensor.

Advantages

- Well-established and simple protocol for microcontrollers.
- Allows easy conversion to analog.
- Only one data wire required.
- Well suited for long wire applications.

Limitations

- Limited amount of information transmitted, e.g. error information.
- Low resolution.
- Low throughput.
- Limited signal verification.

PWM Rates

PWM waveforms typically have rates ranging from 500 to 2,000 Hz with overall protocol latency of approximately one PWM period, depending on sensor settings. Higher PWM frequencies increase output rates but tend to reduce the output resolution.

PWM Error Reporting

When in PWM output mode, the error flags are reported either by disabling the output altogether (High-Z mode) or by transmission error information.

The error information is transmitted by setting the carrier frequency to half of the selected frequency. The duty cycle of the output takes one of several possible values which encode the most significant error. A sensor's datasheet will list error flags in order of their priority. If multiple errors are identified, the one with the highest priority will be transmitted.

In some specific error flag cases, the output is put in a high-impedance state when an error occurs. If the error condition is removed, the output will return to normal operation. This option will prevent the device from transmitting PWM data, however, it will still be possible to read out the error flag via Manchester communication.

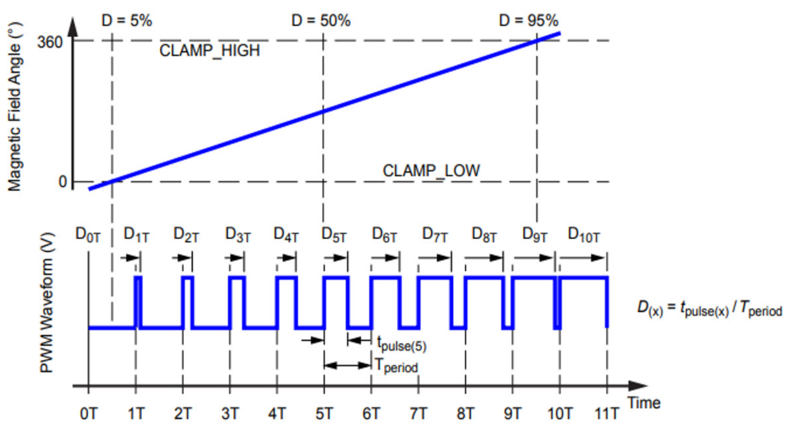

Figure 6: PWM Output Waveform and Magnetic Field Angle

SENT

Allegro supports the Single-Edge Nibble Transmission (SENT) protocol in certain advanced digital output sensor ICs. The SENT protocol is a commonly accepted automotive protocol for highly efficient transfer of sensor data along intravehicular communications networks and is standardized by the Society of Automotive Engineering in publication SAE-J2716.

Advantages

- Optimized for harsh environments.
- Requires just one data line.
- High resolution (12 or 16 bit) data.
- Additional information channels available, e.g. for device temperature or serial number.
- Output information is programmable.
- Low cost.
- Supported by many microcontrollers.

Limitations

- Not as easy to implement as SPI or I²C.
- Low throughput (typically 1 kHz data rate).

General Interface and Timing

A SENT message is a series of nibbles. Each nibble is an ordered pair of a low-voltage interval followed by a high-voltage interval. The low interval is defined as 5 SENT ticks, as shown in Figure 7. The high interval contains information and is variable in duration to indicate the data payload of the nibble.

The duration of a nibble is expressed in clock ticks and the period of a tick can be defined by the user. The duration of the nibble is the sum of the low-voltage interval plus the high-voltage interval (see Table 2). The slew rate of the falling edge can be adjusted within specific EEPROM parameters of the sensor. The nibbles of a SENT message are arranged in the following required sequence (see Figure 8):

1. Synchronization and Calibration: flags the start of the SENT message and provides reference clock synchronization.
2. Status and Communication: provides sensor status and serial message information.
3. Data: magnetic field and optional data.
4. CRC: error checking.
5. Pause Pulse: optional pulse which allows generating constant frame lengths.

