Digital and Intelligent Sensors and Sensor Systems: Practical Design

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Tutorial, August 18, 2012, Rome, Italy

Outline

1. Introduction: Definitions and Markets
2. Modern Technologies
3. Smart Sensors Design: Introduction
4. Quasi-Digital Sensors State-of-the-art
5. Digital and Intelligent Sensors Design
6. Smart Sensor Systems Integration
7. Sensor System's Error Estimation
8. The Future and Summary

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Global Sensor Markets

- **Global Sensor Market** will reach US $ 76.7 billion by 2017 (*Global Industry Analysts*, *Inc*.)
- **European Sensor Market** will US $ 19.0 billion by 2016 (*Frost & Sullivan*)
- **Global Smart Sensors Market** to reach US$ 6.7 billion by 2017 (*Global Industry Analysts*, *Inc*.)
- Sensor networks and smart sensors are being used widely in automotive industry, medical, industrial, entertainment, security, and defence *(BizAcumen, Inc.)*
- Strong growth expected for sensors based on MEMS-technologies, smart sensors, sensors with bus capabilities and embedded processing.

Smart Sensor Definition

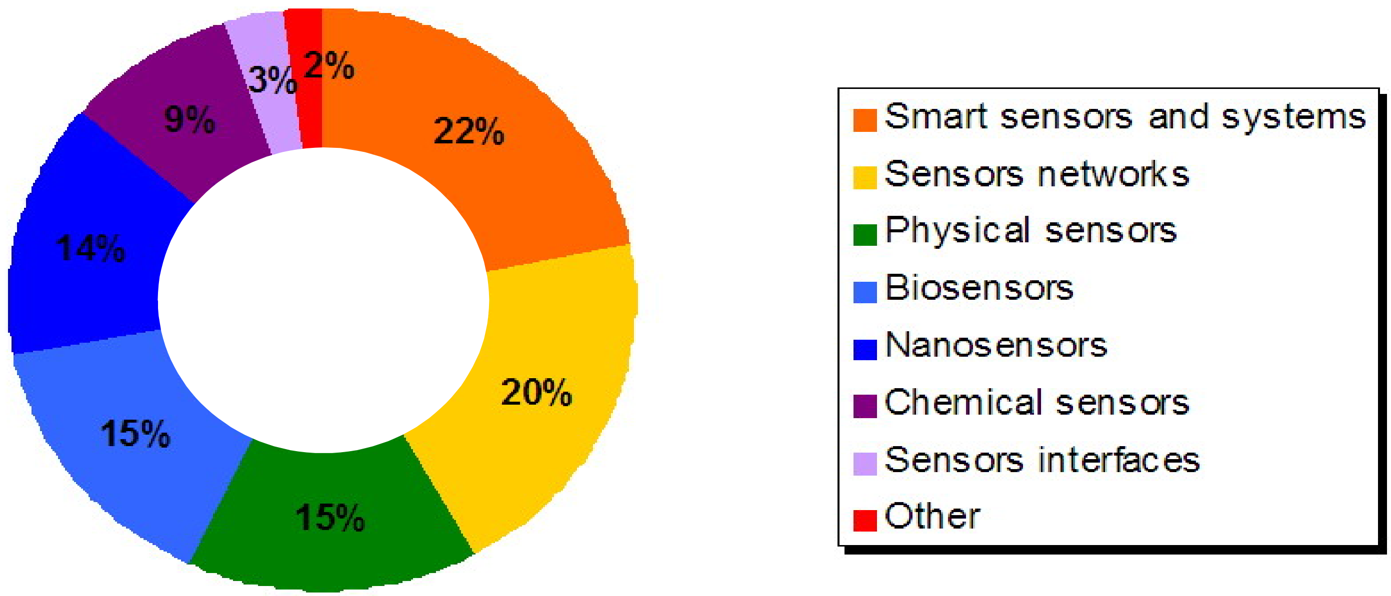
- Sensors: ‘Smart’ vs. ‘Intelligent’
- ‘Smart’ relates to technological aspects
- ‘Intelligent’ relates to intellectual aspects

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

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

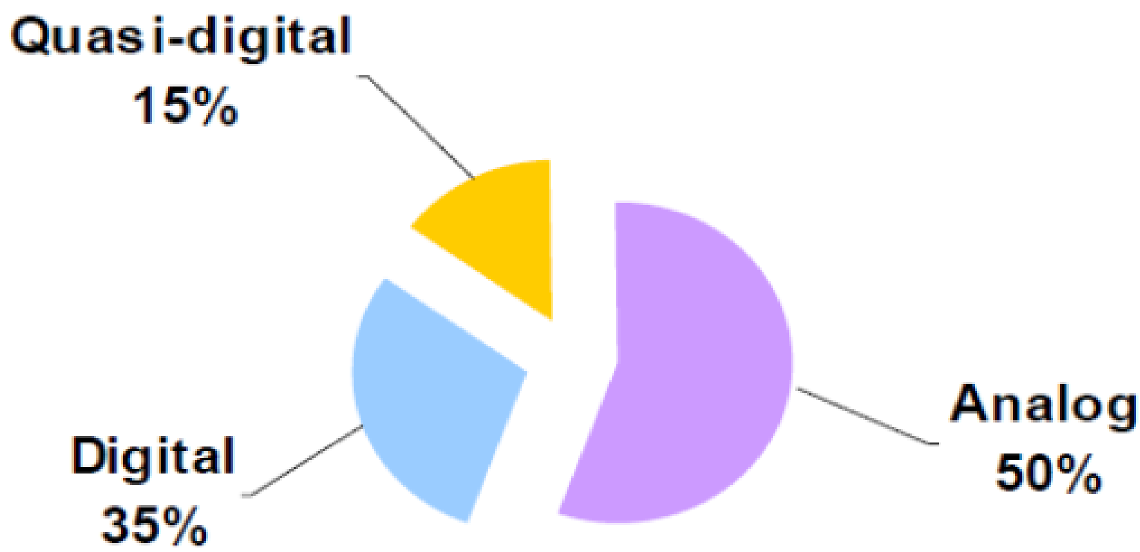
Smart and intelligent sensors and systems ?

Sensor Survey 2010



What is your topic of interest ?
(*Sensors & Transducers Magazine*, 520 respondents)

Sensor Types Divided According to Outputs



International Frequency Sensor Association (IFSA), Study, 2011

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

Analog and Quasi-Digital Sensors

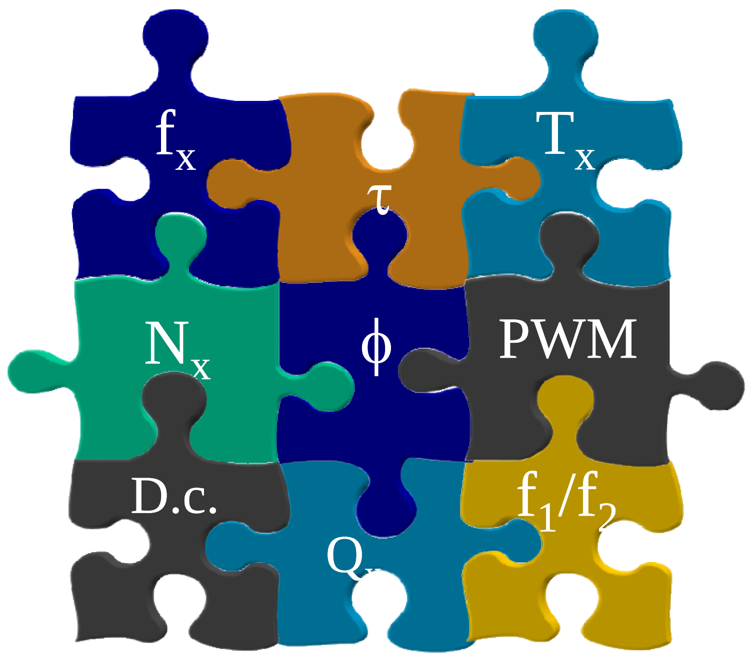
Analog sensor *- sensor based on the usage of an amplitude modulation of electromagnetic processes*

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

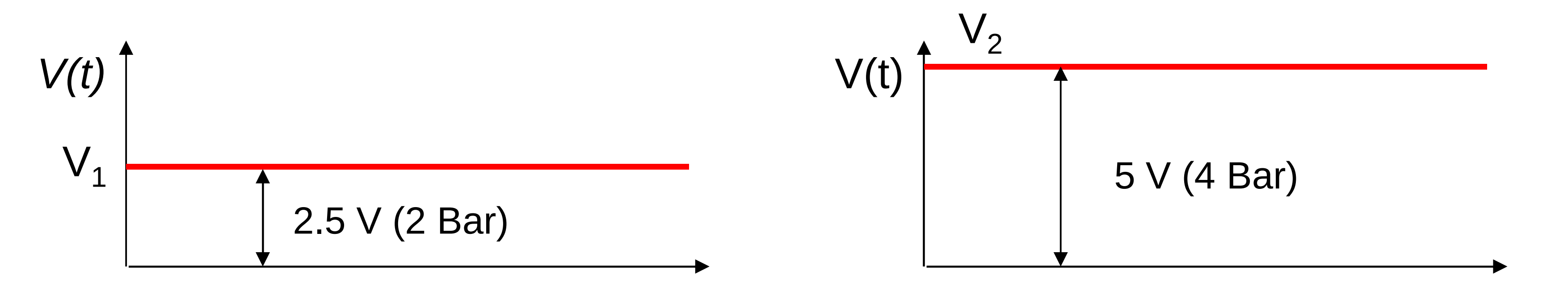
Quasi-digital sensors combine a simplicity and universatility that is inherent to analog devices and accuracy and noise immunity, proper to sensors with digital output

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.

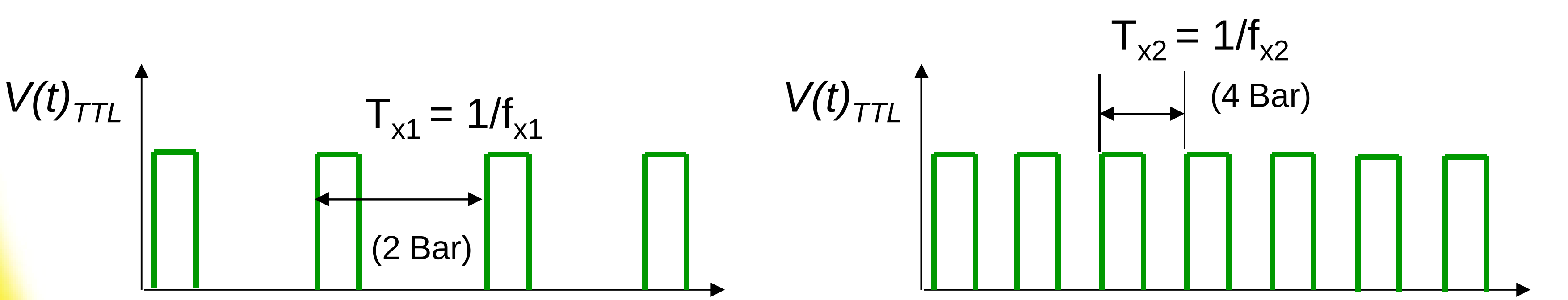


Voltage output vs. Frequency Output



(a) (b)

