New Technological Platform for Digital and Smart Sensor Systems Integration

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Outline

1. Introduction: Definitions and Markets
2. Modern Technologies
3. Smart Sensors Design: Preface
4. Quasi-Digital Sensors State-of-the-art
5. Smart and Intelligent Sensors Design
6. Smart Sensor Systems Integration
7. Summary

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Introduction

- **EPoSS** – The European Technology Platform on Smart Systems Integration
- **3SI** - The European Technology Platform on Smart Sensor Systems Integration

Smart Sensor Definition

- Sensors: ‘Smart’ vs. ‘Intelligent’
- ‘Smart’ relates to technological aspects
- ‘Intelligent’ relates to intellectual aspects

Smart sensor *is a combination of a sensing element, an analog interface circuit, an analog to digital converter (ADC) and a bus interface in one housing*

Intelligent sensor *is the sensor that has one or several intelligent functions such as self-testing, self-identification, self-validation, self-adaptation, etc.*

Smart and intelligent sensors and systems ?

Modern Sensors and MEMS Markets

- Sensors Market in Europe earned revenues of $12.5 billion in 2009 and estimates this to reach $19.0 billion in 2016
- 5 % growing is observed in the sensors industry at the first Q1 of 2010 (*AMA Association for Sensor Technology*)
- World smart sensors market is projected to reach $ 7.8 billion by 2015 (*Global Industry Analysts*, *Inc*.)
- Sensor networks and smart sensors are being used widely in automotive industry, medical, industrial, entertainment, security, and defence *(BizAcumen, Inc*.*)*
- Strong growth expected for sensors based on MEMS-technologies, smart sensors, sensors with bus capabilities and embedded processing.
- MEMS sensors market is set to return to growth in 2010 after two straight years of decline

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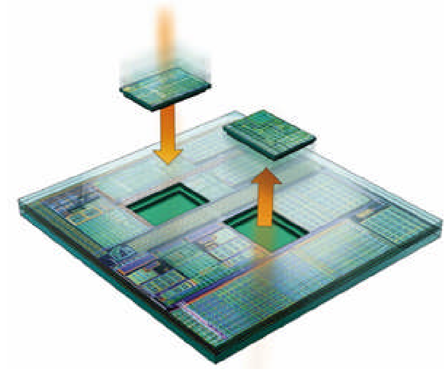
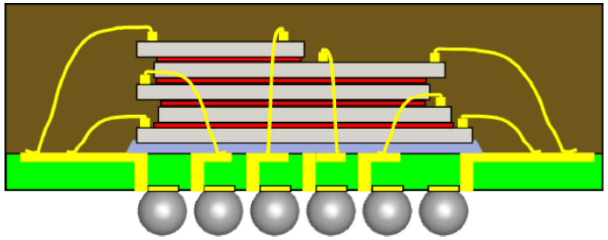
Smart Sensors Technologies



System-on-Chip (SoC)



System-in-Package (SiP)

- Hybrid technologies
- IC-compatible 3D micro-structuring
- System-on-Chip (SoC)
- System-in-Package (SiP)
- 45 nm CMOS process (*STMicroelectronics, CMP*)
- 40 nm CMOS process, (*TSMC, Europractice*)
- 32 nm CMOS process

Technological Limitations

- Below the 100 nm technology processes the design of analog and mixed-signal circuits becomes essentially more difficult
- Long development time, risk, cost, low yield rate and the need for very high volumes
- The limitation is not only an increased design effort but also a growing power consumption
- However, digital circuits becomes faster, smaller, and less power hungry

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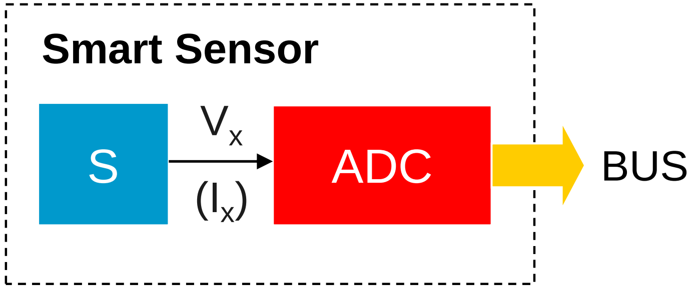
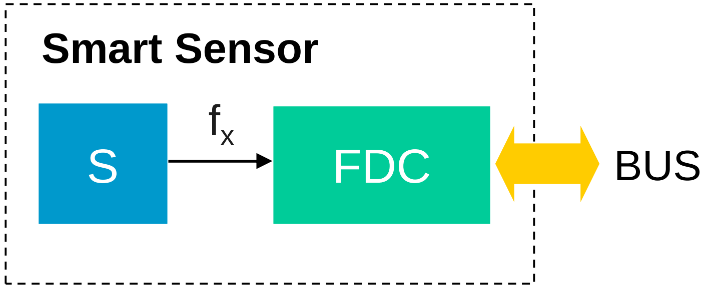
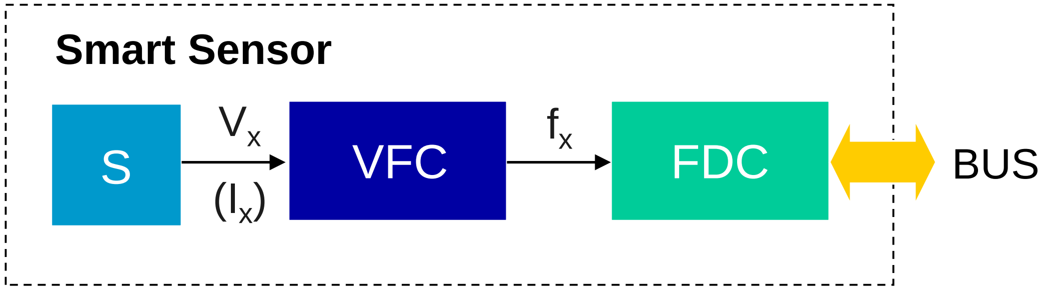
Smart Sensors Design



- Classical approach

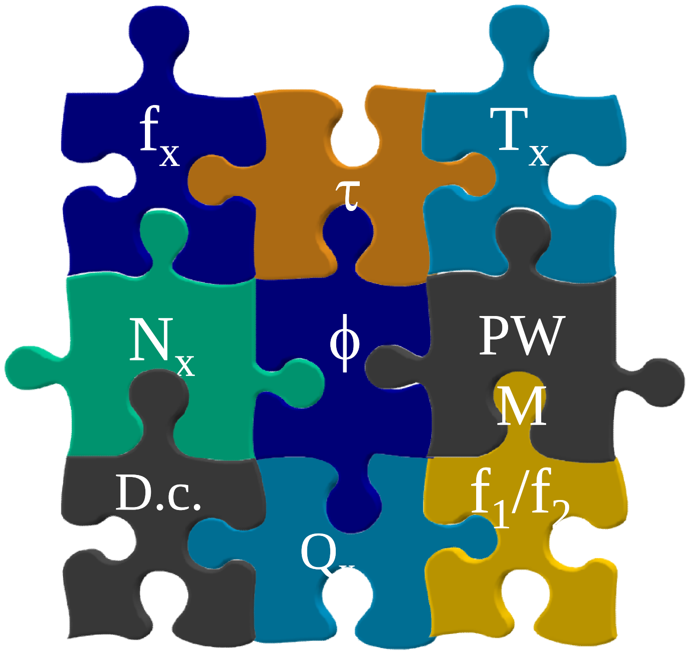




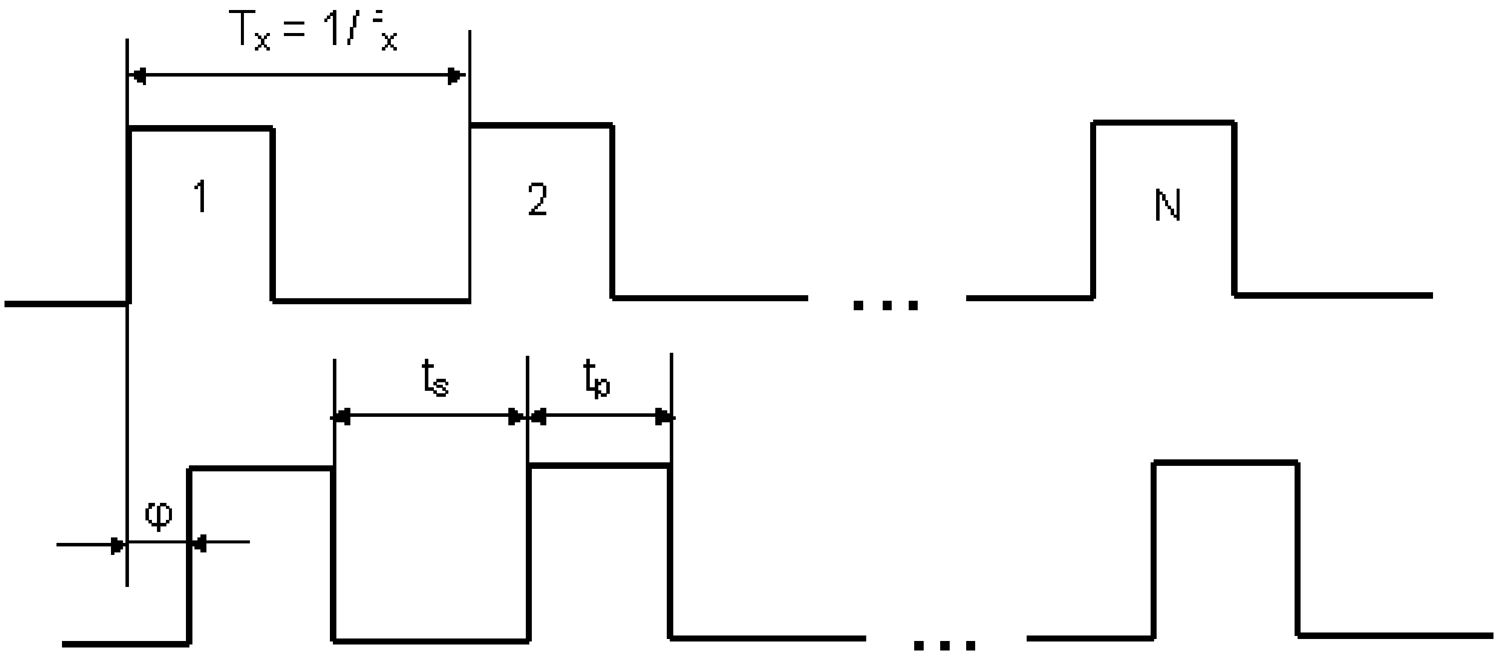
- Proposed approaches

Frequency-Time Domain Parameters of Signal

Frequency-time domain parameters of signal are: frequency, period, its ratio and difference, frequency deviation, duty-cycle (or duty-off factor), time interval, pulse width (or space) pulse number, PWM or phase shift output.



Informative Parameters



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Frequency Advantages

- High Noise Immunity
- High Power Signal
- Wide Dynamic Range
- High Reference Accuracy
- Simple Interfacing
- Simple Integration and Coding
- Multiparametricity

High Noise Immunity

- Objective property due to a frequency modulation
- Frequency signal can be transmitted by communication lines too much greater distance
- Only two-wire line is necessary for transmission of such signal
- Data transmitting does not require any synchronization
- Frequency signal is ideal for high noise industrial environments

High Power Signal

- Section from a sensor output up to an amplifier input is the heaviest section in a measuring channel for signal transmitting from a power point of view
- Losses, originating on this section can not be filled any more by any signal processing
- Output powers of frequency sensors, as a rule, are considerably higher

Wide Dynamic Range

- Dynamic range is not limited by supply voltage and noise
- Dynamic range of over 120 dB may be easily obtained

High Reference Accuracy

- Crystal oscillators can be made more stable, than the voltage reference:
  - non-compensated crystal oscillator has up to $(1 \div 50) \cdot 10^{-6}$ error
  - temperature-compensated crystal oscillator has up to $10^{-8} \div 10^{-10}$ error
- Minimum possible error for frequency measurements with the help of quantum frequency standard is 10^{-14}, minimum possible quantization step for time interval is 10^{-12} seconds

Simplicity of Interfacing

- Parasitic electromotive force (emf), transient resistances and cross-feed of channels in analog multiplexer at the usage of analog sensors are reasons for errors
- Frequency modulated signal is not sensitive to all listed factors
- Multiplexers for frequency output sensors and transducers are simple enough and do not introduce any errors

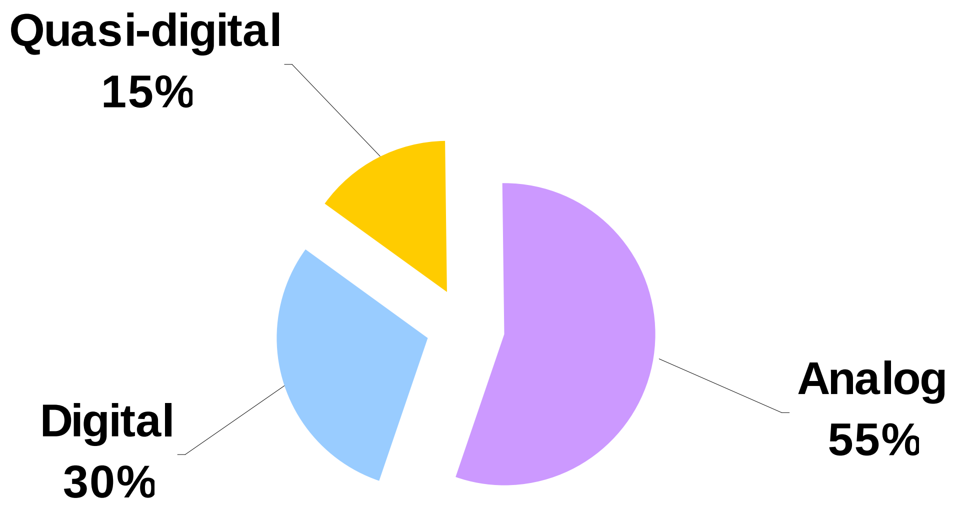
Simplicity of Integration and Coding

- Digital pulse counter is an ideal integrator with unlimited time of measurement
- Frequency signal can be processed by microcontrollers without any additional interface circuitry

Multiparametricity

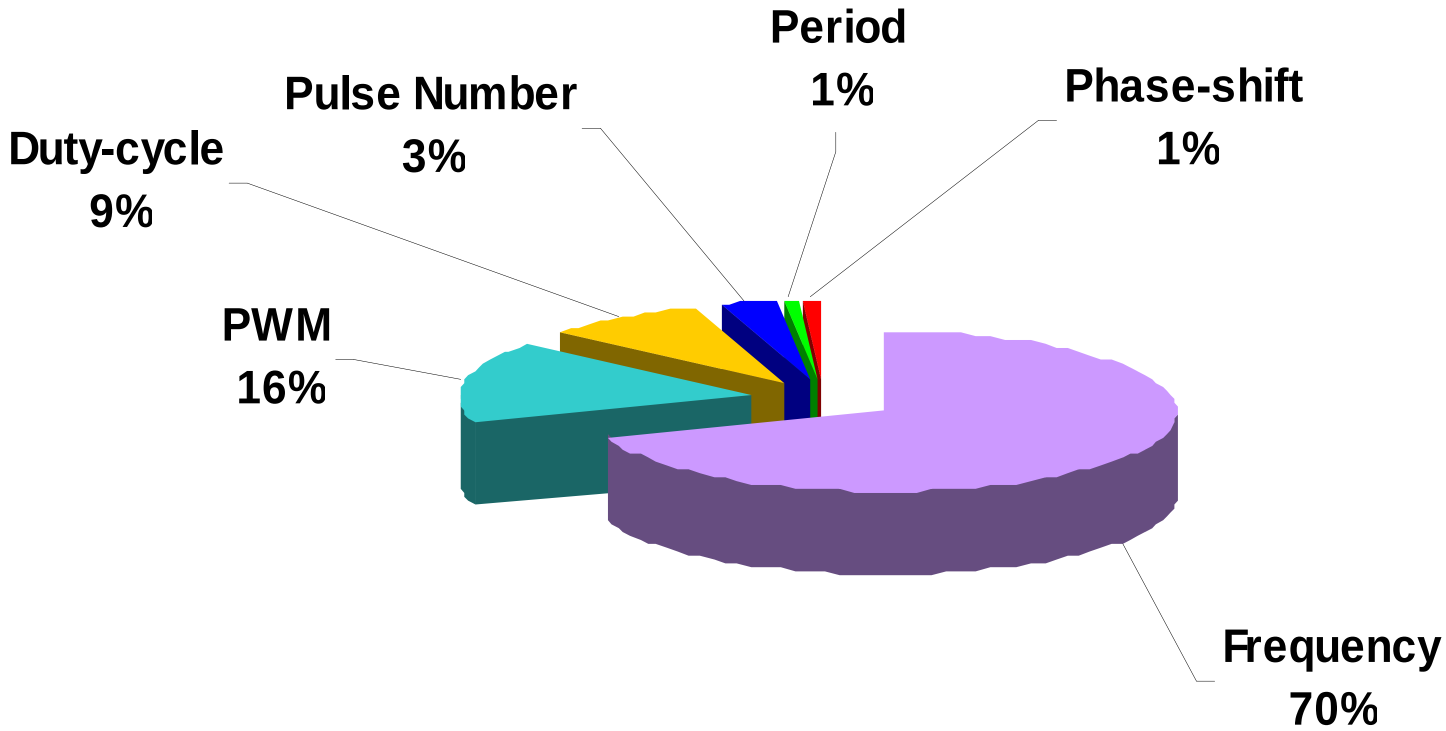
- One sensor's output - two informative parameters: a frequency is proportional to the physical quantity X and duty-cycle at the same output is proportional to the physical quantity Y
- Today there are some examples
- It is the future of multiparametric, multichannel and multifunctional sensors systems

Global Sensor Market



Global sensor market (IFSA, 2009)

Quasi-Digital Sensors



Classification of quasi-digital sensors in term of output signal (IFSA, 2009)

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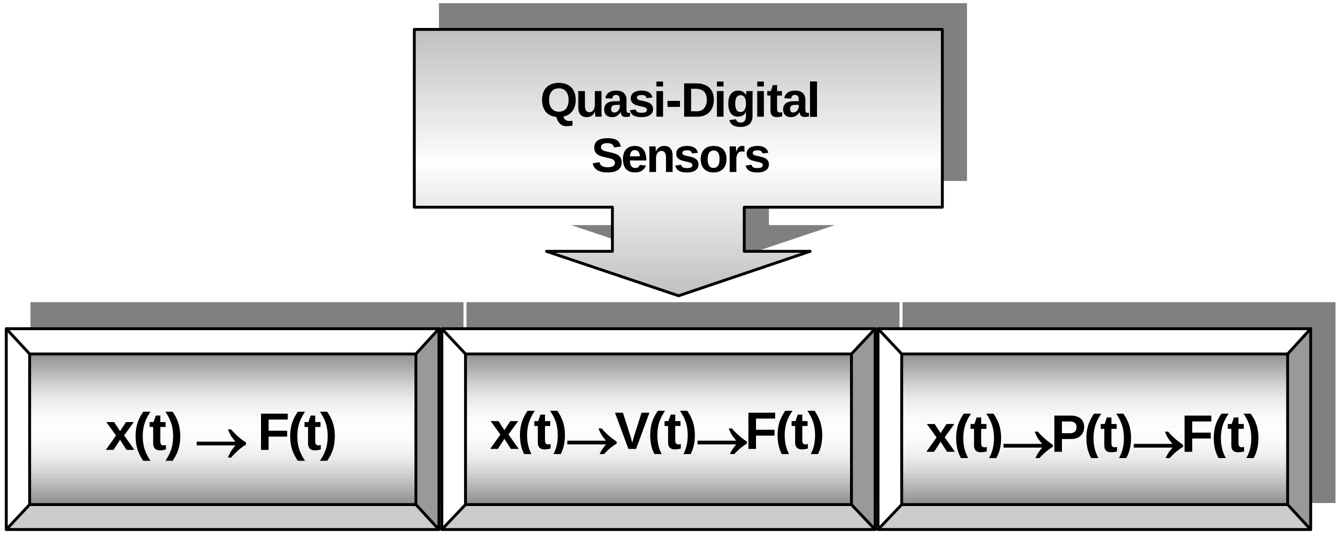
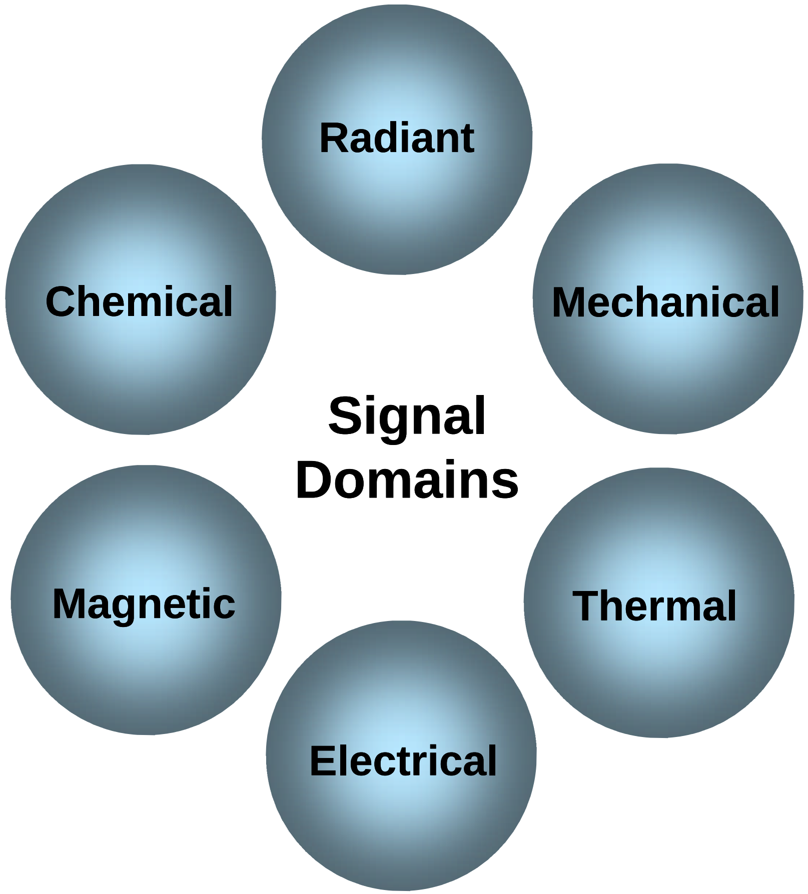
Quasi-Digital Sensor Classification



x(t)–measurand; F(t)–frequency; V(t)–voltage, proportional to the measurand; P(t)–parameter

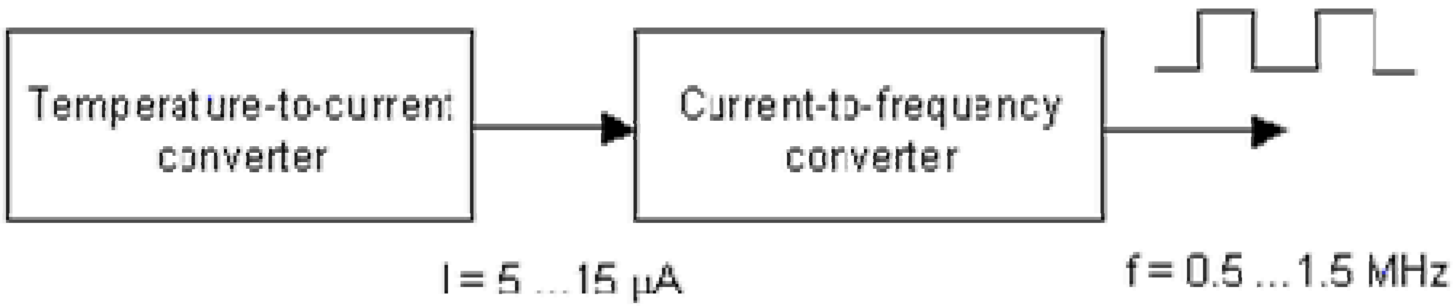
Six Sensors Signal Domains



Temperature Sensors

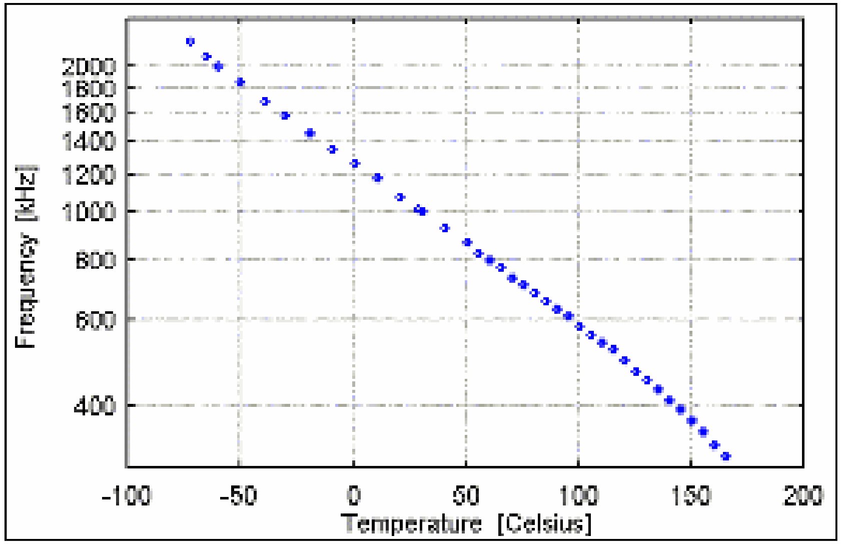
- Sensing element take advantage of the variable resistance properties of semiconductor materials
- Provide a good linear frequency, period, duty-cycle or pulse width modulated (PWM) output
- Direct temperature reading in quasi-digital form

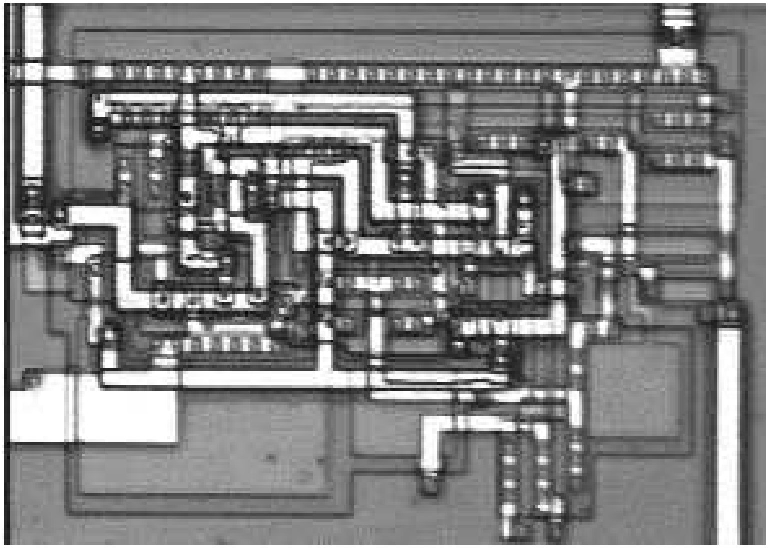
Sensor for Thermal Monitoring



$$f = \frac{I_{out}}{2 \cdot C_x (V_C - V_D)}$$

THSENS-F





$$f_{out} = f_{20Cels} \exp(\gamma(T_{Cels} - 20^0 C)),$$

where γ is the sensitivity, f_{20Cels} is the nominal frequency related to T=20 ^{0}C

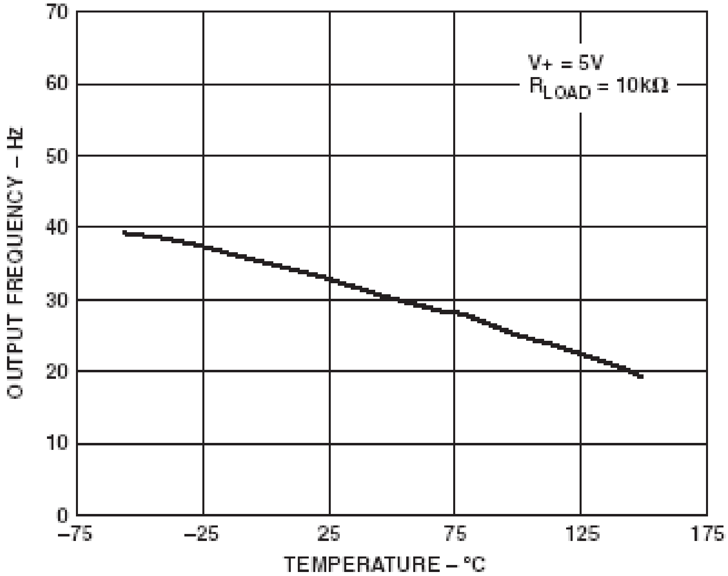
Temperature Sensors

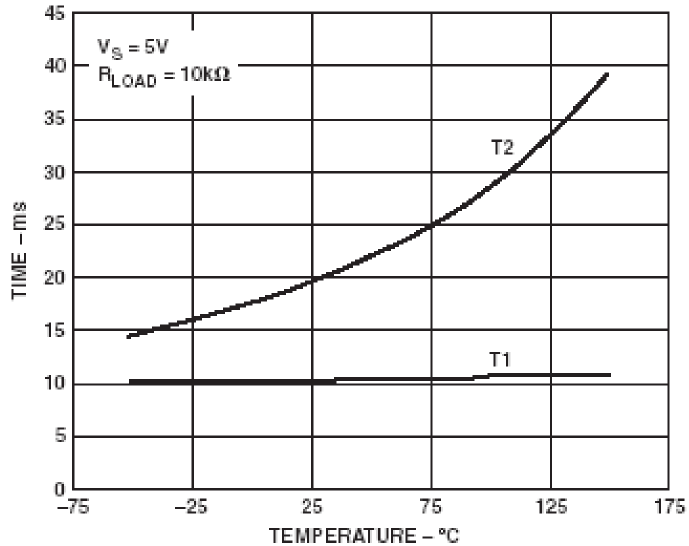
Sensor	Max. Temp. Error, °C	Temp. Range, °C	Resolution, Bits	Output	Output Range
Analog Devices					
TMP03	± 1.5	-40 to +100	16	PWM	-
TMP04	± 1.5	-40 to +100	16	PWM	-
TMP05	± 0.5	-40 to +150	12	PWM	-
TMP06	± 0.5	-40 to +150	12	PWM	-
Maxim Integrated Products					
MAX6576	± 3.0	-40 to +125	N/A	Period	0.0023 to 0.26 s
MAX6577	± 3.0	-40 to +125	N/A	Frequency	14.57to1592.6 Hz
MAX6666	± 1.0	-40 to +125	11	PWM	-
MAX6667	± 1.0	-40 to +125	11	PWM	-
MAX6672	± 3.0	-40 to +125	N/A	PWM	-
MAX6673	± 3.0	-40 to +125	N/A	PWM	-
MAX6676	± 1.5	-40 to +125	N/A	PWM	-
MAX6677	± 1.5	-40 to +125	N/A	PWM	-
Sea-Bird Electronics					
SBE 3F	± 0.001	-5 to +35	N/A	Frequency	2 to 6 kHz
SBE 3plus	± 0.001	-5 to +35	N/A	Frequency	2 to 6 kHz
SBE 8	± 0.01	-3 to +30	16	Frequency	0.1 to 200 Hz
Slope Indicator					
VW	± 0.3	-20 to +80	N/A	Frequency	N/A
Smartec					
SMT160-30	± 0.7	-45 to +130	N/A	Duty-cycle	1 to 4 kHz

