High Performance Digital Sensors Design: How to make it Smarter ?

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Tutorial, November 16, 2014, Lisbon, Portugal

Outline

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1. Introduction: Markets and Definitions
2. Modern Challenges
3. Digital Sensors Design: Introduction
4. Advanced Digital Sensors Design
5. Smart Sensor Systems Integration
7. Sensor System's Error Estimation
8. The Future and Summary

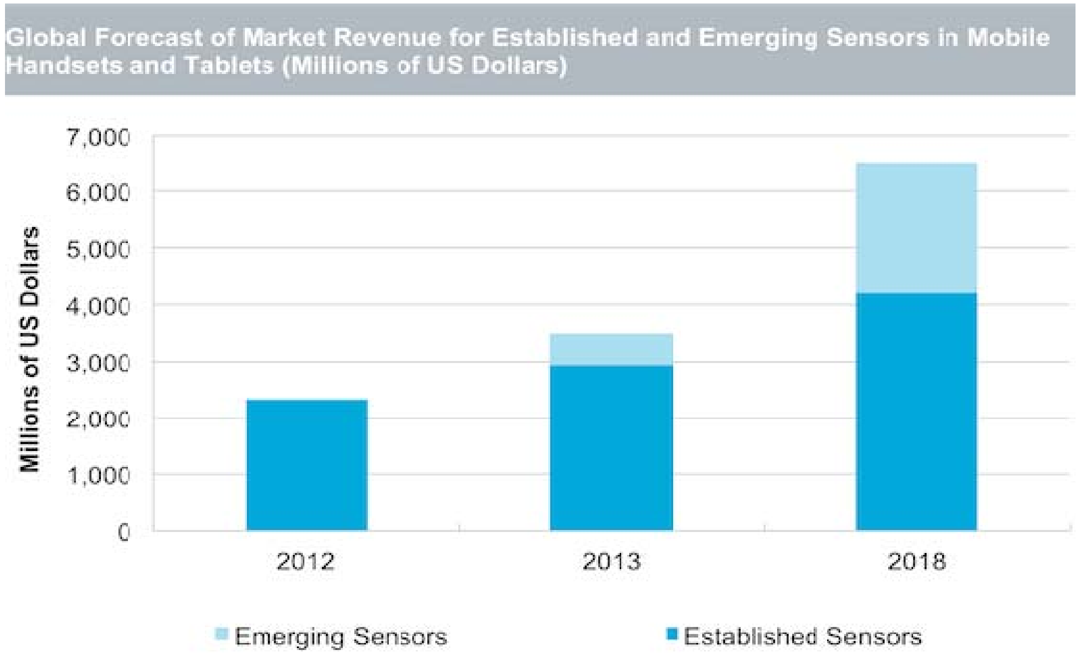
Global Sensor Markets

- **Global Sensor Market** will reach US **$154.4** Billion by 2020 with a five-year compound annual growth rate (CAGR) of 10.1% (*BCC Research*, July 2014)
- **Global Microsensors Market** (including MEMS, biochips and nanosensors) will reach US **$15.8** Billion by 2018 with CAGR) of 10.0 % (*BCC Research*, November 2014)
- **Global Smart Sensors Market** to reach US **$6.7** Billion by 2017 (*Global Industry Analysts*, *Inc*.)
- **European Smart Sensors Market** expected to grow up to US **$2,402.15** million till 2018 with a CAGR of 39.90 %.

IFSA

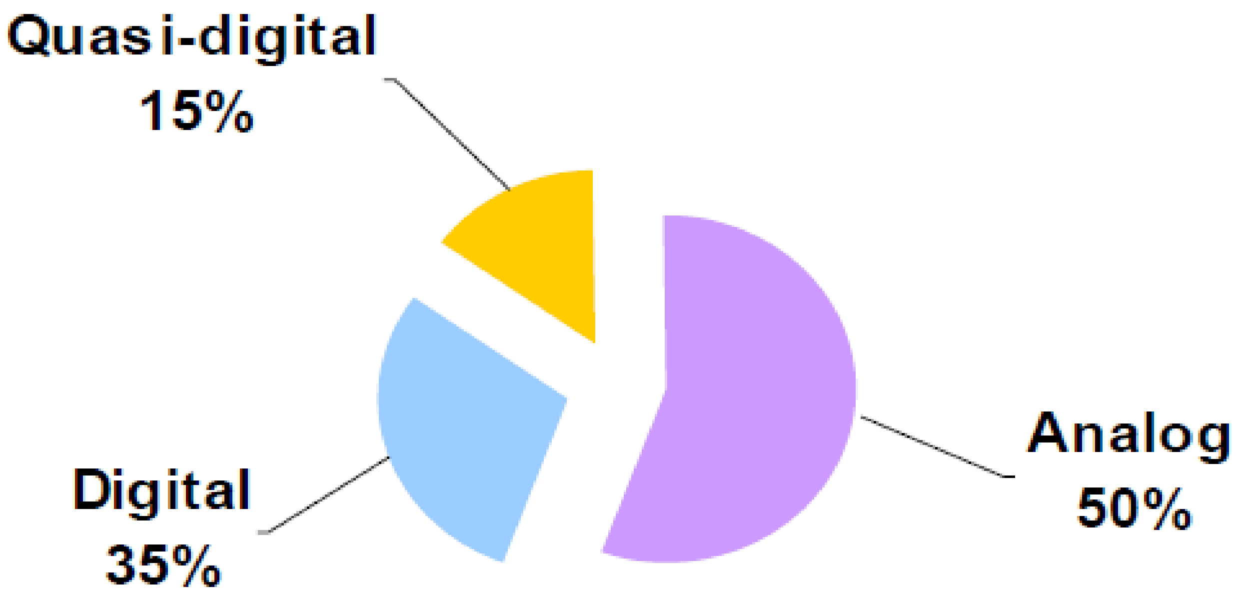
Application Market Niche

- **Smartphone and Tablets Sensors Market** will rise to US $6.5 billion in 2018 (*IHS*)
- **Combo-sensor Market** will growth to 1.5 Billion EUR by 2016



Established sensors: motion, light, proximity, pressure, temperature;
Emerging sensors: fingerprint, optical pulse, humidity, gas, UV and thermal imaging

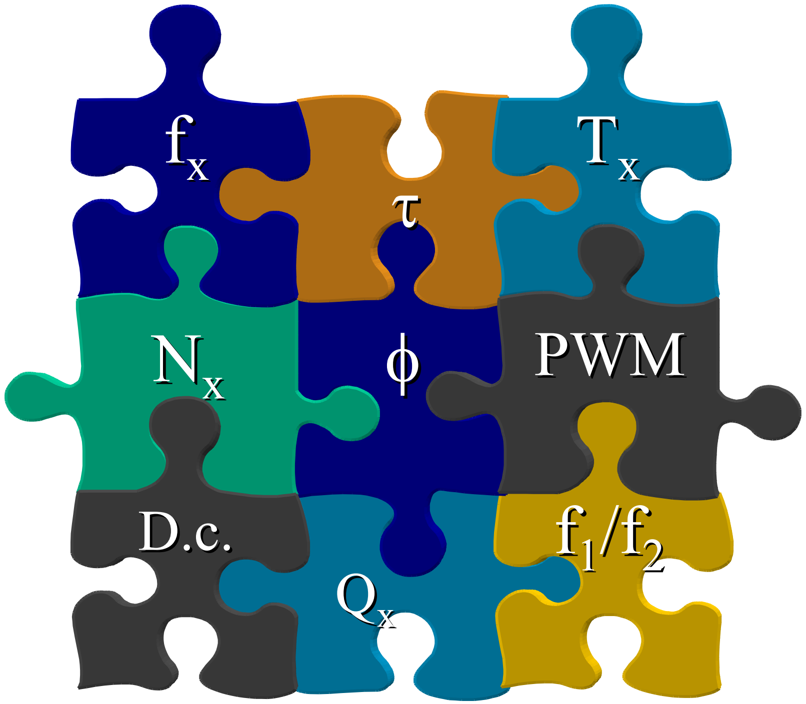
Sensor Types Divided According to Outputs



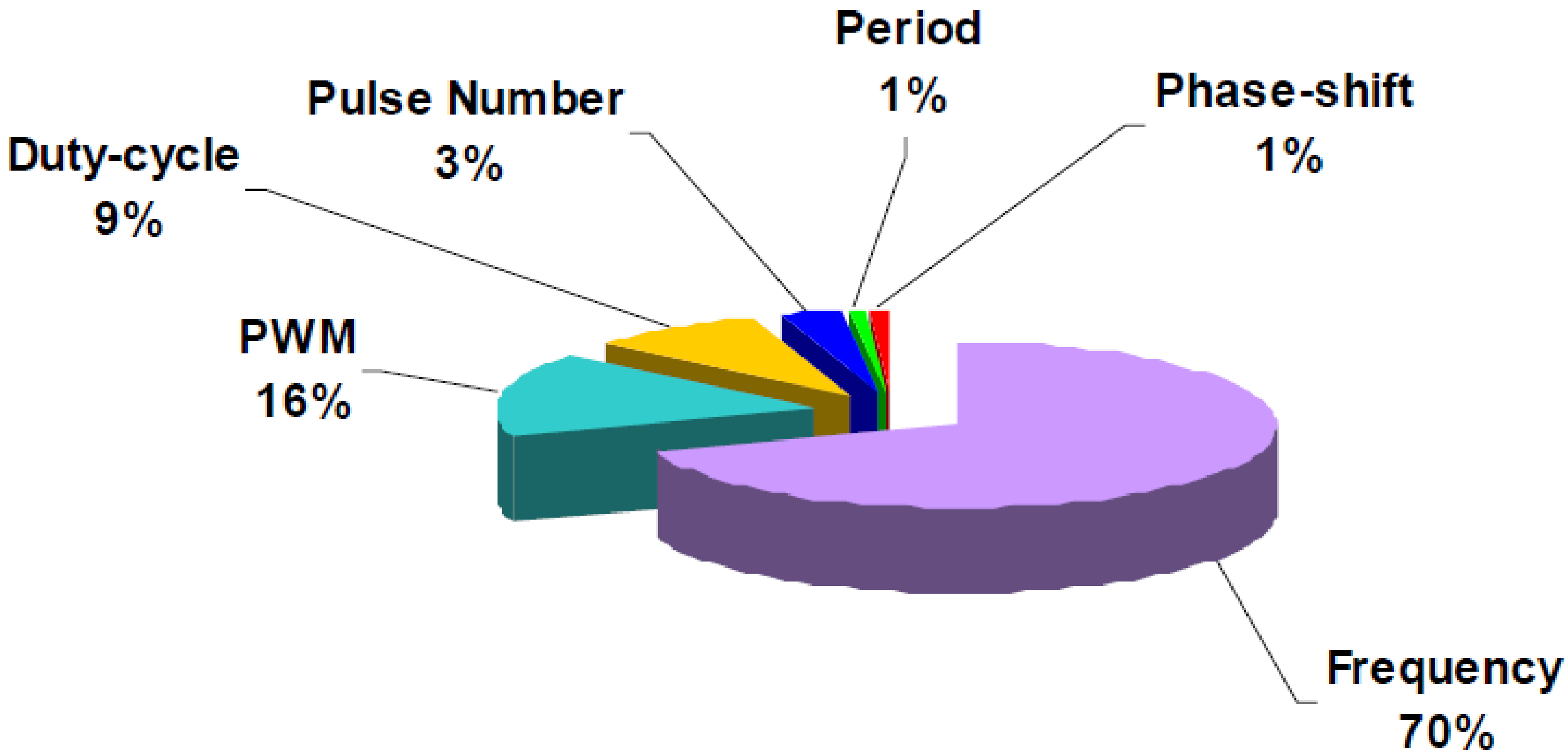
International Frequency Sensor Association (IFSA), Study, 2013

Quasi-Digital Sensors

Quasi-digital sensor is a sensor with frequency, period, its ratio or difference, frequency deviation, duty-cycle (or duty-off factor), time interval, pulse width (or space) pulse number, PWM or phase shift output.



Quasi-Digital Sensors: Types



International Frequency Sensor Association (IFSA), Study 2013

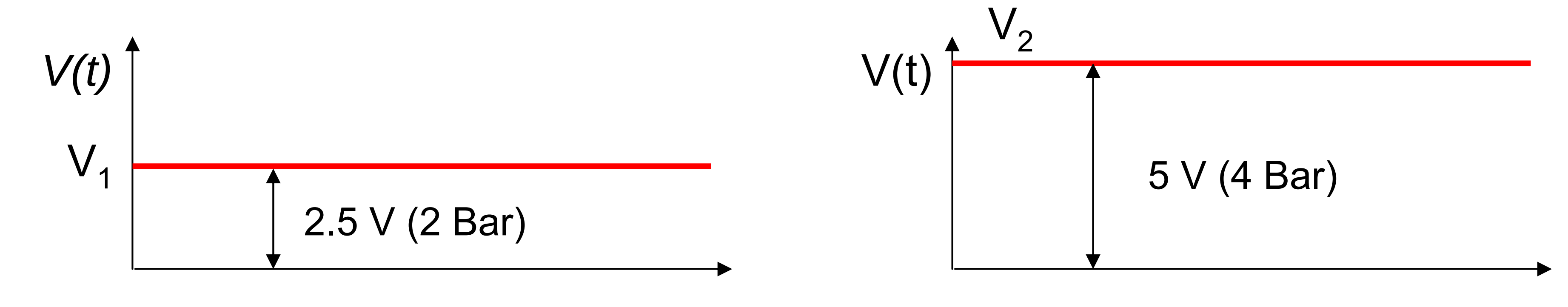
Analog and Quasi-Digital Sensors

Analog sensor *- sensor based on the usage of an amplitude modulation of electromagnetic processes*

Quasi-digital sensors *are discrete frequency-time domain sensors with frequency, period, duty-cycle, time interval, pulse number or phase shift output*

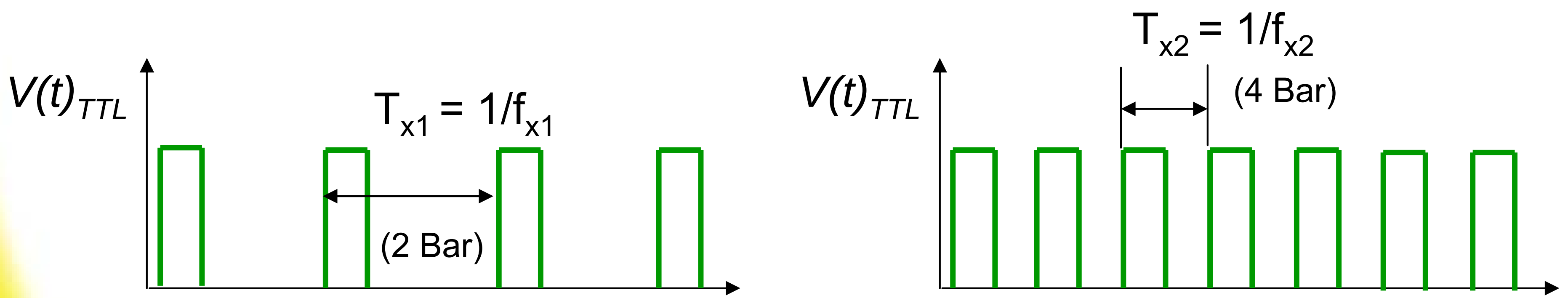
Quasi-digital sensors combine a simplicity and universatility that is inherent to analog devices and accuracy and noise immunity, proper to sensors with digital output

Voltage output vs. Frequency Output



(a) (b)

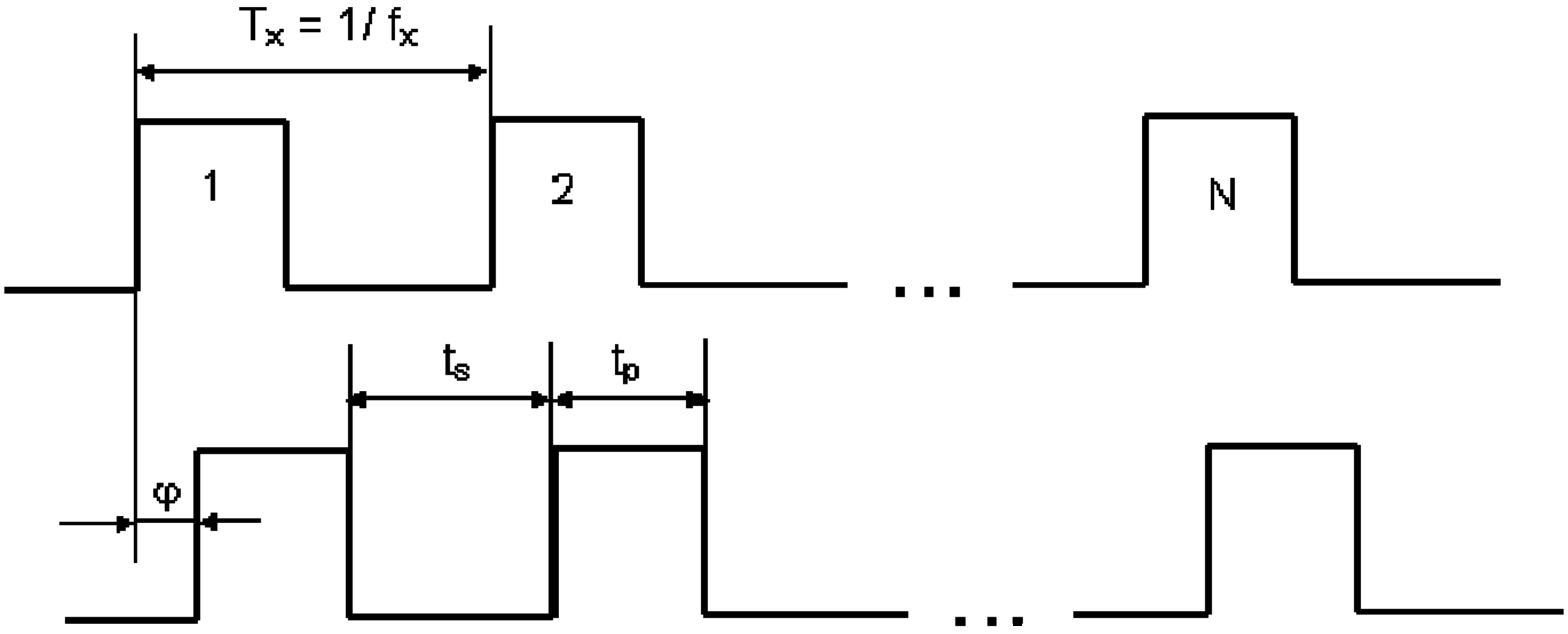
$V_1 < V_2$



(a) (b)

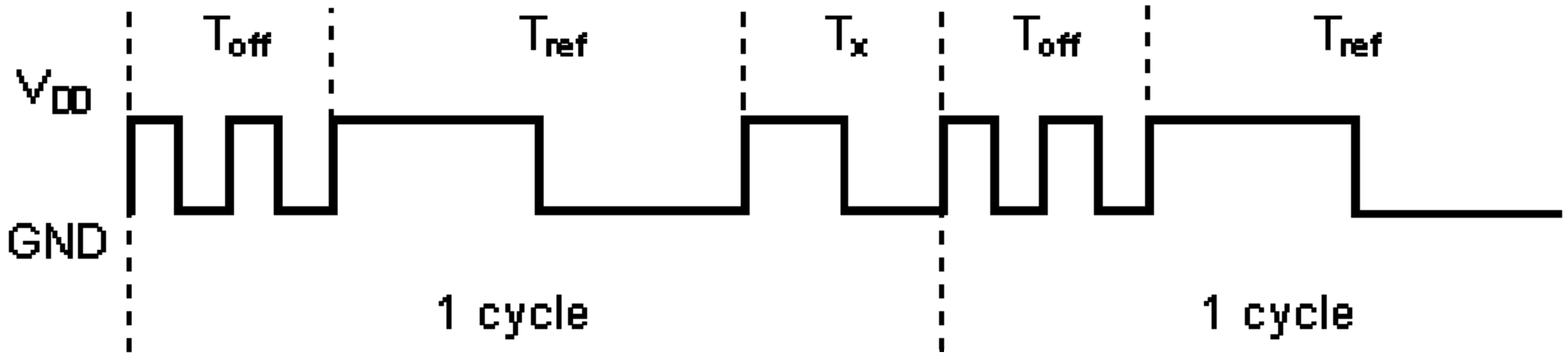
$T_{x1} > T_{x2}\ ,\ f_{x1} < f_{x2}$

Informative Parameters



- Duty-cycle: D.C.= t_p/T_x
- Duty-off factor: 1/D.C. = T_x/t_p
- PWM signal: t_s/t_p ratio at T_x = constant

Period-Modulated Signal



Digital Output Sensors

1
0
1
1
0
1
1
1
…
1
0

Binary code

- Serial interfaces RS232/485/422, USB
- Parallel interfaces (8-, 16-, 32-bits)
- Sensor buses: SPI, I2C, CAN, SMBus, LIN, etc.

1 0 1 1 1 0 0 1 0 1 Binary code

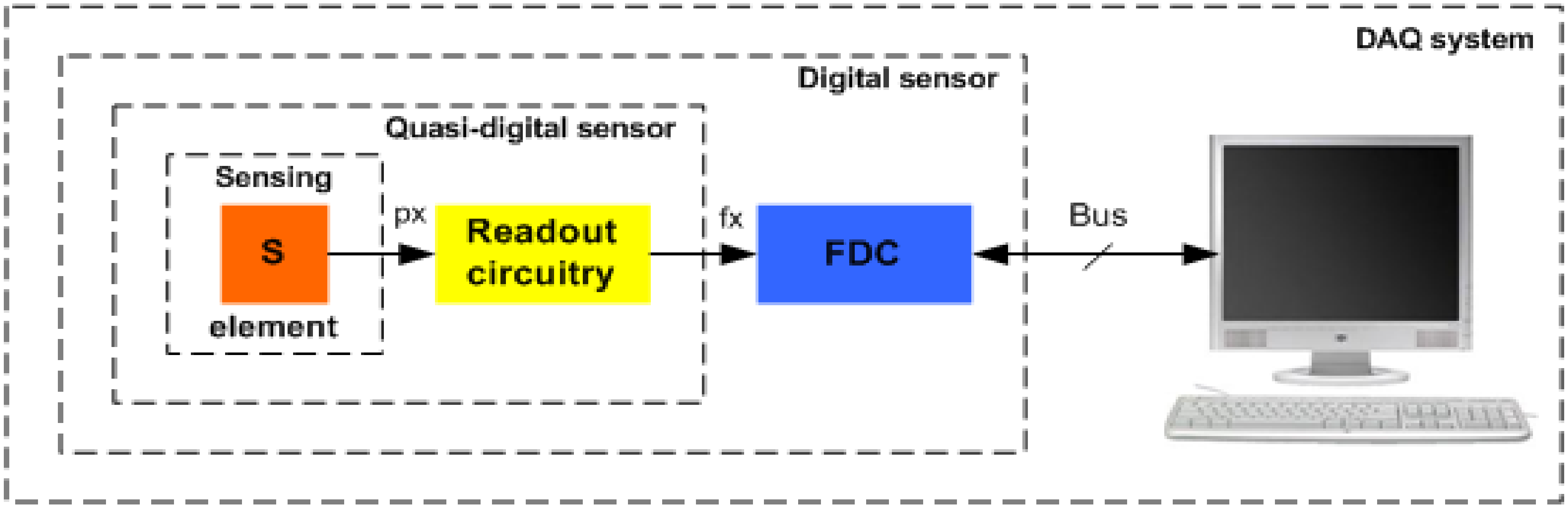
Smart Sensor Definition

- 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.*

Quasi-Digital and Digital Sensors in System Hierarchy



High Performance Digital Sensors Design

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Sensor Technologies

- 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
- 28 nm CMOS process
- 26 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

Signal- and Data Processing Limitations

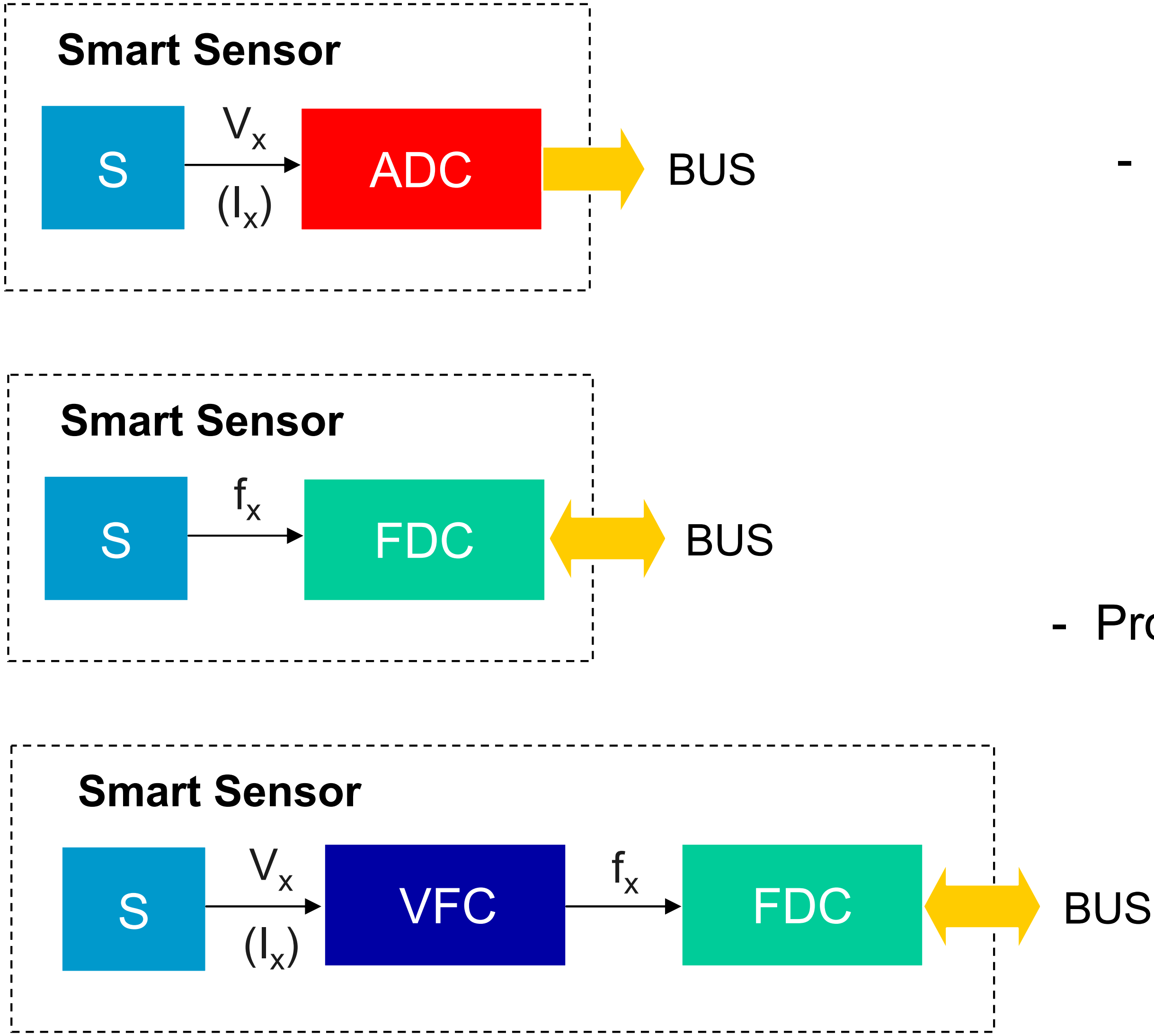
- Sensor Fusion is a complex procedure deals with analog signals
- The limited number of sensing elements can be integrated

Frequency Advantages

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

High Performance Digital Sensors Design

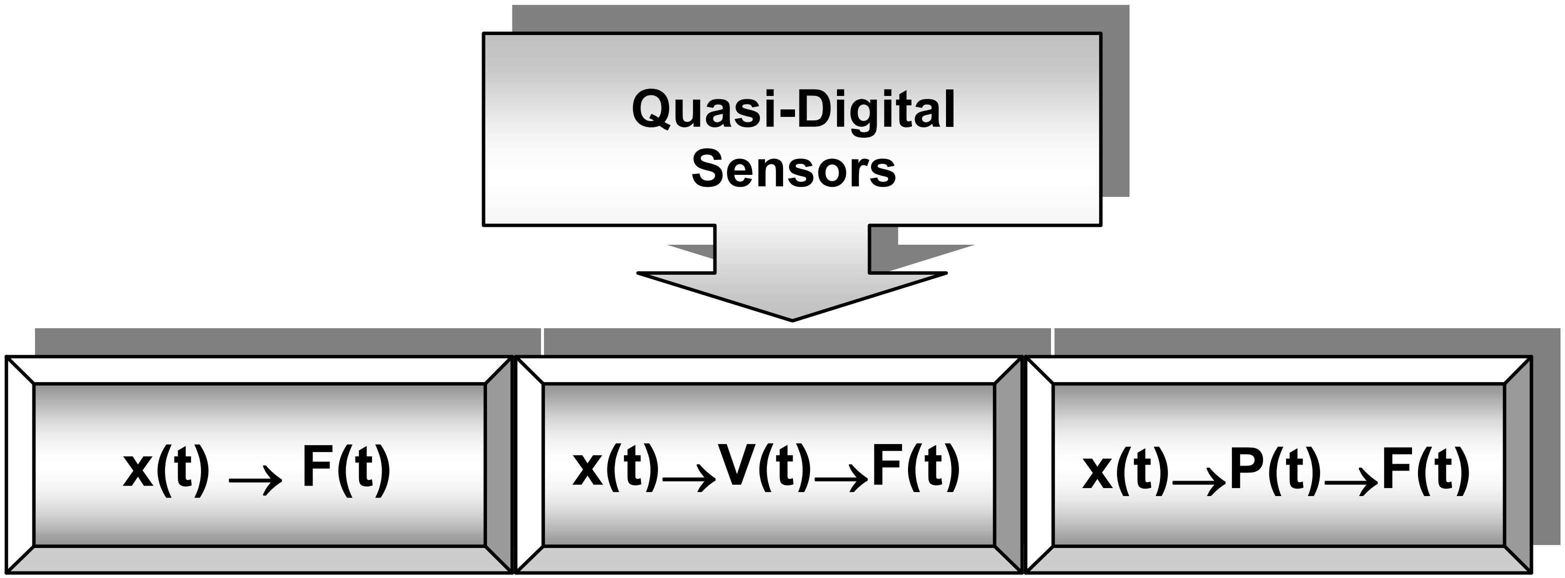
Smart Sensors Design



- Classical approach

- Proposed approaches

Quasi-Digital Sensor Classification



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

Sensors with x(t) → F(t) Conversion

- Sensors themselves generate a frequency output
- Electronic circuitry might be needed for amplification of impedance matching
- One group of such sensors is based on resonant structures (piezoelectric quartz resonators, SAW (surface acoustic wave) dual-line oscillators, etc.), another group is based on the periodic geometrical structure of the sensors (angle encoders)

Examples: inductive, photo impulse, string, acoustic and scintillation sensors

Sensors with x(t)→V(t)→F(t) Conversion

- It is rather numerous sensors group
- Simple voltage-to-frequency or current-to-frequency conversion circuit can be used

Examples: Hall sensors, thermocouple sensors and photo sensors based on valve photoelectric cells

Sensors with $x(t) \rightarrow P(t) \rightarrow F(t)$ Conversion

- Sensors of this group (electronic-oscillator based sensors) are rather manifold and numerous
- Sensor element itself is the frequency-determining element

Examples: inductive, capacity and ohmic parametric (modulating) sensors

Quasi-Digital Sensors: Summary

- There are many quasi-digital sensors and transducers for any physical and chemical, electrical and non electrical quantities
- Various frequency-time parameters of signals are used as informative parameters: f_x, T_x, *D.C.*, *PWM*, *T*, φ_x, etc.
- The frequency range is very broad: from some parts of Hz to some MHz
- Relative error up to 0.01% and better

Integrated FDCs

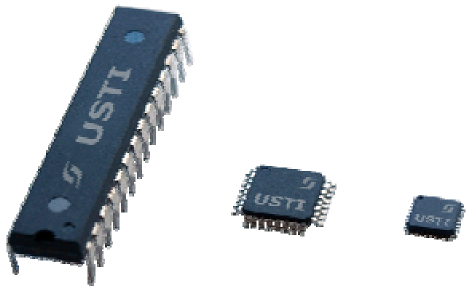
- USP-30 one-chip specialized microprocessor (1980)
- IC of ALU for time interval measurements (1989)
- K512PS11 - frequency-to-digital converter (1990)
- USIC - universal sensor interface chip (1996)
- Single-chip (FPGA) interpolating time counter
- ASIC of single channel frequency-to-digital converter (1999)
- Frequency-to-digital converter from *AutoTEC*
- Time-to-Digital Converter (TDC) from *Acam-messelectronic GmbH*

ICs Disadvantages

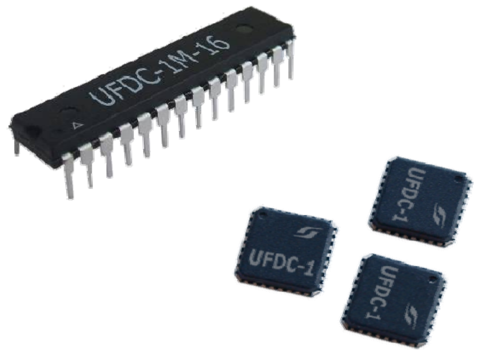
- All ICs except TDCs are based on conventional methods of measurement, hence, quantization error is dependent on measurand frequency f_x , many of ICs have redundant conversion time
- They cannot be used with all existing modern frequency-time domain sensors due to low accuracy or/and narrow frequency ranges
- They do not cover all frequency–time informative parameters of electric signals

Series of UFDC and USTI ICs

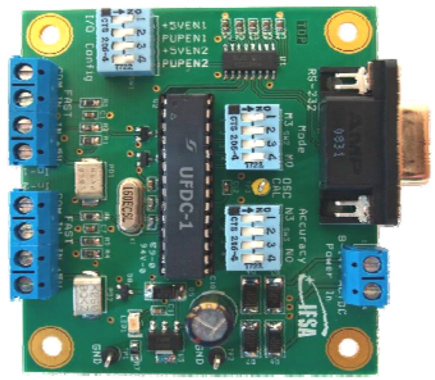
Universal Sensors and Transducer Interface (USTI)



Universal Frequency-to-Digital Converter (UFDC-1 & 1M-16)



Evaluation boards



USTI-EXT for Auto, Aerospace & Defense applications

USTI MOB for ultra-low power applications

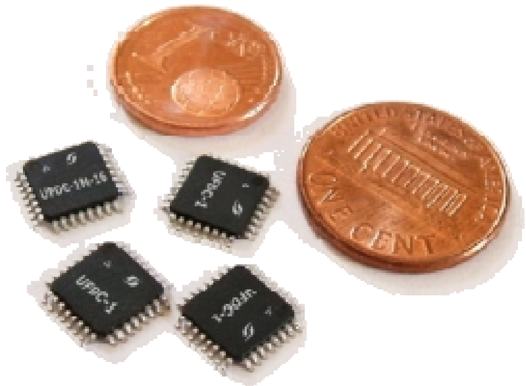
Axcelera

simplify, go faster!

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

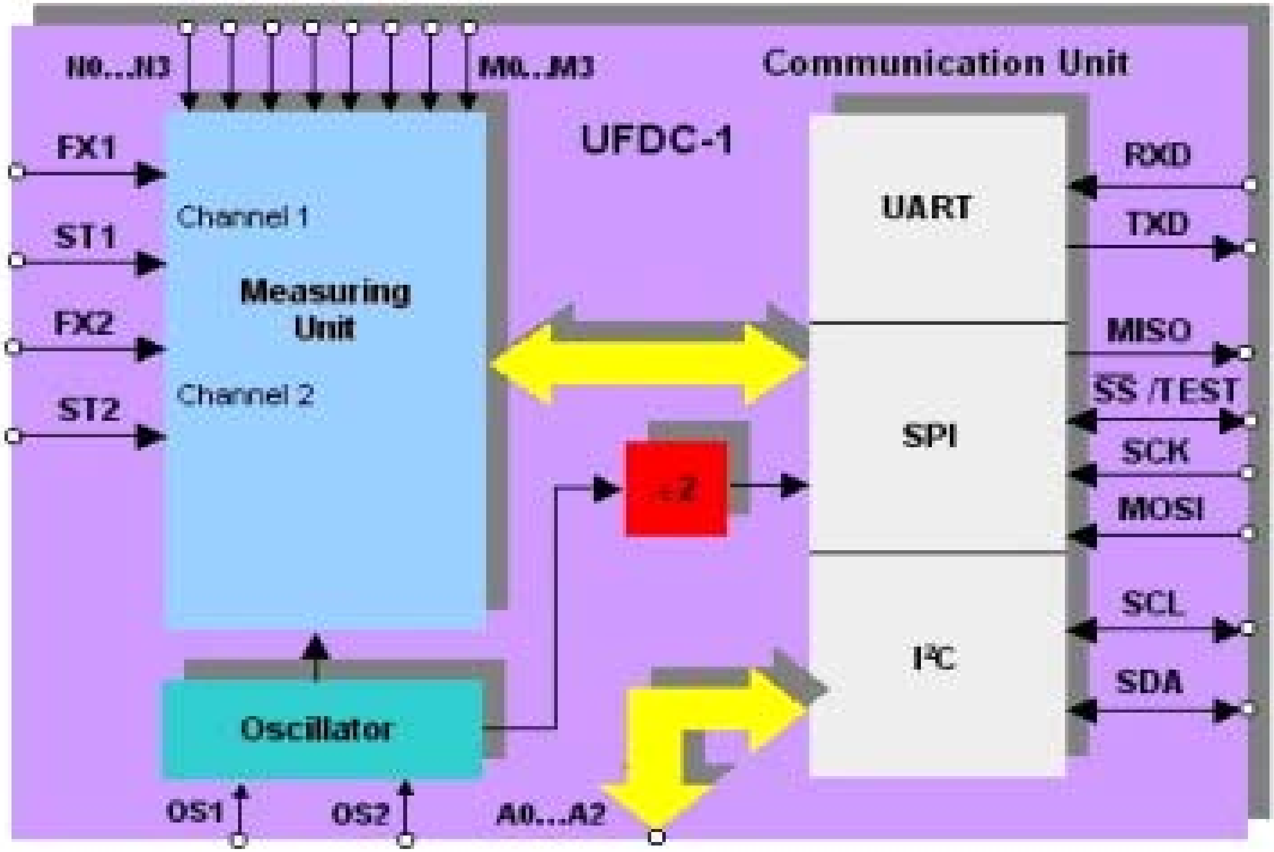
- Low cost digital IC with programmable accuracy
- 2 channels, 16 measuring modes for different frequency-time parameters and one generating mode ($f_{osc}/2$ = 8 MHz)
- Based on four patented novel conversion methods
- Should be very competitive to ADC and has wide applications

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
- RS232/485, SPI and I^2C interfaces

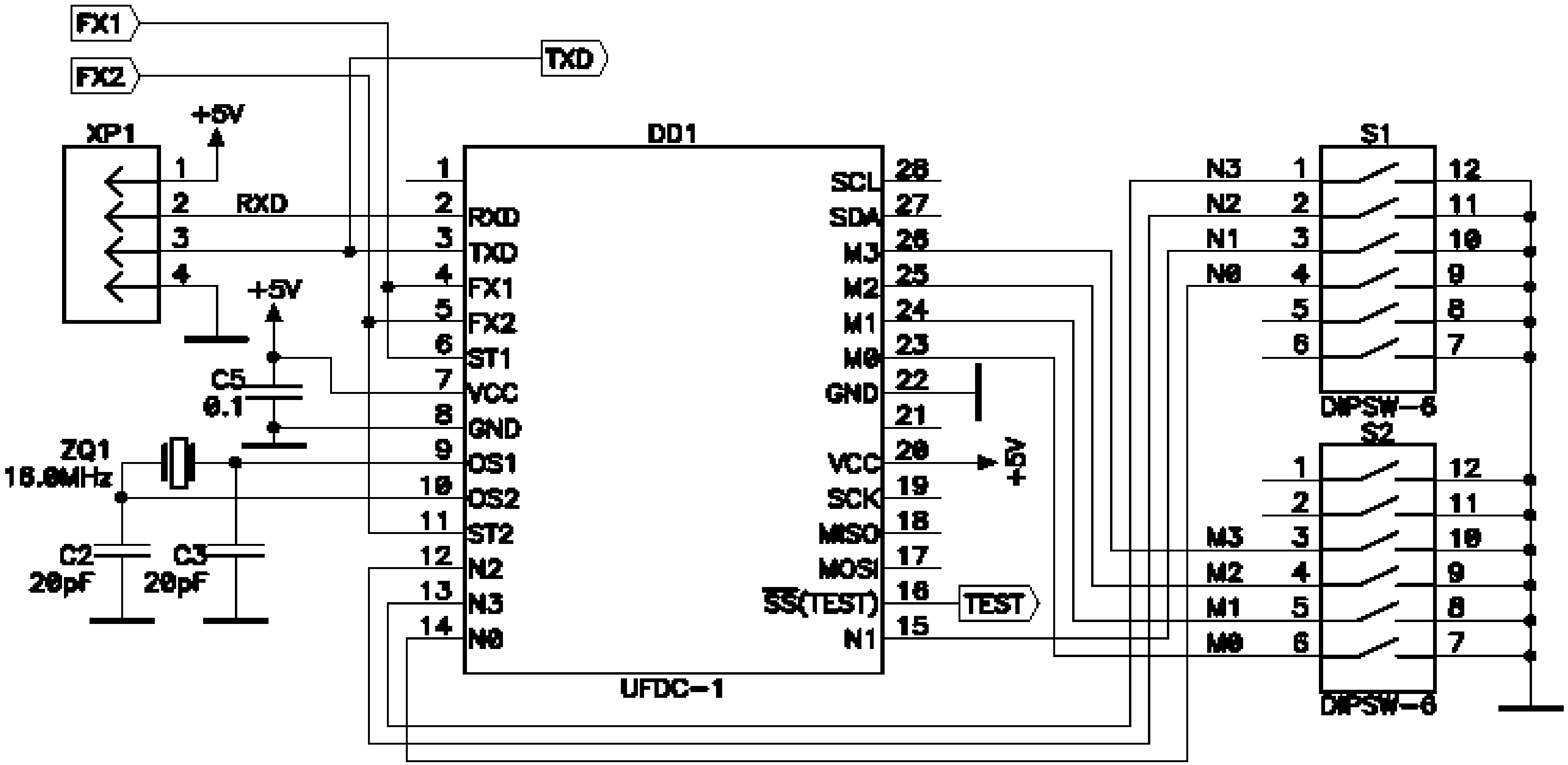
UFDC-1 Block Diagram



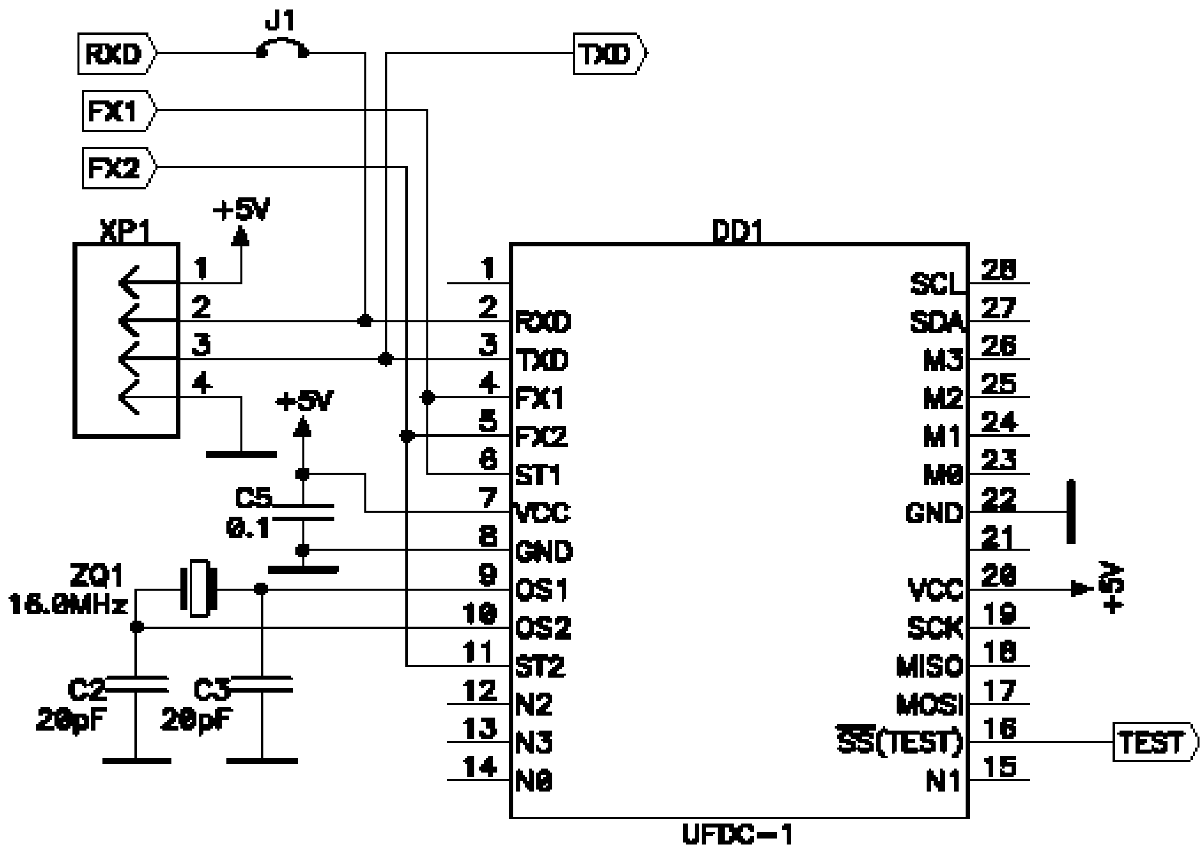
Measuring Modes

- 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 $0 – 4 \cdot 10^9$

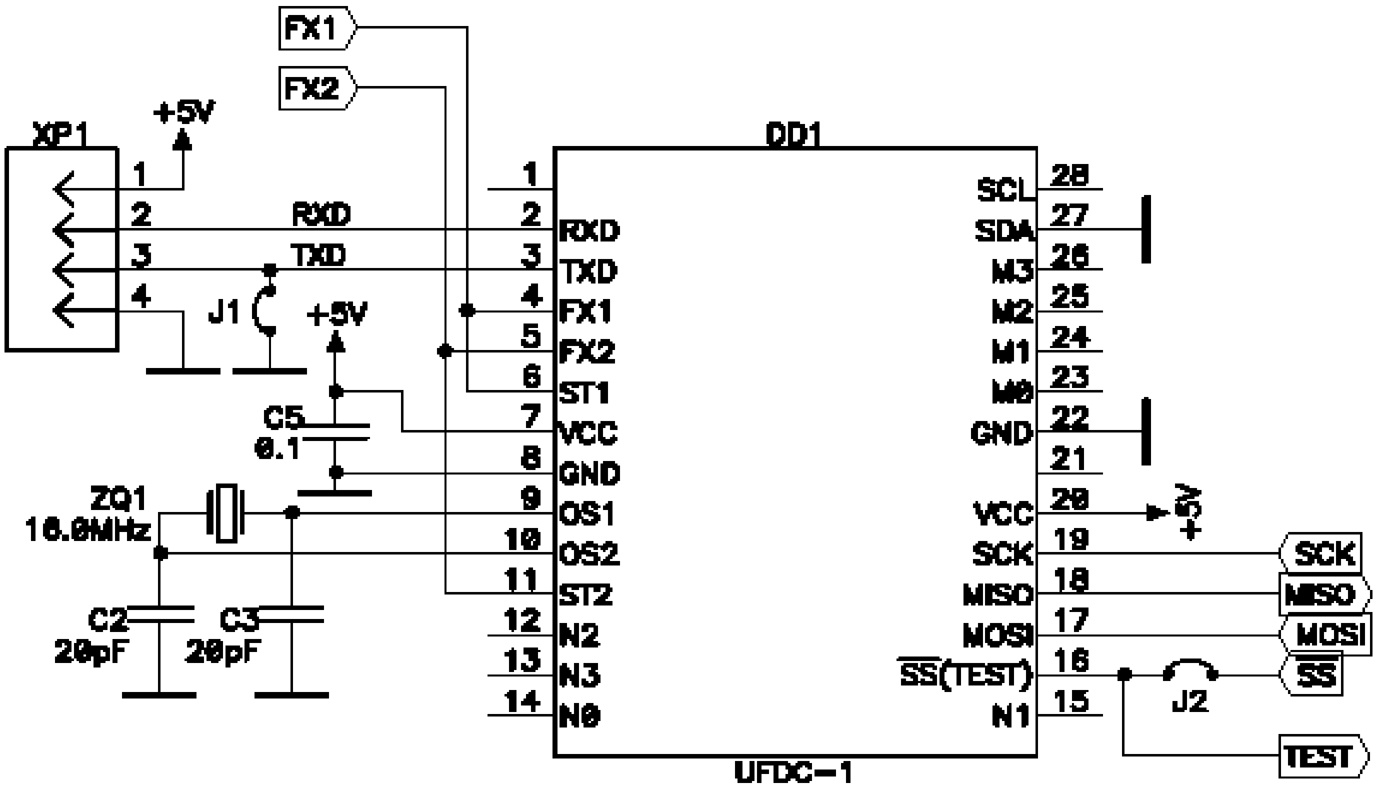
UFDC-1 Master Mode (RS232)



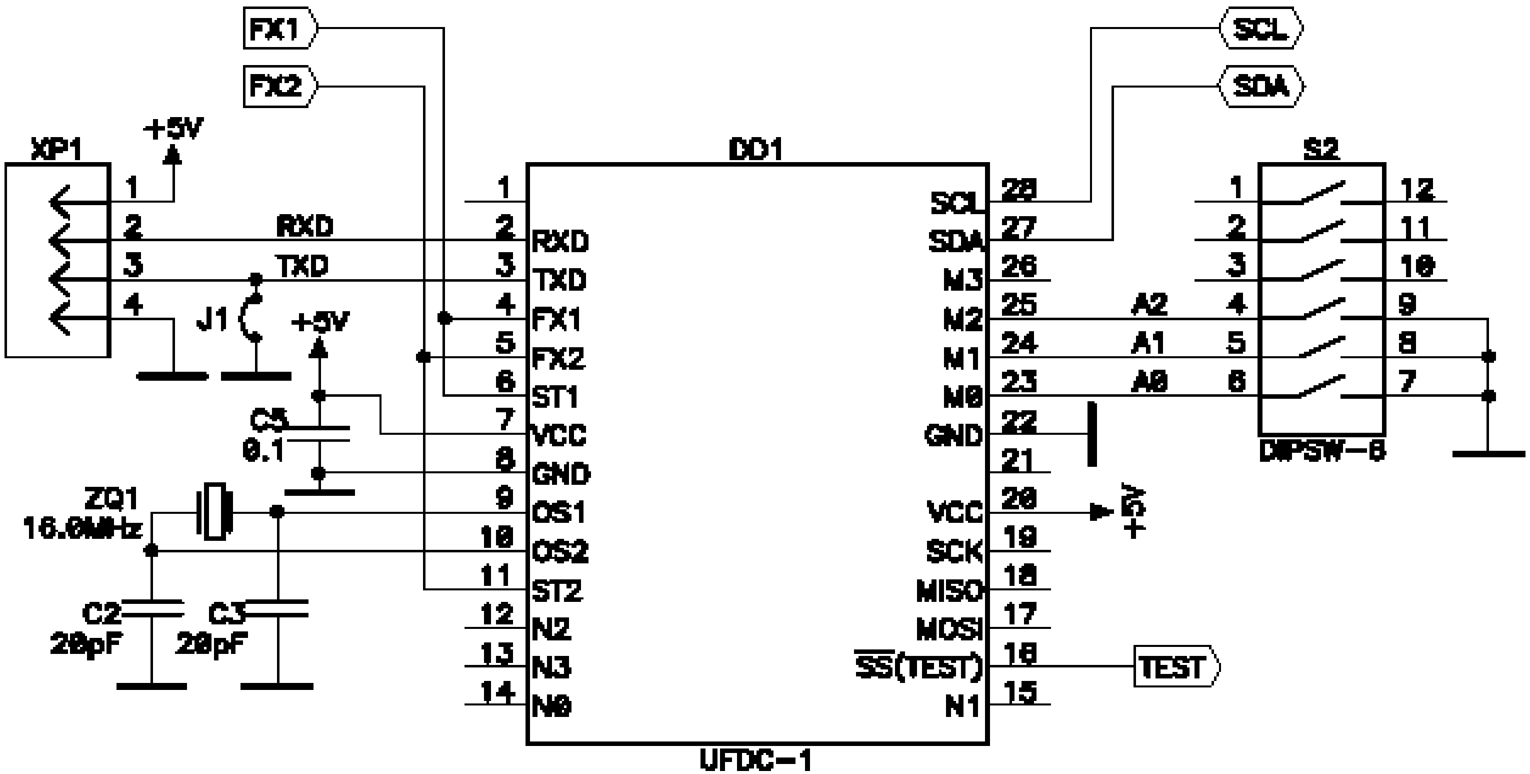
UFDC-1 Slave Mode (RS232)