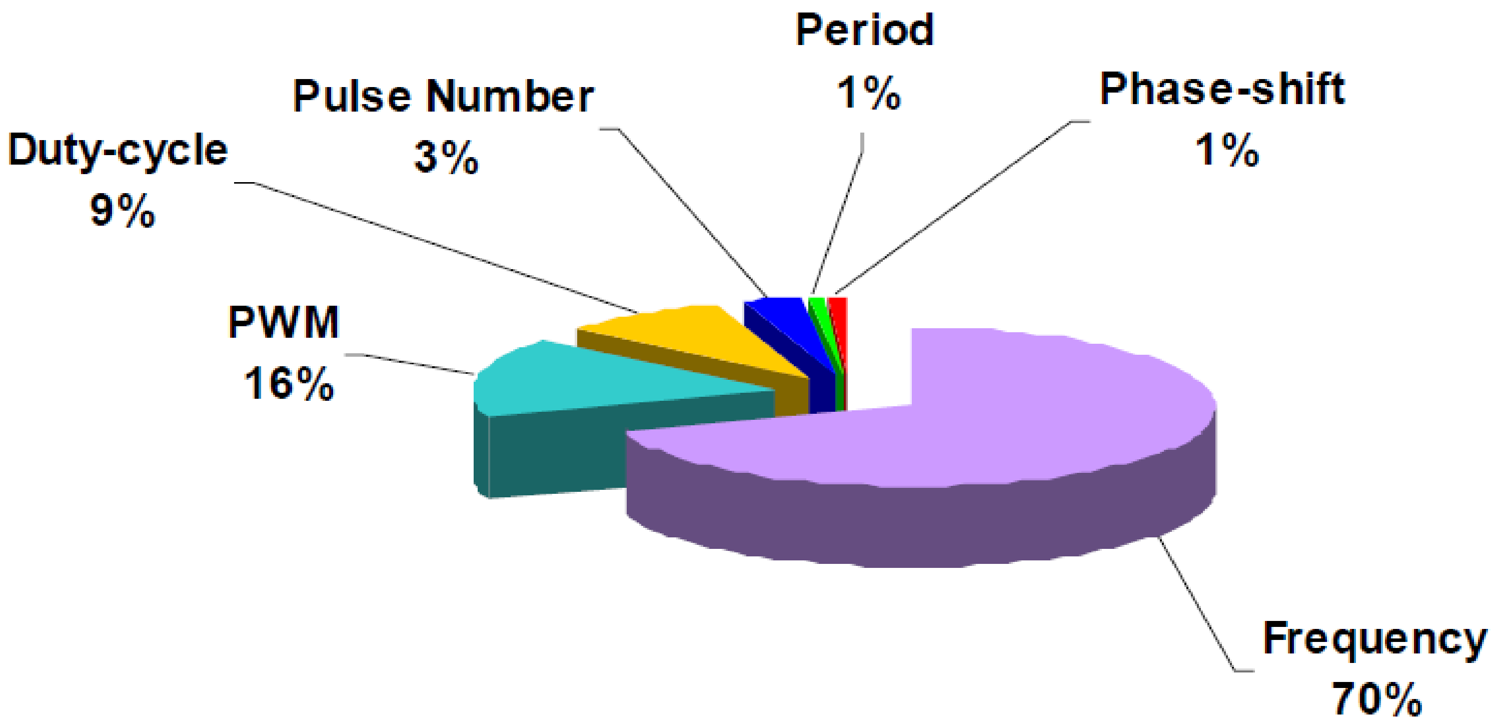
$V_1 < V_2$



(a) (b)

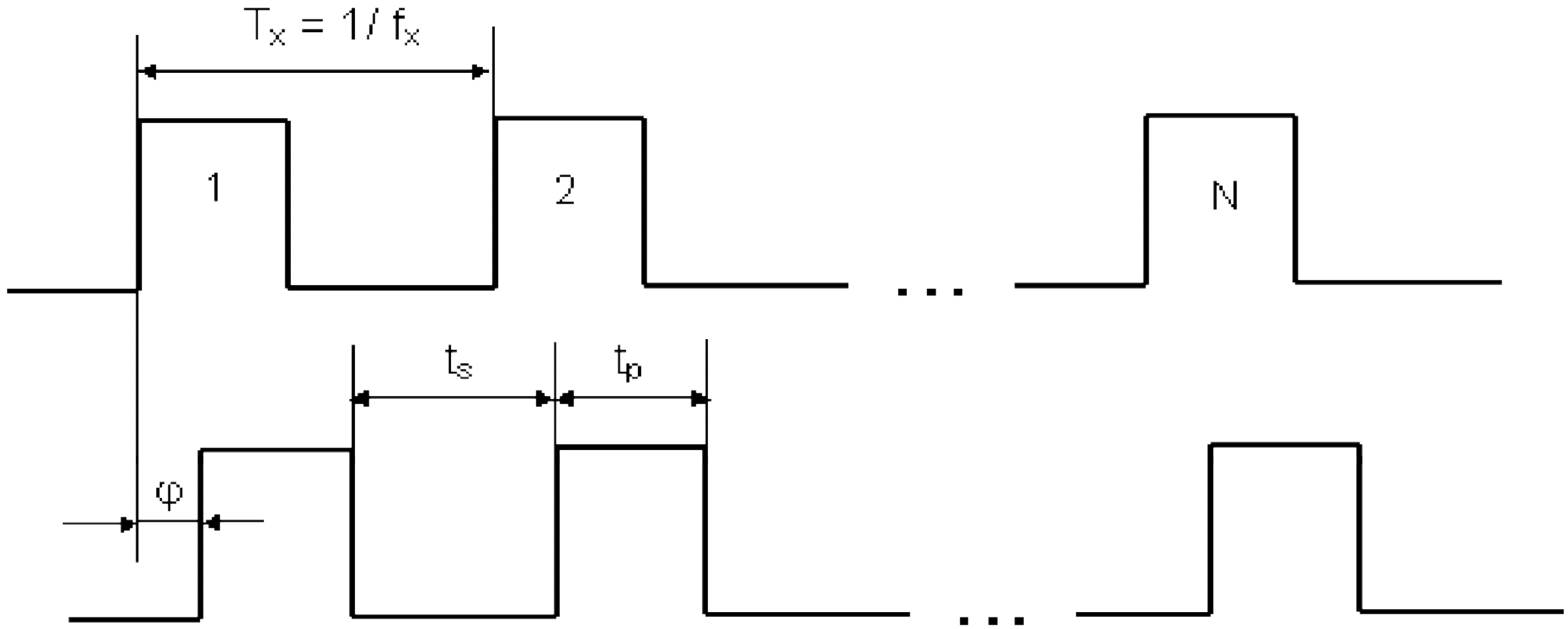
$T_{x1} > T_{x2}$, $f_{x1} < f_{x2}$

Quasi-Digital Sensors: Types



International Frequency Sensor Association (IFSA), Study 2011

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

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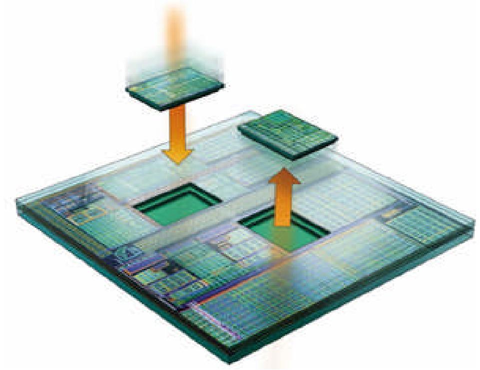
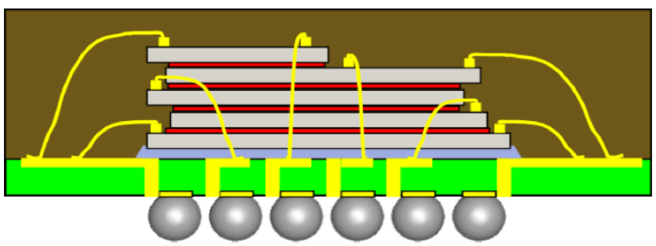
Smart Sensors Technologies



System-on-Chip (SoC)



System-in-Package (SiP)

- Hybrid technologies
- IC-compatible 3D micro-structuring
- System-on-Chip (SoC)
- System-in-Package (SiP)
- 45 nm CMOS process (*STMicroelectronics, CMP*)
- 40 nm CMOS process, (*TSMC, Europractice*)
- 32 nm CMOS process
- 28 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

Frequency Advantages

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

Smart Sensors Systems Design

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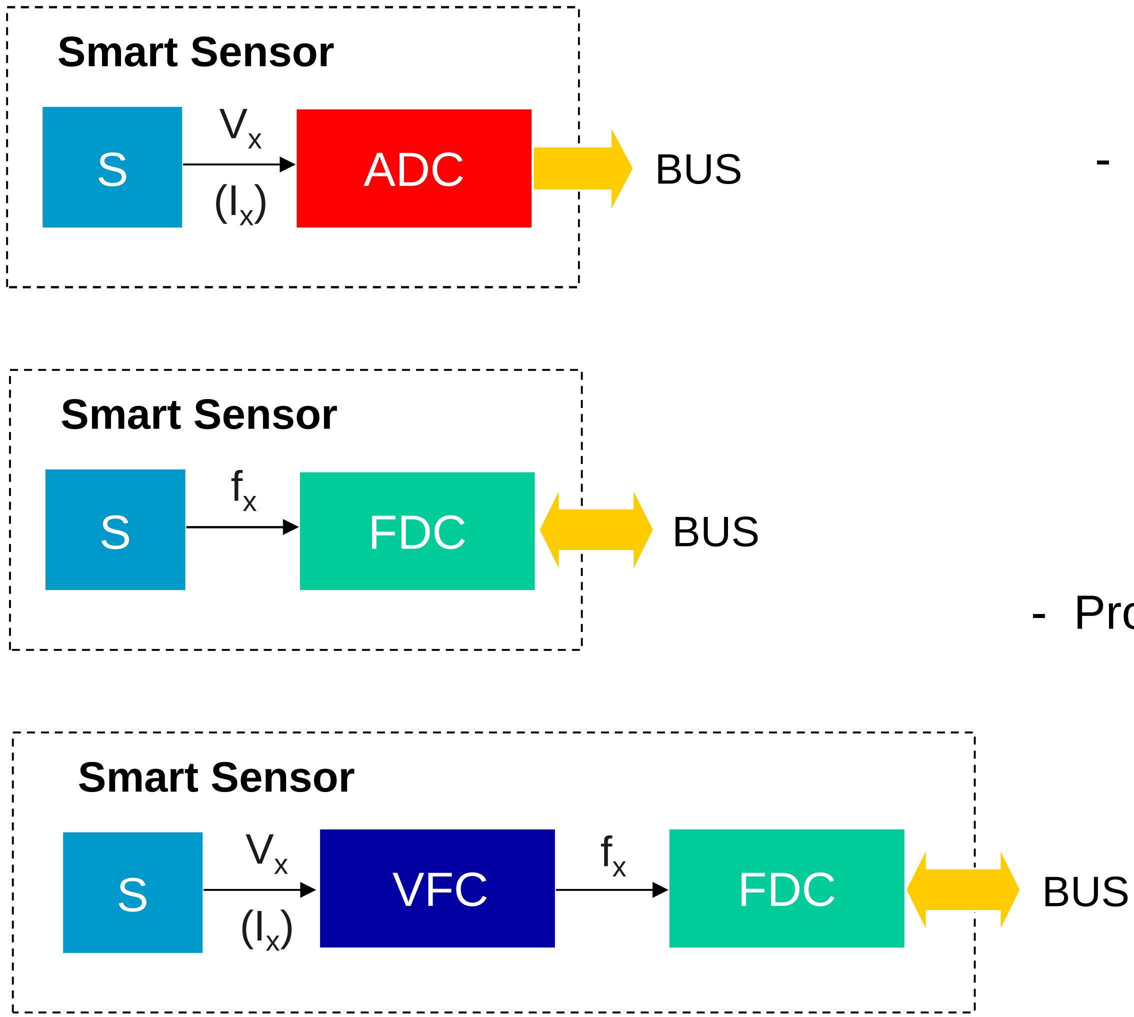
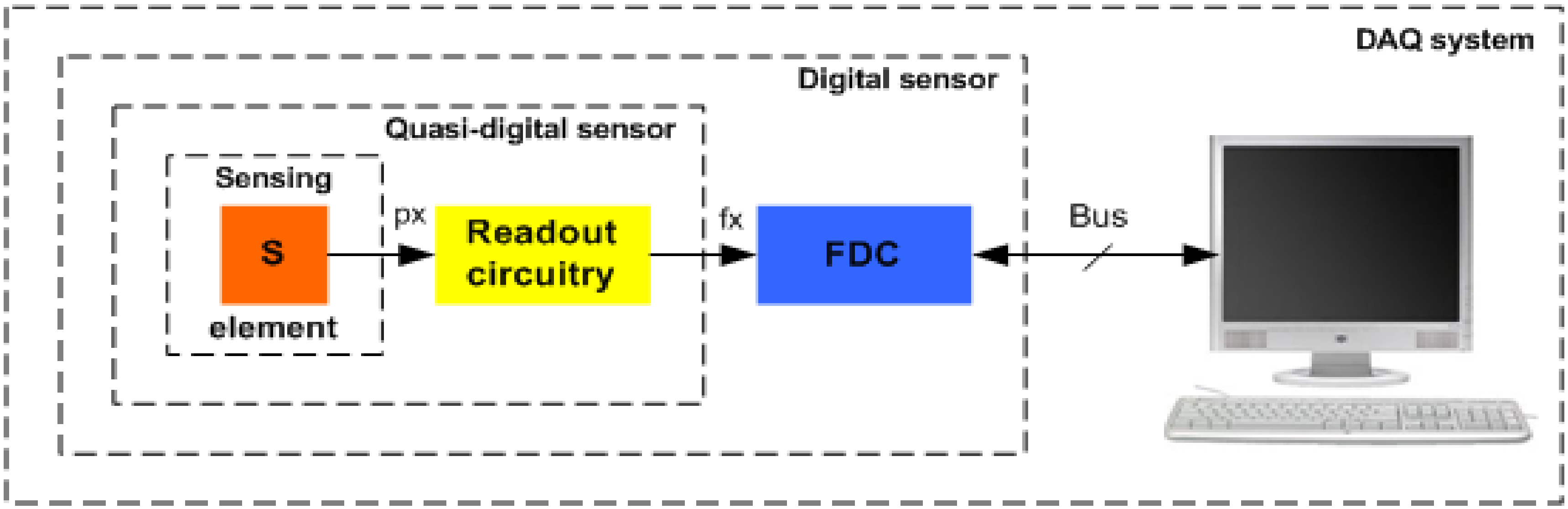
Smart Sensors Design