Temperature Sensors TMP03/TMP04

- Monolithic temperature detectors from Analog Devices
- PWM output
- Accuracy is ±1.5 ^{0}C from –40 ^{0}C to +100 ^{0}C
- 16-bit resolution

TMP03/04 Output





$$T(°C) = 235 - \left(\frac{400 \times T1}{T2}\right)$$

$$T(°F) = 455 - \left(\frac{720 \times T1}{T2}\right)$$

Temperature Sensors TMP05/TMP06

- Monolithic temperature detectors from Analog Devices
- PWM output
- Accuracy is ±0.5 ^{0}C from –40 ^{0}C to +150 ^{0}C
- 12-bit resolution

$$T(°C) = 421 - \left(751 \cdot \frac{T1}{T2}\right)$$

Temperature Sensors MAX6576/MAX6577

- Monolithic low-cost temperature sensors from MAXIM
- Period/Frequency output
- Accuracy is ±3.0 ^{0}C from –40 ^{0}C to +125 ^{0}C

$$T(°C) = \frac{Tx(\mu s)}{Ks} - 273.15$$ - for MAX6576

$$T(°C) = \frac{fx(Hz)}{Ks} - 273.15$$ - for MAX6577

where *Ks* is the scalar multiplier

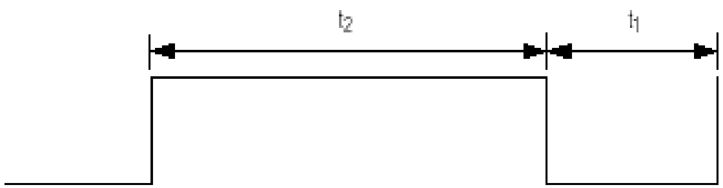
Temperature Sensors MAX6666/MAX6667

- High accuracy temperature sensors from MAXIM
- PWM output
- Accuracy is ±1.0 ^{0}C from –40 ^{0}C to +125 ^{0}C
- Push-pull (MAX6666) and open-drain (MAX6667) output
- T1 is fixed with a typical value of 10 ms and T2 is modulated by the temperature

$$T(°C) = 235 - \left(\frac{400 \times T1}{T2}\right)$$

Temperature Sensors MAX6672/MAX6673

- Low-current temperature sensors from MAXIM
- PWM output
- Accuracy is ±3.0 ^{0}C from –40 ^{0}C to +125 ^{0}C



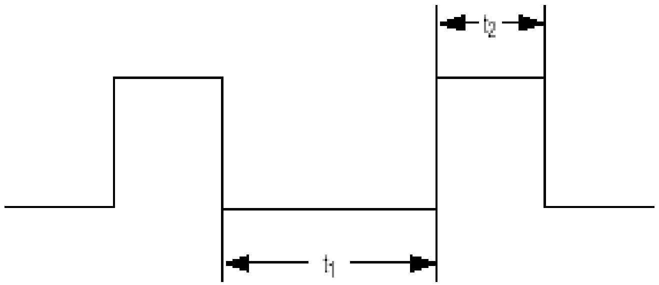
$$T(°C) = -200 \cdot \left(0.85 - \frac{t_1}{t_2}\right)^3 + \left(425 \cdot \frac{t_1}{t_2}\right) - 273$$

$$T(°C) = \left(425 \cdot \frac{t_1}{t_2}\right) - 273$$ - for t > 50^{0}C

Temperature Sensors MAX6676/MAX6677

MAXIM

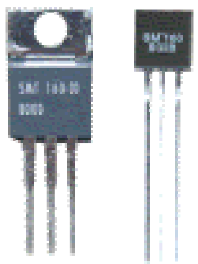
- High accuracy, low-power temperature sensors PWM output
- Accuracy is ±1.5 ^{0}C from –40 ^{0}C to +125 ^{0}C



$$T(°C) = 398.15 \cdot \left(\frac{t_1}{t_2}\right) - 273.15$$

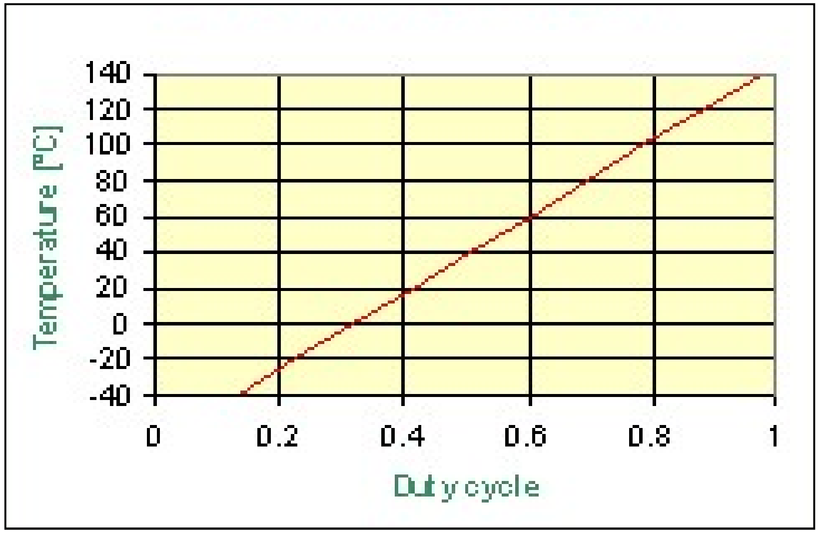
Temperature Sensor SMT 160-30

SMARTEC



- Full silicon sensor with duty-cycle modulated square-wave output
- Accuracy ± 0.7 ^{0}C
- Temperature range –45 ^{0}C to +130 ^{0}C
- Output frequency 1-4 kHz

SMT 160-30 Output



$$D.C. = \frac{t_p}{T_x} = t_p \cdot f_x = 0.320 + 0.00470 \cdot t,$$

where t_p is the pulse width; T_x is the period; f_x is the frequency; t is the temperature in ^{0}C

Temperature Sensor SBE 3F

- High accuracy: initial up to 0.001 ^{0}C (0.003 % FS), typical stable to 0.002 ^{0}C per year
- Sensing element is a glass-coated thermistor bead
- Sensor frequency (2÷6 kHz) is inversely proportional to the square root of the thermistor resistance
- Temperature range: -5 to +35 ^{0}C

Pressure Sensors

1968 - first truly integrated pressure sensor in Europe designed by Gieles at Philips Research Laboratories

1971 - first monolithic integrated pressure sensor with frequency output was designed and tested at Case Western Reserve University (USA)

Modern Pressure Sensors

Sensor	Pressure Range	Relative FS Error, %	Output Frequency
	Chezara (Ukraine)		
VT2101	0.5 - 180 MPa	±0.25 (mean square error)	15 - 22 kHz
VT 1202	0.5 - 60 MPa	±0.15 (mean square error)	15 - 22 kHz
EFT-1-1000	1.7; 3.5; 7; 17; 35; 70; 170; 350 Bar 25; 50; 100; 250; 500; 1000; 2500; 5000 psi	2	5 - 20 kHz
	Druck Incorporated		
RPT 410	17.5 to 32.5 inHg 600 to 1100 mbar (hPa)	0.05	600 - 1100 Hz
	Omega		
PX106 Series	0-6 psi 0-200 psi	1	1 - 6 kHz
	Omron		
D8M-R1	0 to 196.13 Pa (0 to 0.028 psi)	N/A	80 - 300 kHz
D8M-D1/D2	0 to 5.88 kPa (0 to 0.85 psi)	N/A	Pulse count, 1 pulse/9.81 Pa (1/0.0014 psi)
D8M-D82	0 to 4.9 kPa (0 to 0.71 psi)	N/A	Pulse count, 1 pulse/9.81 Pa (1/0.0014 psi)
	Paroscientific, Inc.		
8DP	10 –700 m	0.01	37 – 42 kHz
8B	1400 - 7000 m	0.01	37 – 42 kHz
181KT	0 - 700 m	0.02	30 – 42 kHz
2000 Series	15 - 500 psia	0.01	30 – 42 kHz
3000 Series	1000 psia	0.01	30 – 42 kHz
4000 Series	2000- 40000 psia	0.01	30 – 42 kHz
5300 Series	0 to 3, 0 to 6, 0 to 18 psid	0.01	30 – 42 kHz
	Pressure Systems		
960 Series	15 to 500 psia FS (103 to 3447 kPa)	0.01	30 - 45 kHz
	Seamap		
Gun Depth and Line Pressure Transducers	0-40 m	1	6 - 10 kHz

Quartz Crystal Pressure Transducers

- Digiquartz® Intelligent Transmitters (8DP, 8B,181KT) from Paroscientific Inc.
- Typical full scale (FS) accuracy 0.01 %
- Fully thermally compensated

Quartzonix™ Pressure Standard Series 960

- ± 0.01 % FS accuracy (Pressure Systems)
- ± 0.0001% FS resolution
- Output frequency between 30 and 45 kHz
- Combined pressure and temperature sensors

Accelerometers

- Derivative properties: vibration, shock, tilt
- Accelerometers types: piezo film, electromechanical servo, piezoelectric, liquid tilt, bulk micromachined piezoresistive, capacitive, and surface micromachined capacitive
- Frequency range from: 0.1 Hz to above 30 kHz
- Duty-cycle, frequency or PWM outputs (very suitable for remote sensing and noisy environments)

Quasi-Digital Accelerometers

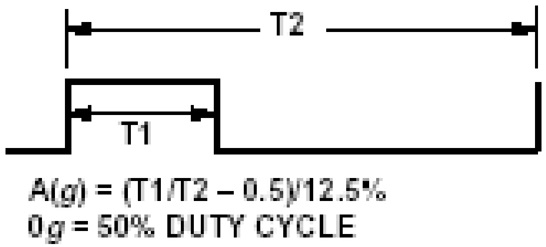
Device	Number of Axis	Range	Sensitivity Accuracy (%)	Max Bandwidth (kHz)
Analog Devices				
ADXL202	2	± 2 g	± 16	6
ADXL210	2	± 10 g	± 20	6
ADXL213	2	± 1.2 g	± 10	2.5
Honeywell				
RBA500	N/A	± 70 g	N/A	> 0.4
SA500	N/A	± 80 g	N/A	> 1
Kionix				
KXG20	2	± 2 g	N/A	< 0.5
MEMSIC, Inc.				
MXD2125	2	± 2 g	± 12.5	> 0.16
Silicon Designs, Inc.				
1010	2	± 2 g ...± 200 g	N/A	0...2

N/A – no available information

ADXL202/210/213 Accelerometers

- Dual-axis accelerometers
- Direct interface to popular microcontrollers
- Duty-cycle output
- 1 ms acquisition time

ADXL202/210/213 Output



$$Acceleration\ (g) = \frac{(T1/T2) - 50\%}{12.5\%}$$ - for ADXL 202

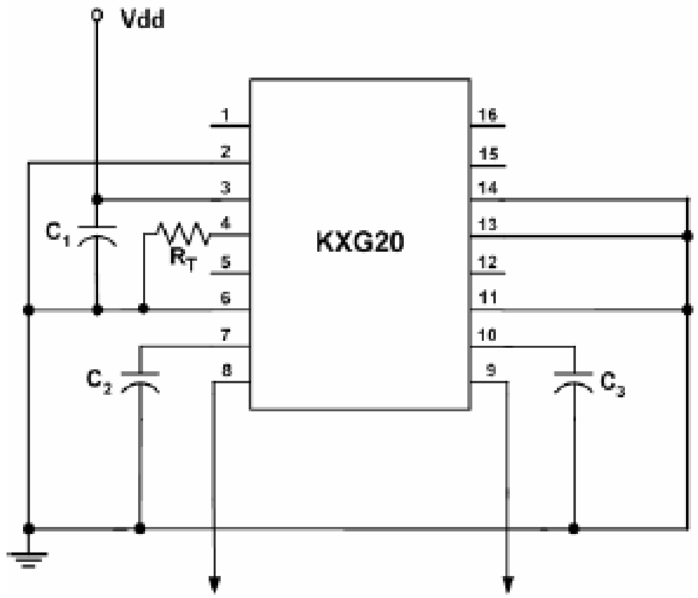
$$Acceleration\ (g) = \frac{(T1/T2 - 0.5)}{4\%}$$ - for ADXL 210

$$Acceleration\ (g) = \frac{(T1/T2 - 0.5)}{30\%}$$ - for ADXL 213

ANALOG DEVICES

KXG-20 Accelerometer

$$Acceleration\ (g) = \frac{(T1/T2 - 0.5)}{20\%}$$



Other Accelerometers

- **MXD7202, 7210, 2020, 6125, 200 4** – CMOS accelerometers with duty-cycle outputs (MEMSIC)
- **Model 1010** - low-cost, integrated accelerometer (Silicon Designs). Output: density of pulses (number of pulses per second) proportional to acceleration
- **Type BB** - frequency output accelerometer (DIGI SENS)

Quasi-Digital Inclinometers

- T6 (US Digital) with quadrature TTL squarewave output
- NG with PWM output (Nordic Transducer)
- SCA830 with PWM output (VTI Technologies)

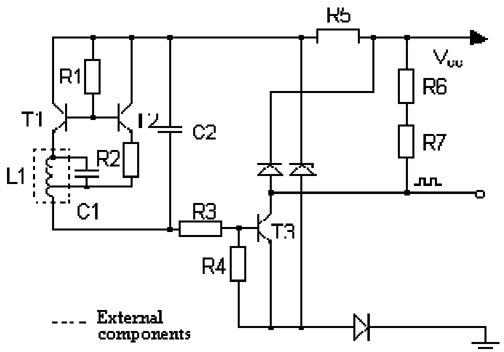
Rotation Speed Sensors

- There are many known rotation speed sensing principles
- Magnetic sensors (Hall-effect and magnetoresistor based sensors)
- Inductive sensors
- Passive and active electromagnetic rpm-sensors are from the frequency-time domain

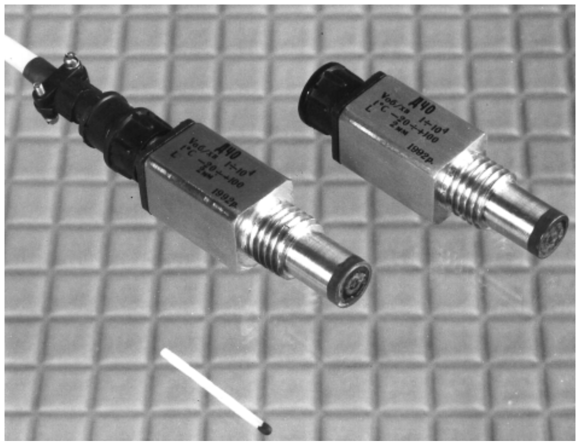
$$n_x = f_x \cdot \frac{60}{Z}$$

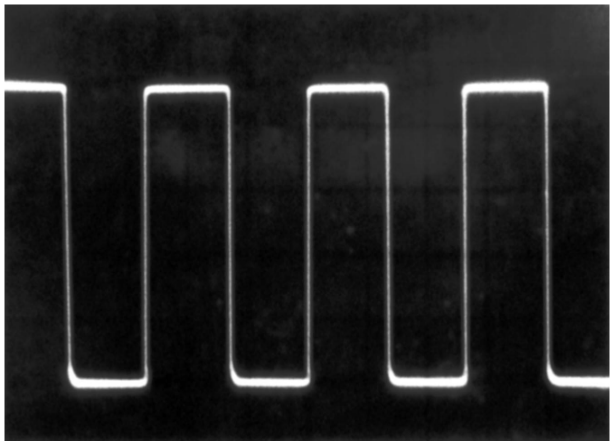
, where *Z* is the number of modulation rotor's (encoder's) gradations (teeth)

Active Sensor of Rotation Speed (ASRS)



Semiconductor active position sensor of relaxation type





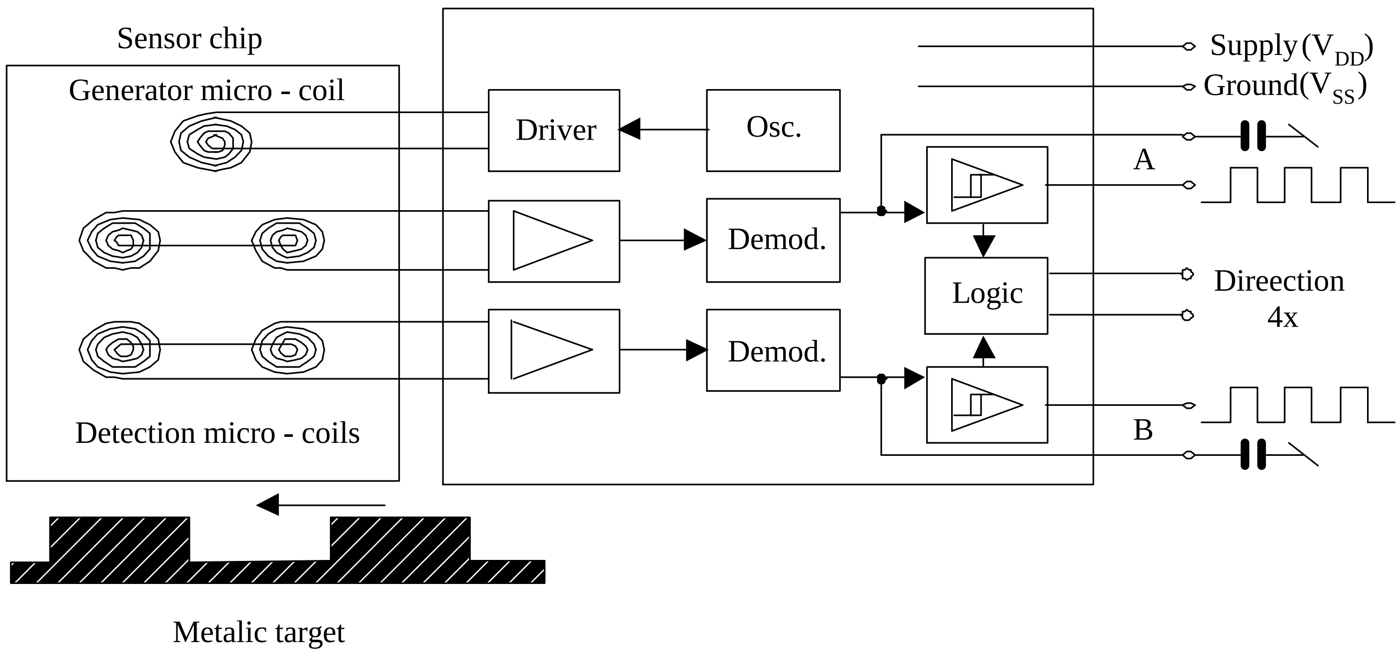
Comparative Analyse

Sensors	Freq. Range, *kHz*	Supply Voltage, *V*	Current Consumption, *mA*	Type
ASRS	0 ÷ 50	4.5 ÷ 24	7 ÷ 15	active
A5S07	0.5 ÷ 25	8 ÷ 28	15 + load current	hall-effect
A5S08/09	0.5 ÷ 25	8 ÷ 25	15	hall-effect
DZ375	0 ÷ 5	4.5 ÷ 16	20 ÷ 50	magnetic
DZH450	0 ÷ 5	4.5 ÷ 30	20	hall-effect
DZP450	1 ÷ 10	4.5 ÷ 16	50	hall-effect
VT1855	0.24 ÷ 160	27	3	inductive
OO 020	0.24 ÷ 720	27	100	photo
4TUC	0.3 ÷ 2	10 ÷ 30	200	mag./inductive
4TUN	0.3 ÷ 2	6.2 ÷ 12	3	mag./inductive
45515	0.002 ÷ 30	25	20	hall-effect
LMPC	up to 10	9 ÷ 17	25	mag./inductive

Active Inductive Position Sensors PO2210/11, PO1604

POSIC

- Frequency range, kHz 0 ÷ 10 (40)
- Air-gap, mm 0 ÷ 1
- Dual-, Single-channel



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Optical Sensors

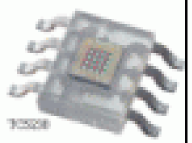
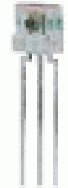
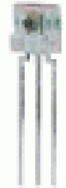
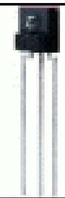
- Low-cost programmable silicon opto sensors TSL230/235/237/245 (TAOS) with monolithic light-to-frequency converter
- Color-to-frequency converter TCS230 (TAOS)
- Square wave output with (0 ÷ 1 MHz) frequency
- Provide programming capability for adjustment of input sensitivity and output scaling
- Light levels of 0.001 to 100 000 μW/am^2 can be accommodated directly without filters

TAOS

Smart Integrated On-chip Colour Sensor

- Principle: wavelength dependence of the absorption coefficient in silicon in the optical part of the spectrum
- Digital output in the IS2 bus format
- Pulse frequency is proportional to optical intensity (luminance)
- Duty cycle is proportional to colour (chrominance)

TAOS Light and Color Sensors

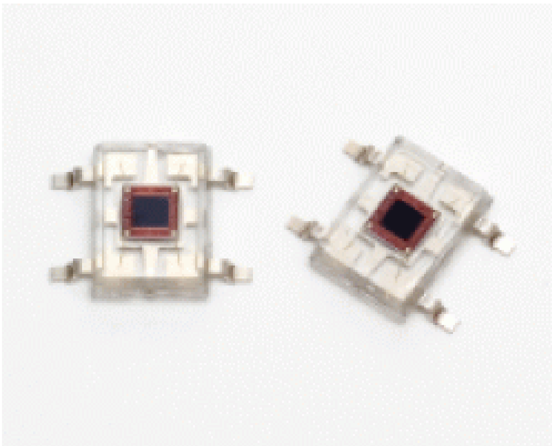
Performance	Frequency Output Light Sensors						
	TCS230	TSL230RD	TSL230R	TSL235R	TSL237	TSL237T	TSL245R
							
Max. output frequency, MHz	1.0	1.0	1.0	0.5	0.6	0.6	0.5
Spectral Response, nm	RGB	350 - 1000	350 - 1000	350 - 1000	350 - 1000	350 - 1000	850 - 1000
Nonlinearity Error, % FS	0.2	0.2	0.2	0.2	1	1	0.2
Programmable	YES	YES	YES	NO	NO	NO	NO

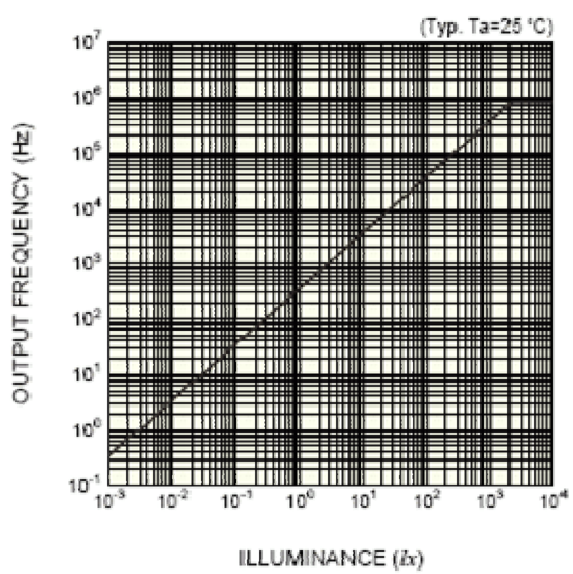
For TSL 230RD: $f_O = f_D + (Re)\,(Ee)$,

where f_O is the output frequency; f_D is the output requency for dark condition (Ee = 0); Re is the device responsivity for a given wavelength of light given in kHz/(mW/cm^2); Ee is the incident irradiance in mW/cm^2

Light-to-Frequency Converter S9705

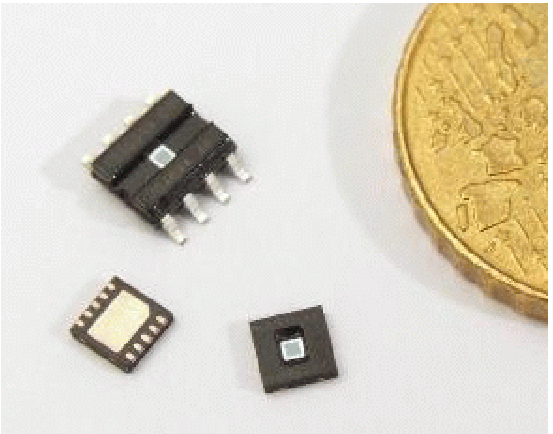
- A photo IC that combines a photodiode and current-to-frequency converter on a monolithic CMOS chip
- Frequency output range: 0.1 Hz to 1 MHz





HAMAMATSU
HAMAMATSU PHOTONICS K.K., Solid State Division

Light-to-Frequency Converter MLX75304



- CMOS integrated Light-to-Frequency Converter
- Extended dynamic range 120 dB; 0.1...100k lux

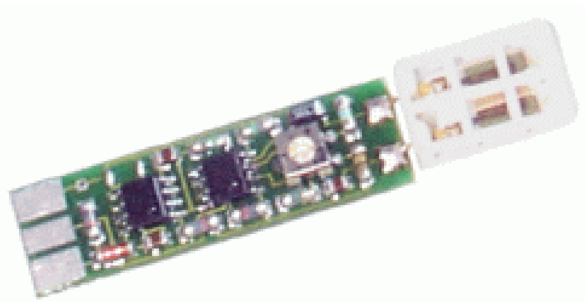
Humidity Frequency Output Sensors

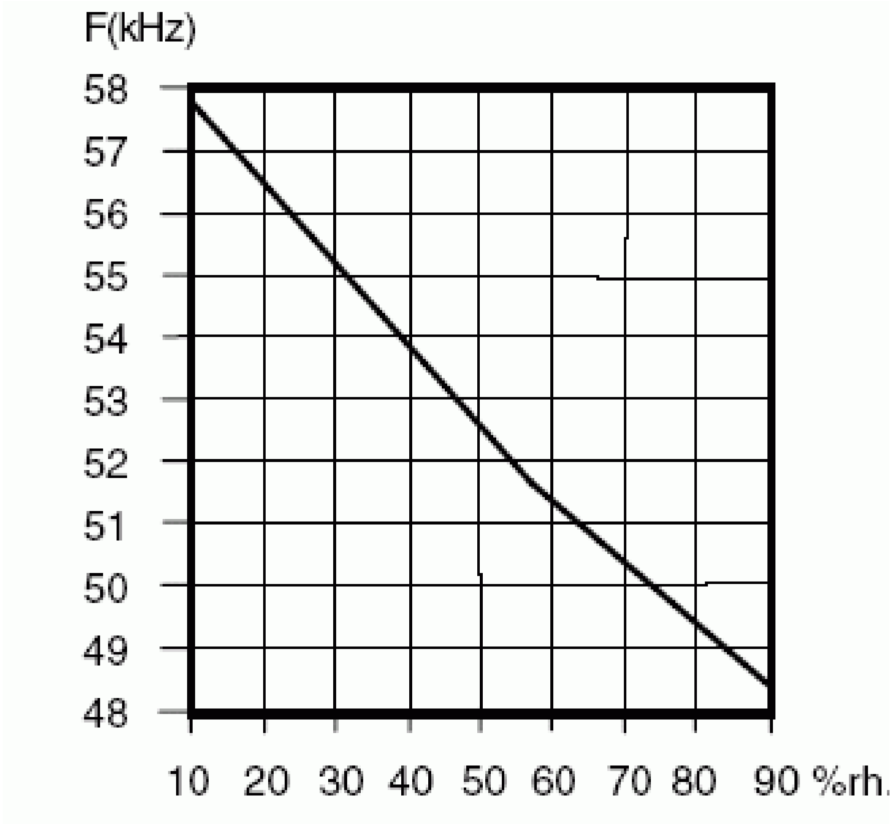
- Based on humidity–capacitance–frequency (time interval or duty-cycle) converters: $X(t) \rightarrow C(t) \rightarrow F(t)$
- Pulsed signal for both humidity and temperature
- Measuring range 0 ÷100% RH
- Frequency ranges from some kHz up to hundreds kHz
- Accuracy up to 1 %

Humidity Quasi-Digital Sensors

Sensor	Humidity Measurement Range, % RH	Relative Humidity Error, %	Output Frequency, kHz
Blue Earth, LLC.			
MiniCap2	10...90	N/A	10...200
E+E Elektronik, GmbH			
EE05 Series, HC200	10...90	±3 at 20°C	61.1...48.6
Galltec+Mela, GmbH			
Humidity Frequency Converter	10...90	±3	57.9...48.4
Humirel			
HTF3100	N/A	±3 at 55 %RH	N/A
HTF3130	10 ... 95	±3 at 55 %RH	7.155...6.210
HTF3223	10 ... 95	±5 at 55 %RH	9.560...8.030
HTF3225	N/A	±5 at 55 %RH	N/A
HTF3226	10 ... 95	±5 at 55 %RH	9.44...8.070
HTF3226LF	10 ... 95	±5 at 55 %RH	9.49...8.225
HTF3227	N/A	±3 at 55 %RH	N/A
Kurabe			
KN-1050	0...95	±5	4.95...5