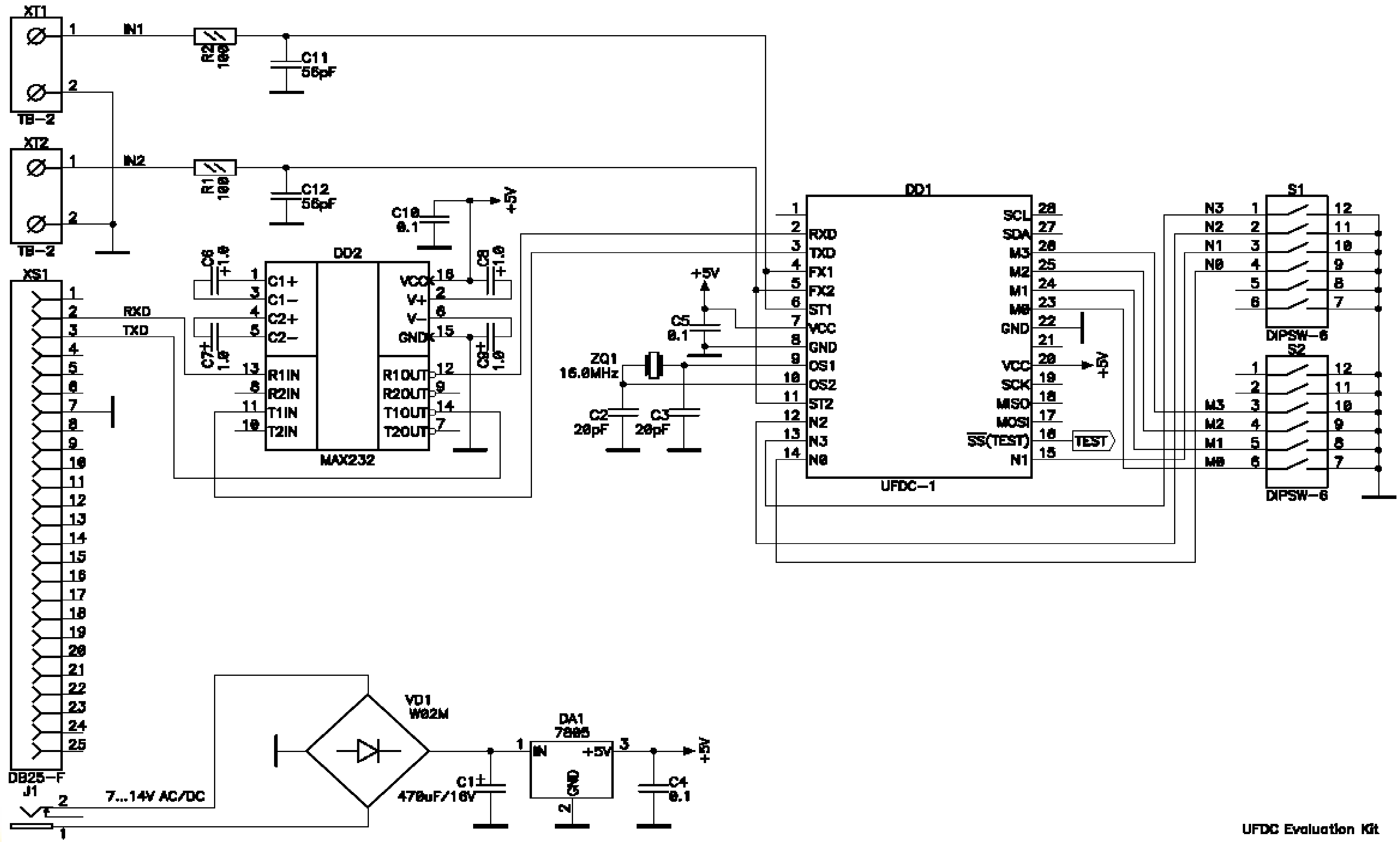
UFDC-1 SPI Interface Connection



UFDC-1 I^{2}C Bus Connection

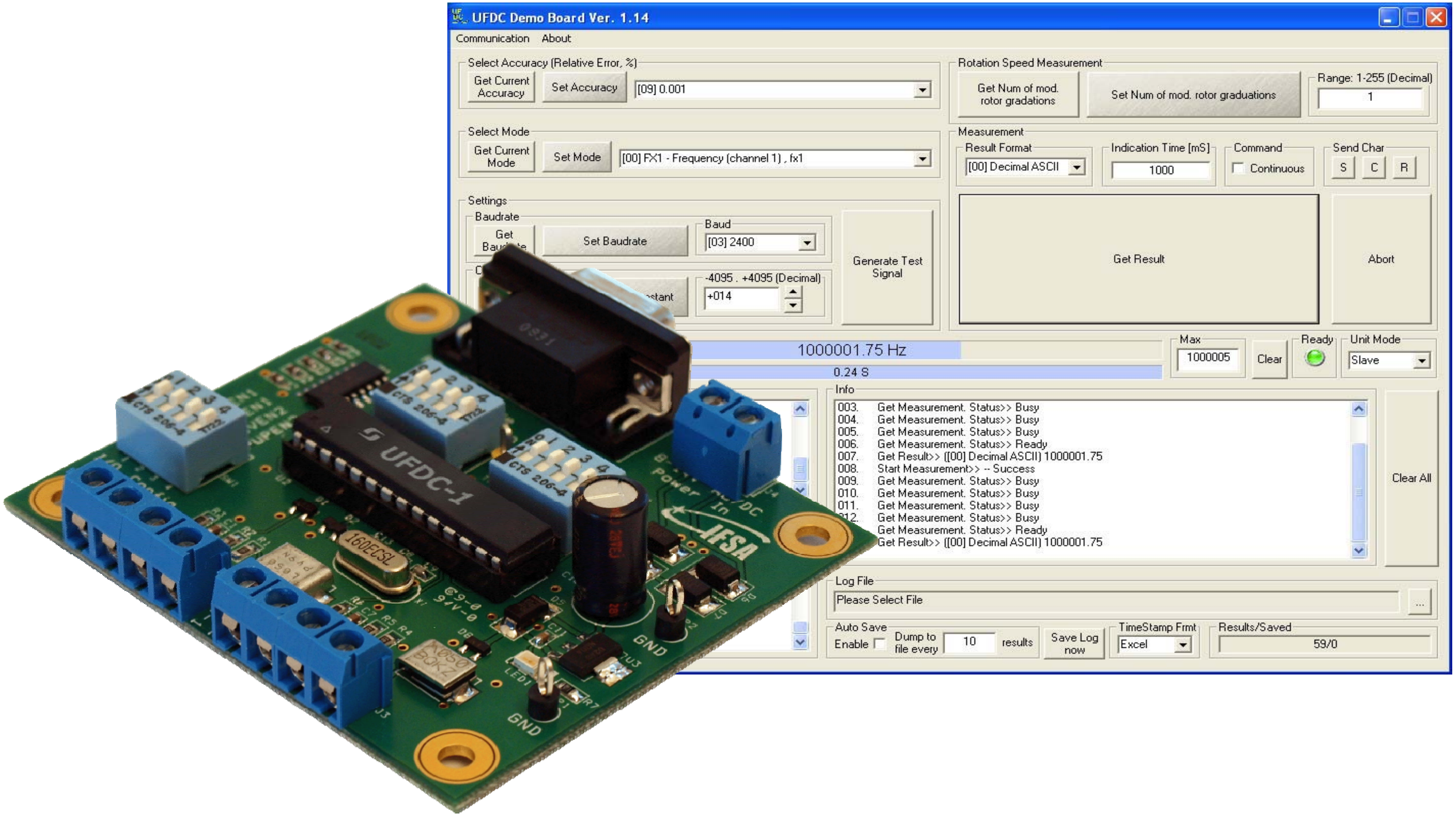


Evaluation Board Circuit Diagram

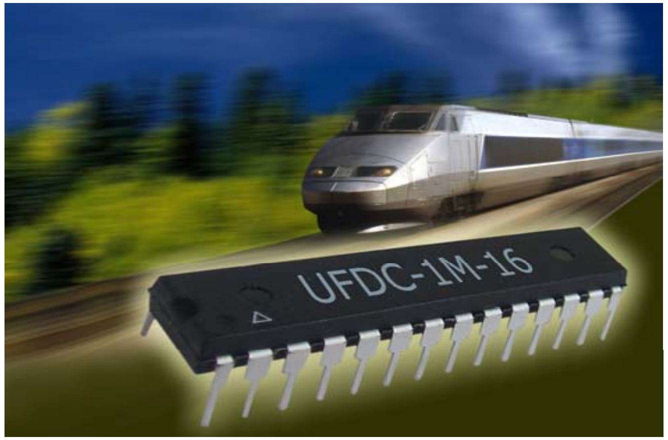


UFDC Evaluation Kit

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

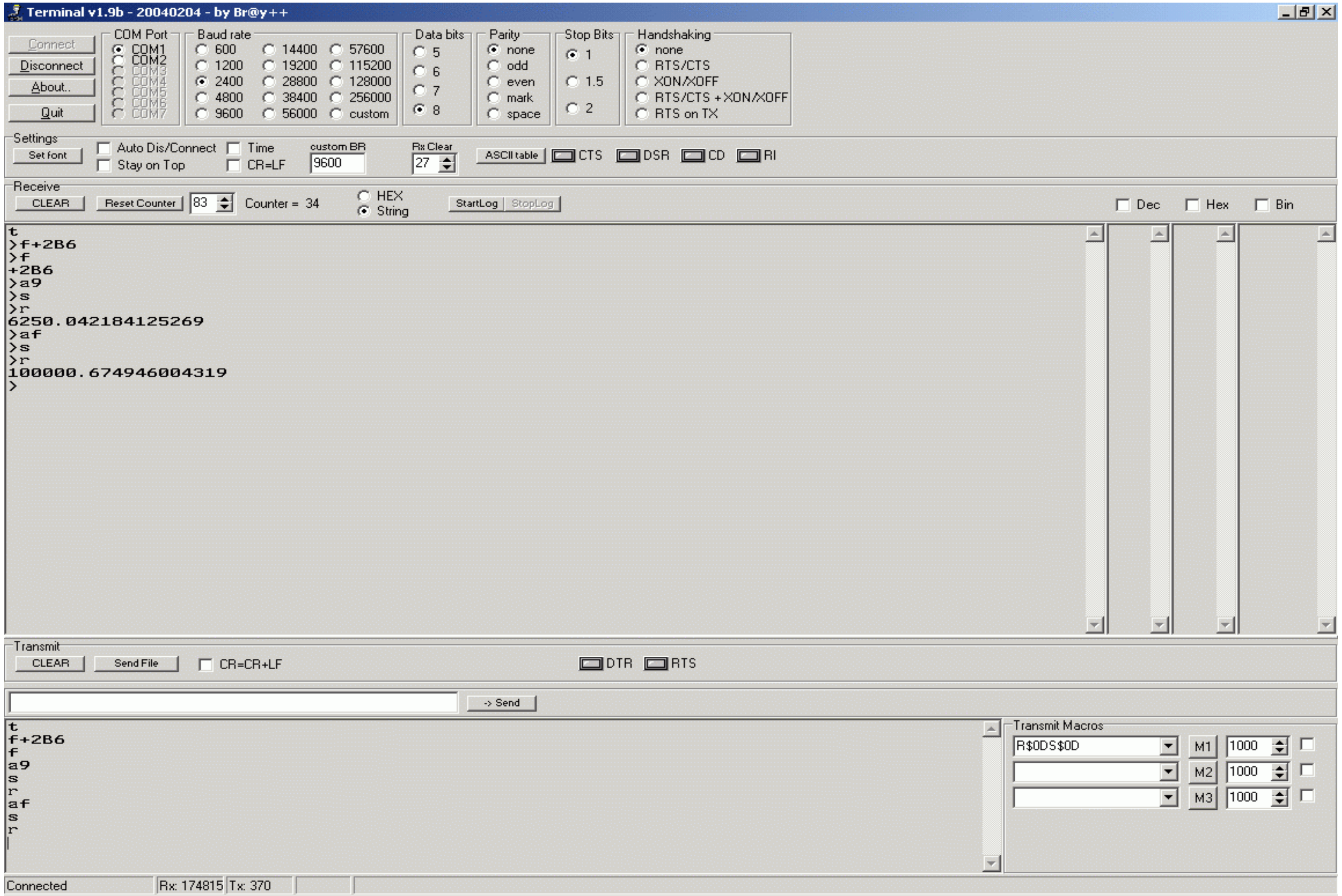


Fast IC UFDC-1M-16

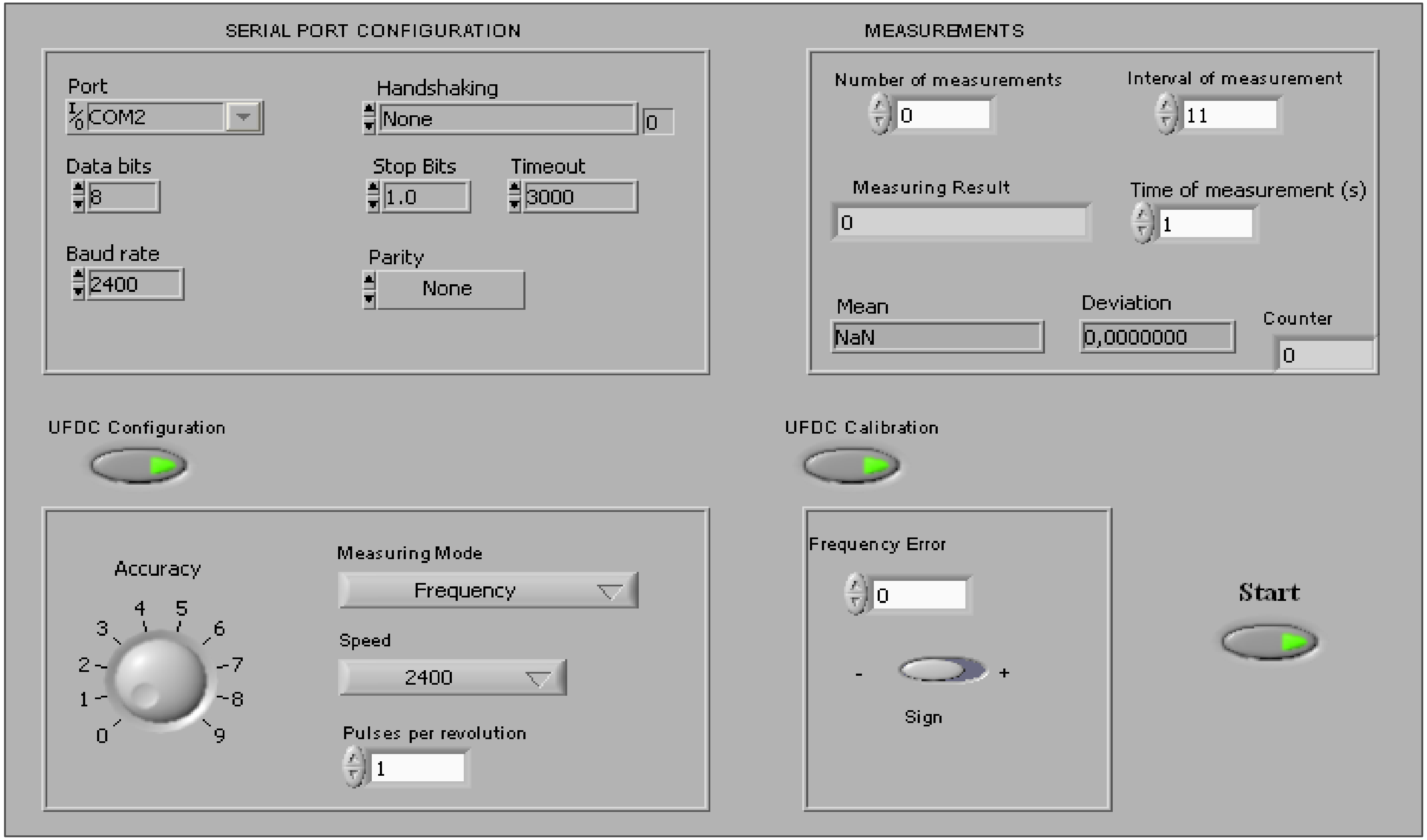


- Frequency range: 1 Hz to 7.5 MHz (120 MHz with prescaling)
- Internal reference frequency 16 MHz
- Non-redundant conversion rate: from 6.25 μs to 6.25 ms

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 ≤ 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 ?

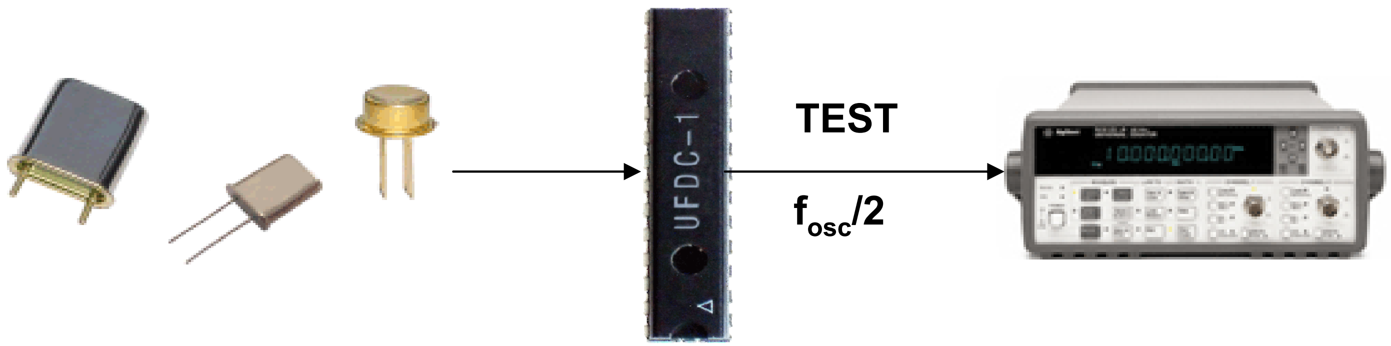
- Should be made in real working conditions with the 16 MHz crystal oscillator
- Connect the UFDC-1 to PC through the serial interface RS232
- Use the test command "T“
- Measure the frequency at the TEST pin by any external frequency counter with accuracy not worse than 0.0001 % or at least 0.0005 %
- Calculate the correction factor Δ
- Input it into the UFDC-1

Calibration Procedure Example

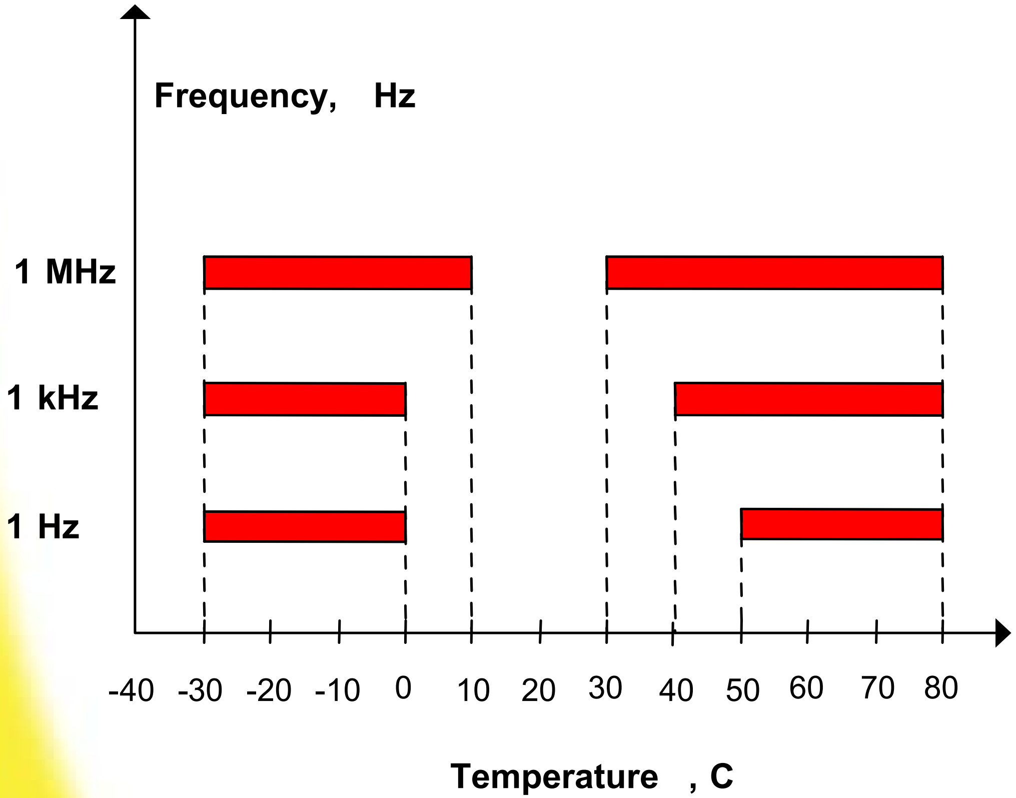
- Let the measured frequency on the TEST output is 8 000 694.257865 Hz
- After rejecting a fractional part the received integer number is 8 000 694 Hz
- Calculate the correction factor 8 000 694 –
- 8 000 000 = 694 Hz
- Convert the result into the hexadecimal number $(694)_{10} = (2B6)_{16}$
- Put the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

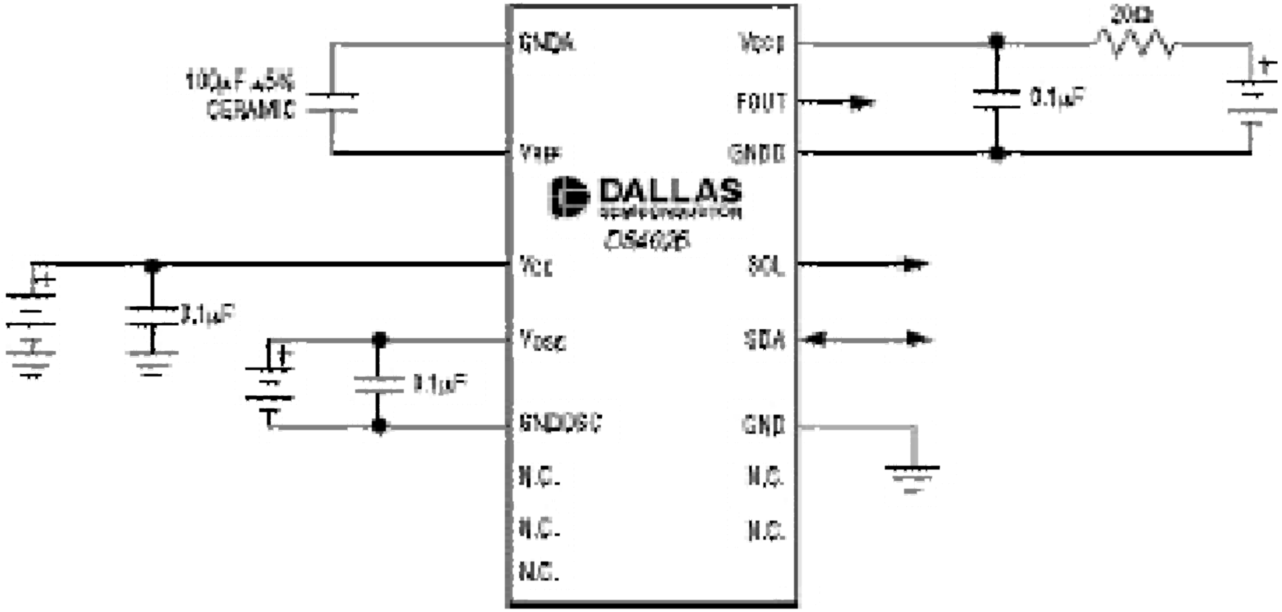


- The UFDC-1 is working in the industrial temperature range: (– 40° C...+ 85° C)
- Temperature drift error can be eliminated by the calibration in appropriate working temperature ranges

No Calibrate if:

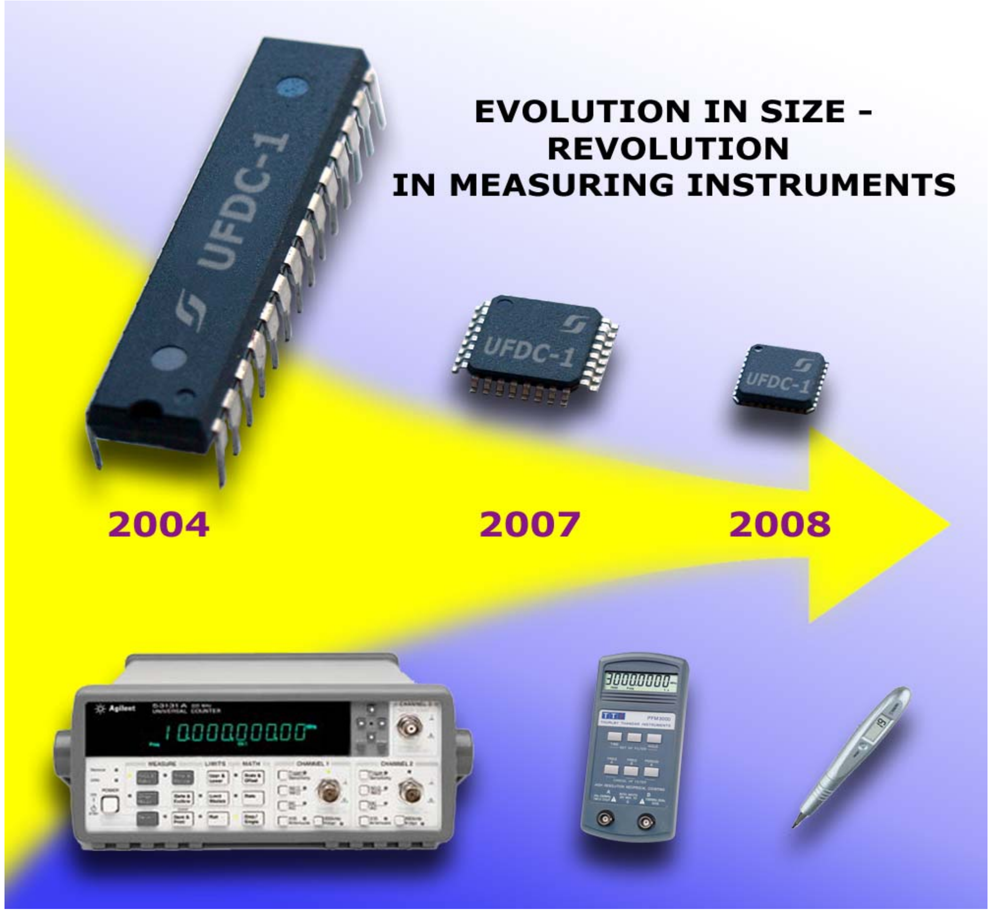
- Relative error > 0.01 %
- Use a precision temperature-compensated integrated generator ± 3 ppm frequency stability over the -40°C to +85°C

External Reference (Example)

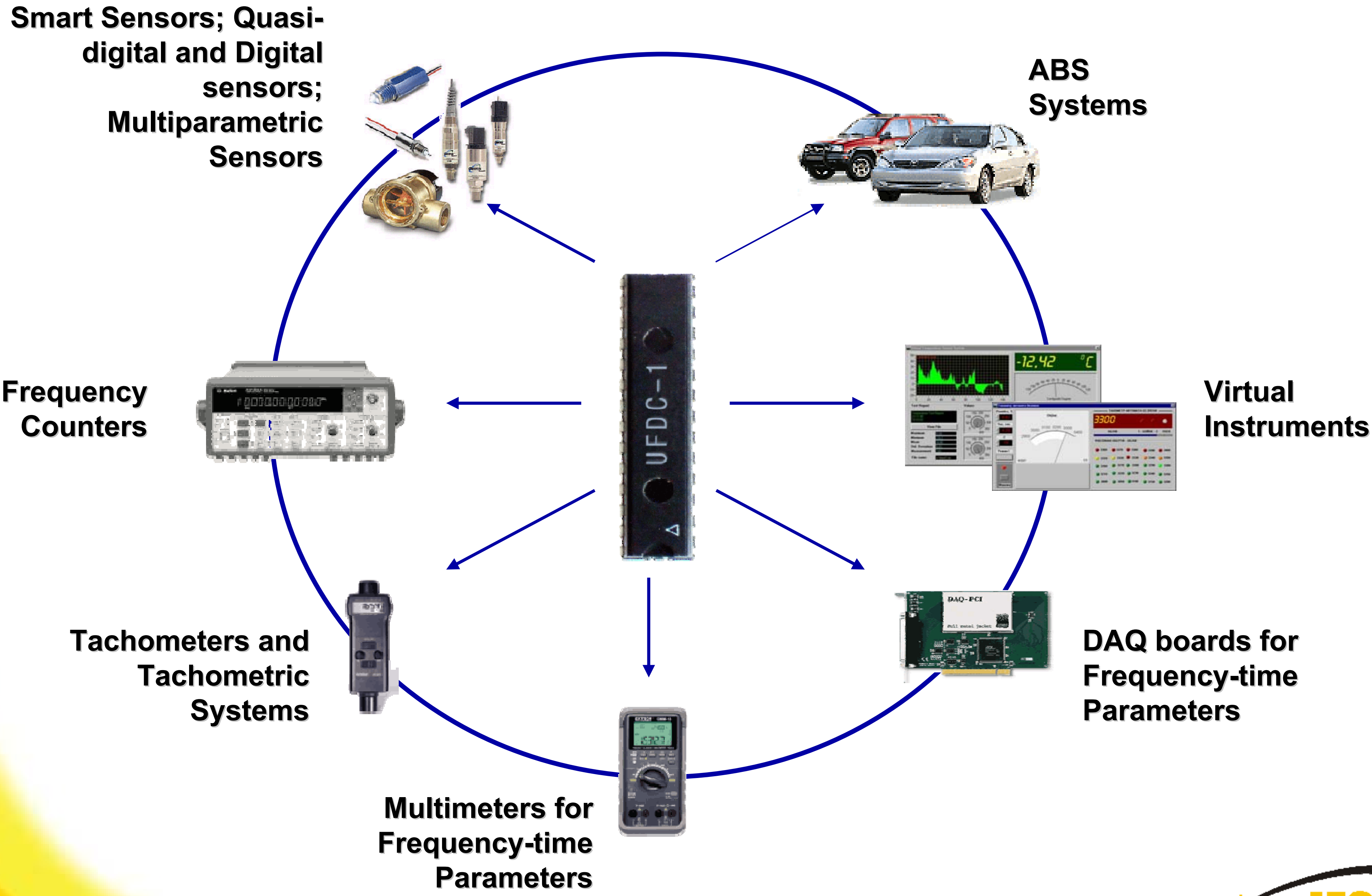


10 MHz to 51.84 MHz integrated generator from *Maxim* for highly accurate timing applications provides ±1 ppm (0.0001 %) frequency stability over the -40 ^{0}C to +85 ^{0}C industrial temperature range

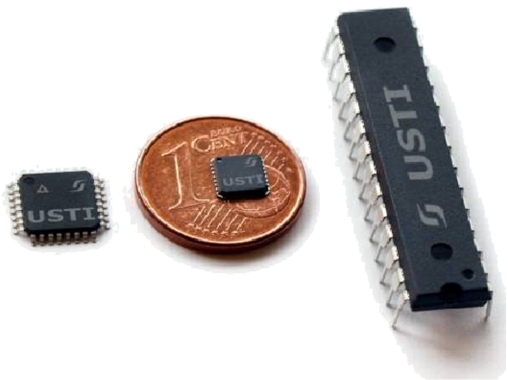
UFDC-1 Packages



Where to use the UFDC-1 ?

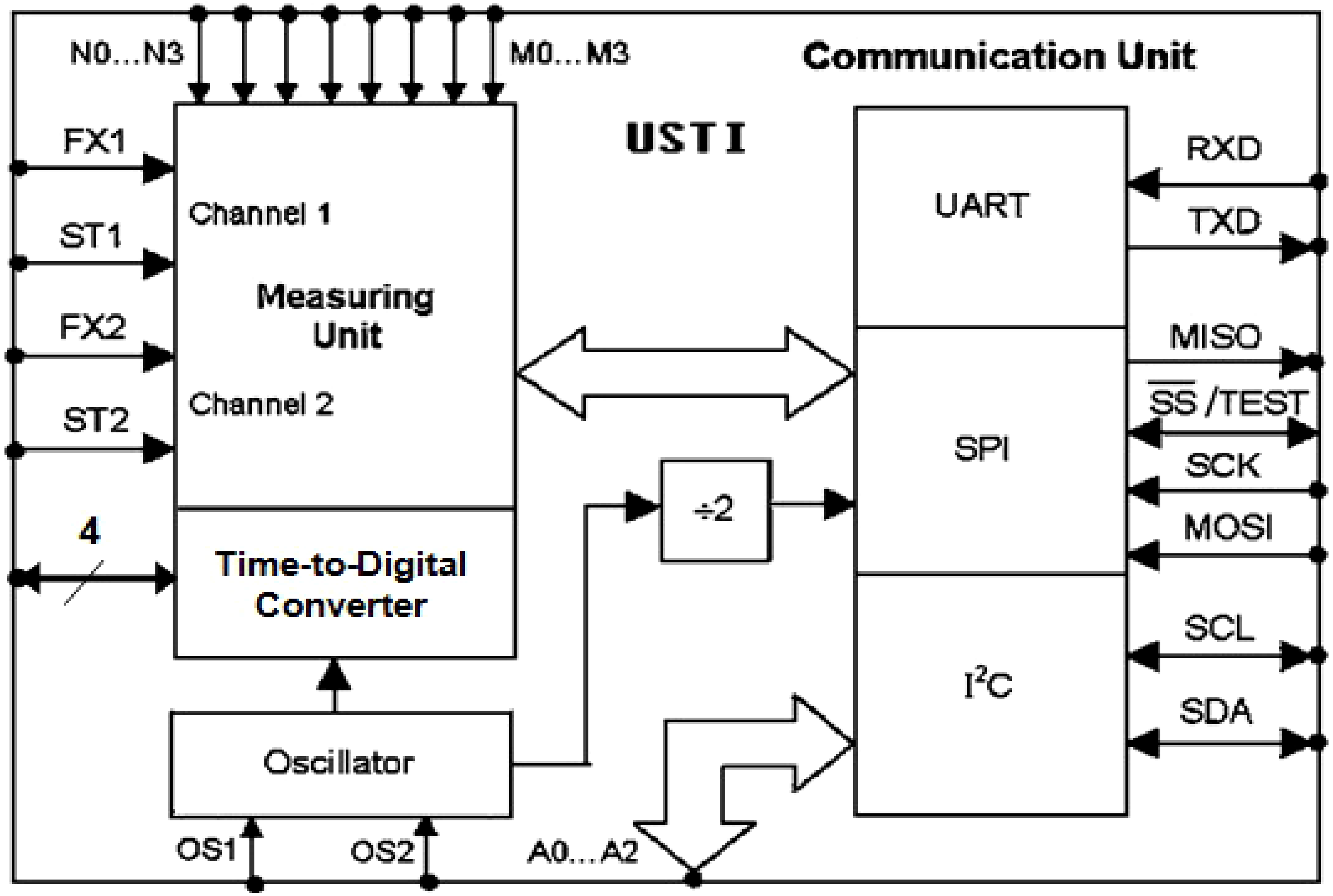


Universal Sensors and Transducers Interface (USTI)



- 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

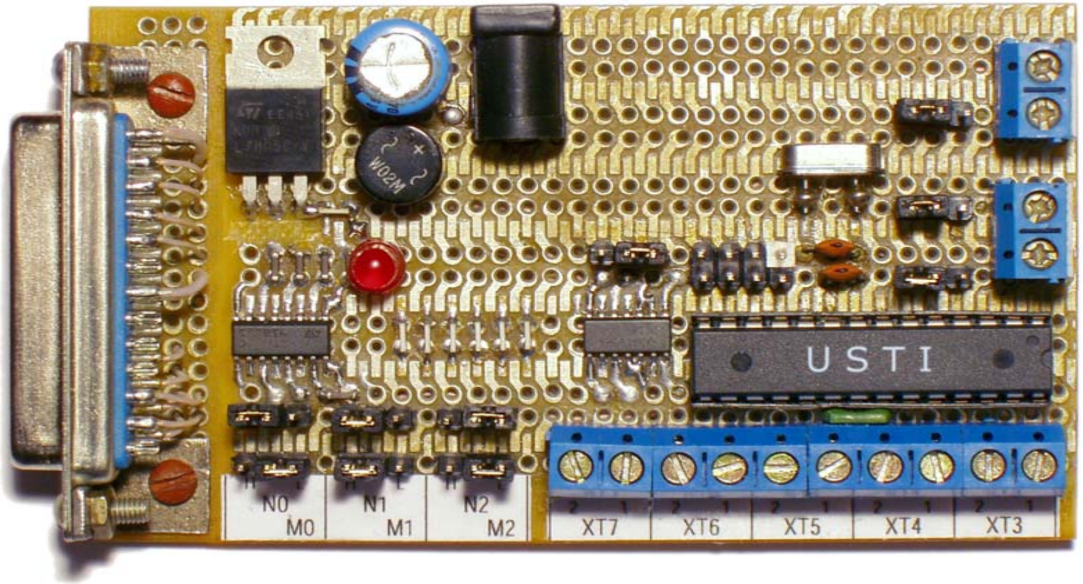
USTI Block Diagram



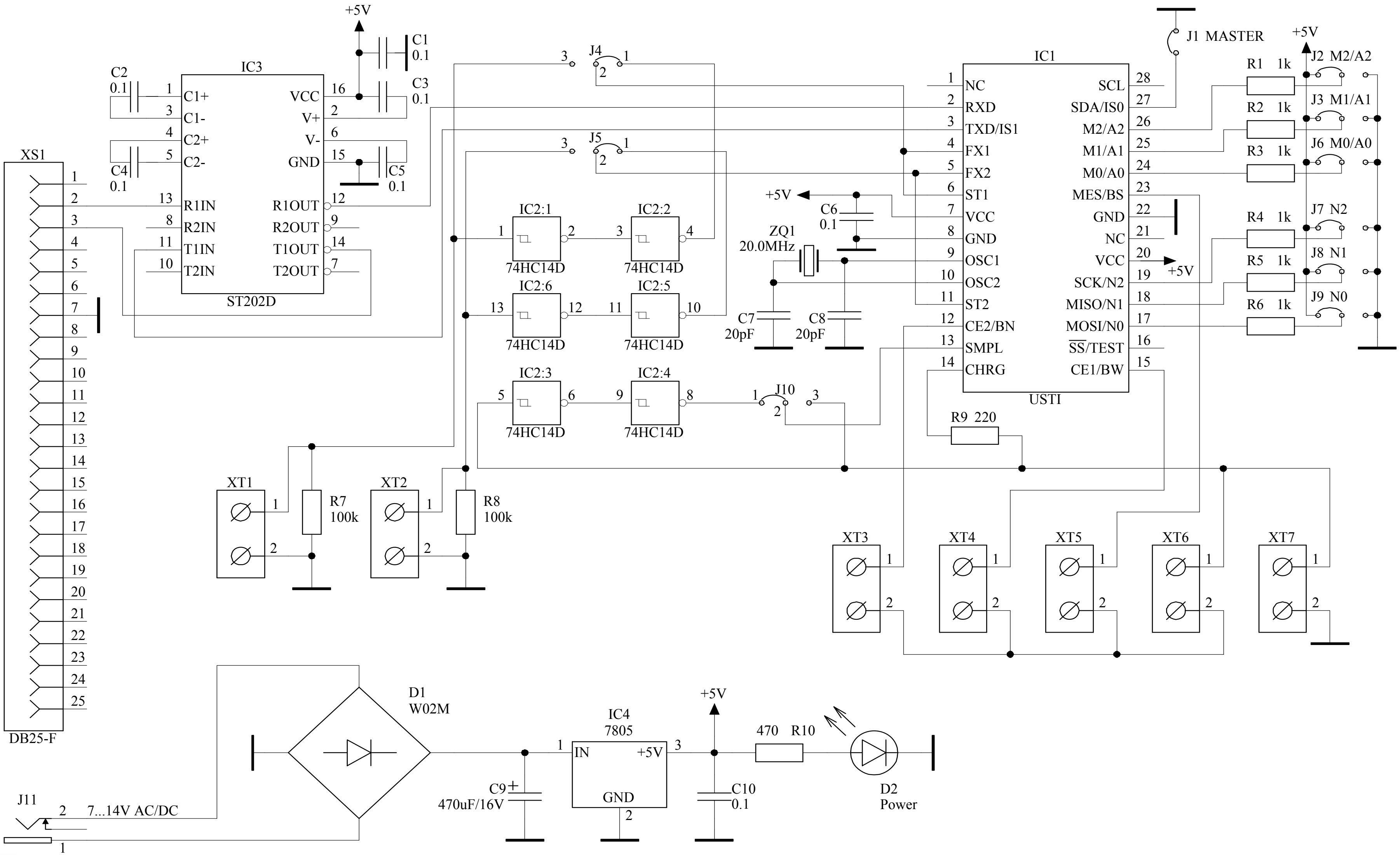
Comparison Performances of UFDC-1 and USTI

Parameter	UFDC-1	USTI
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

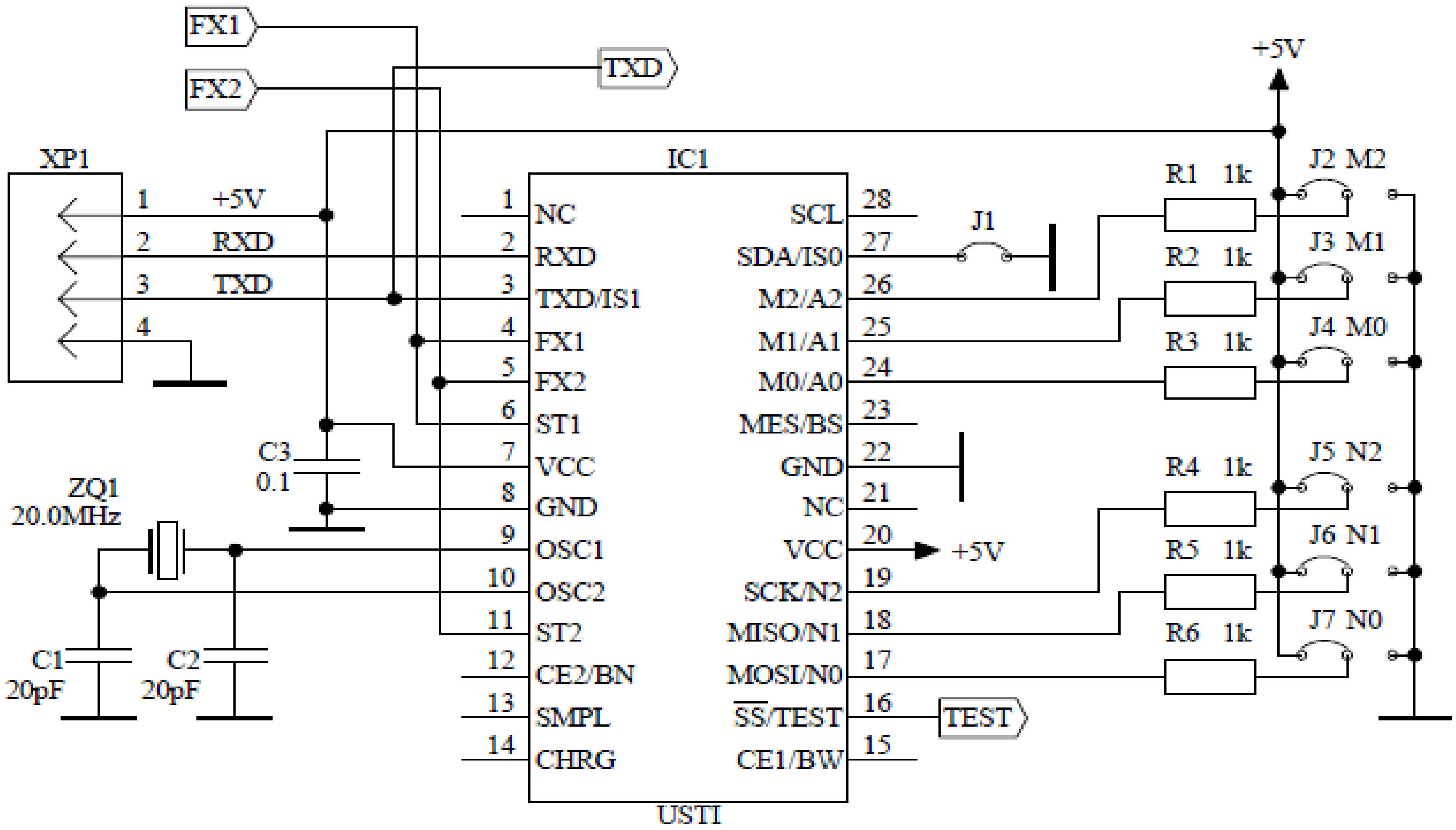
USTI Evaluation Board Prototype



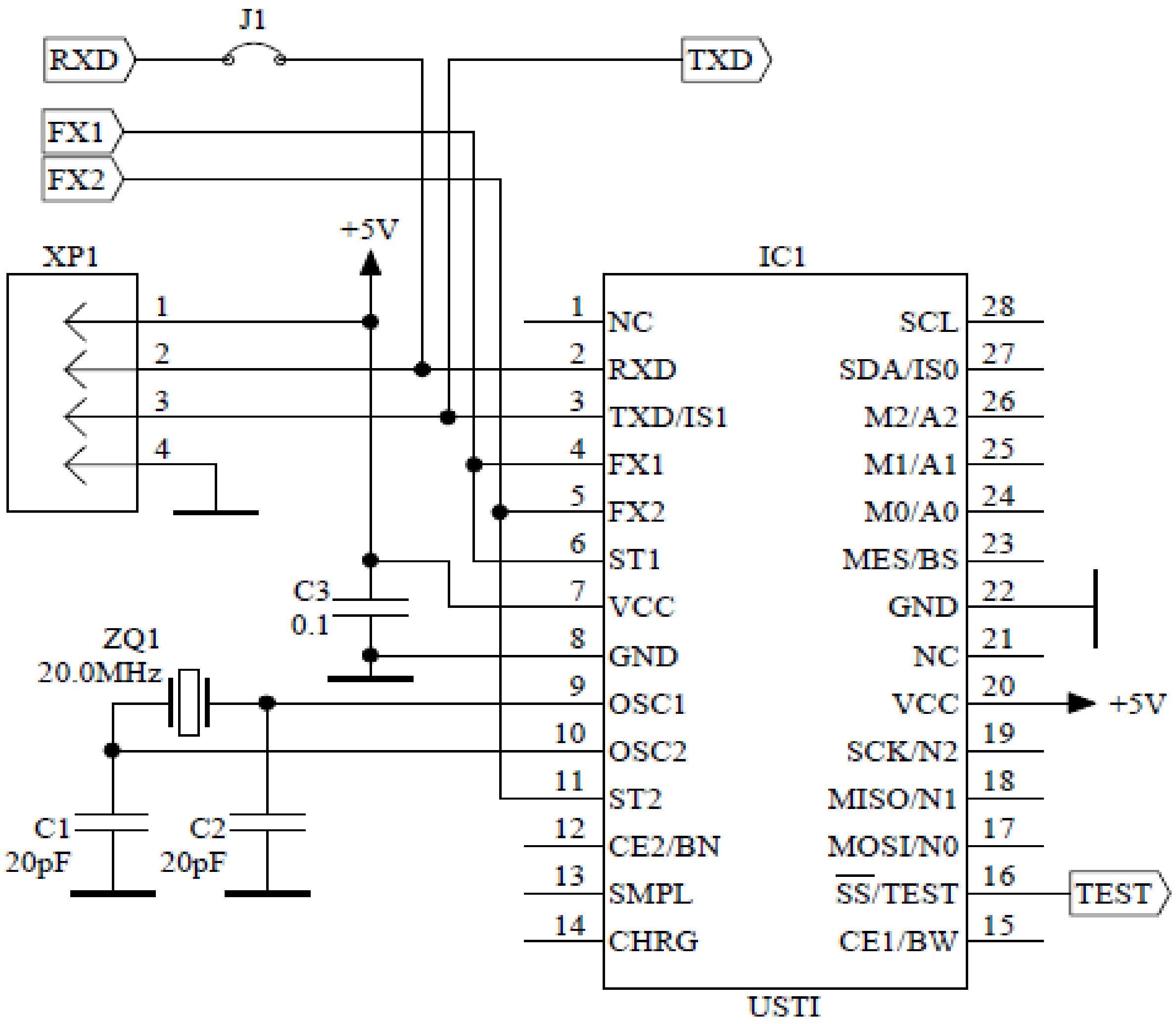
Evaluation Board Circuit Diagram



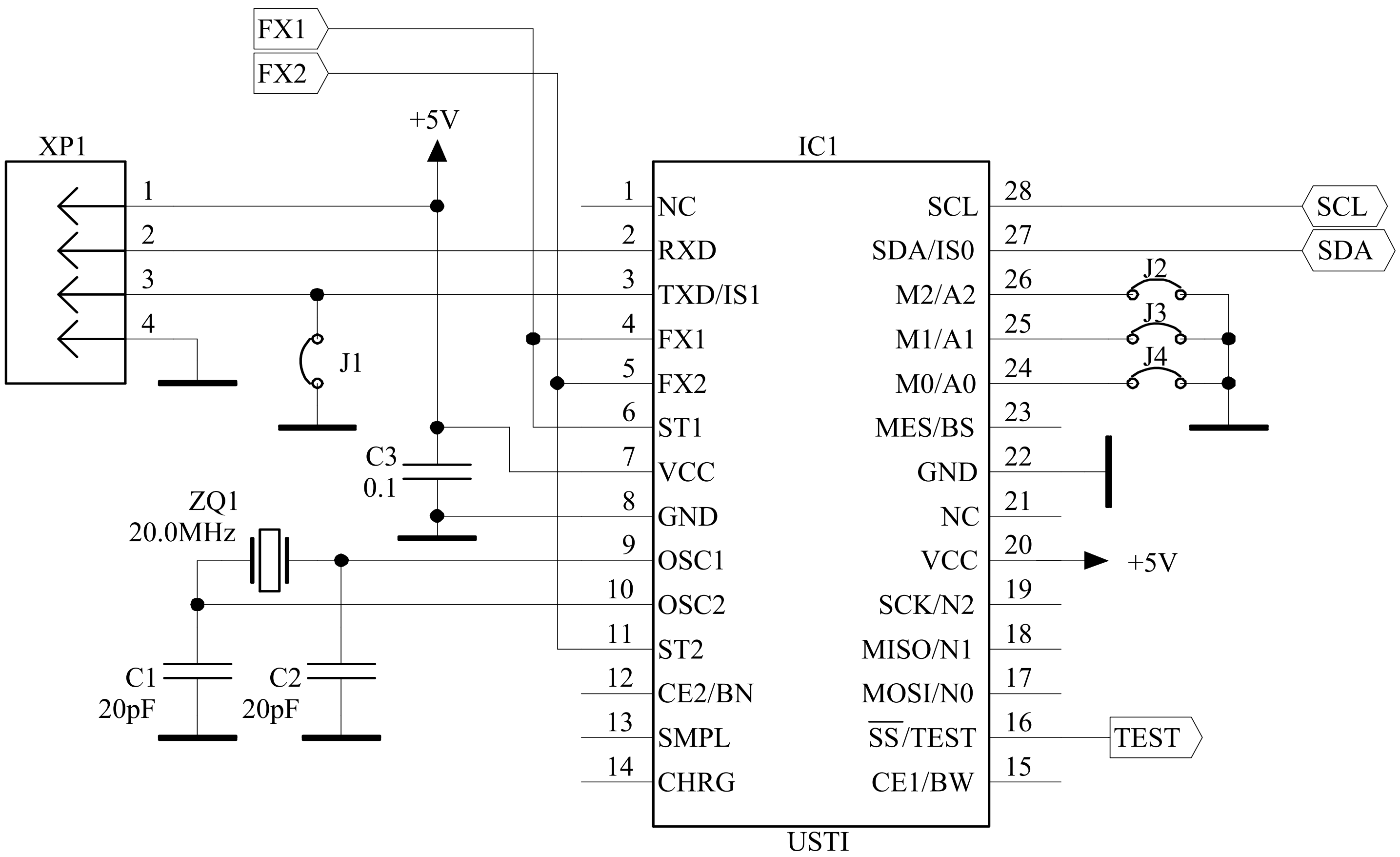
USTI RS232 Interface (Master)



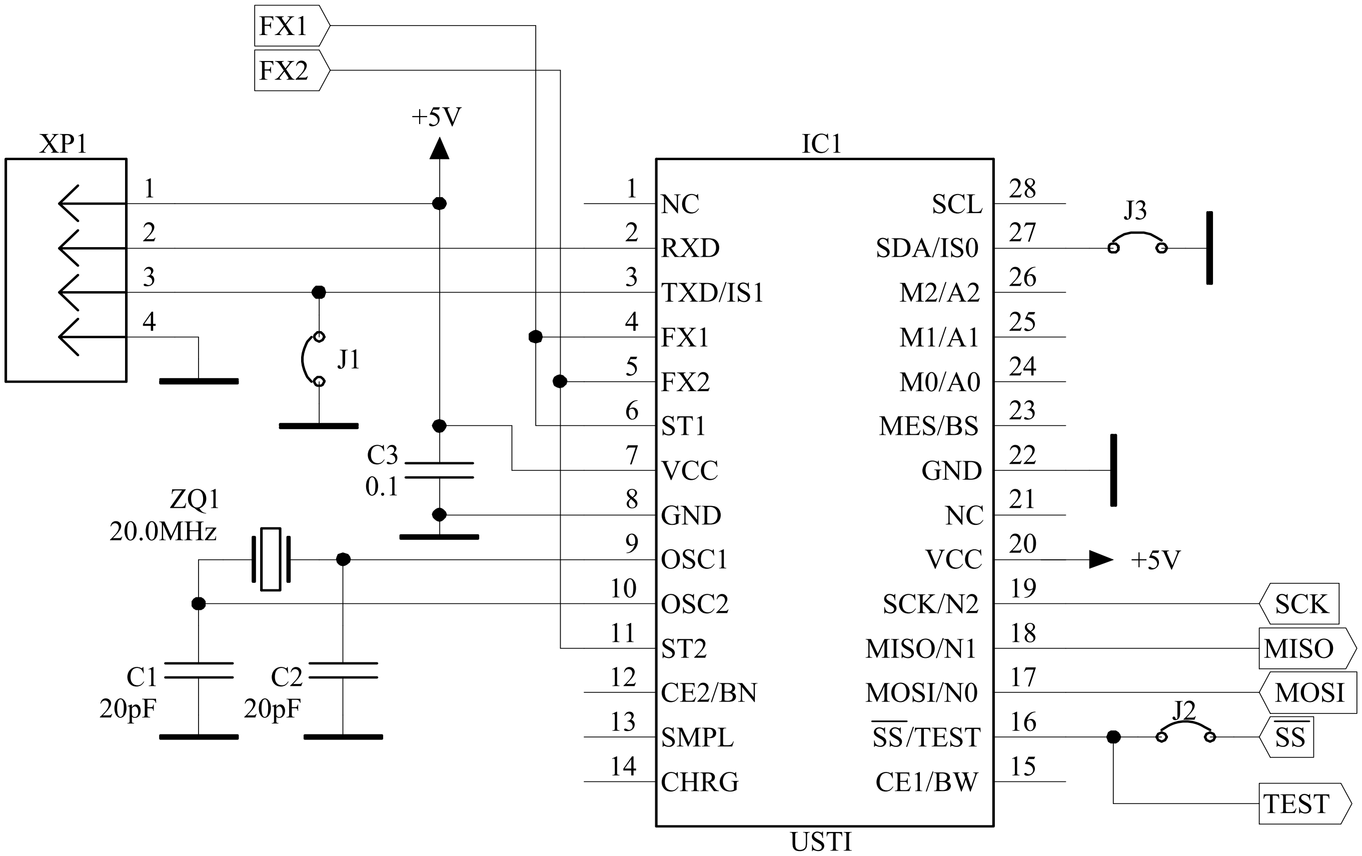
USTI RS232 Interface (Slave)