- Classical approach

- Proposed approaches

Quasi-Digital Sensor in System Hierarchy



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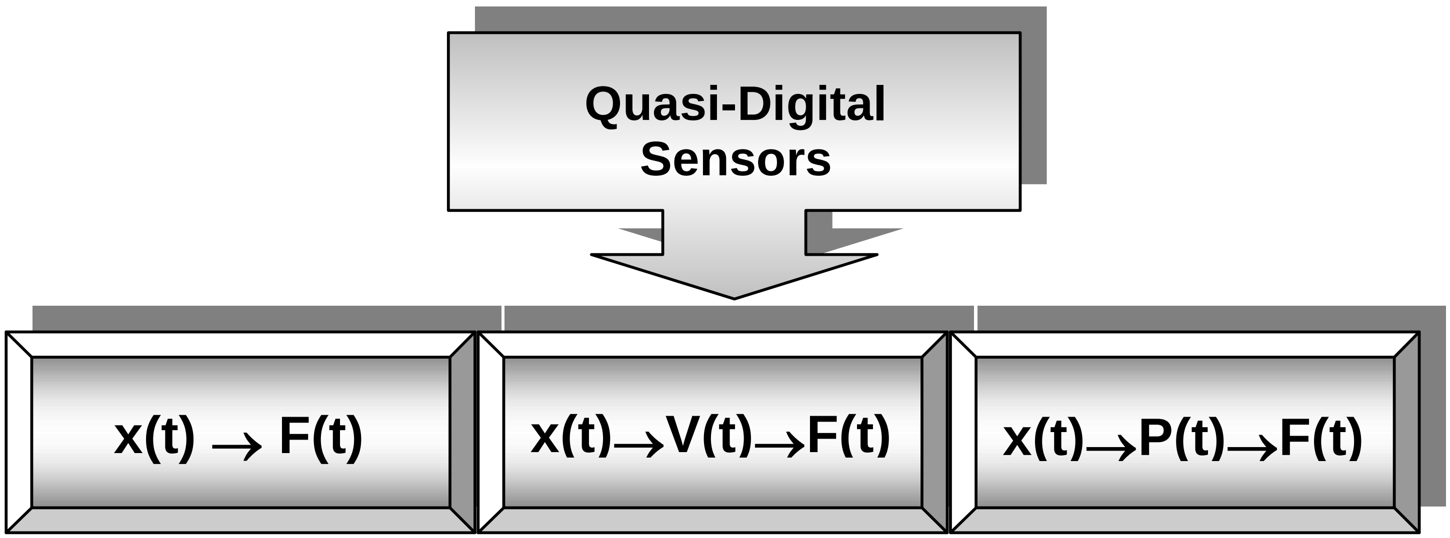
Quasi-Digital Sensor Classification



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

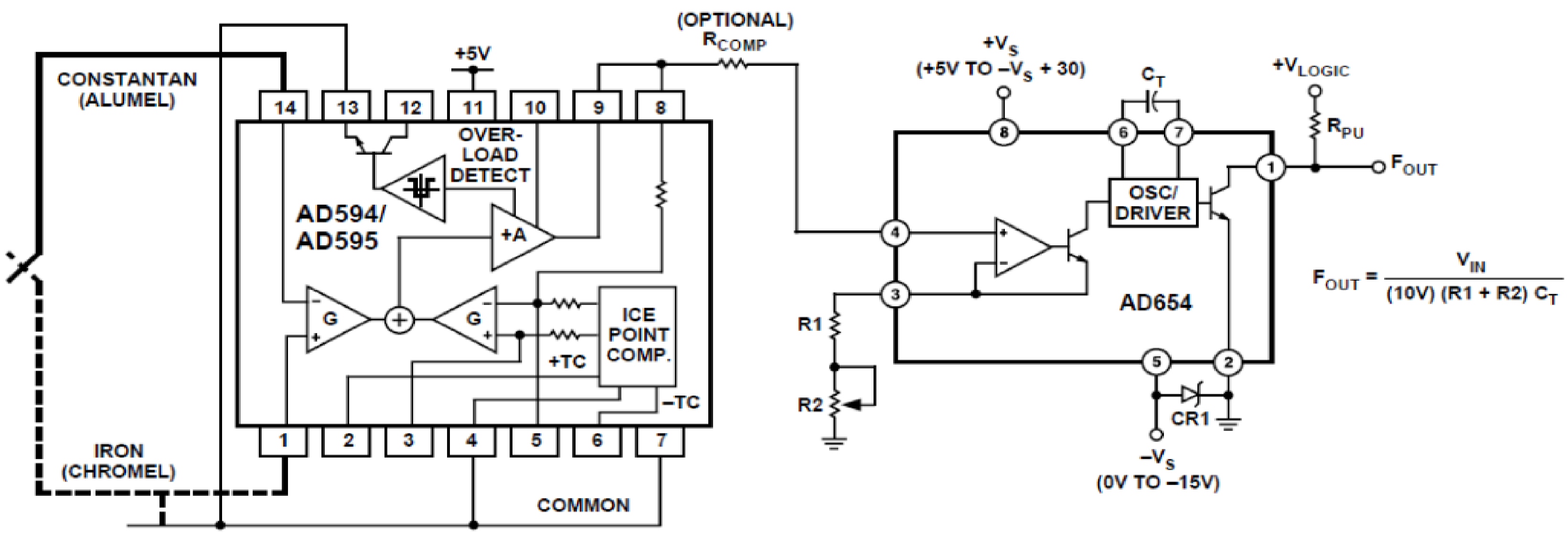
Temperature Sensors

Sensor	Max. Temp. Error, °C,	Temp. Range, °C	Resolution, bits	Output	Output Range
		Analog Devices			
TMP03	± 1.5	-40 to +100	16	PWM	*
TMP04	± 1.5	-40 to +100	16	PWM	*
TMP05	± 0.5	-40 to +150	12	PWM	*
TMP06	± 0.5	-40 to +150	12	PWM	*
		Maxim Integrated Products			
MAX6576	± 3.0	-40 to +125	*	Period	0.0023 ... 0.26 s
MAX6577	± 3.0	-40 to +125	*	Frequency	14.57...1592.6 Hz
MAX6666	± 1.0	-40 to +125	11	PWM	*
MAX6667	± 1.0	-40 to +125	11	PWM	*
MAX6672	± 3.0	-40 to +125	*	PWM	*
MAX6673	± 3.0	-40 to +125	*	PWM	*
MAX6676	± 1.5	-40 to +125	*	PWM	*
MAX6677	± 1.5	-40 to +125	*	PWM	*
		MicReD			
THSENS-F	± 2.0	-50 to +150	*	Frequency	0.2...1...1.8 MHz
		Sea-Bird Electronics			
SBE 3F	± 0.001	-5 to +35	*	Frequency	2...6 kHz
SBE 3plus	± 0.001	-5 to +35	*	Frequency	2...6 kHz
SBE 8	± 0.01	-3 to +30	16	Frequency	0,1 ... 200 Hz
		Slope Indicator			
VW	± 0.3	-20 to +80	*	Frequency	*
		Smartec			
SMT160-30	± 0.7	-45 to +130	*	Duty-cycle	1...4...4 kHz
		Melexis			
MLX90614	± 0.5	-20 to +120	10	PWM	*
		Honsberg			
Flex-T	± 1 % (FS error)	0 to +250	*	Frequency	2000 Hz (max)
		Environdata			
TA40	± 0.2	-20 ... +60	0.025°C	Frequency	0 ... 40 Hz
		Spica Technology			
T/FRQ	± 1.5	-40 ... +80	0.02°C	Frequency	58...90 Hz

RTD-to-frequency Converters

Converter	Temp. Range, °C	Resolution, bits (°C)	Accuracy	Frequency Output Range, Hz
		Omega, Inc.		
DRP-8540	-100 … +400	12 (0.1)	± 0.5 plus RTD conformity	100 … 5 100
		Soclair Electronic, AG		
RTMF 70	*	*	± 0.2 %	0 … 20 000
		Nokeval		
6746B	-60 … +700	*	± 0.1 % of reading +0.1 °C	0 … 2 500
		Loreme		
CNL48/F	-200 … +600	*	± 0.3 °C	0 … 10
		Megatron		
MIFN-PT100	*	*	± 0.5 % FS	0 … 10 000

Temperature-to-frequency Converter



Thermocouple-to-frequency Converter

Converter	Temp. Range, °C	Accuracy	Frequency Output Range, Hz
		Omega, Inc.	
DRP-8511Type J	0 … +500	±2 °C plus conformity error	100 … 5 100
DRP-8512 Type K	0 … +500	±2 °C plus conformity error	100 … 5 100
DRP-8611Type J	0 … +1000	±2 °C plus the error of J Thermocouple	10 … 1 100
DRP-8612 Type K	0 … +1250	±1.2 °C	5 … 2 520
		Soclair Electronic	
TCMF 70 (all type)	All ranges	± 0.2 %	0 … 20 000
		Nokeval	
6746B (all type)	All ranges	± 0.1 % of reading +0.1 °C	0 … 2 500
		Loreme	
CNL48/F (all types)	All ranges	± 0.3 … 2) °C	0 … 10

Pressure Sensors

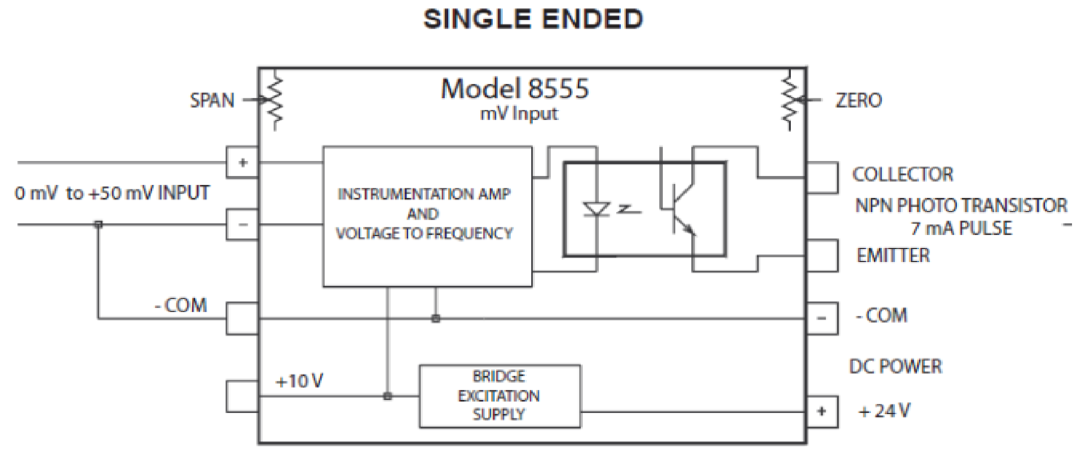
1968 - first truly integrated pressure sensor in Europe designed by Gieles at Philips Research Laboratories