Humidity Frequency Converter (*Galltek +MELA*)

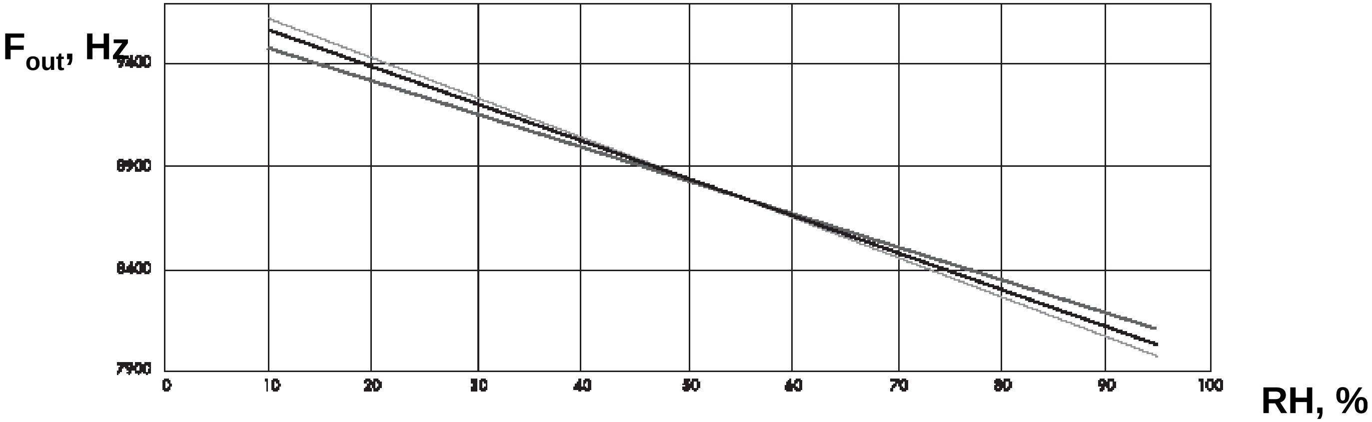




Dedicated Humidity Transducers from Humirel

$F_{out} = 7314 - 16.79 \cdot RH + 0.0886 \cdot RH^2 - 0.000358 \cdot RH^3$,- for **HTF3130**

$F_{out} = 9740 - 18 \cdot RH,$ - for **HF 3223/HTF 3223**

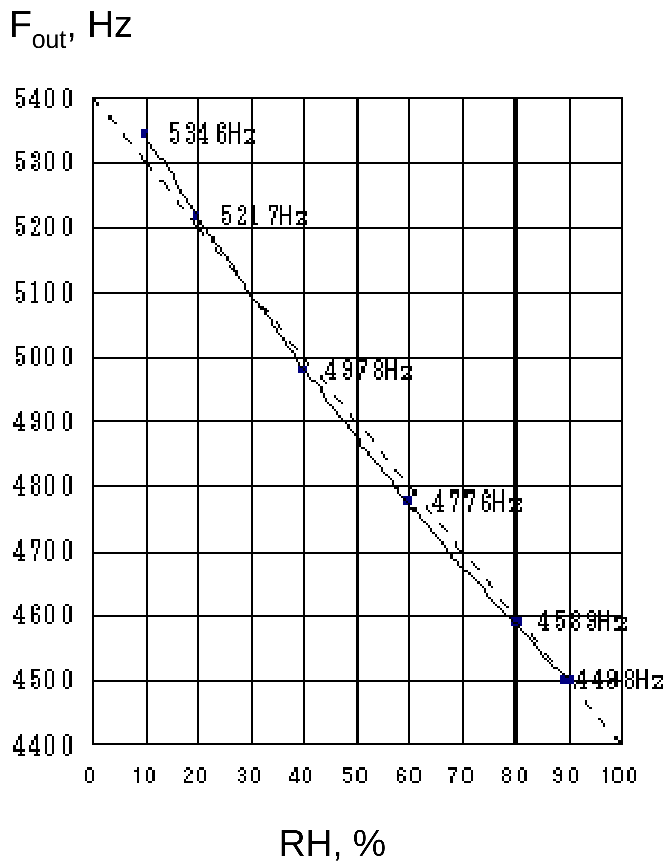


$F_{out} = 9600 - 15.8 \cdot RH$ - for **HTF 3226,** linear reference curve

$F_{out} = 9570 - 14.28 \cdot RH - 0.015 \cdot RH^2$ - for **HTF 3226,** the second order curve

Humidity-to-Frequency Converter KN-1050

Based on a high performance relative humidity sensor of variable capacitance type



Chemical, Gas and Biosensors

- Sensors arrays *(electronic noses and tongues)*
- Square wave with a frequency inversely proportional to the sensor resistance
- Sensors Array based on chemisorbing polymer films
- Acoustic gas sensor based on a gas-filled cell
- Quartz Crystal Microbalance (QCM) sensors
- SAW and bulk acoustic wave sensors

Mass Variation Sensors

- Crystal resonance frequency changes by Δf when a mass change Δm occurs on the crystal according to Sauerbrey equation
- Typical frequency range: up to some MHz
- Needs high accuracy (the relative error should be batter than 0.001 %) reduced time of measurement (less than 0.1 s)

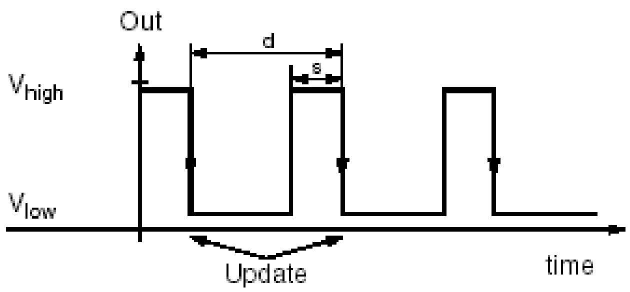
Magnetic Sensors

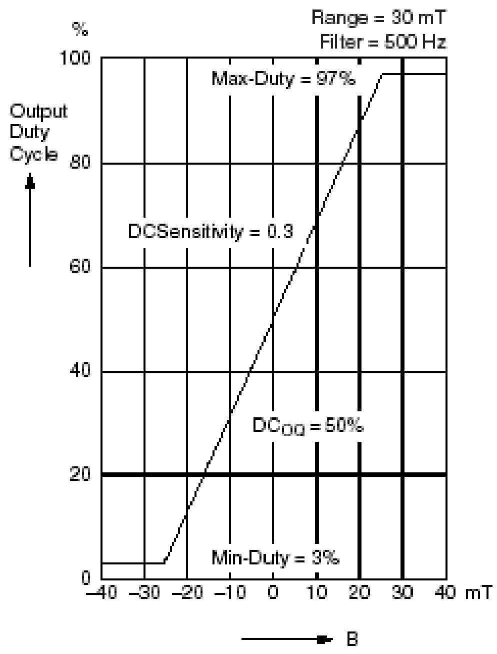
- **HAL810, HAL819** – Hall sensors with PWM output form *Micronas*;
- **MS2G** period output sensor from *Bartington*
- **FGM-series** Magnetic Field Sensors with period output from *Speake & Co Llanfapley*
- High resolution CMOS magnetic field to frequency converter with frequency difference on its output [1]

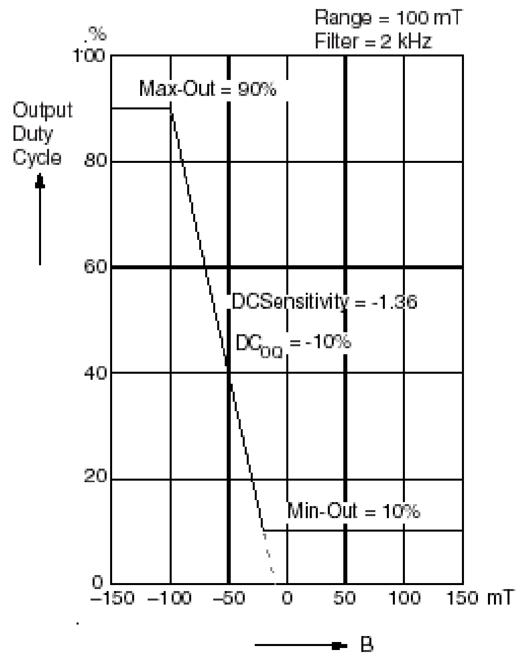
[1]. Shr-Lung Chen, Chien-Hung Kuo, and Shen-Iuan Liu, CMOS Magnetic Field to Frequency Converter, *IEEE Sensors Journal*, Vol.3, No.2, April 2003, pp.241-245

Programmable Magnetic Field Sensor HAL810

Can be used for angle or distance measurements in combination with a rotating or moving magnet





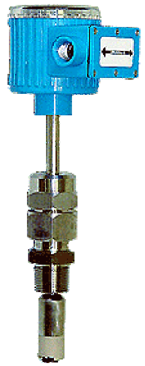


MICRONAS

Other Sensors

- Tilt and inclination sensors with PWM outputs
- Torque transducers with frequency output
- Level sensors with frequency output
- Conductivity sensor SBE4 with frequency output
- Flow sensors with frequency output





Multiparameters Sensors

- Color sensor (TU Delft, The Netherlands): frequency is proportional to optical intensity (luminance) and duty-cycle is proportional to colour (chrominance)
- Pressure and temperature sensors
- Humidity and temperature sensors (transmitters) from *E+E Elektronik, Bitron, etc.*

Historical Facts

- **1930** - string distant thermometer (Pat. No.61727, USSR, Davydenkov N., Yakutovich M.)
- **1931** - string distant tensometer (Pat. No. 21525, USSR, Golovachov D., Davydenkov N., Yakutovich M.)
- **1941** - ADC for the narrow time intervals (Pat. No. 68785, USSR, Filipov V.N. and Negnevitskiy S.B.

Frequency Output Sensors

In 1961 professor P.V. Novitskiy wrote: *"... In the future we can expect, that a class of frequency sensors will get such development, that the number of now known frequency sensors will exceed the number of now known amplitude sensors..."*

Although there are frequency output sensors practically for any physical, chemical, electrical and non-electrical variables, this prognosis has not been fully justified.

Some Subjective Reasons

- Lacking awareness of the innovation potential of modern frequency-to-digital conversion methods
- Major expenditures were invested into development of traditional expensive ADC
- Lack of emphasis being placed on the business and market benefits which such measuring technologies can bring to companies

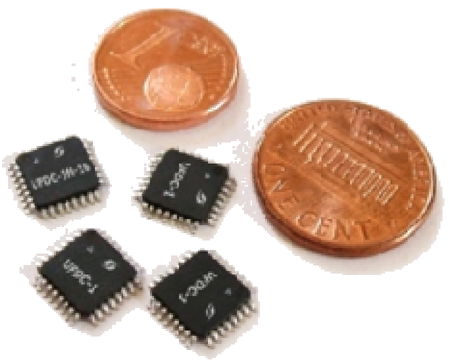
Some Objective Reasons

- Advanced frequency-to-digital conversion methods are patented
- Difficulties in software development for microcontroller based frequency-to-digital controller

Universal Frequency-to-Digital Converter (UFDC-1)

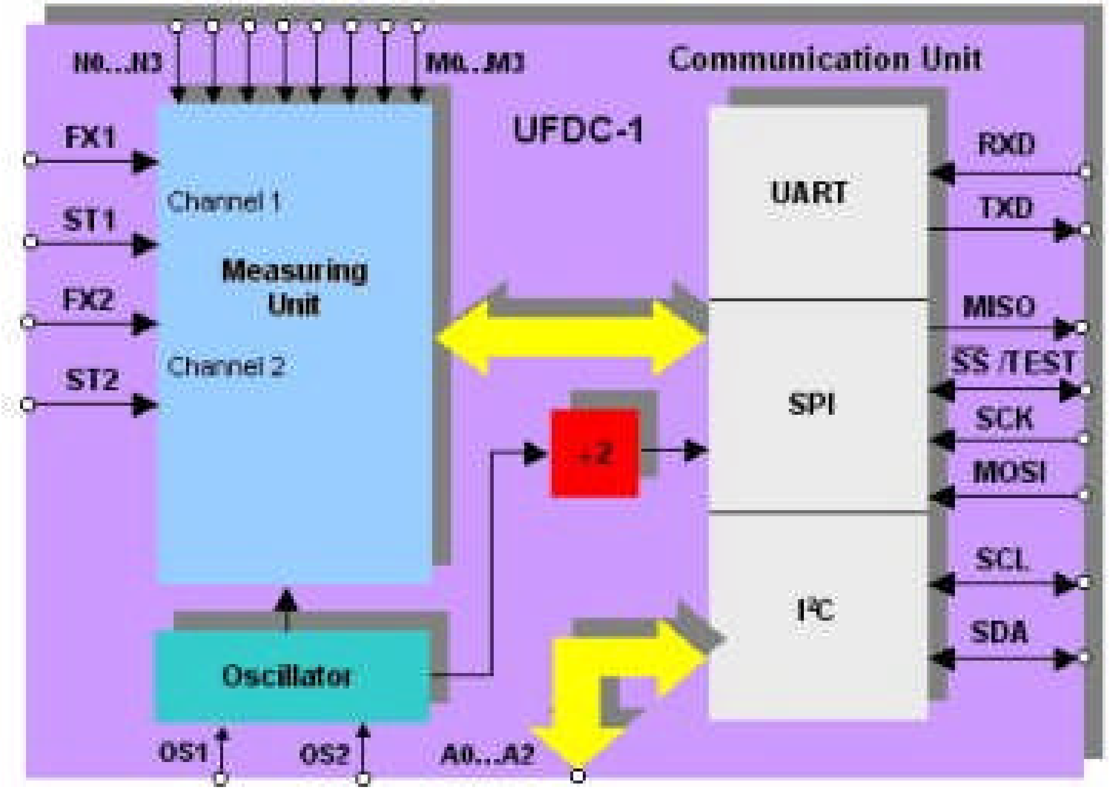
- Low cost digital IC with programmable accuracy
- 2 channels, 16 measuring modes for different frequency-time parameters and one generating mode ($f_{osc}/2 = 8$ MHz)
- Based on four patented novel conversion methods
- Should be very competitive to ADC and has wide applications

Features



- Frequency range from 0.05 Hz up to 7 MHz without prescaling and 112 MHz with prescaling
- Programmable accuracy (relative error) for frequency (period) conversion from 1 up to 0.001 %
- Relative quantization error is constant in all specified frequency range
- Non-redundant conversion time
- Quartz-accurate automated calibration
- RS-232/485, SPI and I^2C interfaces

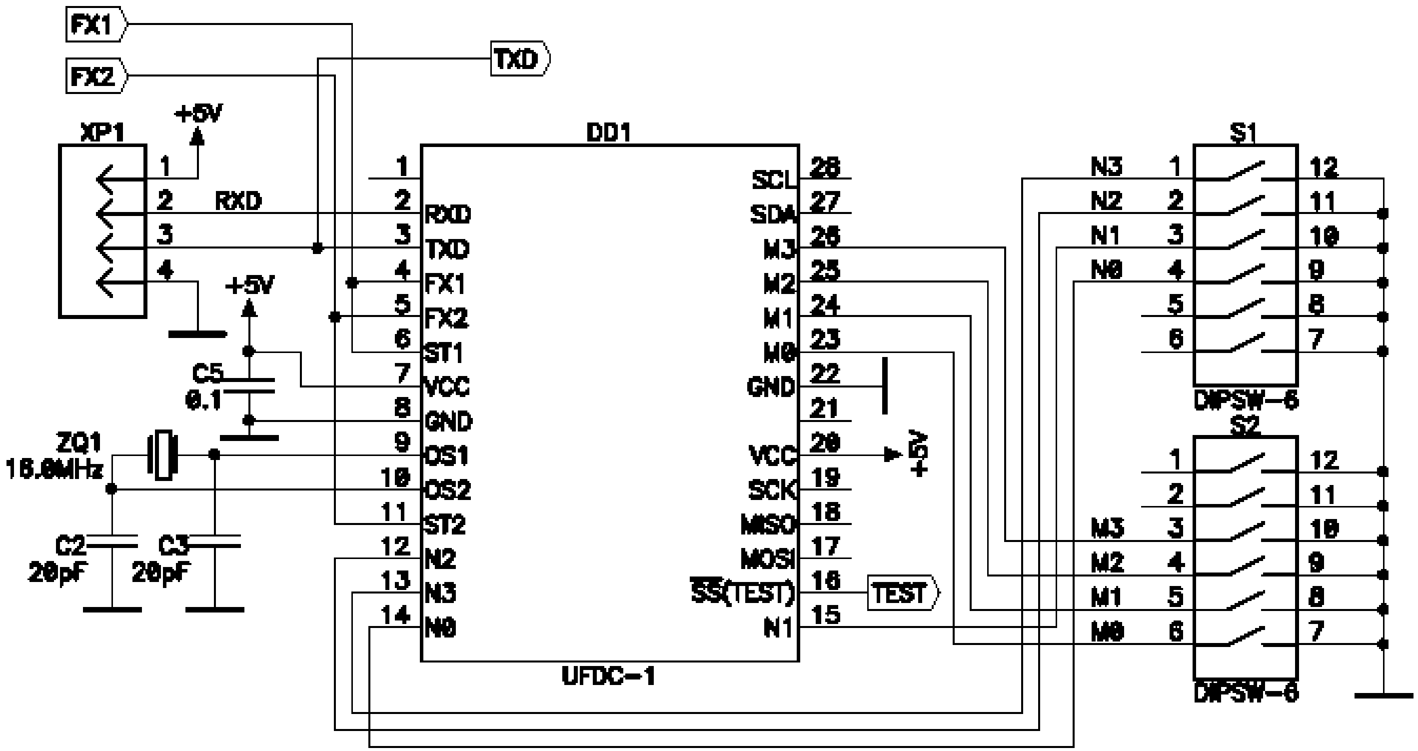
UFDC-1 Block Diagram



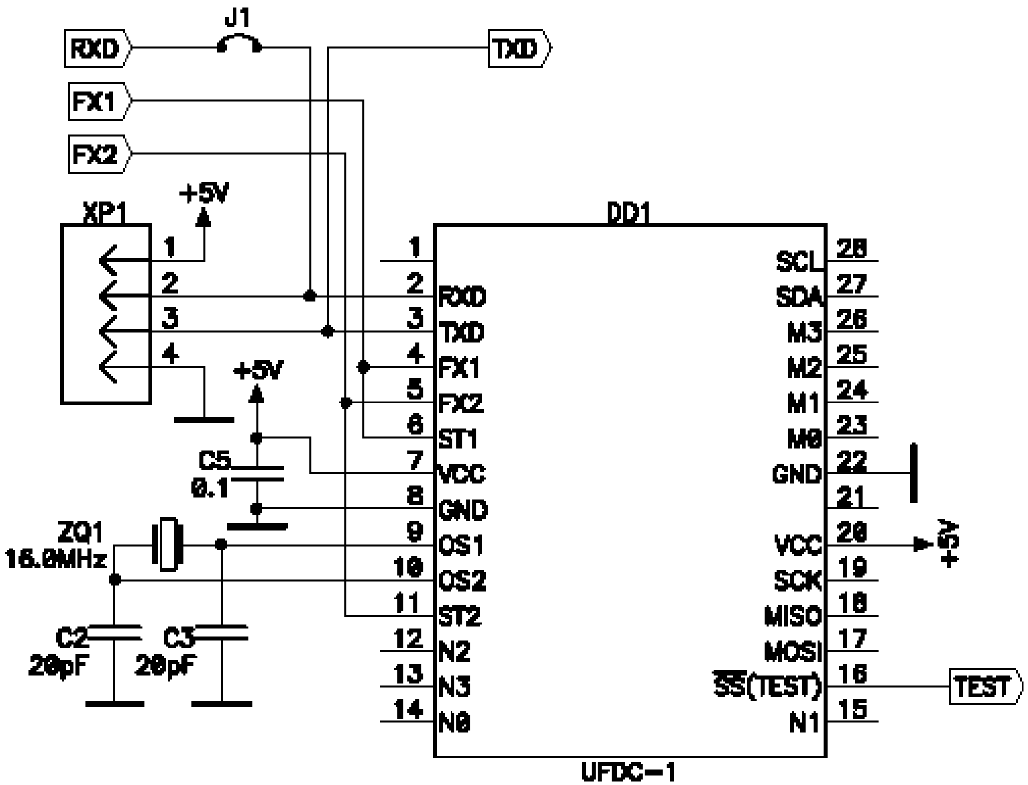
Measuring Modes

- Frequency, f_{x1} 0.05 Hz – 7MHz directly and up to 112 MHz with prescalling
- Period, T_{x1} 150 ns – 20 s
- Phase shift, φ_x 0 - 360^0 at $f_x \leq$ 300 kHz
- Time interval between start- and stop-pulse, τ_x 2.5 μs – 250 s
- Duty-cycle, D.C. 0 – 1 at $f_x \leq$ 300 kHz
- Duty-off factor, Q 10^{-8} – $8 \cdot 10^6$ at $f_x \leq$ 300 kHz
- Frequency and period difference and ratio
- Rotation speed (*rpm)* and rotation acceleration
- Pulse width and space interval 2.5 μs – 250 s
- Pulse number (events) counting, N_x 0 – $4 \cdot 10^9$

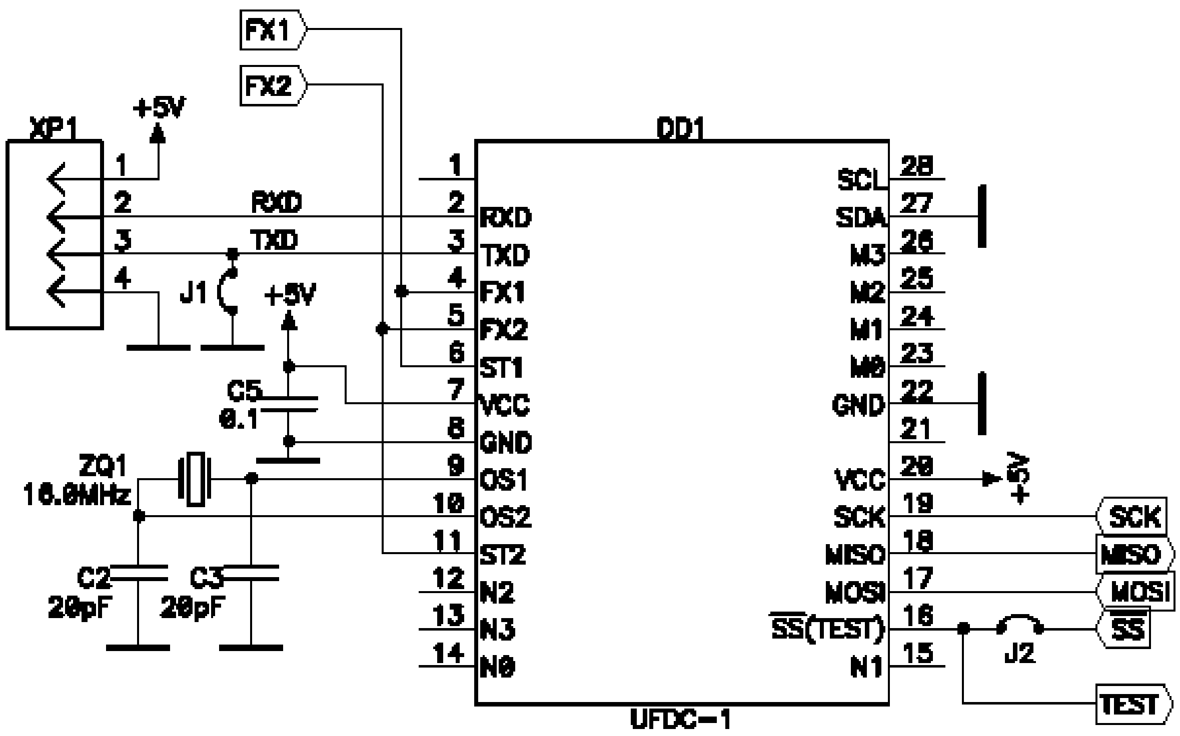
UFDC-1 Master Mode (RS-232)



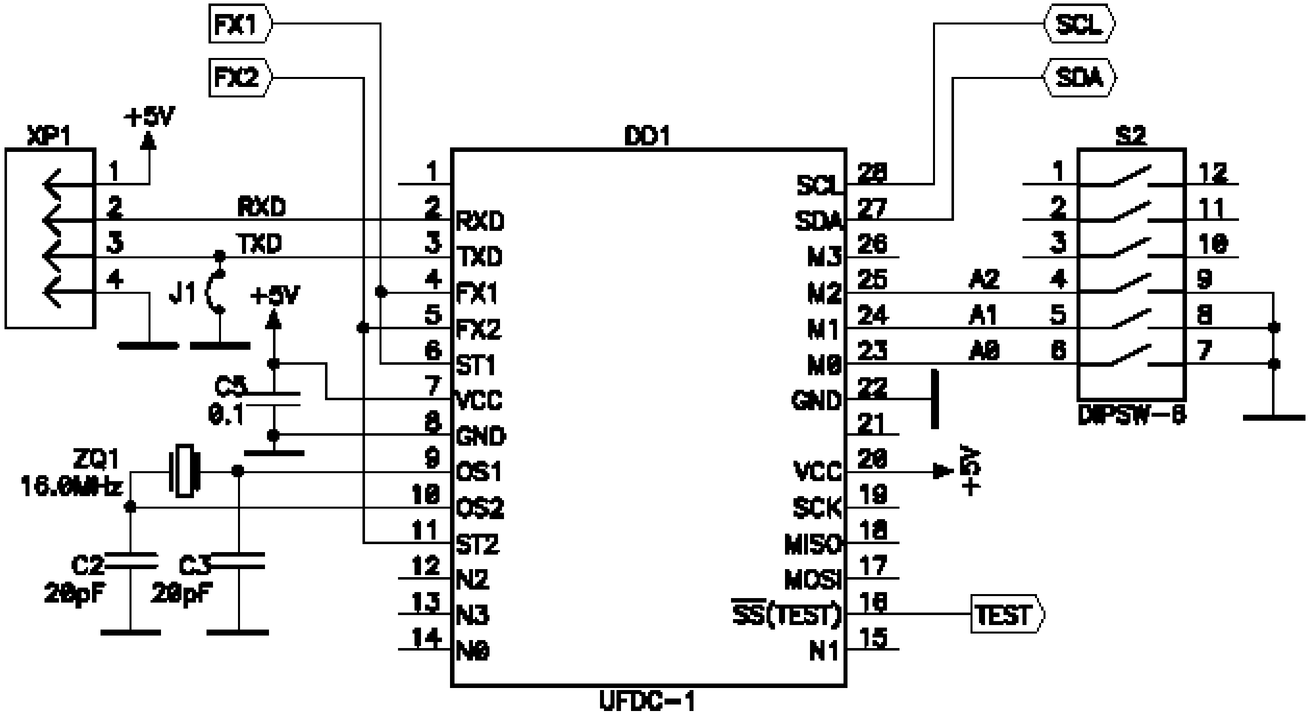
UFDC-1 Slave Mode (RS-232)