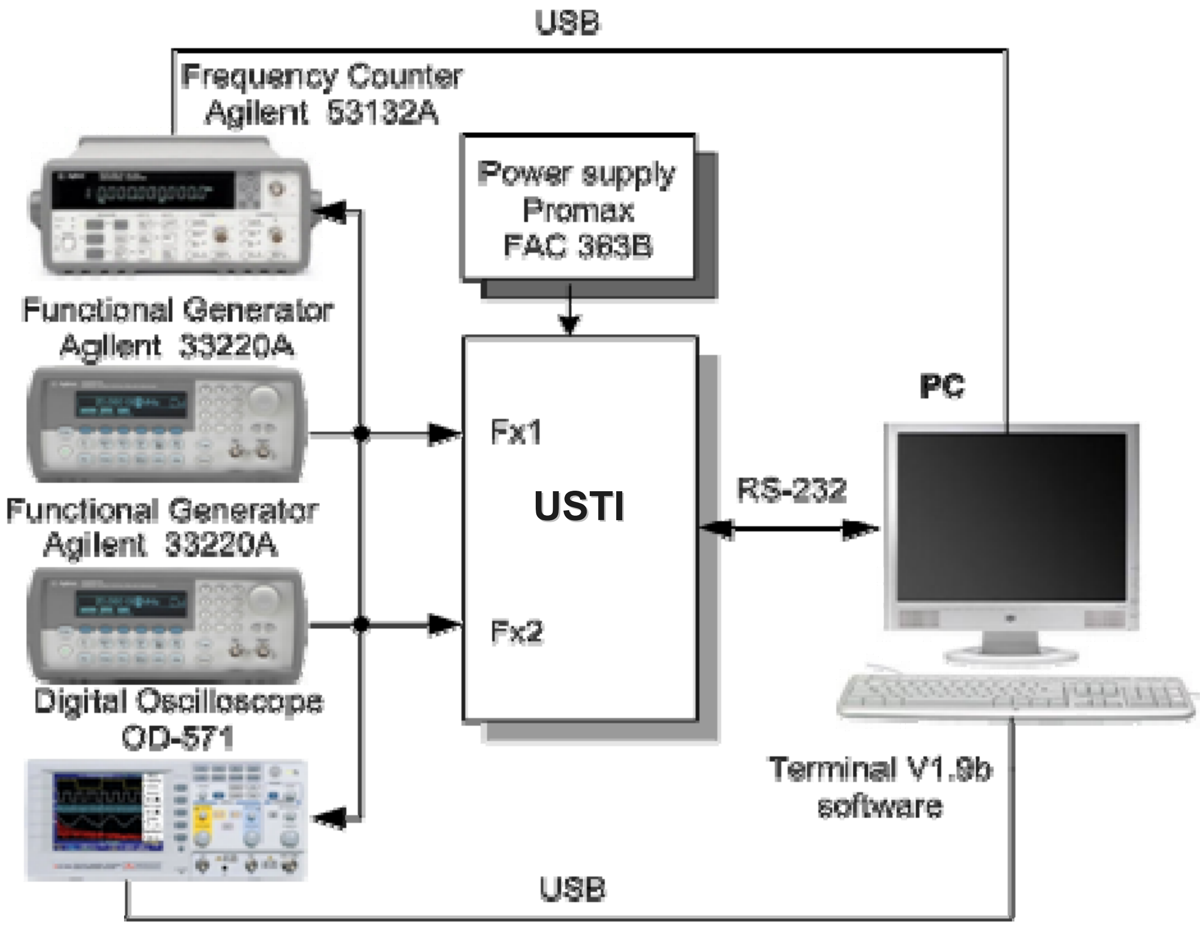
USTI I²C Interface



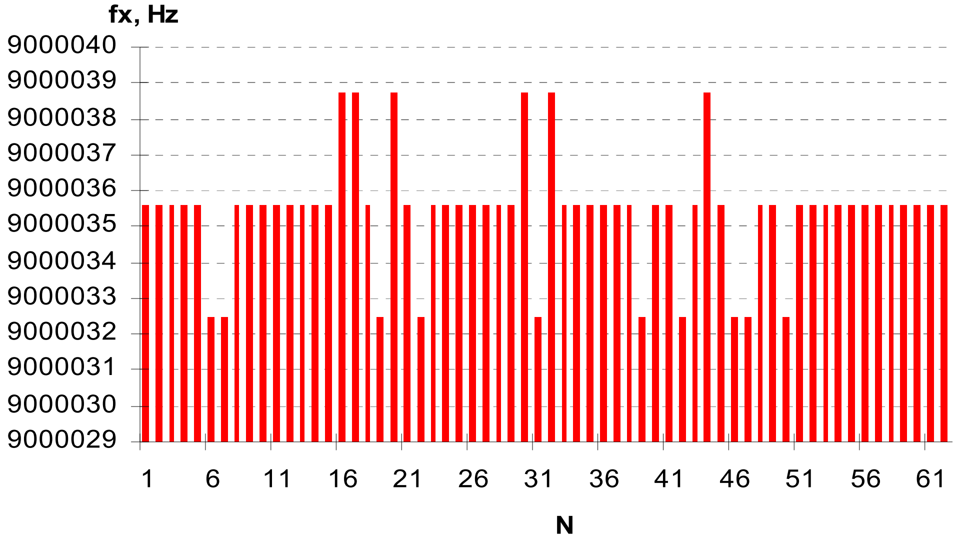
USTI SPI Interface

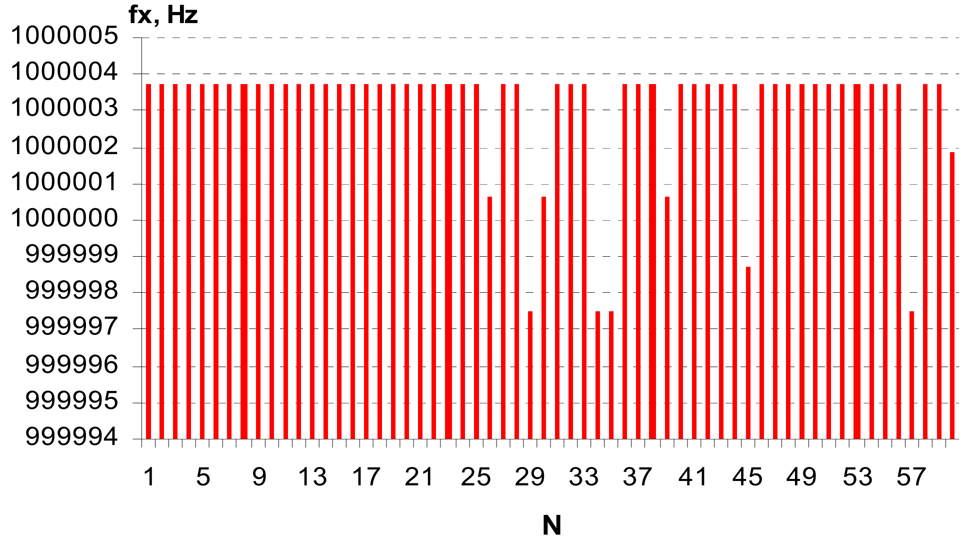


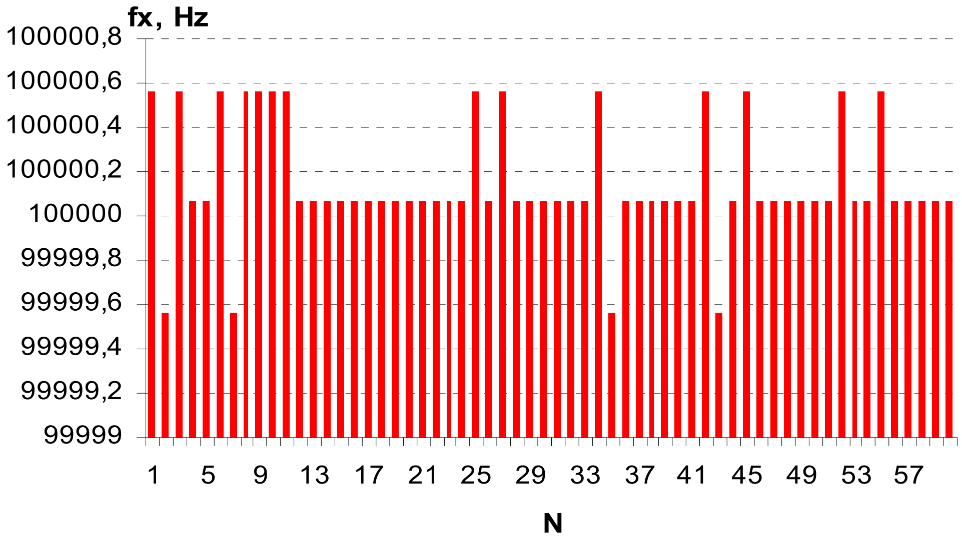
Measurement Set Up



Experimental Results





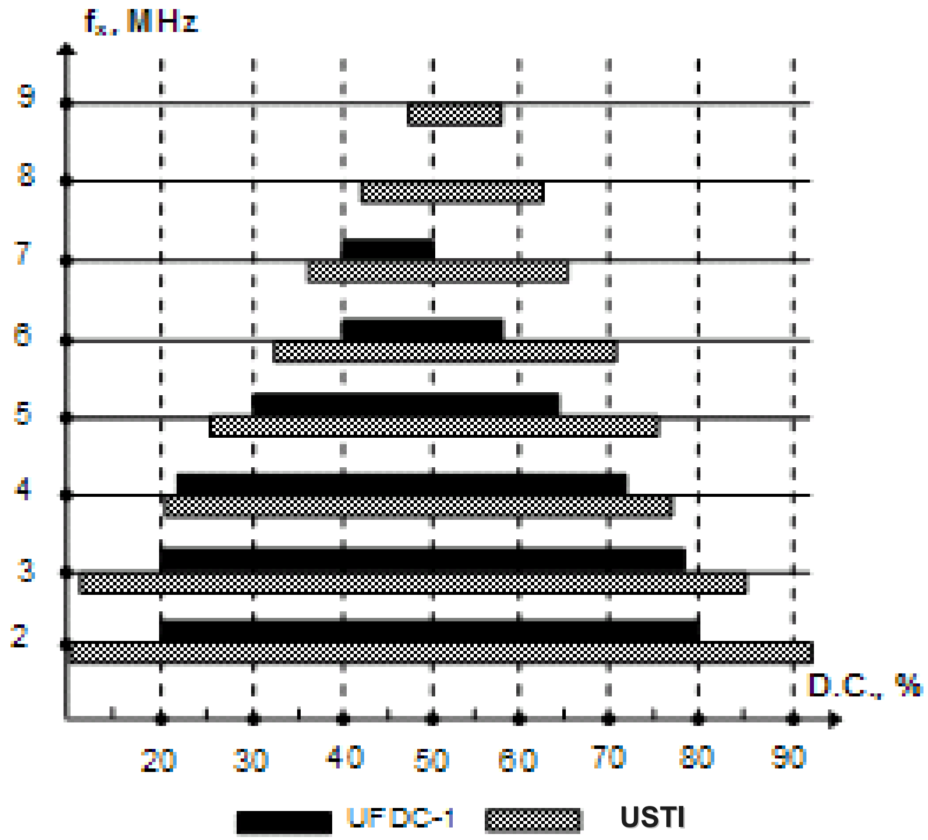


Statistical Characteristics

Parameter	Value		
	9 MHz	1 MHz	100 kHz
Number of measurements, *N*	65	60	60
Minimum f_x (min), Hz	9000032.48	999997.488	99999.5635
Maximum f_x (max), Hz	9000038.73	1000003.74	100000.563
Sampling Range, f_x (max)- f_x (min), Hz	6.2515	6.2515	1
Median	0	0	0
Arithmetic Mean, Hz	9000035.42	1000003.05	100000.146
Variance	2.405	3.1488	0.0692
Standard Deviation	1.5508	1.7745	0.2631
Coefficient of Variation	5803428.66	563543.777	380129.039
Confidence Interval at probability *P* = 97 %	f_x ϵ [9000035 ÷9000035.83]	f_x ϵ [1000002.55 ÷1000003.54]	f_x ϵ [100000.073 ÷ 100000.22]
Relative error, %	0.00039 < 0.00050	0.00030 < 0.00050	0.00014 < 0.00050

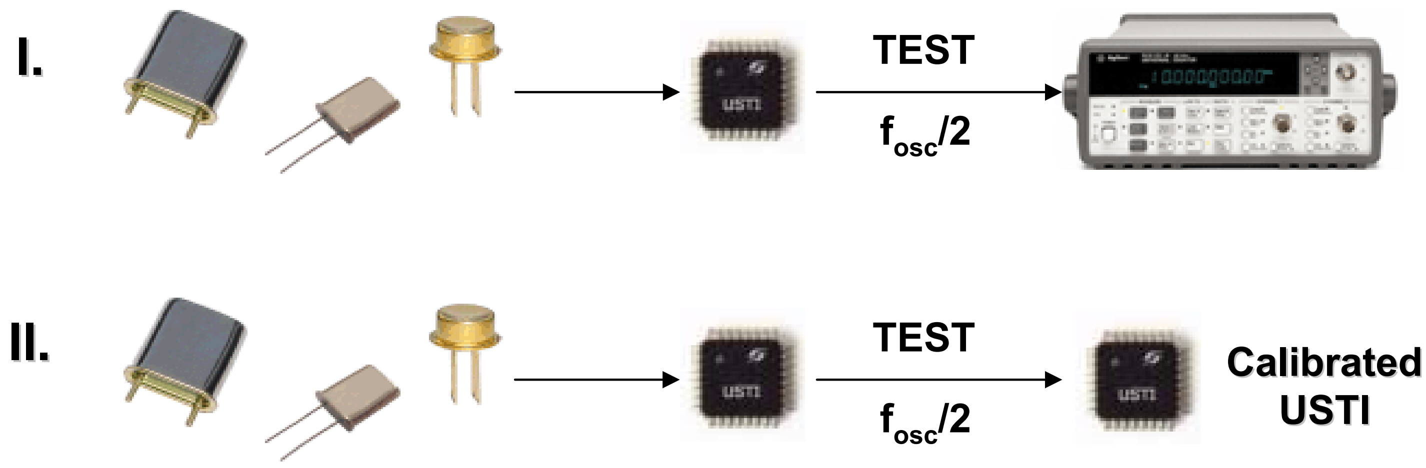
Duty-Cycle for Input Signal

Duty-cycle, %	Frequency f_x, MHz
47.5 ÷ 57.0	9
42.0 ÷ 62.0	8
36.5 ÷ 66.0	7
32.0 ÷ 71.5	6
26.0 ÷ 76.5	5
20.5 ÷ 80.0	4
any	< 3



USTI Calibration Procedure

>T	; set the USTI into the calibration mode
>F10002492.85	; correction command
>F	; check the correction value in the USTI
10002492.85	; returned correction factor



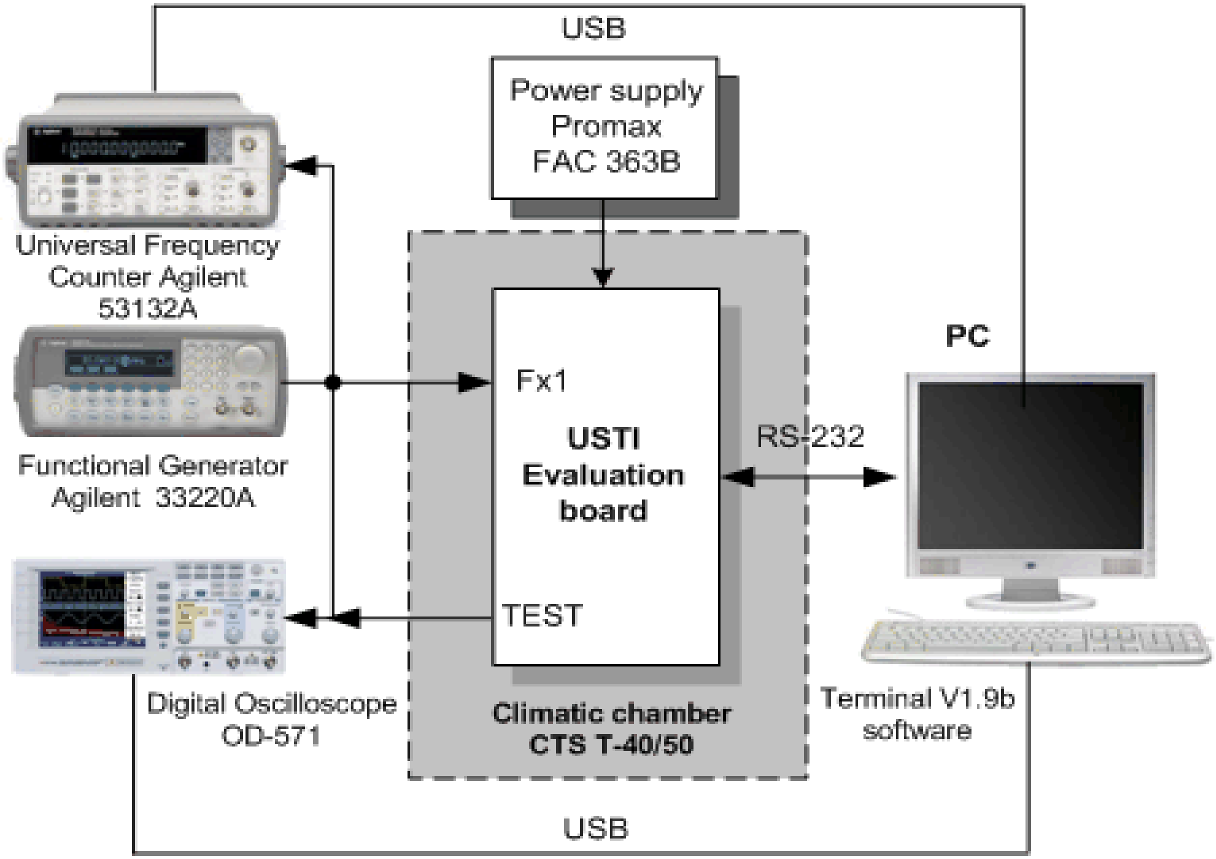
Temperature Drift Calibration

- The USTI is working in the industrial temperature range: – 40^o C...+ 85^o C
- Temperature drift error can be eliminated by the calibration in an appropriate working temperature ranges

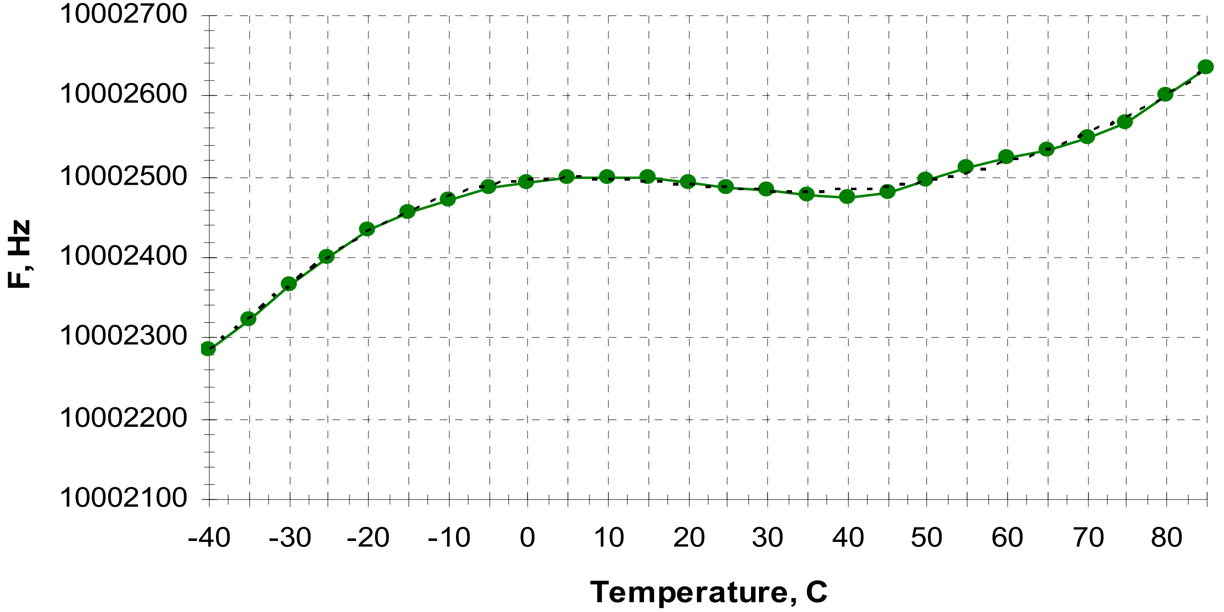
No Calibrate If:

- Relative error of measurement > 0.026 %
- Use a precision temperature-compensated integrated generator ± 1 ppm frequency stability over the -40°C to +85°C, for example, DS4026 from *MAXIM*
- In this case a custom designed USTI should be ordered

Experimental Setup for Advanced Calibration



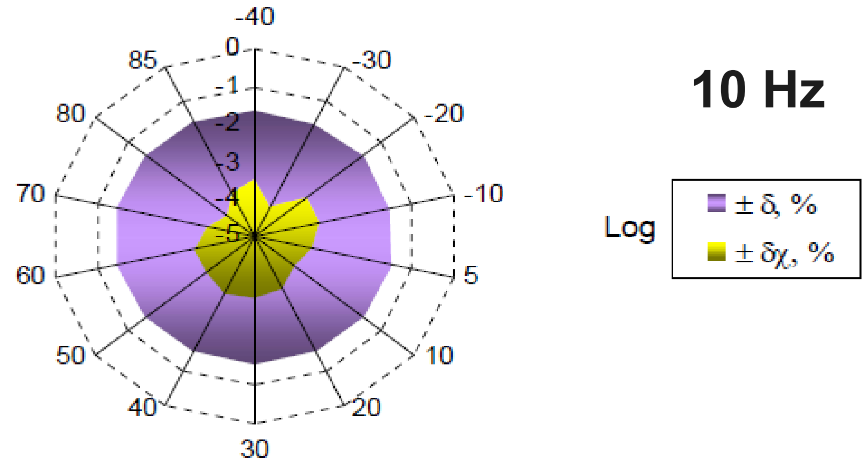
USTI Calibration Results



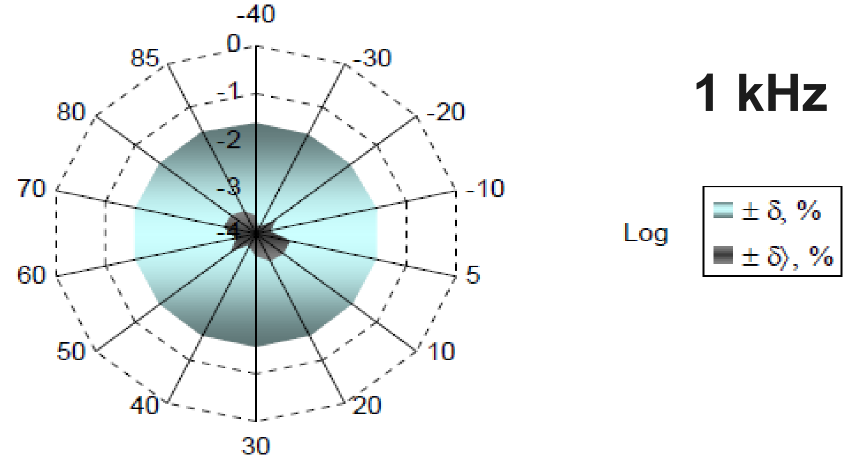
y = 3.10-5 x6 - 0,0025x5 + 0,0871x4 - 1,3113x3 + 6,3954x2 + 26,852x + 107;
R2 = 17,991 – squared value

Calibration Results

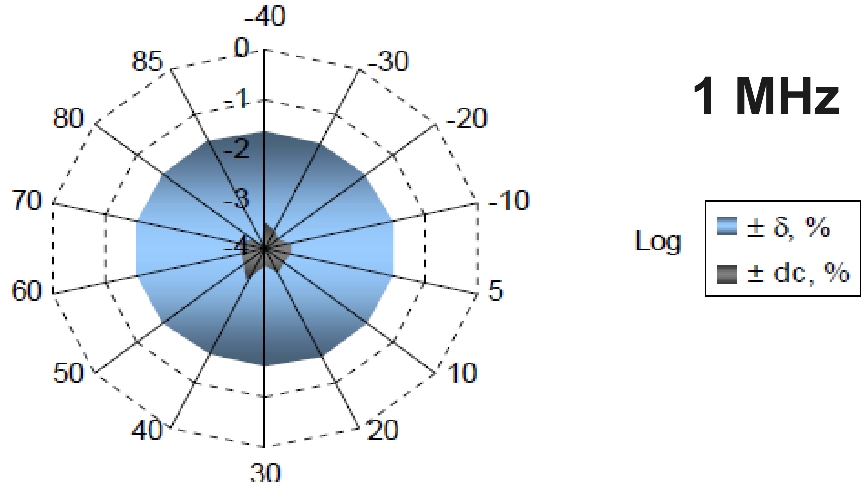
10 Hz



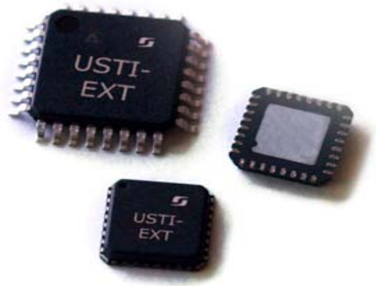
1 kHz



1 MHz



USTI-EXT



- Extended operation temperature range from - 55 ^{0}C to +150 ^{0}C
- Similar metrological performance as UFDC-1M-16
- Wide functionality as in USTI
- Increased baud rate for the RS232 serial interface: up to 76 800
- Active supply current <12 mA
- 32-lead, 7x7 mm TQFP and 32-pad, 5x5 mm (QFN/MLF)
- Applications: automotive industry, avionics, military, etc.

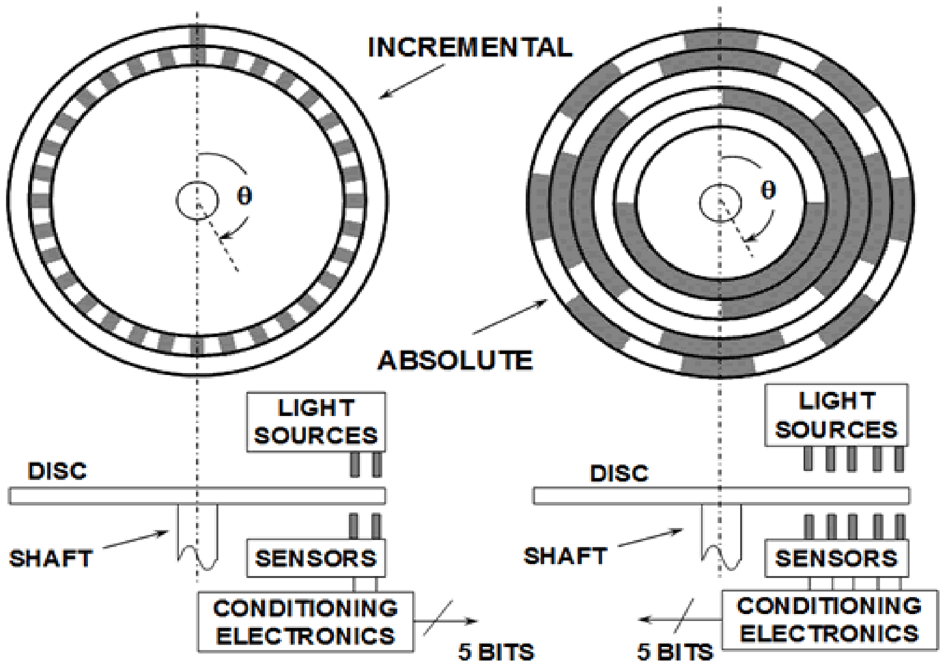
High Performance Digital Sensors Design

1. Introduction: Markets and Definitions
2. Modern Challenges
3. Digital Sensors Design: Introduction
4. Advanced Digital Sensors Design
5. Smart Sensor Systems Integration
7. Sensor System's Error Estimation
8. The Future and Summary

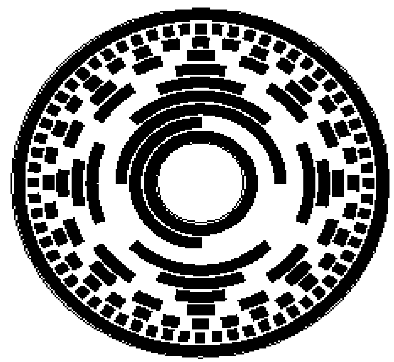
Digital Sensors

- 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.

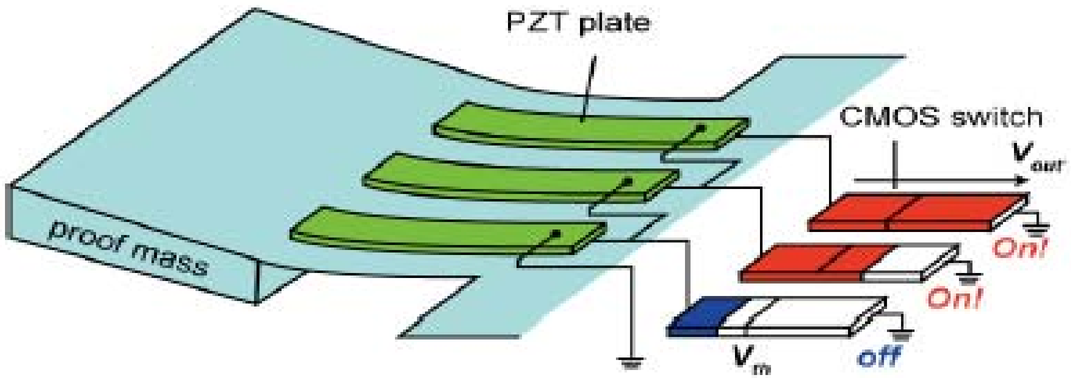
Angular-Position Encoder



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.



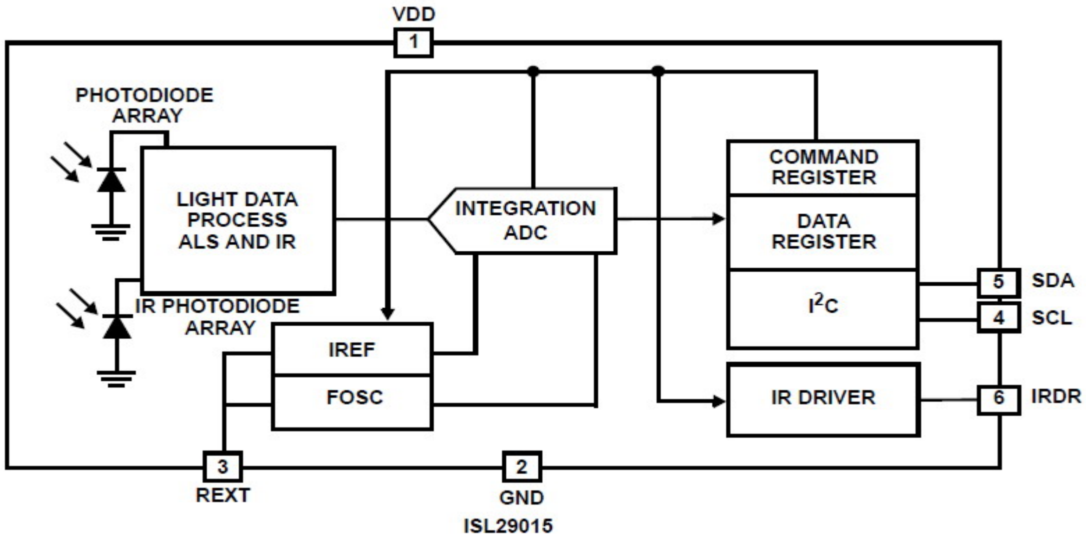
Digital Accelerometer



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

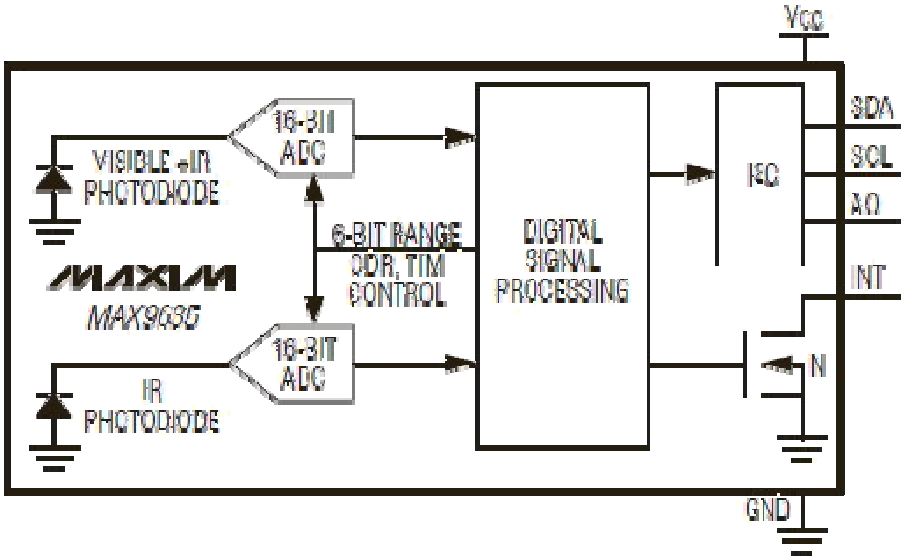
ADC – based digital light sensor ISL29015 (*Intersil*)



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

Smart Sensor Example II

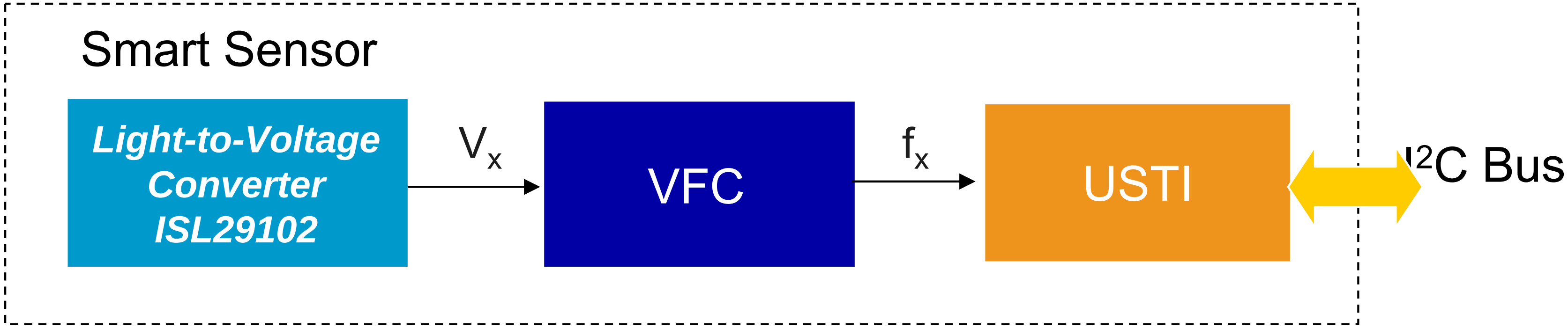
Ambient Light Sensor MAX9635 with ADC (*Maxim*)



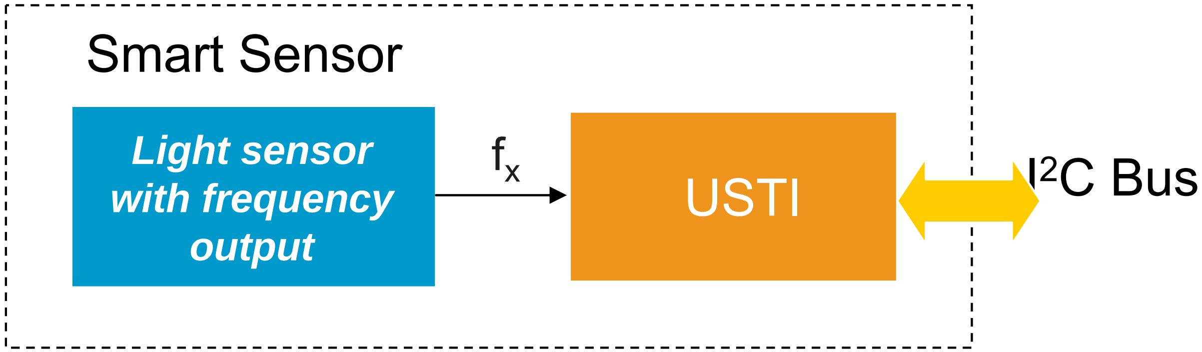
ADC's conversion time: 97 … 100 ms

Smart Sensor Example III

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

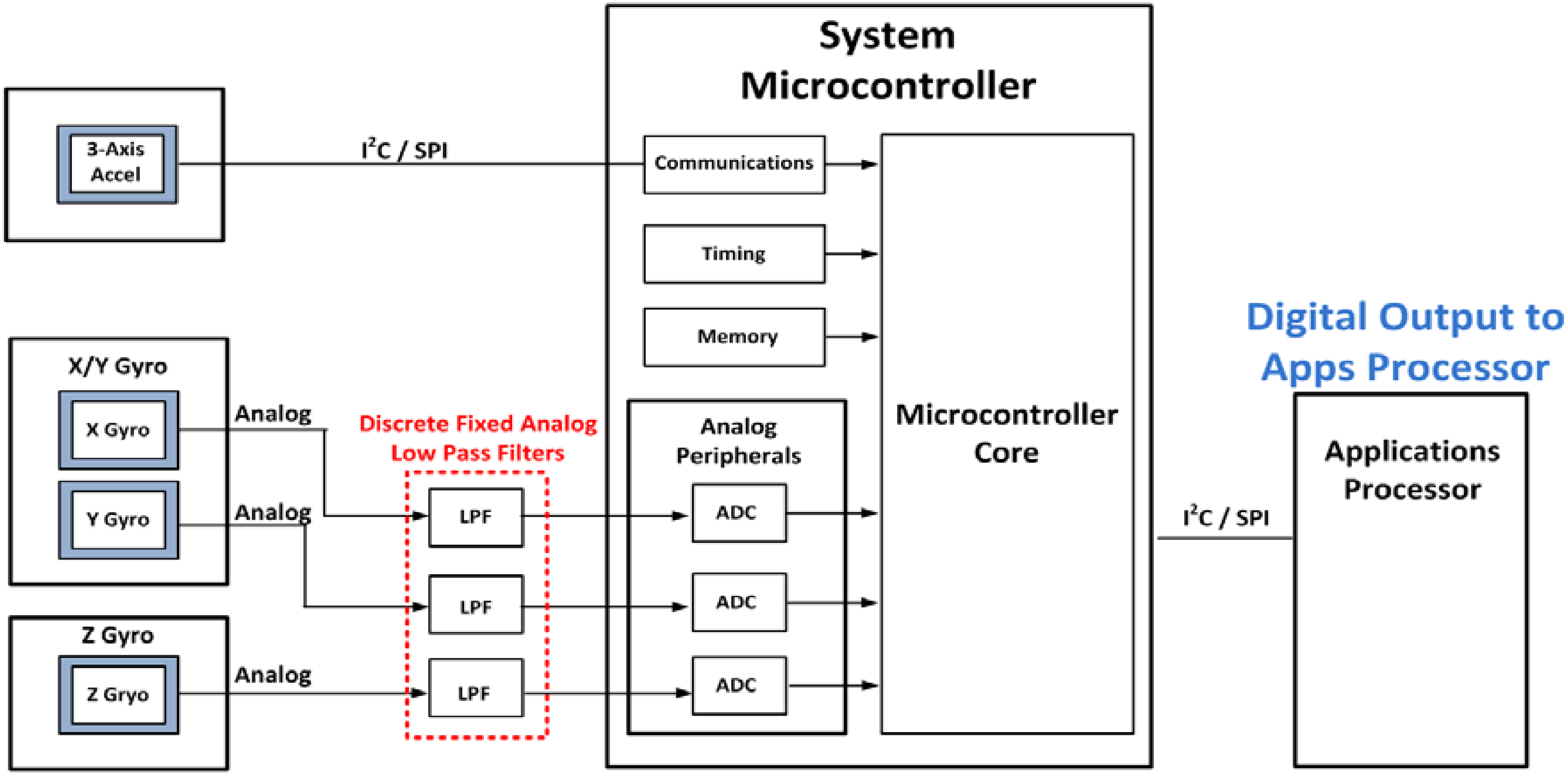
Modern VFCs

- 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

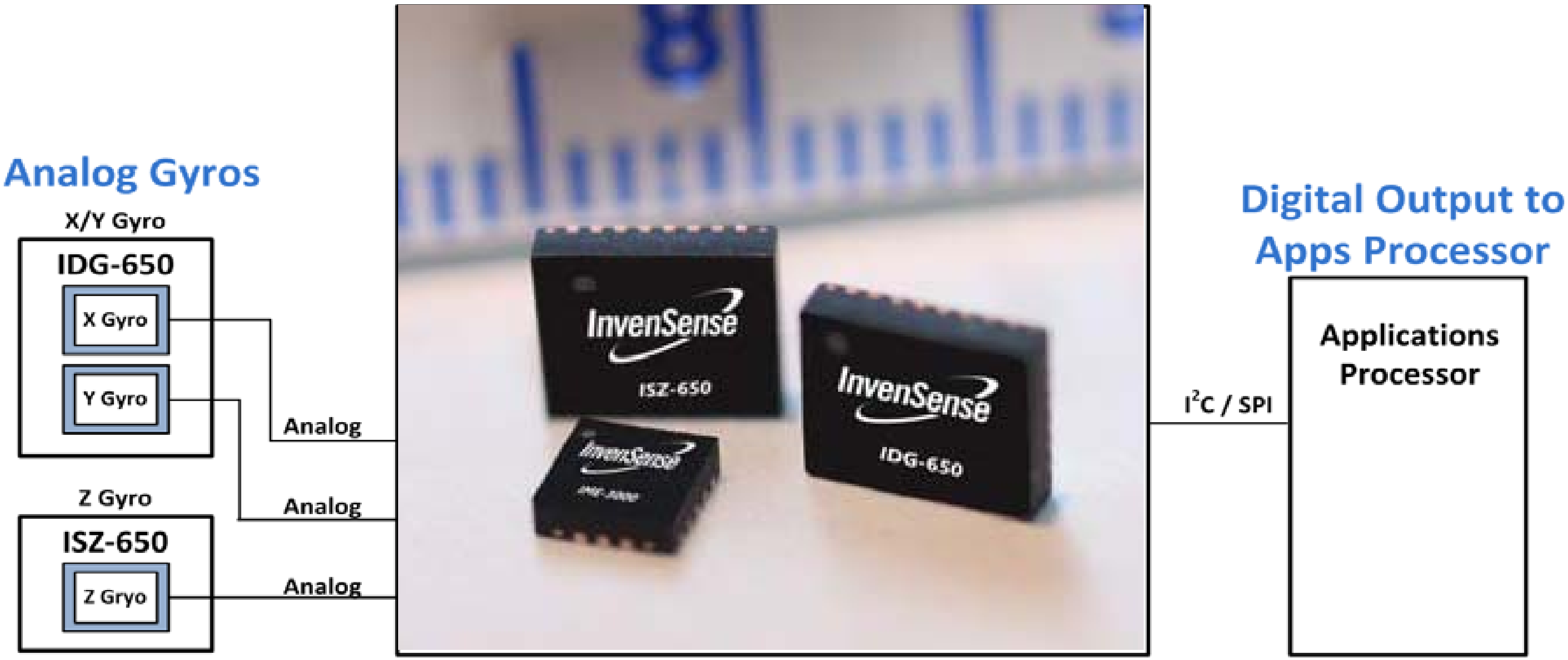
A / D Converter Types

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

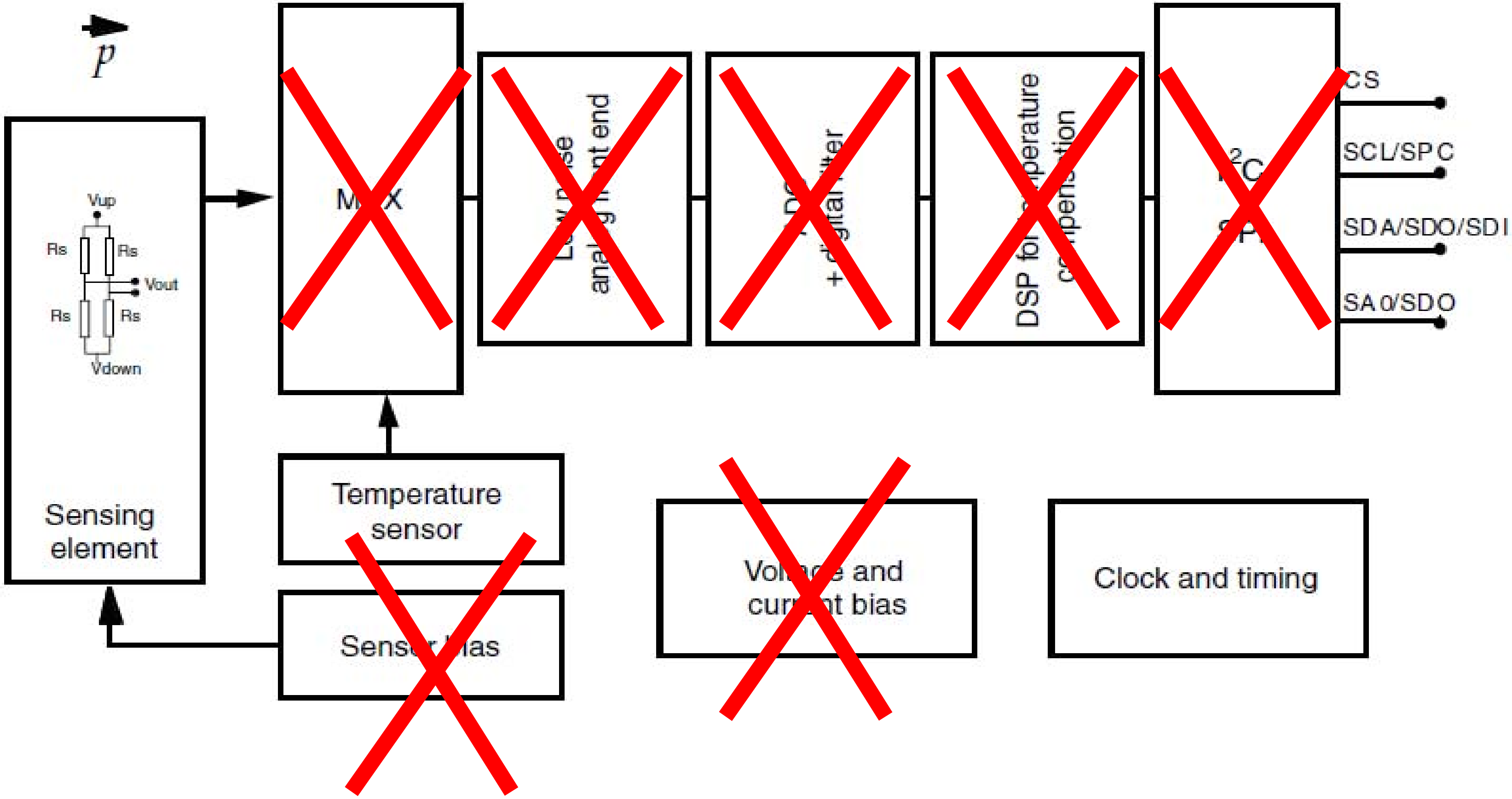
6-Axis Motion Processing Solution (I)



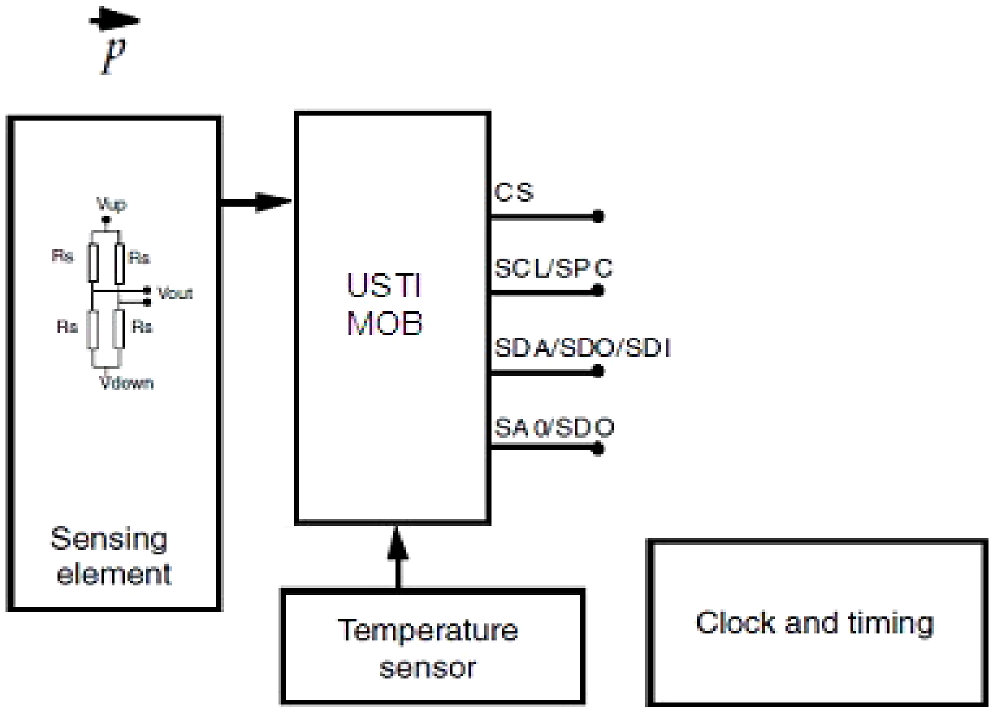
6-Axis Motion Processing Solution (II)



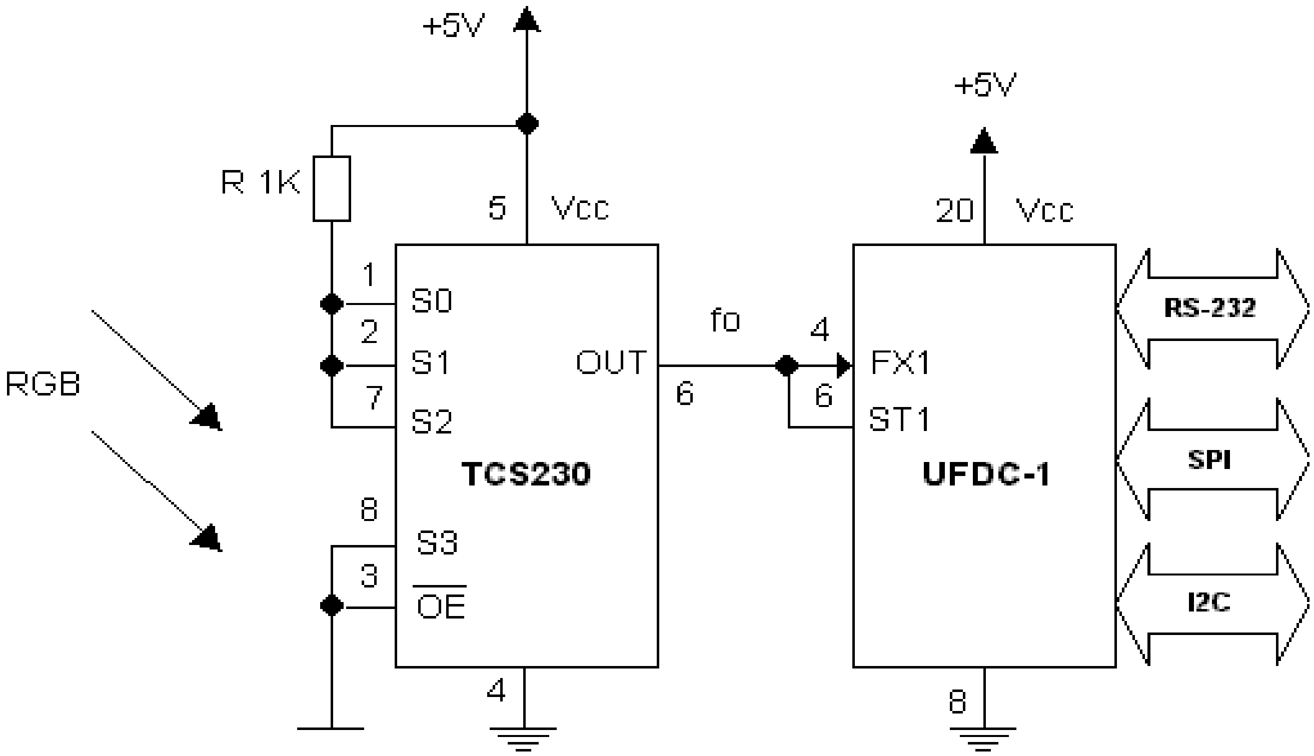
Barometric Pressure Sensor (I)



Barometric Pressure Sensor (II)

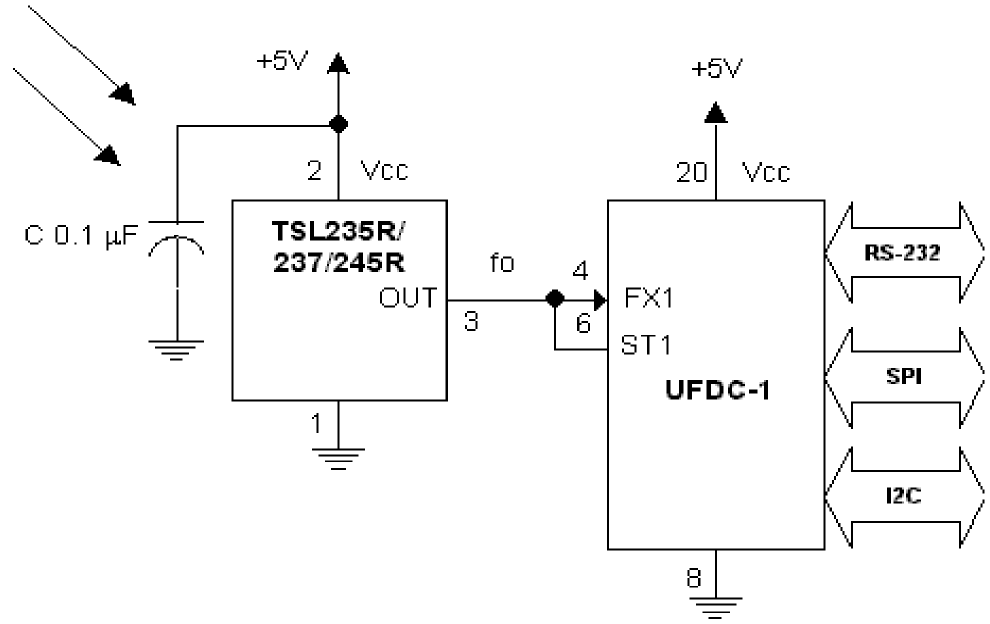


Color-to-Digital Converter

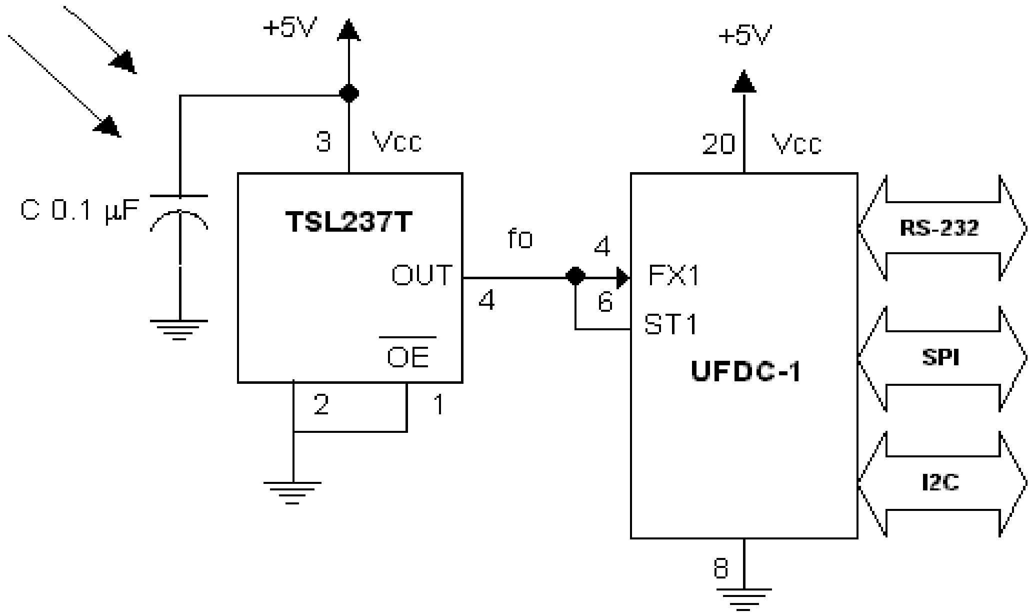


Design notes: 100 % scaling mode for TCS230 (S0, S1 =1) and clear photodiode type (no filter, S2=1, S3=0). Power-supply lines must be decoupled by a 0.01-µF to 0.1-µF capacitor with short leads mounted close to the device package.

