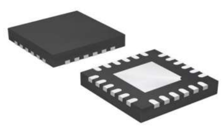
SPX-1 Smart Inductive Proximity Sensor ASIC

Features

- Patented advanced technology platform
- Correction factor 1
- Extended sensing range
- Selective sensing of ferrous or non-ferrous metals
- High switching frequency
- High level magnetic field immunity
- Plug programmable
- Programmable digital temperature compensation
- Intelligent temperature adaptation
- ASIC consumes less than 1.5mA current, suitable for both DC and AC configurations
- Operates with coreless flat sensing coil
- Operates from -40ºC to 125ºC
- Very small 4mm X 4mm QFN24 package



Description

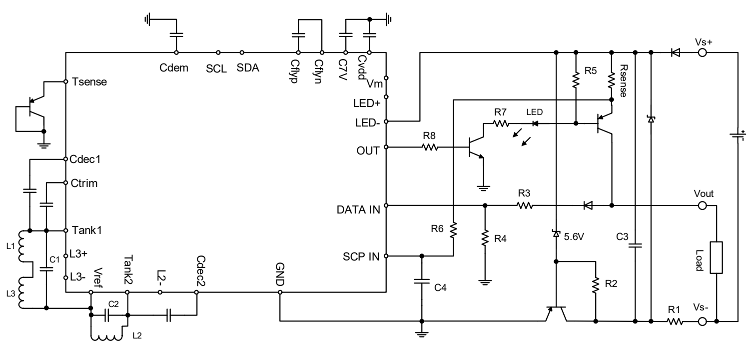
StarryProx® inductive proximity sensor IC is a mixed signal ASIC (SoC) based on a patented technology platform and the industry's first and only smart universal IC capable of both DC and AC applications. The ASIC integrates a microcontroller for controlling multiple detection modes to achieve detection flexibility and programmability. The integrated nonvolatile memory makes programmability and environmental adaptation possible. Since most of the electronics was integrated in the chip the sensor design and manufacturing process is greatly simplified. And reliability is greatly improved. The chip can be used with coreless or PCB coils to achieve high level magnetic field immunity. The chip also has an analog output via I2C for displacement measurement applications.

The plug programmability at the end of production line not only eliminates the need for potentiometer adjustment or laser trimming process, cancels out all production process tolerances and errors, but also greatly simplifies manufacturing process.

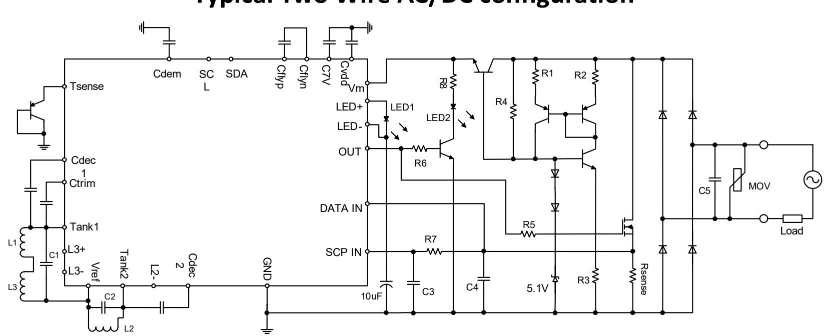
The ASIC can be used for 3 and 4 wire DC, 2 wire AC/DC sensor modules.

The chip's 24pin 4mm x 4mm QFN package makes it possible to build a cylindrical sensor module as small as M8 in diameter. Even smaller sensor modules (down to M5) can be built with tested wafer using chip on board assembly process.

Typical Three Wire DC Source Configuration



Typical Two Wire AC/DC configuration



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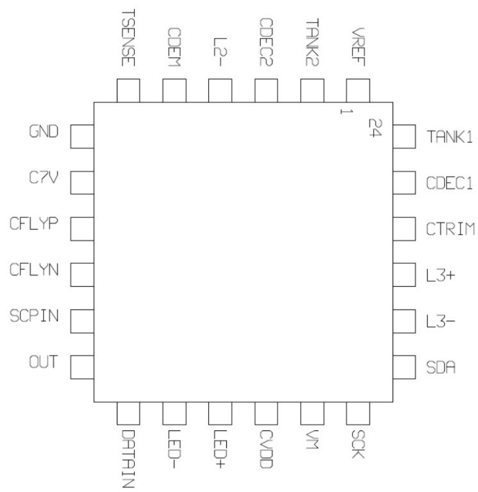
1. Pin Out and Terminal Functions

1.1 Pin Out

SPX-1 QFN24 Package Top View



1.2 Terminal Functions

Terminal Number	Name	Type	I/O	Description
1	Vref	A	O	Middle point of 3.3V regulated voltage rail
2	Tank2	A	O	TANK 2 driver pin
3	Cdec2	A	I	Decoupled TANK 2 signal input
4	L2-	A	O	TANK 2 Miller Inductance driver pin
5	Cdem	A	O	Filter capacitor for signal demodulator
6	Tsense	A	I/O	External temperature sensing diode pin
7	GND	G		Chip ground
8	C7V	A	O	OTP programming voltage filter capacitor
9	Cflyp	A	O	Fly capacitor positive
10	Cflyn	A	O	Fly capacitor negative
11	SCPIN	A	I	Load current sampling input voltage for short circuit protection (SCP)
12	OUT	D/A	O	ASIC output: Analog MOSFET gate control for two wire configuration; Digital output for other configurations.
13	Data In	D	I	Manchester communication input
14	LED-/V+	A	O	Power LED minus for two wire configurations/Supply Voltage for three wire configurations
15	LED+	A	O	Power LED plus for two wire configurations
16	Cvdd	P	O	3.3V regulated voltage filter capacitor
17	Vm	P	I	Power supply for two wire configurations
18	SCK	D	I	I2C communication clock input
19	SDA	D	I/O	I2C communication data input/output

20	L3-	A	O	Optional shielding coil Miller drive pin
21	L3+	A	O	Optional shielding coil Miller input
22	Ctrim	A	O	Phase trimming capacitor drive
23	Cdec1	A	I	Decoupled TANK 1 signal input
24	Tank1	A	O	TANK 1 driver pin

2. Specifications

2.1 Maximum Absolute Ratings

		MIN	MAX	UNIT
Voltage at Vm, LED+		GND-0.3	8	V
Voltage at all other analog pins		GND-0.3	6	V
Voltage at all digital pins		GND-0.3	6	V
OUT pin current	Digital Output		1.5	mA
	Analog Output		60	µA
Current drawn from Tank1 and Tank2 pins			2.5	mA
ESD Tolerance	Human Body Model		1.5	kV
	Charge Device Model		500	V
Junction Temperature, Tj			+150	^oC
Storage Temperature, Tstg		-50	+150	^oC

2.2 Recommended Operating Conditions

Name	Description	MIN	MAX
Vm	Chip supply voltage for two wire configurations	6V	7V
Vled	Power LED forward voltage between LED+ and LED-	1.8V	2.2V
V+	Chip supply voltage for three/four wire configurations	4V	5.5V
Ta	Operating ambient temperature range	-40 ^oC	+125 ^oC

2.3 Electrical Characteristics

Parameter	**Description**	**Conditions**	**Min**	**Typ**	**Max**	**Unit**
Power Supply						
Iv+	Chip supply current	Under recommended operating conditions		1.2	1.5	mA
Iprog	OTP programming current	Additional current consumed during OPT programming		2.5	3.0	mA
Von	LED-/V+ pin power on threshold		3.65	3.70	3.75	V
Voff	LED-/V+ pin power off threshold		3.55	3.60	3.65	V
Tpod	Power on delay time	Two wire AC configuration; Cled- = 10µF; Vac=120V		100		ms