UFDC-1 SPI Interface Connection

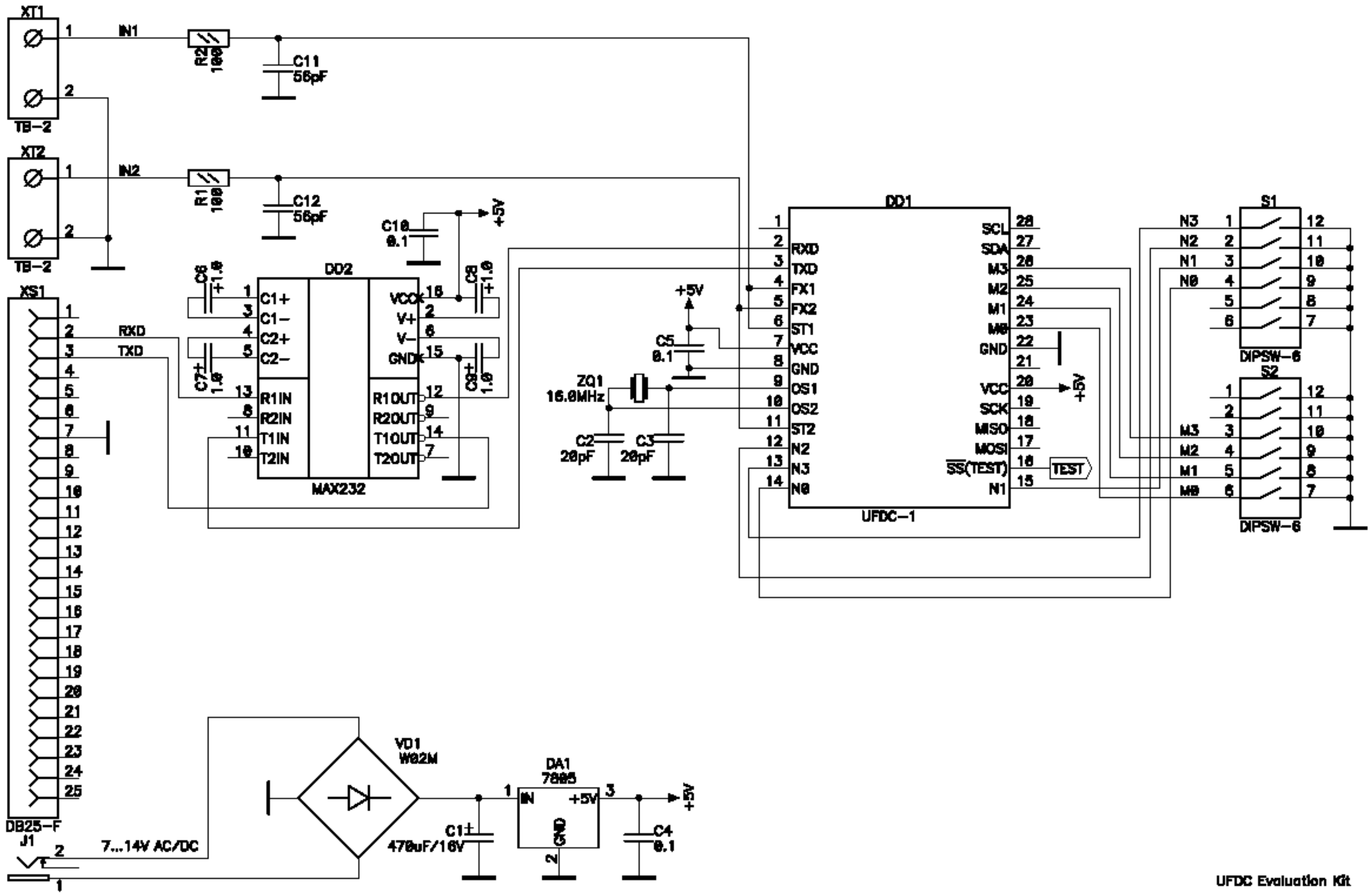


UFDC-1 I^{2}C Bus Connection



IFSA

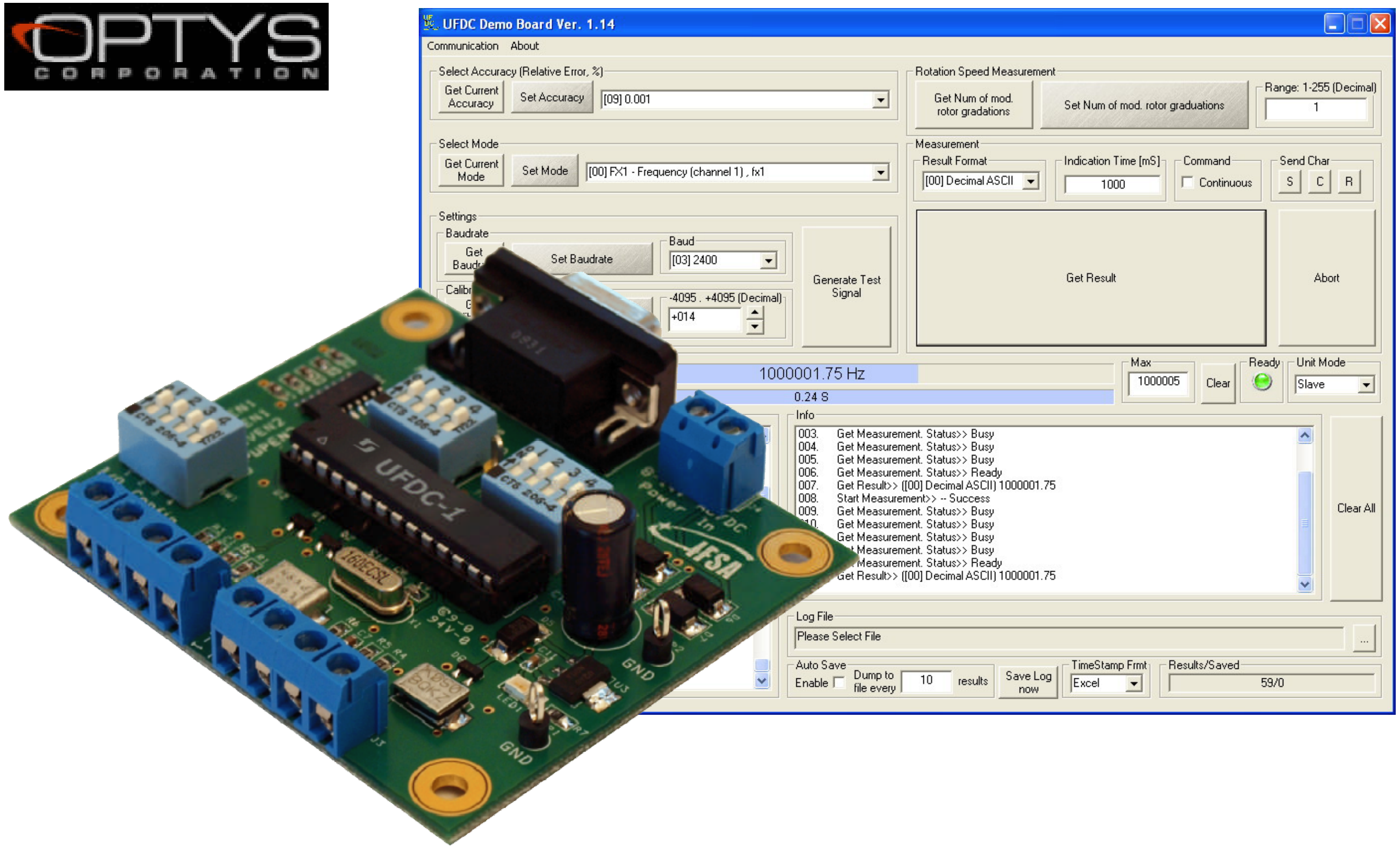
Evaluation Board Circuit Diagram



UFDC Evaluation Kit

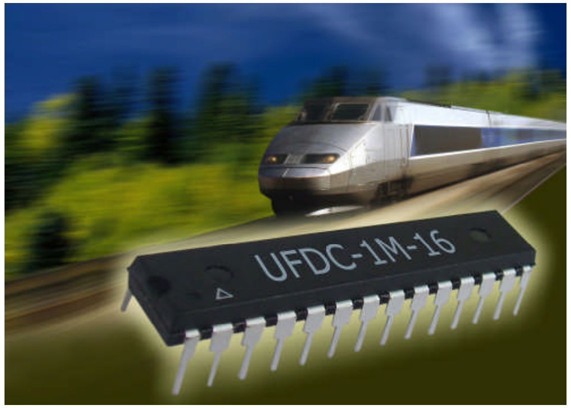
Evaluation Board EVAL-UFDC1/UFDC-1M-16

OPTYS CORPORATION



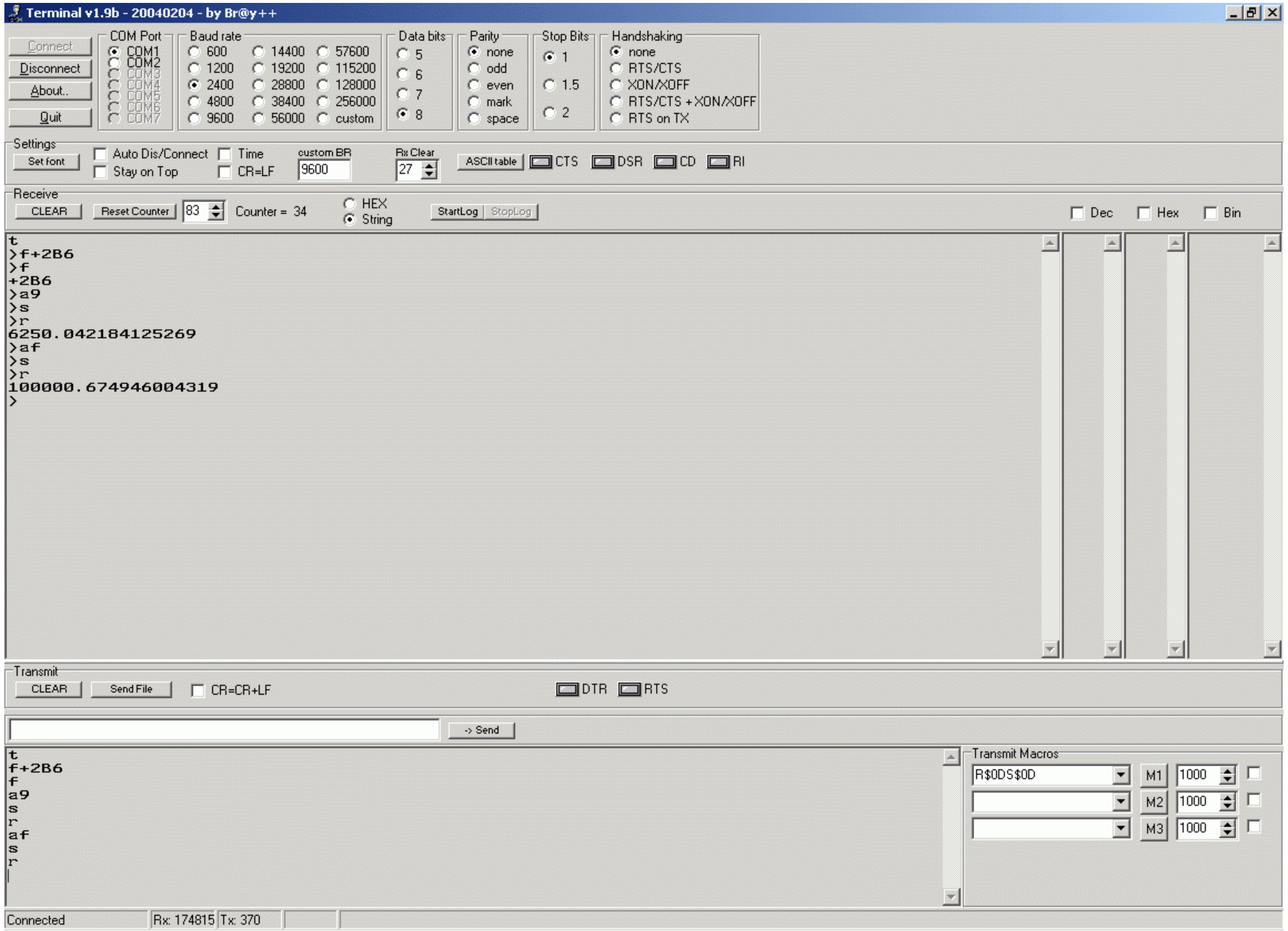
IFSA

Fast IC UFDC-1M-16

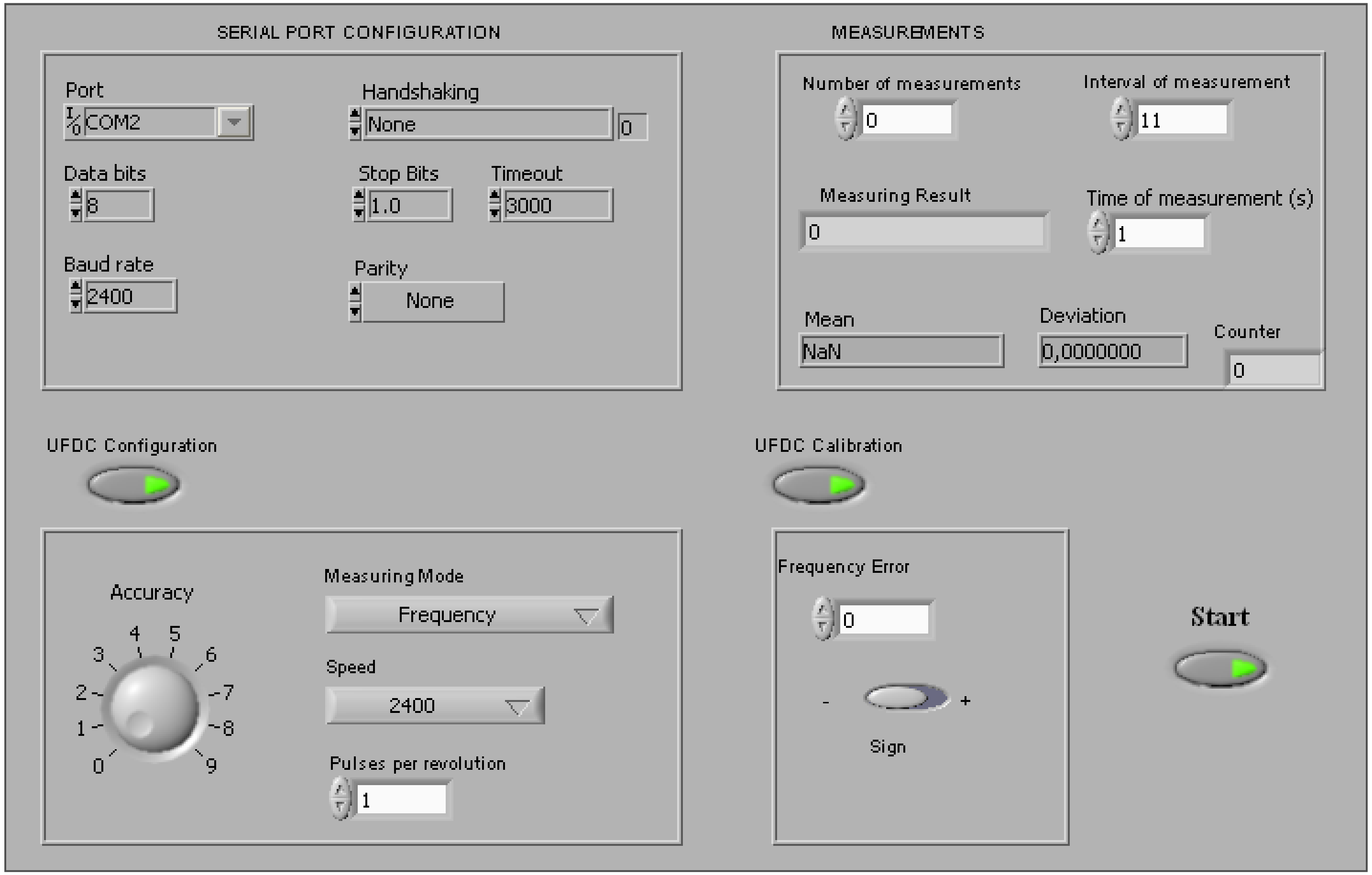


- Frequency range: 1 Hz to 7.5 MHz (120 MHz with prescaling)
- Internal reference frequency 16 MHz
- Non-redundant conversion rate: from 6.25 μs to 6.25 ms

Software (Terminal V1.9b)



LabView Based Software



What Calibrate ?

- Systematic quartz-crystal error to reduce the adjustment or trimming inaccuracy
- Temperature drift
- Quartz-crystal aging error

Why Calibration ?

- Taking into account a high UFDC-1 accuracy (up to 0.001 %) it needs a very accurate reference at least $\leq$ 0.0001 %
- Low cost crystal oscillators does not have a good stability due to systematic error

Example: A 16 MHz crystal oscillators from *Siward* with 30 ppm determined tolerance has the real frequency 16 001 400 Hz that corresponds to 90 ppm (0.009 %) reference error

When Calibrate the UFDC-1 ?

- In order to use the UFDC-1 with any low cost crystal oscillators for conversions with the relative error less than 0.01 % it is necessary to calibrate it with the aim to compensate the adjustment or trimming inaccuracy
- If application needs relative error ≥ 0.01 % no calibration is necessary
- If the UFDC-1 is working in specified temperature range

How to Calibrate ?

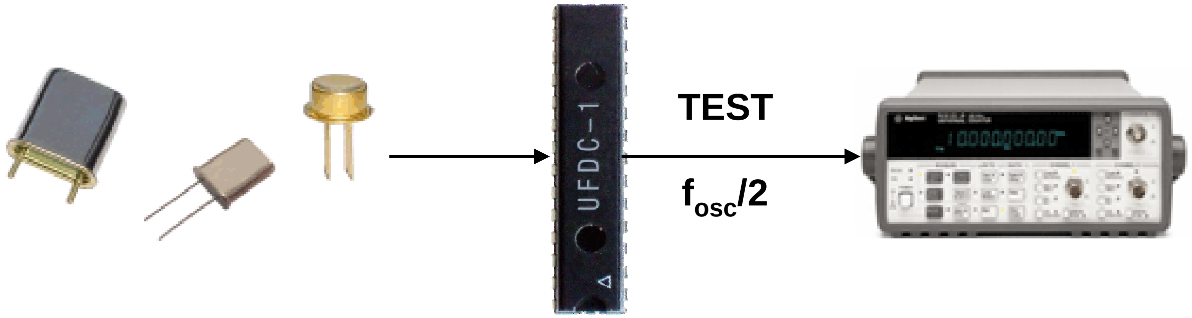
- Should be made in real working conditions with the 16 MHz crystal oscillator
- Connect the UFDC-1 to PC through the serial interface RS-232
- Use the test command "T“
- Measure the frequency at the TEST pin by any external frequency counter with accuracy not worse than 0.0001 % or at least 0.0005 %
- Calculate the correction factor Δ
- Input it into the UFDC-1

Calibration Procedure Example

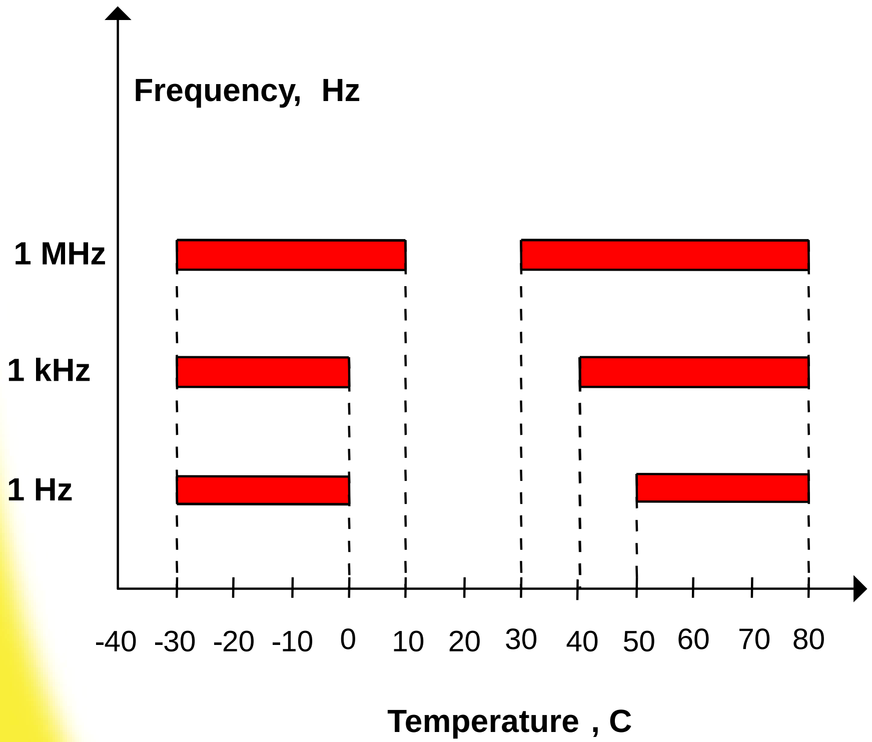
- Let the measured frequency on the TEST output is 8 000 694.257865 Hz
- After rejecting a fractional part the received integer number is 8 000 694 Hz
- Calculate the correction factor 8 000 694 –
- 8 000 000 = 694 Hz
- Convert the result into the hexadecimal number $(694)_{10} = (2B6)_{16}$
- Put the correction command (with taking into account the correction factor's sign) into the UFDC-1

UFDC-1 Calibration Commands

>T	; set the UFDC-1 into the calibration mode
>F+2B6	; correction command
>F	; check the correction value in the UFDC-1
2B6	; returned correction factor Δ=+2B6



Temperature Drift Calibration



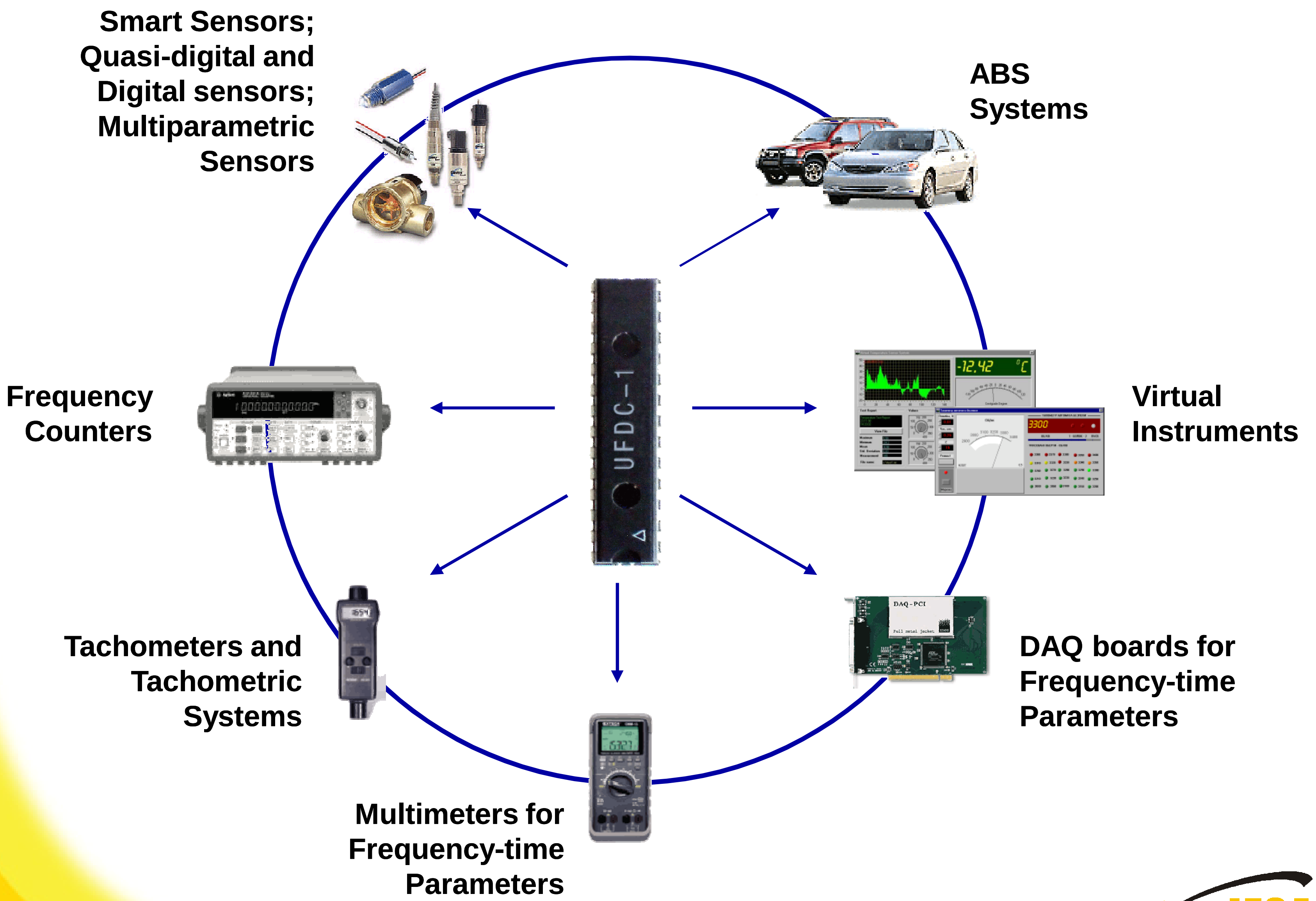
- The UFDC-1 is working in the industrial temperature range: (– 40° C...+ 85° C)
- Temperature drift error can be eliminated by the calibration in appropriate working temperature ranges

No Calibrate if:

- Relative error > 0.01 %
- Use a precision temperature-compensated integrated generator ± 3 ppm frequency stability over the -40°C to +85°C

UFDC-1 Packages

Where to use the UFDC-1 ?



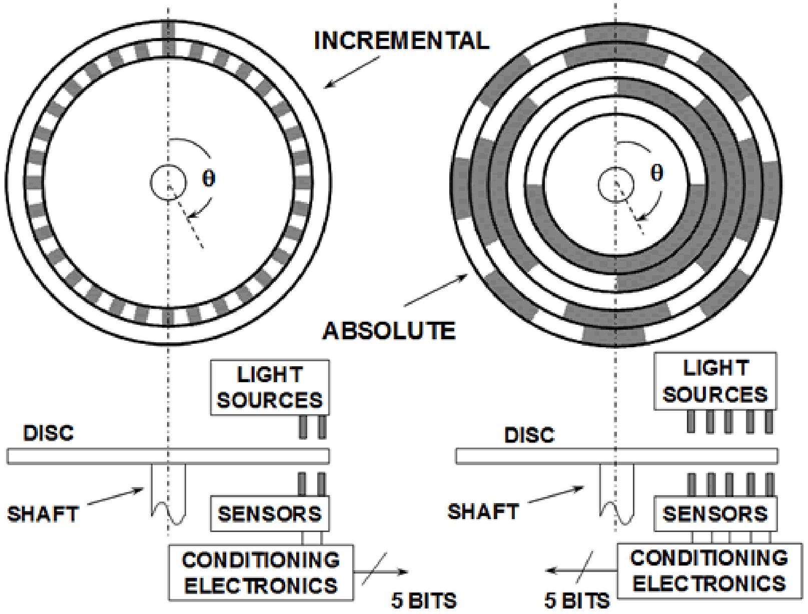
New Technological Platform for Smart Sensor Systems Integration

1. Introduction: Definitions and Markets
2. Modern Technologies
3. Smart Sensors Design: Preface
4. Quasi-Digital Sensors State-of-the-art
5. Smart and Intelligent Sensors Design
6. Smart Sensor Systems Integration
7. Summary

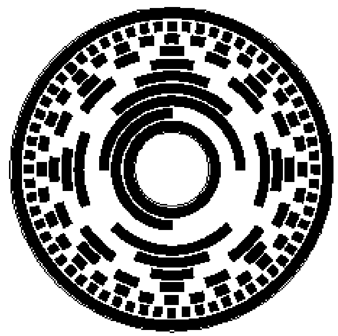
Digital Sensors

- Number of physical phenomenon, on the basis of which direct conversion sensors with digital outputs can be designed, is essentially limited
- Angular-position encoders and cantilever-based accelerometers – examples of digital sensors of direct conversion
- There are not any nature phenomenon with discrete performances changing under pressure, temperature, etc.

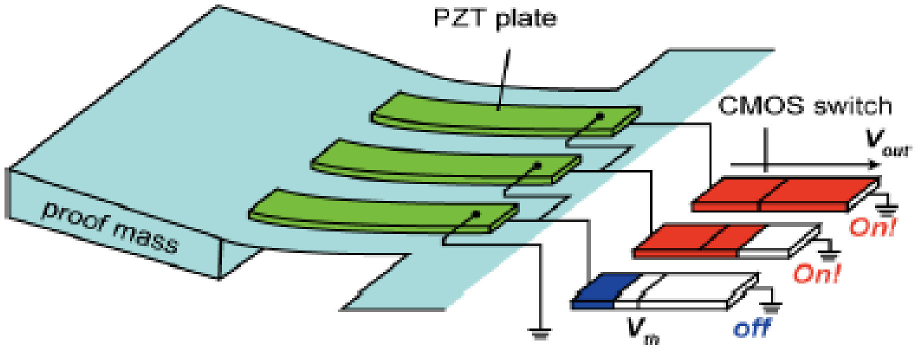
Angular-Position Encoder



decimaal	Gray-code
0	0000
1	0001
2	0011
3	0010
4	0110
5	0111
6	0101
7	0100
8	1100
9	1101
10	1111
11	1110
enz.	enz.



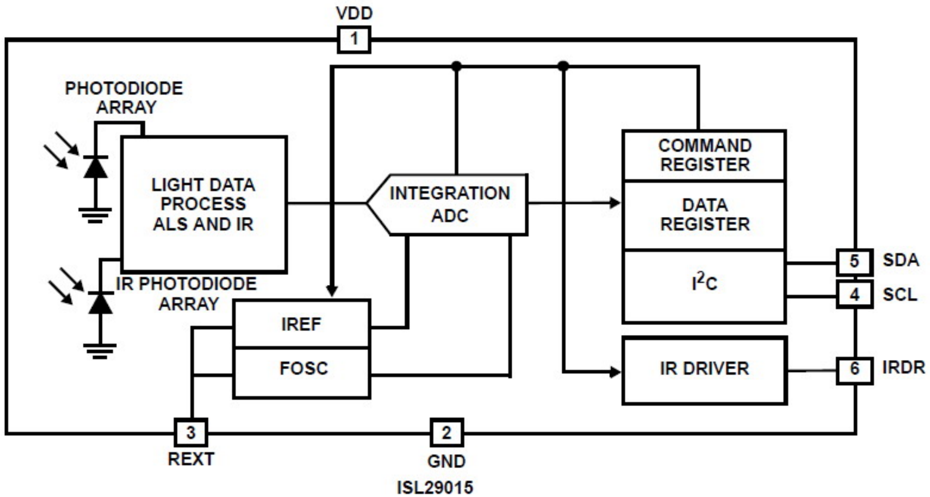
Digital Accelerometer



Toshihiro Itoh, Takeshi Kobayashi, Hironao Okada, A Digital Output Piezoelectric Accelerometer for Ultra-low Power Wireless Sensor Node, in *Proceedings of IEEE Sensors 2008*, 26-29 October 2008, Lecce, Italy, pp.542-545.