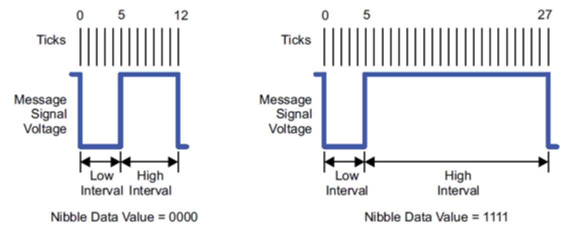

Figure 7: General SENT Nibble Composition

Table 2: SENT Nibble Composition and Value

Quantity of Ticks			Binary (4-bit) Value	Decimal Equivalent Value
Low Voltage Interval	High Voltage Interval	Total		
5	7	12	0000	0
5	8	13	0001	1
5	9	14	0002	2
…	…	…	…	…
5	21	26	1110	14
5	22	27	1111	15

SENT

When configured for Free Running Mode (SENT), the SENT output transmits continuously while in normal operating conditions with no extended pause pulse. There is also an option to add a pause pulse to ensure a constant output rate.

SENT Slow Serial Output

SENT output supports an optional serial message to transmit additional data. The slow serial mode enables transmission of additional data by encoding information in the Status and Communication (SCN) nibble. The encoded data is captured over several transmissions and is then decoded to indicate additional short serial message data. There is a 4-bit Message ID, an 8-bit Data, and a 4-bit CRC for each transmission.

There is also an enhanced serial message, which uses the same bits to transmit information, but is more flexible. The enhanced serial message is able to transmit data in either 12- or 16-bit format. For the 12-bit format, there is an 8-bit Message ID, and for the 16-bit format, there is a 4-bit Message ID. Both have a 6-bit CRC. For more details on the short serial message, refer to the SENT SAE J2716 specification.

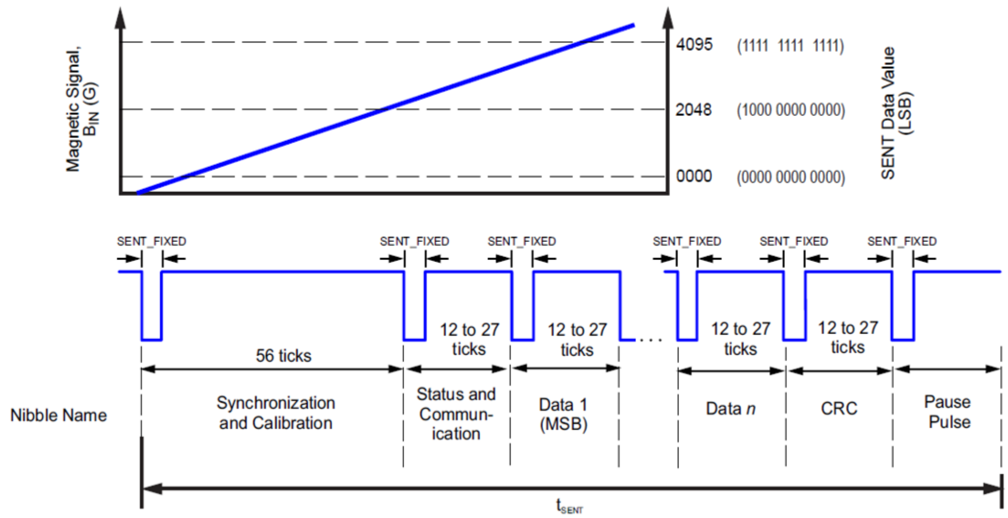

Figure 8: General Format for SENT message

Triggered SENT (TSENT)

When configured for External Trigger Mode, the SENT output transmissions when requested by the external controller. The pause pulse is extended until the next trigger pulse. The external controller initiates a trigger pulse by holding the SENT data line low. The SENT frame is transmitted when external controller releases the output, the rising edge of the trigger pulse. After the rising edge of the trigger pulse, the output remains high for minimum of seven SENT tick times before going low to initiate the start of the SENT synchronization pulse. When using TSENT in SCN sample mode, the latest data from the signal path will be sampled on the falling edge of the SCN nibble to provide the newest possible data for the sensor. When using TSENT in the trigger sample mode, the sensor will sample the data on the falling edge of the trigger. This will allow reduced ambiguity as to when data may be latched between multiple sensors if triggered at the same point in time.