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		All other configurations	5	ms
Front End and Control				
fosc	Oscillating frequency range		0.005 5	MHz
Rp1	Tank1 impedance	At oscillating frequency	0.5 50	kΩ
Idac	Tank1 current drive trim bit		6	bit
Osc Offset	Tank offset trim bit		5	bit
TCdac	Temperature compensation bit		10	bit
Ctrim DAC	Phase trim bit		10	bit
Miller Ctrl	Miller Inductance control bit		4	bit
Data Acquisition and Processing				
ADC Res	Signal ADC resolution		10	bit
ADC Time	ADC conversion time		20	µS
Npulses	Number of pulses used for phase measurement		8	bit
Output and Protection				
Vout	Output voltage range	Two wire configurations	0 Vled-	V
		All others	0 Vdd	V
Iout	Output current	Two wire configurations	60	µA
		All others	1.2	mA
fswitch	Output switching frequency		5	kHz
Vscp	Short circuit or over load condition detection threshold	PNP: Refer to LED-/V+ pin	-220 -180	mV
		NPN: Refer to GND pin	180 220	mV
		Two wire: Refer to GND pin	180 220	mV
Tscp	Short circuit or over load detection response time	Minimum overload current transient pulse width that can be detected	3	µS
Tm	SCP output mark time	For three wire DC configurations	10	µS
Ts	SCP output space time	For three wire DC configurations	200	µS
fled	SCP power LED flashing frequency	For two wire AC/DC configurations	2	Hz
Communication				
fmcc	Manchester comm. clock frequency	Two wire AC configuration	0.5 1	kHz
		All others	0.5 10	kHz
Vdatain	Data input voltage range	Two wire config. Logic 0	0 20	mV
		Two wire config. Logic 1	120 150	mV
		All others Logic 0	0 0.5	V
		All others Logic 1	1.5 5.0	V

fsck	I2C clock frequency			100	kHz
Vsda	I2C data line voltage		Logic 0	0 0.5	V
			Logic 1	1.5 5.0	

3. Detailed Description

3.1 Overview

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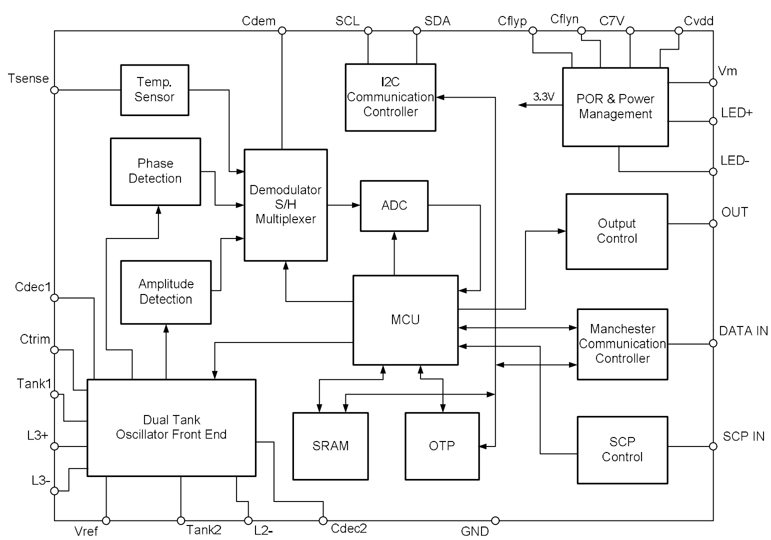
3.2 Functional Block Diagram



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3.3 Feature Description

3.3.1 Dual Tank Oscillator Front End

StarryProx-1 (SPX-1) inductive proximity sensing IC is based on a dual tank LC oscillator architecture. The sensing tank (Tank1) and the matched compensation tank (Tank2) generate differential amplitude and phase signals which are used to detect approaching of a metal target. Different oscillating frequencies as well as different combinations of amplitude and phase signals are used for achieving different sensing modes such as all metal equal sensing (sometimes called “Correction Factor 1”), ferrous or non-ferrous selective sensing.

The third coil (L3) can be used for mounting compensation (active shielding) in shielded sensor module design.

Inductance of both L3 and L2 can be amplified by connected to on-chip Miller Inductance circuitry. This allows use of smaller coils or inductors to achieve influence of much larger ones, which is often desirable for shielded sensor design, or for selective sensing sensor design that needs to run at much lower frequency.

3.3.2 Data Acquisition

Oscillator amplitude signal is acquired through a synchronized demodulation circuit to achieve highly accurate and repeatable data conversion. And phase signal is acquired through leading phase detector and lagging phase detector which consist of high speed zero crossing detection circuit and demodulation circuit, to achieve high resolution phase measurement for oscillation frequency up to 5MHz.

The demodulated DC signals are then fed to sample and hold circuit followed by a 10 bit A to D converter, and the resultant digital signal is processed by the MCU.

3.3.3 Automatic Calibration

The embedded microcontroller and multiple control registers and DACs automatically calibrate the oscillator precisely according to target conditions (without target, with target at trip on point, with target at trip off point), based on the sensing mode selected by user. The calibration is conducted under commands received via one wire Manchester serial communication from an external Programmer. The Manchester communication is usually through the sensor module’s output pins. That means the sensor module is plug programmable.

3.3.4 Embedded MCU, Static and Nonvolatile Memory

The embedded MCU configures and calibrate the oscillator, manages data acquisition and processing, runs software temperature compensation, makes decision and controls sensor output. The MCU makes the chip smart.

The Static memory holds all the system control and status registers for configuration, calibration, and output control. During programming/calibration, the control data is stored in static memory and at the end of the process the data will be burned into the nonvolatile memory which is one time programmable (OTP). If the chip is already programmed, upon power up the configuration and control data will be uploaded into static memory for normal operation.

The following table is the address map of static memory and OTP memory. They share the same address.