Light-to-Digital Converters



(a)

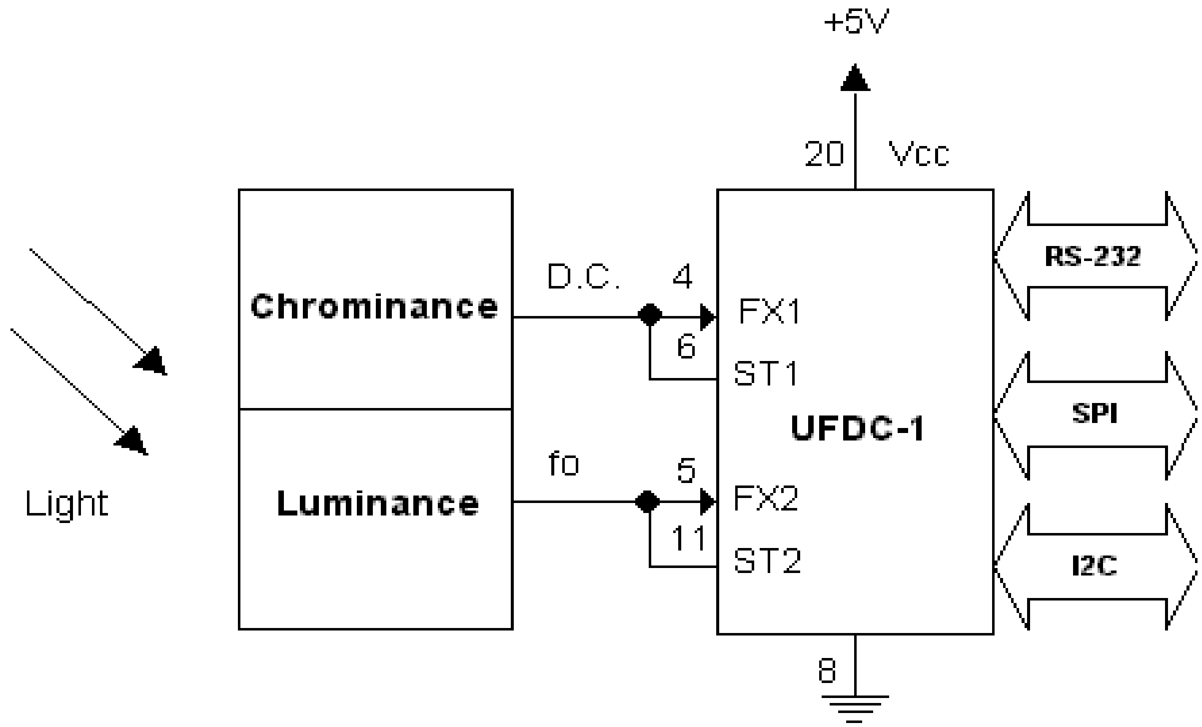


(b)

Commands Example (RS232 interface)

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

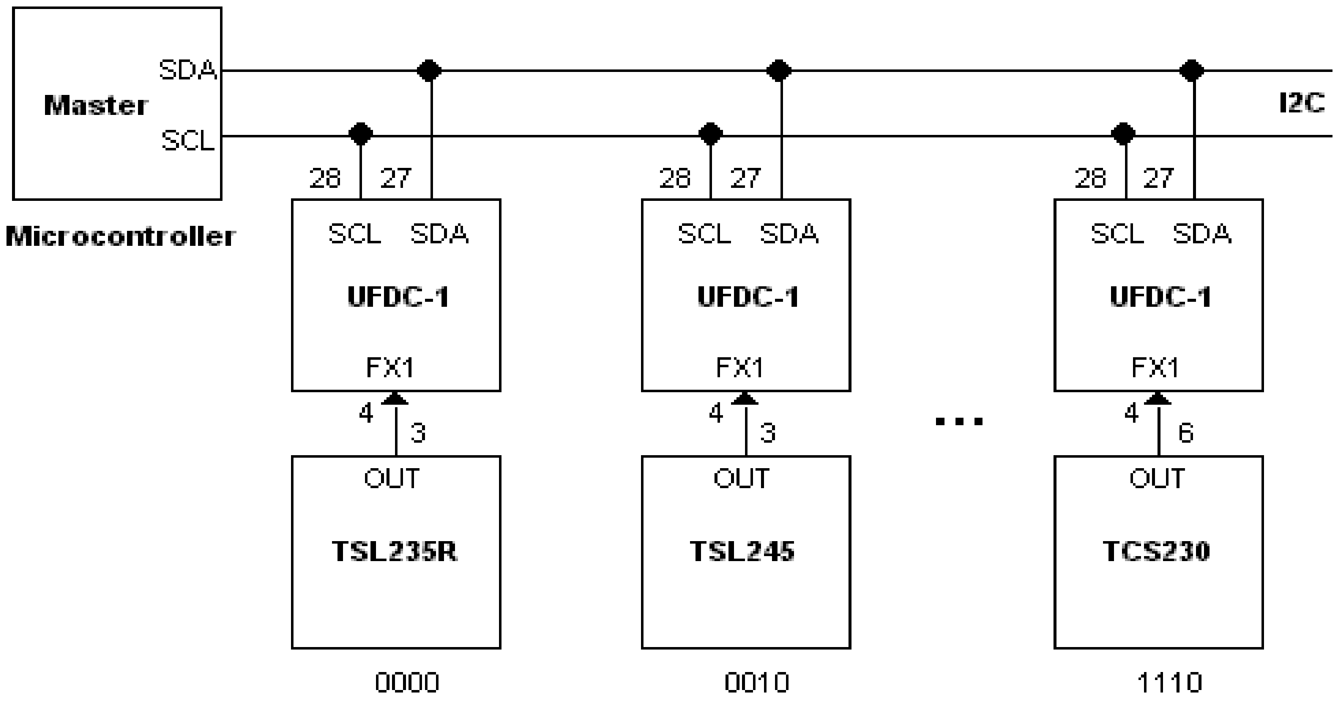
Multiparameters Sensor Interfacing



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 2nd 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



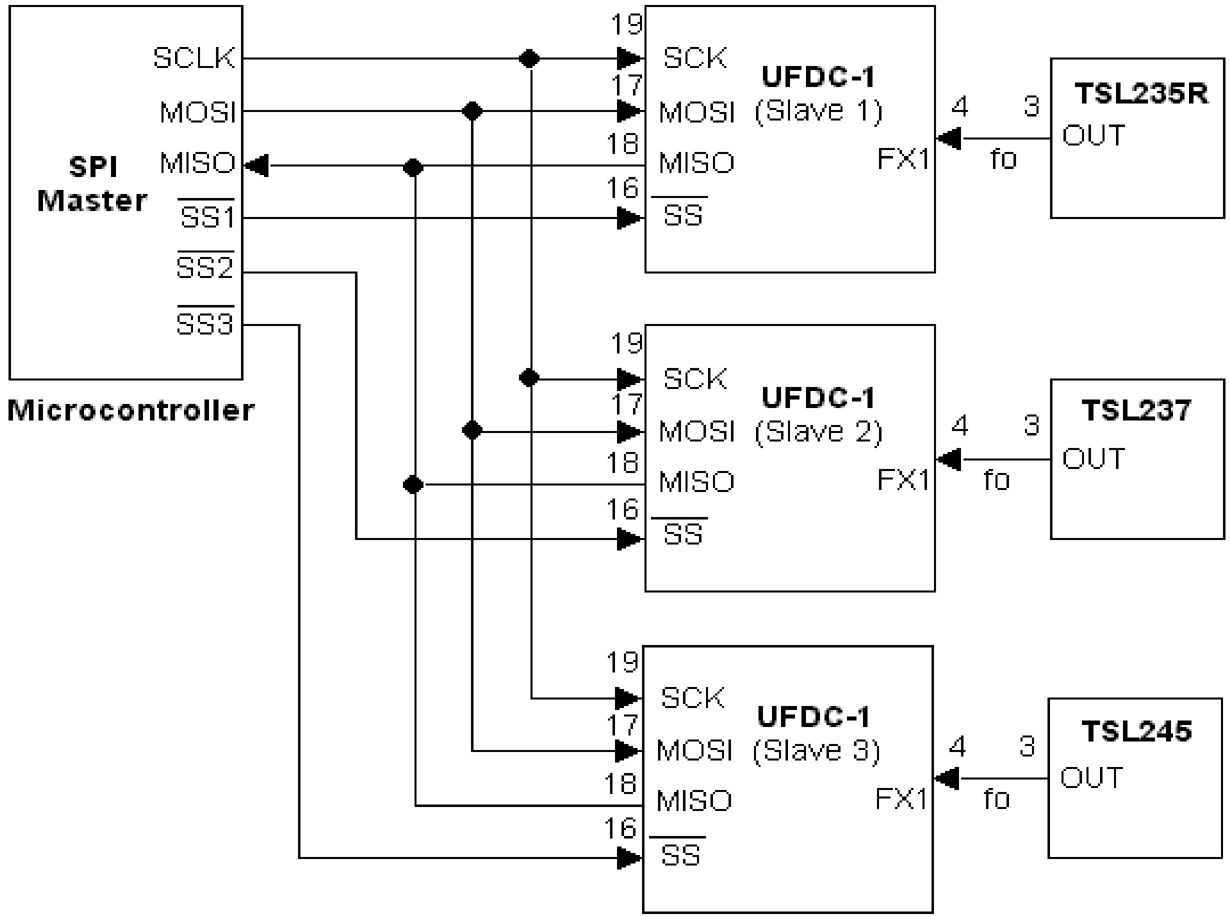
<06><00> ; Frequency measurement initialization

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

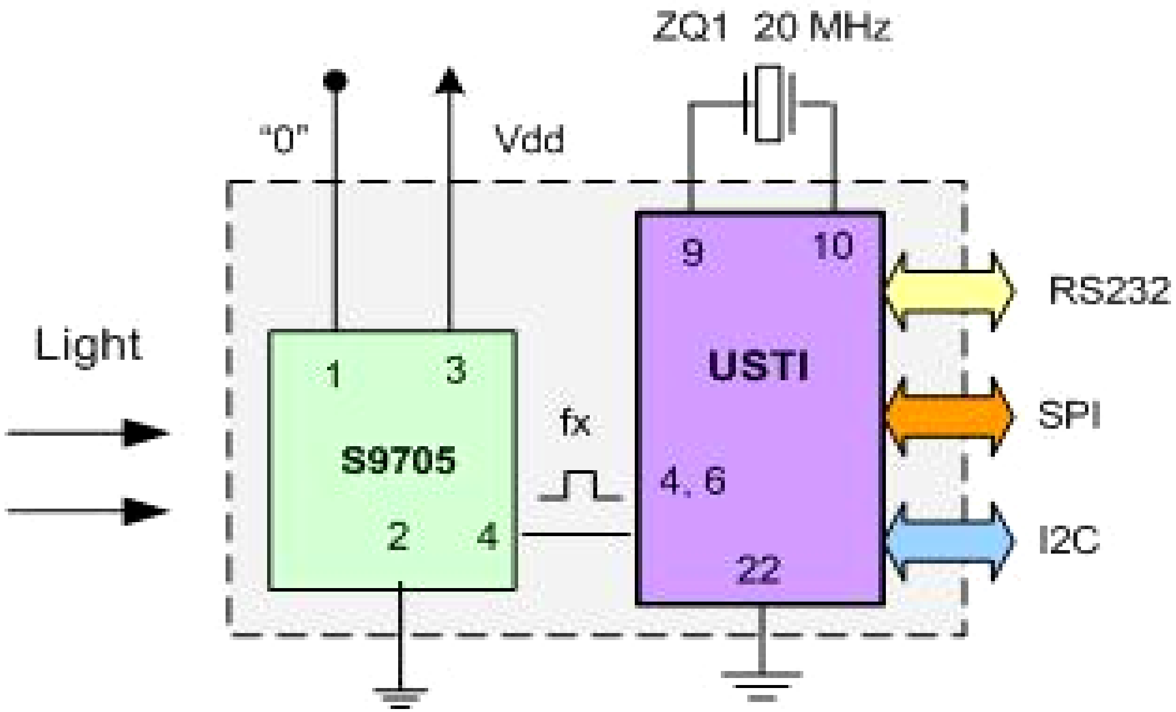
<09> ; Start a measurement

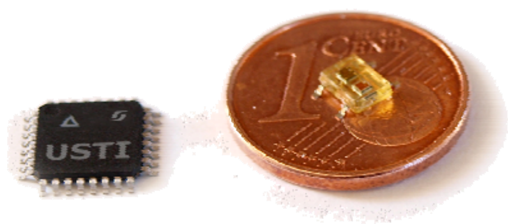
<07> ; Get measurement result in BCD format

SPI Interface to TAOS Opto Sensors



Optoelectronic Sensor System

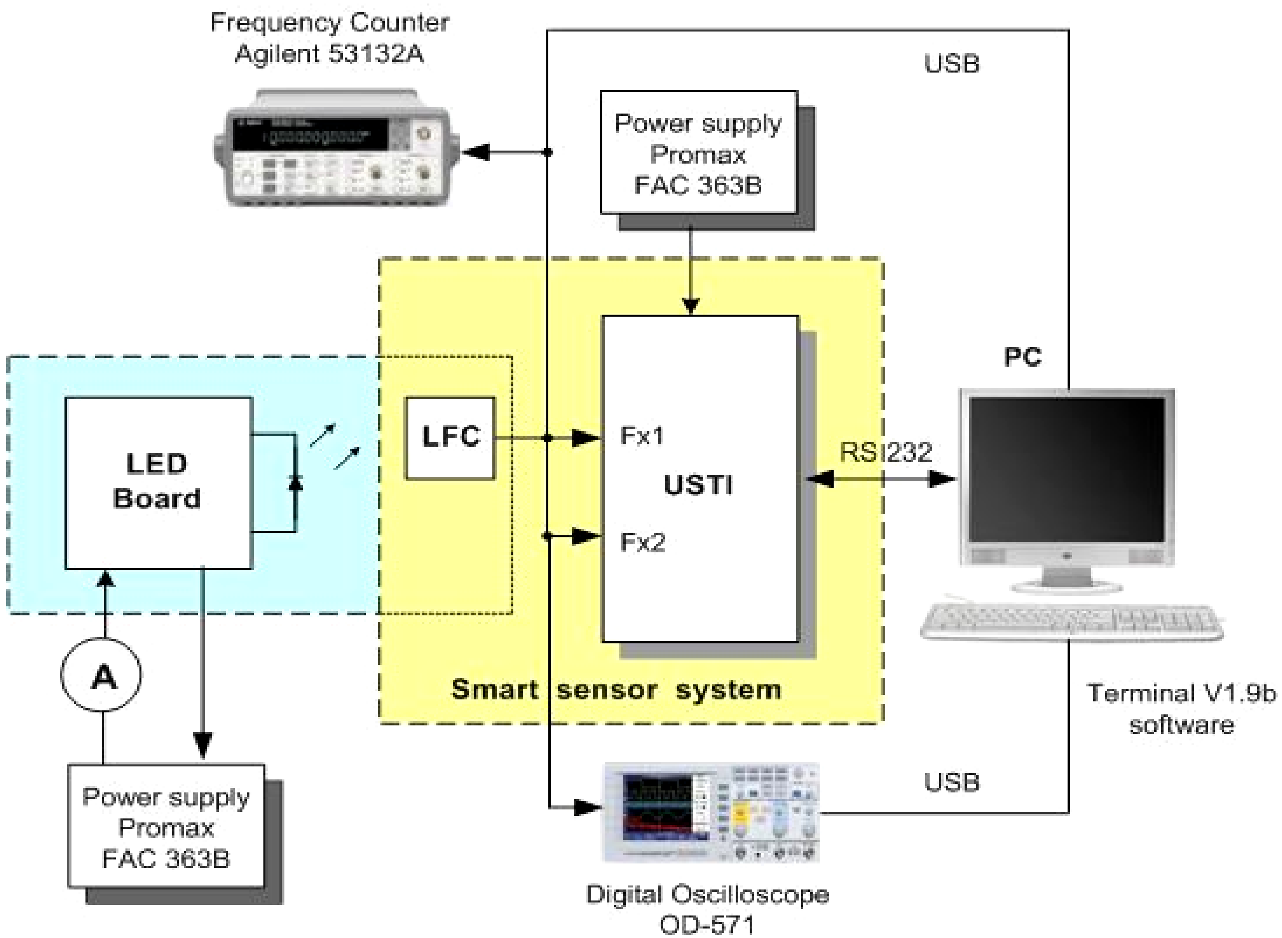




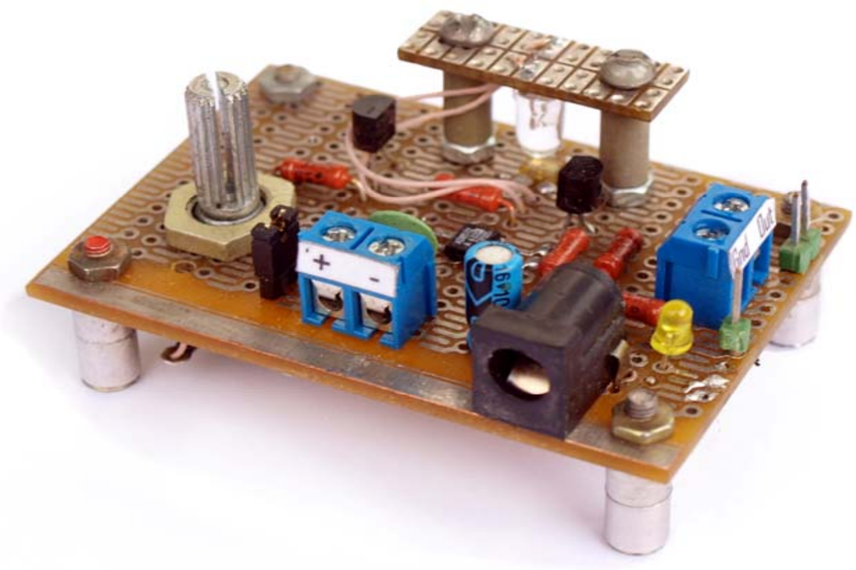
Commands for RS232 Communication Mode

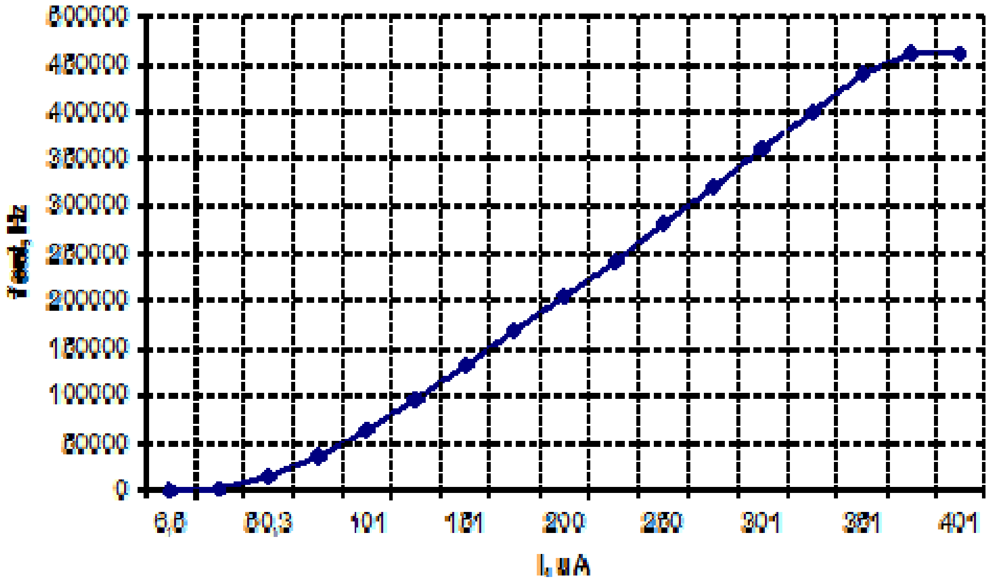
```
>A02   ;Set the relative error 0.25 %
>M00   ;Set up a frequency measurement mode in the 1st channel
>S     ;Start a frequency measurement (light sensor)
>C     ;Check the measurement status (‘r’-ready, ‘b’ -in progress
>R     ;Read a result of frequency measurement in Hz
>462987.345

>M0E   ;Set  up a frequency measurement mode in the 2nd channel
>S     ;Start a frequency measurement (colour sensor)
>C     ;Check the measurement status (‘r’ -ready, ‘b’-in progress
>R     ;Read a result of frequency measurement in Hz
>37005.0119
```

Measuring Set-up

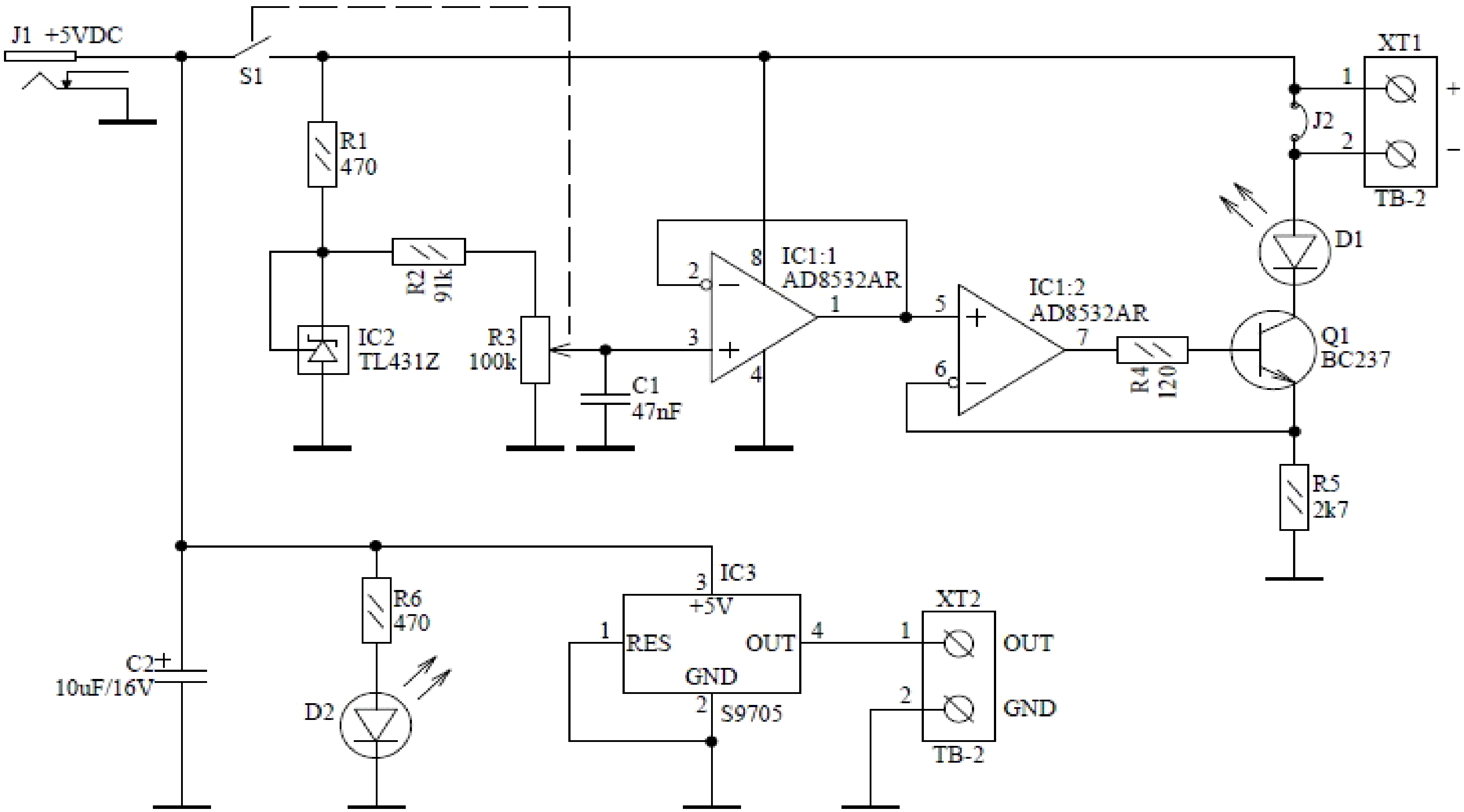


LED Evaluation Board

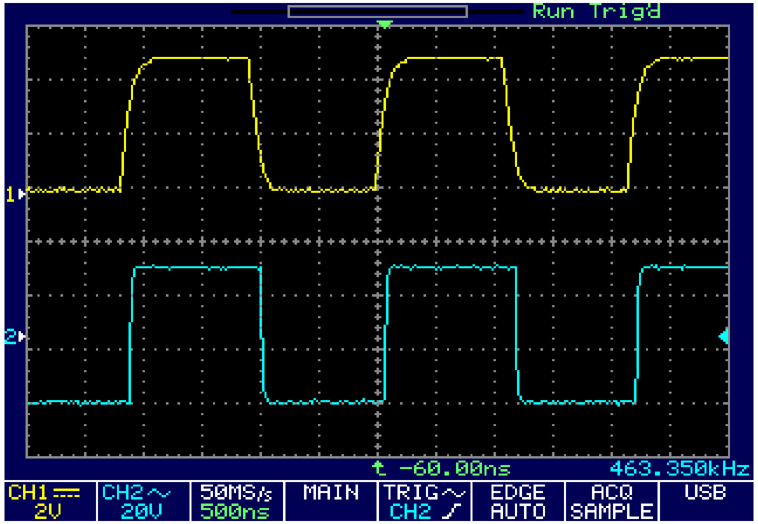


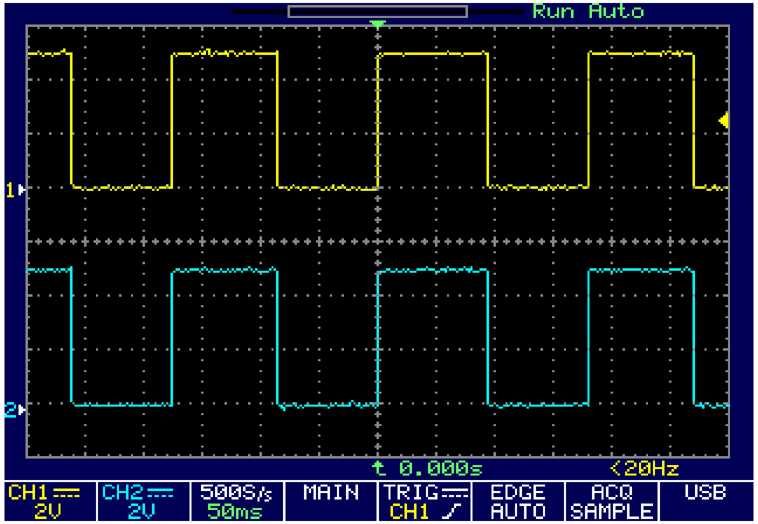


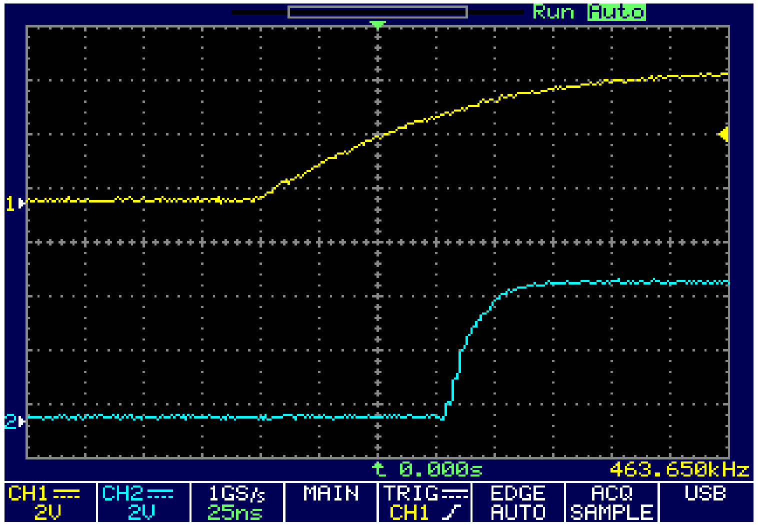
LED Evaluation Board Circuit Diagram

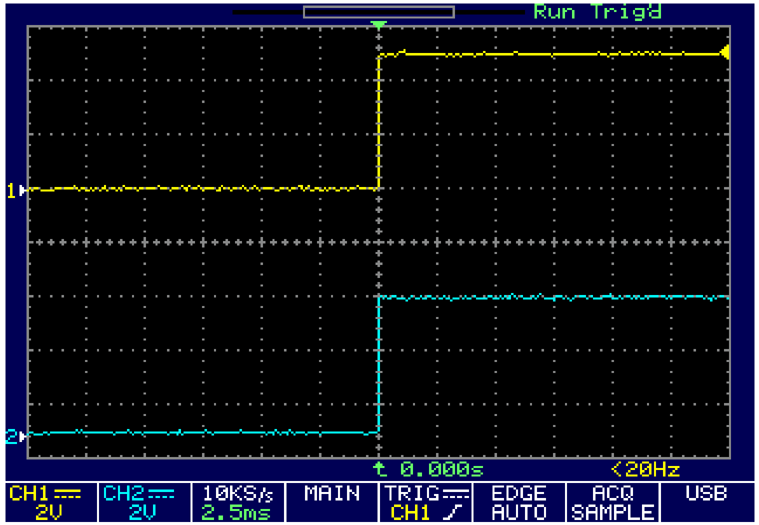


LFC's Oscillograms

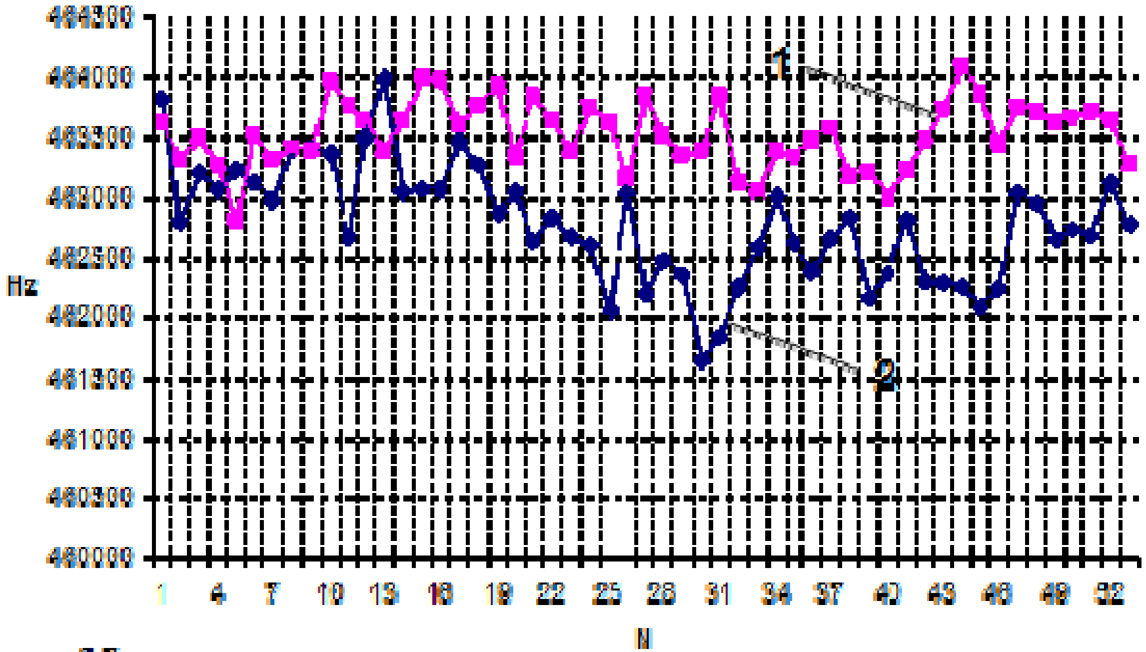


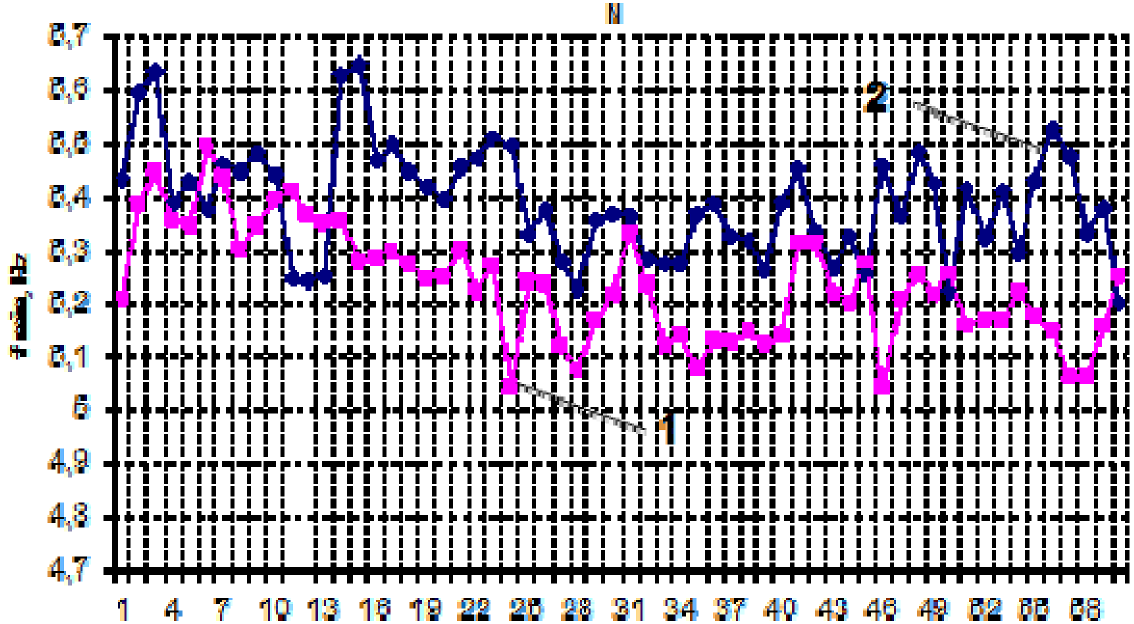






Experimental Results





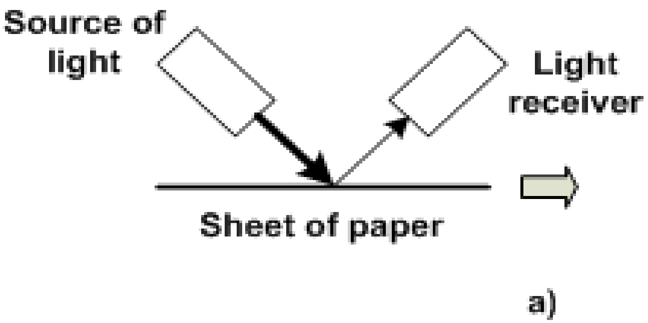
Statistical Characteristics (~ 463 kHz)

Parameter	463 kHz	
	Without Schmidt trigger	With Schmidt trigger (74HC14D)
Number of measurements, *N*	53	60
Minimum f_x (min)	461653.265	464151.555
Maximum f_x (max)	463991.336	0.0062
Sampling Range, f_x (max) - f_x (min)	2338.0705	1354.2603
Arithmetic Mean	462788.685	463572.681
Variance	234229.738	6.6E-0009
Standard Deviation	483.9729	283.4972
Coefficient of Variation	956.2286	1635.1932
Confidence interval for arithmetic mean at *P*=97 %	$462644.42 < f_x < 462932.95$	$463493.257 < f_x < 463652.105$
Relative error, %	0.014	0.16
χ^2 – test (S) at: k=6; *P* = 97 % χ^2_{max} = 8.9	1.7272	2.5423
Hypothesis about Gaussian distribution	Accepted	Accepted

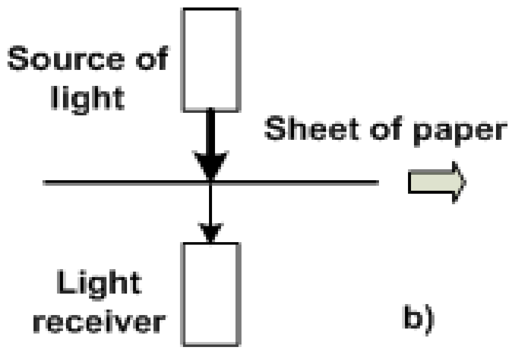
Statistical Characteristics (~ 5 Hz)

Parameter	5 Hz	
	Without Schmidt trigger	With Schmidt trigger (74HC14D)
Number of measurements, *N*	60	60
Minimum f_x (min)	5.2014	5.041
Maximum f_x (max)	5.6466	5.4959
Sampling Range, f_x (max) - f_x (min)	0.4452	0.454
Arithmetic Mean	5.3899	5.236
Variance	0.0109	0.1071
Standard Deviation	0.1045	0.0001
Coefficient of Variation	51.577	48.907
Confidence interval for arithmetic mean at *P*=97 %	$5.3606 < f_x < 5.4192$	$5.206 < f_x < 5.266$
Relative error, %	0.54	0.57
χ^2 – test (S) at: k=6; *P* = 97 % χ^2_{max} = 8.9	6.6726	1.8498
Hypothesis about Gaussian distribution	Accepted	Accepted

Paper Type Detection

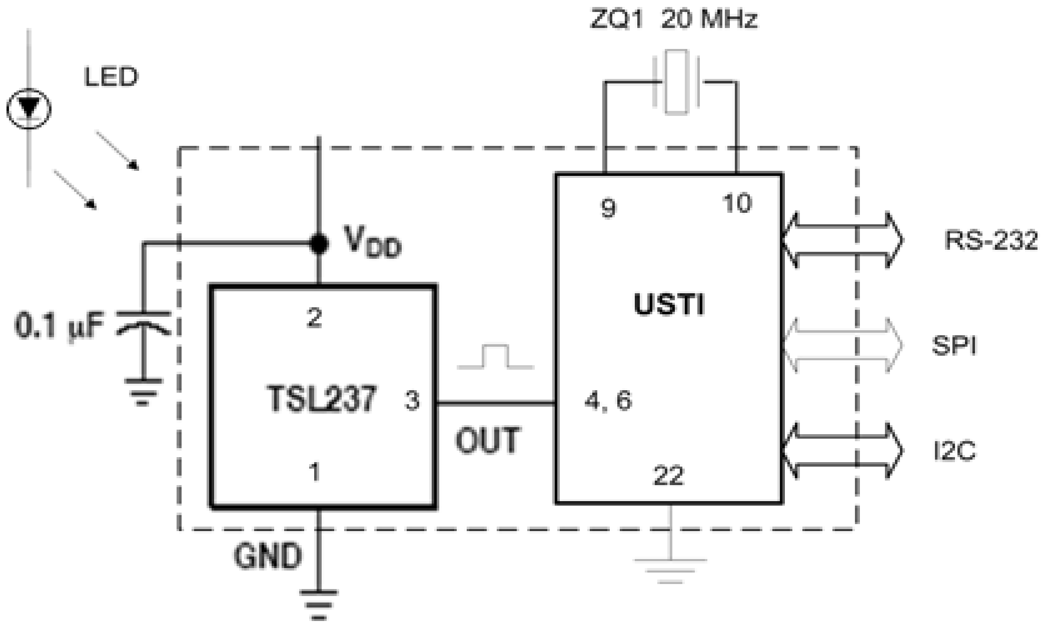


- Reflective type sensor



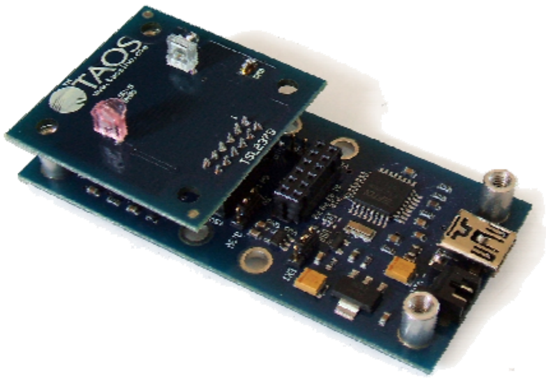
- Transmission type sensor

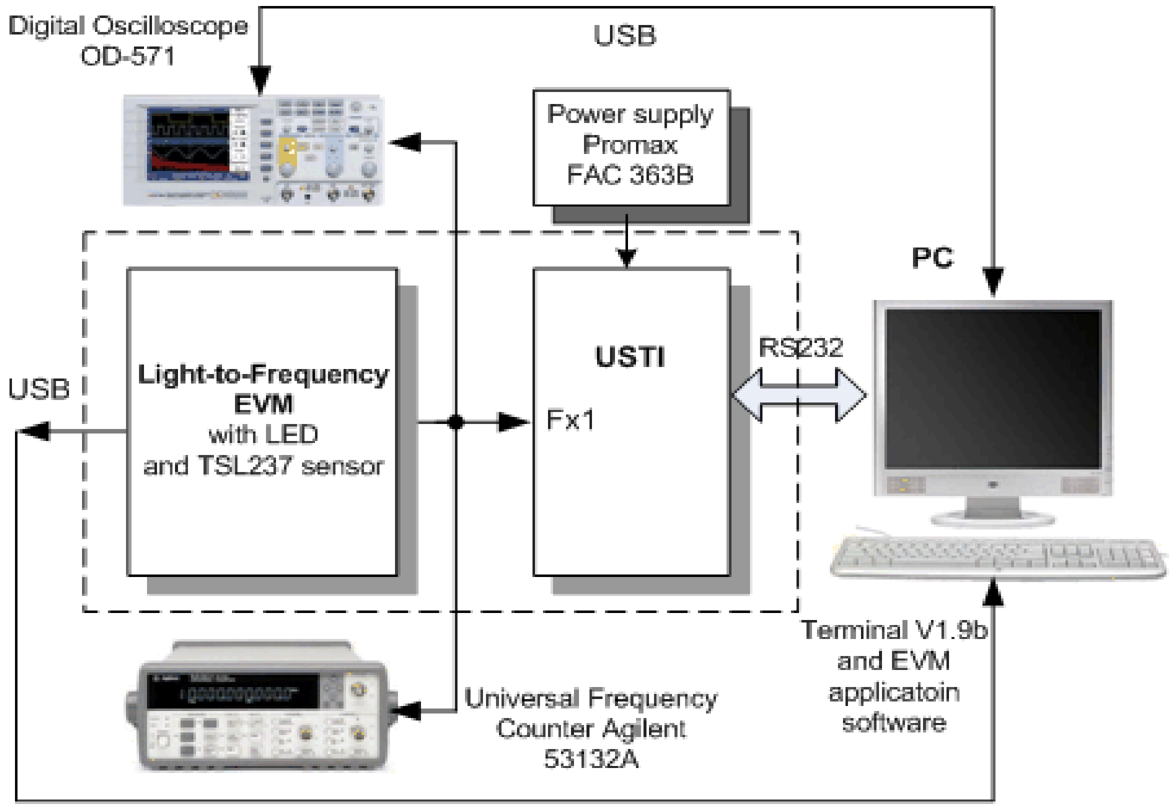
Paper Thickness Sensor System



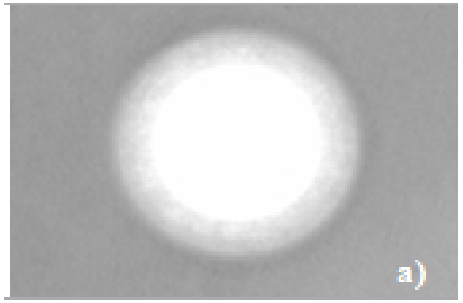
1. Light sensor TSL237
2. LED
3. USTI

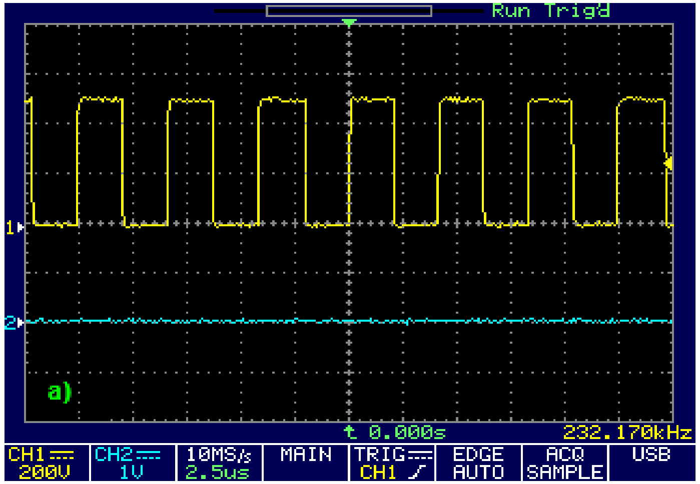
Measurement Set-up for Sensor System Investigation

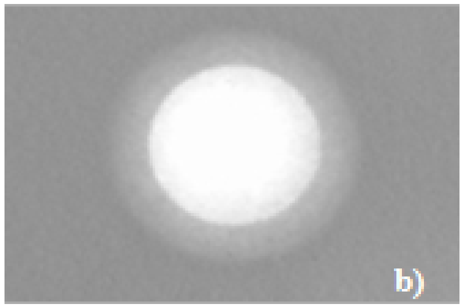


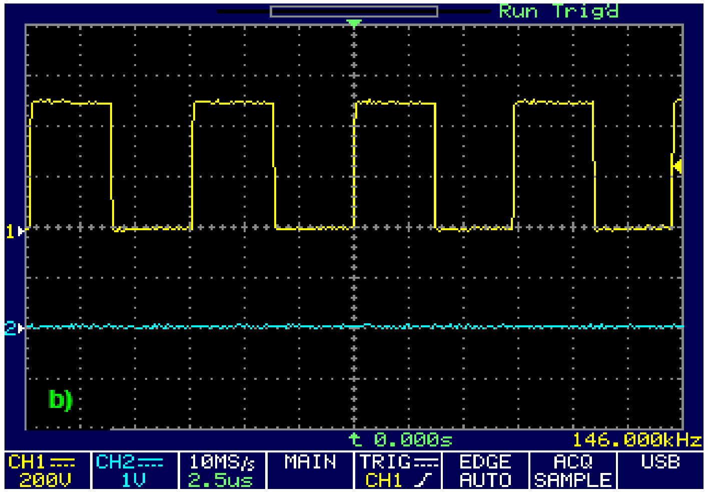


Sensor Output Signals at 0.086 mm (a), and 0.217 mm

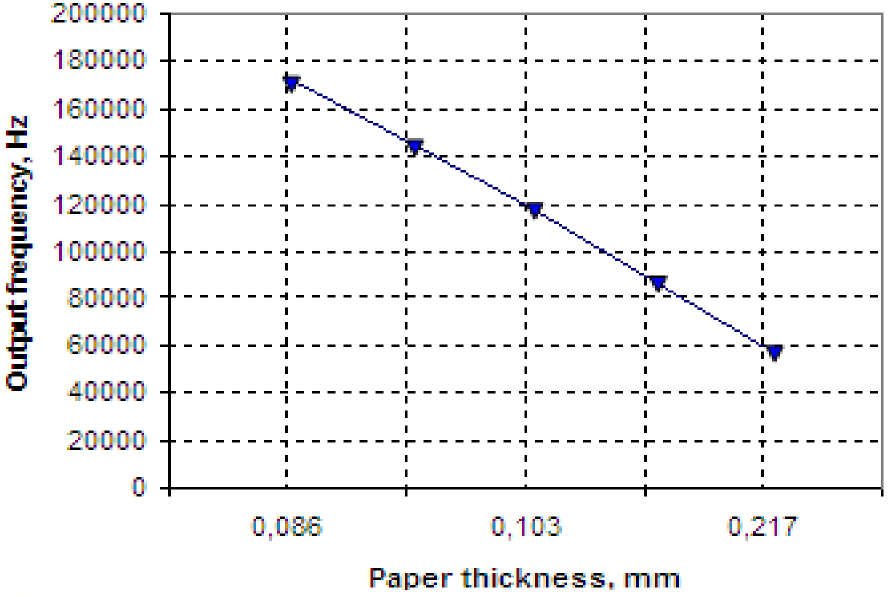


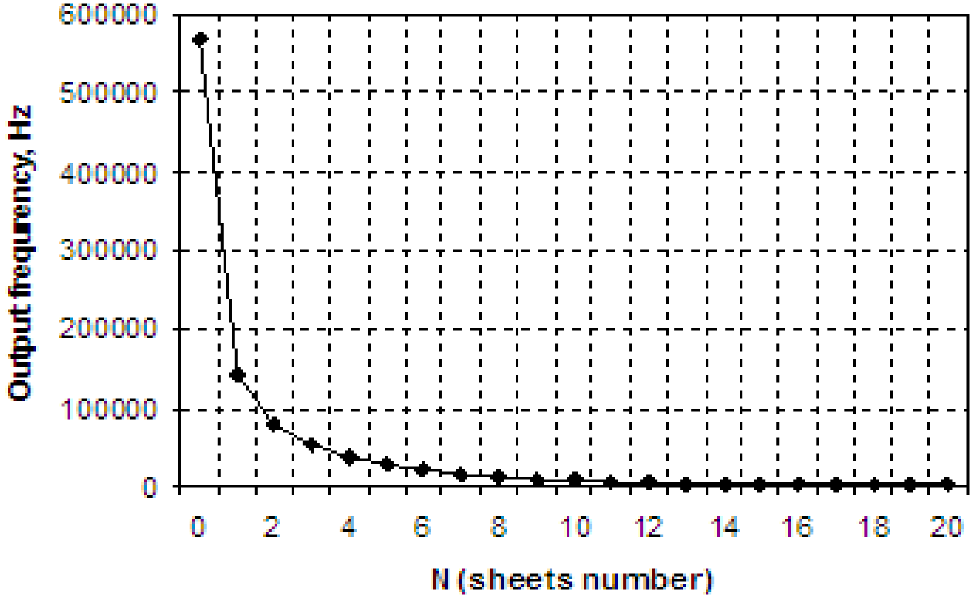






Experimental Results

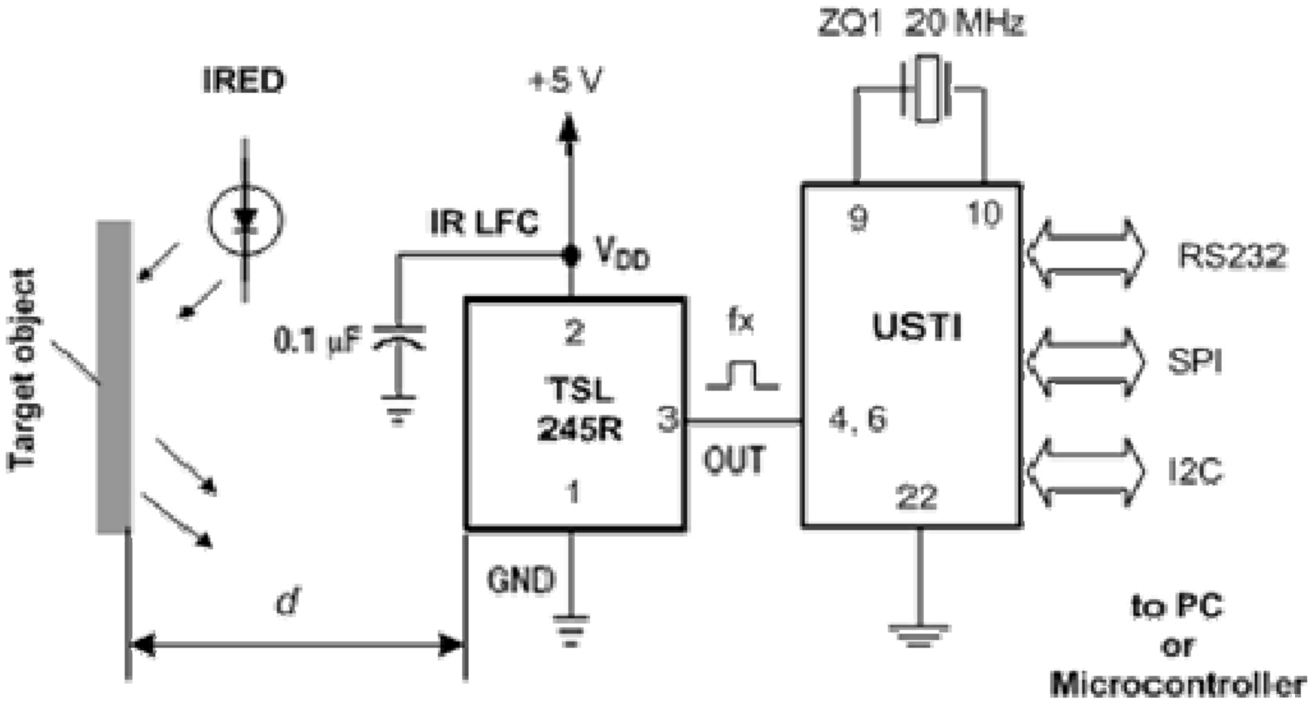




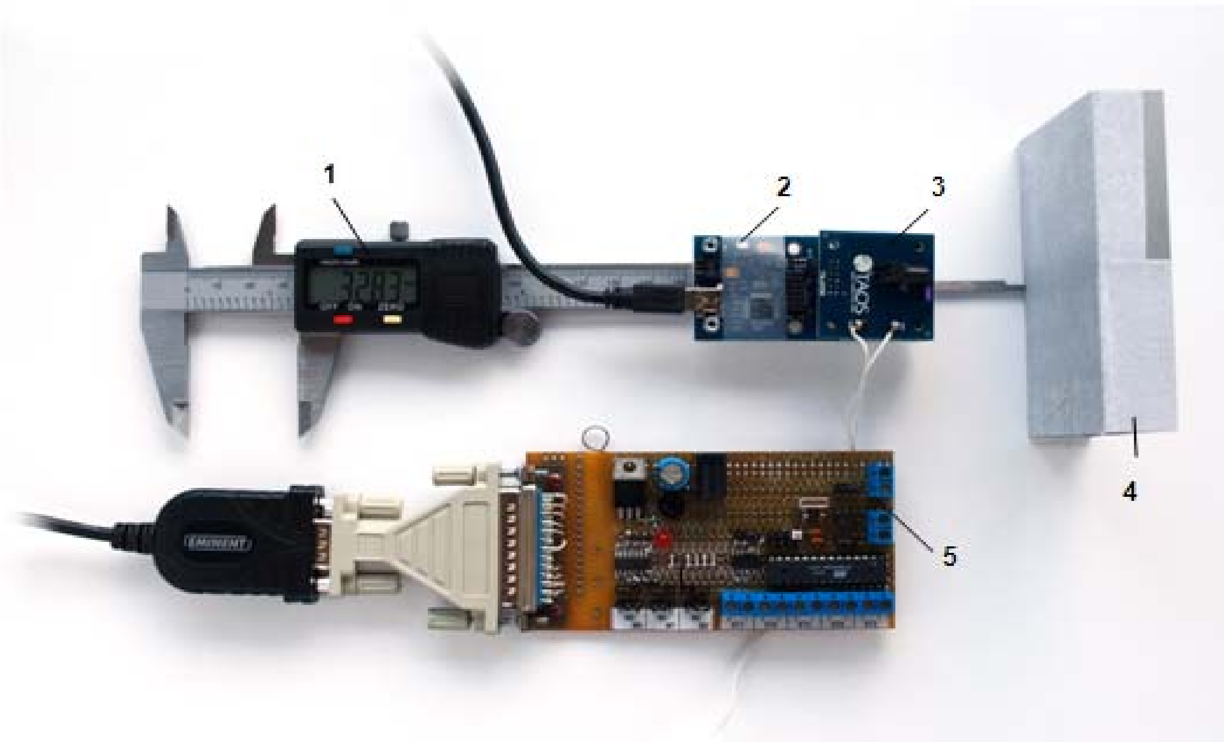
N	1	2	3	4	5	6	7	8	9	10
f_x, Hz	143000	81100	55500	39400	29500	22400	17350	12600	10350	8300

N	11	12	13	14	15	16	17	18	19	20
f_x, Hz	6900	5800	4600	3980	3400	2850	2510	2150	2000	1900

Non-Contact, Short Distance Measuring System

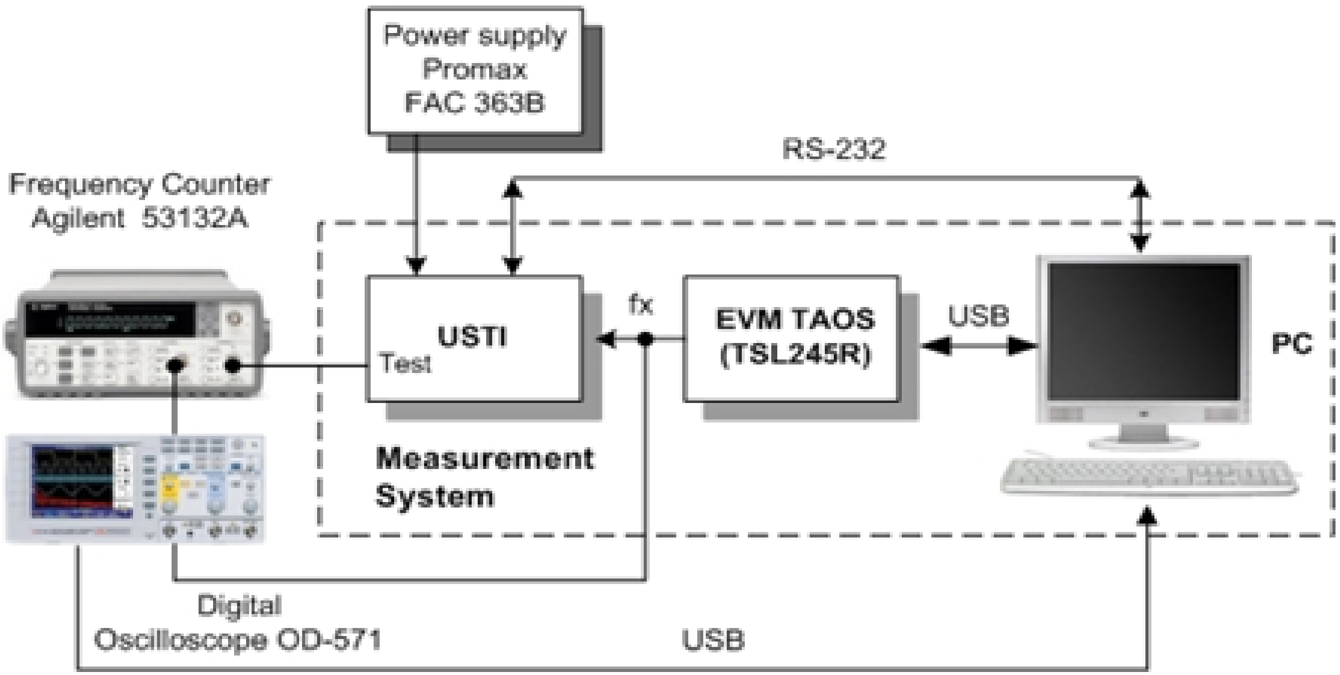


Sensor System Prototype

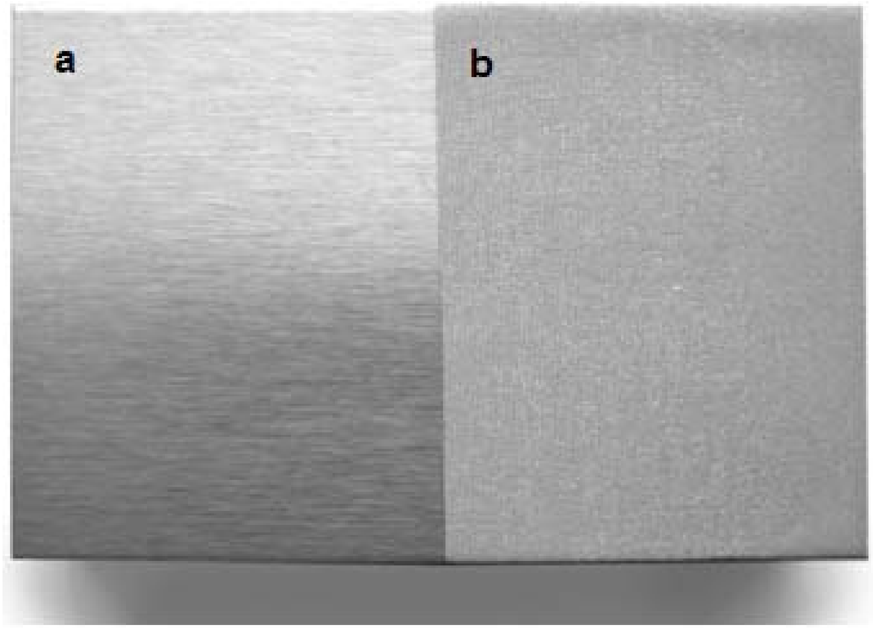


1-Electronic digital caliper Z22855 Powerfix; 2-LTF EVM motherboard
3-TAOS LTF EVM TSL245R daughterboard; 4-Target object;
5-USTI Evaluation Board