Sequential SENT (SSENT)

The SSENT protocol is used for example in the A1346, which is split into two options, short trigger mode (SSENT Short) and long trigger mode (SSENT Long). Both SSENT options require polling the sensors in sequential order, as seen in Figure 9.

The difference between these two options is how it handles function pulses or triggers of certain lengths. With both protocols, the host controller must pull the output line low for a set length of time to tell the sensor IC to either send the magnetic data, perform a diagnostic test, latch magnetic data, or resynchronize its counter. SSENT Long mode allows for a larger range of F_OUTPUT pulse (SENT trigger) lengths to allow for SPC compatibility. This allows a shorter trigger to be used to request the SENT message, resulting in a faster total message time.

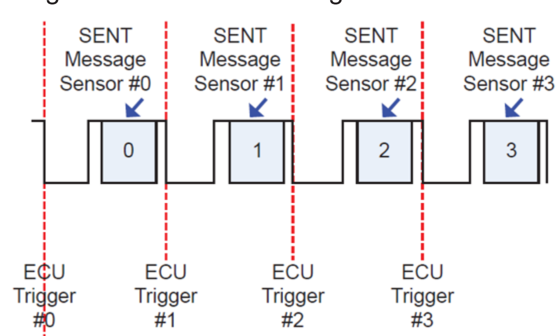

Figure 9: Sequential SENT Output Bus

Addressable SENT (ASENT)

Unlike the SSENT protocol, where the sensors must be polled in sequential order, the ASENT protocol in the A1346 allows for random polling of the sensors. This makes the protocol more robust for when the sensor's handle goes offline and allows for more flexibility in sensor sampling. This robust nature of the protocol comes at a cost of additional message length. For it to be clear which sensor is being polled, the function pulse is accompanied by an addressing pulse consisting of a 7-tick high period followed by the 5-tick low period. This is incremented for each sensor address, with sensor 1 (address 0) having none of these pulses, sensor 2 (address 1) having one of these pulses, etc., as shown in Figure 10. This can add up to 36 additional ticks to the message length for the sensor with address 3, resulting in a trade-off between the robust data bus and possible message polling rate.

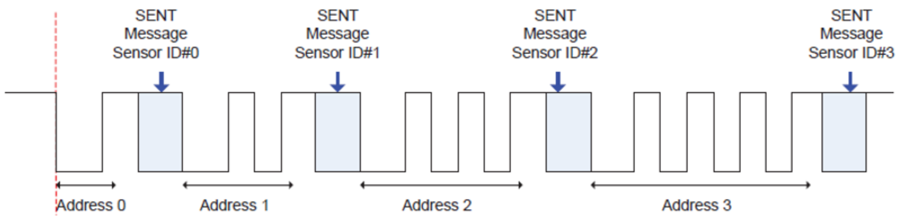

Figure 10: Addressable SENT Output Bus

ANALOG OUTPUT

Analog protocol outputs a linear analog signal between a max and min value proportional to the magnetic field. While in quiescent state, no field is applied, the output voltage equals half of the supply voltage, then under an applied magnetic field the output voltage either increases or decreases linearly depending on the magnet's polarity. This output protocol is illustrated in Figure 11, were the output is converted into a percentage based off the supply voltage. Voltage values beyond the upper or lower limits represent diagnostic regions.

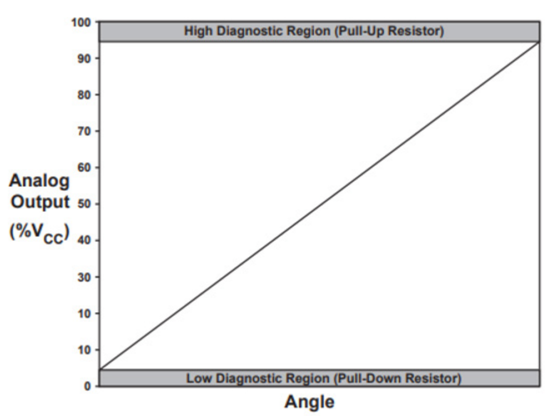

Figure 11: Analog Output

Advantages

- Fast.
- Limited circuitry required.
- Simple output.
- Compatibility between analog sensor often is simple.
- Only one output wire required.