Memory Address	Registers	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
0x00 NO_OTP	System Status		WDT_ FLAG	2W/3W	ADC_ BUSY	Sink/ Source		SCP IN	Output
0x01 NO_OTP	ASIC Configuration	SHRT_ LED	ADC_ START	COMP_ FST	CPMP_ ON	TSENSE_ EXT	Signal/ Tempera ture	M1	M0
0x02 NO_OTP	ADCT_L	ADCT7	ADCT6	ADCT5	ADCT4	ADCT3	ADCT2	ADCT1	ADCT0
0x03 NO_OTP	ADCT_M							ADCT9	ADCT8
0x04 NO_OTP	ADCS_L	ADCS7	ADCS6	ADCS5	ADCS4	ADCS3	ADCS2	ADCS1	ADCS0
0x05 NO_OTP	ADCS_M							ADCS9	ADCS8
0x06 NO_OTP	Output Control				FRC_ BANG	OSC_ STRT	Output Enable	Output control	Power LED control
0X07	Phase Pulses	LL7	LL6	LL5	LL4	LL3	LL2	LL1	LL0
0x08	AMPLITUDE_ ADJUST			DBL	IDAC4	IDAC3	IDAC2	IDAC1	IDAC0
0x09	MILR_CONF	MIL_X5	MIL_X2	MIL_ ON2	MIL_ ON1	TC_table		TCo9	TCo8
0x0A	TC_PROG	TCo7	TCo6	TCo5	TCo4	TCo3	TCo2	TCo1	TCo0
0x0B	CTRIM_DAC	VGA27	VGA26	VGA25	VGA24	VGA23	VGA22	VGA21	VGA20
0x0C	OSC_offset	OTR4	OTR3	OTR2	OTR1	OTR0		VGA29	VGA28
0x0D	TEMP_SLOPE	TS7	TS6	TS5	TS4	TS3	TS2	TS1	TS0
0x0E	CurrentLimit/ Tmpres	TMP_ RES2	TMP_ RES1	TMP_ RES0	ILIM_2	ILIM 1	ILIM_ 0	T25-9	T25-8
0x0F	25deg reading	T25-7	T25-6	T25-5	T25-4	T25-3	T25-2	T25-1	T25-0
0x10	TRIP_OFF	OFF-7	OFF-6	OFF-5	OFF-4	OFF-3	OFF-2	OFF-1	OFF-0
0x11	Config/Prog_fla g	PROG_ DONE	TC_ ADPT	TC_AD PT DONE	NO/NC	ES	FS	NS	ST
0x12	ADAPT_ TIME			AT5	AT4	AT3	AT2	AT1	AT0
0x13	Phase_Lead Threshold	Phld7	Phld6	Phld5	Phld4	Phld3	Phld2	Phld1	Phld0
0x14								Phld9	Phld8
0x15	Phase_Lag Threshold	Phlg7	Phlg6	Phlg5	Phlg4	Phlg3	Phlg2	Phlg1	Phlg0
0x16								Phlg9	Phlg8
0x17	NTA (No target amplitude goal of Tank1)	NTA7	NTA6	NTA5	NTA4	NTA3	NTA2	NTA1	NTA0
0x18								NTA9	NTA8
0x20	TC Table / On_ Threshold@ (-40C)	TC07	TC06	TC05	TC04	TC03	TC02	TC01	TC00
0x21								TC09	TC08
…									
0x54	On_Threshold@ 25C	TC267	TC266	TC265	TC264	TC263	TC262	TC261	TC260
0x55								TC269	TC268

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…									
0xA4	TC Table / On_ Threshold@ (+125C)	TC667	TC666	TC665	TC664	TC663	TC662	TC661	TC660
0xA5								TC669	TC668
…									
0XF9	Part Date code			Week	Week	Week	Week	Week	Week
0xFA	Part Date code	YEAR	YEAR	YEAR	YEAR	YEAR	YEAR	YEAR	YEAR
0xFB	WFR_LOT								
0xFC	WFR_NO								
0xFD	Xcoord								
0xFE	Ycoord								
0xFF	Firmware Revision number								

0x00: System Status Register, read only

Bit 0: Output. Indication of pin Out status. “0”—Out low; “1”—Out high.

Bit 1: SCP IN. Indication of short circuit/over load condition. “0”—no; “1”—yes. Setting of SCP IN means a 200mV threshold (irrespective of source or sink) has been detected for at least 3uS. Setting of SCP IN also cause an interrupt to the MCU.

Bit 2: Not used.

Bit 3: Sink/Source. Sensor module output circuit configuration. “0”—Source, when SCPIN pin is near LED-/V+ voltage; “1”—Sink, when the SCPIN pin is near GND.

Bit 4: ADC_BUSY. ADC status. “0”—Not busy or conversion completed; “1”—Busy. Set of ADC_BUSY means there is a measuring operation taking place. This could mean a temperature measurement, a phase detection, or an amplitude detection. It is initiated by set of ADC_START bit (see register 1) and is self-cleared when the measurement is completed. Notice the length of time is variable for different measurements, for example, a phase detection could take many tens of uS plus another 13uS for the ADC proper, meaning a 100uS measuring cycle is not unexpected. A temperature or amplitude measurement should take less than 20uS.

Bit 5: 2W/3W. Sensor module circuit configuration. “0”—three wire; “1”—two wire. 2W/3W is a measurement of the VM pin. VM is high only for 2W configuration and consequently bit 5 is set for 2W mode.

Bit 6: WDT_FLAG. “0”—No watch dog timer reset; “1”—WDT reset occurred. WDT_FLAG is normally low. The WDT_FLAG is set when the watchdog timer reaches terminal count. Clearing the WDT is a MCU function (or a reset function) .

Bit 7: Not used.

0x01: ASIC Configuration Register, R/W

Bits [3:0] control the input mux to the ADC, and are assigned as follows:

[X,1,0,0] = Measure TANK1 amplitude
[X,1,0,1] = Measure DIFF signal (TANK1 - TANK2)
[X,1,1,0] = Measure LEAD (TANK2 leads TANK1)
[X,1,1,1] = Measure LAG (TANK2 lags TANK1)
[0,0,X,X] = Measure Temperature INTERNAL
[1,0,X,X] = Measure Temperature EXTERNAL

Bit 4: CPMP_ON. Charge pump is turned on if set. This is used to write to the OTP section. It can be operated by the Manchester, but is usually operated by the MCU.

Bit 5: COMP_FST. Phase detection voltage comparator in “fast” mode if set. It’s only expected to use this fast mode for initial calibration. Comparator consumes more current when works in fast mode.

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Bit 6: ADC_START. Setting this bit initiates measurement cycles irrespective of what is being measured, and automatically sets ADC_BUSY bit. ADC_BUSY resets when measurement completed. The ADC_START bit self clears at the end of a measurement cycle.

Bit 7: SHRT_LED. This control bit is used in 2W mode to turn-off the power led between LED+ and LED-. Normally SHRT_LED is LOW and the LED is on; making this bit HIGH will short LED+ to LED-.

0x02: ADCT_L. Temperature (internal or external) ADC result, LSBs. 8 bits.

0x03: ADCT_M. Temperature (internal or external) ADC result, MSBs. 2 bits in Bit0 and Bit1.

0x04: ADCS_L. Signal (amplitude or phase) ADC result, LSBs. 8 bits.

0x05: ADCS_M. Signal (amplitude or phase) ADC result, MSBs. 2 bits in Bit0 and Bit1.

0x06: Output Control Register.

Bit 0: Power LED Control. Power LED is turned off when set. Used for flashing power LED under short circuit/over load protection conditions. The difference between this bit and SHRT_LED bit is that there is a 800ohm resistor connected between LED+ and LED- internally, instead of shorting LED+ and LED-.

Bit 1: Output Control. “0”—Make Out pin OFF (low). “1”—Make Out pin ON (high). Output Control has different meanings depending on 2W or 3W operation. For 2W, output control LOW means the external gate drive is near GND, when HIGH the gate is driven to maintain a CLOSED_LOOP control irrespective of the output load resistance. In 3W mode the OUTPUT is HIGH when the BIT1 is HIGH; the OUTPUT will be LOW when Bit 1 is LOW.

Bit 2: Output Enable. “0”—Out pin is disabled (tri-state); “1”—Out pin is enabled (controlled by Output Control bit). Output Enable allows tri-state over-ride at the OUTPUT pin. In 2W mode tri-state means holding the output FET gate near GND. In 3W mode tri-state means the output is neither a HIGH or a LOW, the output is not driven at all and appears to be an open circuit. The tri-state condition is the default state upon power up. Output Enable must be HIGH to allow any output control at the OUTPUT pin.

Bit 3: OSC_STRT. Start oscillator once set. It is used to “kick-start” the tank (with the programmed current amplitude) by providing a current pulse during positive half cycle through the internal comparator in the oscillator circuit. Osc_Start default state is LOW, the MCU must bring it HIGH to initiate the oscillation of TANK1.