Measurement Set-up for Experimental Investigation



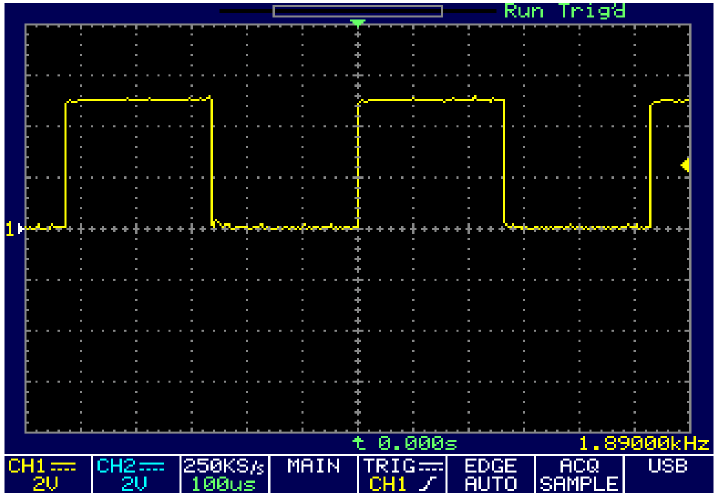
Targeted Objects

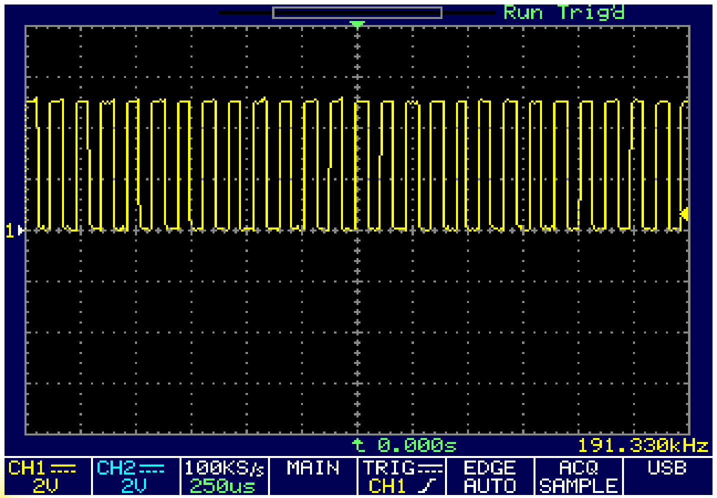


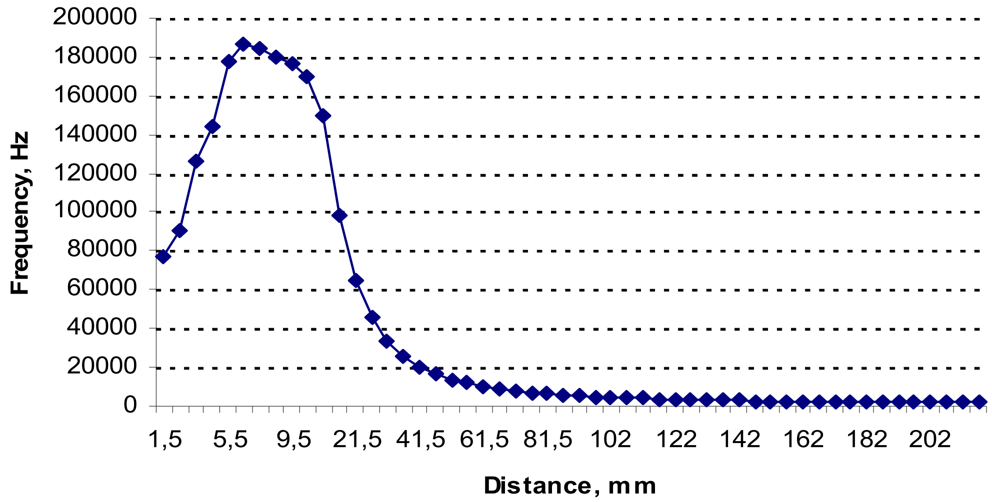
a) Duraluminium surface

b) Standard Calibration Reflective Surface: 18 % reflective gray paper

Experimental Results

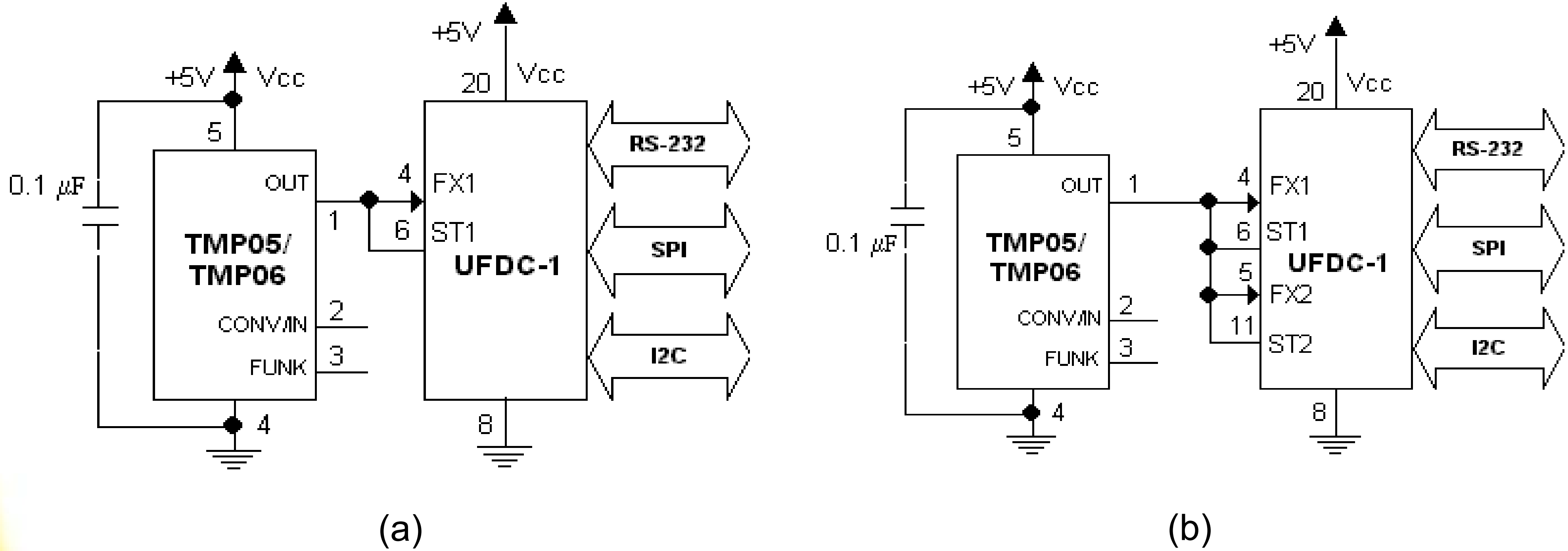






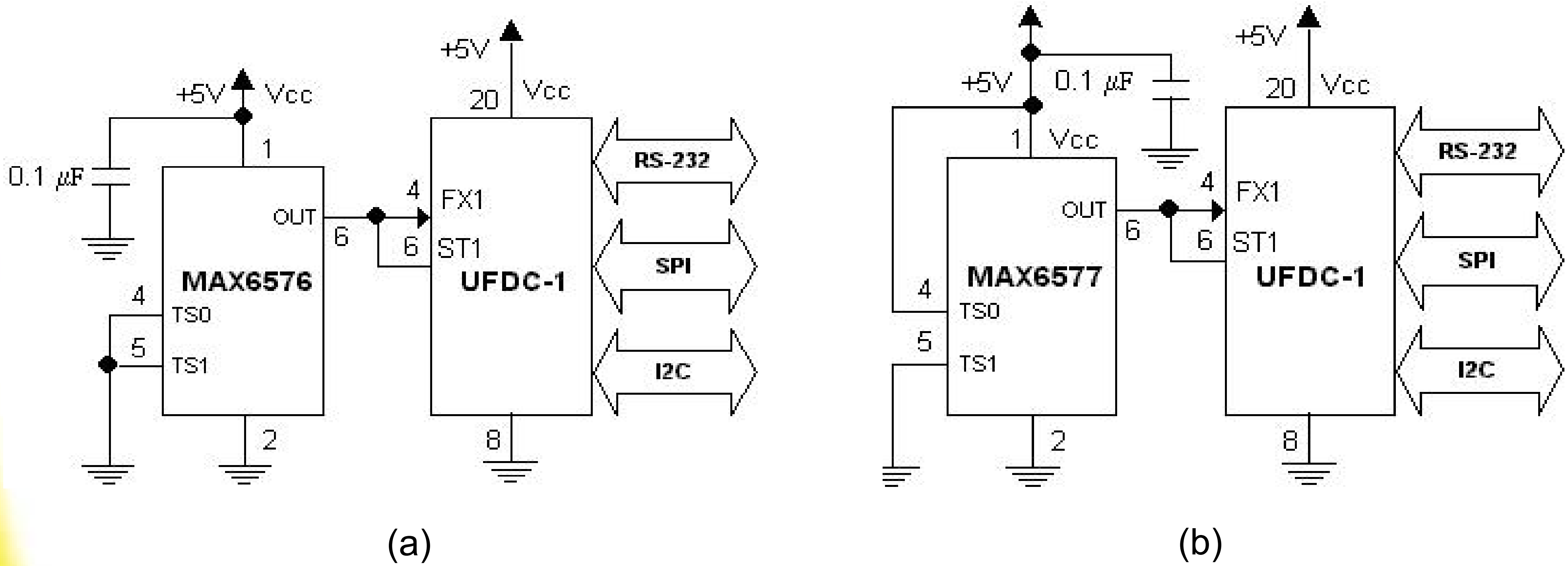
- Measurement range, 1.5 to 215 mm
- Frequency output ~1.8 to 190 kHz
- Resolution 0.01 mm
- Response 34 Hz/0.01 mm at 75 mm
- Decreased in 9.5 …38 times measuring time in comparison with 0.25 to 1 s in standard systems

TMP05/TMP06 Sensors Interfacing



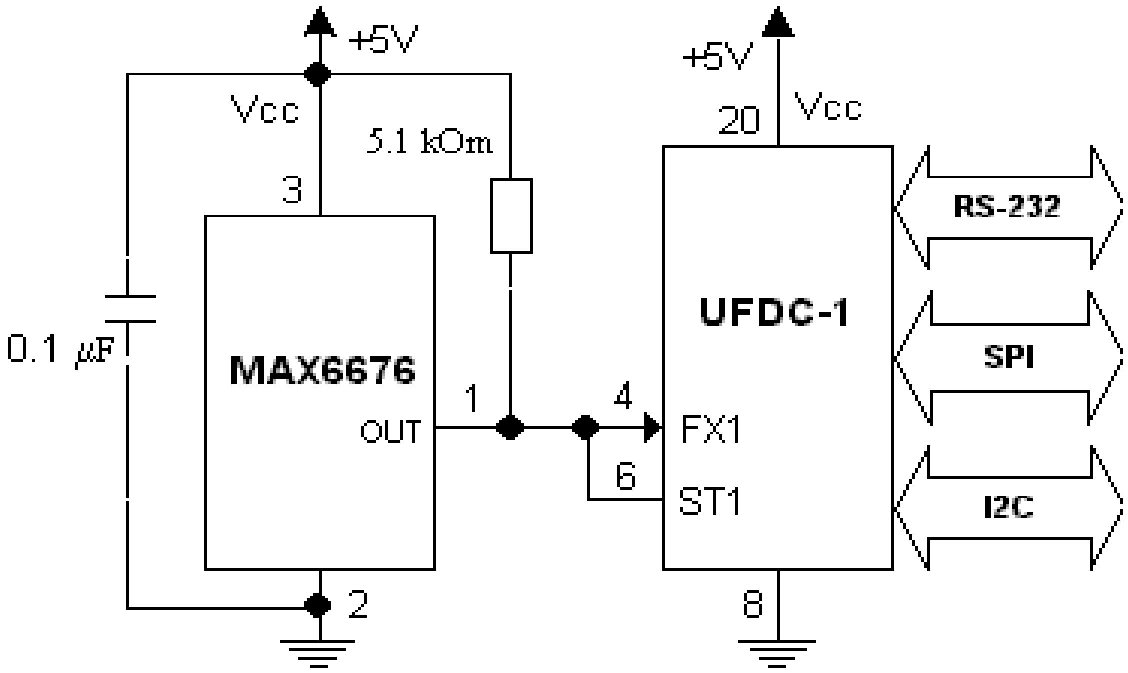
TMP05/TMP06 interfacing: T1 and T2 time intervals measurement (a), and period (T1+T2) and space interval (T2) measurement (b)

MAXIM Temperature Sensors Interfacing (I)



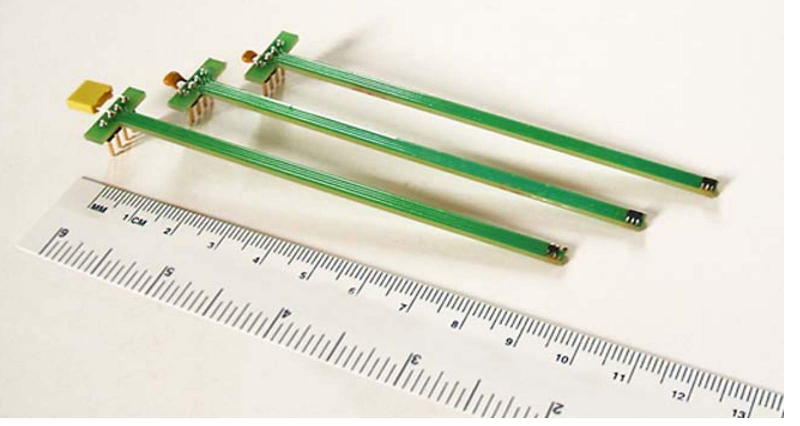
MAX6576 period output sensor interfacing (a) and MAX6577 frequency output sensor interfacing (b)

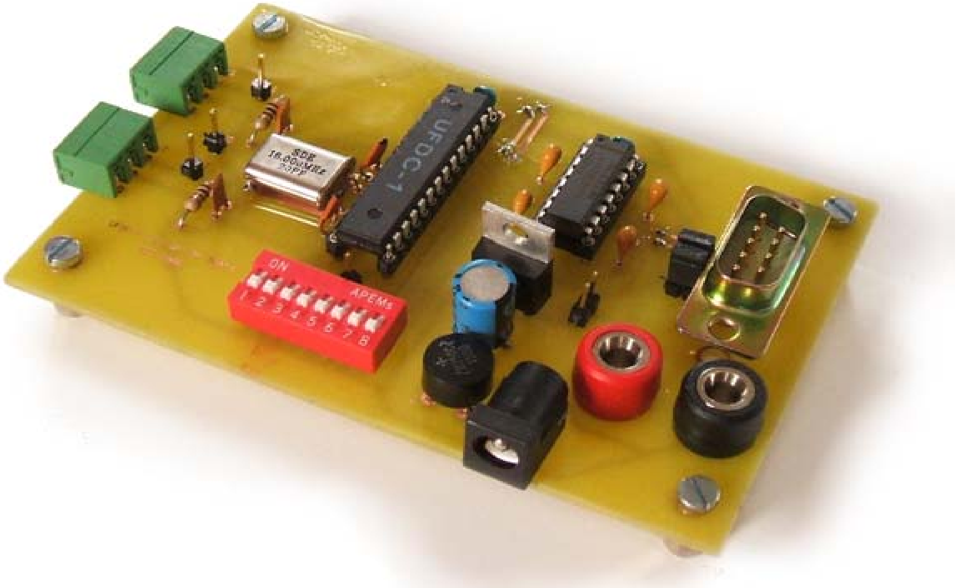
MAXIM Temperature Sensors Interfacing (II)



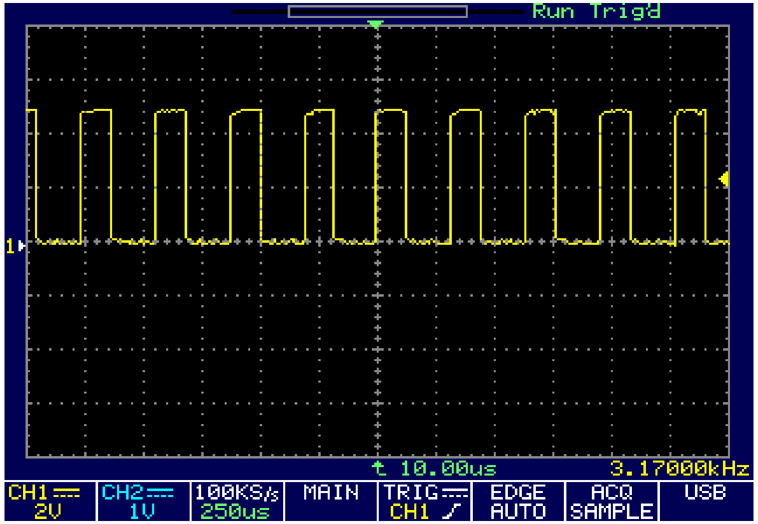
MAX6676 to UFDC-1 interfacing functional diagram

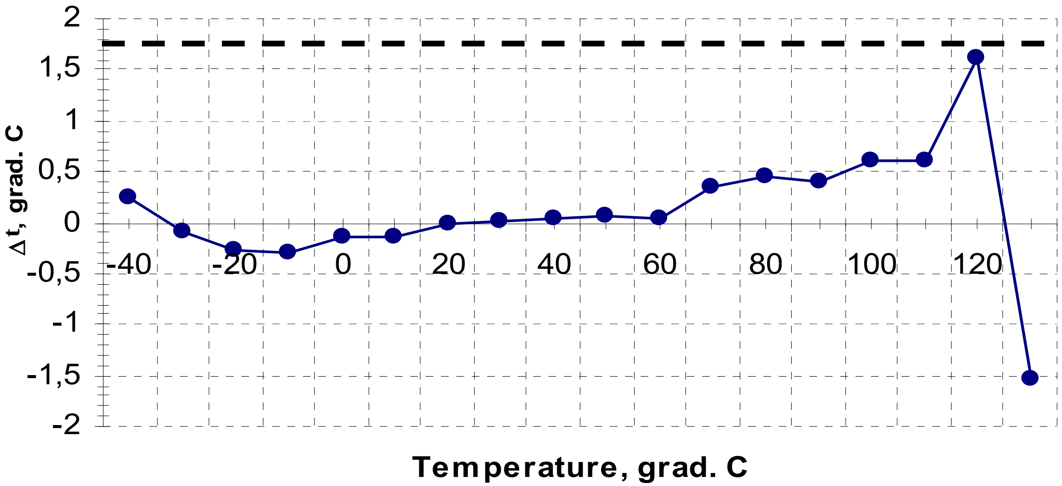
Low Cost Temperature Sensor System

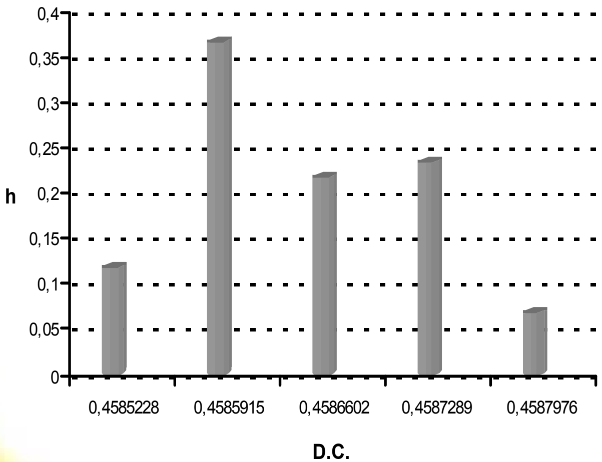




Experimental Results

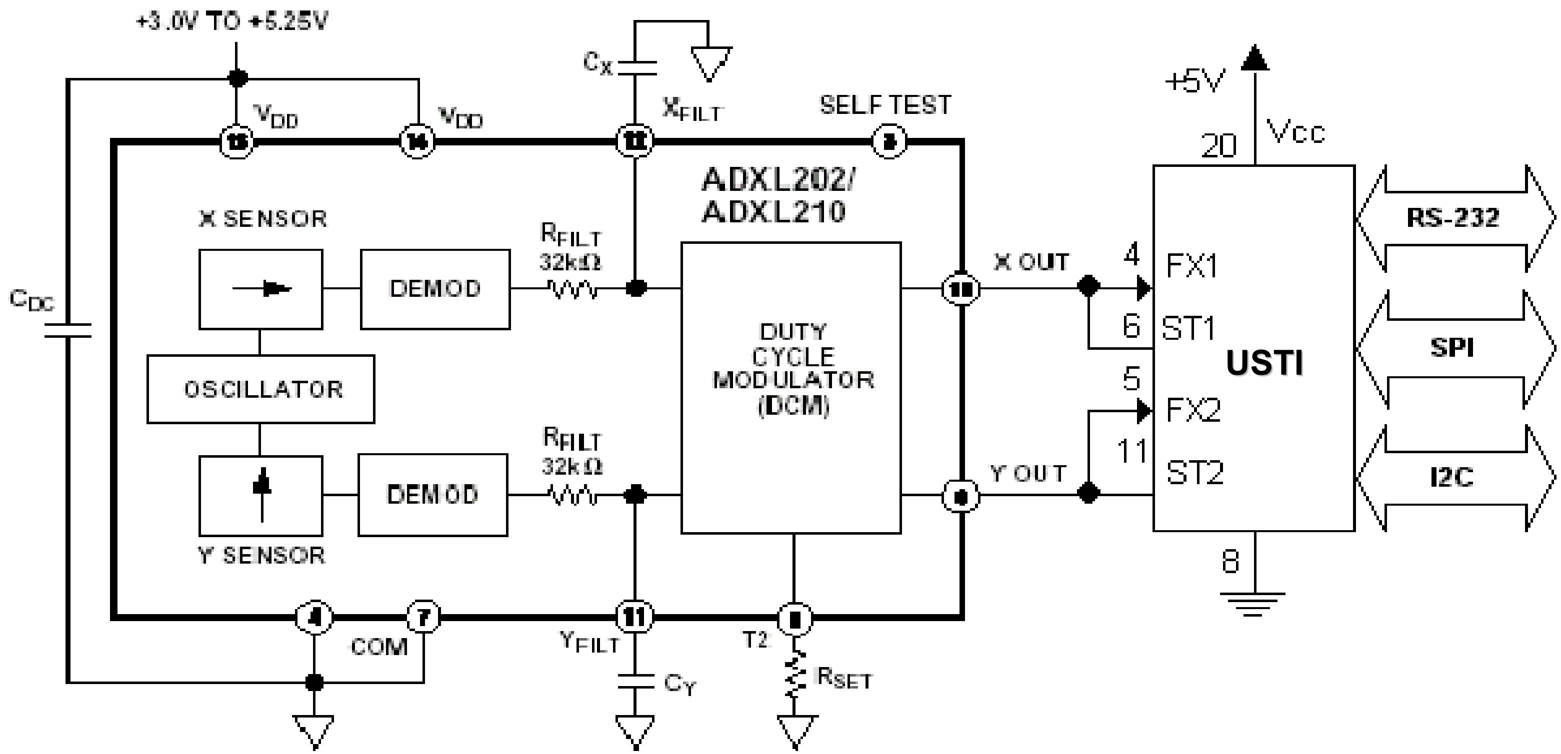






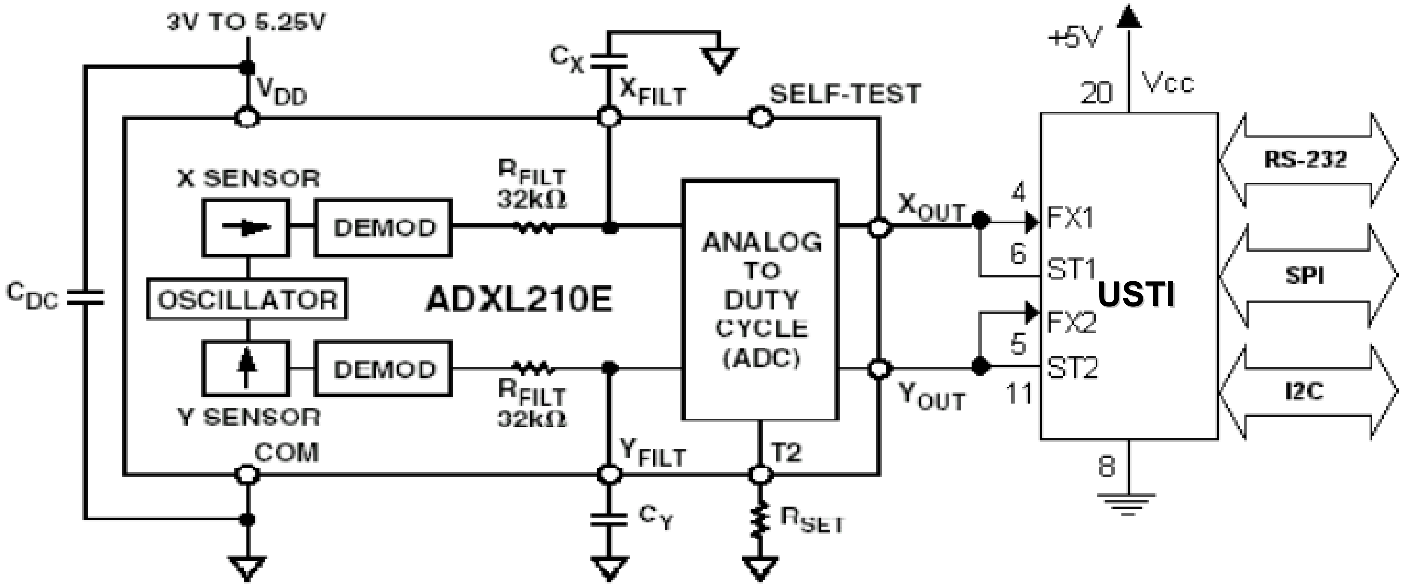
Parameter	Duty-cycle, %
Number of measurements, *N*	60
Minimum *D.C.* (min)	0.4585
Maximum *D.C.* (max)	0.4588
Sampling Range, *D.C.* (max)- *D.C.* (min)	0.0003
Median	0
Arithmetic Mean	0.4586
Variance	6.6E-0009
Standard Deviation	0.0001
Coefficient of Variation	5666.7026
Relative error, %	0.044
Confidence interval	$0.4586 \le D.C. \le 0.4587$
χ^2 – test (S) at: k=5; P = 97 % χ^2max = 7.0	5.1699

Accelerometers Based Systems (I)



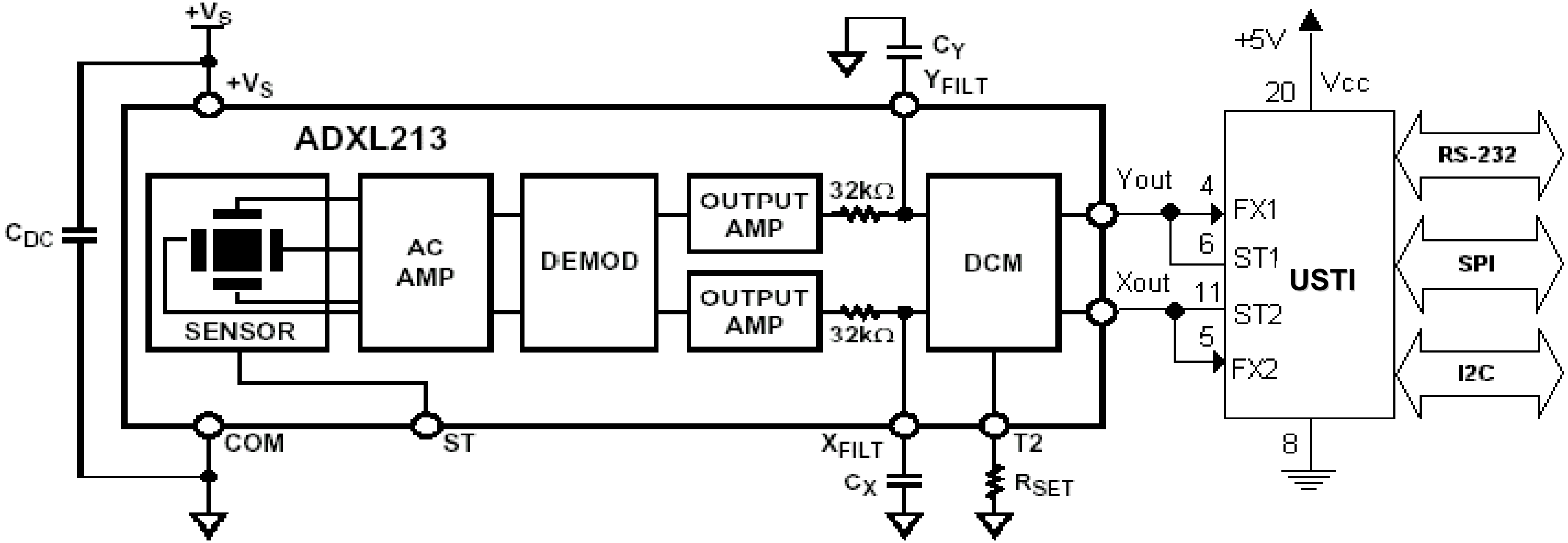
ADXL202 to USTI interfacing functional diagram

Accelerometers Based Systems (II)



ADXL210 to USTI interfacing functional diagram

Accelerometers Based Systems (III)

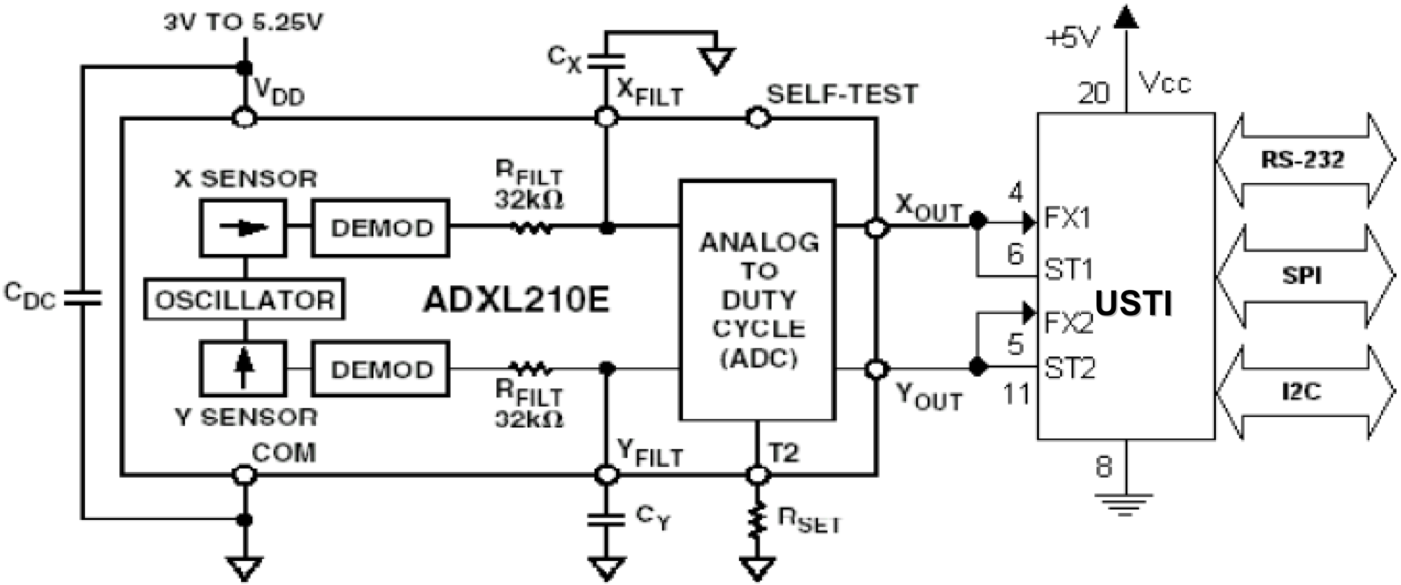


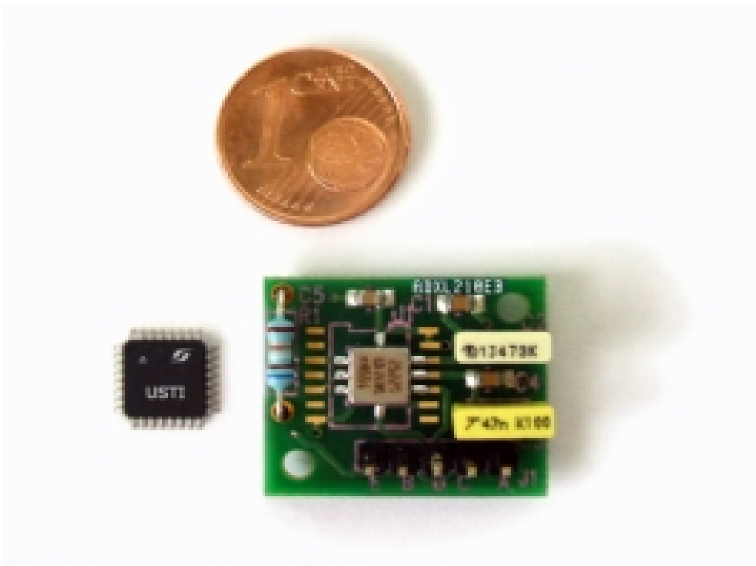
ADXL213 to USTI interfacing functional diagram

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

Dual-Axis Inclinometer



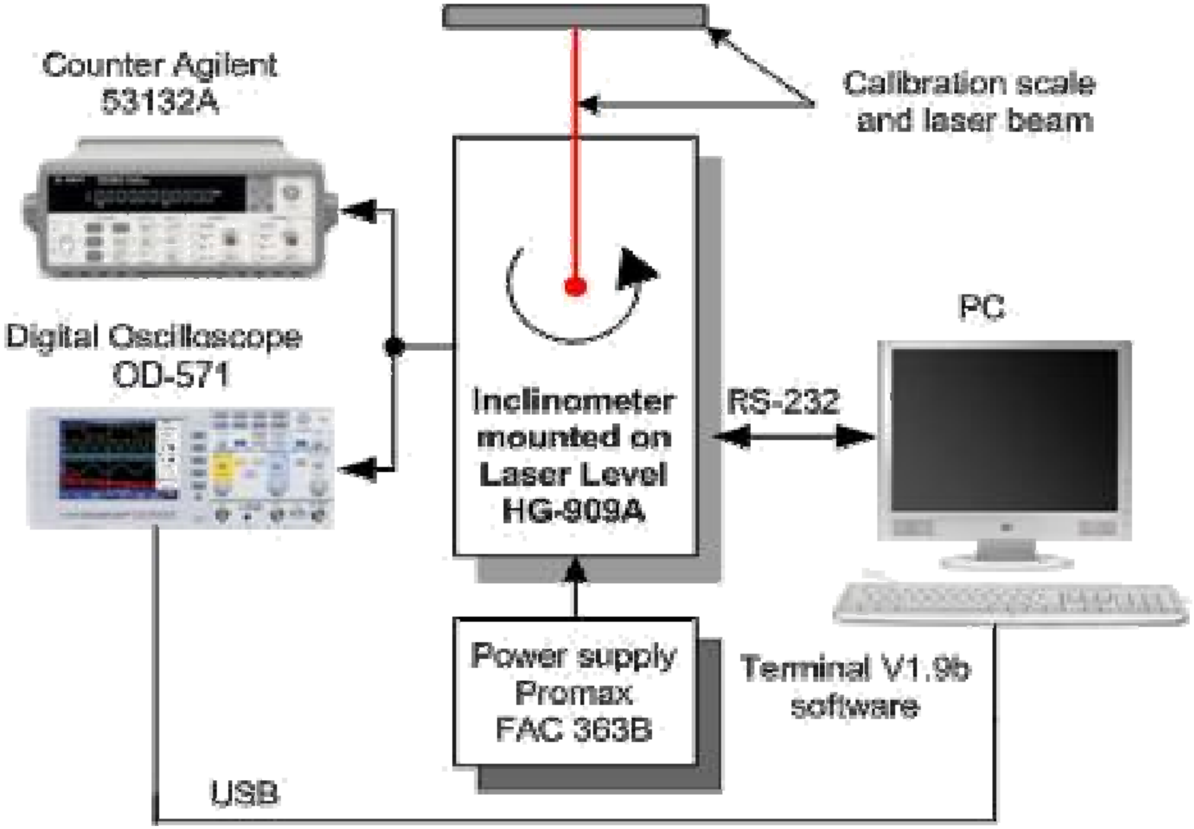


Commands for USTI

> M04 ; Duty-cycle measurement in the 1st channel
> S ; Start measurement
> R ; Read result

> M14 ; Duty-cycle measurement in the 2nd channel
> S ; Start measurement
> R ; Read result

Experimental Set-Up

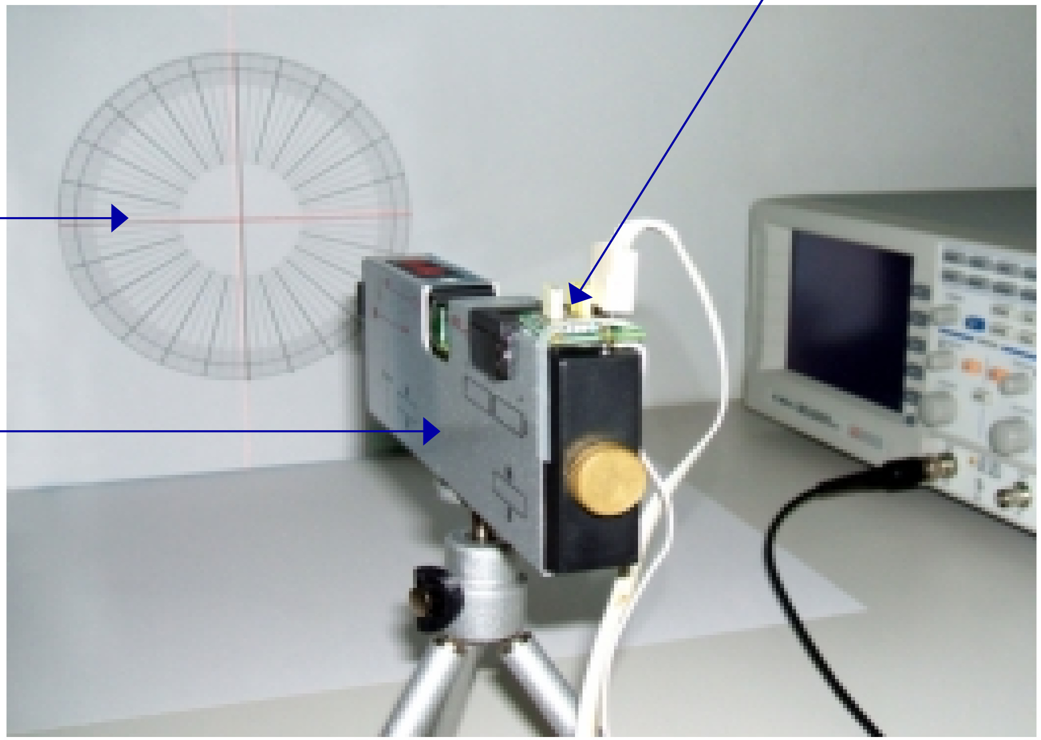


Calibration Set-Up

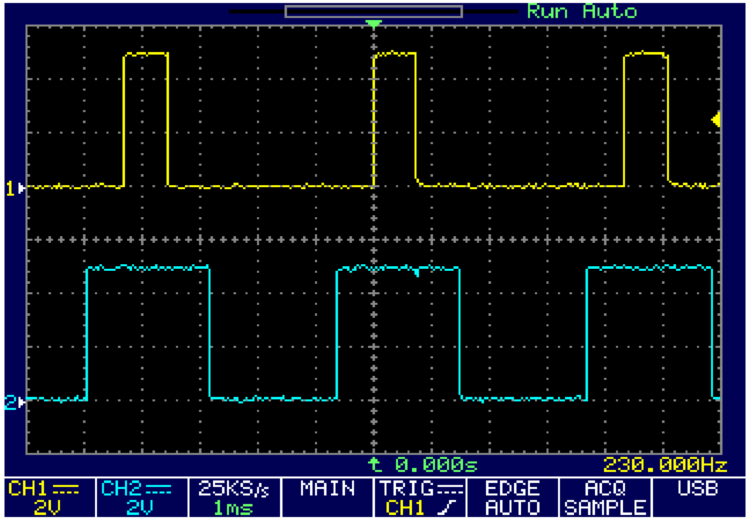
Inclinometer

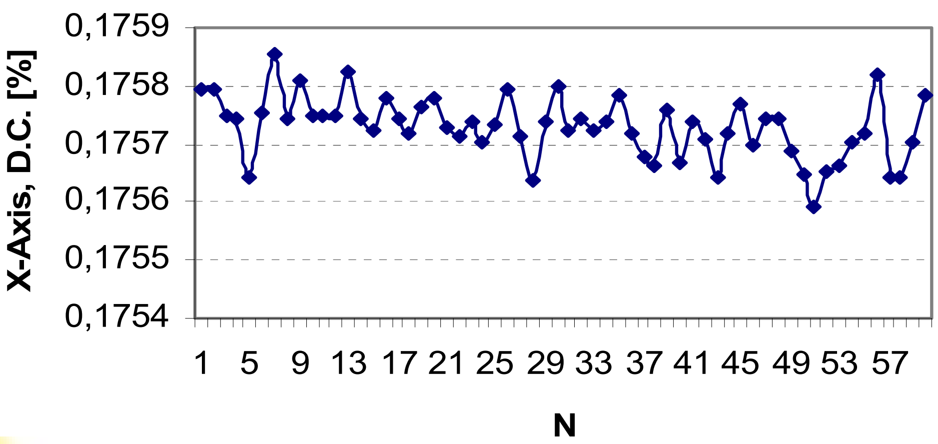
$0\text{-}360^0$ calibration scale-disc

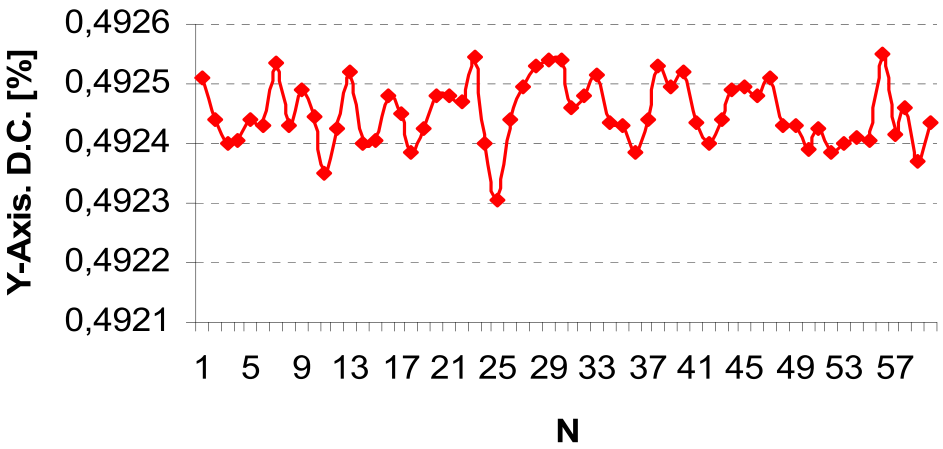
Laser level HG 909A



Experimental Results



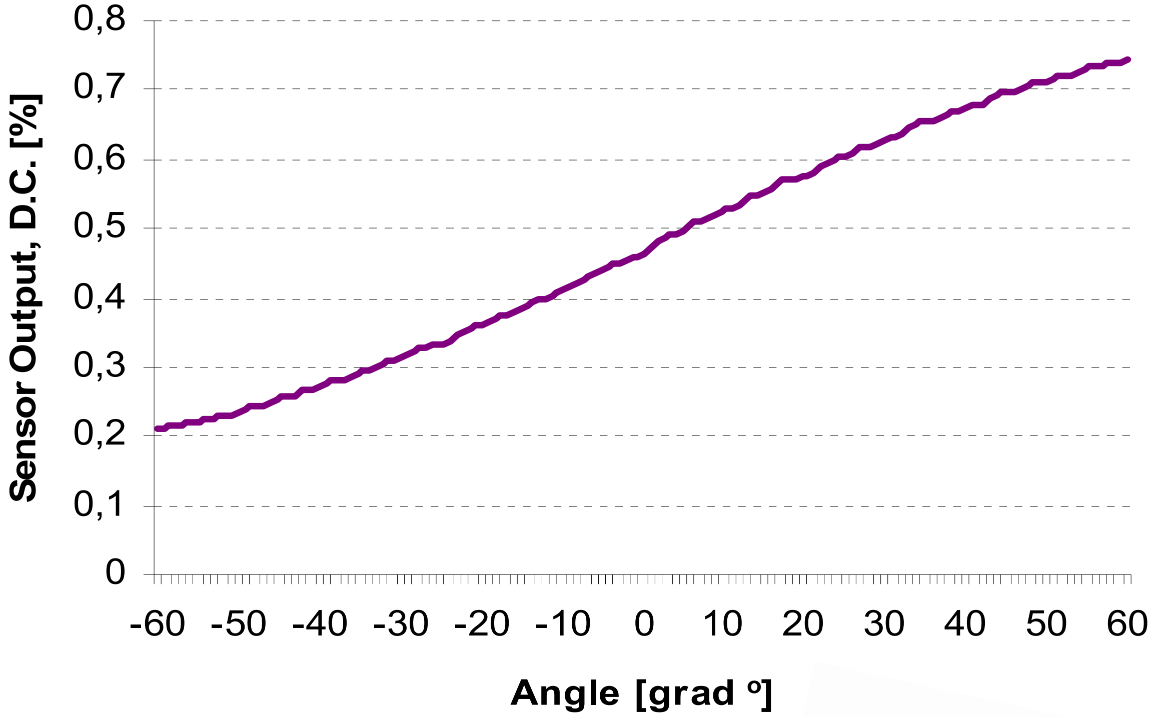


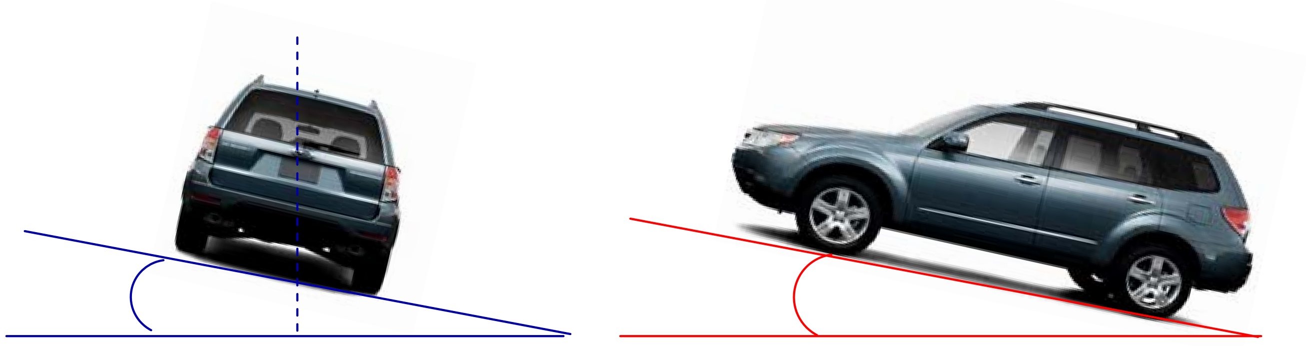


Statistical Characteristics

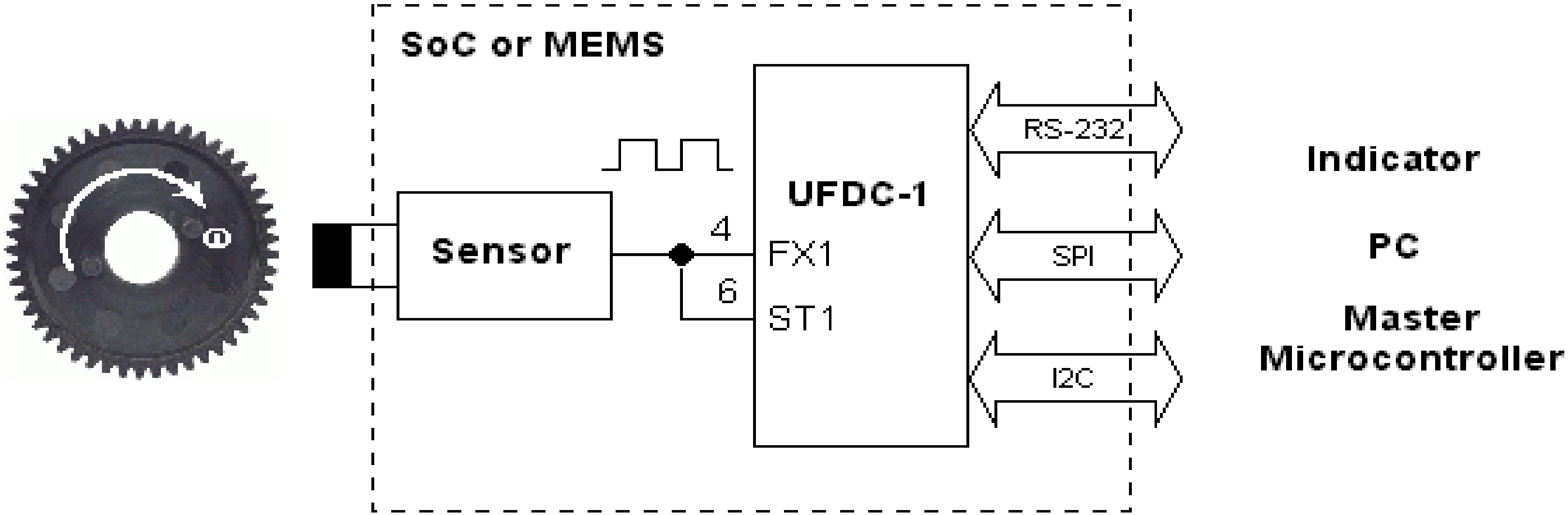
Parameter	Value	
	X-Axis	Y-Axis
Number of measurements, *N*	60	60
Minimum *D.C.* (min)	0.1756	0.4923
Maximum *D.C.* (max)	0.1759	0.4926
Sampling Range, *D.C.* (max)- *D.C.* (min), Hz	0.0003	0.0002
Median	0	0
Arithmetic Mean	0.1757	0.4925
Variance	2.8E-9	2.9E-9
Standard Deviation	0.0001	0.0001
Coefficient of Variation	3296.8533	9204.0289
Relative error, %	0.11	0.041
χ^2 – test (S) at: k=5; *P* = 97 % χ^2_{max} = 7.0	6.1584	4.084
Hypothesis about Gaussian distribution	S < χ^2_{max} (accepted)	S < χ^2_{max} (accepted)

Output Signal vs. Angle





Rotation Speed Smart Sensor



Commands Example (RS232)

>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*

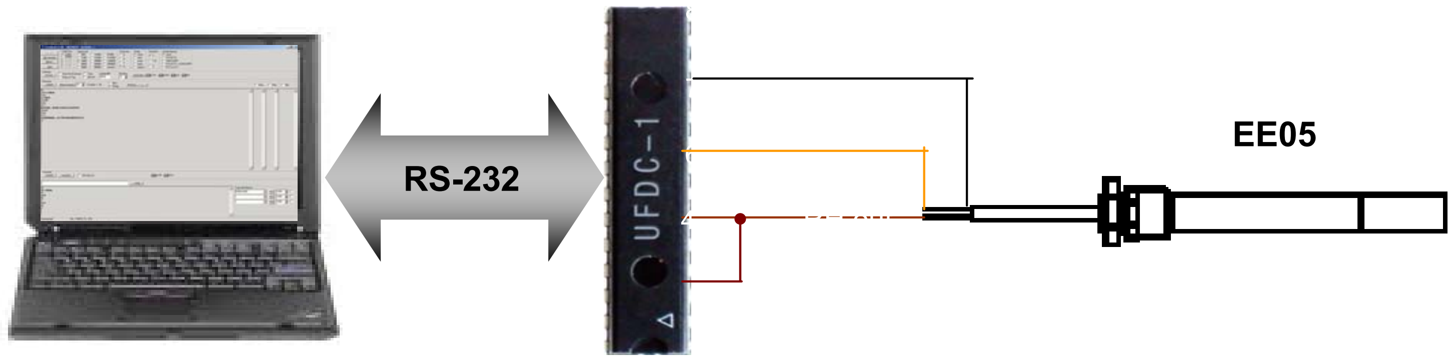
Rotation Acceleration Measurement

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

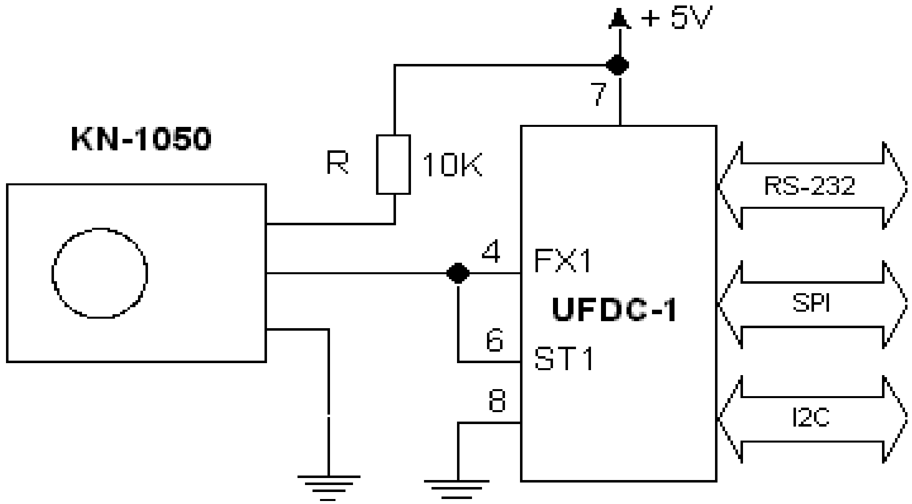
where n_1 and n_2 of rotation speed and time interval for the second measurement t_2

Smart Humidity Sensors

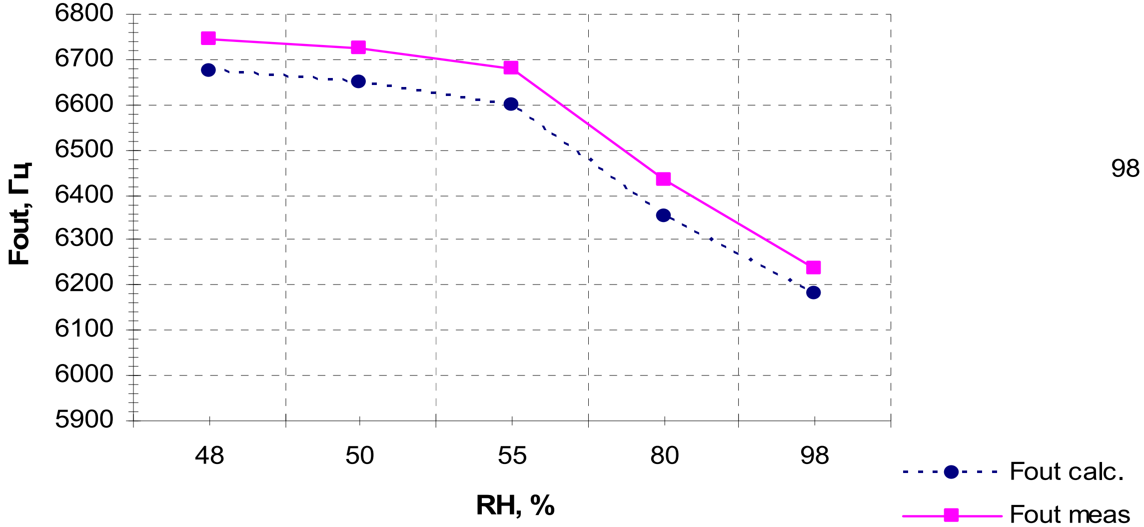
(a)

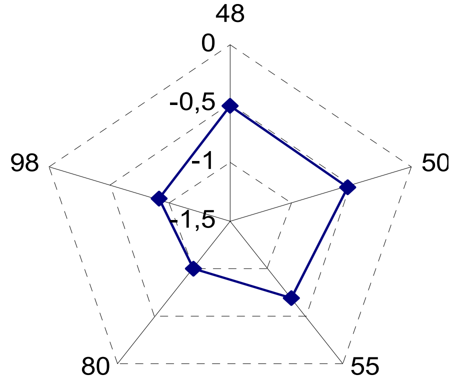


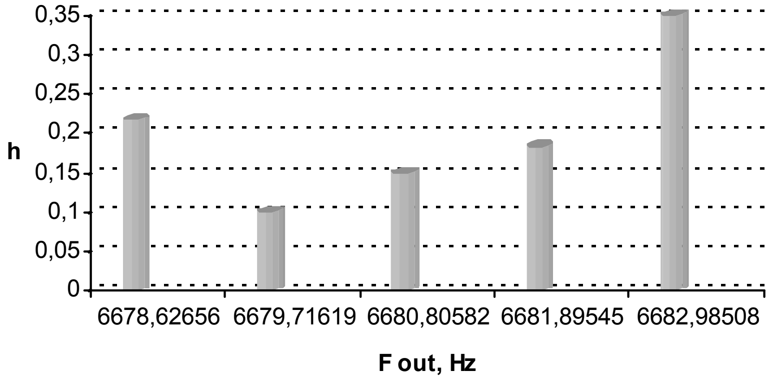
(b)



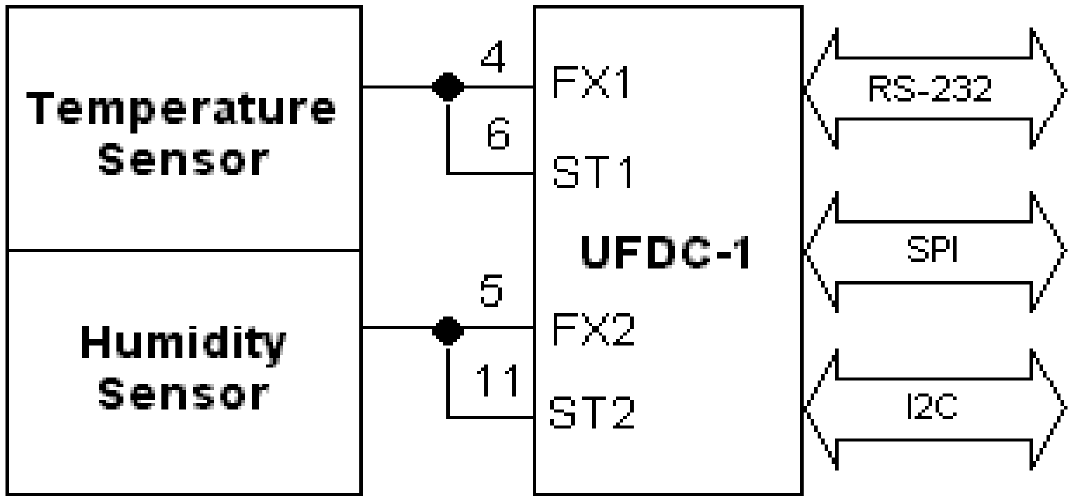
Experimental Results







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 (RS232)

>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)

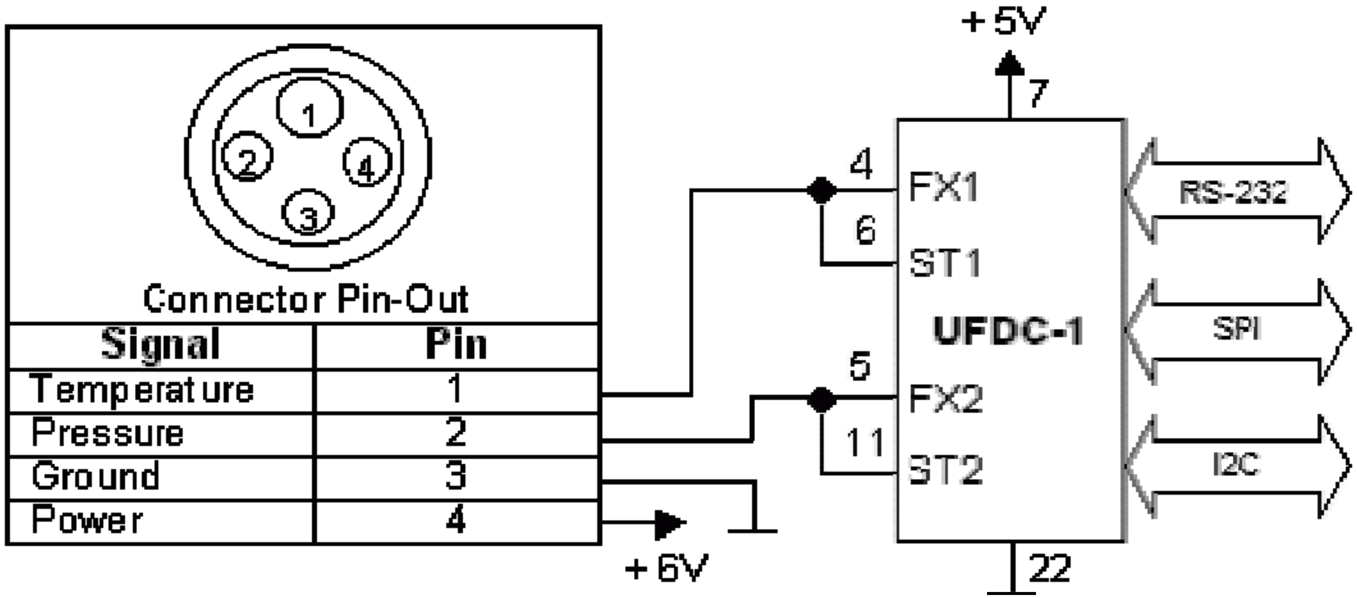
>ME; Frequency measurement, 2nd channel, HTF3130 humidity sensor