Smart Sensor Example I

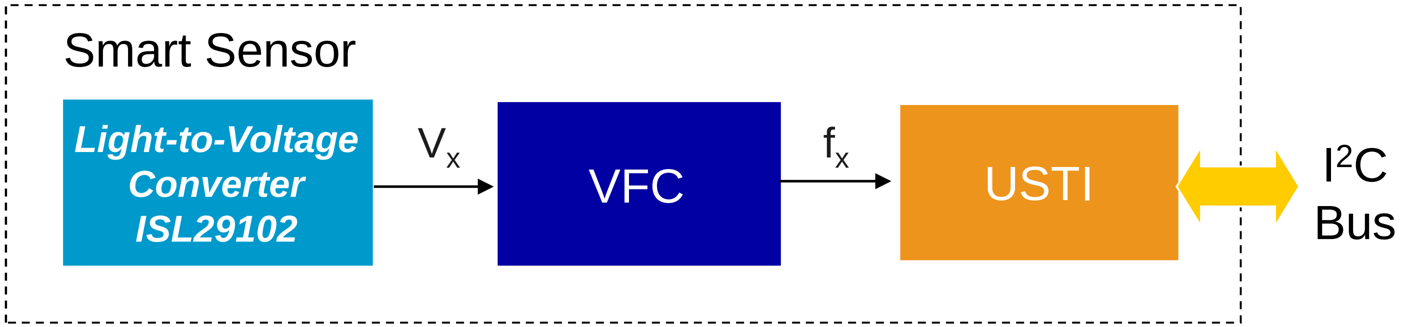
ADC – based digital light sensor ISL29015 (*Intersil*)



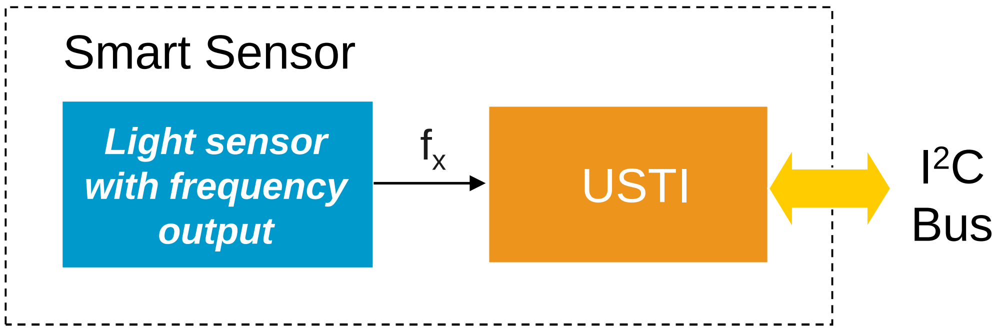
Integration time of 16-bit ADC: 45 … 90 ms

Smart Sensor Example II

VFC/FDC – based digital light sensor (I):



FDC – based digital light sensor (II):



Conversion time in both cases at 0.01 %

relative error: 0.5 … 16 ms

VFC Advantages in ADC Conversion Scheme

- Monotonicity is inherent under all supply and temperature conditions
- Analog circuitry (the VFC and analog signal conditioning circuits) to be located close to the signal source
- Digital circuitry (frequency-to-digital converter) to be located elsewhere
- Resolution can be increased almost indefinitely

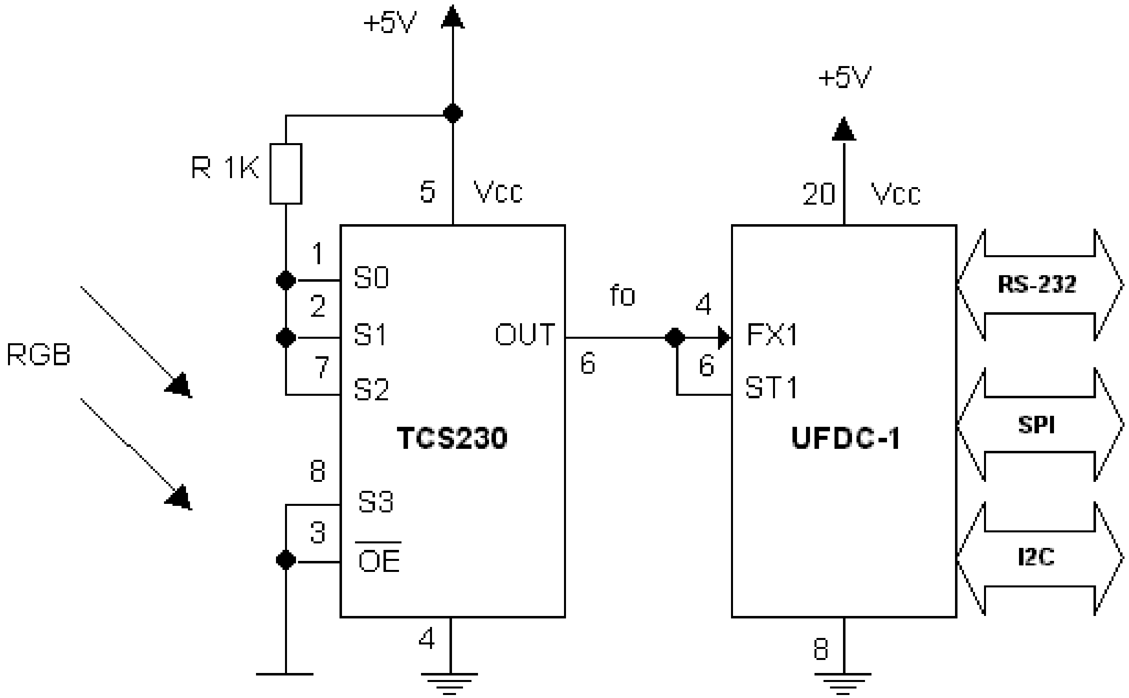
Modern VFCs

- There are a lot of commercially available types of integrated VFCs to meet many requirements (0.012 % integral nonlinearity)
- Ultra-high speed 1 Hz-100 MHz VFC with 0.06 % linearity
- Fast response (3 μs) 1 Hz-2.5 MHz VFC with 0.05 % linearity
- High stability quartz stabilized 10 kHz – 100 kHz VFC with 0.005 % linearity
- Ultra-linear 100 kHz – 1 MHz VFC with linearity inside 7 ppm 0.0007 %) and 1 ppm resolution for 17-bit accuracy applications
- Ultra-linear 100 kHz – 1 MHz VFC with linearity inside 7 ppm 0.0007 %) and 1 ppm resolution for 17-bit accuracy applications

A/D Converter Types

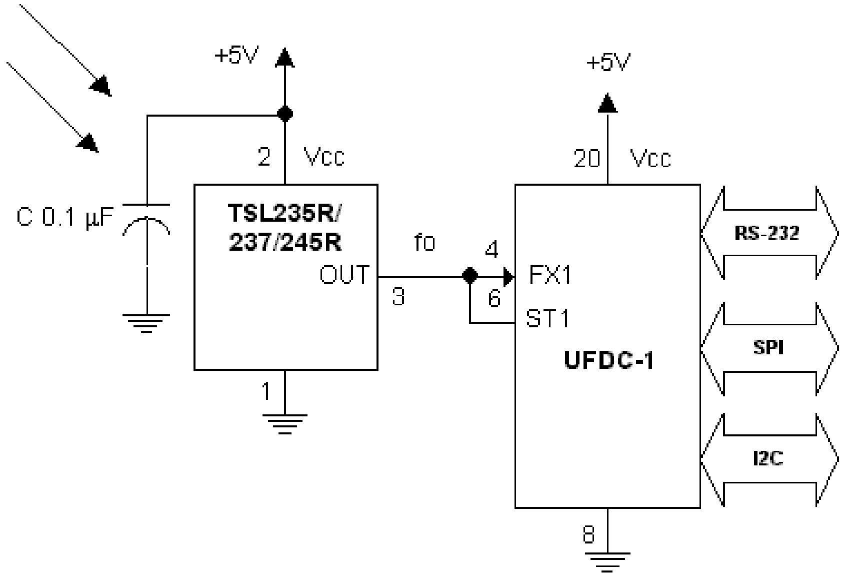
Type	Max Speed	Resolution	Noise Immunity	Relative Cost
Successive Approximation	Medium (10 kHz to 1 MHz)	6-16 bits	Little	Low
Integrating	Slow (10 Hz to 30 Hz)	12-24 bits	Good	Low
VFC-based	Medium (160 kHz to 1 MHz)	16-24 bits or more	Excellent	Low
Sigma-Delta	Slow to Medium (Up to 1 MHz or higher)	16 bits or more	High	Low
Flash	Very Fast (1 MHz to 500 MHz)	4-8 bits	None	High

Color-to-Digital Converter

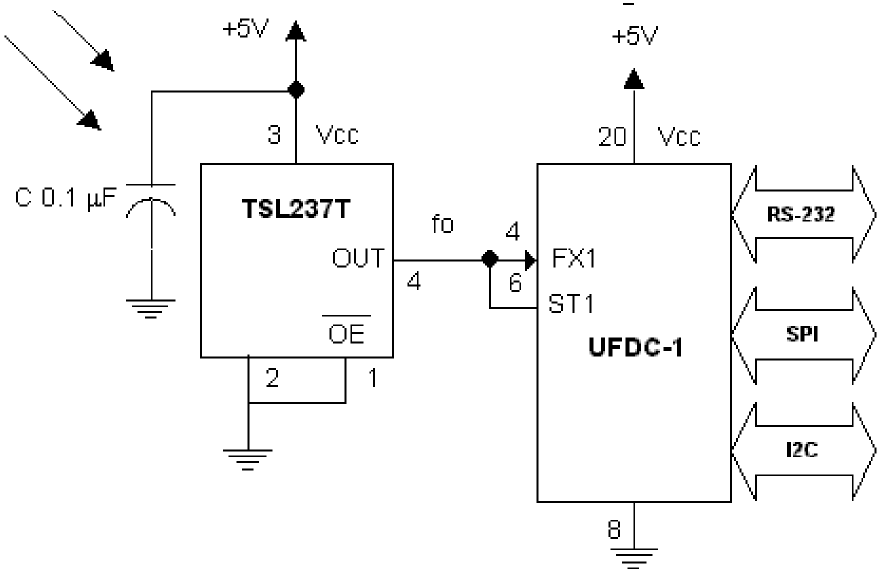


Design notes: 100 % scaling mode for TCS230 (S0, S1 =1) and clear photodiode type (no filter, S2=1, S3=0). Power-supply lines must be decoupled by a 0.01-µF to 0.1-µF capacitor with short leads mounted close to the device package.

Light-to-Digital Converters



(a)

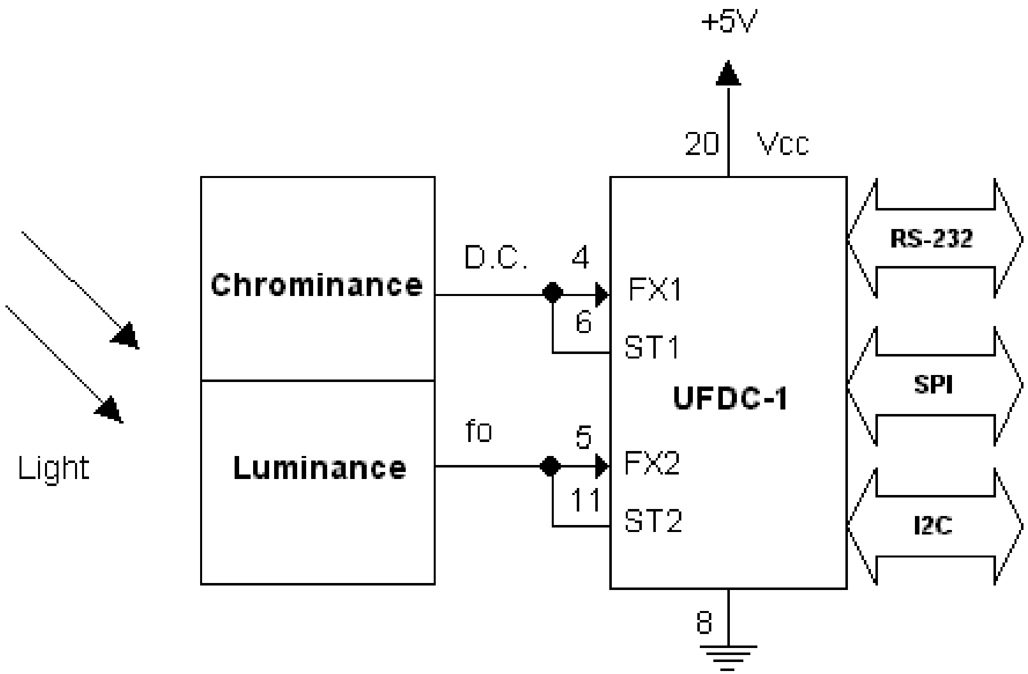


(b)

Commands Example (RS-232 interface)

>M0	; Frequency measurement initialization
>A0	; 1 % conversion error set up
>S	; Start a measurement
>R	; Read a result
1000.674946004319	; Measurement result indication

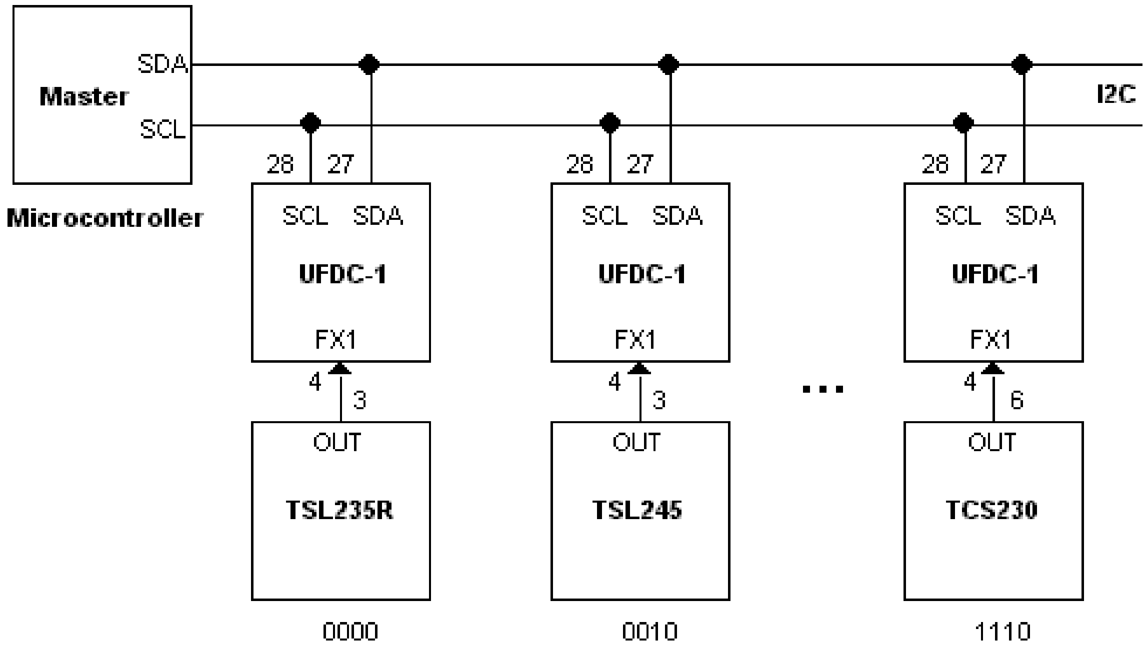
Multiparameters Sensor Interfacing



Multiparameters Sensor Interfacing (cont.)

>M4	; Duty-cycle measurement initialization
>S	; Start a measurement
>R	; Read a result
60.9786	; Duty-cycle measurement result indication
>ME	; Frequency measurement initialization on the 2^{nd} input FX2
>AX	; Appropriate ‘X’ conversion error set up
>S	; Start a measurement
>R	; Read a result
100.578698673	; Frequency measurement result indication

I²C Interface to TAOS Opto Sensors



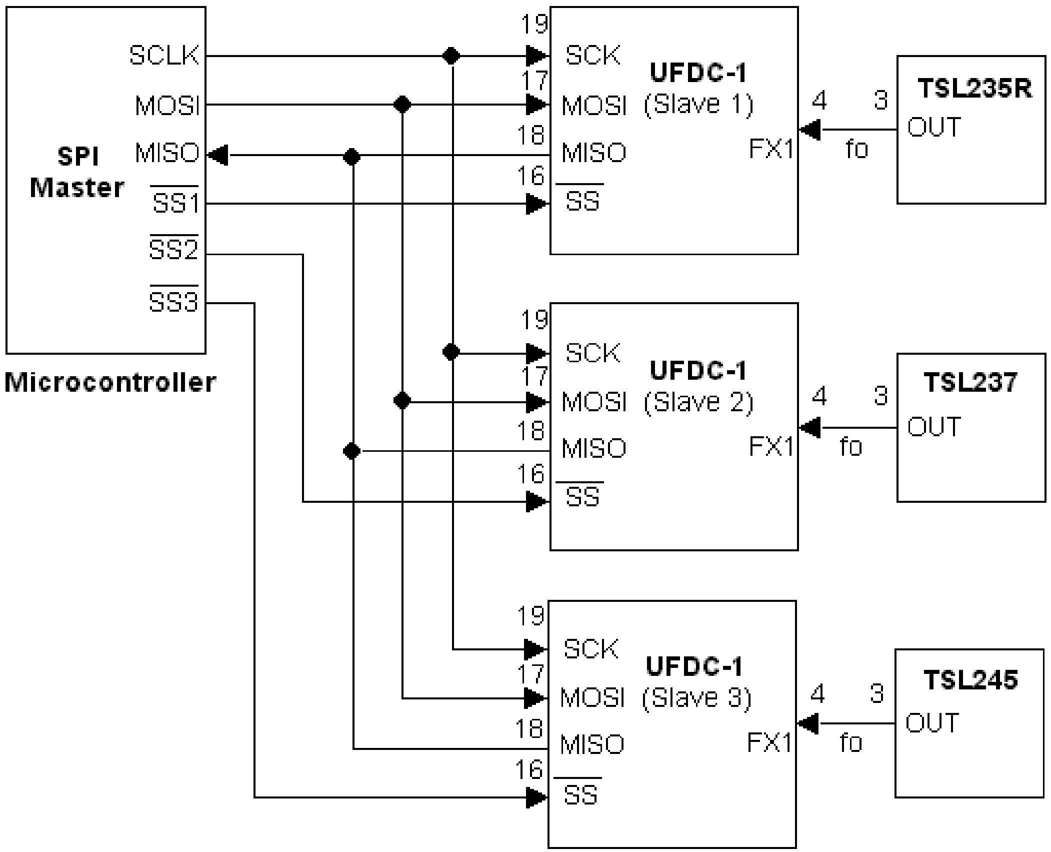
<06><00> ; Frequency measurement initialization

<02><00> ; 1 % conversion error set up

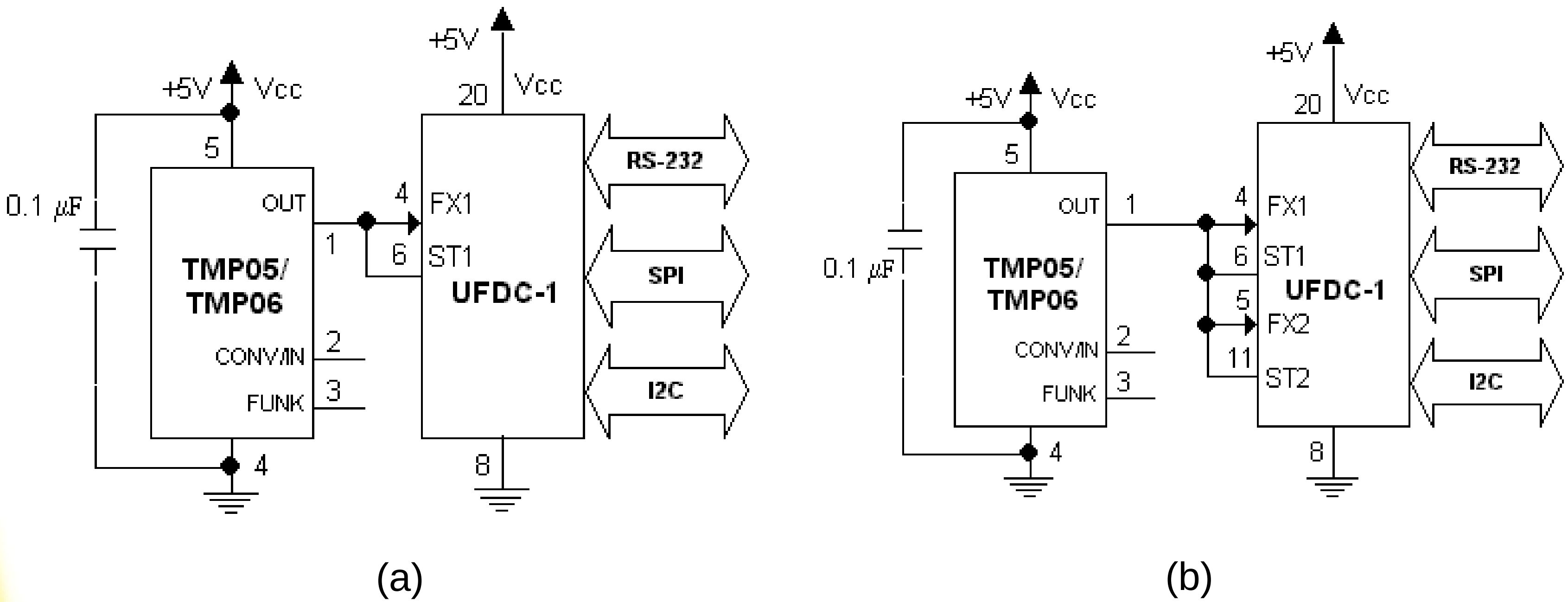
<09> ; Start a measurement

<07> ; Get measurement result in BCD format

SPI Interface to TAOS Opto Sensors

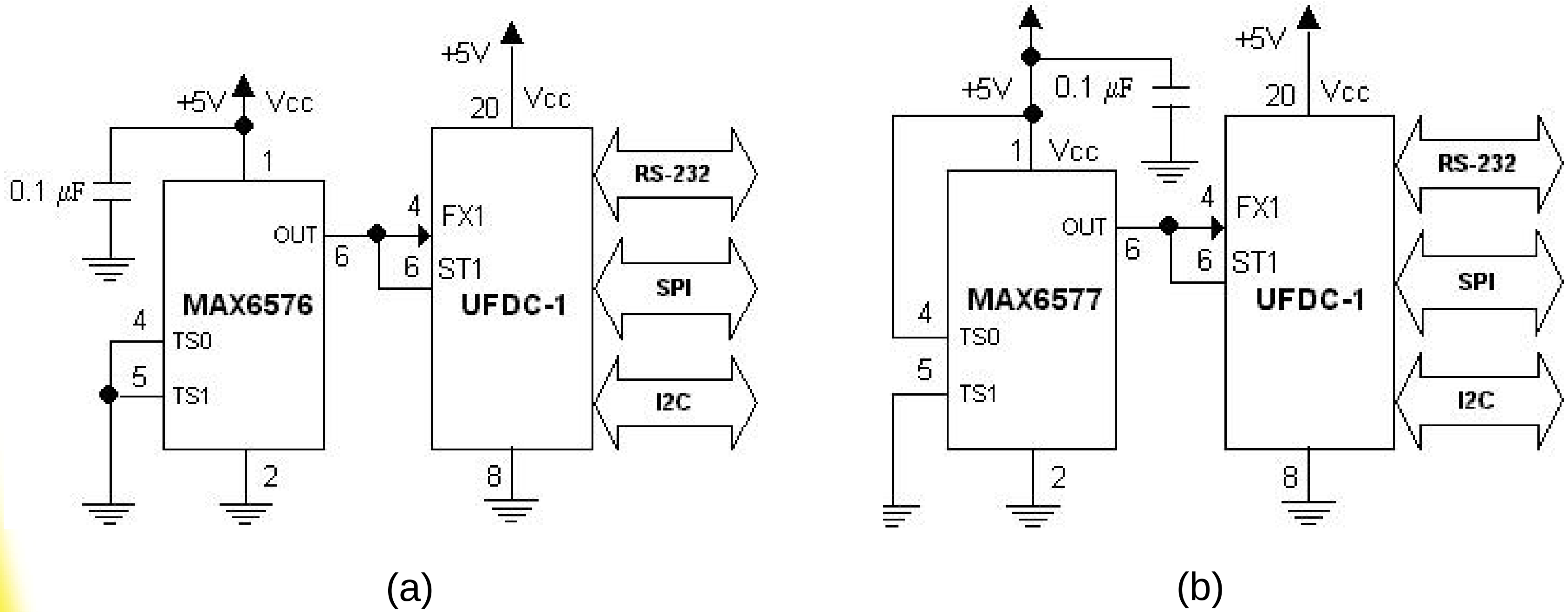


TMP05/TMP06 Sensors Interfacing



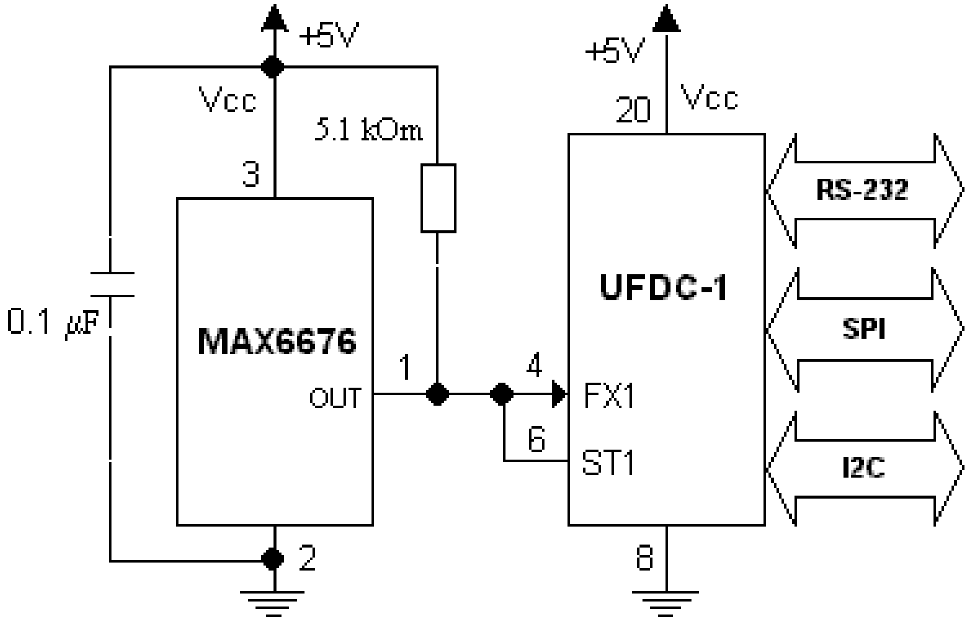
TMP05/TMP06 interfacing: T1 and T2 time intervals measurement (a), and period (T1+T2) and space interval (T2) measurement (b)

MAXIM Temperature Sensors Interfacing (I)



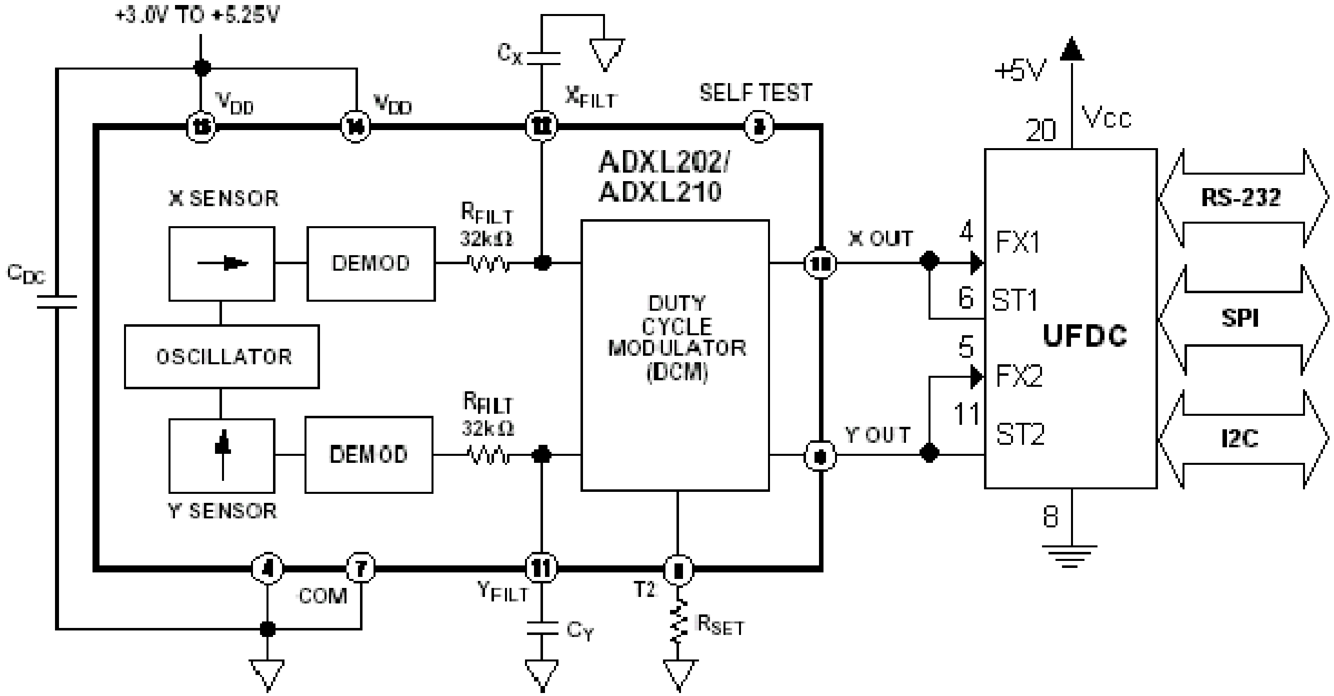
MAX6576 period output sensor interfacing (a) and MAX6577 frequency output sensor interfacing (b)

MAXIM Temperature Sensors Interfacing (II)