Bit 4: FRC_BANG. Emergent start of oscillator once set. Frc_Bang is used to force a large current pulse (400uA) directly into Tank1. This is a “fail-safe” method to start the sensor-oscillator in the unlikely case of the oscillation not starting via the Bit 3 control. This is considered an “emergency” condition, it is under control of the MCU.

NOTE: Registers 0x01 through 0x06 reside in static memory only. Data in these registers (static memory cells) cannot be moved into OTP memory by Manchester command OTP.

0x07: Phase Pulses. Number of pulses used for phase measurement. 01-FF.

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0x08: AMPLITUDE_ADJUST. Adjust oscillation amplitude through controlling current pumped into Tanks. 6 bits.

0x09: MILR_CONF. Miller Inductance configuration register and others.
Bit 0-1: TCo9 TCo8. Hardware temperature compensation TC MSBs.
Bit 2: Not used.
Bit 3: TC_Table. Flag for indication of existence of a TC table for software TC compensation.
Bit 4: MIL_ON1. Coil L3 Millered when set.
Bit 5: MIL_ON2. Coil L2 Millered when set.
Bit 6: MIL_x2. Miller gain=2 when set.
Bit 7: MIL_x5. Miller gain=5 when set.

Bit 7	Bit 6	Miller Gain
0	0	10
0	1	2
1	0	5

0x0A: TC_PROG. Hardware temperature compensation TC LSBs. 8 bits.

0x0B: CTRIM_DAC. Phase trim register LSBs. 8 bits.

0x0C: OSC_Offset. Fine trim of Tank amplitude offset.
Bit 3-7: 5 bit OSC_Offset register.
Bit 0-1: Phase trim register MSBs. 2 bits.
Bit 2: Not used.

0x0D: TEMP_SLOPE. Digital changes of temperature sensor ADC data per temperature step (2.5°C). 8 bits.

0x0E: CurrentLimit/TMPres.
Bit 0-1: T25-8, T25-9. Temperature sensor reading at 25°C, MSBs. 2 bits.
Bit 2-4: ILIM0, ILIM1, ILIM2. Chip current peak limiter.
Bit 5-7: TMP_RES0, TMP_RES1, TMP_RES2. Temperature chamber resolution in ±°C.

0x0F: 25deg reading. Temperature sensor reading at 25°C, LSBs. 8 bits.

0x10: TRIP_OFF. Sensor trip off hysteresis. 8 bits.

0x11: Config/Prog_Flag. Sensing mode configuration and programming flags.
Bit 0: ST. Single tank sensing configuration when set.
Bit 1: NS. Non-ferrous selective sensing configuration when set.
Bit 2: FS. Ferrous selective sensing configuration when set.
Bit 3: ES. All metal equal sensing configuration when set.
Bit 4: NO/NC. “0” –Normally closed output; “1”—Normally open output.
Bit 5: TC_ADPT Done. Set when TC adaptation is completed.
Bit 6: TC_ADPT. “0”—No TC adaptation is to be done. “1”--TC adaptation is to be done.

Bit 7: PROG_DONE. “0”—Chip will go to Manchester communication mode upon power on. “1”—Chip will bypass Manchester communication and goes to normal operation mode.

0x12: ADAPT_TIME. Total time needed for TC adaptation process, in hours. Bit 0-5, 6 bits.

0x13: Phase_Lead Threshold, LSBs. Leading phase threshold for non-ferrous selective sensing.

0x14: Phase_Lead Threshold, MSBs. Phld8, Phld9, 2 bits.

0x15: Phase_Lag Threshold, LSBs. Lagging phase threshold for ferrous selective sensing.

0x16: Phase_Lag Threshold, MSBs. Phlg8, Phlg9, 2 bits.

0x17: NTA (No target amplitude goal of Tank1), LSBs.

0x18: NTA, LSBs. 2 bits.

0x19: Not used.

0x20-0xA5: TC Table for software TC compensation. Each term is the output decision threshold at different temperature point, with 8 bits LSBs at address 0xaa and 2 bits MSBs at 0x(aa+1).

0xA6-0xF8: Not used.
0xF9: Chip date code, week.
0xFA: Chip date code, year.
0xFB: WFR_Lot. Wafer lot.
0xFC: WFR_NO. Wafer number.
0xFD: Xcoord. Die X coordinate on wafer.
0xFE: Ycoord. Die Y coordinate on wafer.
0xFF: Firmware Revision Number.

3.3.5 Programmable Temperature Compensation

To achieve highly accurate and sophisticated temperature compensation, the ASIC implemented a two stage programmable temperature compensation scheme. The first is a hardware linear temperature compensation with a programmable TC that can be chosen by user. On top of that, the second temperature compensation is a look up table based software compensation scheme that achieves nonlinear temperature compensation of output decision making threshold. The TC look up table can be acquired in two ways: through characterization data based on typical sensor module samples, or through a self-learning process called Temperature Adaptation.

TC table made up of characterization data should be good enough for most applications. For applications that require the longest sensing distance or extremely stable temperature performance, the Temperature Adaptation process allows acquisition of individual TC table for each and every sensor module, after it’s fully made.

Please see Section 4 (Typical Applications) and Section 7 (Advanced Design Technics and Atypical Applications) for details.

3.3.6 Output Control and Short Circuit/Over Load Protection

The ASIC consumes less than 1.5mA current and can be used for two wire AC/DC, three wire DC pnp/npn (source or sink), or four wire complimentary output sensor modules, with simple external voltage regulators.

The chip OUT pin has digital output voltage levels of 0V and 3.3V for three and four wire DC configurations. It has 0V-5V continuous analog output MOSFET gate control voltage for two wire AC/DC configurations.

The load current can be sampled through an external current sampling resistor and the load current signal will be fed to SCP IN pin. When SCP IN signal reaches above the SCP protection threshold for minimum 3µs, the chip will go into SCP/OL protection mode. In SCP/OL protection mode, the OUT pin will pulse at 5% duty cycle for three/four wire configurations. The sensor output will return to normal operation once SCP/OL conditions removed. For two wire configuration, the OUT pin will be latched low once going into SCP/OL mode. And the power LED will be flashing at a frequency of 2 Hz. The only way to get the sensor back to normal operation is to have the SCP/OL condition removed and the power reset.

The ASIC automatically detects the two/three/four wire and PNP/NPN configurations according to module level PCB connections and components installed.

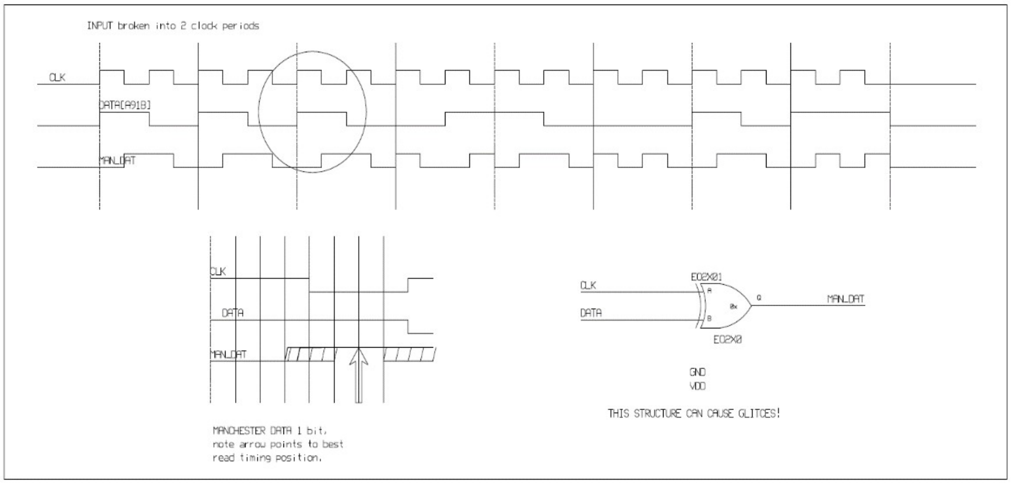
3.3.7 Manchester Communication

SPX-1 uses one wire Manchester communication protocol through sensor module’s existing power and signal leads for communicating to the chip programmer.