>A2; Choose the conversion error 0.25 %

>S; Start a measurement

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

Pressure Sensors Interfacing

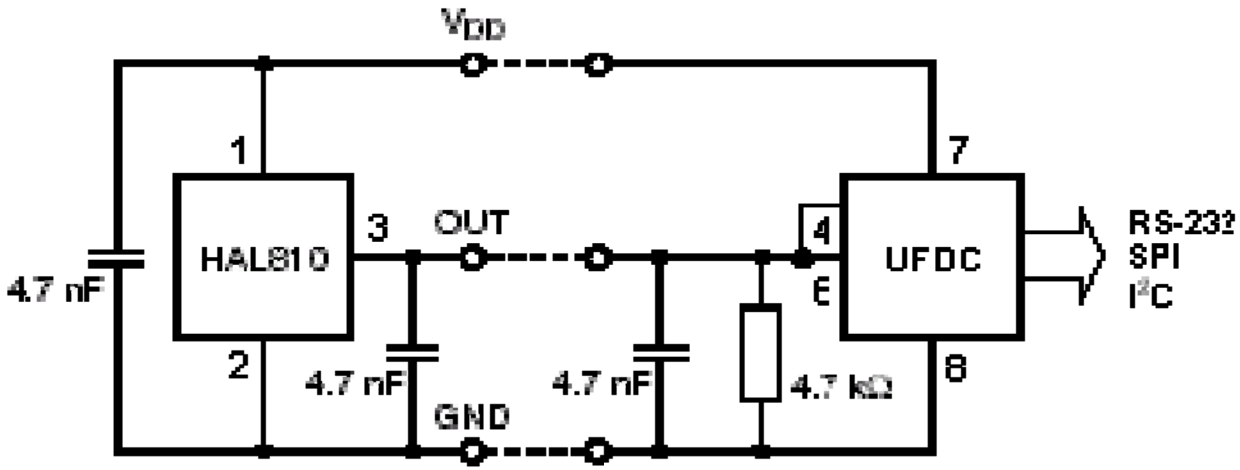


Connection diagram for 8000 Series of frequency output depth sensors from *Paroscientific, Inc.*

Commands Example (RS232)

>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

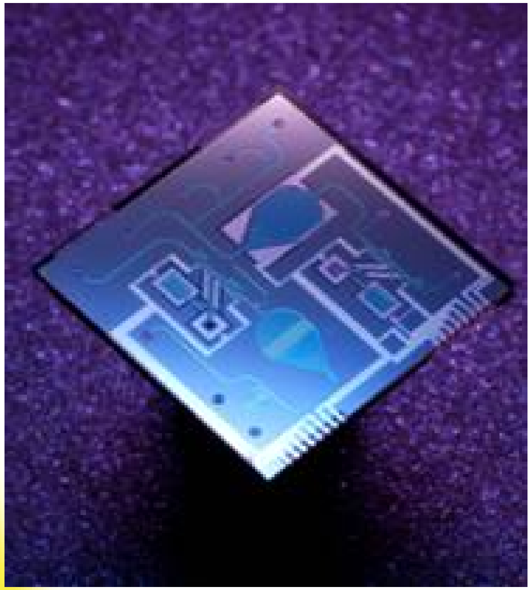


HAL819 to UFDC-1 interfacing circuit

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

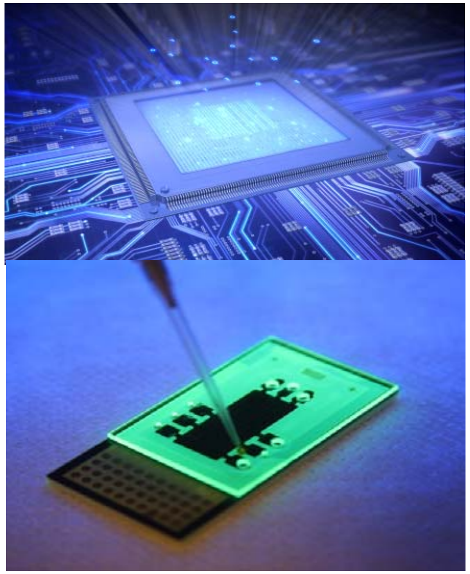
Micro-Nano Bio Systems (MNBS)

Micro-Nano Bio Systems (MNBS) *are smart systems combining microsensing and micoactuation, microelectronics, nano-materials, molecular biology, biochemistry, measurement technology and ICT*



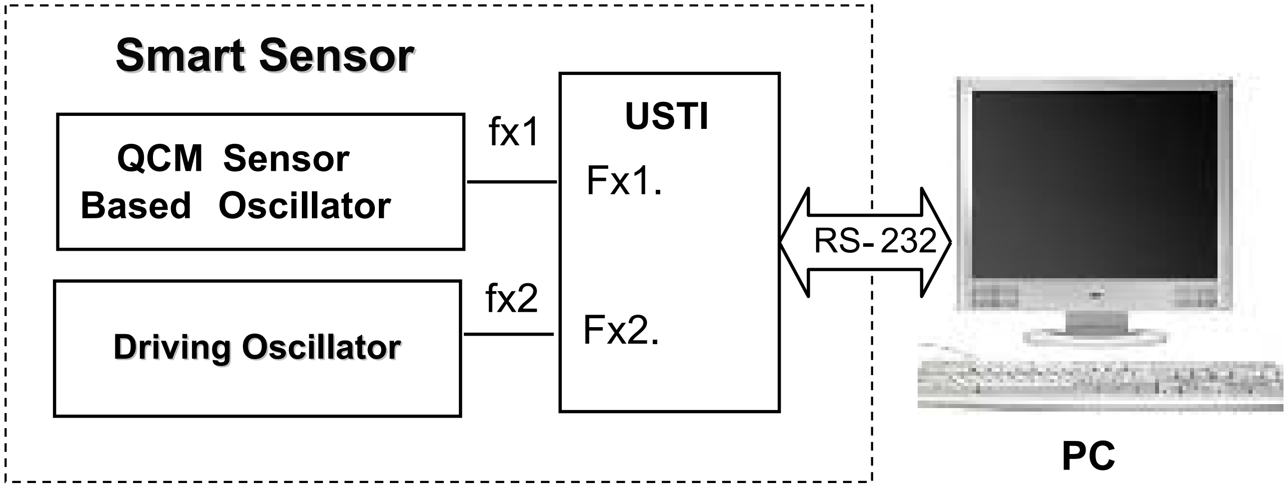
- Increased intelligence (computation/decision power, sensing capabilities)
- Enhanced miniaturization and integration of devices and systems
- Increased integration of bioactive components (molecular and cellular components, bio/nanochemistry) as well as processes

Requirements to the Novel Generation of MNBS



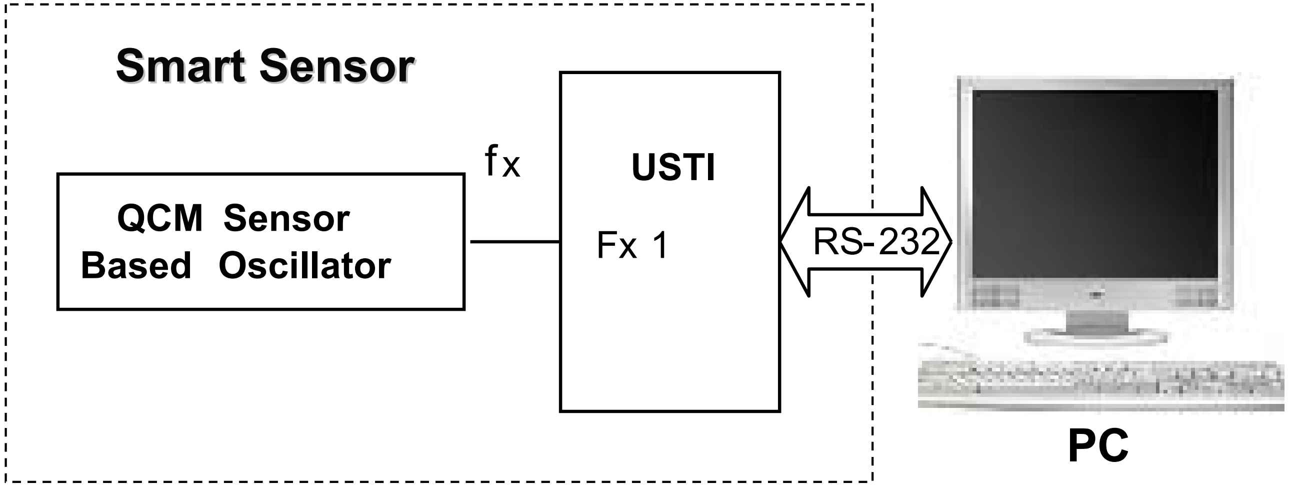
- Smaller
- Perform better
- Faster
- Cheaper
- Delivering highly reproducible results
- Increased sensitivity
- Extremely and proven reliable

QCM Sensor System: Example 1



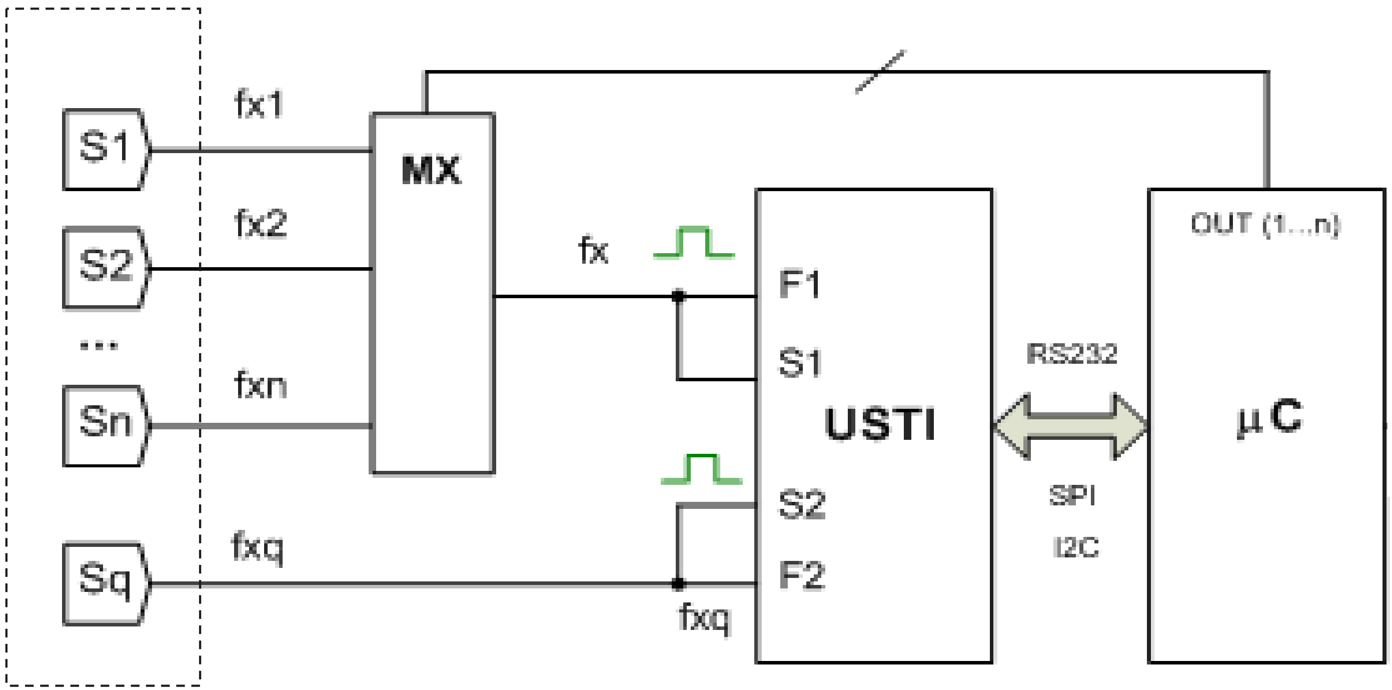
>M06 ; Frequency difference measurement initialization
>A0A ; 0.0005 % conversion relative error set up
>S ; Start a measurement
>R ; Read a result
7054.07537 ; Measurement result indication

QCM Sensor System: Example 2



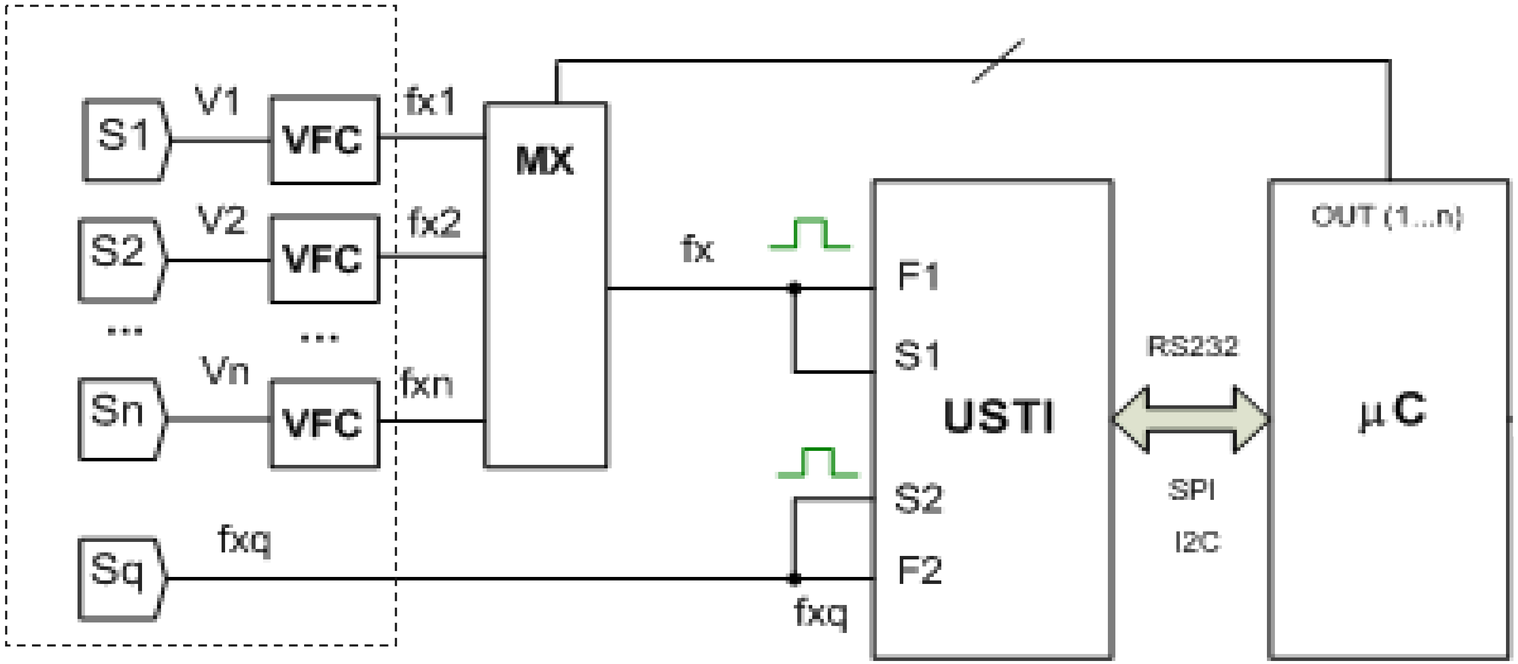
>M13	; Frequency deviation measurement
>A0A	; Absolute deviation measurement, 5×10^{-4} % error
>E7000000.34	; Set the reference frequency f_{ref} (Hz)
>S	; Start a measurement
>R	; Read a result
6000.7824	; Measurement result indication

Frequency Output Sensors Array



+ capacitive (C_x), resistive (R_x) or resistive bridge (B_x) sensing element

Analog Output Sensors Array



R, C and Resistive Bridge Sensing Elements

3-Signal Calibration Technique:

100 g m_x

The scale is linear. Calculate m_x

Mode of Functioning

- USTI converts resistance, capacitance and resistive bridge signals to time intervals, and then to digital
- Signal conversion is carried out according to the linear law:

$$M_i = k \cdot S_i + M_{off},$$

where S_i is the output sensor's signal, k and M_{off} are parameters of measuring converter

Method of Measurement

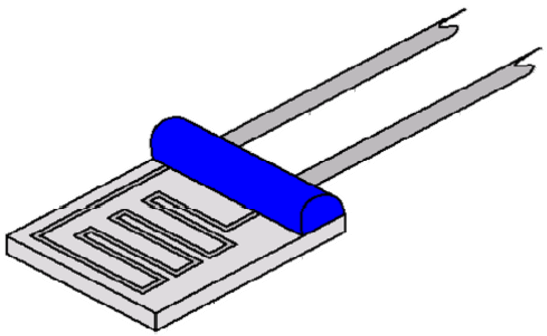
$$M_{off} = M_{off}$$

$$M_{ref} = k \cdot S_{ref} + M_{off}$$

$$M_x = k \cdot S_x + M_{off}$$

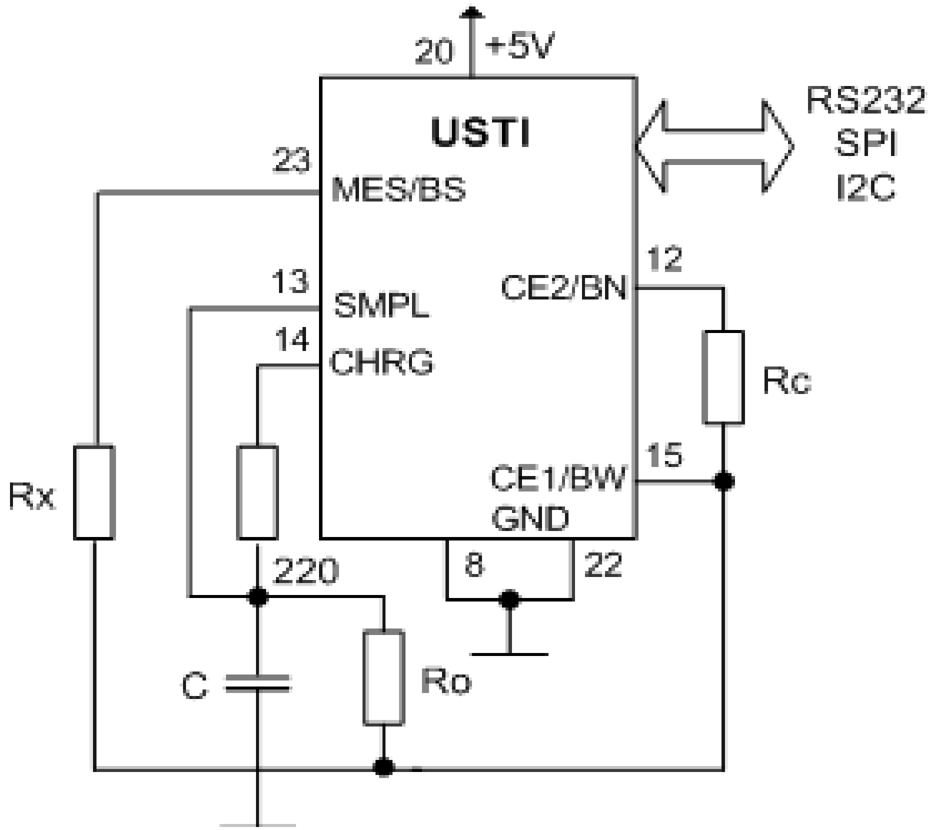
- USTI operates in condition of auto-calibration, that is base on a 3-phase differential method of measurement
- Three signals: $S_1 = 0$, $S_2 = S_{ref}$ and $S_3 = S_x$ (zero, reference and measurand) during one cycle

Resistive Sensing Elements



- Resistive sensing elements are widely used in various physical and chemical sensors and transducers for gas, temperature, humidity, distance, etc.
- They have a wide measurement ranges: from tens Ω to several MΩ
- Existing ICs, ASICs or µC-based solutions have low accuracy or/and narrow measurement range
- No any universal solution for both: resiatance-to-digital or resistance-to-frequency (or time interval)-to-digital conversion did exist till 2011

Direct Resistive Sensing Element Interfacing



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

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

$$R_c \leq R_x$$

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

$$T = 2200 \times C$$

Charging Time

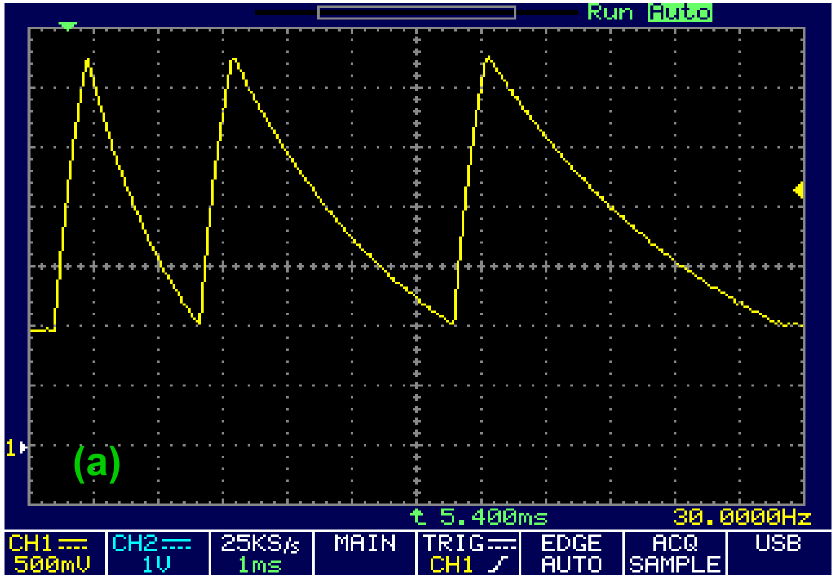
No.	Command "Wnn"	Charging Time
1	00	100 μs
2	01	200 μs
3	02	300 μs
4	03	400 μs
5	04	500 μs
6	05	600 μs
7	06	700 μs
8	07	800 μs
9	08	900 μs
10	09	1 ms
11	0A	2 ms
12	0B	3 ms
13	0C	4 ms
14	0D	5 ms
15	0E	6 ms
16	0F	7 ms
17	10	8 ms
18	11	9 ms
19	12	10 ms
20	13	20 ms
21	14	30 ms
22	15	40 ms
23	16	50 ms
24	17	60 ms
25	18	70 ms
26	19	80 ms
27	1A	90 ms
28	1B	100 ms

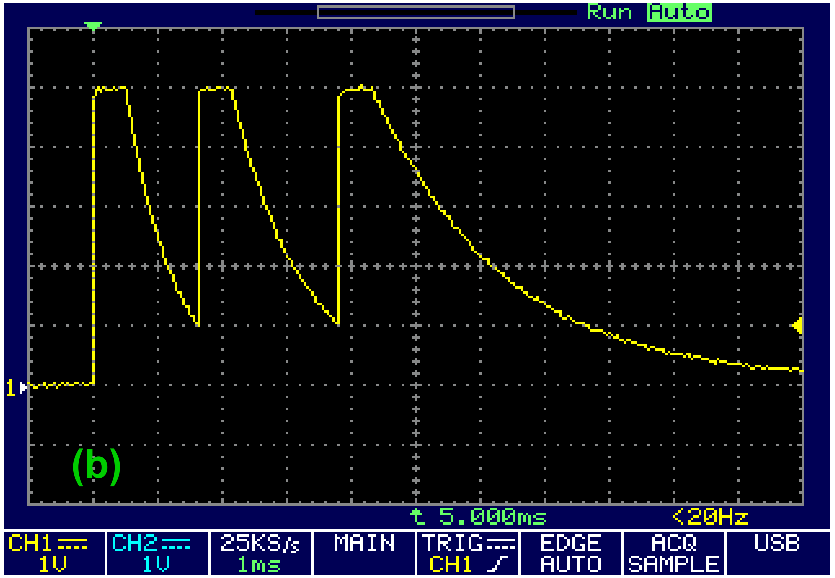
The time interval can be measured in a wide measuring range: from 2 μs to 250 s.

The quantization error:

$$\delta_x = \frac{1}{f_0 \times t_x} \times 100, \%$$

Oscillograms of Three-point Calibration Technique



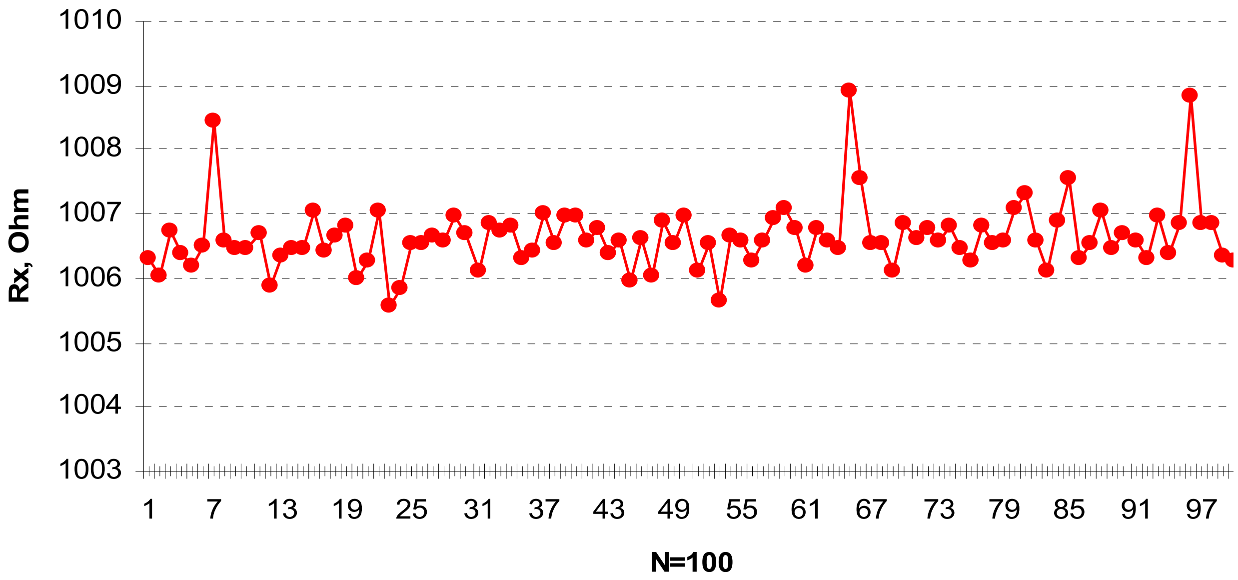


R_x=1006.5 Ω; R_c=604.02 Ω; C= 3 μF and R_0=328.63 Ω (a); and R_x=10 237 000 Ω (b)

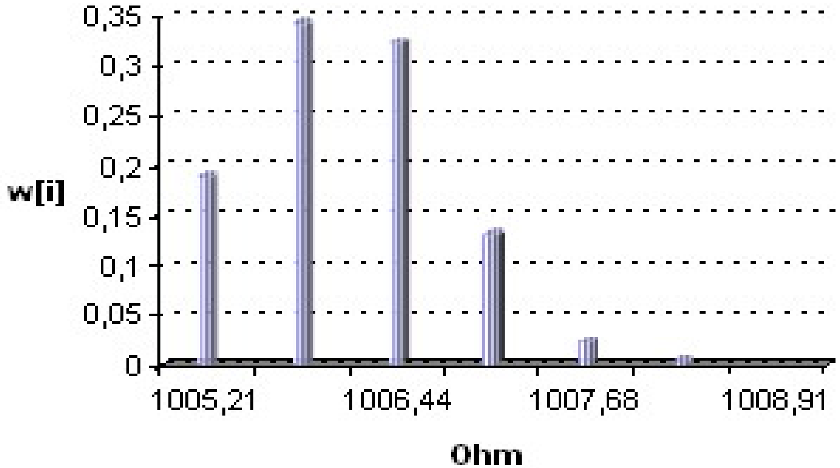
USTI Commands for Resistive Measurement (RS232 Interface)

>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

Experimental Results



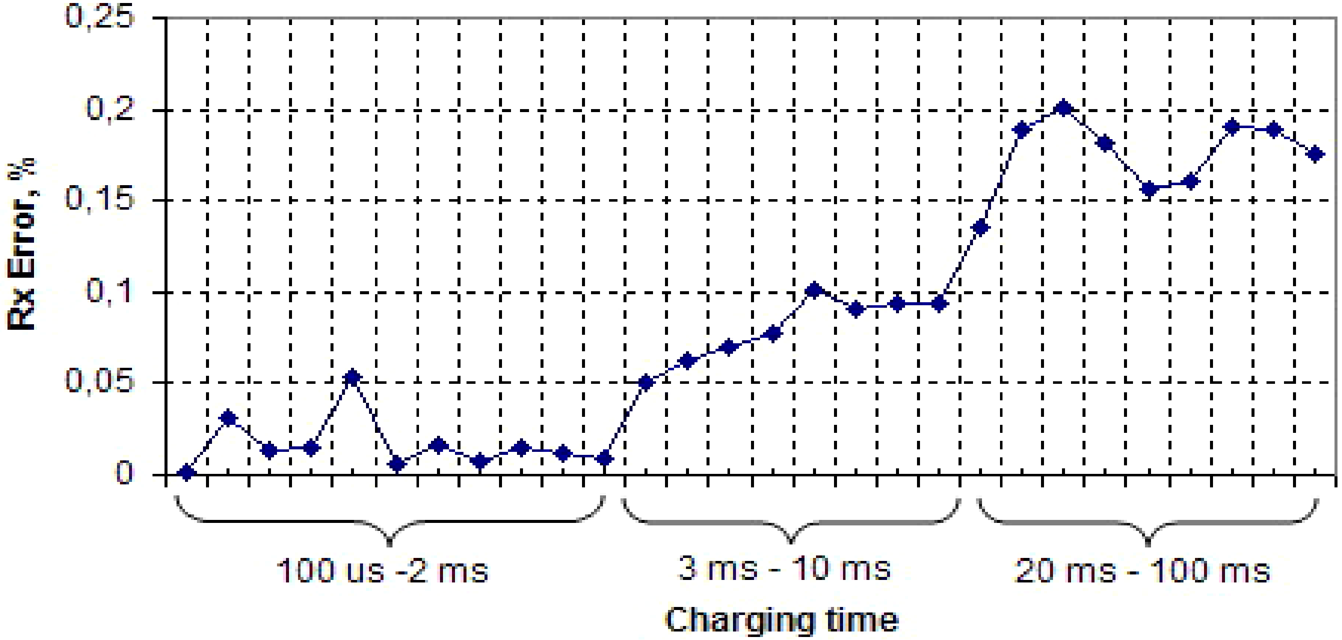
Parameter	Value
Number of measurements, N	100
Minimum R_x (min), Ω	1004.5897
Maximum R_x (max), Ω	1008.9129
Sampling Range, R_x (max) - R_x (min), Ω	4.3232
Median	0
Arithmetic Mean, Ω	1005.7816
Variance	0.4172
Standard Deviation	0.6459
Coefficient of Variation	1557.1612
Confidence interval for arithmetic mean at P=97 %	1005.6414≤ R_x ≤ 1005.9218
Relative error, %	0.07
χ^2 – test (S) at: k=7; P = 97 % χ^2_{max} = 10	231.2859
Hypothesis about Gaussian distribution	No acceptable



$$k_{max} = 1.25 \times n^{0.4}$$

IFSA

Relative Error vs. Charging Time at R_x = 2 043 300 Ω



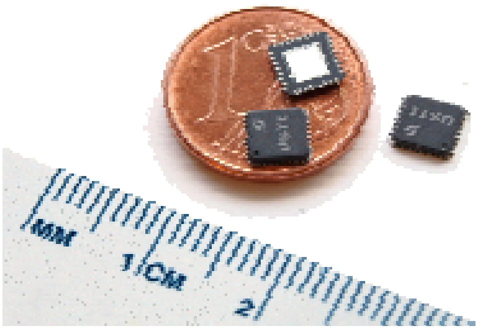
USTI Commands for Frequency Measurement, RS232, Slave Mode

```
> A09   ; Set up the relative error 0.001 %
> M00   ; Frequency measurement in the 1st channel
> S     ; Start measurement
> C     ; Check in the result is ready
r       ; Returns ‘b’-if in progress; ‘r’-if ready
> R     ; Read result
100000.07507

> M04   ; Duty-Cycle measurement in the 2nd channel
> S     ; Start measurement
> C     ; Check in the result is ready
r       ; Returns ‘b’-if in progress; ‘r’-if ready
> R     ; Read result
```

Comparative Resistance Measurement Results

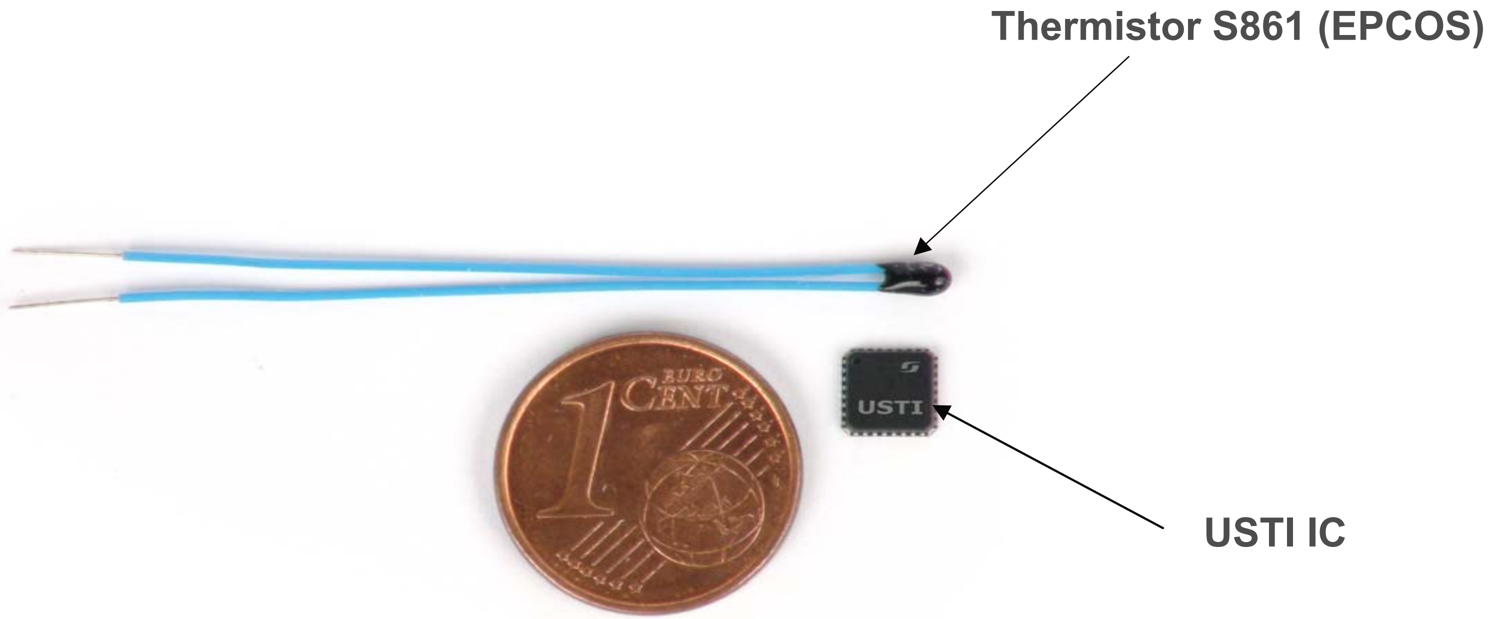
Relative Resistance Error			
Marked Value	PICMETER [4] Error, %	USTI Error, %	Measurement conditions
0.10 K	N/a	0.24	R_x=329.66 Ω; C=2μF R_0=609.86 Ω
0.30 K	N/a	1.58	R_x=432 260 Ω; C=2μF R_0=609.85 Ω
0.82 K	N/a	1.31	
1.0 K	N/a	0.026	R_x=604.02 Ω; C=3μF R_0=328.63 Ω
1.2 K	1.3	1.17	R_x=432 260 Ω C=2 μF R_0=609.85 Ω
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	
91 K	0.6	0.491	
150 K	0.5	0.392	
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_x=563 960 Ω
2.0 M	N/a	0.065	R_x=432 280 Ω C=2.1 nF R_0=464 240 Ω

Metrological Performance

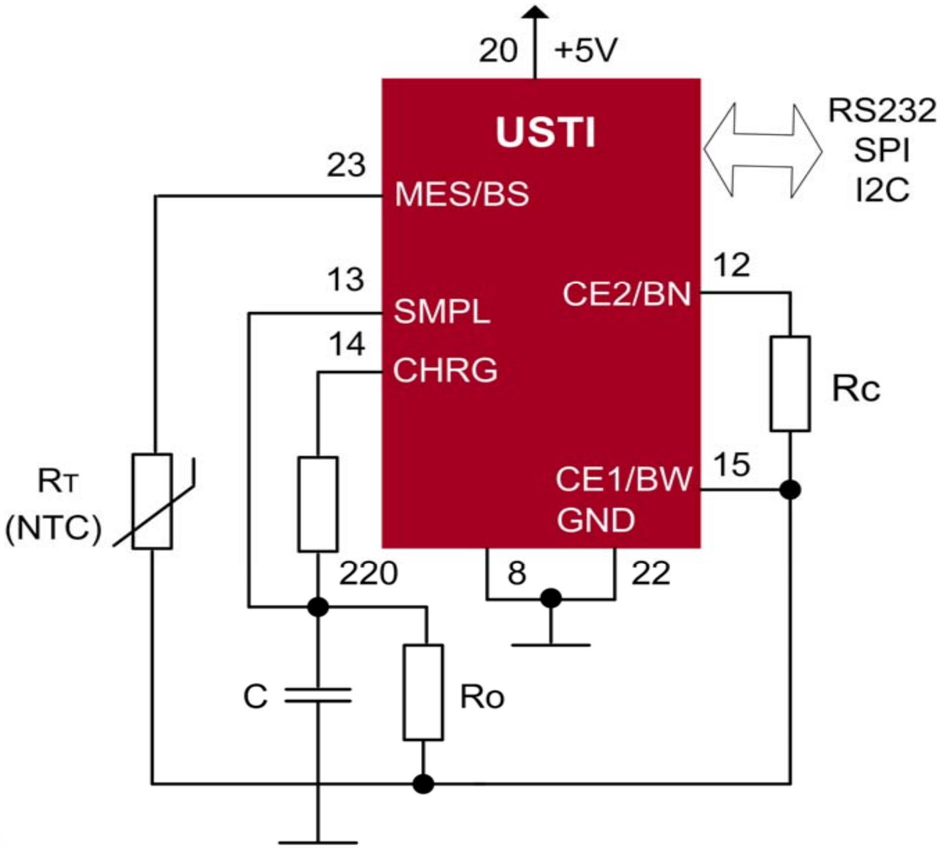


- Measuring range: 10 Ω …10 MΩ
- Average relative error: ± 0.47 %
- ± 0.01 % relative error at splitting of the range of into sub ranges
- Can work with any known resistance-to-time or resistance-to-frequency converters

NTC Temperature Sensor System: Main Components (Example)



Universal Sensors and Transducers Interface (USTI): Resistive Mode



$$R_T = \frac{N_T - N_{off}}{N_{ref} - N_{off}} \cdot R_c$$

Commands for Resistance Conversion at I²C Bus

<06><10>;	Set up a resistance R_T measurement mode
<0E><i><f>;	Set the reference value Rc =3011 Ω*
<10><08>;	Set the charging time 900 µs
<09>;	Start measurement
<03>;	Check result. "0" if the result is ready
<07>;	Read conversion result in BCD format.

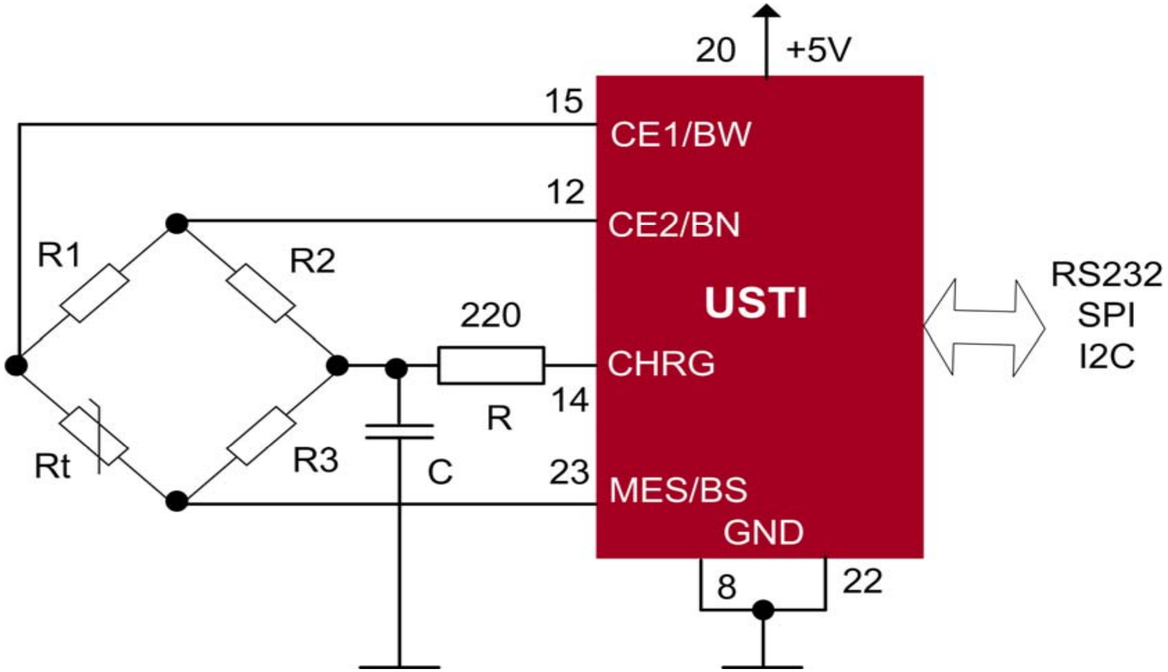
Returns sign byte and 12 bytes of result in BCD code

Command format:

<I5><I4><I3><I2><I1><I0><F0><F1><F2><F3><F4><F5>,

where <I5>…<I0> integer part of BCD number;
<F0>…<F5> fractional part of BCD number.

USTI: Resistive Bridge Mode

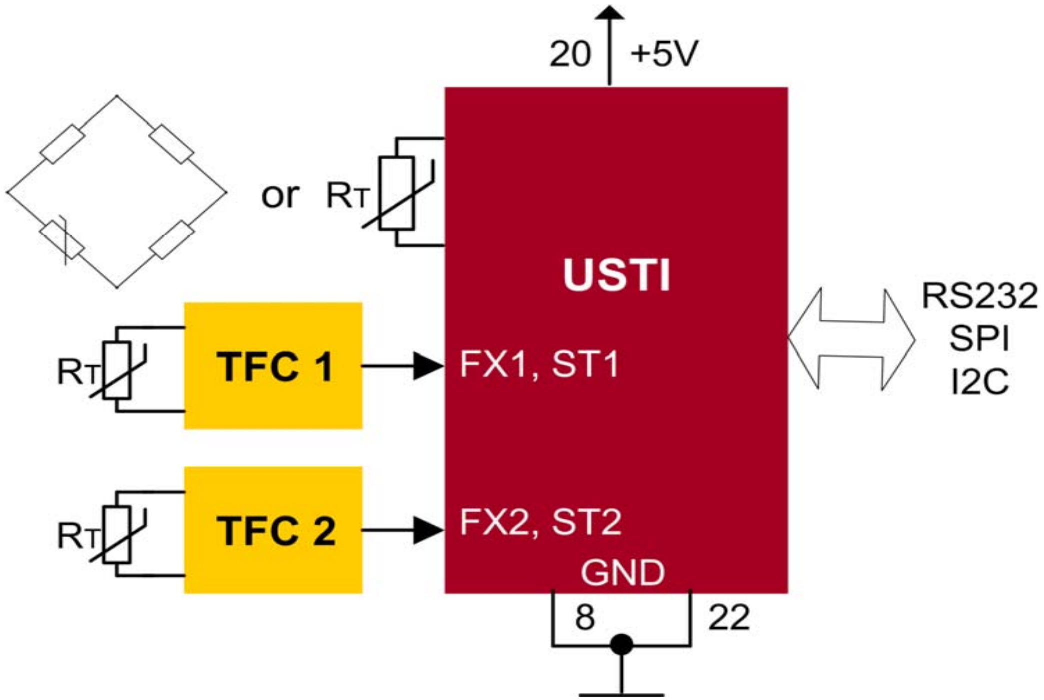


$$x = \frac{t_1 - t_3}{t_2}$$

Commands for Resistive Bridge Conversion at I^2C Bus

<06><12>;	Set up a resistance-bridge B_x mode
<10><13>;	Set the charging time, for example, 20 ms
<09>;	Start measurement
<03>;	Check result. Returns "0" if result is ready
<07>;	Read conversion result in BCD format.

USTI: Frequency (Period) Measuring Mode



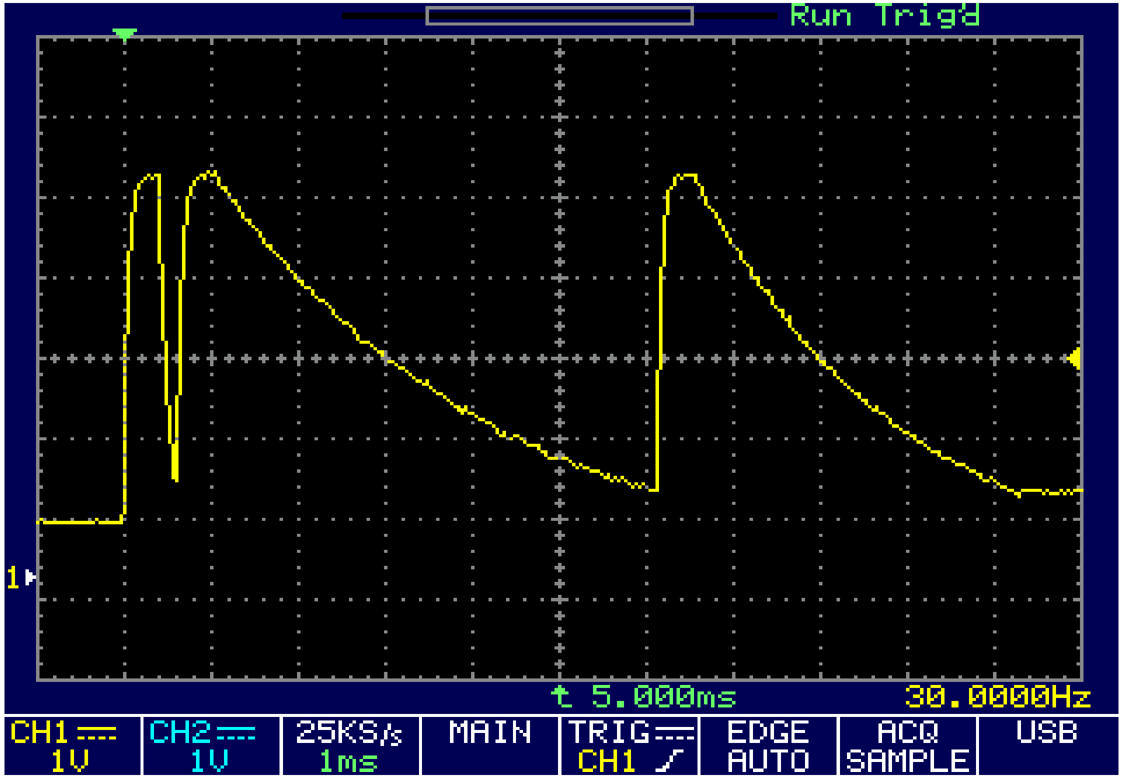
Commands for Frequency Measuring Mode

```
<06><00>;    Set up frequency mode in the 1st channel
<02><09>;    Set up the relative error, 0.001 %
<09>;        Start measurement
<03>;        Check result. Returns "0" if result is ready
<07>;        Read conversion result in BCD format
```

Integrated Converters for NTC Thermistors

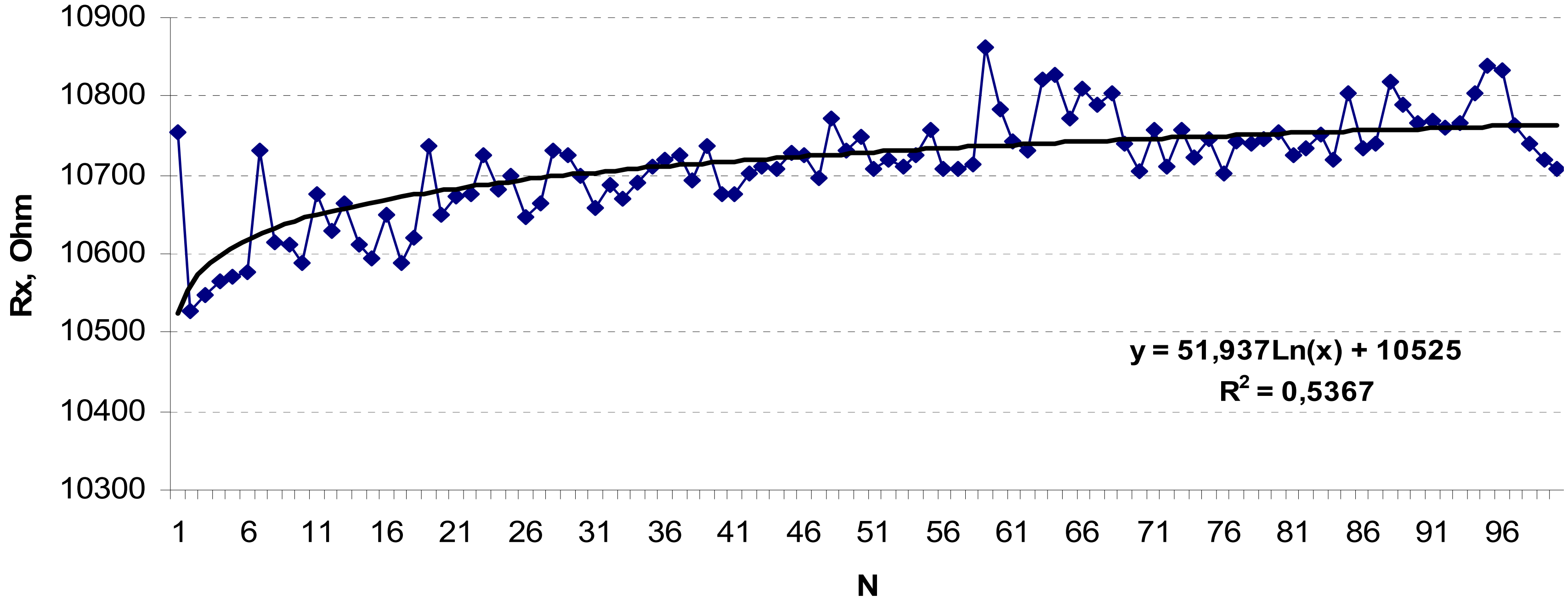
IC	Number of Channels	Output
ispPAC30	1	Analog (V)
MAX6682	1	SPI
MAX6691	4	Pulse-width modulated
UTI	1	Period-modulated
USTI	3	SPI, I2C, RS232

Oscillograms on the USTI's CHRG Pin



$$\delta_q = \frac{1}{f_0 \cdot t_x} \times 100\,\%,$$

Experimental Results



T, ^0C	R_{nom}, Ω	R_{min}, Ω	R_{max}, Ω	Error, %	ΔT, ^0C	$R_{x\ aver}$, Ω
22	11418	11282	11553	1.2	0.3	-
23	10921	10797	11046	1.1	0.3	10713.84
24	10449	10335	10563	1.1	0.2	-

Capacitive Sensing Elements

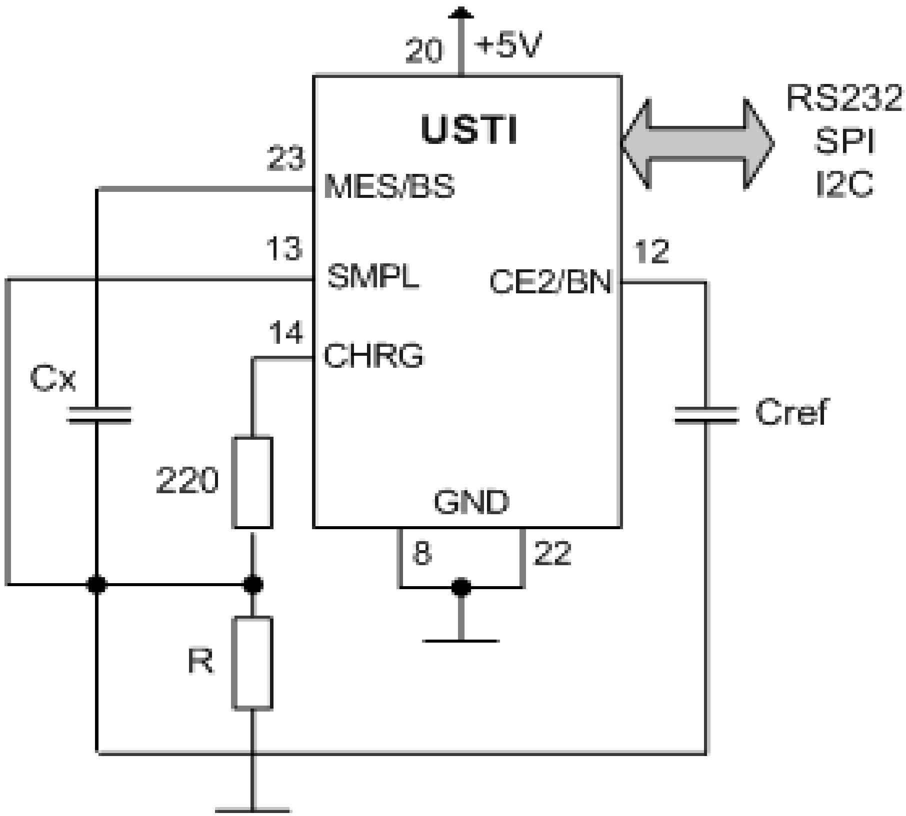
- Capacitive sensing elements are widely used in humidity, level, pressure, acceleration, position, proximity, chemical sensors, biosensors and transducers
- They have a wide measurement ranges: from tens pF to hundreds pF
- Existing ICs, ASICs or µC-based solutions have low accuracy or/and narrow measurement range
- No any universal solution for both: capacitance-to-digital or capacitance-to-frequency (or time interval)-to-digital conversion did exist till 2011

Integrated Capacitance-to-Digital Converters

IC	Capacitance Range	Relative Error, FS %	Interfaces	Communication Mode
		ZMDI		
ZSSC31210	2 pF to 260 pF	± 0.25	I²C, SPI	Slave
ZSSC3122	< 10 pF	± 0.25	I²C, SPI	Slave
ZSSC3123	< 260 pF	± 0.25	I²C, SPI	Slave
		Smartec		
UTI 03	2 pF to 300 pF	n/a	Period modulated	Slave
		acam messelectronic, GmbH		
PCap01	1 pF to 1000 pF	n/a	I²C, SPI	Slave
		Technology Assistance BCNA 2010, S. L.		
USTI	50 pF to 100 µF	*±0.036 %	I²C, SPI, RS232	Slave and master (RS232)

IFSA

Direct Capacitance Sensing Element Interfacing



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

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

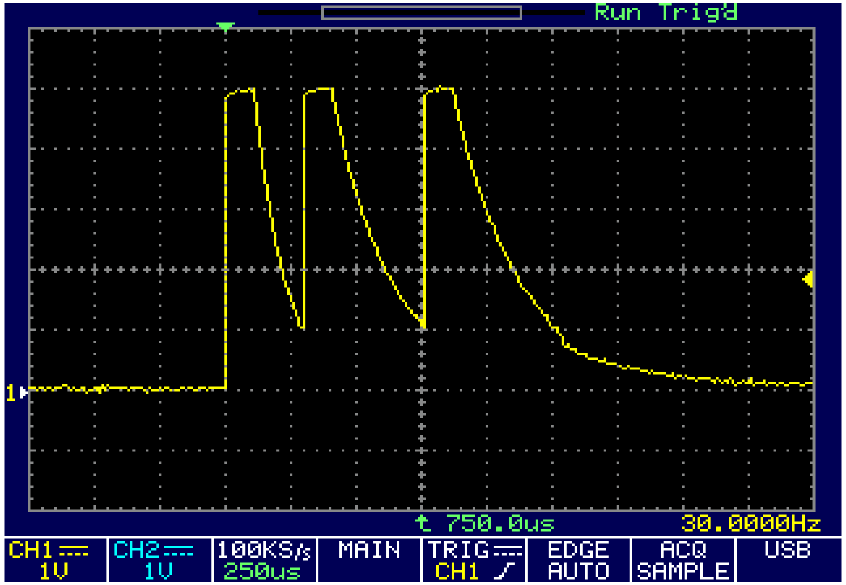
$$T = 2200 \times C$$

USTI Commands for Capacitance Measurement (RS232 Interface)