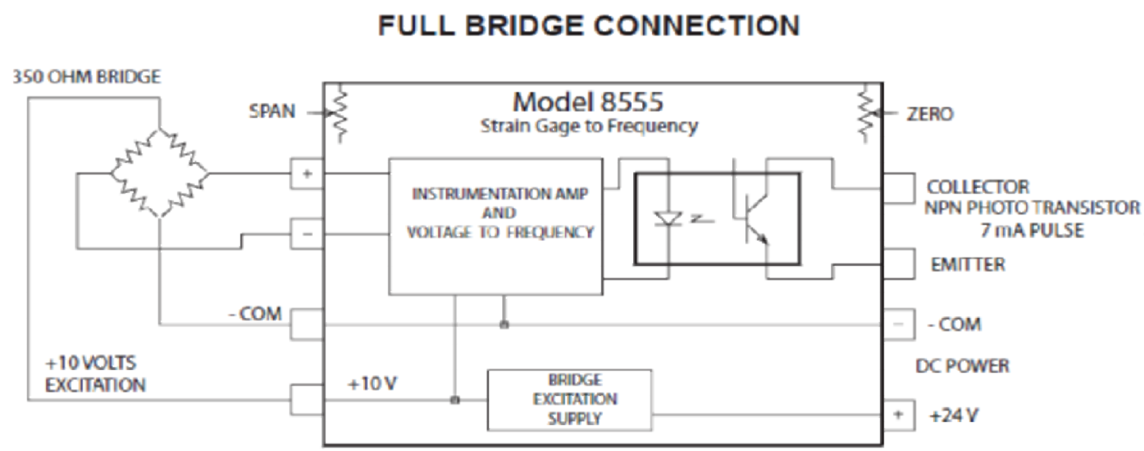
1971 - first monolithic integrated pressure sensor with frequency output was designed and tested at Case Western Reserve University (USA)

Modern Pressure Sensors

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

Strain-Gauge – to – Frequency Converter for Pressure Sensors

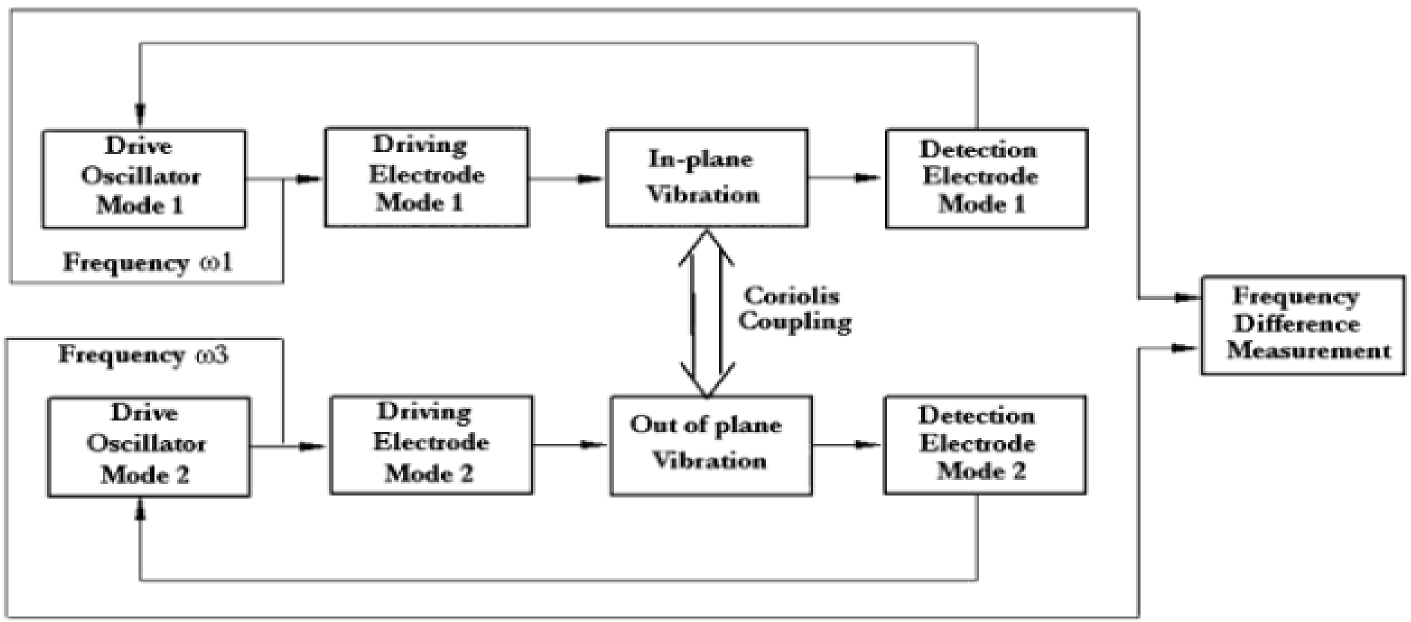




Quasi-Digital Accelerometers

Device	Number of Axis	Range, g	Sensitivity Accuracy, %	Output
		Analog Devices		
ADXL202	2	± 2	± 16	Duty-cycle
ADXL210	2	± 10	± 20	Duty-cycle
ADXL212	2	± 2	*	Duty-cycle
ADXL213	2	± 1.2	± 10	Duty-cycle
		Honeywell		
RBA500	*	± 70	*	Frequency
SA500	*	± 80	*	Frequency
		Kionix		
KXG20	2	± 2	*	Duty-cycle
		MEMSIC, Inc.		
MXD2020 E	2	± 1	*	Duty-cycle
MXD2125	2	± 2	*	Duty-cycle
MXD6025	2	± 2	*	Duty-cycle
MXD6125	2	± 0.5 ÷ 2	*	Duty-cycle
		Silicon Designs, Inc.		
1010	1	± (2 ÷ 200)	± 2	Pulse density
2010	1	± (2 ÷ 200)	± 2	Pulse density
2420	3	± (2 ÷ 200)	± 2	Pulse density
		DIGI SENS AG		
BB / ED21		± (0.3 ÷ 7.7)	< 0.03 % (max. error)	Frequency: 8 … 19 kHz

Direct Frequency Difference Output Vibrating Gyroscope



Quasi-Digital Inclinometers

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

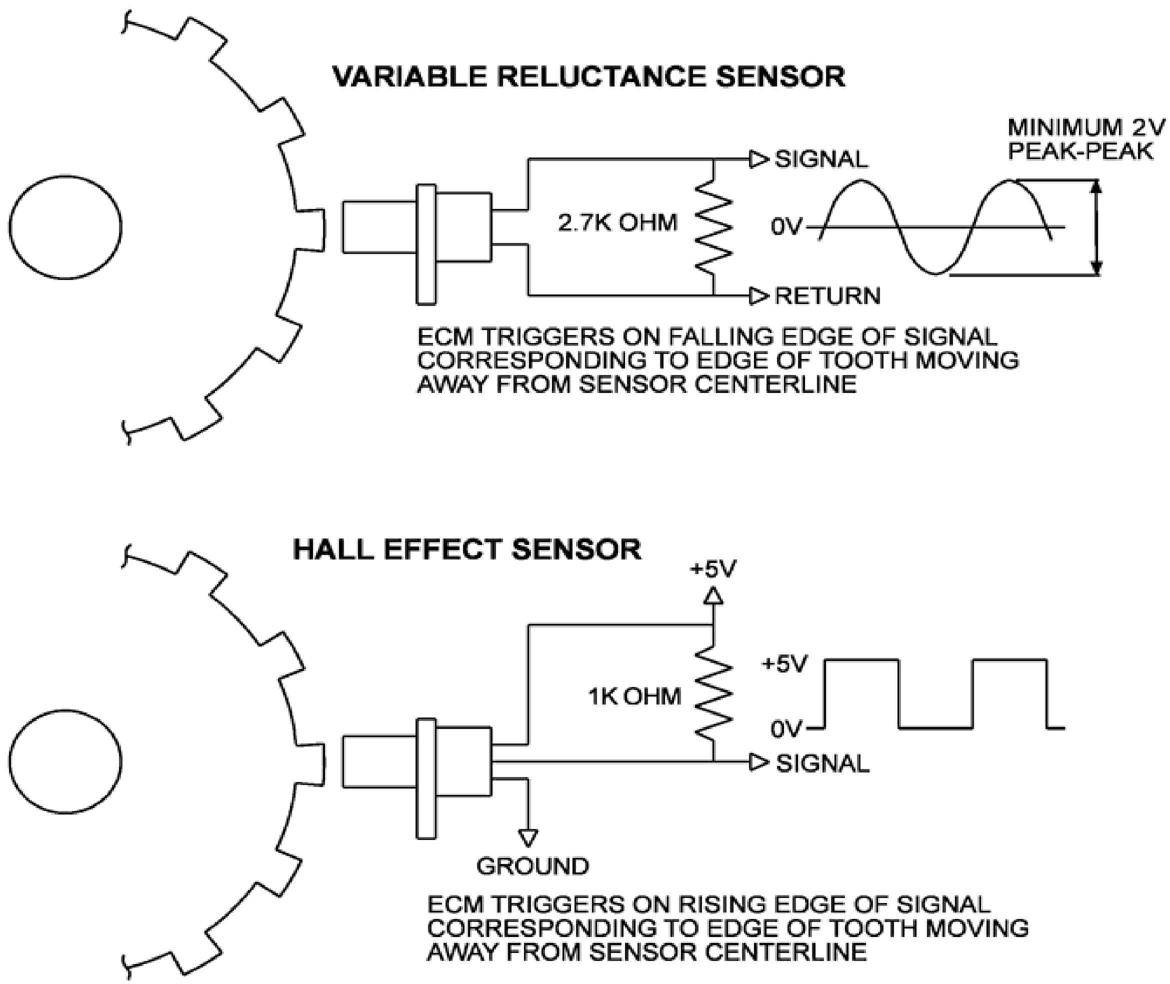
Rotation Speed Sensors

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

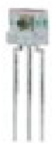
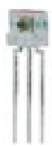
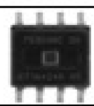
$$n_x = f_x \cdot \frac{60}{Z}$$

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

Rotation Speed Measurement



Optoelectronic Sensors

Sensor (LFC) (Images not to scale)		Performances		
		Output Frequency Range	Spectral Response, nm	Non-linear FS Error, %
TAOS (USA)				
	TSL230	0.4 Hz … 1.1 MHz	350 … 1000	0.2
	TSL235	0.4 Hz … 500 kHz	350 … 1000	0.2
	TSL237	2 Hz … 600 kHz	350 … 1000	1
	TSL238D	2 Hz … 600 kHz	320 … 1050	1
	TSL245	0.4 Hz … 500 kHz	850 … 1000	0.2
Hamamatsu (Japan)				
	S9705	0 Hz … 1 MHz	300 … 1000	3
Melexis (Belgium)				
	MLX75304	1 Hz … 1.6 MHz	500 … 1000	N/a

Humidity Frequency Output Sensors

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

Humidity Quasi-Digital Sensors

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

Chemical, Gas and Biosensors

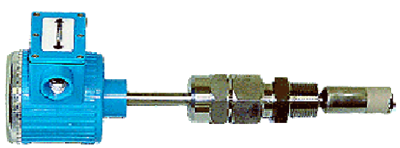
- Sensors arrays *(electronic noses and tongues)*
- Square wave with a frequency inversely proportional to the sensor resistance
- Sensors Array based on chemisorbing polymer films
- Acoustic gas sensor based on a gas-filled cell
- Quartz Crystal Microbalance (QCM) sensors
- SAW and bulk acoustic wave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