MANCHESTER GUIDELINES:

Manchester communications occur on a single wire.
Communications are “burst” mode, meaning there are no spaces or blank intervals in a single transmission. After the transmission to the ASIC occurs, the line is left at “zero” and later the ASIC responds on the same line.
Transmissions can be as fast as 20KHz guaranteed. The 20KHz refers to the CLK line that is used to generate the Manchester code. Transmissions as slow as 500Hz are allowed.
The encoding scheme is shown in figure below, CLK is the top trace.

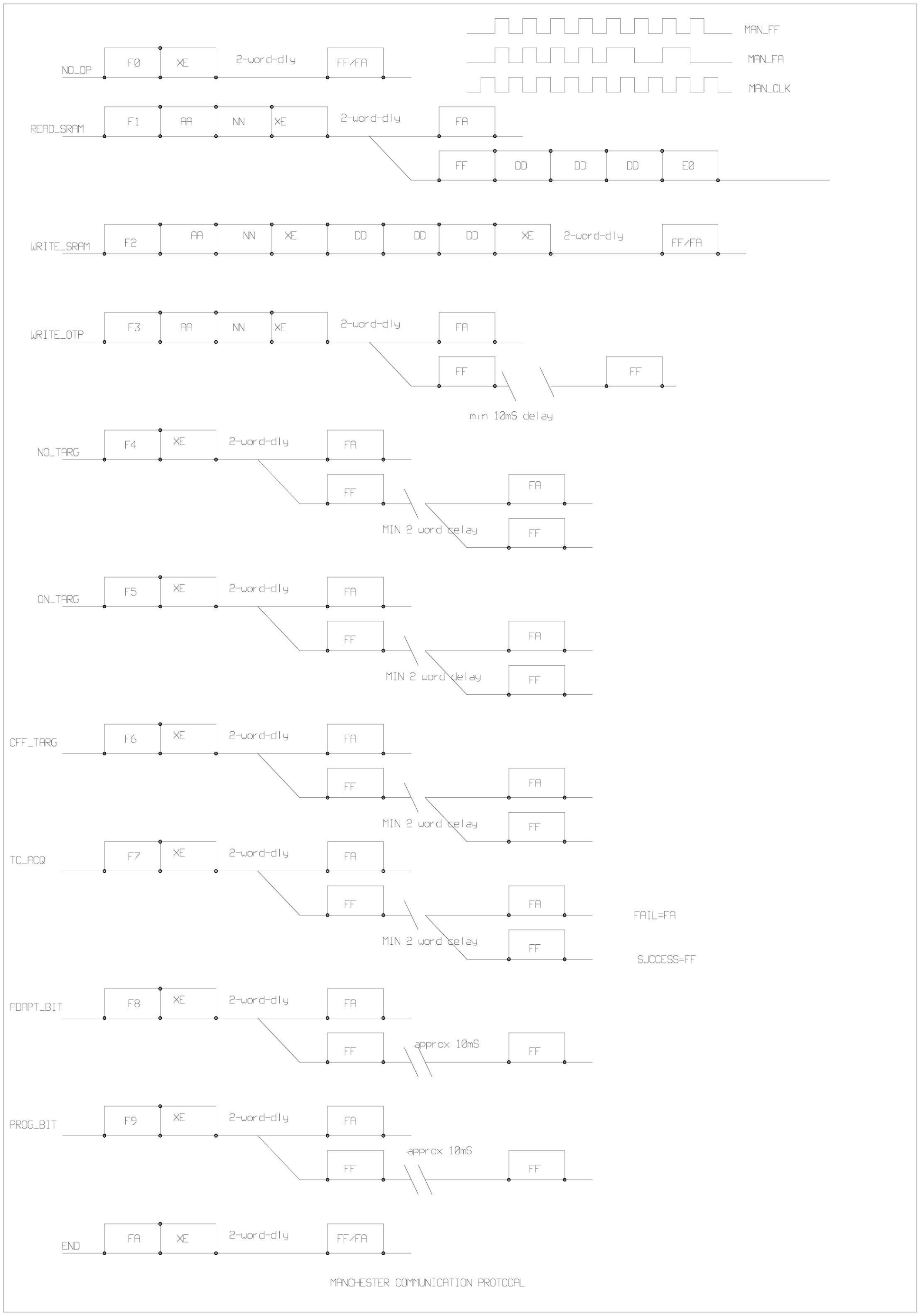
SPX-1 Smart Inductive Proximity Sensor ASIC



In the above figure we see the data is changing on the positive edge of clock. The MAN_DAT is the result of CLK and DATA being XOR'ed. The bottom left section of the figure is not germane to the transmission protocol, rather, it shows the “sweet spot” for the RECEIVER to recover the data.

The figure below shows the available commands along with timing expectations.
X refers to a single nibble, which will affect the E (CRC) calculation. This allows the user to select any code to “improve” the possibility of error correction detection.
The only responders are FF or FA. FF is the positive responder, FA is the negative responder.
READ commands have a CRC at the end of the read response. This E is calculated using the RESPONSE only (nothing from the command) and INCLUDES the FF synch bits.
WRITE commands include 2 E (CRC) calculations. The first E is used to validate the command and the second E is used to validate the ENTIRE string, from FF synch all the way to last data byte.
The seed value for all CRC is 10011.

SPX-1 Smart Inductive Proximity Sensor ASIC



SPX-1 Smart Inductive Proximity Sensor ASIC

3.3.8 I2C Communication

I2C COMMUNICATIONS

The I2C interface is able to write and read all memory on the chip. The total memory space is 8Kbytes (requiring 13 address bits). Each memory word is 8bits. The OTP registers are made of 256 words each and the RAM blocks are 256 or 128 blocks each.

The address space is as follows (notice each entry is a 13 bit address):

0_0000_(00h-FFh) (this represents 256 registers, each has a 13 bit addresse)
0_0001_(00h-FFh)
0_0010_(00h-FFh)
0_0011_(00h-FFh)
continues in sequence..
0_1111_(00h-FFh)
1_0000_(00h-FFh)
1_0001_(00h-FFh)
continues in sequence..
1_1011_(00h-FFh) so far we have 28 blocks of PROG_ROM OTP.
Continues in sequence..
1_1100_(00h-FFh) this is 256 bytes of SRAM , accessible to Manchester.
1_1101_(00h-FFh) this is 256 bytes of OTP , for mirroring the Manchester.
1_1110_(00h-FFh) this is 256 bytes of OTP as "standby", generally for overwrites
1_1111_(00h-7Fh) ONLY 128 bytes of RAM, used by the MCU.
1_1111_(80h-EFh) NON EXISTANT, will always return 0 when read.
1_1111_(F0h-FFh) Special registers for OTP write.

USER NOTE: The manchester can read and write to 256 addresses (registers) because it has 8 bits of address available. For the I2C to access the same physical address space requires an I2C address of 1_C_[XX]h

I2C WRITES

We assume the user is familiar with the I2C buss concepts of START, STOP, ACK, and NACK. The slave address for this device is 0101010. Note this is 7 bits because the lsb of the slave address is R/WR. (1 for read, 0 for write).