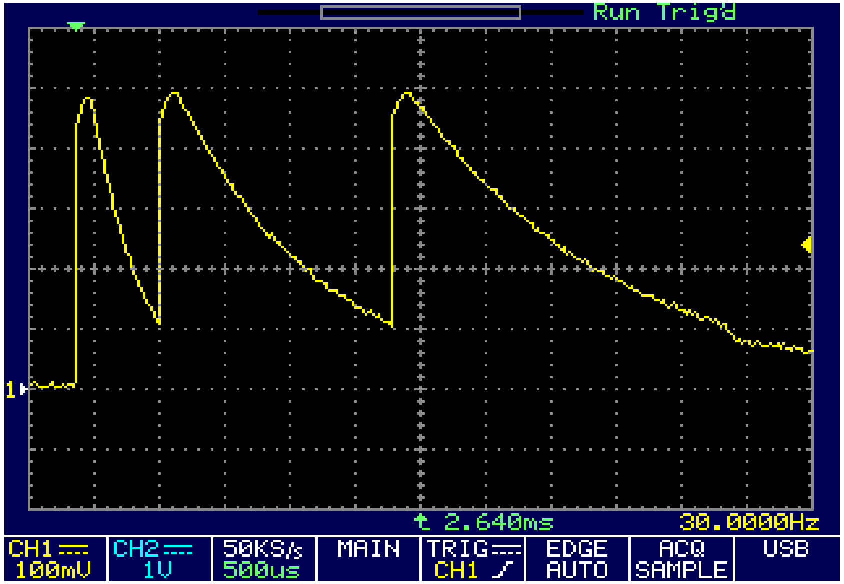
> **M11**; Capacitance measurement mode
> **E0.00000000012543**; Reference set up C_{ref} =125.43 pF
> **W00**; Set up the charging time constant number (100 μs)
> **S**; Start Measurement
> **C**; Check the measurement status: b-in progress; r-ready
> **R**; Get the result

0.00000000015222; Measuring result C_x = 152.22 pF

Oscillograms of Three-point Calibration Technique

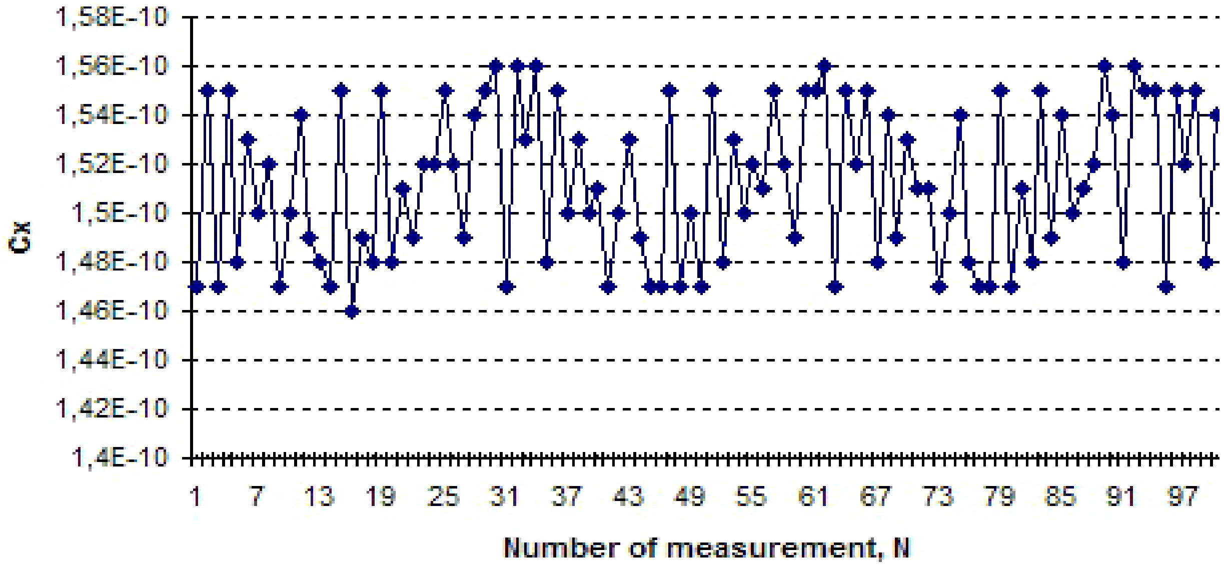


152.22 pF measurement

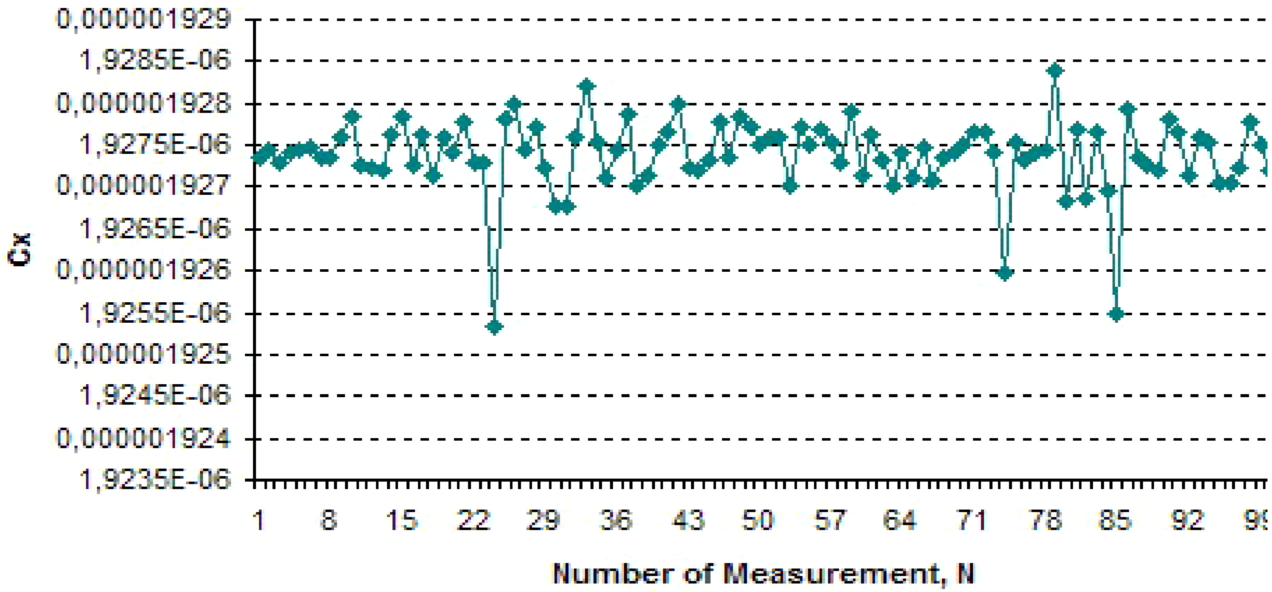


257 pF measurement

Experimental Results



C_x=152.22 pF at C_{ref}=125.43 pF and R=20 MΩ

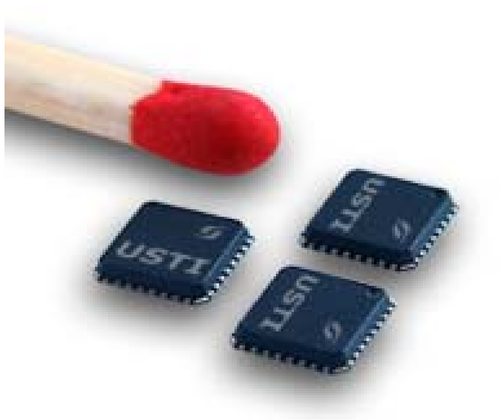


C_x=1.9279 μF at C_{ref}=1.9286 μF and R=99 Ω

Comparative Capacitance Measurement Results

Relative Capacitance Error			
Marked Value	PICMETER 's Error, %	USTI's Error, %	Measurement conditions
150 pF	N/a	0.6400	C_{ref} = 125.43 pF, R = 20 MΩ
180 pF	N/a	0.2300	C_{ref} = 174.04 pF, R = 20 MΩ
233 pF	N/a	0.6200	
470 pF	N/a	0.7000	C_{ref} = 449.25 pF, R = 20 MΩ
2.2 nF	4.3	0.0680	C_{ref} = 22 nF, R = 91 kΩ
20 nF	1.2	0.0158	
33 nF	1.7	0.0011	
47 nF	1.1	0.0019	
100 nF	6.7	0.1400	C_{ref} = 94.63 nF, R = 91 kΩ
470 nF	2.1	0.0010	C_{ref} = 464.89 nF, R = 5 kΩ
940 nF	6.6	0.0230	C_{ref} = 961.11 nF, R = 2.3 kΩ
2 µF	N/a	0.0270	C_{ref} = 1.9286 µF, R = 1 kΩ
47 µF	N/a	0.1000	C_{ref} = 42.206 µF, R = 99 Ω

Capacitance Measurement Performance



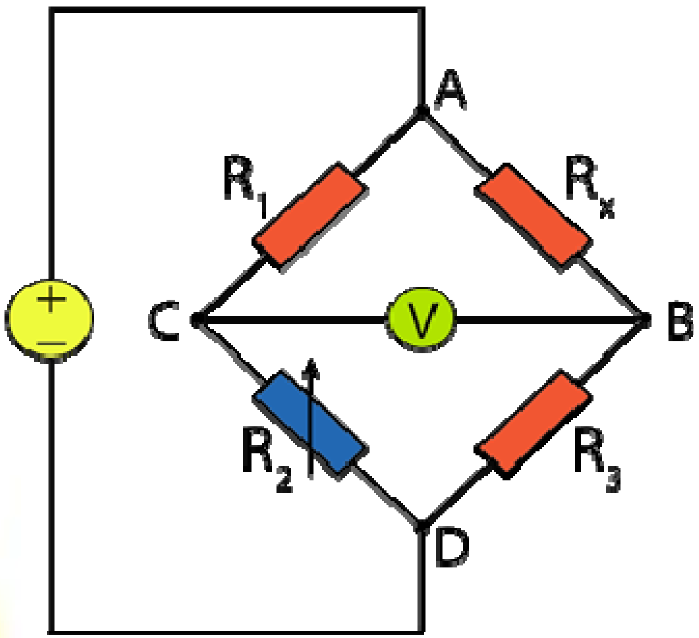
- Capacitance measurement range from 50 pF to 100 μF.
- Average relative error ± 0.036 %
- Worst case relative error for reported results is not more than ± 0.7 %
- Can work with any known capacitance-to-frequency converters

Resistive-bridge Sensors

Charles Wheatstone
(1802-1875)

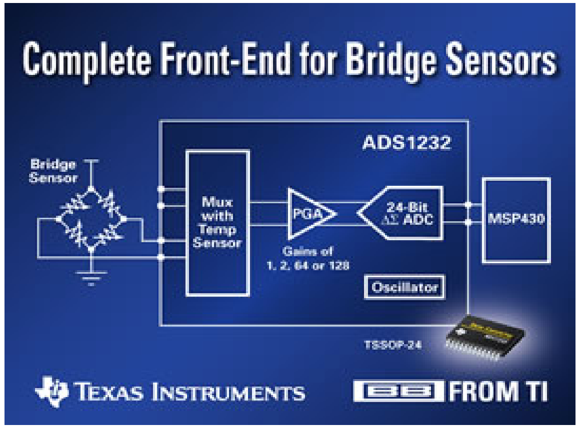
- A Wheatstone bridge is widely used to convert the resistance variation of sensors, related to the physical quantity, into a voltage or current
- A lot of manufacturers produce resistive-bridge sensors
- In such sensors systems output bridge voltages should be converted into digital

Resistive-bridge Sensors



- A Wheatstone bridge is widely used to convert the resistance variation of sensors, related to the physical quantity, into a voltage or current
- A lot of manufacturers produce resistive-bridge sensors
- In such sensors systems output bridge voltages should be converted into digital

Bridge-voltage – to – Digital Conversion



- ADC (18-, 20-, 24-bit) plus reference, amplifier and filter
- Microcontroller with embedded ADC plus multiplexer, operation amplifier and 6 external passive components
- Direct resistive-bridge sensors – to – microcontroller interface
- Integrated sensor signal conditioners for resistive-bridge sensors

Sensor Signal Conditioners

Type	Resolution, bit	Output	Notices
		ZMDI	
ZMD21013	-	SPI	3 channel sensor bridge
ZMD31010	14	ZACwire serial 1-wire	Offset and gain compensation
ZMD31014	14	I^2C and SPI	14-bit resolution
ZMD31015	14	Digital 1-wire	12-bit resolution
ZMD31020	12	I^2C	Piezo-resistive bridge sensor types
ZMD31030	12	PWM, LIN compatible	Sample rate 100 Hz
ZMD31035	12	Digital 1-wire, LIN compatible protocol	Piezo-resistive bridge sensor types
ZMD31050	9 to 15	PWM, I^2C, SPI, ZACwire	Additional analog outputs
ZMD31150	13 to 16	ZACwire and I^2C	Sensor specific correction
		Smartec	
UTI03	13 to 14	Period modulated output	Resistive bridges 250 Ω - 10 Ω with maximum imbalance ± 4 % or ± 0.25 %

Task Definition

- Often, a resistance variation is converted into a frequency in remote applications
- Multiparametric applications: frequency is related to the fractional bridge unbalance and duty-cycle is function of overall sensor bridge resistance

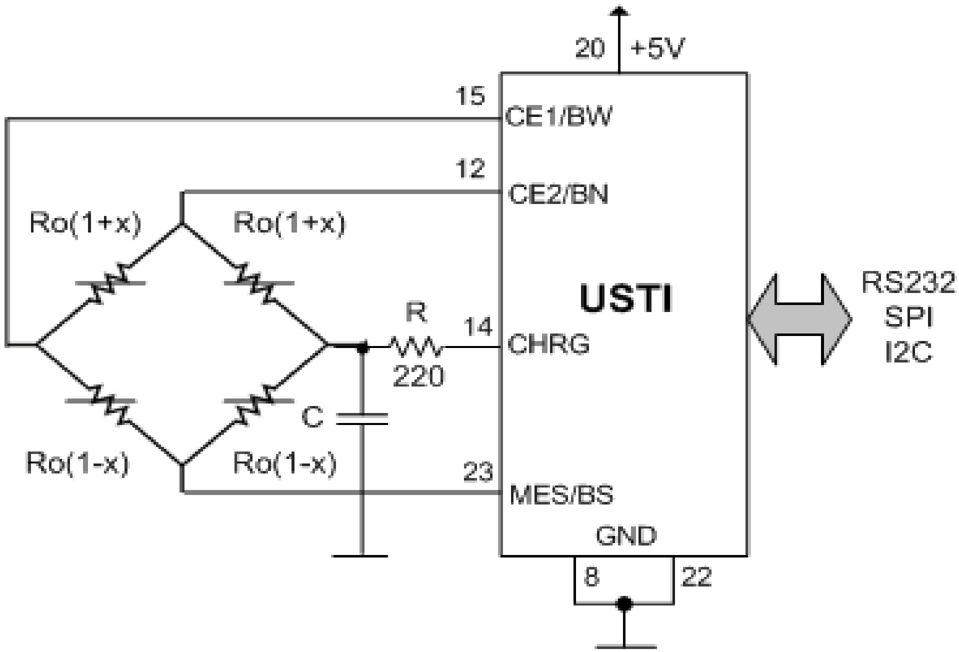
No one existing integrated converter for resistive bridge sensors can work with both: resistive-bridge sensing elements, frequency and duty-cycle signal conditioners' outputs

Conversion Method

- Resistive sensor bridge is considered as a resistor network with 3 inputs and 1 output
- Capacitor connected to the bridge output is charged/discharger and it yields three different time intervals
- Fractional resistance change for each bridge arm should be calculated as:

$$x = \frac{t_1 - t_3}{t_2}$$

Sensor Bridge Interfacing Circuit Diagram



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

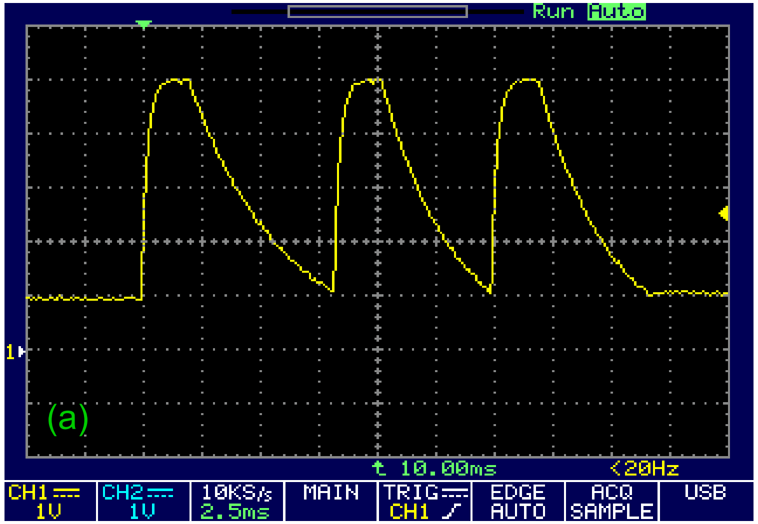
$$T = 2200 \times C$$

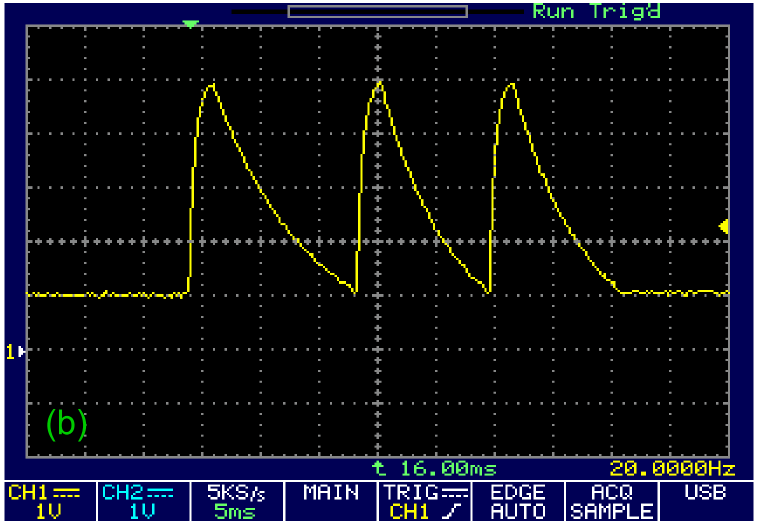
USTI Commands for Resistive Bridge Measurements (RS232)

>M12	; Set up a resistance-bridge B_x measurement mode
>W12	; Set the charging time 20 ms
>S	; Start measurement
>C	; Check the measurement status:
r	; Returns ‘b’-if in progress; ‘r’-if ready
> R	; Read result

0.006005379986

Oscillograms at CHRG Output Pin

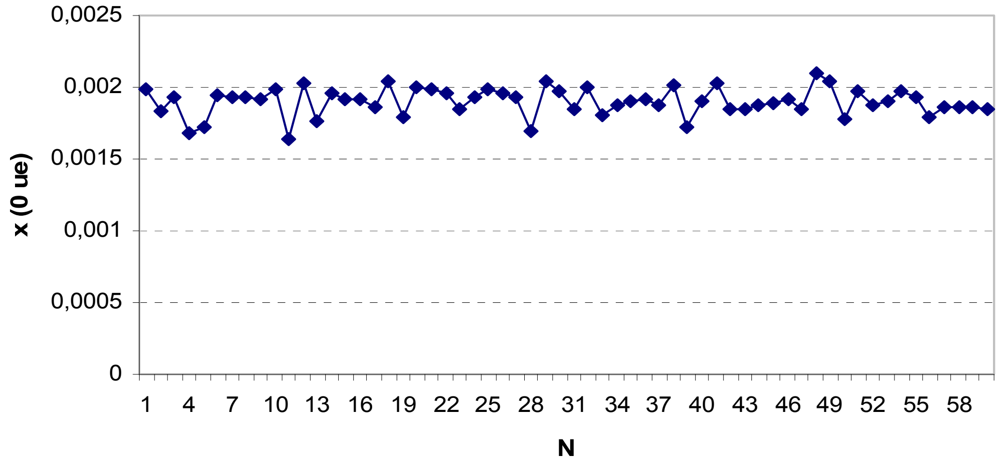


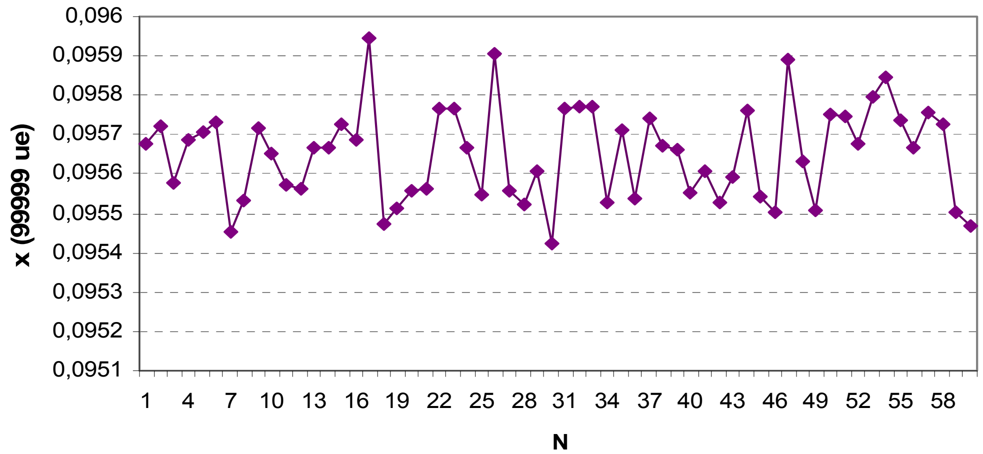


C=1 μF , charging time 2 ms (a) C=2 μF , charging time 4 ms (b)

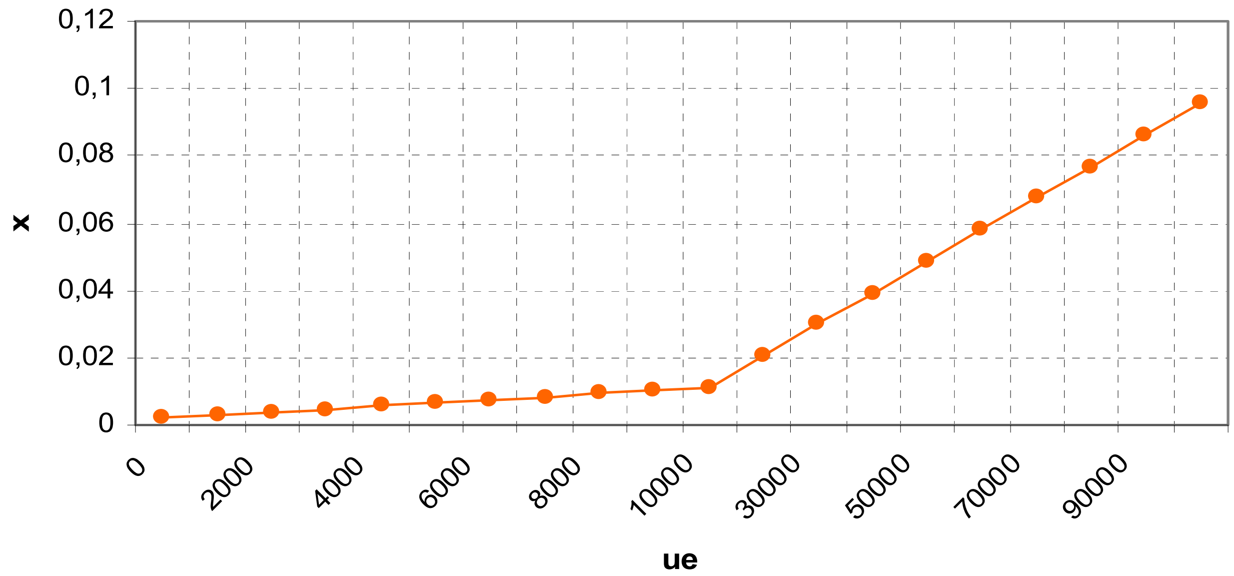
Experimental Results I: Strain Gauge Emulator

1550A Strain Indicator Calibrator (VISHAY)





X Changes Through the Strain Gage Measuring Range



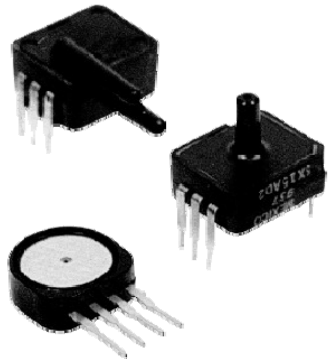
Relative quantization error for time interval measurement:

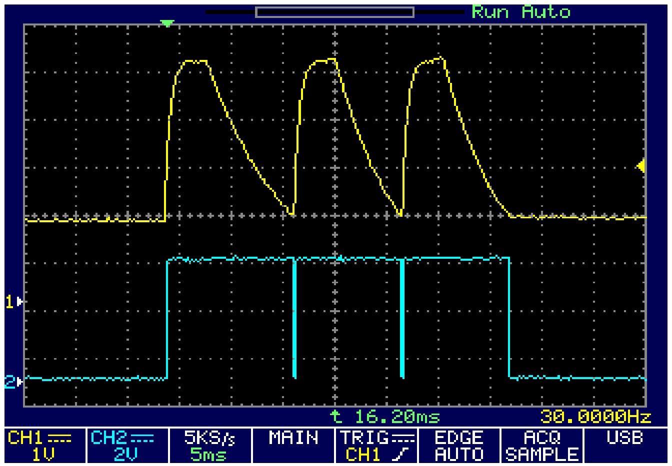
$$\delta_x = \frac{1}{f_0 \times t_x} \times 100$$

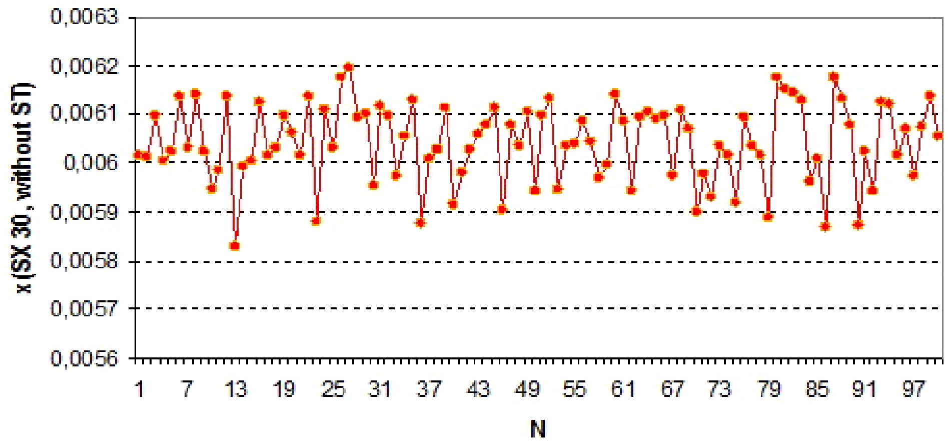
Statistical Characteristics

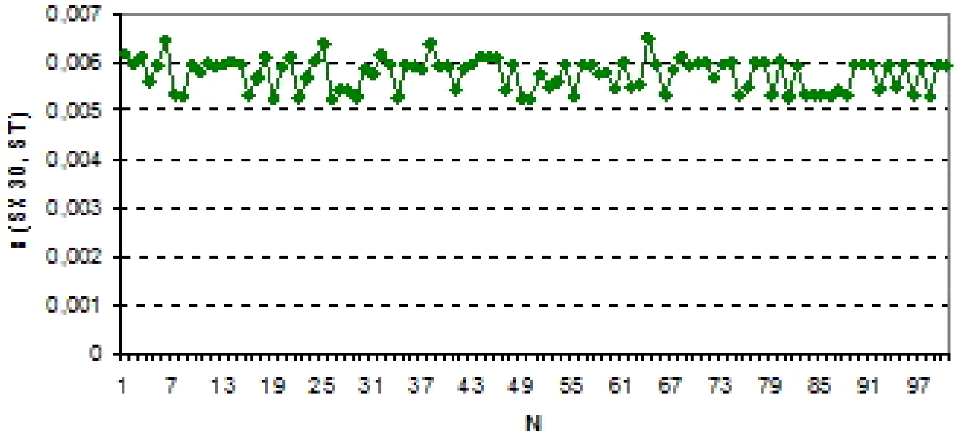
Parameter	Value	
	x (0 με)	x (99900 με)
Number of measurements, *N*	60	60
Minimum R_x (min)	0.0016	0.0954
Maximum R_x (max)	0.0021	0.0959
Sampling Range, R_x (max) - R_x (min)	0.0005	0.0005
Median	0	0
Arithmetic Mean	0.0019	0.0957
Variance	9.5E-0009	1.4E-0008
Standard Deviation	0.0001	0.0001
Coefficient of Variation	19.5202	803.946
χ^2 – test (S) at: k=6; P = 97 % χ^2_{max} = 8.9	2.2572	5.354
Hypothesis about Gaussian distribution	Accepted	Accepted

Experimental Results II: Differential Pressure Sensor Series SX30GD2 (*Honeywell*)









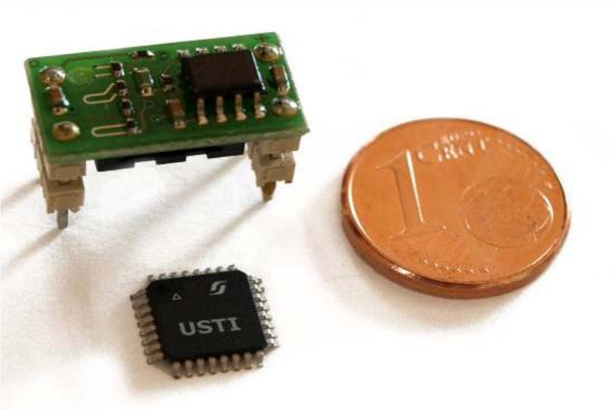
Statistical Characteristics

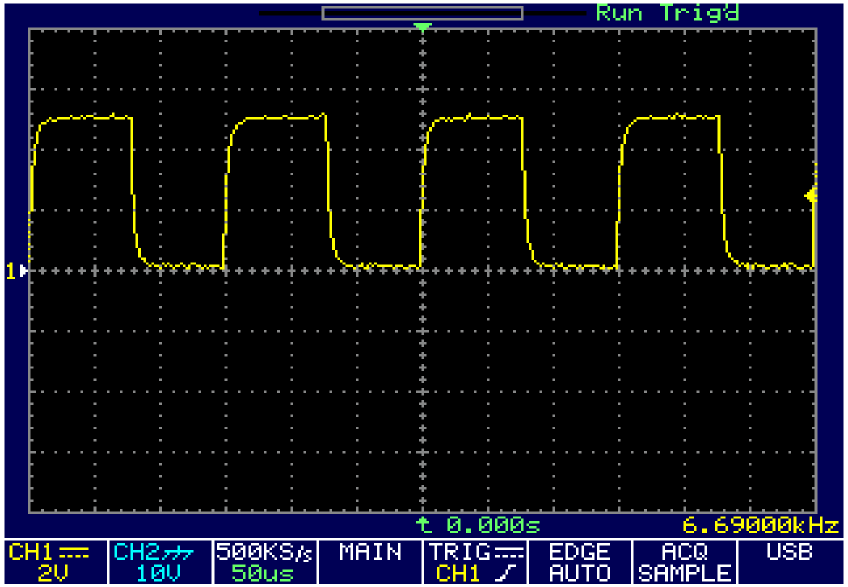
Parameter	x (p = 0 psi)	
	With Schmidt trigger	Without Schmidt trigger
Number of measurements, *N*	100	100
Minimum R_x (min)	0.0053	0.0058
Maximum R_x (max)	0.0065	0.0062
Sampling Range, R_x (max) - R_x (min)	0.0012	0.0004
Median	0	0
Arithmetic Mean	0.005757267	0.006041671
Variance	1.0E-0007	6.6E-0009
Standard Deviation	0.0003	0.0001
Coefficient of Variation	17.805	74.3148
Confidence interval for arithmetic mean at P=97 %	$0.0057 < x < 0.0058$	$0.006 < x < 0.0061$
Relative error, %	0.87	0.83
χ^2 – test (S) at: k=8; P = 97 % χ^2_{max} = 12	57.0539	7.4373
Hypothesis about uniform distribution	Not accepted	Accepted

USTI Features

- USTI can work with various resistive bridge sensors that do not include any internal components other than the arms
- Converter can also work with any known resistance-bridge – to - frequency or to - duty-cycle converters, industrial sensor signal conditioners and interfaceing circuits with PWM and period-modulated outputs
- USTI supplies 3 channels: one for passive resistive bridges and two for resistance-bridge – to - frequency or to - duty-cycle converters

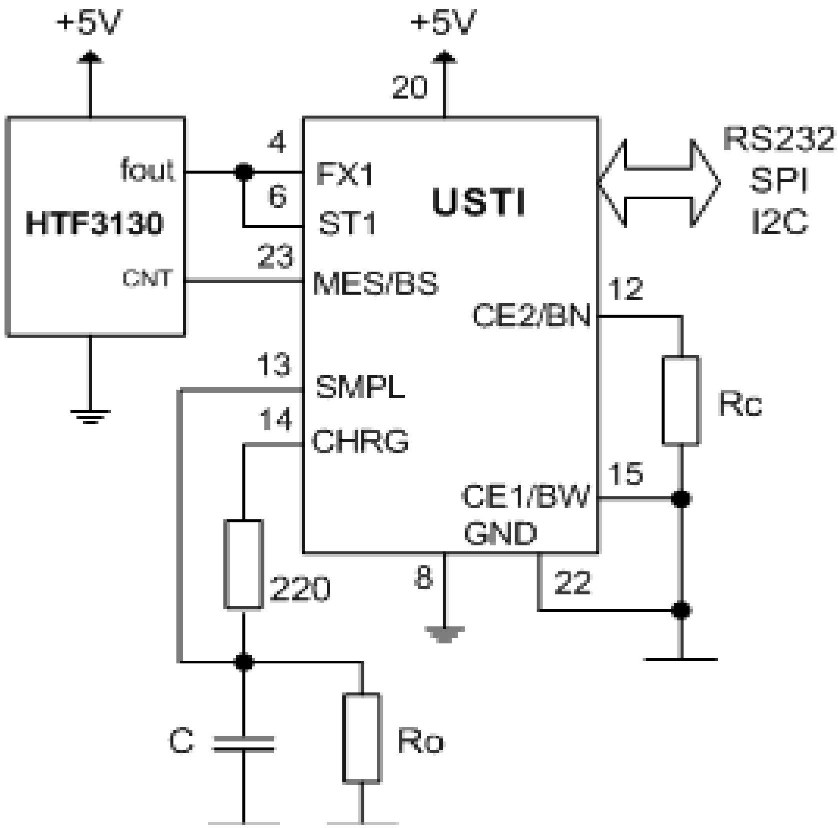
Low-Cost Smart Self-Adaptive Humidity Sensors





Oscillograms on humidity sensor's output at 58 % RH

Humidity and Temperature Sensor System: Hardware

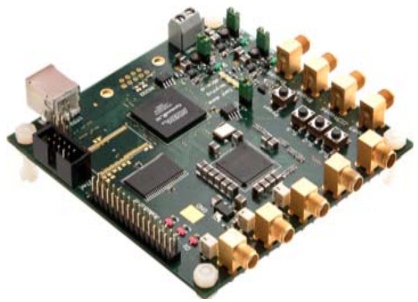


Humidity and Temperature Sensor System: Commands

>M00	; Set up a frequency measurement mode in the 1st channel
>A02	; Set up the relative error 0.25 %
>S	; Start a frequency measurement (humidity)
>C	; Check result status: returns ‘r’ if ready or ‘b’ if busy
>R	; Read a result of frequency measurement (humidity)
>M10	; Set a resistance *Rx* measurement mode
>E263000.0	; Set the reference value of *Rc* =263 kΩ
>W1B	; Set the charging time 100 ms
>S	; Start a resistive measurement (temperature)
>C	; Check result status: returns ‘r’ if ready or ‘b’ if busy
>R	; Read a result of resistive measurement (temperature)

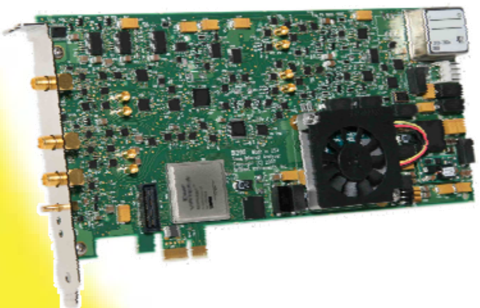
High Performance Digital Sensors Design

DAQ Systems and Modules



Picosecond Timing System (EOS Optronics, GmbH, Germany)

Time/Frequency Counter 2X00 (Vigo System S.A., Poland)



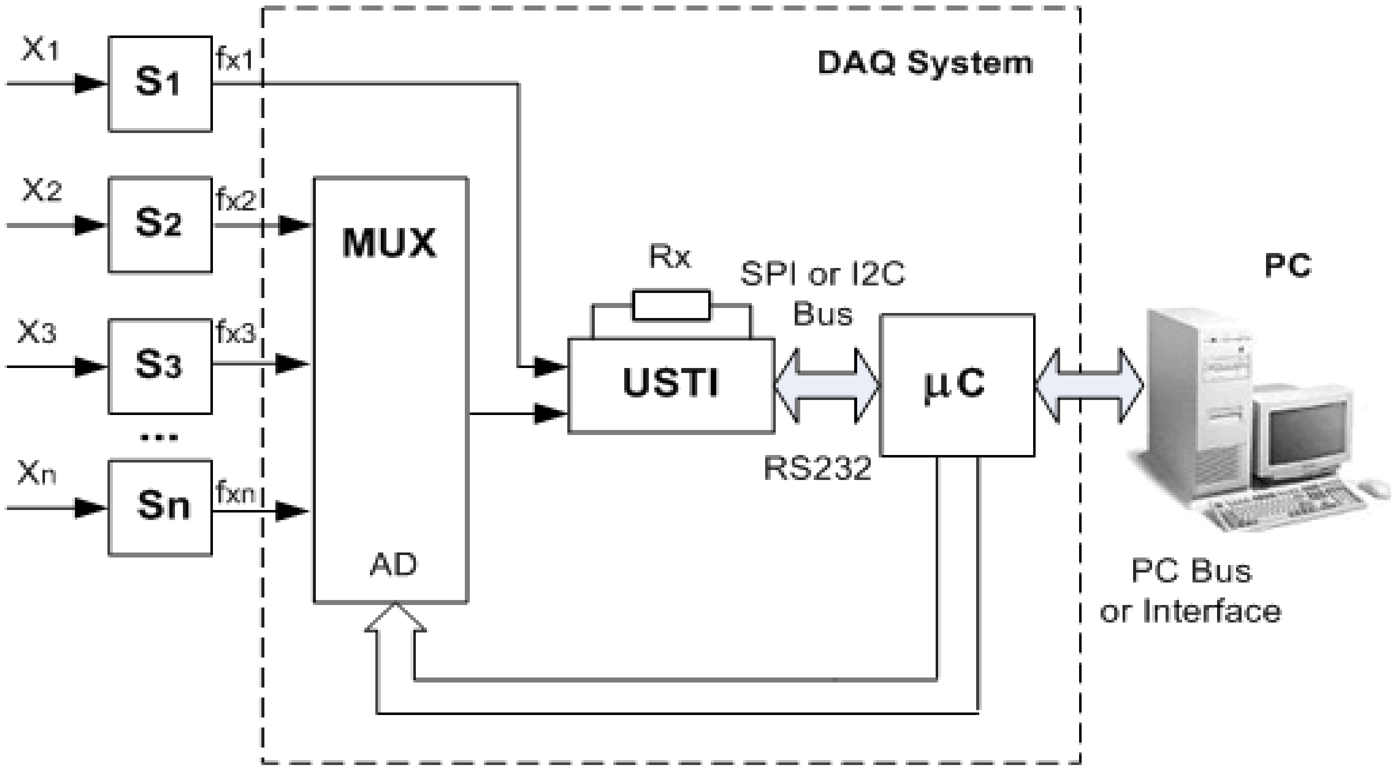
BI200 Time Interval Analyzer (Brilliant Instruments, Inc., USA)

Type	fx max, MHz	Number of Channels	Error, %
Timing I/O Board, *National Instruments* (USA)			
PC-TIO-10	7	10	0.01
NI 660X	20 … 80 (60 …125)*	4 … 8	0.005 (clock accuracy)
PCI-DAQ Boards *Kiethley* (USA)			
KPCI-31XX	5 (20)**	3 … 4 (8)**	n/a
Frequency-input Card, *IOTECH* (USA)			
DBK7	0.95	4	0.1 (relative error)
Counter and Digital I/O Board, *Mielhaus Electronic* (Germany)			
ME-1400A/B	10	3 … 6	0.01
Time-to-Digital Converter, *Agilent-Acqiris* (USA)			
TC840	20 s (time interval)	12	0.0002 (clock accuracy)
DAQ System *Intelligent Instrumentation* (USA)			
UDAS-1001E	10	1	n/a
Multi-Function Counter/Timer Card *ADLINK Technology* (Taiwan)			
ACL-8454/X	10	6 … 12	n/a
PCI-8554	10	16	n/a
Timer/Counter Boards, *OMEGA* (USA)			
CIO-CTR10HD	7	10	n/a
CIO-CTR20HD	7	20	n/a
Timer/Counter Boards, *Contec* (Japan)			
CNT16-32S	0.2	32	n/a
CNT24-4	1	4	n/a
TCR-10	7	10	n/a
Frequency Module, *NPP Mera* (Russia)			
MC-451	0.01 Hz … 400 kHz	8	0.001 ÷ 0.01 (FS error)
Digital I/O and Counter Card, *Advantech* (USA)			
PCL-720	2.6	3	n/a
Timer/Counter Boards, *Axiom* (Taiwan)			
AX5216	7	5	n/a
AX5218	7	10	n/a
AX5220	10	3	n/a
Field Module, *MicroControl* (Germany)			
µCAN.4.ci-BOX	0.5	4	0.1 Hz (resolution)

DAQ Systems Features

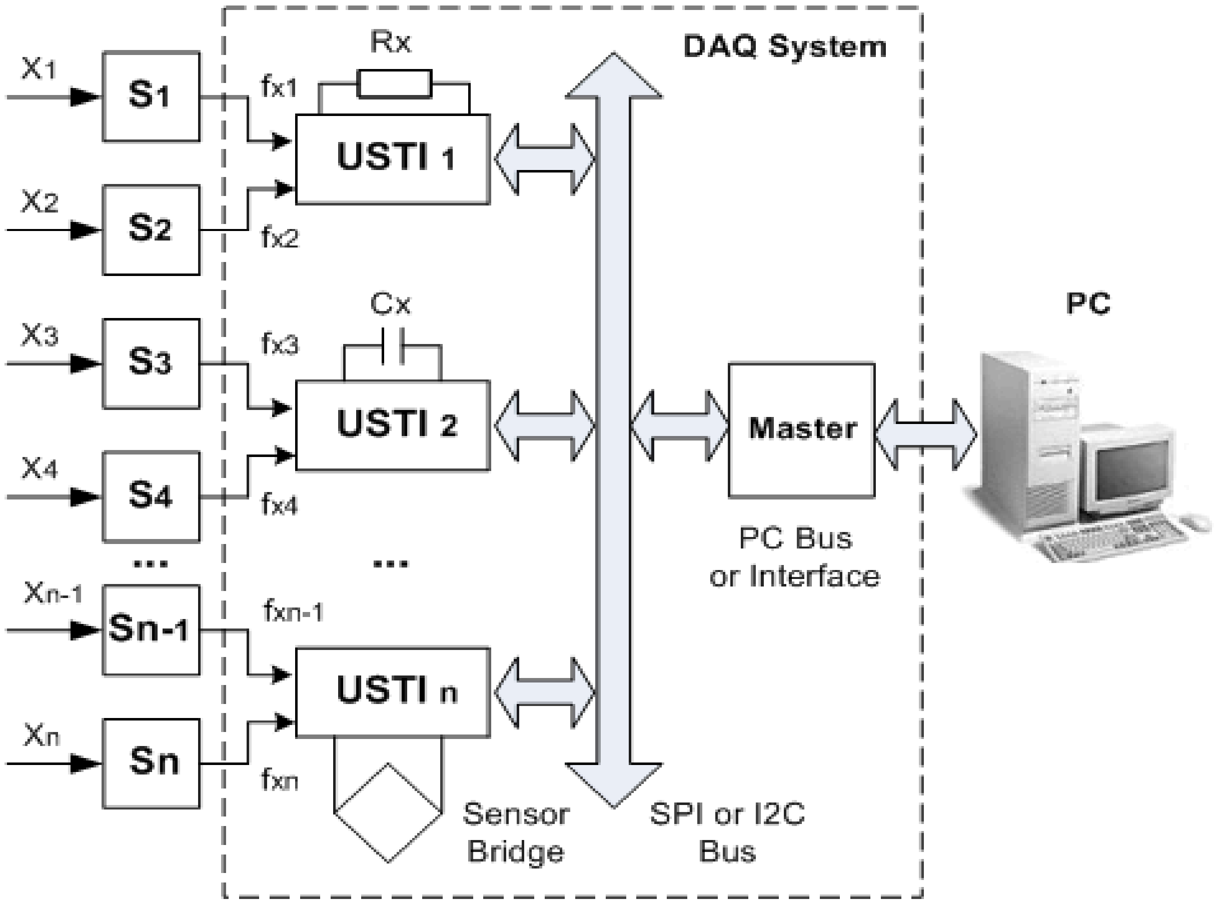
- More or less good maximum frequency range f_{xmax}
- Excellent number of channels (up to 32)
- Low accuracy due to use of classical methods for frequency measurement
- Mostly satisfy programmers (due to software and drivers) but not metrologist

DAQ System with Time-Division Channeling

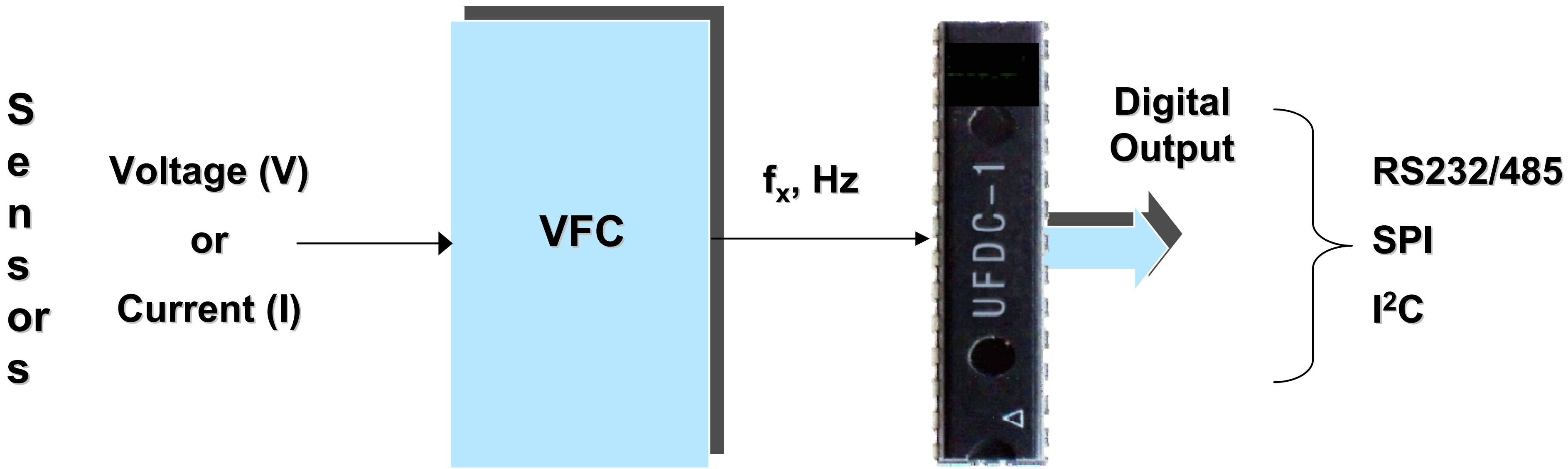


$$\tau = n \cdot (T_{meas} + \tau_{delay1} + \tau_{delay2})$$

DAQ System with Combined Space- and Time-division Channeling

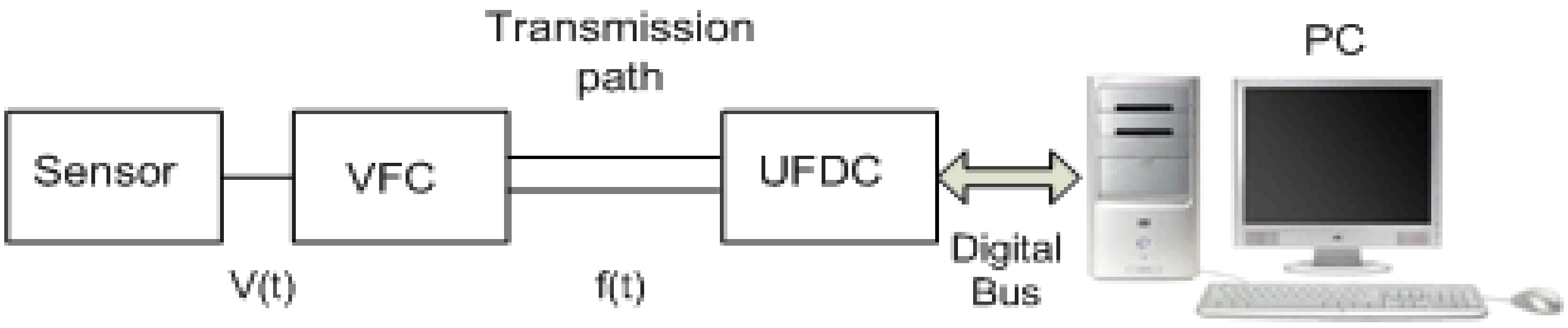


UFDC-1 / USTI and Analog Signal Domain

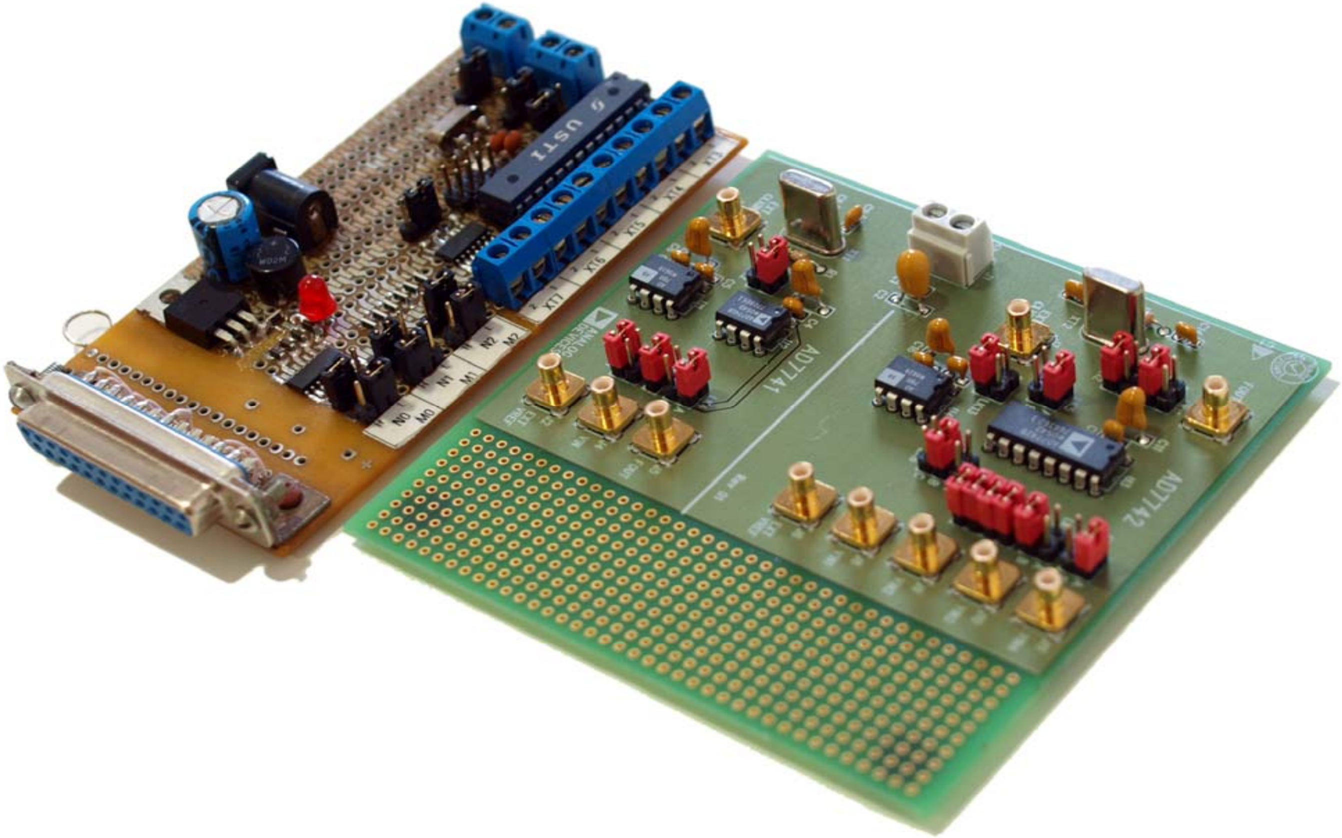


Any Voltage-to-Frequency Converter (VFC) can be used to convert an analog signal to quasi-digital (frequency) signal

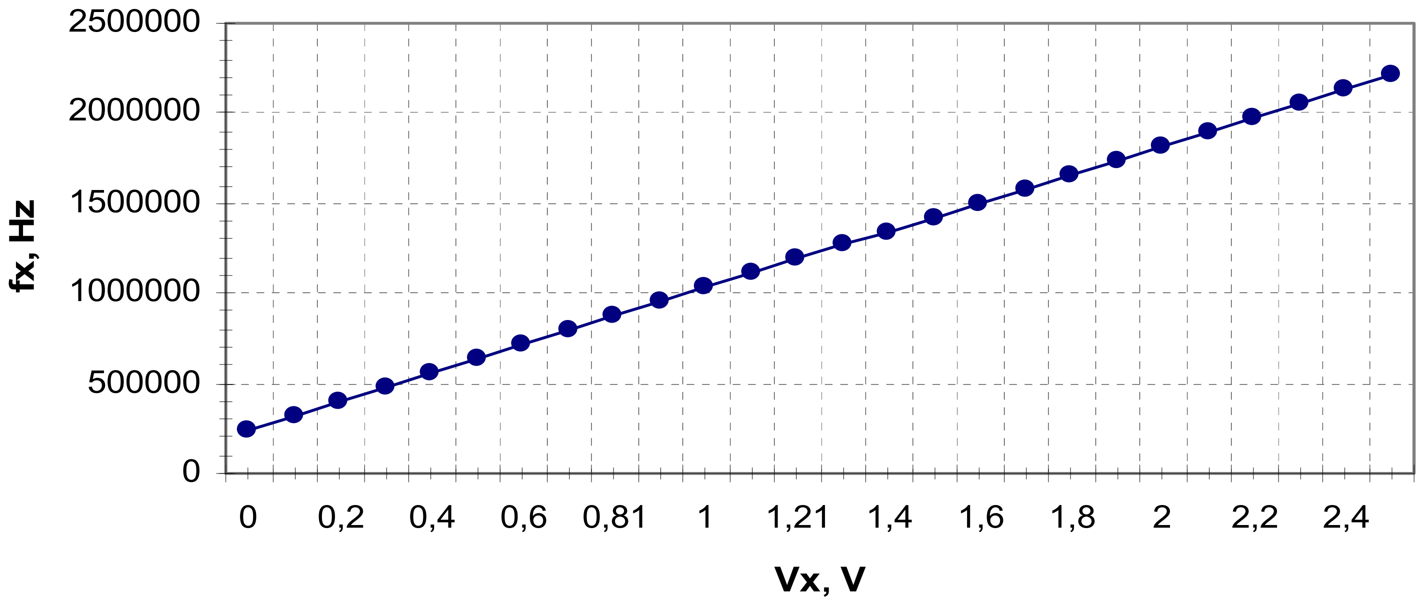
Data Acquisition System for Remote Sensors



DAQ Board Prototype



Experimental Results



Measurement Time Calculation

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

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

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

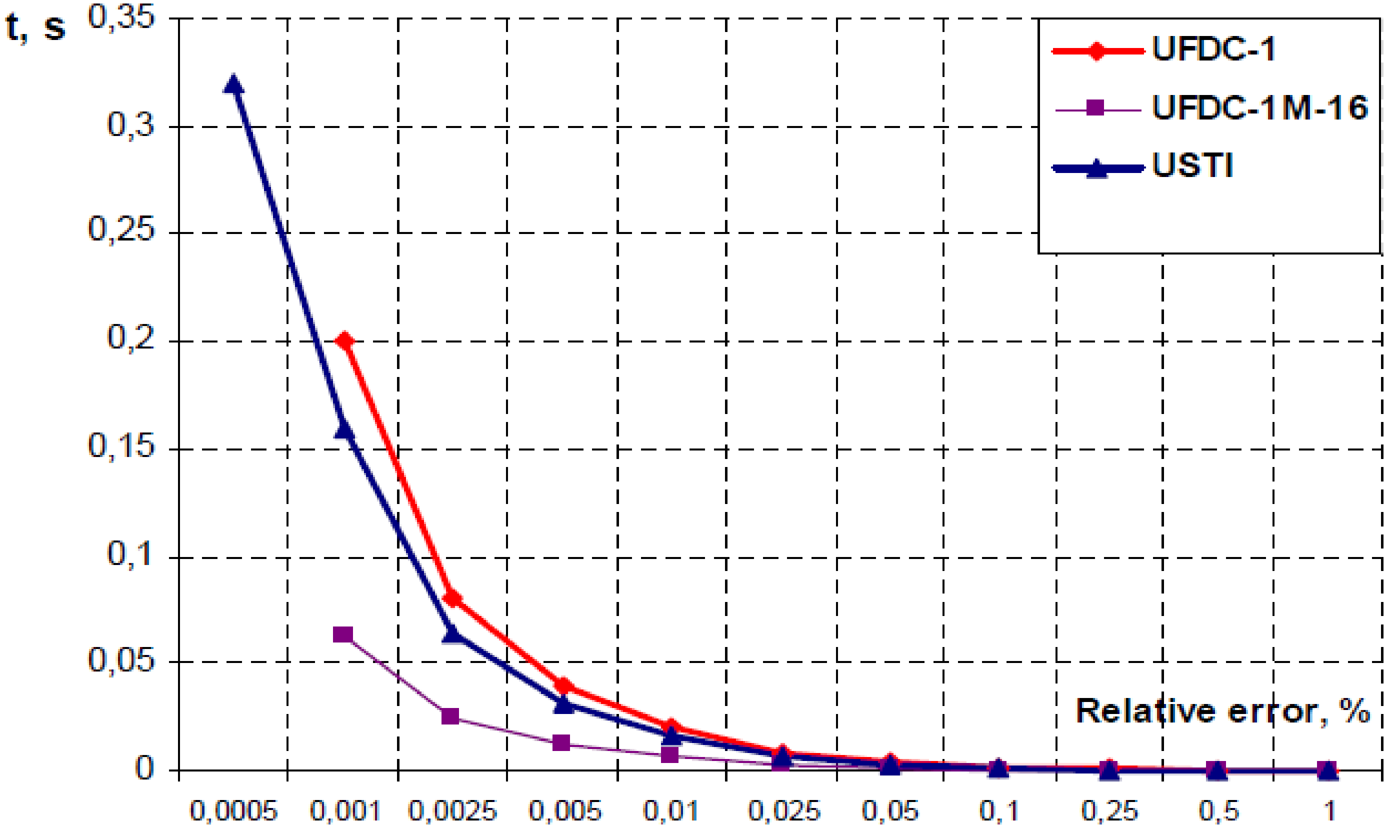
- **For I²C interface:** $$t_{comm} = 8 \cdot n \cdot \frac{1}{f_{SCL}}$$

  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).