Limitations

- Sensor not capable of outputting additional information.
- Limited amount of information transferred.

Ratiometric and Non-Ratiometric modes

There are two modes for the Analog output: Ratiometric Mode, where the output voltage follows the supply voltage providing a proportional change in the output for any change in supply, and Non-Ratiometric Mode, where a regulated internal supply is used for the output voltage reference. Most Allegro devices offer both options, though selection may depend on the supply being used.

ANALOG OUTPUT ERROR REPORTING

To prevent the device from transmitting an angle reading through the analog output when an error condition is present, the output will go to one of two diagnostic regions defined by the resistive load, which can be a pull-down to ground or a pull-up to a specific voltage. It achieves this by entering a high-impedance state.

ANALOG (SINE / COSINE)

Analog sine / cosine is also a common output protocol in which the angle is represented by a sine and cosine wave output, as shown in Figure 12.

Advantages

- Easy to integrate with most microcontrollers.
- Suitable for long distance wires.
- Low latency.

Limitations

- When operating with a differential and/or dual-die sensor, more signal lines are required.
- Poor interference resistance.
- Requires differential signal lines for robustness.

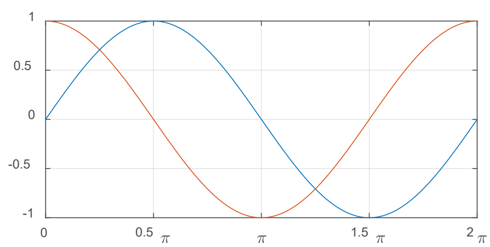

Figure 12: Sine Cosine Output Example

With an analog sine / cosine output, the receiver can use for example an arctan- or cordic function to calculate the angle.

BRUSHLESS DC MOTOR OUTPUT (UVW)

Allegro angle and linear position sensors offer U, V, and W signals for stator commutation of brushless DC (BLDC) motors. Some sensors are mode-selectable for 1 to 16 pole-pairs. The BLDC signals (U, V, and W) are generated based on the quantity of pole-pairs and on angle information from the angle sensor. The U, V, and W outputs switch when the measured mechanical angle crosses the value where a change should occur. If hysteresis is used, then the output update method is different. Hysteresis can be applied to the compensated angle to moderate jitter in the angle output due to noise or mechanical vibration. Figure 13 shows a UVW output for a three-pole pair; it can also be used with a five pole-pair BLDC motors.

Advantages

- Suitable for long wire applications.
- Compatible with hall switches.

Limitations

- Lower output resolution than ABI.
- 3 output lines required.
- Read only.

UVW Rate and Latency

Depending on the selected slew rate, UVW output can be updated at sensor sampling rate, i.e. 1 MHz. Slew rate limiting is enabled through the sensor's EEPROM settings.

UVW error reporting

If the sensor encounters an error, UVW reports this by entering a high-impedance state. The error can later be identified via Manchester communication.

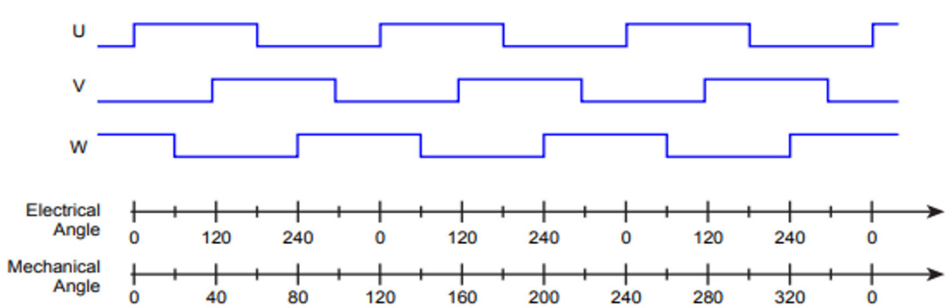

Figure 13: UVW Protocol for a Three-Pole Pair

INCREMENTAL OUTPUT INTERFACE (ABI)

The A1339 offers an incremental output mode in the form of quadrature A/B and index outputs to emulate an optical or mechanical encoder. The A and B signals toggle with a 50% duty cycle (relative to angular distance, not necessarily time) at a frequency of 2N cycles per magnetic revolution, giving a cycle resolution of (360 / 2N) degrees per cycle. B is offset from A by ¼ of the cycle period. The "I" signal is an index pulse that occurs once per revolution to mark the zero (0) angle position. One revolution is shown in Figure 14.