The device handles single writes..

A single write consists of a slave address, the destination address (16 bytes), and the data. All data and address are MSB first.

The address space has 16 bits available, and the physical memory has only 13 bits leaving 3 bits of special use. The address bits then are:

[CHPMP, PRG, AUTO, address[12:0].

The CHGPMP turns on the Charge-pump.
The PRG is a bit to enable writing to OTP.
The AUTO is used to auto-increment the address counter for reads.

I2C READS

The format of the read command is slave-address(including the read), ACK, read, read, read, until a NACK is incurred. The read begins at the last address that was written.

Note the special function of the AUTO bit in the write command. When AUTO is set by a previous write, the read sequence is incremented automatically; when the AUTO is not set the read command continuously reads the same register.

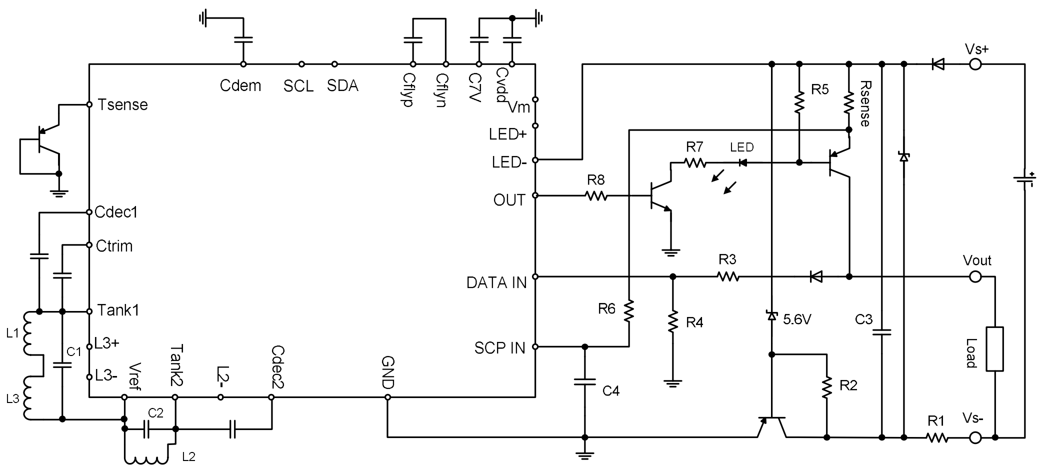
Setting the AUTO bit allows the entire memory to be read, leaving the AUTO not set allows one to observe changes in the memory, for example, watching the ADC register for changes real time.

The MCU clock operates at 2Mhz, the I2C clock can run at 25Mhz; the master must be able to operate at I2C clock speeds.

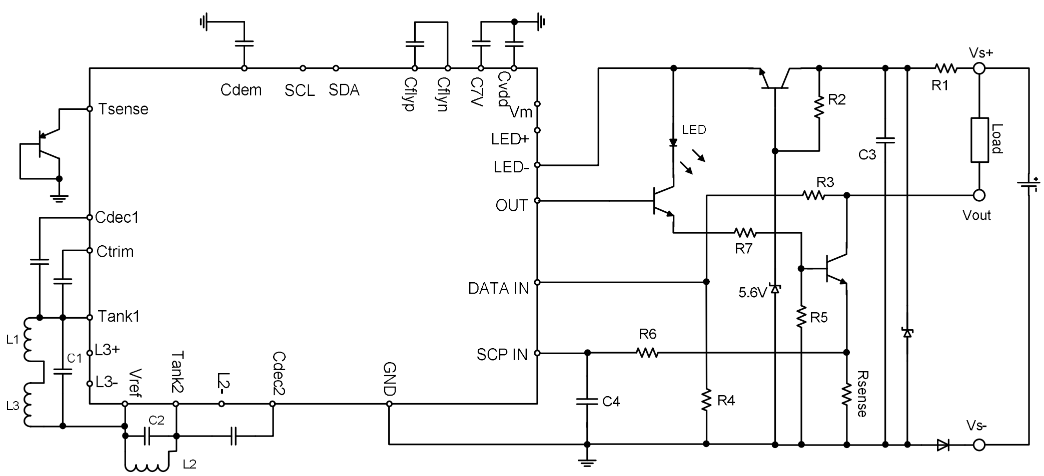
4. Typical Applications

4.1 Typical Output Configurations

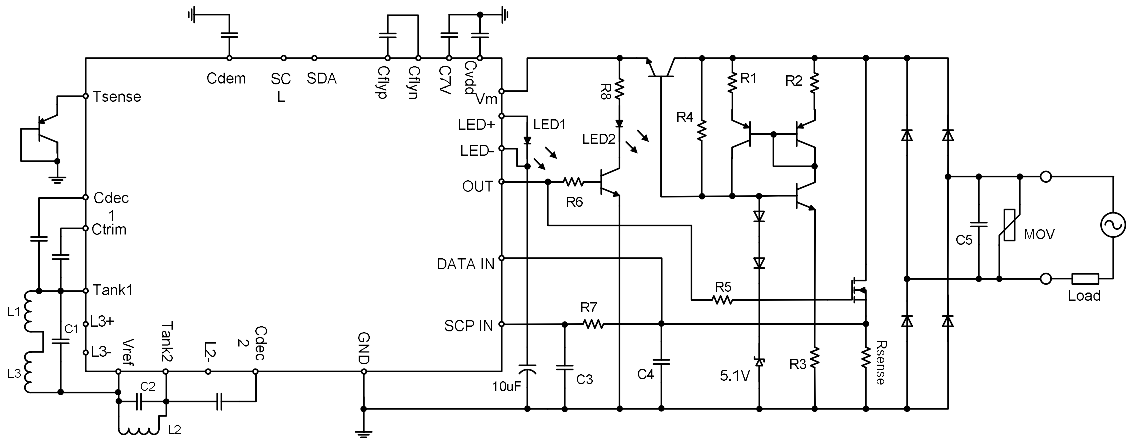
4.1.1 Three Wire DC PNP (Source) Configuration



4.1.2 Three Wire DC NPN (Sink) Configuration



4.1.3 Two Wire AC/DC Configuration



4.2 Typical Sensing Modes

The SPX-1 can be configured and programmed for four different sensing modes: All Metal Equal Sensing, Non-ferrous Selective Sensing, Ferrous Selective Sensing, and Conventional Eddy Current Loss Sensing.

4.2.1 All Metal Equal Sensing

All metal equal sensing sometimes is also called Correction Factor 1. It means all metals are sensed at the same distance.

To achieve equal sensing, two matched LC tanks (one sensing tank and one reference tank) are used and the oscillator runs at relatively high frequency (>500 kHz). The sensing coil (L2) usually takes the form of a multilayer PCB coil (of course it could be any coil winding), and the inductor within the reference tank (L1) can be in the form of a multilayer PCB coil on the main PCB of the sensor module, or any coil winding or inductor components.

Program the Config/Prog_flag register (0x11) to set the “ES” bit:

0x11	Config/Prog_flag	PROG_ DONE	TC_ ADPT	TC_AD PT DONE	NO/NC	ES	FS	NS	ST

The SPX-1 automatically matches the two tanks’ resonance frequency through adjusting a trimming capacitance (Ctrim) in parallel with reference tank, and matches two tanks’ oscillation amplitude through adjusting the offset current pumping into the two tanks. These will be done without a target in front of the sensing coil. This process is done when SPX-1 receives a Manchester command called “NO_TARG” (means No Target Calibration), and it achieves minimized differential signal between the two tanks.