Magnetic Sensors

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

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

Flow Sensor Types



Type 7000, 7001

- Open channel
- Differential pressure
- Variable area
- Positive displacement
- Vortex
- Electromagnetic
- Coriolis
- Insertion thermal mass
- Ultrasonic
- Turbine
- MEMS

Flow Sensors

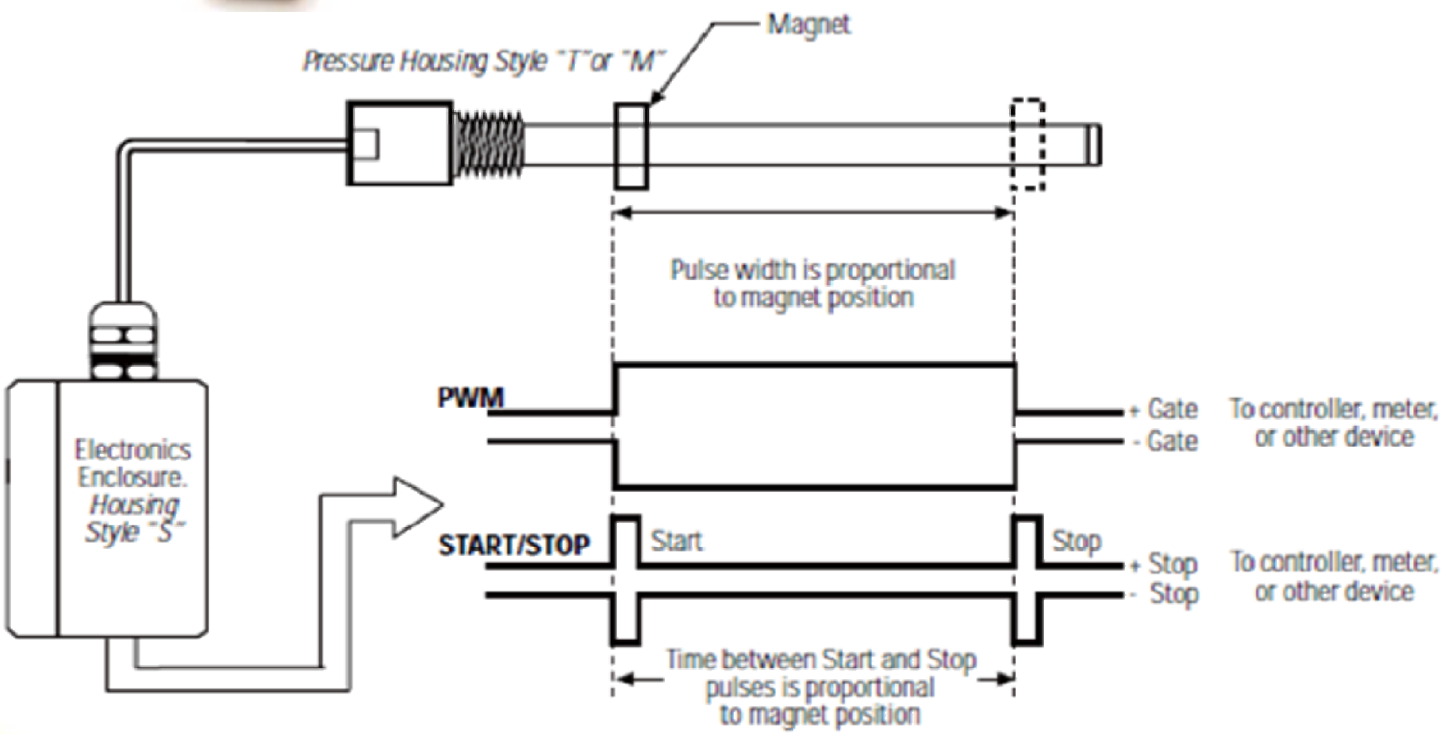
Model	Type	Range	Error, %	Output
		+GF+ SIGNET		
7000	Vortex	0.3 to 4 m/s	± 1	Frequency
7002	Vortex	N/a	± 1	Frequency
2550/2560	Electro-magnetic	0.1 to 7 m/s	± 2	Frequency
		KOBOLD Instruments, Inc.		
DF	Paddlewheel	0.02 - 0.14 GPM to 1.5 - 36 GPM	± 2.5	Frequency
		Badger Meter		
SDI	N/a	0.3 ft/sec to over 20 ft/sec	± 1	Frequency
		Newport		
FP7000	Paddlewheel	N/a	± 2	1 Hz/fps
		Clark Solutions		
CFT110	Turbine	0.1 GPM to 8 GPM	± 3	33 - 1150 Hz
		Omega		
FP7001	Paddlewheel	N/a	± 2	1 Hz/fps
FMG3000 FMG3100	Magnetic	0.05 to 5 m/s	N/a	Frequency
		Dwyer Instruments, Inc.		
SFI-100T	N/a	N/a	± 5	0 to 100 Hz
		INTEC Controls		
SDI	Turbine	0.3 ft/sec to over 20 ft/sec	± 1	800 Hz max
		Proteus Industries, Inc.		
PS600	Turbine	0.1 – 60 GPM	N/a	5 -120 Hz
		ERDCO		
3600	N/a	N/a	N/a	0-1000 Hz
3700	N/a	N/a	N/a	Frequency

Level Sensors

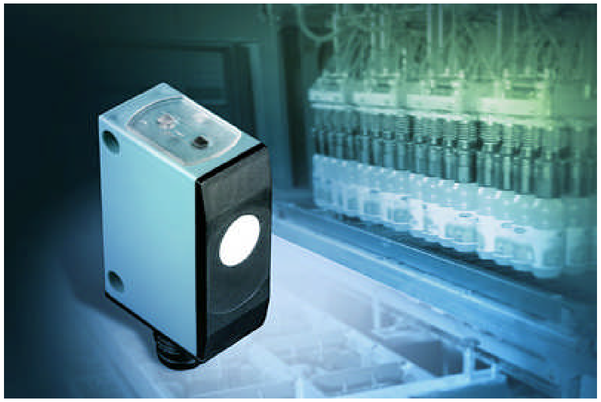
Model	Type	Range	Error	Output, Hz
		Flowline, Inc.		
EchoPod DX10	Ultrasonic	1.25 m	± 3 mm	976 ... 2000
		CKPT		
DUT-E-F	Capacitive	Length 180 - 2000 mm	± 1 %	500 … 1500
		Oceanscan, Ltd.		
DIGIQUARTZ	Pressure	0 ... 7000 m	± 0.01 %	Frequency output
		Strela		
F	Capacitive	Max. Length up to 4000 mm	± 0.1 %	500 ... 1500

Position Sensors

- Temposonics LD absolute linear position sensor (*MTS Systems Corporation*)

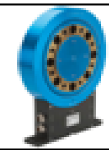
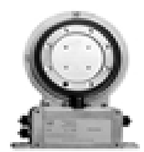
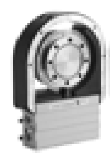
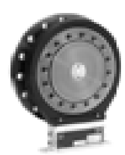


Proximity Sensors



- **Bi8-M18-LF10** from *Hans Turck GmbH & Co*
- **SIMATIC PXS240** *ultrasonic sensor (Siemens)*
- **SIMATIC PXS200** *sonar sensor (Siemens)*
- **UC 80 CND 40** *(Carlo Gavazzi)*

Torque Transducers

Model		Range, N·m	Accuracy Class, %	Output, kHz
Kistler				
4504B		50 - 5000	± 0.1 (± 0.05 optional)	10 ± 5 60 ± 20 100 ± 40
4510B		100 - 4000	± 0.2	100 ± 40
HBM				
T10F		50 - 10000	± 0.1	10 ± 5
T12		100- 10000	*	10 ± 5 60 ± 30
T40FM		50-80	± 0.1 (± 0.05 optional)	10, 60, 240
Honeywell				
TMS 9000		200000 lb-ft	± 0.1	10 ± 5 60 ± 20

Multiparameters Sensors

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

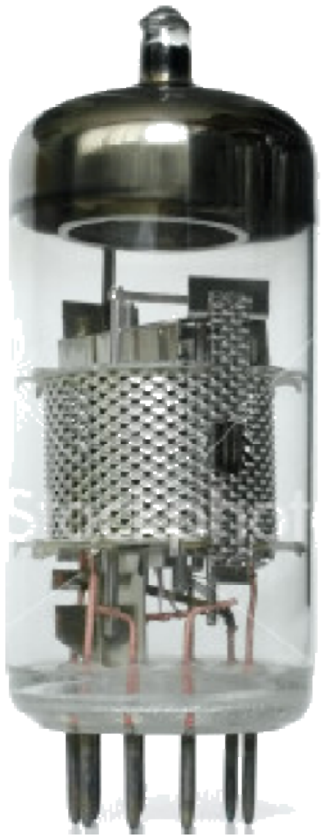
Other Sensors

- Load Cells (iLoad Mini from *Loadstar Sensors*)
- Tilt sensors with PWM outputs
- Conductivity sensor SBE4 with frequency output
- Rain detector HD 2013.2, *Delta OHM*
- Frequency output anemometers A100L2, A100M, A100K, *Vector Instruments*
- Power transducer XD303F with pulse number output

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

Electronic Component (1905)

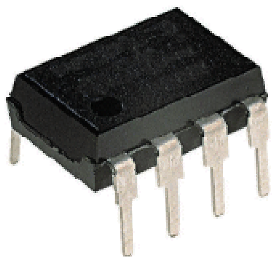


Vacuum valve

Electronic Component (1947)

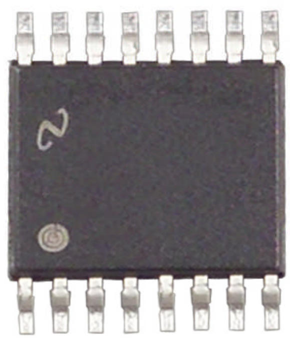
Transistor

Electronic Component (1963)



Operational amplifier

Electronic Component (1974)



Analog-to-digital converter

Electronic Component (2004)

Frequency-to-digital converter

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*

USP-30 Microprocessor

- 48-pin one-chip specialized microprocessor (USSR)
- It works in a pipeline mode
- Measuring modes: frequency, period, time interval, pulse width and count pulse number
- Narrow frequency range: from 0.1 Hz to 100 kHz
- High power consumption

ALU for Time Intervals (USSR)

- The absolute accuracy $\Delta_T = \pm$ 33 ns at the reference frequency f_0=30 MHz
- Standard counting method for frequency measurements and indirect counting methods for time interval
- High power consumption
- Low functional possibilities

Frequency-to-Digital Converter K512PS11

- 42-pin CMOS IC (USSR)
- Two modes: single conversion and multiple conversion
- Parallel 16-bit digital output
- Based on the indirect counting method with interpolation and standard counting method
- Maximum converted frequency $f_{x\ max}$ = 1 MHz reference frequency f_o=10 MHz

Universal Sensor Interface Chip (USIC)

- CMOS IC (UK)
- 80-pin QFP pack
- Frequency and pulse width measurement
- Maximum converted frequency $f_{x\ max}$ = 1 MHz
- RS232/485 interface

Single-Chip Interpolating Time Counter

- FPGA-based 84-pin IC
- Resolution 200 ps with a further development to 150 ps
- Based on the classical method for time interval measurement with interpolation
- Maximum possible time interval 43 s
- A few measuring functions

Frequency-to-Digital Converter from *AutoTEC*

- IC based on the FPGA from *Xilinx*
- Reference frequency f_o=1 MHz
- Frequency range is from 35 Hz to 24 kHz
- Absolute error: ± 5 Hz (0.2 % FS error)

ASIC Based Single Channel FDC

- One channel
- Frequency range from 100 Hz to 100 kHz
- Frequency measurement accuracy is 0.1 %
- 16-bit bus output
- Hybrid technique for frequency measurement

Time-to-Digital Converters (TDC)