Advantages

- Can output the absolute angle.
- Suitable for long wire applications.
- Can apply angle hysteresis to moderate jitter.
- Offers higher resolution than UVW.
- Compatible with encoders.

Limitations

- Three output lines required in most applications (sometimes the user can omit some).
- Protocol does not show an absolute position prior to seeing the index pulse.
- Read only.

ABI working principle

Since A and B are offset by ¼ of a cycle, they are in quadrature and together have four unique states per cycle. Each state represents R = [360 ÷ (4 × 2N)] degrees of the full revolution. This angular distance is the quadrature resolution of the encoder. The order in which the states change, or the order of the edge transitions from A to B, allow the direction of rotation to be determined. If a given B edge (rising/falling) precedes the following A edge, the angle is increasing from the perspective of the electrical (sensor) angle and the angle position should be incremented by the quadrature resolution (R) at each state transition. Conversely, if a given A edge precedes the following B edge, the angle is decreasing from the perspective of the electrical (sensor) angle and the angle position should be decremented by the quadrature resolution (R) at each state transition. The angle position accumulator wraps each revolution back to 0. ABI output resolutions can be set through a sensor's EEPROM.

The index pulse I marks the absolute zero position of the encoder. Under rotation, this allows the receiver to synchronize to a known mechanical/magnetic position, and then use the incremental A/B signals to keep track of the absolute position. To support a range of ABI receivers, the width of the I pulse can be adjusted within the sensor's EEPROM. The edge of the index pulse corresponding to the "zero" position, as observed by the sensor, will change based on rotation direction. With the magnet rotating such that the observed angle is increasing, the 0° position will be indicated by the rising edge of the Index pulse. If the magnet is rotated in the opposite direction to produce a decreasing angle value, the 0° position will be represented by the falling edge of the index pulse.

ABI error reporting

If the sensor encounters an error, ABI reports this by entering a high-impedance state. The error can later be identified via Manchester communication.

ABI Rate and Latency

Depending on slew rate settings, ABI can have data transfer rates up to 1 MHz with a latency of approximately one sampling period. Slew rate limiting can be enabled through the sensor's EEPROM settings.

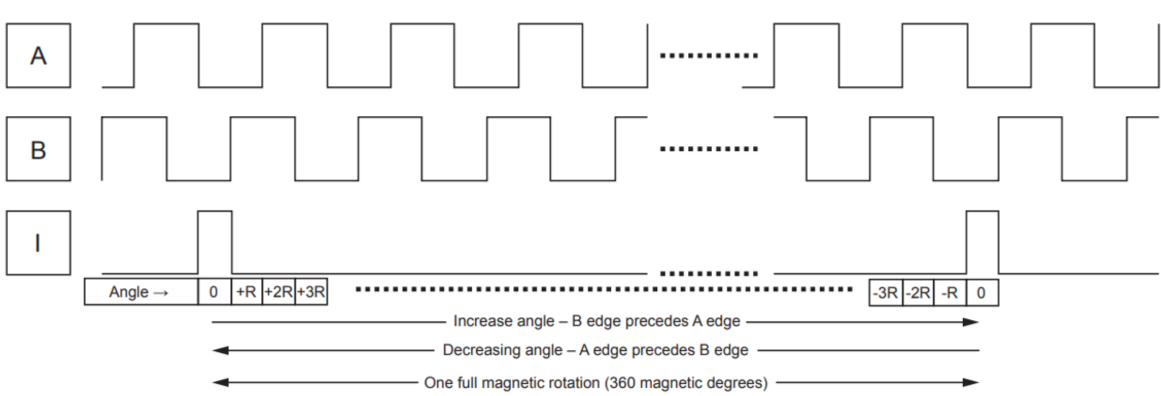

Figure 14: ABI Output Protocol

Revision History

Number	Date	Description
–	July 15, 2020	Initial release

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