The presence of a metal target in front of sensing coil L2 will cause the differential signal between the two tanks to increase. With a standard target sitting at the intended sensing distance, a Manchester command “ON_TARG” will prompt SPX-1 to take the differential signal as the trip on threshold. Move target farther to the intended trip off point and a Manchester command “OFF_TARG” will prompt SPX-1 to take the differential signal as trip off threshold.

4.2.2 Non-ferrous Selective Sensing

Non-ferrous selective sensing means the sensor will sense target made of non-ferrous materials only and ignore any target made of ferrous materials.

Similar to equal sensing, this sensing mode also requires two matched LC tanks—one sensing tank (Tank 2) and one reference tank (Tank 2). The major difference is the oscillator needs to oscillate at frequency below 30 kHz. This usually requires both coils wound on a ferrite core. A typical arrangement of the two coils (sensing coil L2 and reference coil L1) is placing them back to back, with the sensing coil open to the sensing face.

Program the Config/Prog_flag register (0x11) to set the “NS” bit:

0x11	Config/Prog_flag	PROG_ DONE	TC_ ADPT	TC_AD PT DONE	NO/NC	ES	FS	NS	ST

The calibration process is the same as that of equal sensing, except that the target used for calibration is made of a non-ferrous material (e.g. copper).

4.2.3 Ferrous Selective Sensing

Configuration and program of ferrous selective sensing is the same as those of non-ferrous selective sensing except the following:

Program the Config/Prog_flag register (0x11) to set the “FS” bit:

0x11	Config/Prog_flag	PROG_ DONE	TC_ ADPT	TC_AD PT DONE	NO/NC	ES	FS	NS	ST

Use a target made of ferrous material (e.g. mild steel) for calibration.

4.2.4 Conventional Eddy Current Loss Sensing

This sensing mode gives user an opportunity to design a sensor module with just one tank (Tank 2) without a reference tank. The oscillator becomes a more conventional eddy current killed oscillator (ECKO) but with advanced two stage programmable TC compensation. The sensor will have correction factors less than 1 for different materials.

The calibration process is similar to the above modes except for the following:

Program the Config/Prog_flag register (0x11) to set the “ST” bit:

0x11	Config/Prog_flag	PROG_DONE	TC_ADPT	TC_ADPT DONE	NO/NC	ES	FS	NS	ST

Use a target made of mild steel for calibration.

4.3 Designing Temperature Compensation

4.3.1 Hardware TC Compensation

The programmable hardware temperature compensation can be programmed by user choosing a value for the 10 bit TC_PROG register:

0x09	MILR_CONF	MIL_X5	MIL_X2	MIL_ON2	MIL_ON1	TC_table		TCo9	TCo8
0x0A	TC_PROG	TCo7	TCo6	TCo5	TCo4	TCo3	TCo2	TCo1	TCo0

The value can be chosen by experience or experiment to minimize the signal drift over temperature. This TC compensation is linear and is aimed to compensate the coil winding copper resistance drift over temperature.

4.3.2 TC Compensation Look Up Table Through Sample Characterization

On top of hardware TC compensation, the SPX-1 has an additional TC compensation look up table which holds 67 terms of 10 bit values that cover temperature range from -40^{o}C to +125^{o}C, with temperature step size of 2.5^{o}C. The storage of the look up table in the memory map is shown in the following table.

The contents of the look up table are actually the variable decision making threshold of the sensor at different temperature points.

Formation of TC Table:

With target sitting at “trip on” point, collect differential output amplitude (or Tank1 amplitude for ST mode) values (trip on threshold), at temperature step size of 2.5^{o}C from minimum temperature to maximum temperature (up to 67 temperature points for maximum temperature range from -40C to 125C), using sample module devices. For reduced temperature range, say from -25C to 75C, or with larger temperature steps (say, 5^{o}C, or 10^{o}C), data needs to be extrapolated or interpolated to fill the whole table (total 67 terms).

Follow these steps to make the table:

1) For each sample i, calculate “trip on threshold” TC at each temperature point Tj using formula: TCij=(TOTH@Tj)/(TOTH@25C)
2) Calculate average TCj among all samples at each temperature point Tj using formula: TCAj=1/n*∑TCij, (i=1, …, n—number of sample devices used for TC data characterization)
3) Run interpolation if necessary to get TCA values at all temperature points with

temperature step size 2.5^{o}C within interested temperature range.

4) Fill the table with 67 terms by “Saturating” the data that may be outside the specified temperature range (extrapolation).
5) Times TCAj with a constant (Mid, about 512) to get a 10 bit value (0-1023 decimal) table.
6) Save generated 10 bit TC table to a file that will be later attached to sensor module configuration profile.
7) During sensor module product programming process, the programmer will calculate “trip on threshold” value at each temperature point using formula: TOTH@Tj=TOTH@25^{o}C*TCAj/Mid.
8) The above TOTH@25^{o}C was made available from “With Target ON Calibration” of that particular sensor module during product programming process, at 25^{o}C.

0x20	TC Table / On_ Threshold@ (-40C)	TC07	TC06	TC05	TC04	TC03	TC02	TC01	TC00
0x21								TC09	TC08
…									
0x54	On_Threshold@ 25C	TC267	TC266	TC265	TC264	TC263	TC262	TC261	TC260
0x55								TC269	TC268
…									
0xA4	TC Table / On_ Threshold@ (+125C)	TC667	TC666	TC665	TC664	TC663	TC662	TC661	TC660
0xA5								TC669	TC668

Two more register parameters needed for software TC compensation operation:

- 0x0D: TEMP_SLOPE. Digital changes of temperature sensor ADC data per temperature step (2.5^{o}C). 8 bits.

0x0D	TEMP_SLOPE	TS7	TS6	TS5	TS4	TS3	TS2	TS1	TS0

This register value needs to be put in during product programming. The value was obtained during TC table acquisition.

- 0x0E and 0x0F: 25deg reading. Temperature sensor reading at 25^{o}C, 8 bits LSBs in 0x0F and 2 bits MSBs in 0x0E.

0x0E	CurrentLimit/ Tmpres	TMP_ RES2	TMP_ RES1	TMP_ RES0	ILIM_2	ILIM 1	ILIM_ 0	T25-9	T25-8
0x0F	25deg reading	T25-7	T25-6	T25-5	T25-4	T25-3	T25-2	T25-1	T25-0

This temperature sensor reading at 25C is obtained during product programming process.

4.3.3 TC Compensation Look Up Table Through TC Adaptation

To achieve even higher sensing distance or even better temperature performance, SPX-1 has a TC adaptation feature that allows each individual sensor module to acquire its own unique TC table through self-learning after the sensor module is fully built and preprogrammed at room temperature. This is done by resetting the power of the sensor module in a sweeping temperature chamber for some time (typically 24 hours).

To do this, the TC_ADAPT bit in the Config/Prog_Flag register will need to be set during programming.

0x11	Config/Prog_flag	PROG_DONE	TC_ADPT	TC_ADPT DONE	NO/NC	ES	FS	NS	ST

The programming procedure is the same as that described in Section 4.3.2 except that the TC table doesn't need to be generated and stored in SPX-1's memory during product programming.