- CMOS ICs provide frequency, time and phase measurement
- **TDC-GP1:** 2-channel; resolution 125 ps; measurement range of maximum 200 ms, 44-pin, 500 kHz – 35 MHz reference frequency; 8-bit bus interface
- **TDC-GP2:** resolution 50 ps; SPI interface; measurement range 3.5 ns ÷ 1.8 μs
- **TDC-GP21:** 2-channel; resolution 90 ps, 45 ps, 22 ps measurement range is 500 ns to 4 ms; 4-wire SPI bus; QFN 32 package
- **TDC-GPX:** resolution 10 – 81 ps; measurement range 10 ns ÷ 10 μs

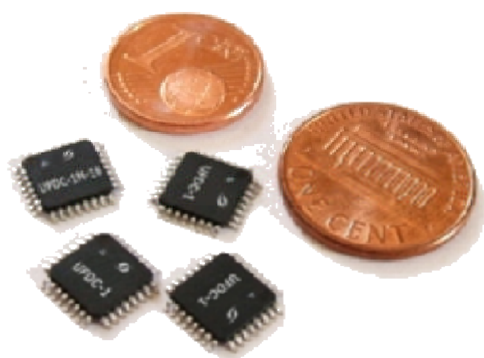
ICs Disadvantages

- 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

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

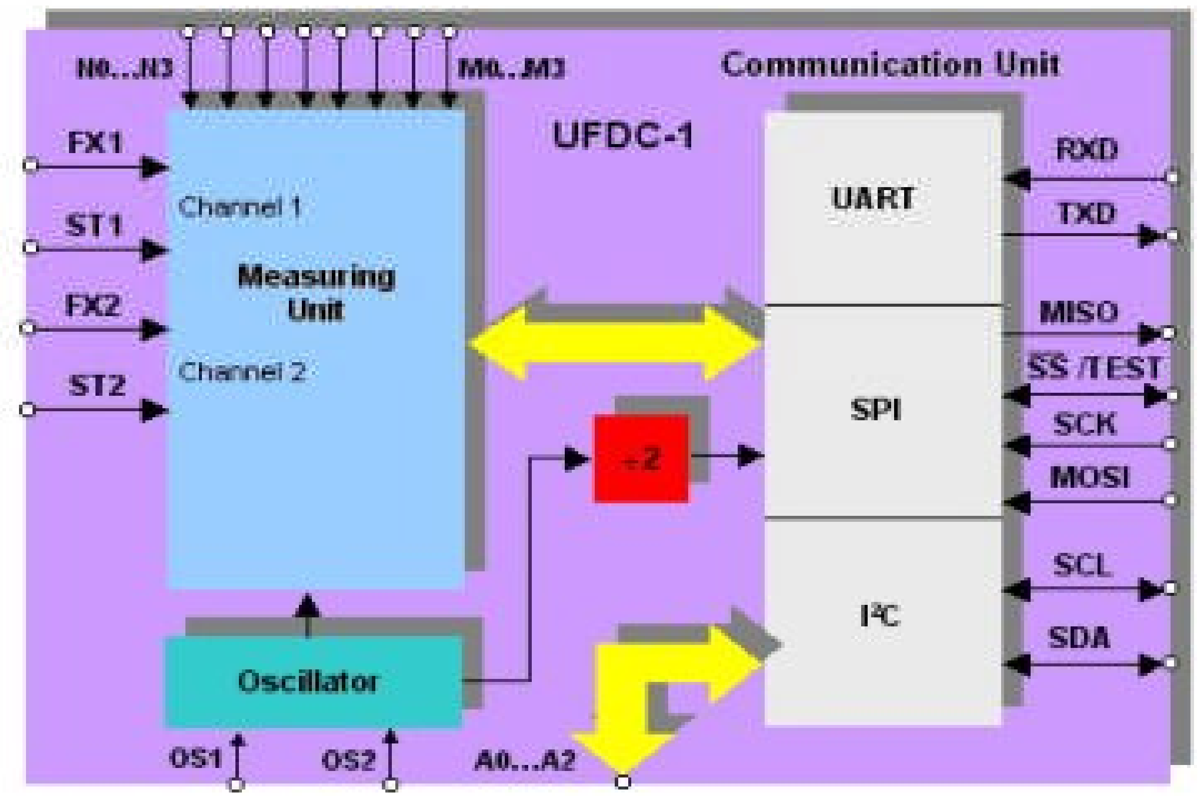
- Low cost digital IC with programmable accuracy
- 2 channels, 16 measuring modes for different frequency-time parameters and one generating mode ($f_{osc}/2 = 8$ MHz)
- Based on four patented novel conversion methods
- Should be very competitive to ADC and has wide applications