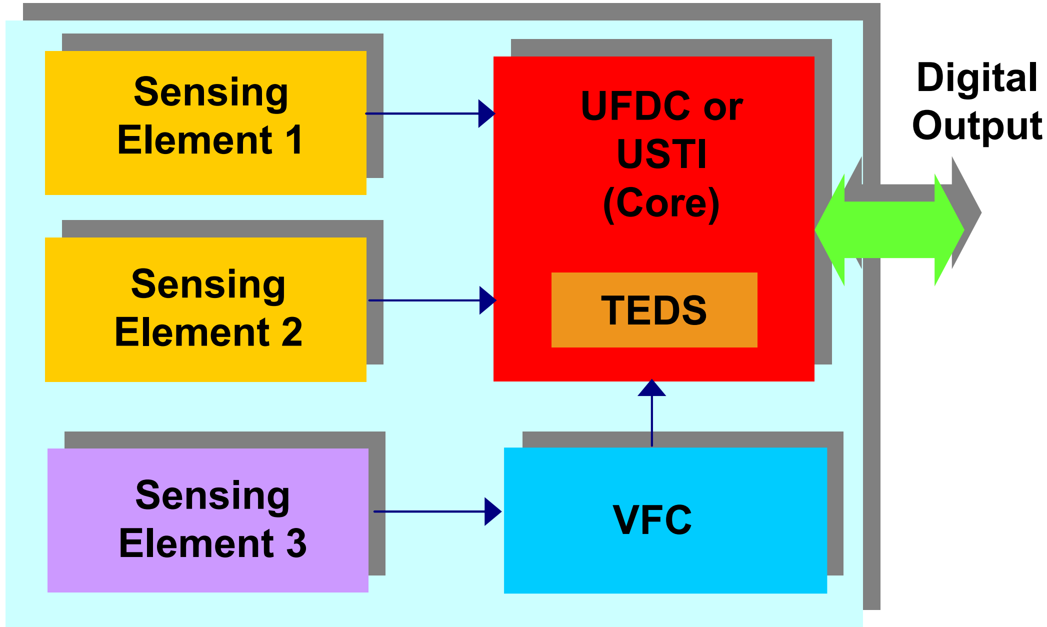
Relative Error vs. Conversion Time

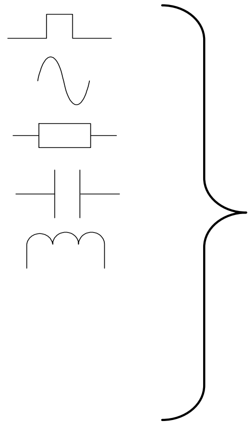
Relative error, δ_x %	$N_\delta = 1/\delta_x$	UFDC-1 (at f_0=500 kHz)	UFDC-1M-16 (at f_0=16 MHz)	USTI (at f_0=625 kHz)	USTI-EXT (at f_0=16 MHz)
		t_{conv}, s			
1	100	0.0002	0.00000625	0.00016	0.00000625
0.5	200	0.0004	0.0000125	0.00032	0.0000125
0.25	400	0.0008	0.000025	0.00064	0.000025
0.1	1000	0.002	0.0000625	0.0016	0.0000625
0.05	2000	0.004	0.000125	0.0032	0.000125
0.025	4000	0.008	0.00025	0.0064	0.00025
0.01	10000	0.02	0.000625	0.016	0.000625
0.005	20000	0.04	0.00125	0.032	0.00125
0.0025	40000	0.08	0.0025	0.064	0.0025
0.001	100000	0.2	0.00625	0.16	0.00625
0.0005	200000	-	-	0.32	0.0125

Conversion Times vs. Relative Error



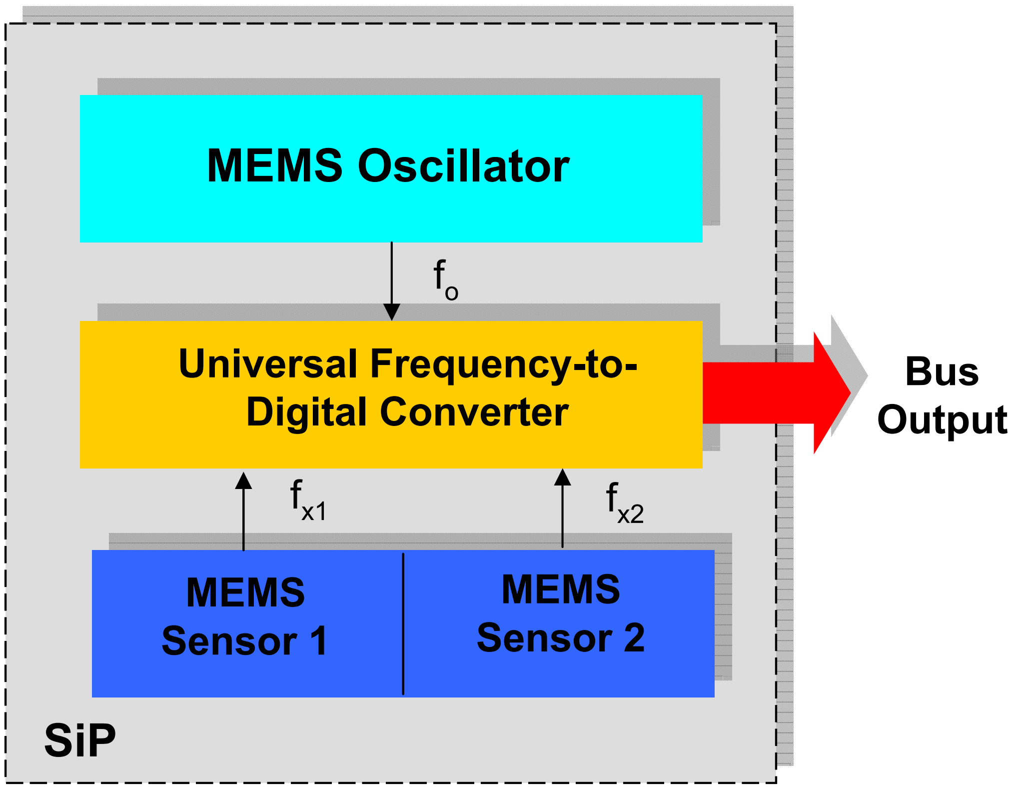
SoP and SiP



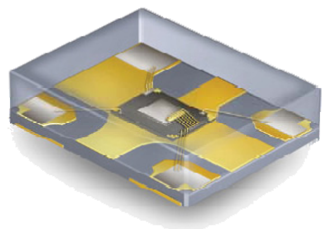


Sensors and
sensing elements

System-in-Package



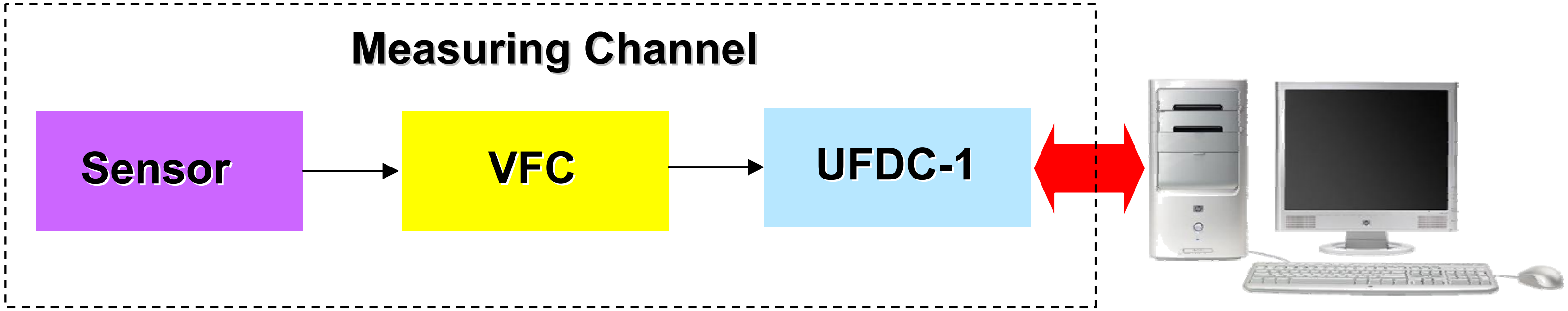
- Sensors system does not require any external time or frequency references
- UFDC lets solve problems with the interface circuit design and additional circuitry for MEMS oscillators in order to increase its short frequency stability



High Performance Digital Sensors Design

1. Introduction: Markets and Definitions
2. Modern Challenges
3. Digital Sensors Design: Introduction
4. Advanced Digital Sensors Design
5. Smart Sensor Systems Integration
7. Sensor System's Error Estimation
8. The Future and Summary

Measuring Channel



Relative Error's Components:

$\pm\delta_s$, %

$\pm\delta_{VFC}$, %

$\pm\delta_q$, % - quantization error

$\pm\delta_o$, % - reference error

Main considerations:

- UFDC's relative error (δ_q) must be in one order less (or at the lease in 5 times less than the sensor's error)
- The reference error for calibrated UFDC-1 is δ_o=0.00001 %

Error Summation

$$\delta_{\Sigma} = \delta_s + \delta_{VFC} + \delta_q + \delta_o$$

- an overestimation in 2-4 times !

$$\sigma_{\Sigma} = \sqrt{\sigma_s^2 + \sigma_{VFC}^2 + \sigma_q^2 + \sigma_o^2},$$

where σ_s, σ_{VFC}, σ_q, σ_0 are the root-mean-square deviations of appropriate components of error

Input Data

Error's Component	Relative Error, %	Distribution Law	Root-mean Square Deviation, %
Sensor' error	δ_s^*	Normal (Gaussian)	$\sigma_s = \frac{\delta_s}{2.3}$
VFC's error	δ_{VFC}^*	Normal (Gaussian)	$\sigma_{VFC} = \frac{\delta_{VFC}}{2.3}$
Quantization error	δ_q^{**}	Triangular (Simpson's)	$\sigma_q = \frac{\delta_q}{\sqrt{6}}$
Reference error	$\delta_0 = 0.00001$	Uniform	$\sigma_0 = \frac{\delta_0}{\sqrt{3}}$

* - should be found in data sheets

** - should be chosen according to the consideration

Output Data

$$\sigma_{\Sigma} = \sqrt{\sigma_s^2 + \sigma_{VFC}^2 + \sigma_q^2 + \sigma_o^2}$$

$\delta_{\Sigma} = 1.64 \times \sigma_{\Sigma}$ - for up to 3 components at p=0.9

$\delta_{\Sigma} = 1.96 \times \sigma_{\Sigma}$ - for 4 components and more at p=0.95

The distribution law of resulting error should be accepted as close to the normal (Gaussian) distribution

Example

A sensor system consist of an analog pressure sensor, for example, Type 740C Baratron from *MKS Instruments, Inc.* with the voltage output (0-10 V) and full scale error $\delta_s = \pm 0.1$ % ; a voltage-to-frequency converter (μ 2.0 Series from *Canopus Instruments*), with the relative error $\delta_{VFC} < \pm 0.1$ %, and non-calibrated UFDC-1 IC with the 30 ppm ($\delta_{fo} = \pm 0.003$ %) low cost quartz crystal oscillator form *Siward Crystal Technology Co., Ltd.*

Error's component	Relative error, %	Distribution law	Standard mean square error, %
Sensor's error	$\delta_s = \pm 0.1$	Gaussian	$\sigma_s = \frac{\delta_s}{1.96} = \pm 0.051$ %
VFC's error	$\delta_{VFC} = \pm 0.1$	Gaussian	$\sigma_s = \frac{\delta_s}{1.96} = \pm 0.051$ %
Quantization error	$\delta_q = \pm 0.01$	Triangular	$\sigma_q = \frac{\delta_q}{\sqrt{6}} = \pm 0.0041$ %
Reference error	$\delta_{fo} = \pm 0.003$	Uniform	$\sigma_{fo} = \frac{\delta_{fo}}{\sqrt{3}} = \pm 0.0017$ %

Calculations and Result

$$\sigma_{\Sigma} = \sqrt{0.051^2 + 0.051^2 + 0.0041^2 + 0.0017^2} =$$

$$= \sqrt{0.0026 + 0.0026 + 0.000017 + 0.0000029} = \sqrt{0.00522} = 0.0723$$

$$\delta_{0.95\Sigma} = \sigma_{\Sigma} \times 1.96 = \pm 0.0723 \times 1.96 = \pm 0.142\,\%$$

The confidence interval for the total sensor system's error with probability *P*=0.95 is $\delta_{0.95\Sigma} \in$[- 0.142 % … + 0.142 %].

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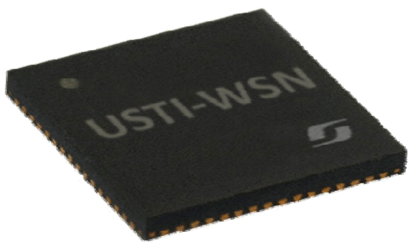
The Future

- USTI-WSN
- UST-MOB
- FDCP
- SoC/SiP

USTI-WSN

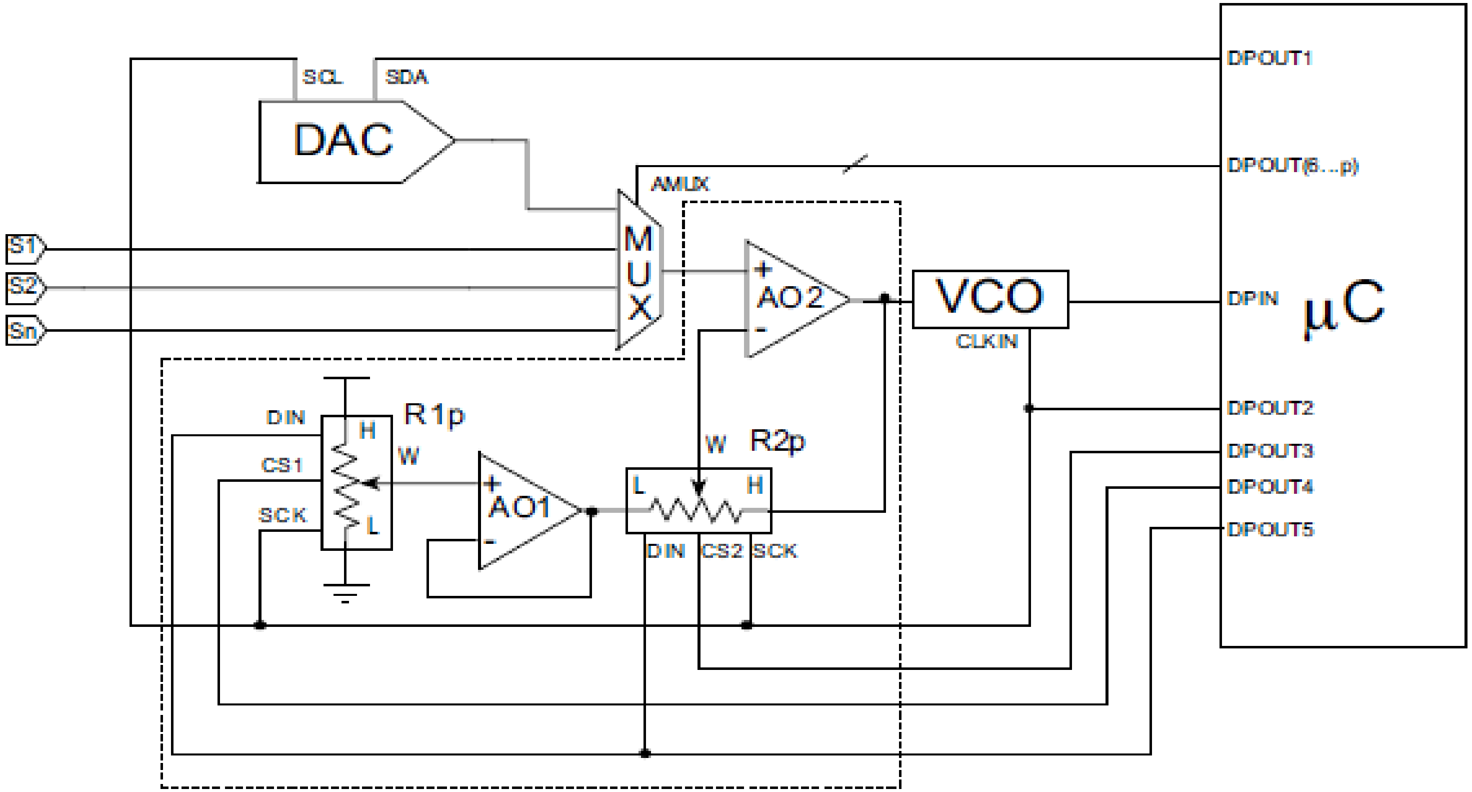


- The same metrological performance and functionality as USTI IC
- Includes RF-CMOS 2.4 GHz radio transceiver
- IEEE 802.15.4, ZigBee, IPv6/6LoWPAN, RF4CE, SP100, WirelessHART and ISM applications
- Supply voltage is 3.6 V
- Power consumption is less than 18.8 mA in active mode
- 64-pad QFN package

Traditional Approach

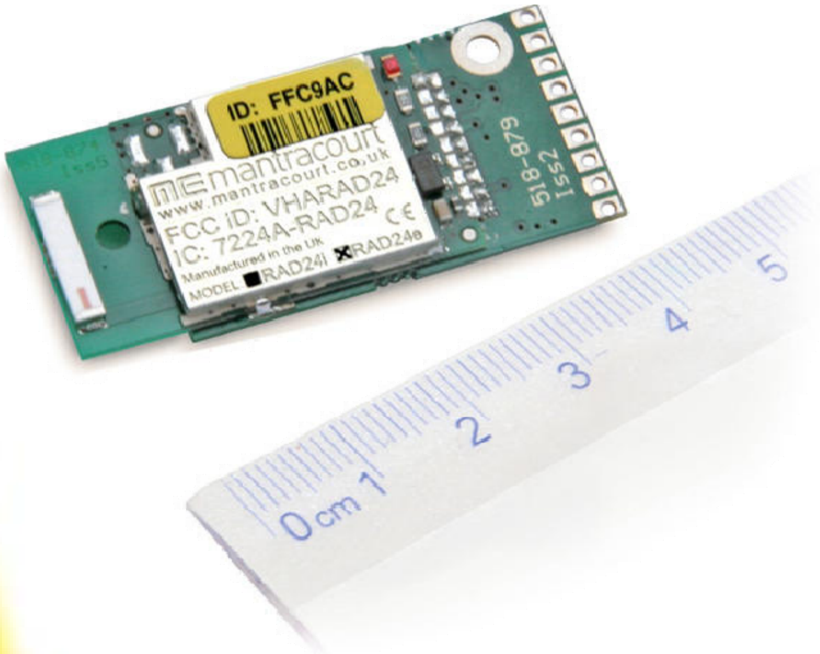
- Analog sensors with voltage or current outputs
- Analog multiplexer
- Multichannel ADC

Sensor Node Interface



A. Bayo, N. Medrano, B. Calvo, S. Celma, A Programmable Sensor Conditioning Interface for Low-Power Applications, *Proc. of the Eurosensors XXIV*, 5-8 September, 2010, Linz, Austria, Procedia Engineering, Vol. 5, 2010, pp. 53–56.

Wireless Telemetry Pulse Acquisition Module T24-PA



- Frequency range: 0.5 Hz … 3 kHz
- Relative error: 0.15 % …0.25 %
- Frequency, time and RPM measuring modes

mantracourt
Advanced Intelligent Instrumentation

Pulse-to-Wireless Converters

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Advanced Intelligent Instrumentation

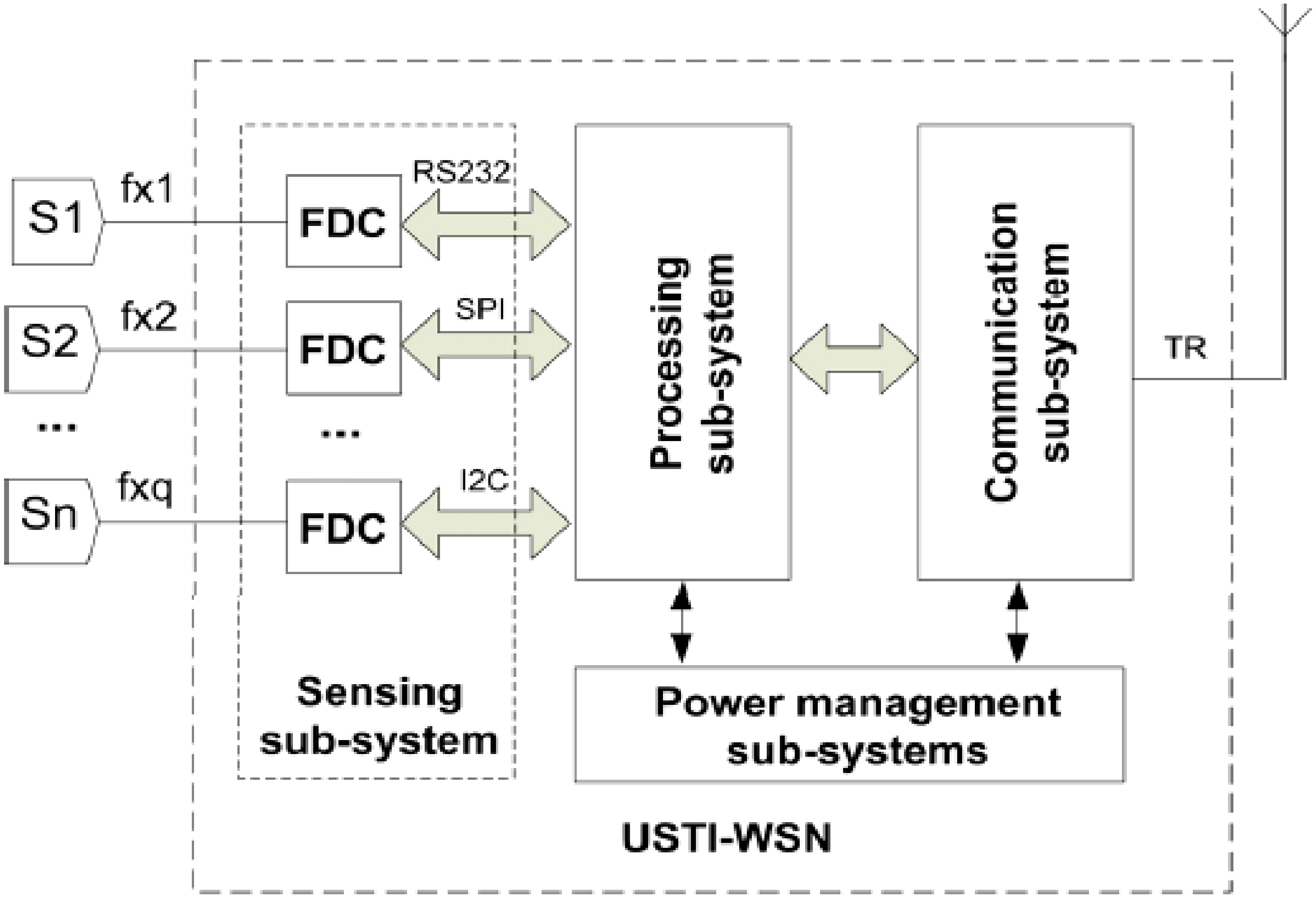
Sensor Node Architecture

- Sensing Sub-system
- Processing Sub-system
- Communication Sub-system
- Power Management Sub-system

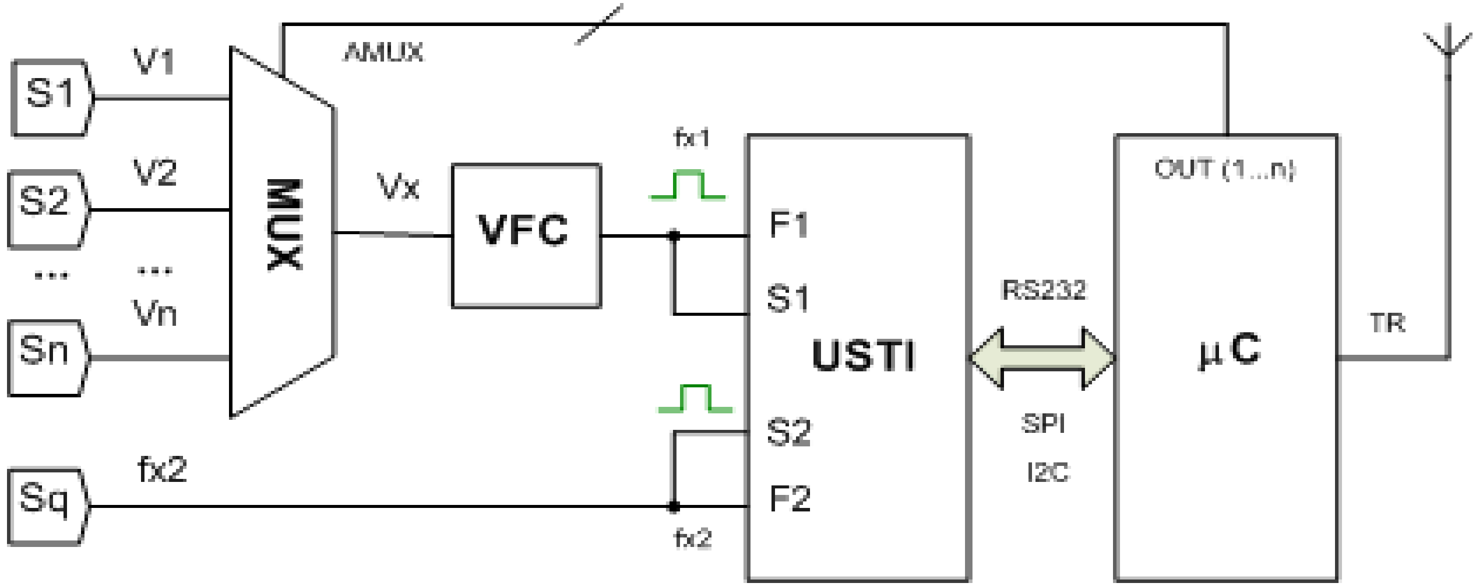
Sensor Node Architecture

- Sensing Sub-system
- Processing Sub-system
- Communication Sub-system
- Power Management Sub-system

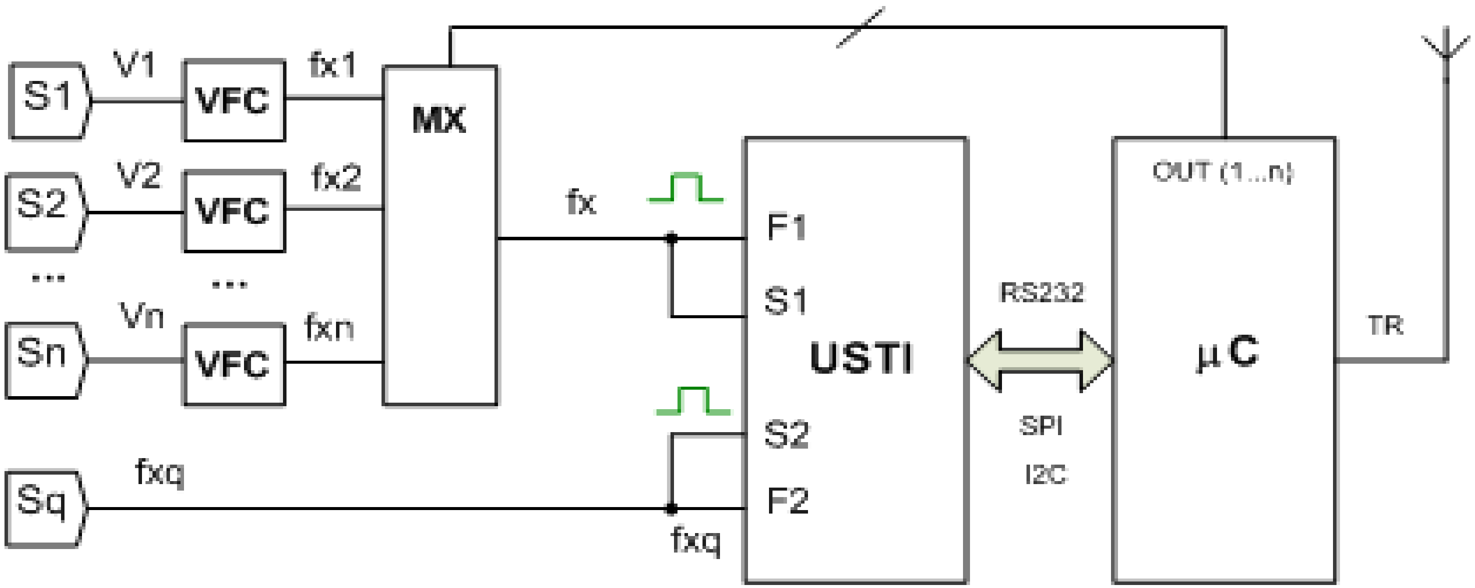
Node on Chip


S1
fx1
S2
fx2
...
Sn
fxq
FDC
FDC
...
FDC
RS232
SPI
I2C
Sensing sub-system
Processing sub-system
Communication sub-system
TR
Power management sub-systems
USTI-WSN

Sensor Node Architecture with Analog Multiplexer

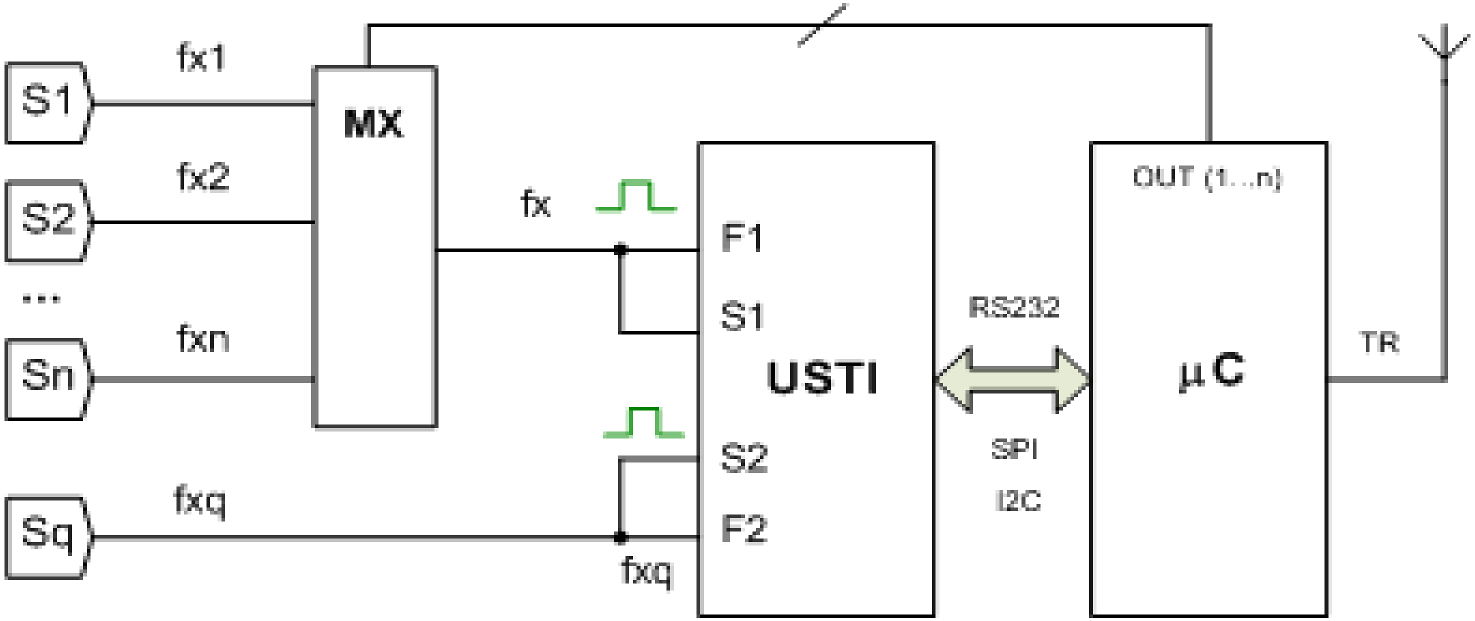


Sensor Node Architecture with Digital Multiplexer



$$\tau = n \cdot (T_{meas} + \tau_{delay\,1} + \tau_{delay\,2})$$

Sensor Node for Quasi-Digital Sensors and Transducers



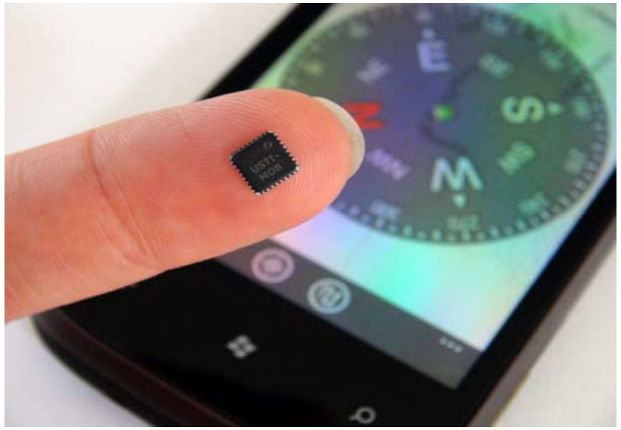
Comparative Performances

Parameter		
	T24-PA	USTI IC
Relative error, %	0.15 … 0.25	0.0005
Frequency Range, Hz	0.5 … 3 000	0.04 … 9 000 000
Time range, s	333E-06 … 2	1.5E-06 … 250
RPM range (presuming 1 pulse/rev), rpm	30 … 180 000	3 … unlimited
Power Supply Current, mA	35	9.5

Price Comparison

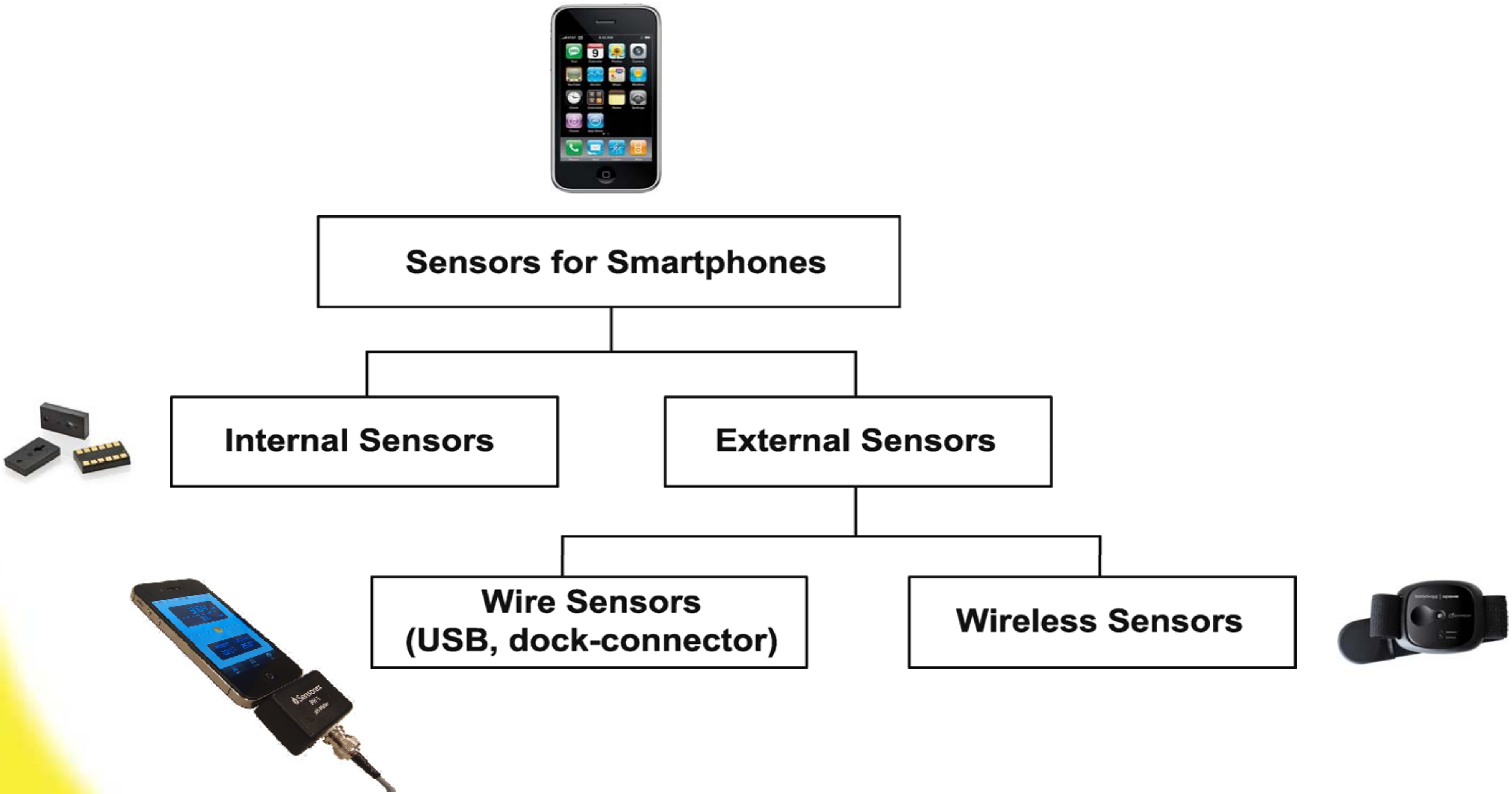
ICs	Manufacturers	Price, $ US (in quantities of 1, 000)
ADS1278, 24-bit, 8 channels, SPI	Texas Instruments	23.95
USTI, 3 channels, SPI, I2C, RS232 + any digital multiplexer	Technology Assistance BCNA, 2010, S.L.	18.95
	Saving:	23.95-18.95 = 5.00

USTI-MOB

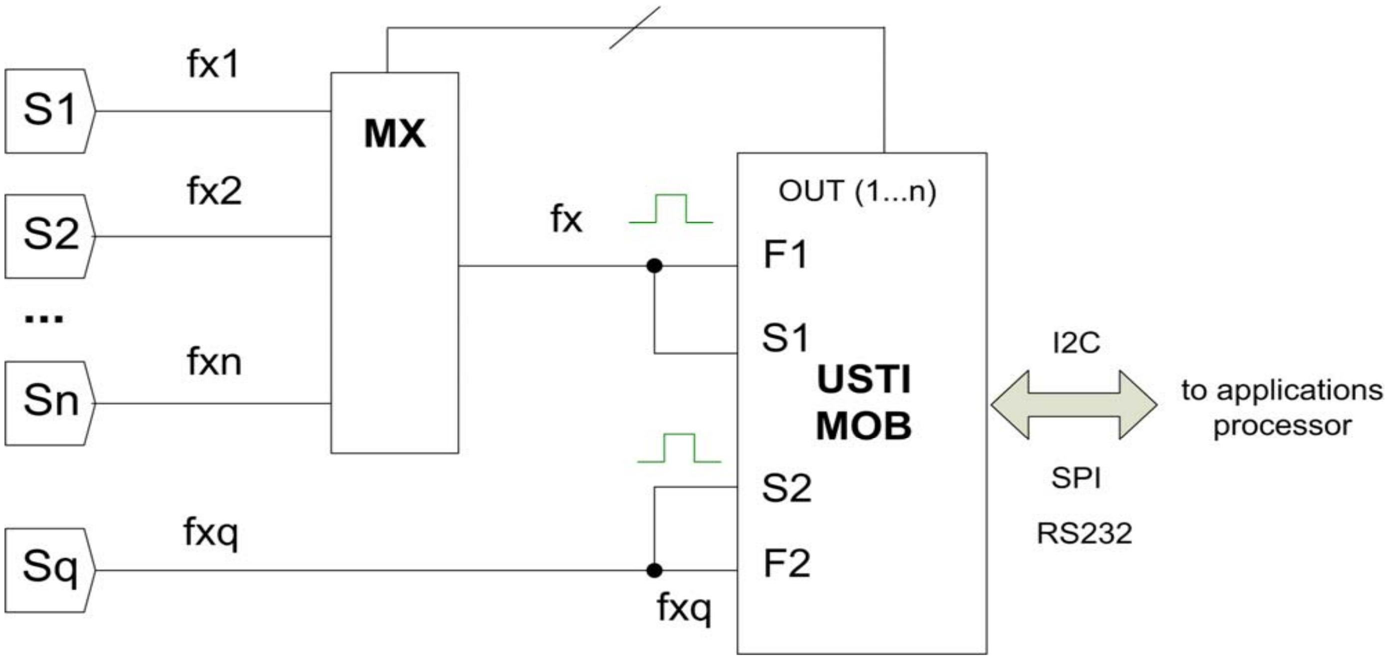


- Can measure all frequency-time parameters of signal
- Low relative error up 0.0005 %
- Wide frequency range: 0.25 Hz to 2 (32) MHz
- I2C, SPI and RS232 interfaces
- 2-channel + sensing elements
- Supply voltage: 2.7 V
- Active supply current < 3 mA
- 5 x 5 mm MLF package (4 x 4 mm MLF package is coming)

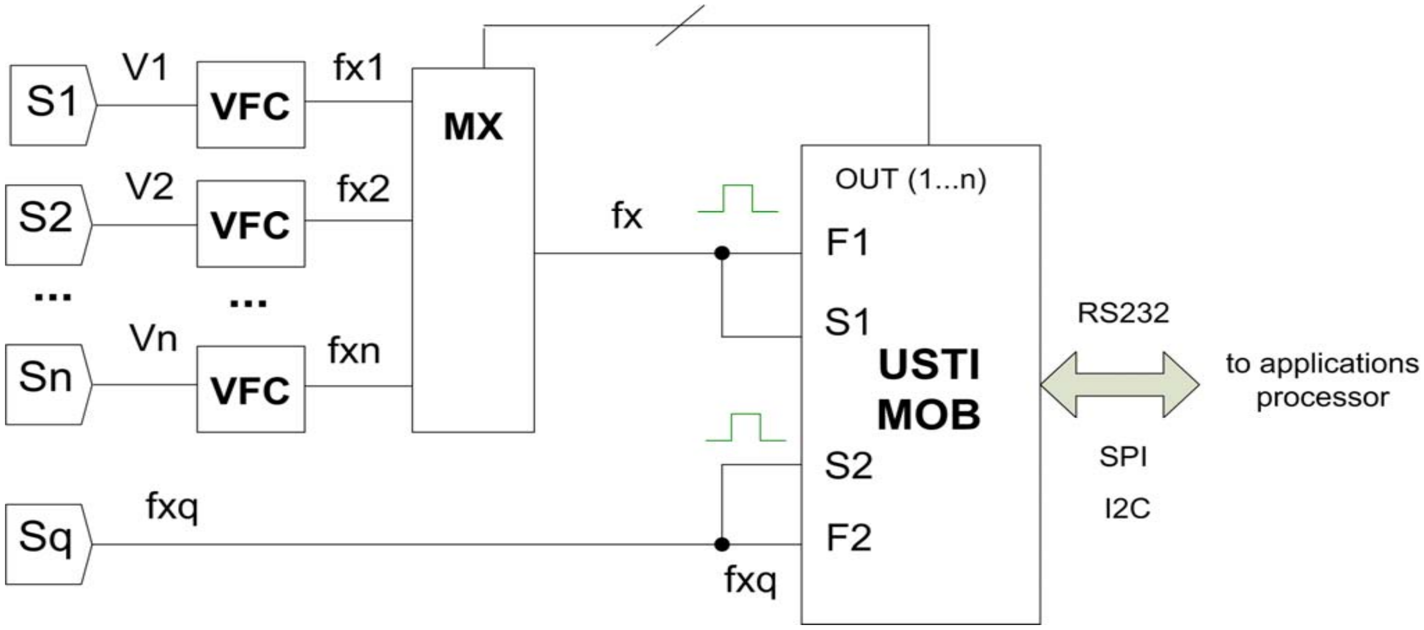
Smartphone Sensors Classification



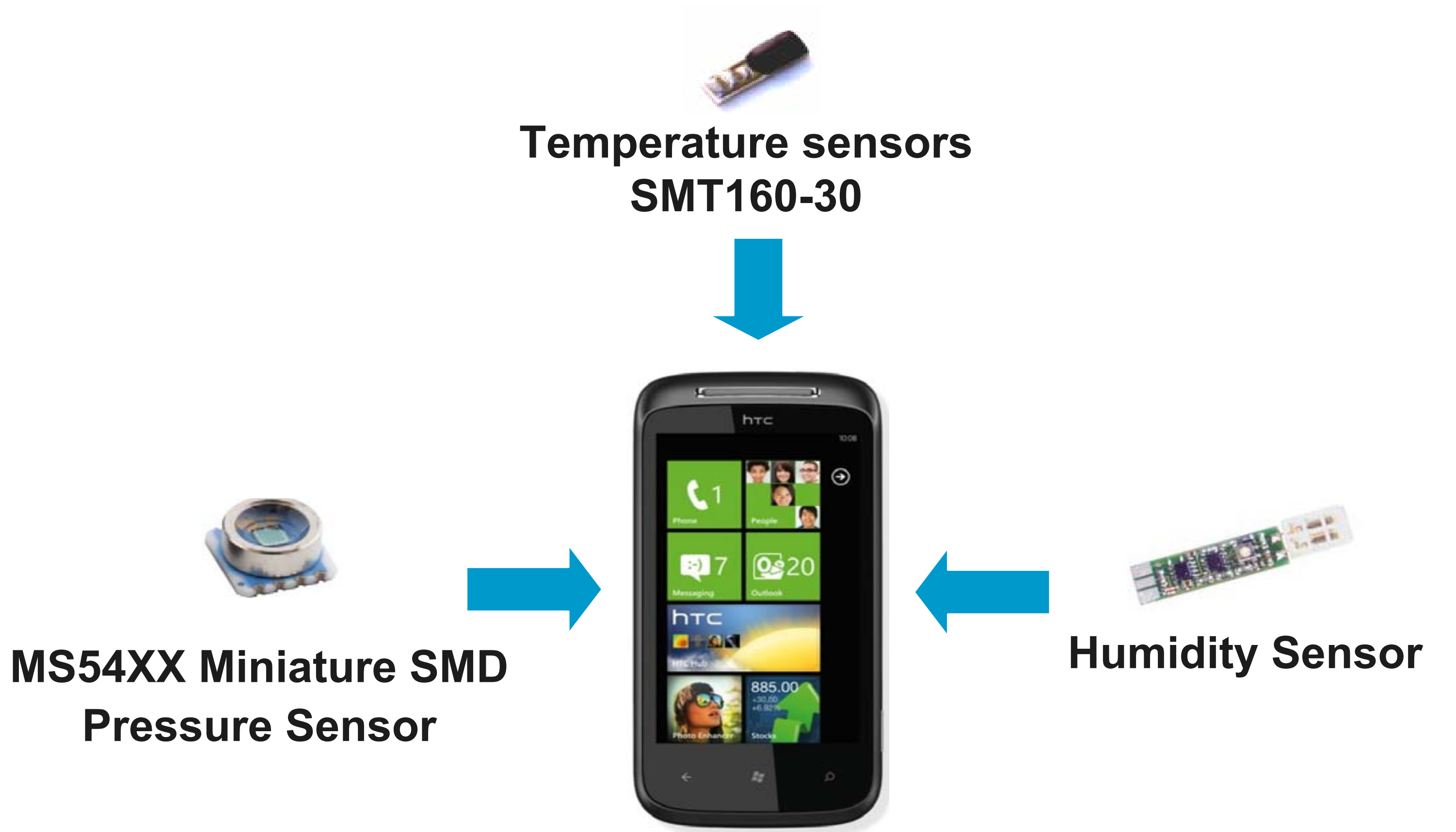
Multisensor System for Smartphones and Tablets



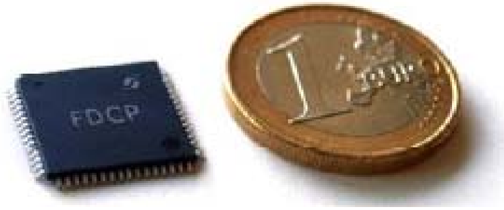
Analog Sensors Interfacing



Smartphone based Weather Station



Frequency-to-Digital Converter with Parallel Interface (FDCP)



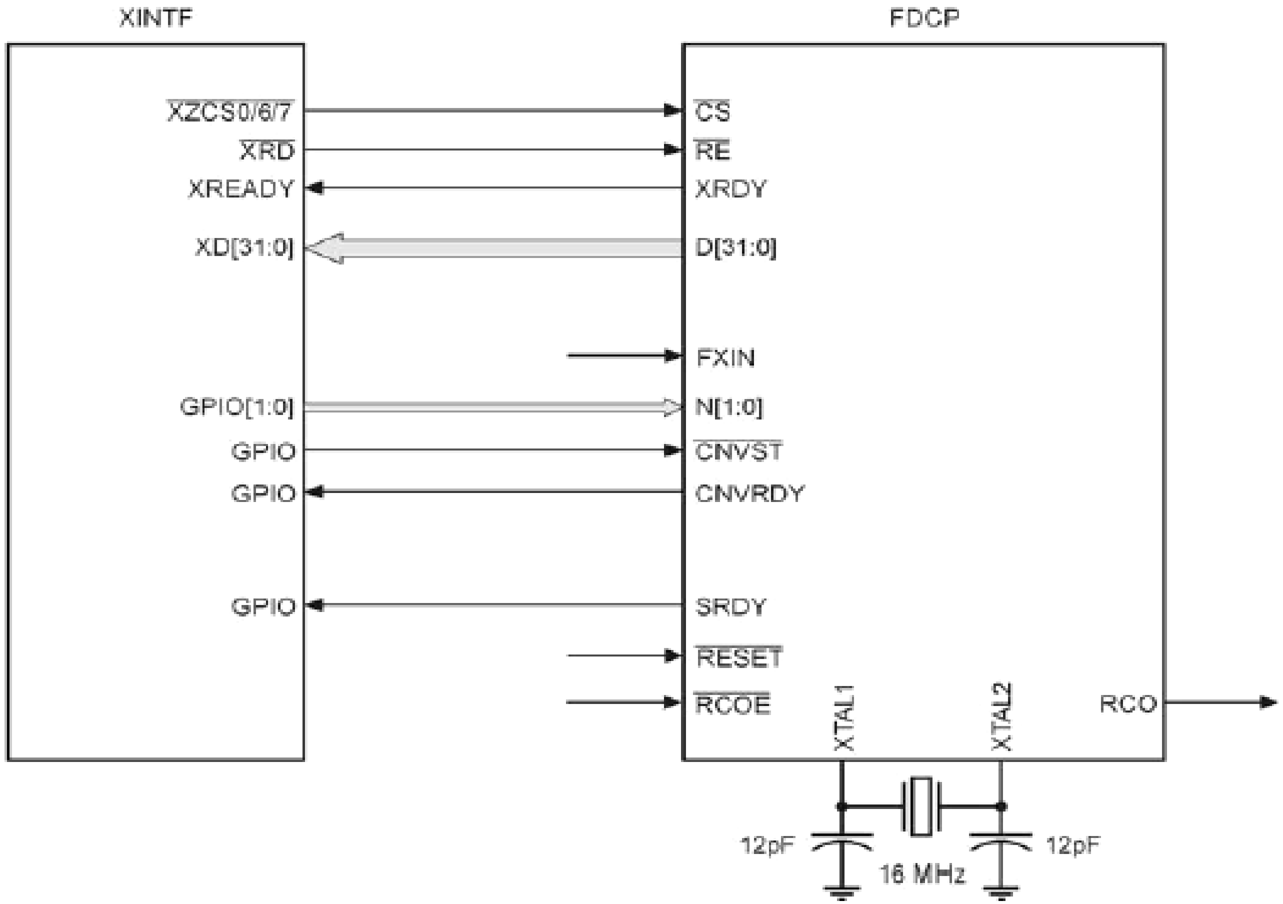
- Fully digital, low-power CMOS IC
- Non-Redundant conversion time 6.7 μs to 1.6.ms
- One generating output (fo=32 MHz
- 64-lead TQFP package 14 × 14 mm
- Parallel output: two 16-bit words N_x and N_r
- Slave communication mode

$$f_x = \frac{N_x}{N_r} \times f_0 \qquad T_x = \frac{N_r}{N_x \times f_0},$$

FDCP Metrological Performance and Electrical Characteristics

Parameter	Value
Minimal converted frequency, Hz	≥ 500
Maximal converted frequency, MHz	≤ 16
Programmable relative errors, %	1; 0.1; 0.01; 0.002 %
Microcontroller (DSP microprocessor) compatible parallel interface, bit	32
External clock oscillator frequency, MHz	16
Internal clock frequency, MHz	32
Supply current, mA	12
Power supply, V	3.3
Operating temperature range, ^{0}C	-40 to +85

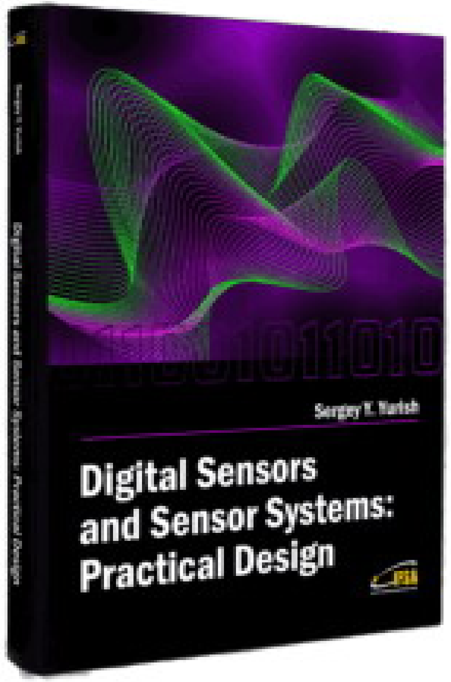
FDCP interfacing with the DSC TMS320F28335



Summary

- Quasi-digital sensors are more attractive due to easy system integration and advantages
- Proposed advanced design approach lets significantly increase a sensor system integration level and metrological performance
- A lot of different sensors can be integrated by the same way

Reading and Practice



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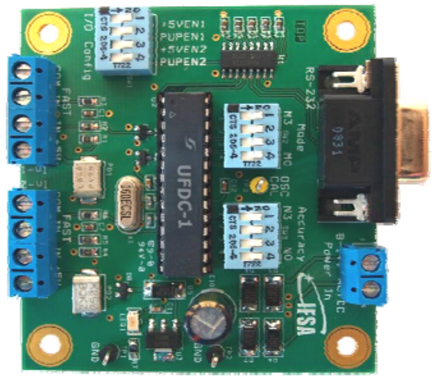

http://www.sensorsportal.com/HTML/BOOKSTORE/Digital_Sensors.htm

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Questions & Answers

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