Install the programmed sensor module in a temperature chamber with a target at the nominal sensing distance. Upon power up, the sensor module will enter TC Adaptation mode. Sweep the chamber temperature within the product's specified temperature range. To get best result, the temperature should be evenly swept with a temperature step size as close to 2.5°C as possible and make sure enough soak time is maintained at every temperature point. Larger temperature step size will work too, as the SPX-1 will do linear interpolation between temperature points with larger step size.

The TC Adaptation operation will complete when total time period set for the operation runs out. The register ADAPT_TIME holds the total hours set for the operation. The total time is up to 63 hours.

0x12	ADAPT_TIME			AT5	AT4	AT3	AT2	AT1	AT0

Register Tmpres (Bit 5-7) holds temperature chamber resolution (or tolerance) when it reaches a steady state, which is used by SPX-1 to identify if the chamber has stabilized at a temperature. The range of this register is up to ±7°C.

0x0E	CurrentLimit/ Tmpres	TMP_RES2	TMP_RES1	TMP_RES0	ILIM_2	ILIM 1	ILIM_0	T25-9	T25-8

4.4 Designing Active Shielding for Flush Mountable Sensor Module

One of the biggest technical challenges when designing an inductive proximity sensor with aggressively extended sensing range is to make it flush mountable into a metal mounting fixture without changing sensor's performance. SPX-1's detection principle allows use of an active shielding mechanism to actively compensate the influence of the surrounding metal.

L3 seen in the DC Source configuration typical application diagram in Section 4.1.1 is such an active shielding coil. The design principle is that when properly designed, the surrounding metal's influence on the sensing coil L2 will be compensated by its influence on the active shielding coil L3.

One Starrycom's proprietary implementation of the active shielding scheme is illustrated in Fig.1 below. A close-up look of the design details is shown in Fig.2.

SPX-1 Smart Inductive Proximity Sensor ASIC

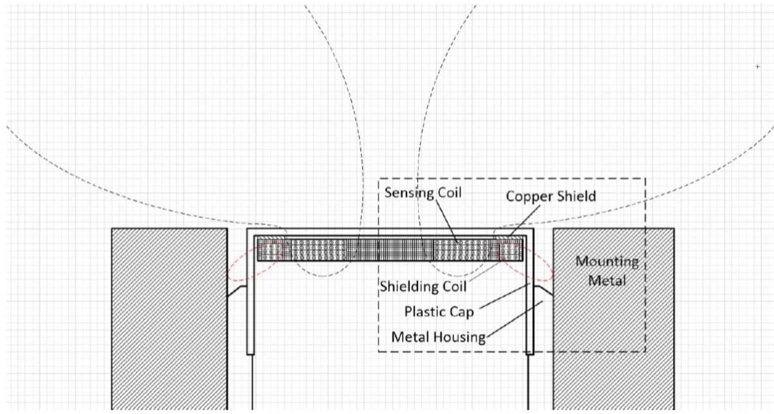


Fig. 1 An Implementation Scheme of Active Shielding

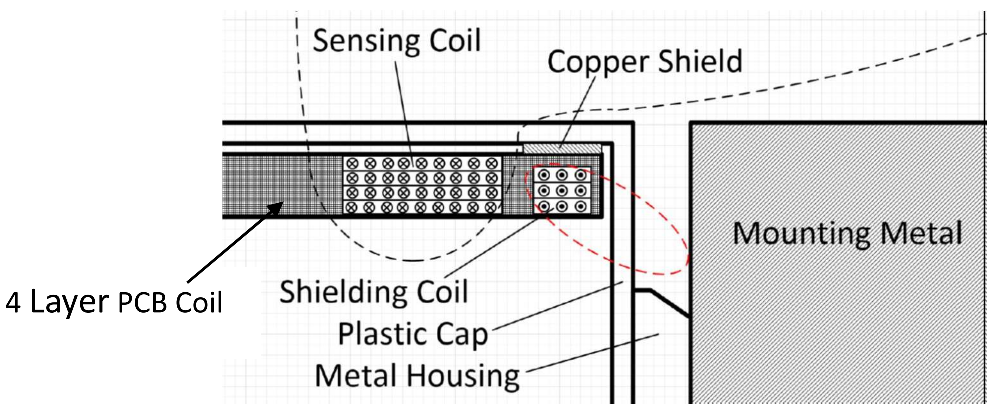
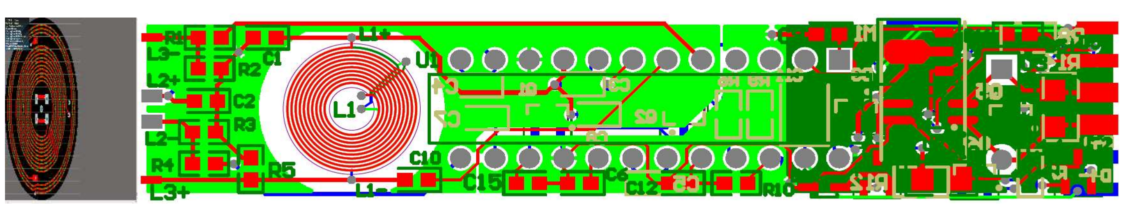


Fig.2 A Close-up Look at the Design Details

The design comprises a copper ring shield with thickness of 0.25mm and is placed in front of the shielding coil (L3); the sensing coil (L2) and the shielding coil (L3) implemented with a single piece of 4 layer printed circuit board (PCB); the plastic cap protruding approximately 4 mm to the front end of the metal housing. With properly designed coils L2 and L3 the cylindrical sensor module can be mounted flush with the surrounding metal as shown in the figures, even with aggressively extended sensing distance.

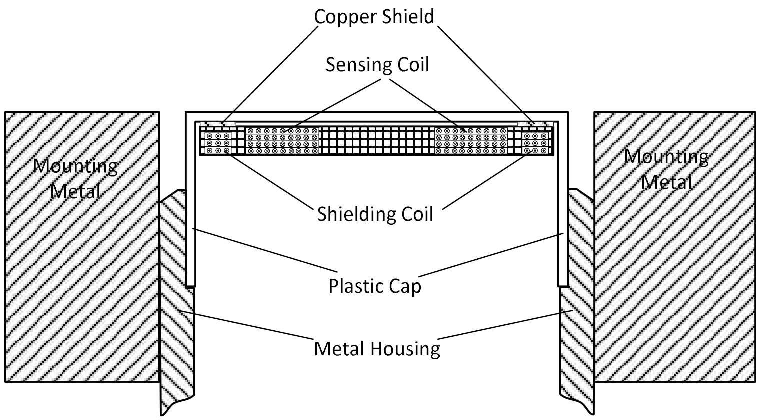
5. PCB Design Guidelines



6. Mechanical Design Guidelines

SPX-1 Smart Inductive Proximity Sensor ASIC

The mechanical design of a typical flush-mountable cylindrical proximity sensor module is shown below.



Sensing coil and shielding coil are constructed on a single 4 layer PCB, with shielding coil made of three layers and sensing coil of four layers of conductors.

A copper ring with 0.25mm thickness is placed in front of shielding coil for better shielding and sensing performance.

The plastic cap that holds the coil PCB and the copper shield ring is inserted into the metal housing with about couple of millimeters protrusion outside the housing. The resulted sensor module may look like unshielded or semi-shielded, but actually it can be fully flush mounted into metal without changing performance.

7. Advanced Design Technics and Atypical Applications

   SPX-1 has some special features that can be used to achieve certain module design objectives like

8. Footprint and Package Data

9. Order Information

10. Technical Support

    10.1 SPX-1 Programmer

    10.2 SPX-1 Evaluation Board

    10.3 Application Notes

    10.4 Support Contacts