Features



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

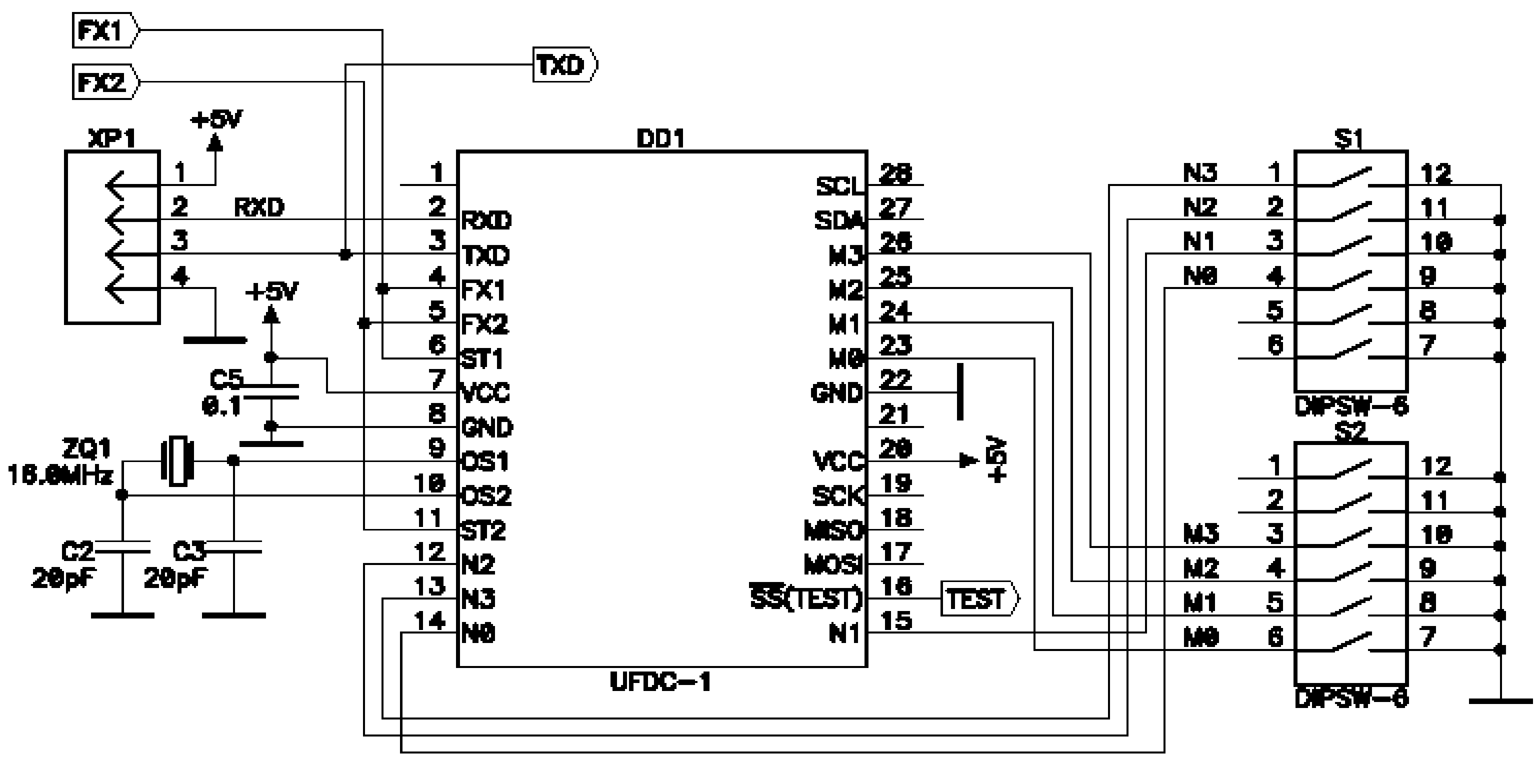
UFDC-1 Block Diagram



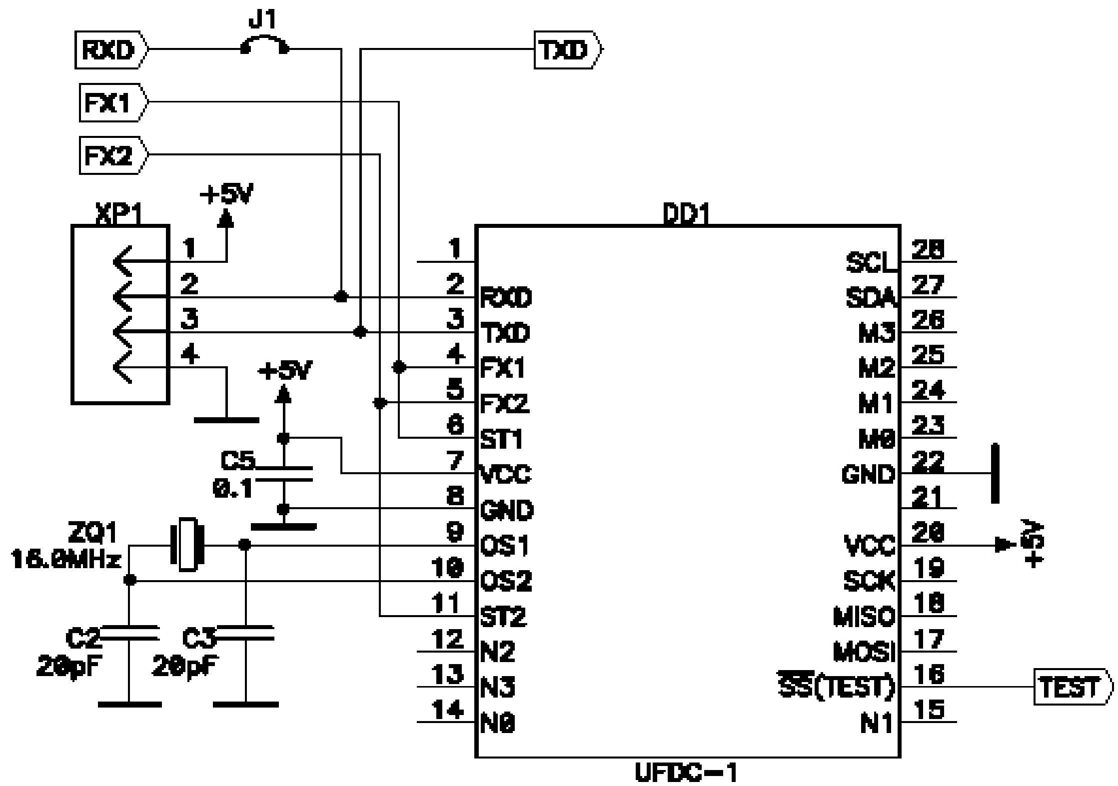
Measuring Modes

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

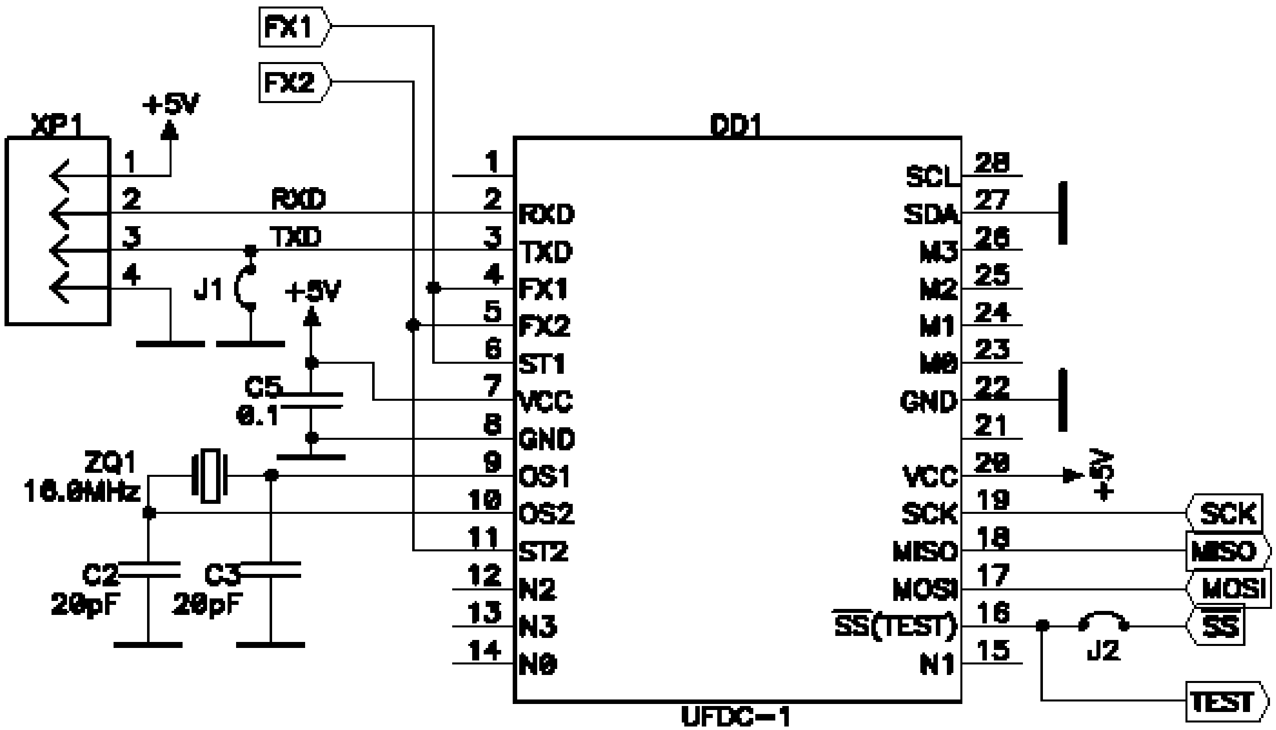
UFDC-1 Master Mode (RS232)



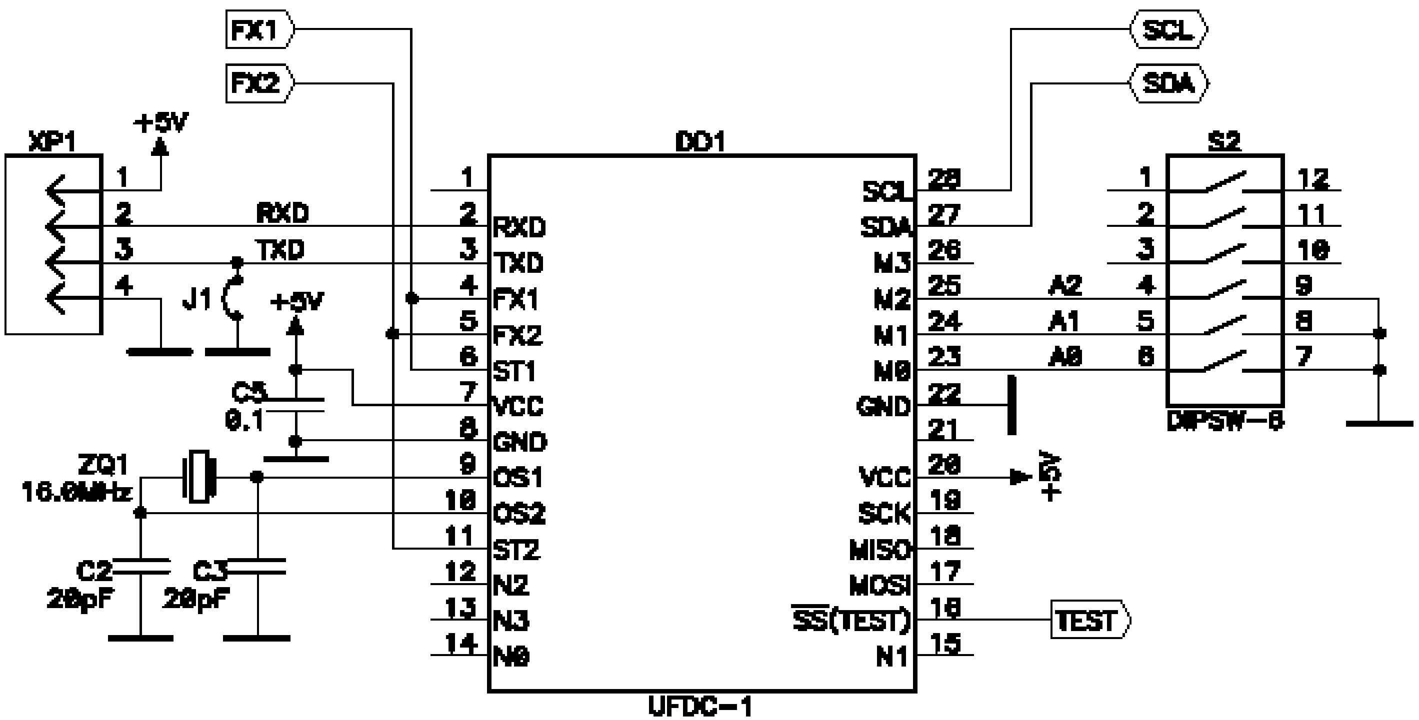
UFDC-1 Slave Mode (RS232)