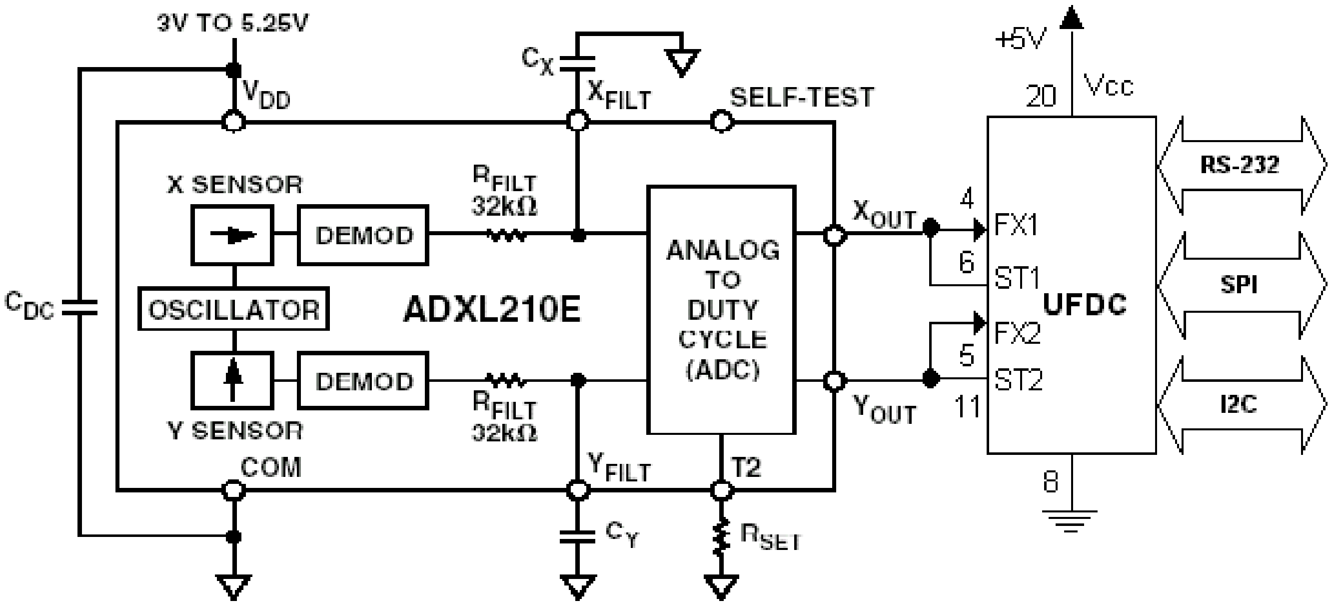
MAX6676 to UFDC-1 interfacing functional diagram

Accelerometers Based Systems (I)



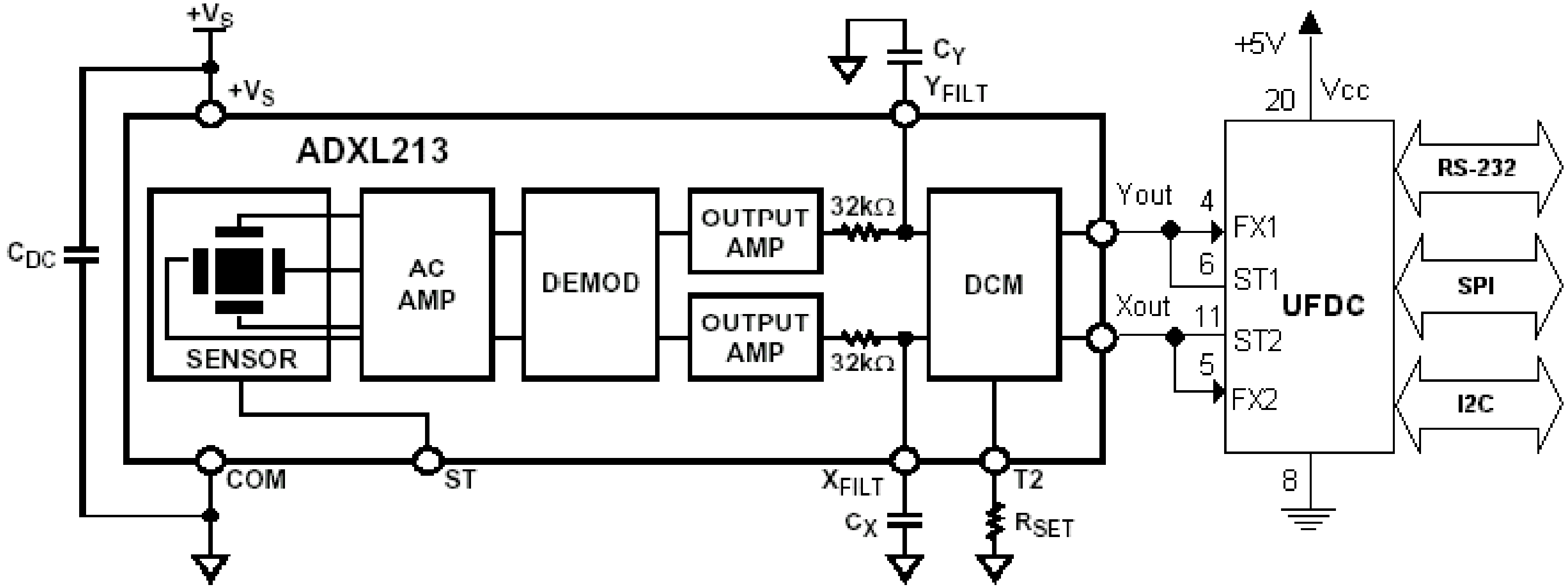
ADXL202 to UFDC-2 interfacing functional diagram

Accelerometers Based Systems (II)



ADXL210 to UFDC-2 interfacing functional diagram

Accelerometers Based Systems (III)

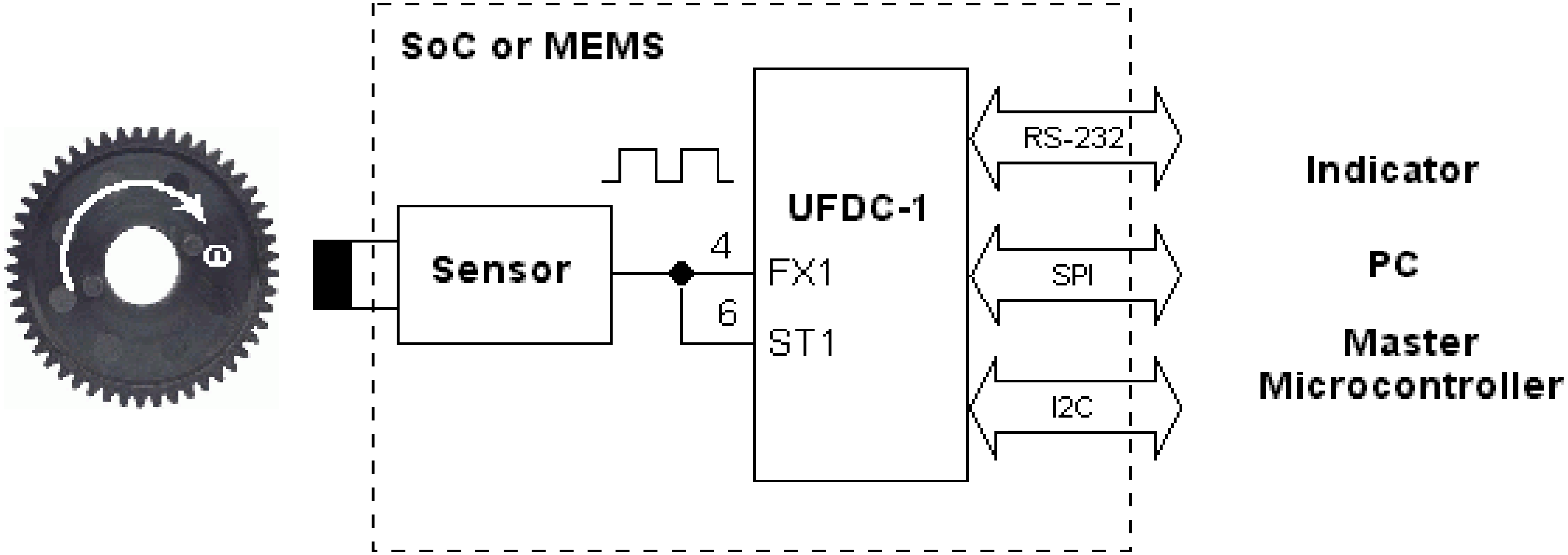


ADXL213 to UFDC-2 interfacing functional diagram

Acceleration to Frequency Circuits

- Accelerometers with voltage output may be paired with a circuit whose output changes with frequency to provide a TTL level frequency output
- Acceleration-to-frequency circuits based on different voltage-to-frequency converters, for example, AD654 VFC (ADXL05 + AD654) or 555 timer

Rotation Speed Smart Sensor



Commands Example (RS-232)

>MA	;Rotation speed measurement initialization
>Z0C	; Set up $Z=12_{(10)}=C_{(16)}$
>A9	;Choose the conversion error 0.001 %
>S	;Start a measurement
>R	;Read a result of measurement in *rpm*

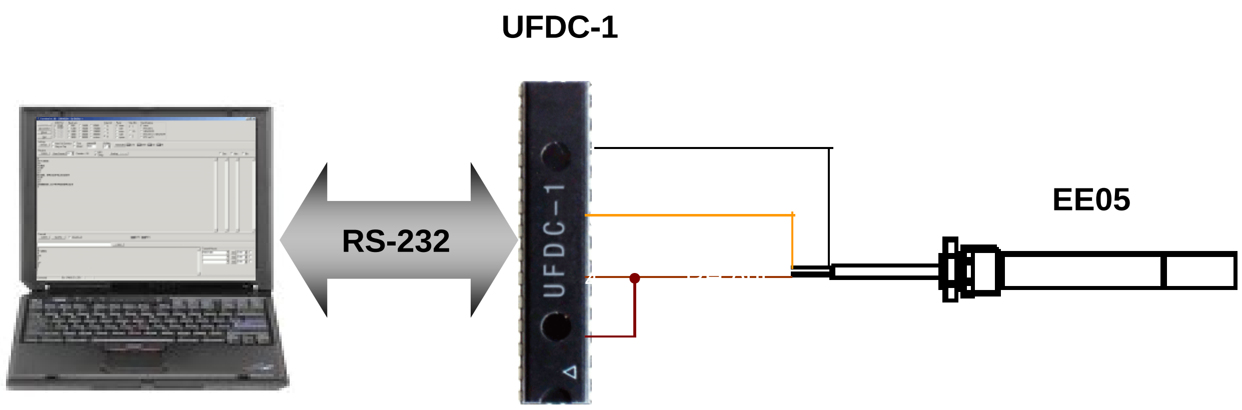
Rotation Acceleration Measurement

$$\varepsilon_x = \frac{n_1 - n_2}{t_2},$$

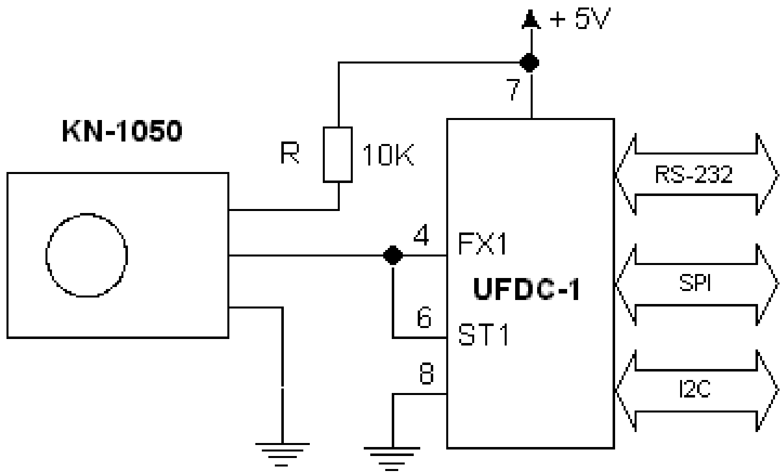
where n_1 and n_2 of rotation speed and time interval for the second measurement t_2

Smart Humidity Sensors

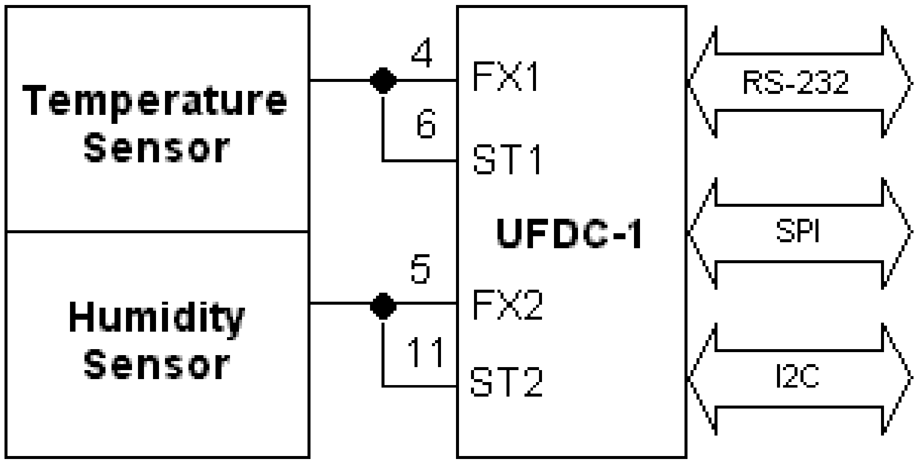
(a)



(b)



Temperature and Humidity Multisensors System



Multisensors systems with the HTF3130 sensor for humidity measurement (the second channel) and temperature sensor MAX6576 temperature measurement (the first channel)

Commands Example (RS-232)

>M1; Period measurement, 1st channel, MAX6576 temperature sensor

>A2; Choose the conversion error 0.25 %

>S; Start a measurement

>R; Read a result (period proportional to the temperature)

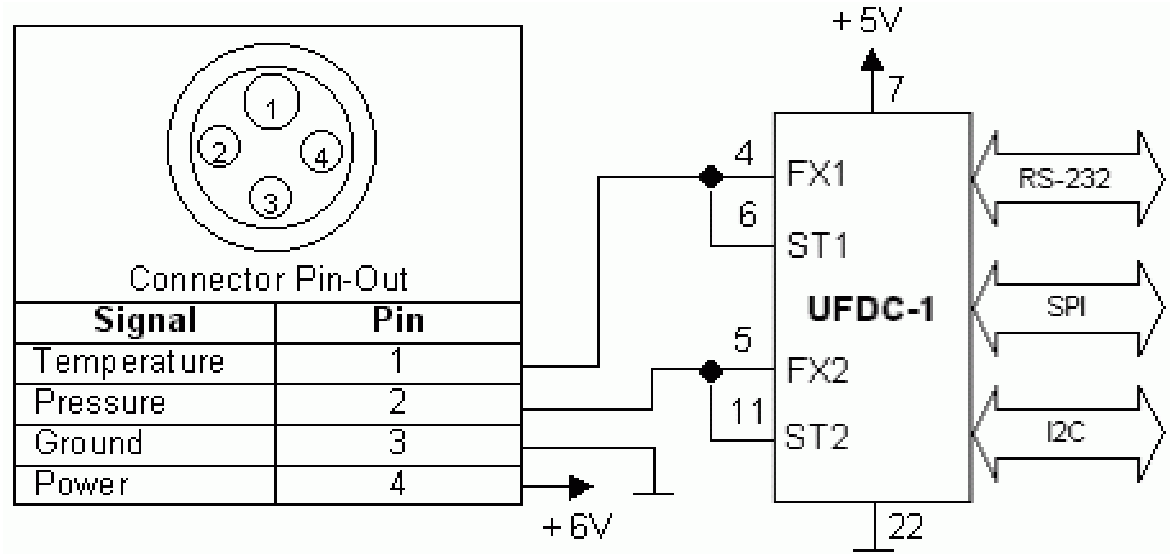
>ME; Frequency measurement, 2nd channel, HTF3130 humidity sensor

>A2; Choose the conversion error 0.25 %

>S; Start a measurement

>R; Read a result (frequency proportional to the humidity)

Pressure Sensors Interfacing

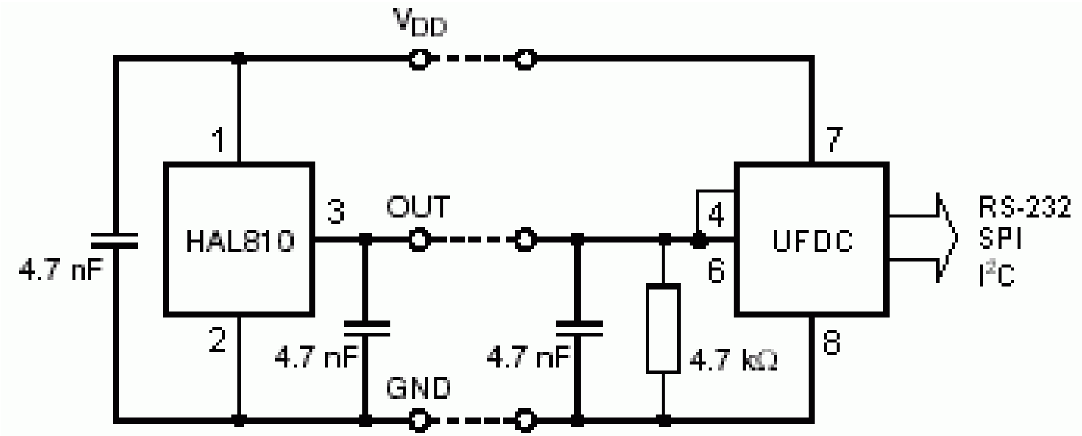


Connection diagram for 8000 Series of frequency output depth sensors from Paroscientific, Inc.

Commands Example (RS-232)

>M0	; Frequency measurement initialization in the first channel
>A0	; Choose the conversion error 0.001 %
>S	; Start a measurement
>R	; Read a result proportional to temperature
>ME	; Frequency measurement initialization in the second channel
>A0	; Choose the conversion error 0.001 %
>S	; Start a measurement
>R	; Read a result proportional to pressure

Smart Magnetic Sensors



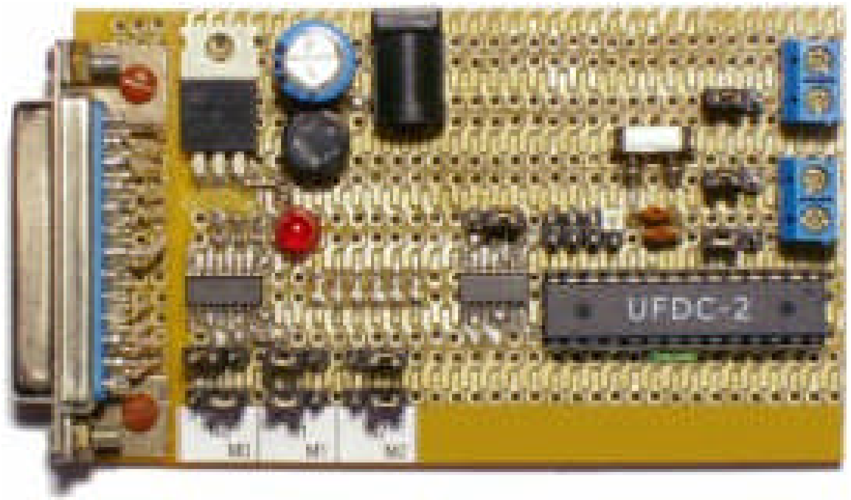
HAL819 to UFDC-1 interfacing circuit

>M4;	Duty-cycle measurement initialization (mode 4)
>S;	Start measurement
>R;	Read result

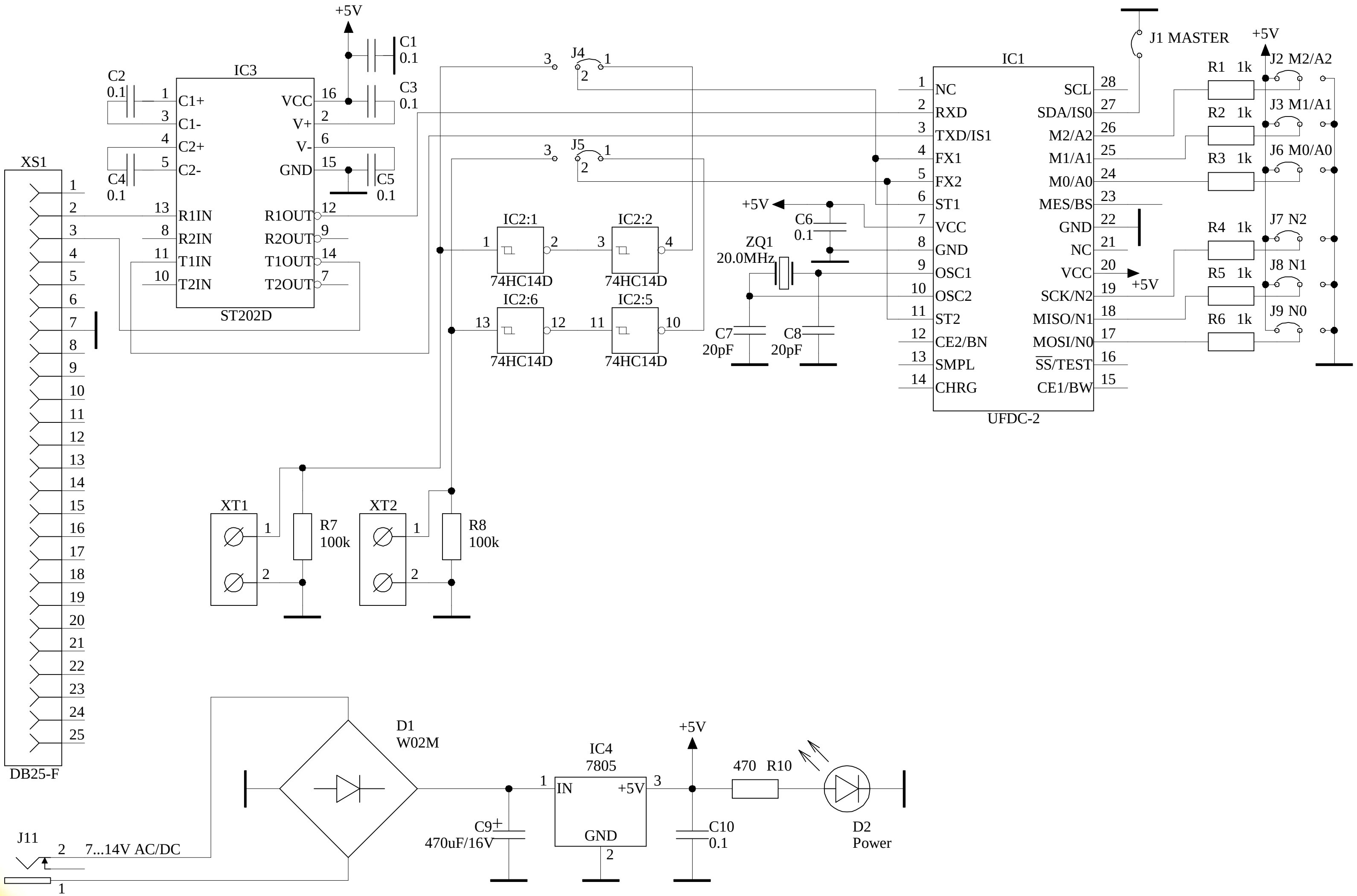
UFDC-2

- UFDC-1 modes + frequency deviation (absolute and relative) measuring mode
- Improved metrological performances: extended frequency range up to 9 MHz (144 MHz with prescaling), programmable relative error up to 0.0005 %, etc.
- Two channel measurements for every parameters
- Improved calibration procedures
- Very suitable for different QCM and other resonator based bio- and chemical sensors

Evaluation Board Prototype



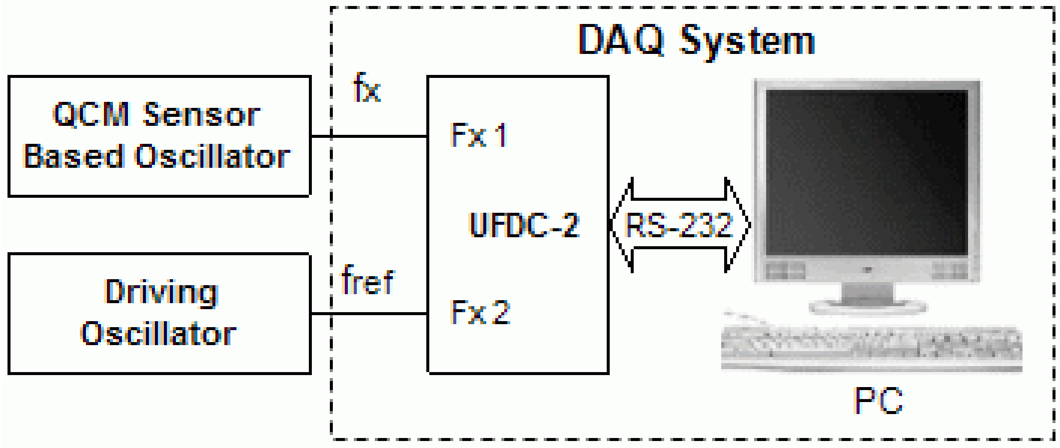
Evaluation Board Circuit Diagram



Comparison Performances of UFDC-1 and UFDC-2

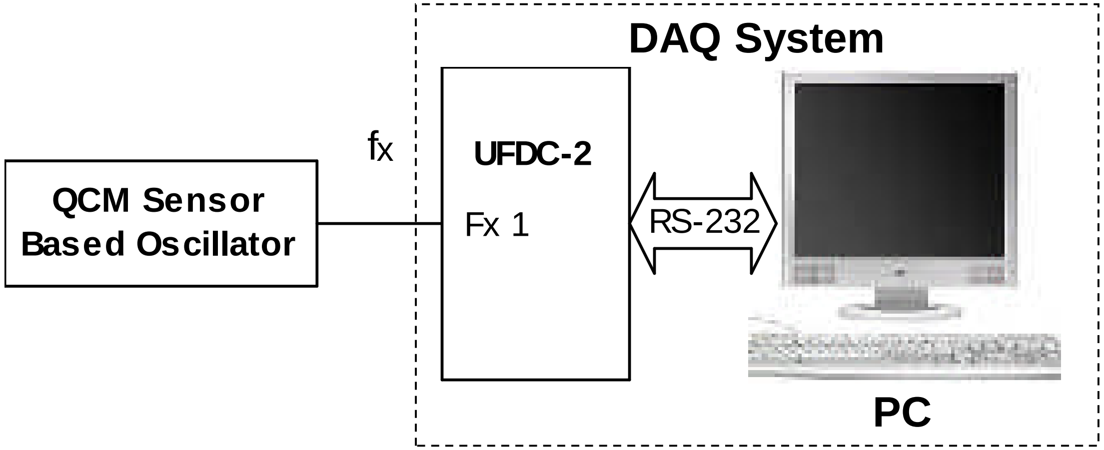
Parameter	UFDC-1	UFDC-2
Programmable relative error, %	± (1…0. 001)	± (1…0. 0005)
Maximal frequency range, MHz **- without prescaling** **- with prescaling**	7.5 120	9 144
Reference frequencies, MHz	0. 5 / 16	0. 625 / 20
Generating mode, MHz	8	10
Frequency deviation measurement mode	No	Yes
TEDS Support	No	Yes
2-channel conversion for	Frequency and period	All parameters
Number of measuring modes	16	26

QCM Sensor System: Example 1



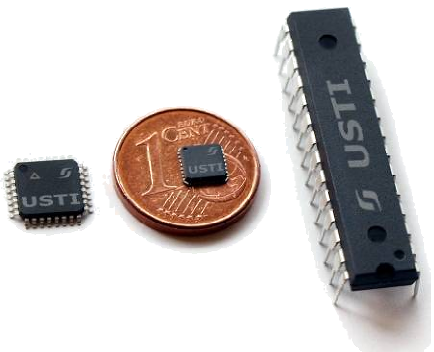
>M06	; Frequency difference measurement initialization
>A0A	; 0.0005 % conversion relative error set up
>S	; Start a measurement
>R	; Read a result
7054.07537	; Measurement result indication

QCM Sensor System: Example 2



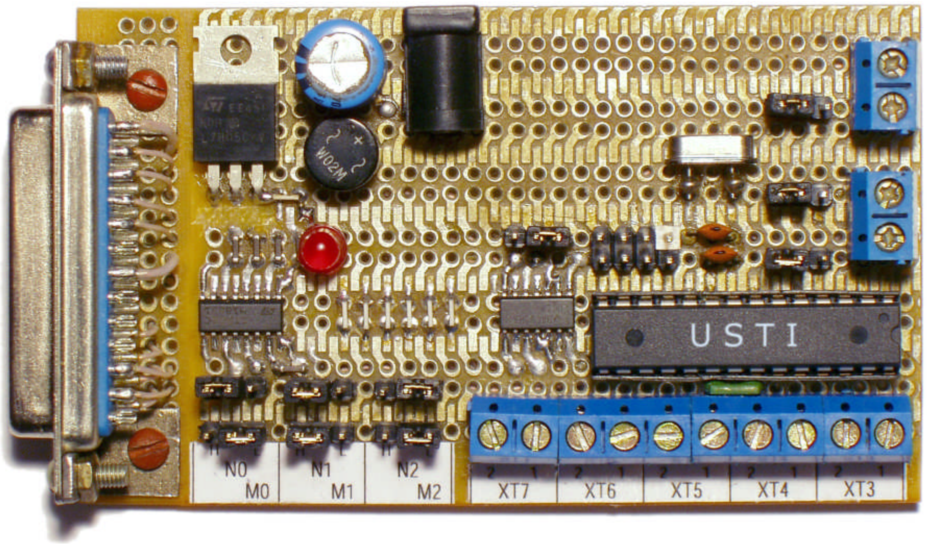
>M13	; Frequency deviation measurement in the1st channel
>A0A	; Absolute deviation measurement, 5×10^{-4} % relative error
>E7000000.34	; Set the reference frequency f_{ref} (Hz)
>S	; Start a measurement
>R	; Read a result
6000.7824	; Measurement result indication

Universal Sensors and Transducers Interface (USTI)

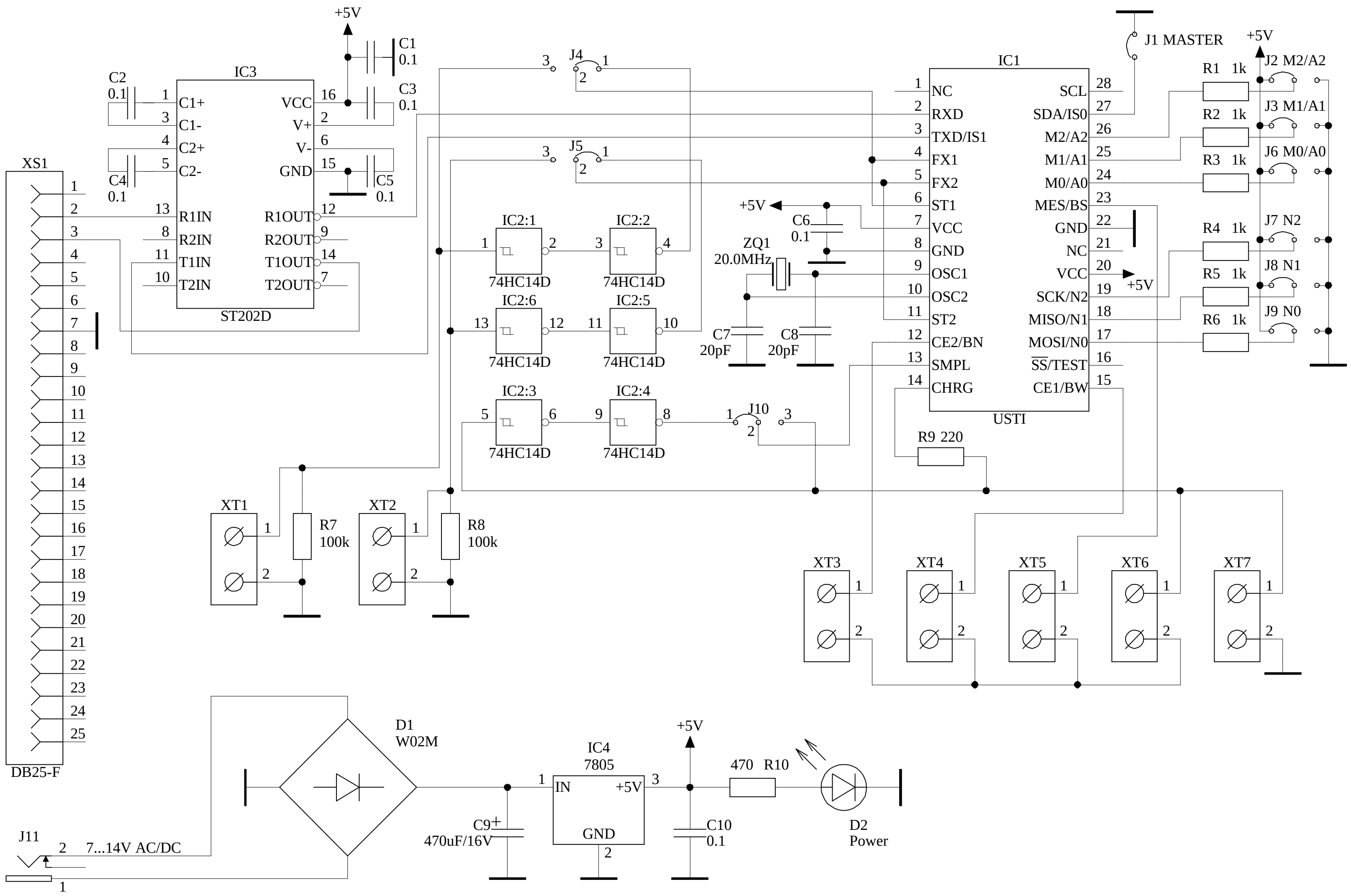


- All UFDC's modes plus a frequency deviation (absolute and relative) measuring mode
- Improved metrological performances: extended frequency range up to 9 MHz (144 MHz with prescaling), programmable relative error up to 0.0005 %, etc.
- Two channel measurements for every parameters
- Improved calibration procedures
- Resistance, capacitance and resistive bridge measuring modes
- Can also contain a TEDS in its flash memory

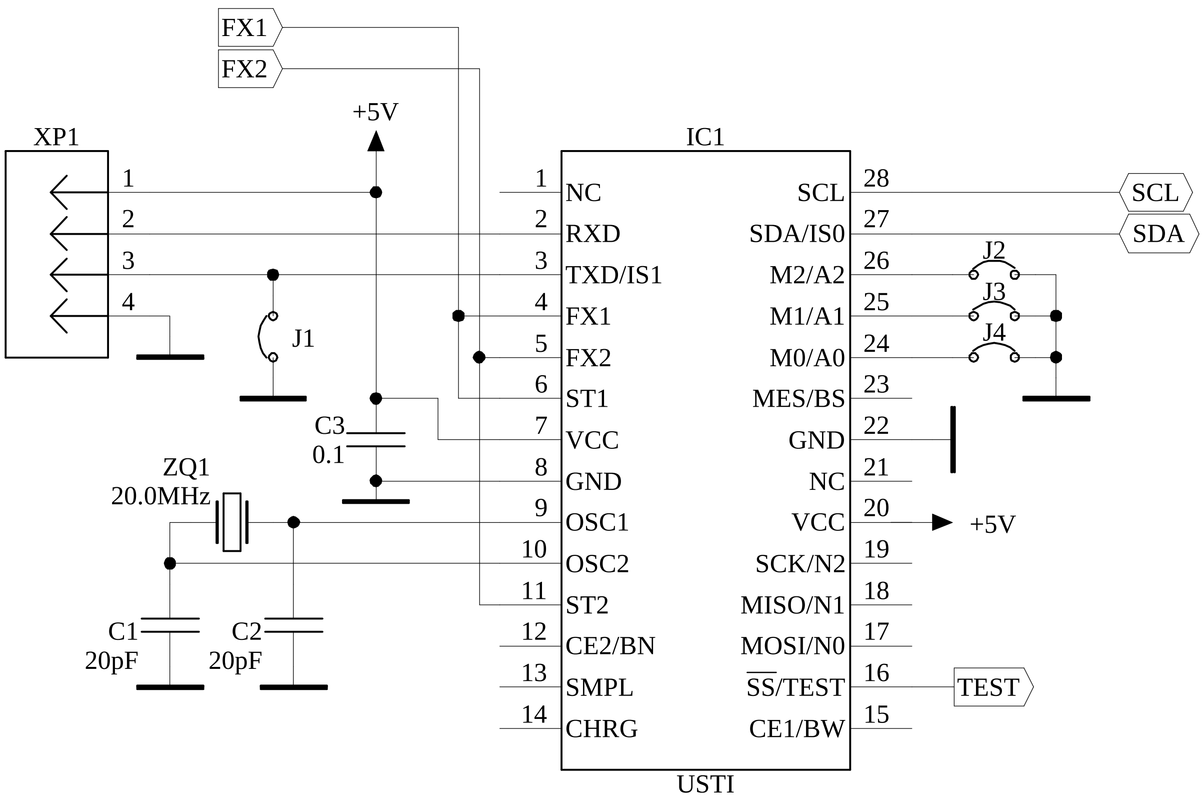
USTI Evaluation Board



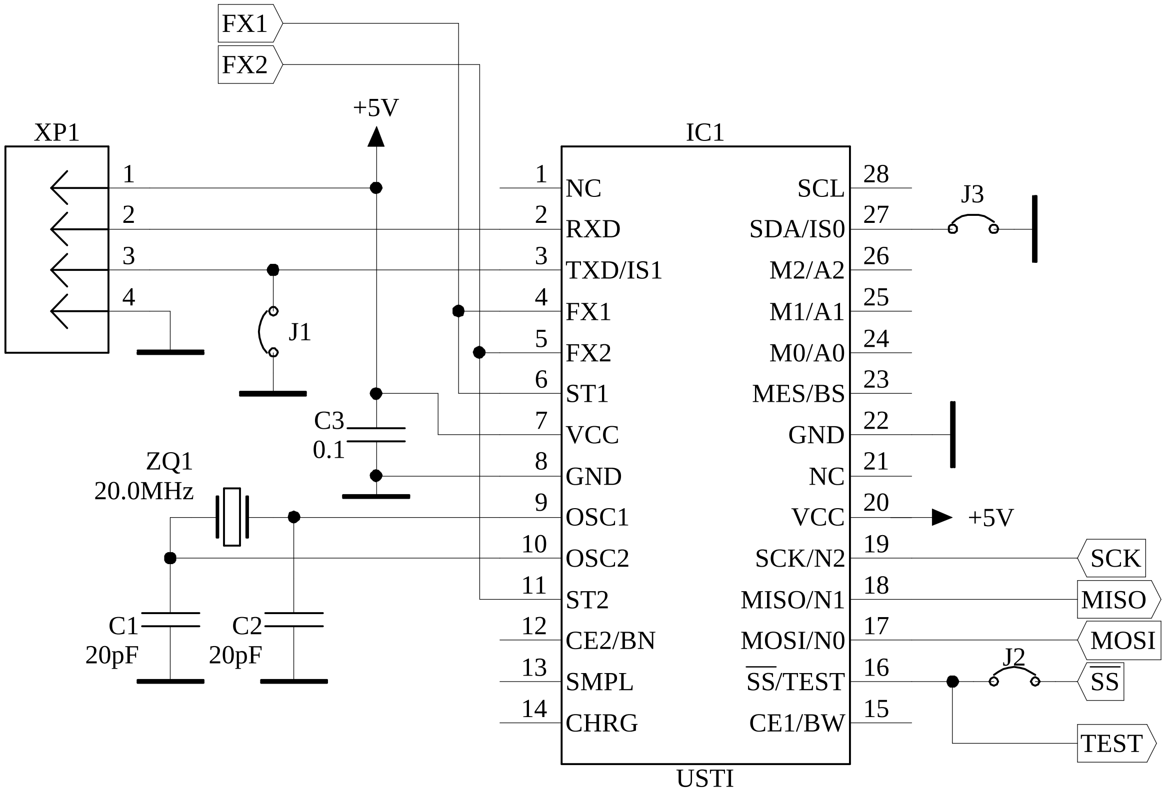
Evaluation Board Circuit Diagram



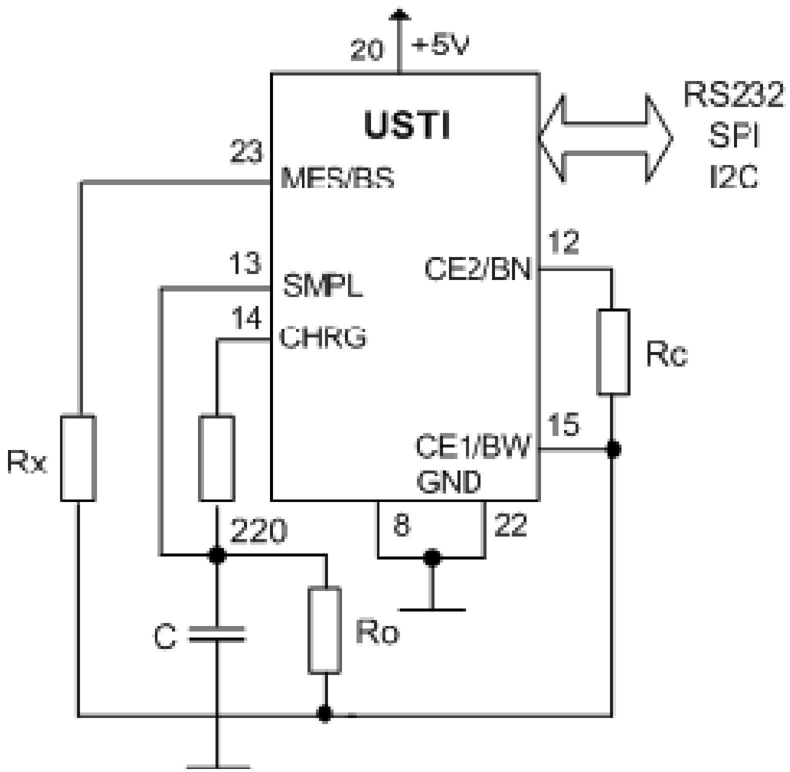
USTI I²C Interface



USTI SPI Interface



Direct Resistive Sensing Element Interfacing



$$R_x = \frac{N_x - N_{off}}{N_{ref} - N_{off}} \cdot R_c$$

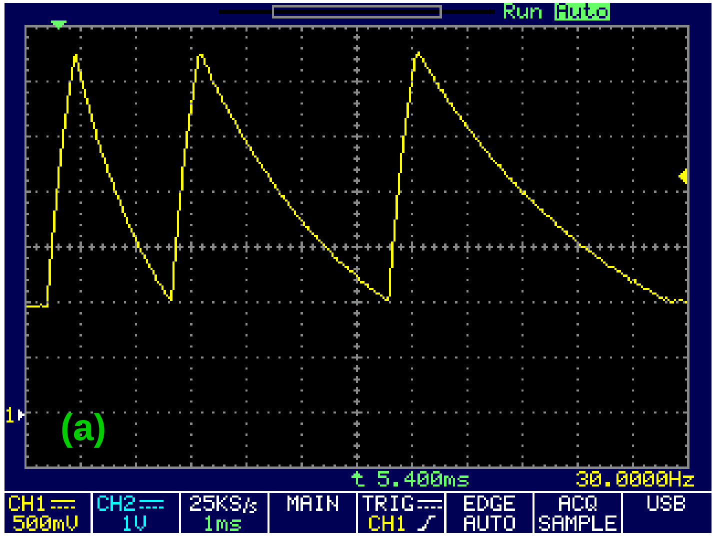
$$C \geq \frac{0.002}{R_c}$$

$$R_c \leq R_x$$

$$R_0 \approx 300 \ldots 600\ \Omega.$$

$$T = 2200 \times C$$

Oscillograms of Three-point Calibration Technique



R_x=1006.5 Ω; R_c=604.02 Ω; C= 3 μF and R_0=328.63 Ω (a); and R_x=10 237 000 Ω (b)

USTI Commands for Resistive Measurement (RS232 Interface)

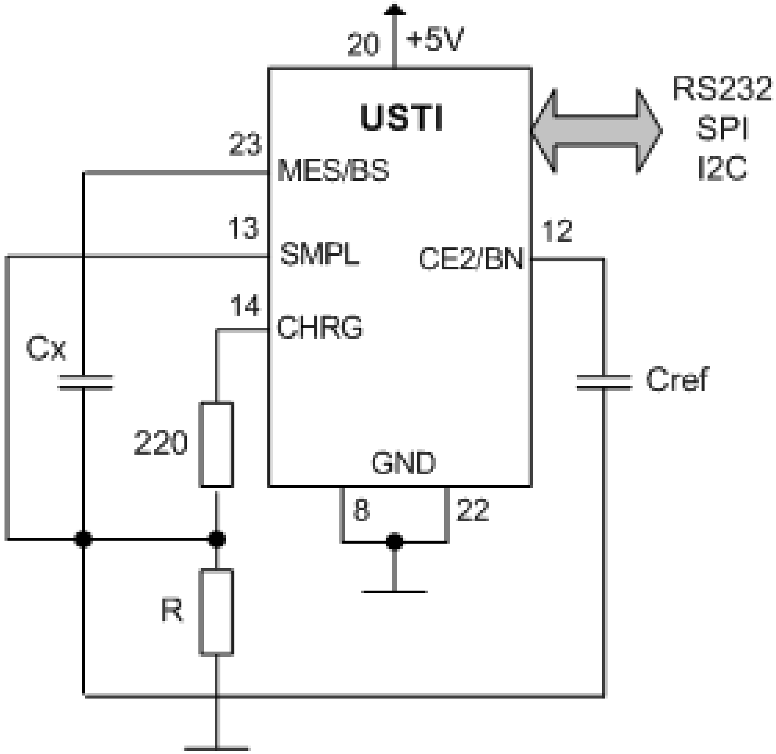
>M10	; Set up a resistance R_x measurement mode
>E263000.0	; Set the reference value R_c =263 kΩ
>W1B	; Set the charging time 100 ms
>S	; Start measurement
>C	; Check the measurement status:
r	; Returns ‘b’-if in progress; ‘r’-if ready
> R	; Read result in Ω

Comparative Resistance Measurement Results

Relative Resistance Error			
Marked Value	PICMETER [4] Error, %	USTI Error, %	Measurement conditions
0.10 K	N/a	0.24	R_c=329.66 Ω; C=2μF R_0=609.86 Ω
0.30 K	N/a	1.58	R_c=432 260 Ω; C=2μF
0.82 K	N/a	1.31	R_0=609.85 Ω
1.0 K	N/a	0.026	R_c=604.02 Ω; C=3μF R_0=328.63 Ω
1.2 K	1.3	1.17	
5.1 K	1.0	1.067	
8.2 K	2.0	0.92	
10 K	2.0	0.918	
15 K	1.7	0.860	
20 K	1.5	0.805	
30 K	1.4	0.759	
51 K	1.0	0.641	
75 K	1.0	0.566	R_c=432 260 Ω
91 K	0.6	0.491	C=2 μF
150 K	0.5	0.392	R_0=609.85 Ω
200 K	0.3	0.309	
300 K	0.2	0.2	
430 K	0.4	0.137	
560 K	0.6	0.062	
680 K	0.7	0.02	
820 K	0.7	0.0091	
910 K	0.8	0.0026	
1.0 M	N/a	0.0493	
1.5 M	N/a	0.122	R_0=464 240 Ω C=2.1 nF R_c=563 960 Ω
2.0 M	N/a	0.063	R_c=432 280 Ω C=2.1 nF R_0=464 240 Ω

- Measuring range: 10 Ω …10 MΩ
- Average relative error: ± 0.47 %
- ± 0.01 % relative error at splitting of the range of into sub ranges
- Can work with any known resistance-to-time or resistance-to-frequency converters

Direct Capacitance Sensing Element Interfacing

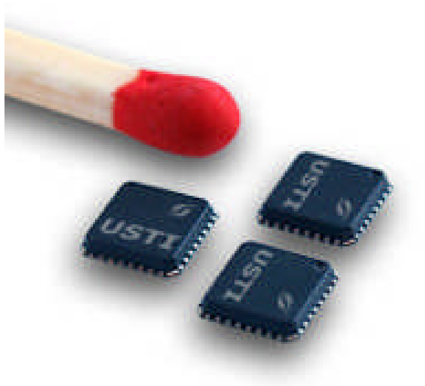


$$C_x = \frac{N_x - N_{off}}{N_{ref} - N_{off}} \cdot C_{ref}$$

$$R \geq \frac{0.002}{C_{ref}}$$

$$T = 2200 \times C$$

Capacitance Measurement Performance



- Capacitance measurement range from 50 pF to 100 μF.
- Average relative error ± 0.036 %
- Worst case relative error for reported results is not more than ± 0.7 %
- Can work with any known capacitance-to-frequency converters

Direct Resistive-Bridge Sensing Element Interfacing

SENSORDEVICES 11:

Sensors Signal Conditioning and Interfacing Circuits II

Universal Interfacing Circuit for Resistive-Bridge Sensors

Wednesday, July 21, 13:45

Measurement Time Calculation

$$T_{meas} = t_{conv} + t_{comm} + t_{calc}$$

$$\begin{cases} t_{conv} = \dfrac{1}{f_x} & if \quad \dfrac{N_\delta}{f_0} \prec T_x \\ t_{conv} = \dfrac{N_\delta}{f_0} + (0 \div T_x) & if \quad \dfrac{N_\delta}{f_0} \geq T_x \end{cases}$$

where $N\delta = 1/\delta$ is the number proportional to the required programmable relative error δ

The calculation time depends on operands and is as usually

$t_{calc} \leq 4.5$ ms

Communication Time

- **For RS-232 interface:** $$t_{comm} = 10 \cdot n \cdot t_{bit}$$

  where t_{bit} = 1/300, 1/600, 1/1200, 1/2400, 1/4800, 1/9600, 1/14400, 1/19200, 1/28800 or 1/38400 is the time for one bit transmitting; *n* is the number of bytes (*n* = 13÷24 for ASCII format).

- **For SPI interface:** $$t_{comm} = 8 \cdot n \cdot \frac{1}{f_{SCLK}}$$

  where f_{SCLK} is the serial clock frequency (from 100 to 500 kHz); *n*=12÷13 is the number of bytes: for BCD (*n*=13) or binary (*n*=12) formats

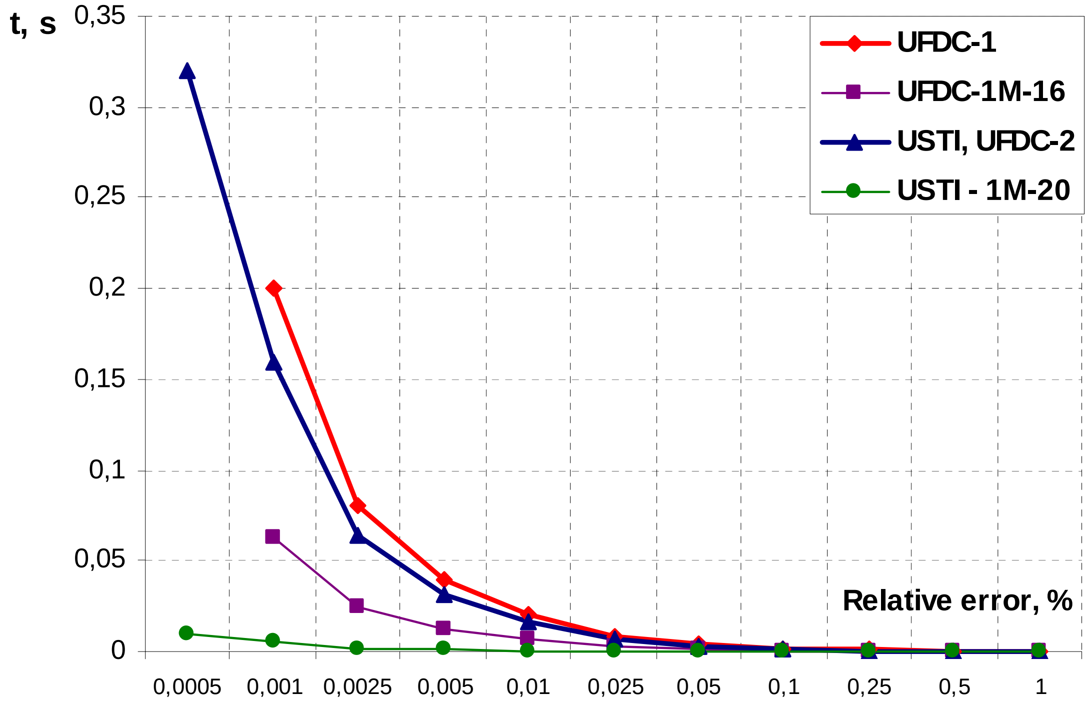
- **For I^{2}C interface:** $$t_{comm} = 8 \cdot n \cdot \frac{1}{f_{SCL}}$$

  where f_{SCL} is the serial clock frequency100 kHz *n*=12÷13 is the number of bytes for measurement result: BCD (*n* = 13) or binary (*n* =12).

Relative Error vs. Conversion Time

Relative error, δ_x %	$N_\delta = 1/\delta_x$	UFDC-1 (at f_0=500 kHz)	UFDC-1M-16 (at f_0=16 MHz)	USTI (at f_0=625 kHz)	USTI-1M-20 (at f_0=20 MHz)
		t_{conv}, s			
1	100	0.0002	0.00000625	0.00016	0.000005
0.5	200	0.0004	0.0000125	0.00032	0.00001
0.25	400	0.0008	0.000025	0.00064	0.00002
0.1	1000	0.002	0.0000625	0.0016	0.00005
0.05	2000	0.004	0.00125	0.0032	0.0001
0.025	4000	0.008	0.0025	0.0064	0.0002
0.01	10000	0.02	0.00625	0.016	0.0005
0.005	20000	0.04	0.00125	0.032	0.001
0.0025	40000	0.08	0.0025	0.064	0.002
0.001	100000	0.2	0.00625	0.16	0.005
0.0005	200000	-	-	0.32	0.01

Conversion Times vs. Relative Error



Adaptive Algorithms

- An adaptation in smart sensors systems can be used for increasing of measurement accuracy and/or decreasing of measuring time, etc.
- Adaptive measuring algorithms:

$$\lambda_j^* = T_s L \gamma_j(t) \vee \delta_s L \gamma_j(t);$$

where L is the algorithm of measurement; T_s and δ_s are operations for speed and accuracy increasing; $\gamma_j(t)$ is the input action

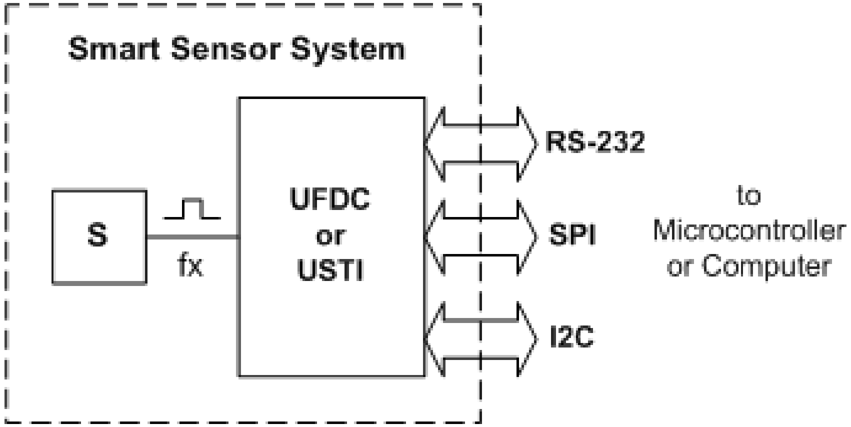
Parametric Adaptation

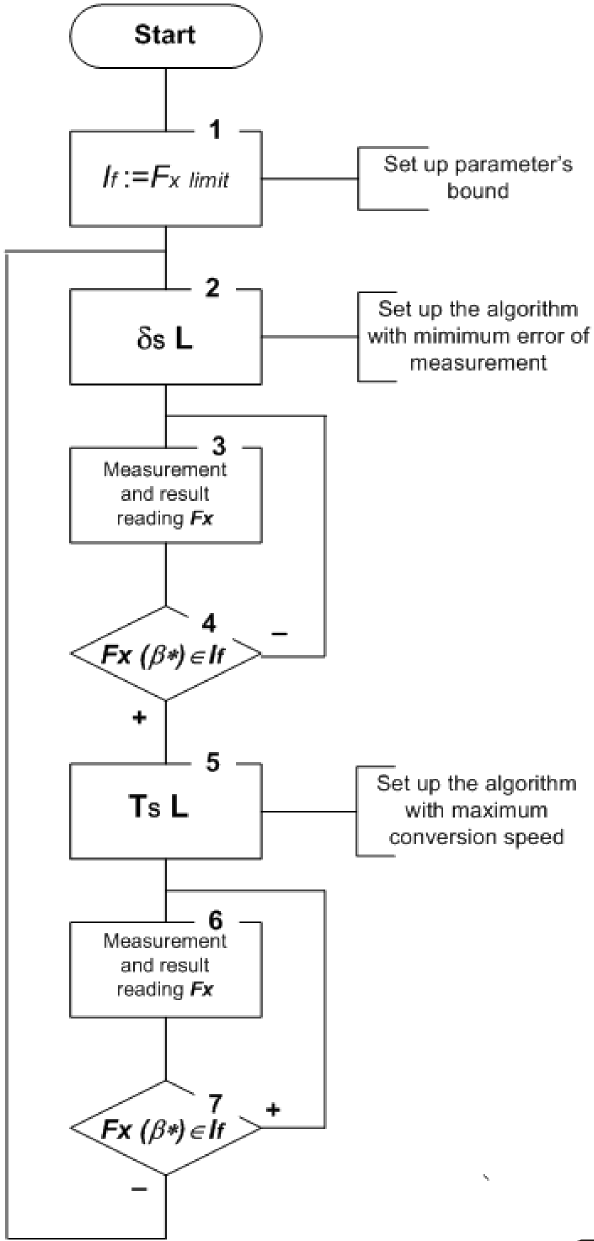
For the modified MDC:

$$\begin{cases} \lambda^{*}{}_{j} = T_{s} L \gamma_{j}(t), \; if \;\; F_{x}(\beta^{*}) \in I_{f} \\ \lambda^{*}{}_{j} = \delta_{s} L \gamma_{j}(t), \; if \;\; F_{x}(\beta^{*}) \notin I_{f} \end{cases} \quad \text{at} \quad I_{f} \in I;$$

where $F_x(\beta^*)$ is the characteristic of input action or measuring conditions
I_f is the subset of certain area I of possible values of characteristic $F_x(\beta^*)$

Adaptive Systems and Algorithm





Advanced ABS Algorithm

- Automatic choice of the quantization time depending on the given conversion error
- Required conversion error can be selected by the microcontroller depending on the current rotation speed
- It will allow to increase speed at measurement of critical rotation speeds

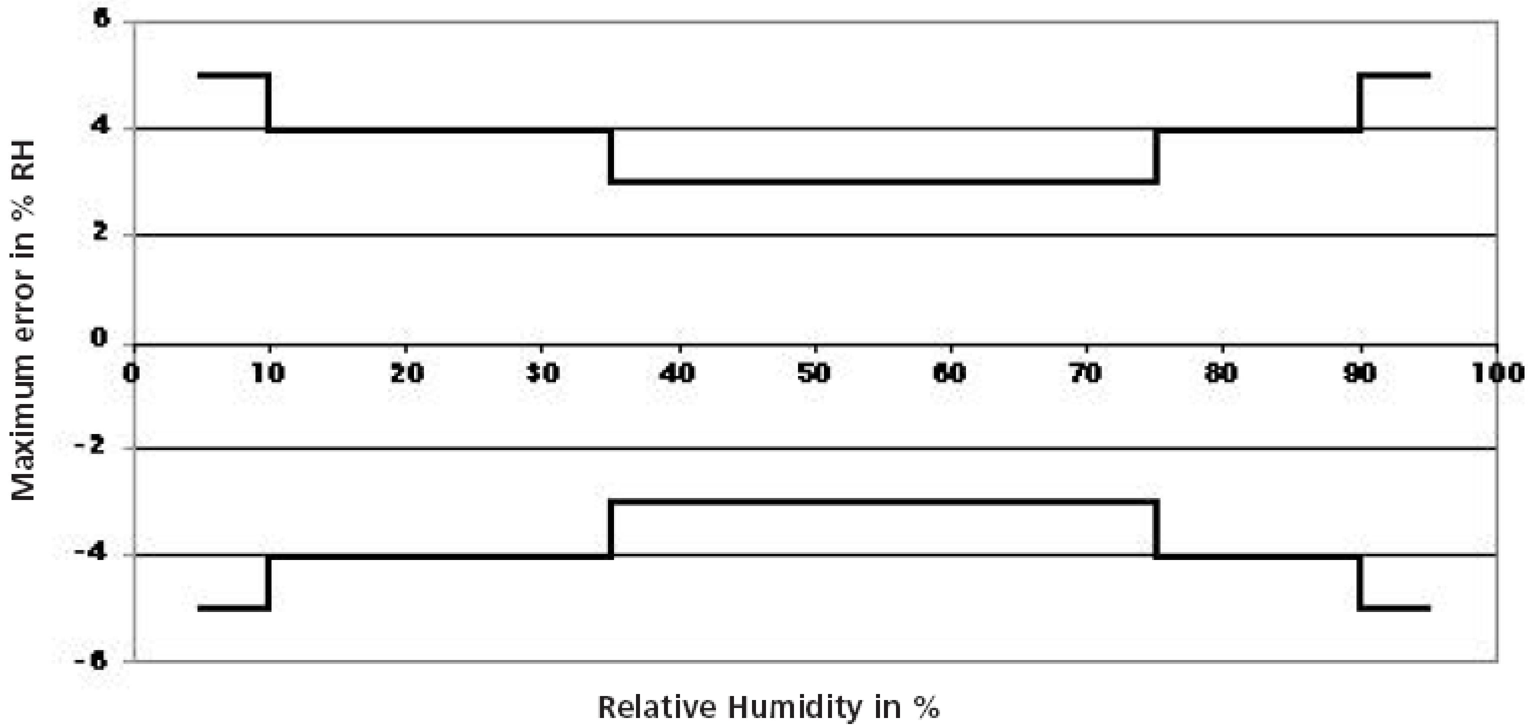
Adaptive Rotation Speed Measurements

>MA; Rotation speed measurement initialization in the 1st channel
>Z30; Set up the modulation rotor teeth number Z=48(10)=30(16)
>A9; Choose the relative error of frequency measurement 0.001 %
>S; Start a measurement
>R; Read a result of measurement in *rpm*

; Here microcontroller or computer should check the condition for an algorithm changing and prepare the UFDC-1 to measure with highest speed (maximum relative error) if a critical rotation speed has been achieved:

>A0; Choose the relative error of measurement 1 %
>S; Start a measurement
>R; Read a result of measurement in *rpm*

Relative Humidity Accuracy of HTF 3130 @ 25°C



Commands for UFDC-1 (RS232 Interface)

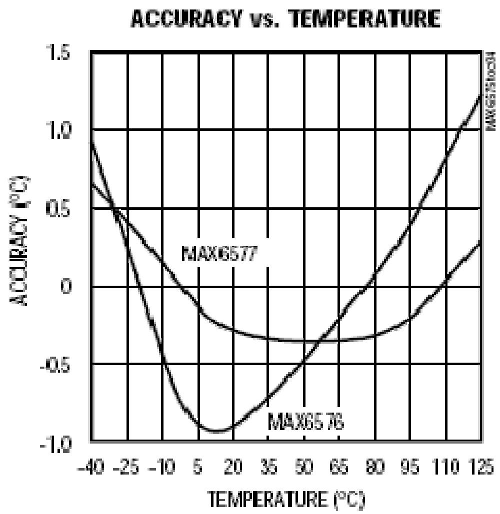
>M0;	Frequency measurement initialization in the 1st channel
>A2;	Choose the relative error of frequency measurement 0.25 %
>S;	Start a measurement
>R;	Read a result of measurement

; Here microcontroller or computer should check the condition for an algorithm changing and prepare the UFDC-1 to measure frequency with 0.5 % relative error if a value of humidity is in the 0 – 10 % RH or 90-100 % RH relative humidity range.

>A1;	Choose the relative error of measurement 0.5 %
>S;	Start a measurement
>R;	Read a result of measurement

Absolute Errors for MAX6576/77

Temperature Sensor Error (Note 1)		MAX6576	T_A = -20°C	-7.5	±1.1	+7.5	°C
			T_A = 0°C	-5.5	±0.9	+5.5	
			T_A = +25°C	-3.0	±0.8	+3.0	
			T_A = +85°C	[illegible]	±0.5	+4.5	
			T_A = +125°C	-5.0	±0.5	+5.0	
		MAX6577	T_A = -20°C	-7.5	±1.1	+7.5	°C
			T_A = 0°C	-6.5	±0.9	+6.5	
			T_A = +25°C	-3.0	±0.8	+3.0	
			T_A = +85°C	-3.5	±0.5	+3.5	
			T_A = +125°C	-4.5	±0.5	+4.5	



Commands for UFDC-1 (RS232 Interface)

>M0	;Start frequency measurement in the 1st channel
>A4	;Set the relative error 0.05 %
>S	;Start a measurement
>R	;Read a result of measurement

; Here microcontroller or computer should check the condition for an algorithm changing and prepare the UFDC-1 to measure frequency with 1 % relative error if a value of temperature is in the -20^{0}C … 0^{0}C range.

>A0	;Choose the relative error of measurement 1 %
>S	;Start a measurement
>R	;Read a result of measurement

IEEE 1451 Standard

- The standard defines the concept of plug-and-play sensors with analog outputs, maintaining compatibility with the large existing base of analog instrumentation and interfaces.
- IEEE 1451 family of standards become more and more popular
- Since 2004 more than 3200 different models of sensors were manufactured according to IEEE 1451.4

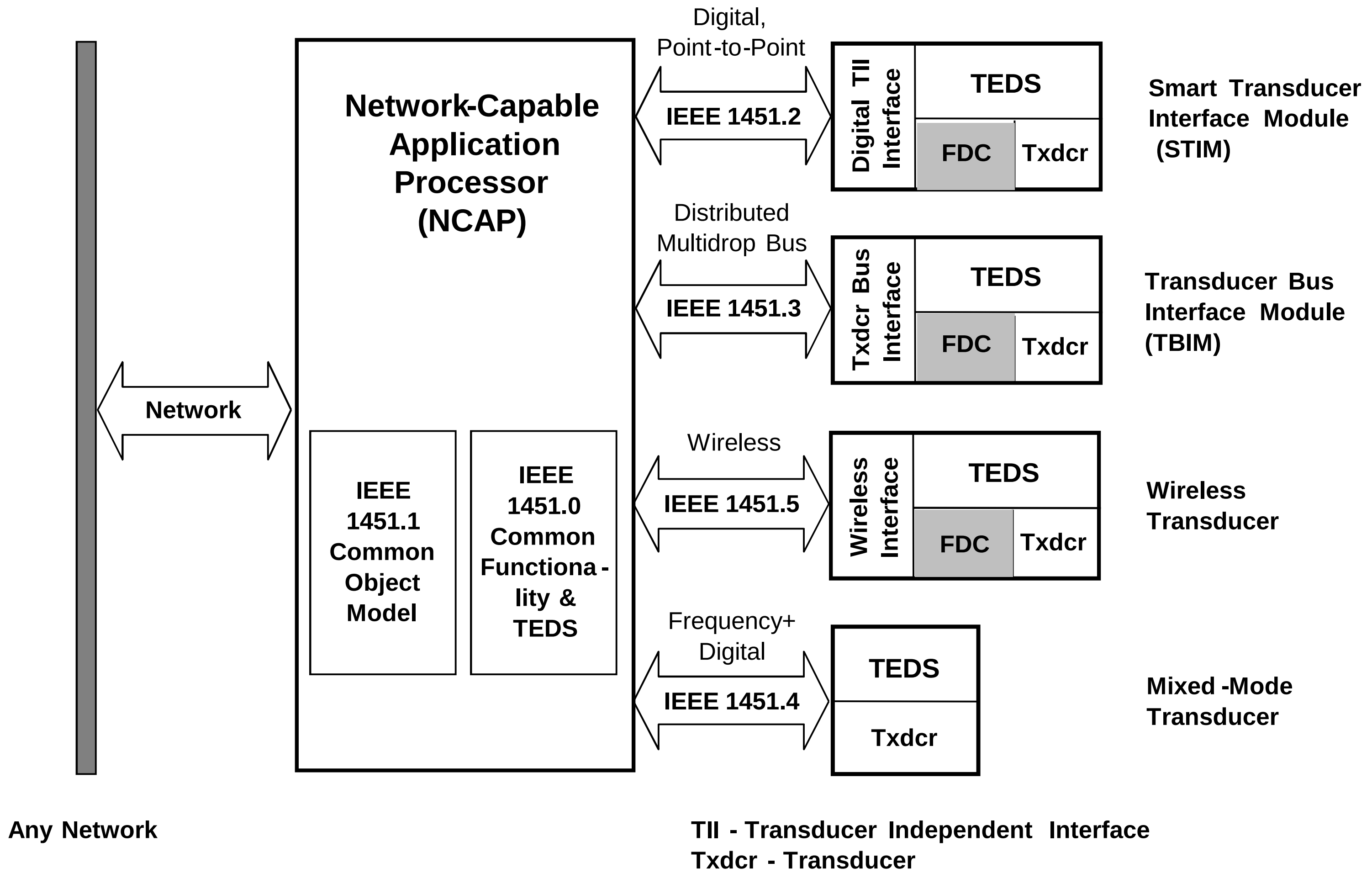
IEEE 1451 Standard Family Members

- **IEEE 1451.1** Information Model for Smart Transducers (Approved 1999)
- **IEEE 1451.2** Transducer to Microprocessor Communication Protocols and Transducer Electronic Data Sheet (TEDS) Formats
- **IEEE 1451.3** Digital Communication and TEDS Formats for Distributed Multidrop Systems (Approved 1999)
- **IEEE 1451.4** Mixed-mode Communication Protocols and Transducer Electronic Data Sheet (TEDS) Formats (2004)
- **IEEE 1451.5** Wireless Communication Protocols
- **IEEE 1451.6** A High-speed CANopen-based Transducer Network Interface (Proposed)

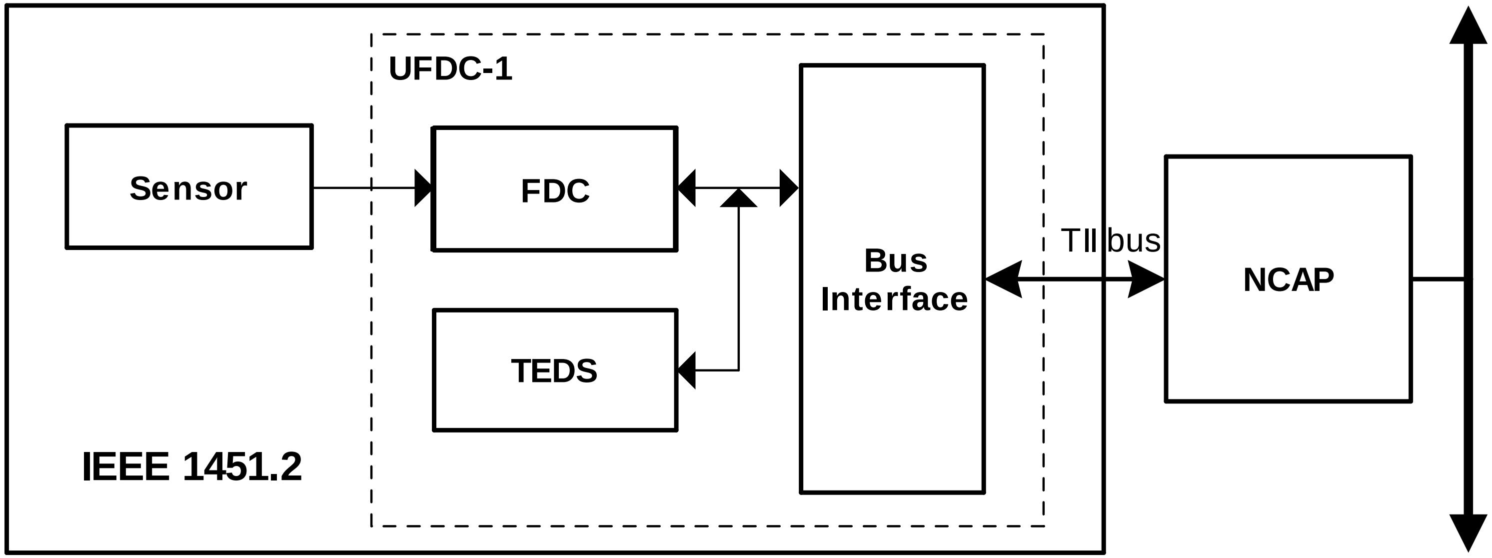
IEEE 1451 Standard and Frequency Output Sensors

- Frequency sensors also mentioned in some documents, articles and papers about this standard
- Real results are not observed
- No exist any TEDS example for frequency-time domain sensors
- Reasons: (a) there is no any standardized frequency-to-digital conversion method; (b) sensor system's error depends on frequency range

Standard's Extension



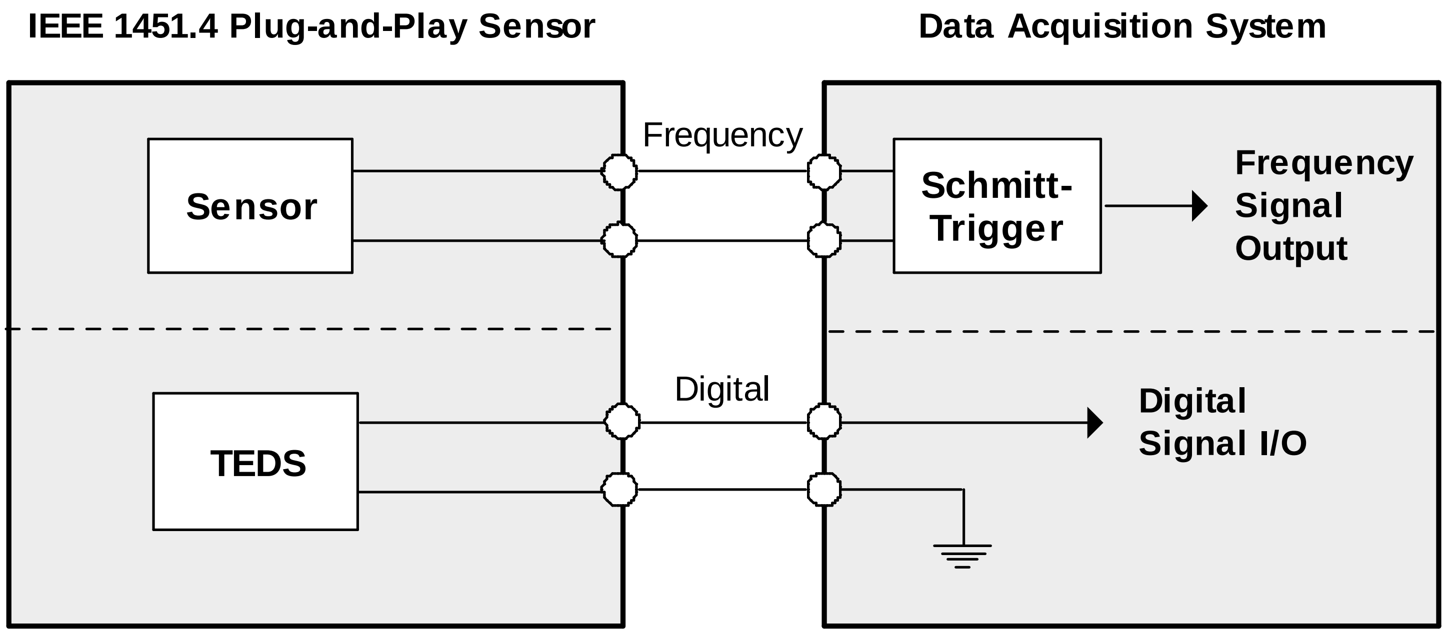
Physical Representation of IEEE 1451.2



IEEE 1451 TEDS for Temperature Sensor

TEDS Structure	Example of Frequency Output Temperature Sensors	
Basic TEDS	Manufacturer ID	19
	Model ID	11
	Version letter	A
	Serial number	2399
Standard and Extended TEDS	Calibration date	28 /11/06
	Min. temperature	-40 ^{0}C
	Max. temperature	+125 ^{0}C
	Min. frequency output	1 kHz
	Max. frequency output	4 kHz
	Absolute error	$\pm$ 0.5 ^{0}C
	FDC quantization error	$\pm$ 0.1 %
	Sensor response time	5 ms
User Area	Sensor location	P1-P5
	Calibration due date	27/11/08

Mix-Mode Interface for Frequency Output Sensors

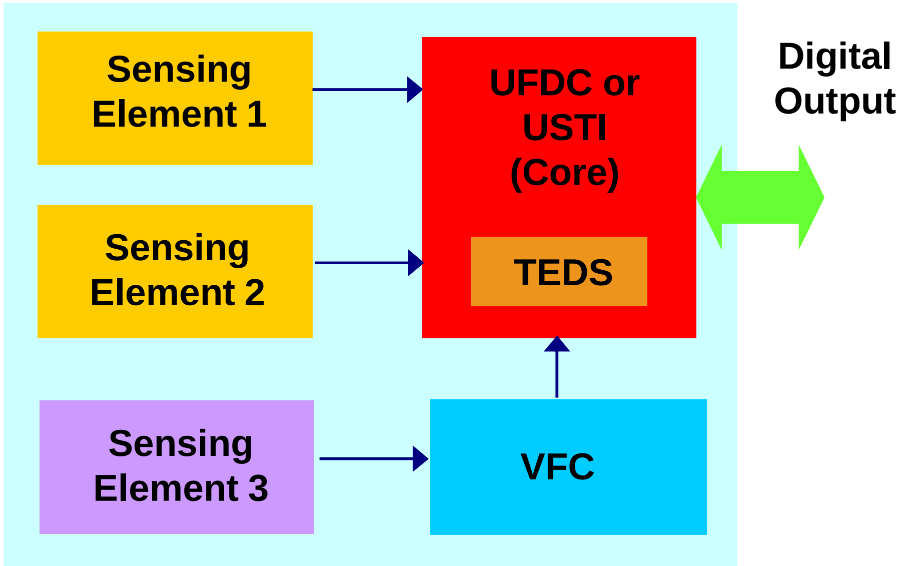


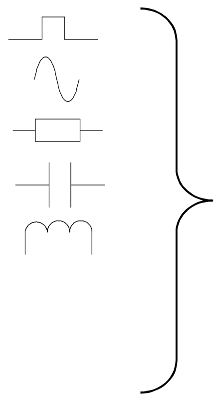
Class II multiwire interface

New Technological Platform for Smart Sensor Systems Integration

1. Introduction: Definitions and Markets
2. Modern Technologies
3. Smart Sensors Design: Preface
4. Quasi-Digital Sensors State-of-the-art
5. Intelligent and Smart Sensors Design
6. Smart Sensor Systems Integration
7. Summary

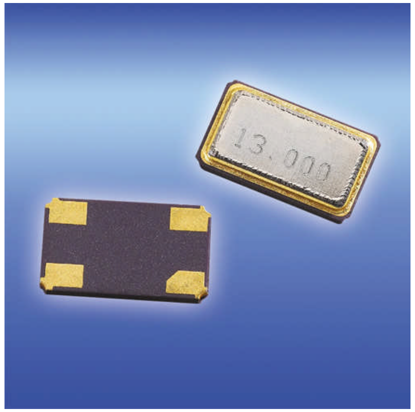
SoP and SiP



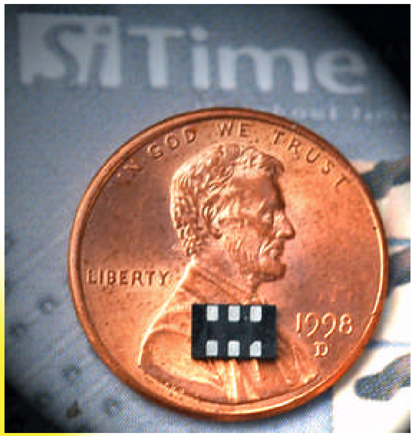


Sensors and sensing elements

Miniature Quartz and MEMS Oscillators

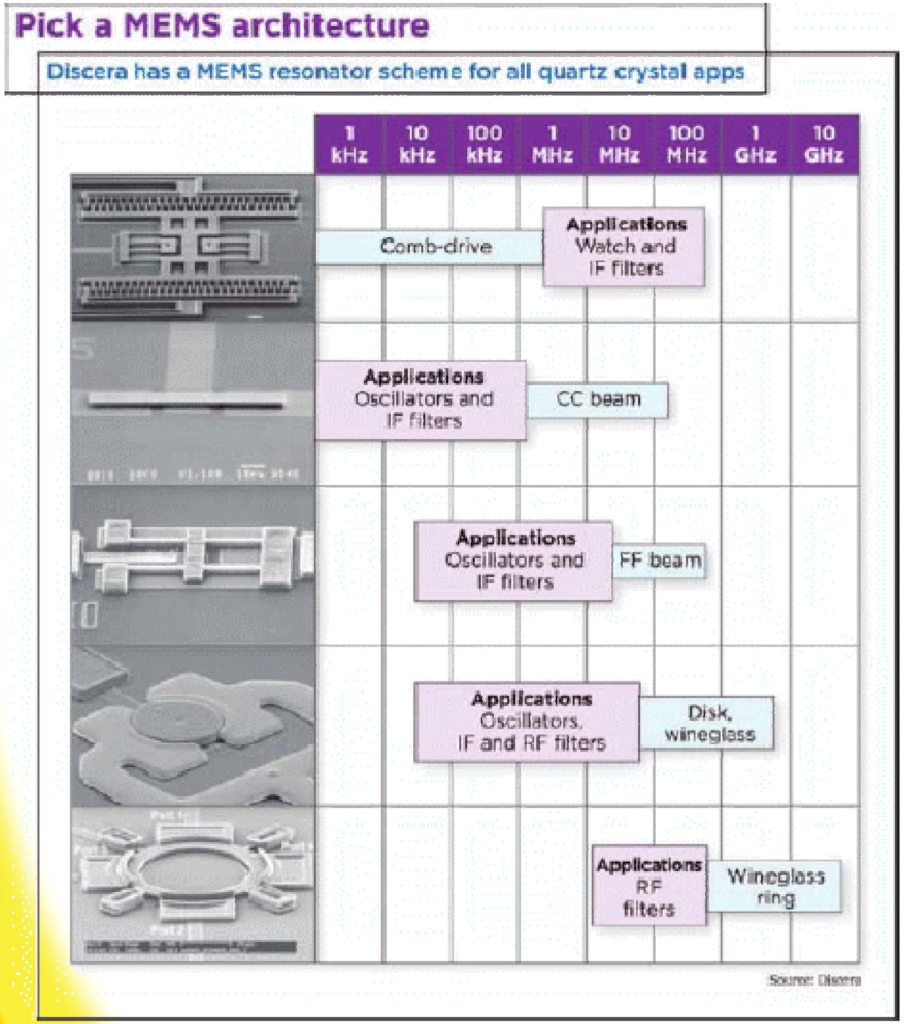


- SMD03025 miniature 3.2 × 2.5 × 0.8 mm, cost-effective surface-mount quartz (*Petermann-Technik*)
- 13 to 40 MHz frequency range
- -40 to +125 ^{0}C temperature range
- Ultra-precise frequency tolerance of ± 5 ppm



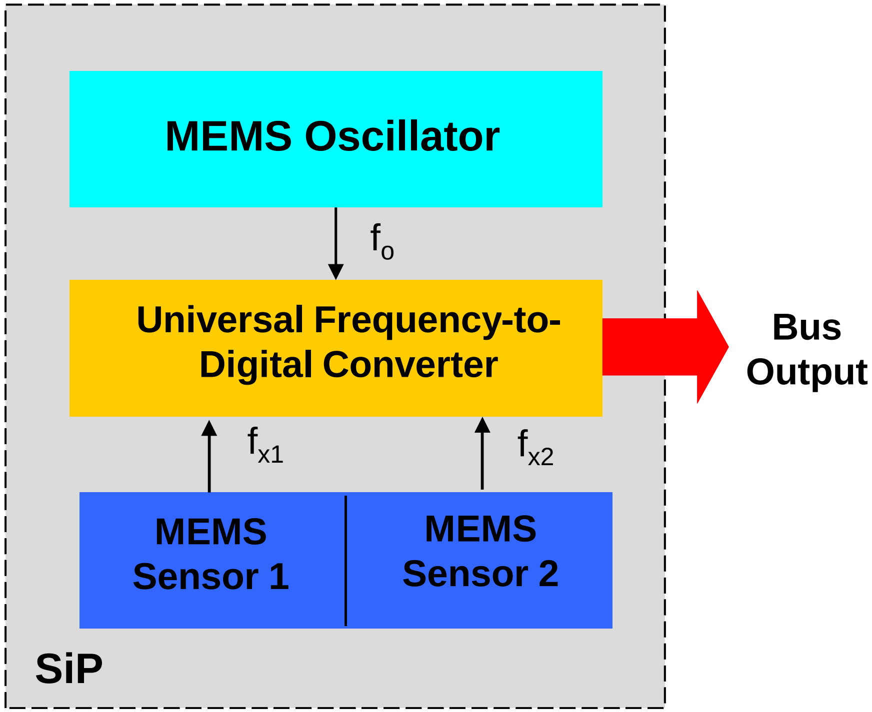
- SiT9102, a programmable MEMS oscillator (*SiTime*)
- Frequency stability of ± 10 ppm
- 10 to 220 MHz frequency range

MEMS Oscillators

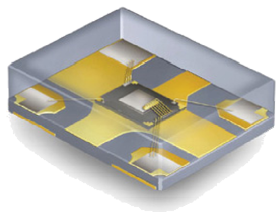


- Next generation oscillator technology
- Smaller, higher-precision references
- Immune to temperature and vibration
- Long-term stability of 0.05 ppm
- 10 ppm frequency variations
- Can go in plastic packages
- Much more rugged than quartz crystal oscillators

System-in-Package



- Sensors system does not require any external time or frequency references
- UFDC lets solve problems with the interface circuit design and additional circuitry for MEMS oscillators in order to increase its short frequency stability

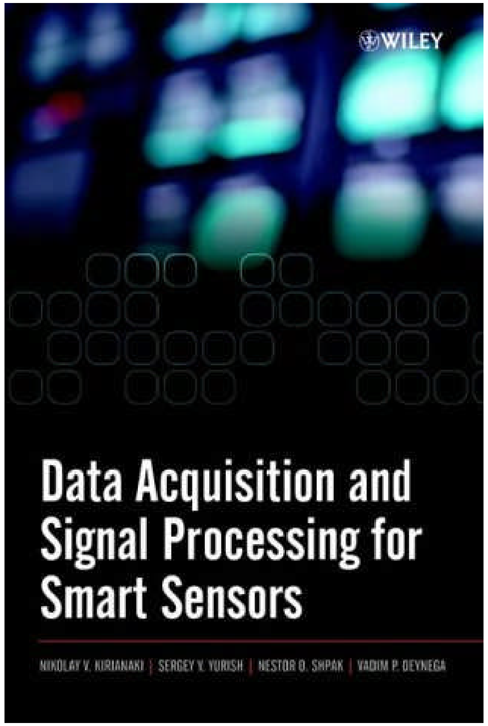


Summary

- Smart sensors and systems should be intelligent
- The ability of intelligent sensors systems to process information is not enough
- Efficient coupling this ability with decision making based on data processing in order to learn and adapt will be required
- In order to overcame technological limitations we should move from traditional analog signal domain to frequency signal domain, and implement as much system components as possible in digital or quasi-digital domain (New Technological Platform 3SI challenge)
- Namely by this way we will be able to go ahead: from MEMS devices to MEMS-based systems

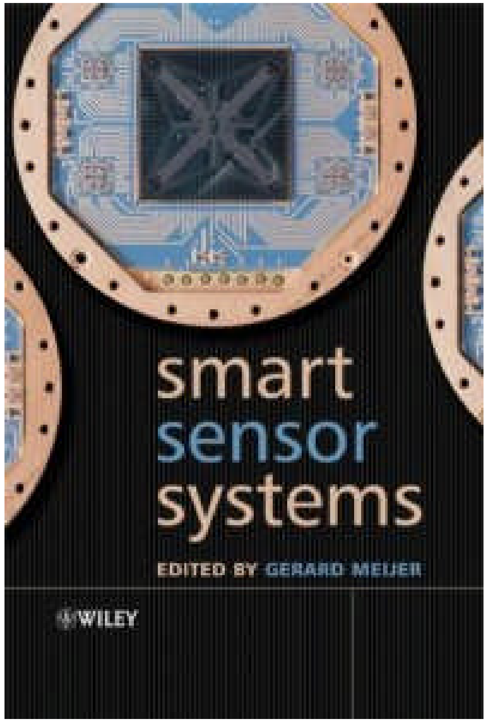
Reading

[1]. Kirianaki N.V., Yurish S.Y., Shpak N.O., Deynega V.P., Data Acquisition and Signal Processing for Smart Sensors, *John Wiley & Sons*, Chichester, UK, 2002



Reading (cont.)

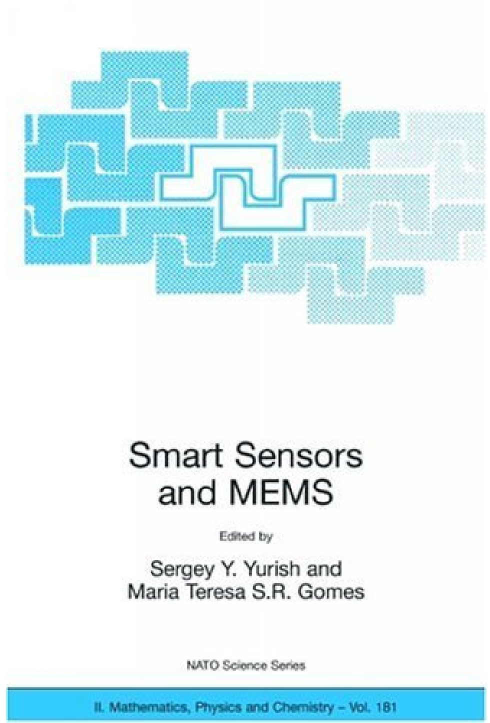
[2]. Smart Sensor Systems, ed. by Gerard C.M. Meijer, *John Wiley & Sons*, Chichester, UK, 2008



Reading (cont.)

[3]. Smart Sensors and MEMS, ed. by S.Y. Yurish and M.T. Gomes, *Springer Verlag*, 2005

[4]. Sensors Web Portal: http://www.sensorsportal.com



Questions & Answers