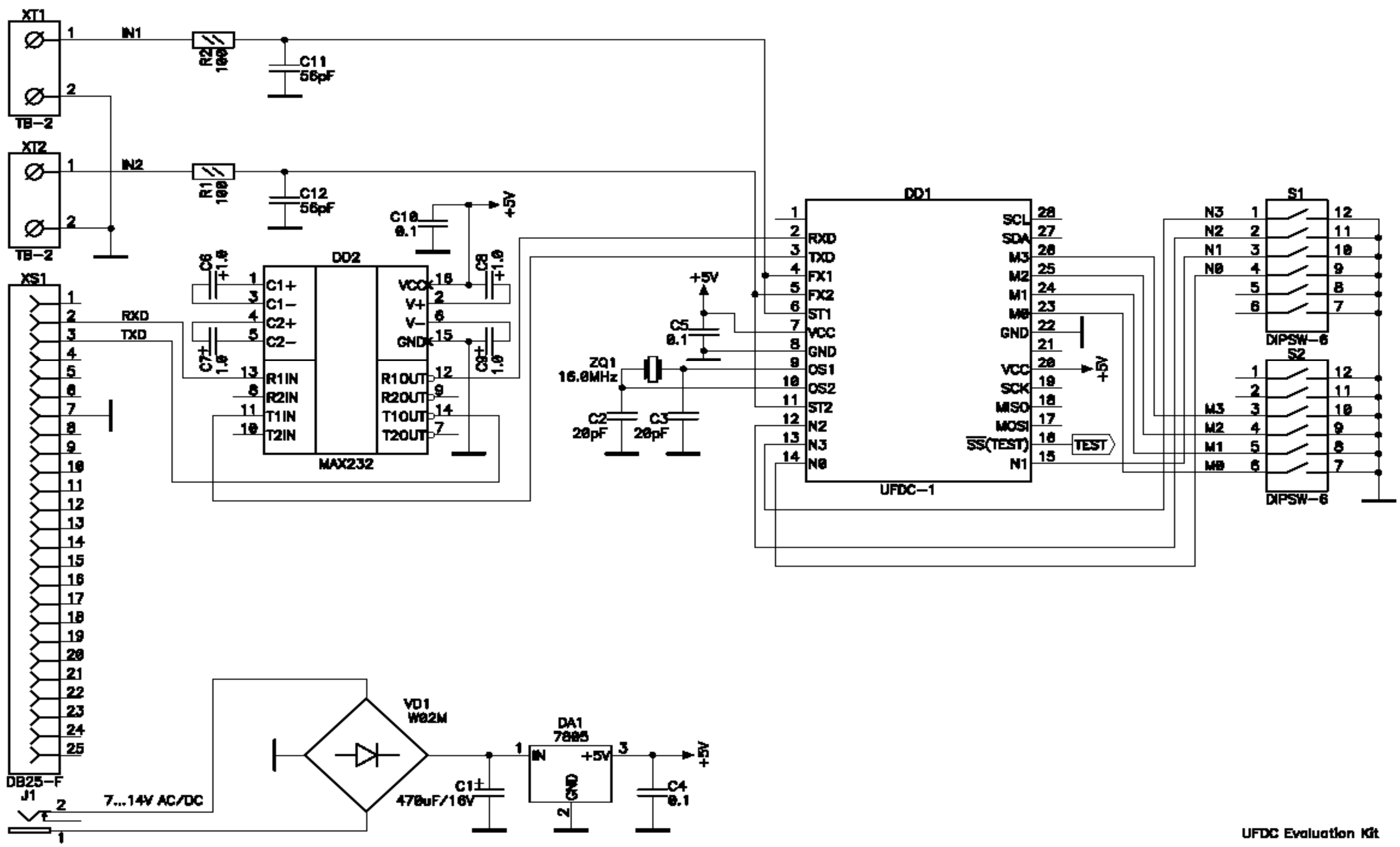
UFDC-1 SPI Interface Connection



UFDC-1 I^{2}C Bus Connection



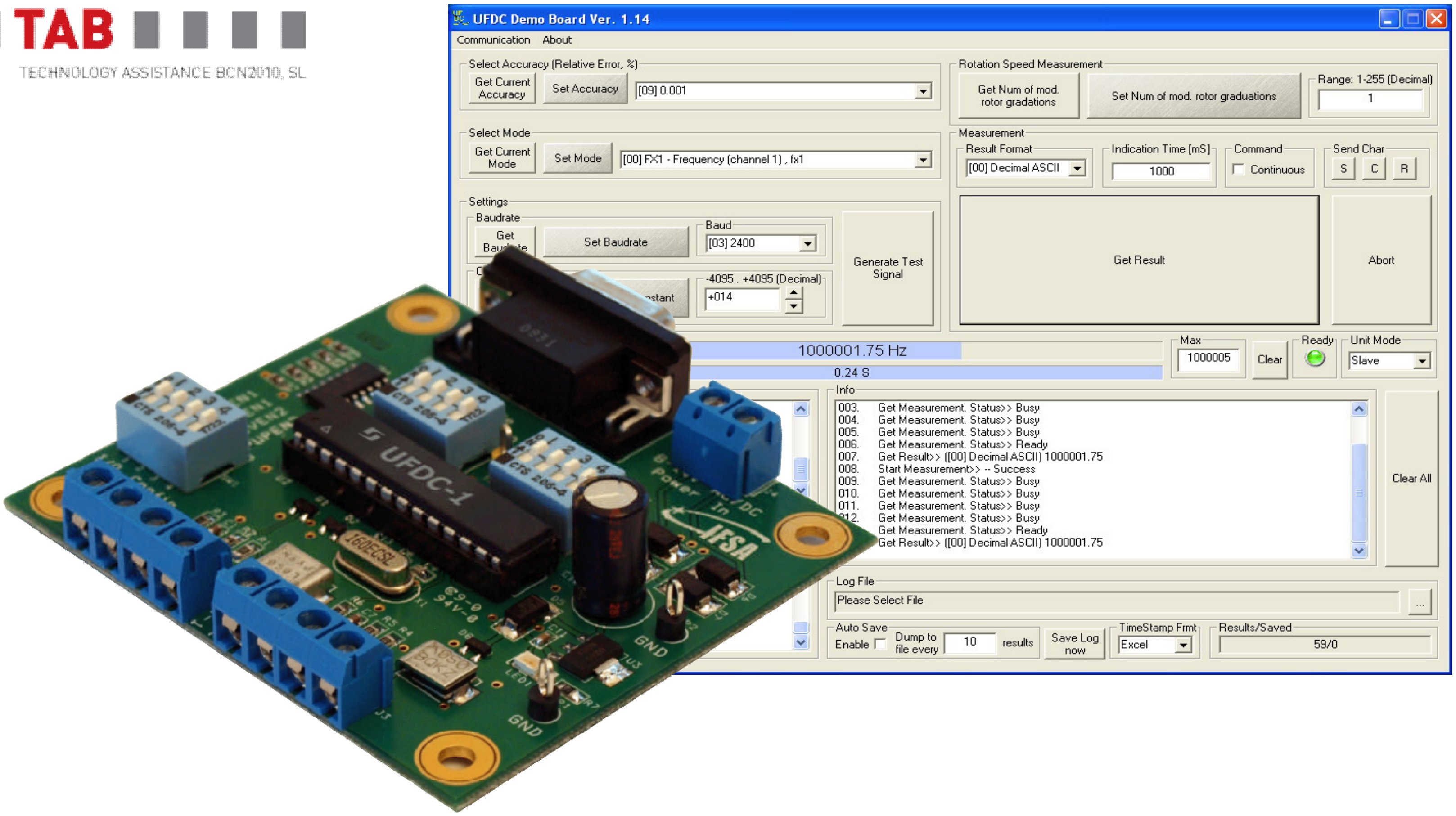
Evaluation Board Circuit Diagram



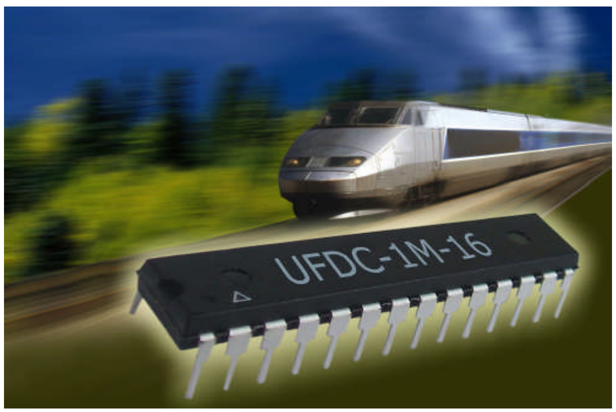
UFDC Evaluation Kit

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

TAB
TECHNOLOGY ASSISTANCE BCN2010, SL

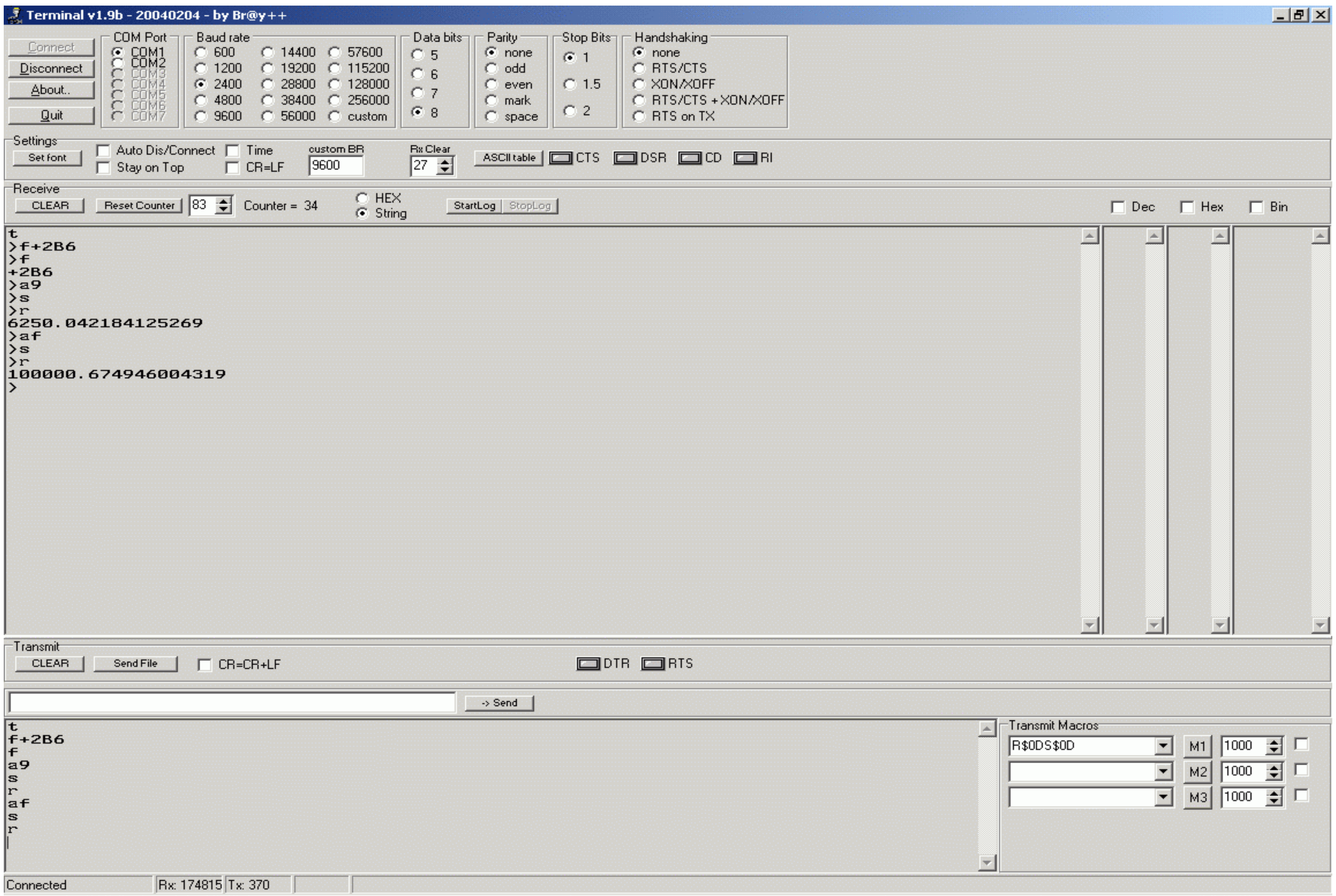


Fast IC UFDC-1M-16

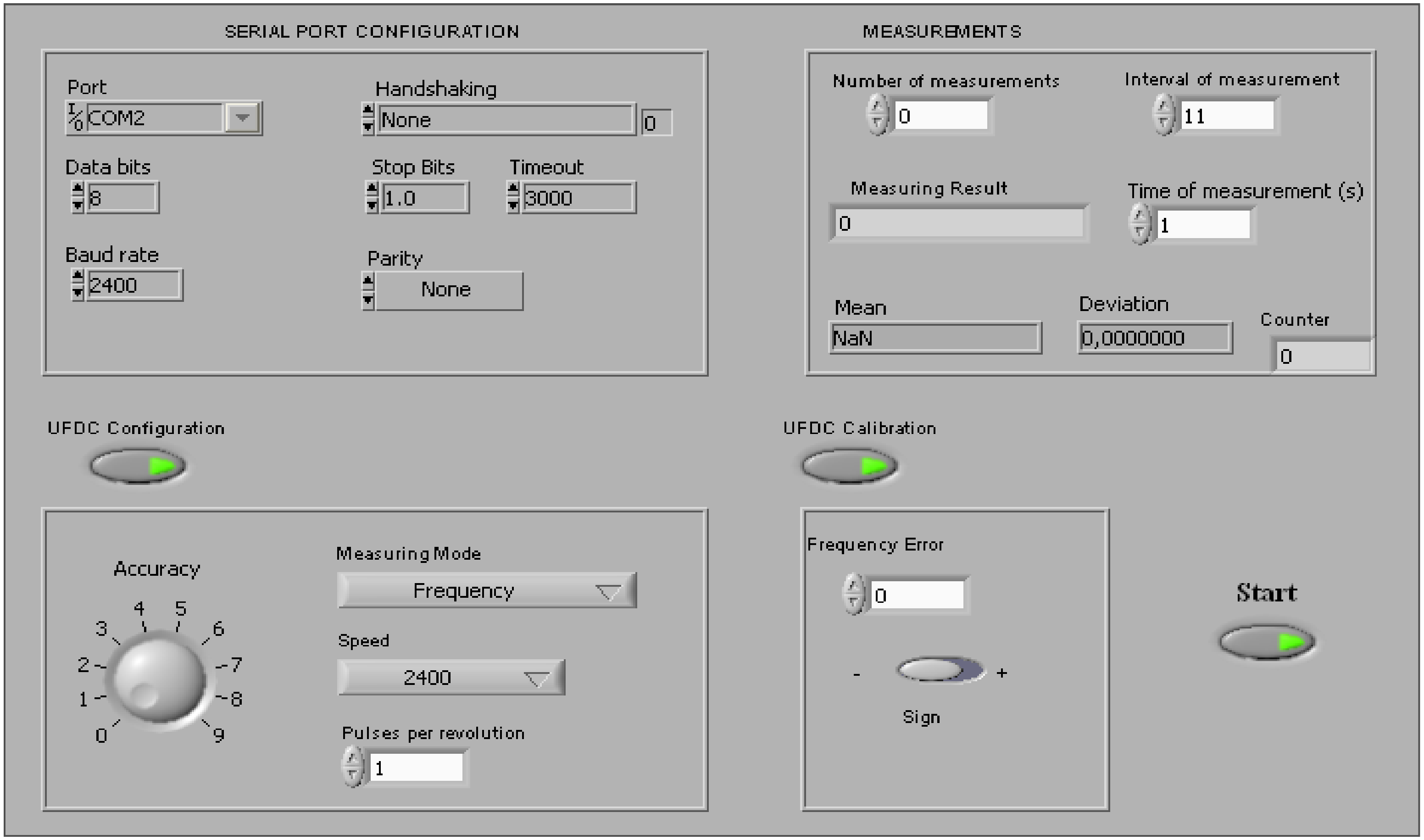


- Frequency range: 1 Hz to 7.5 MHz (120 MHz with prescaling)
- Internal reference frequency 16 MHz
- Non-redundant conversion rate: from 6.25 μs to 6.25 ms

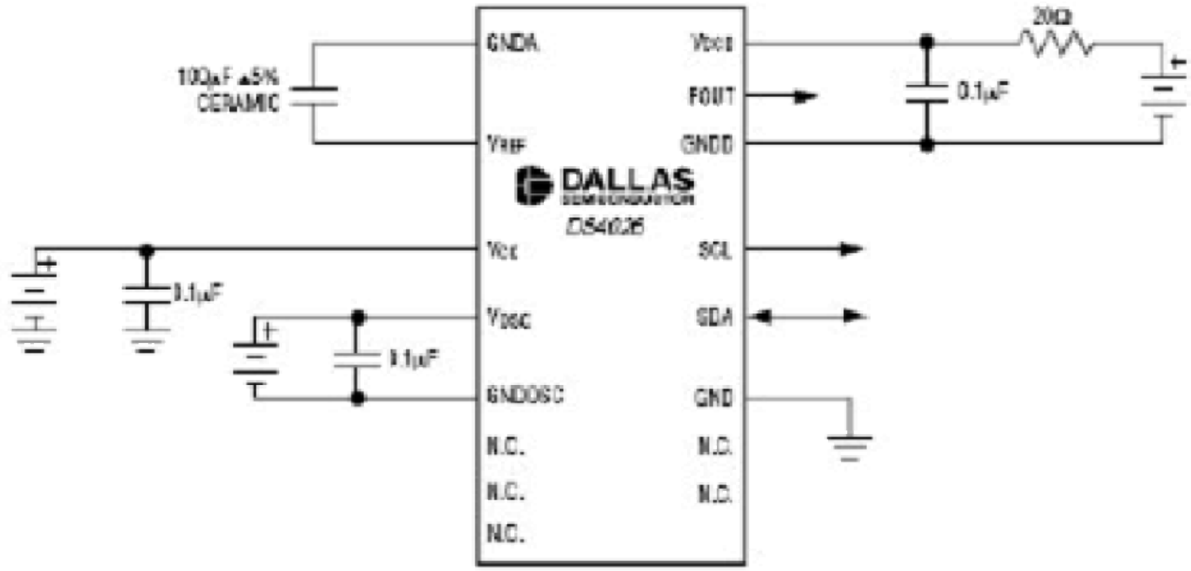
Software (Terminal V1.9b)



LabView Based Software

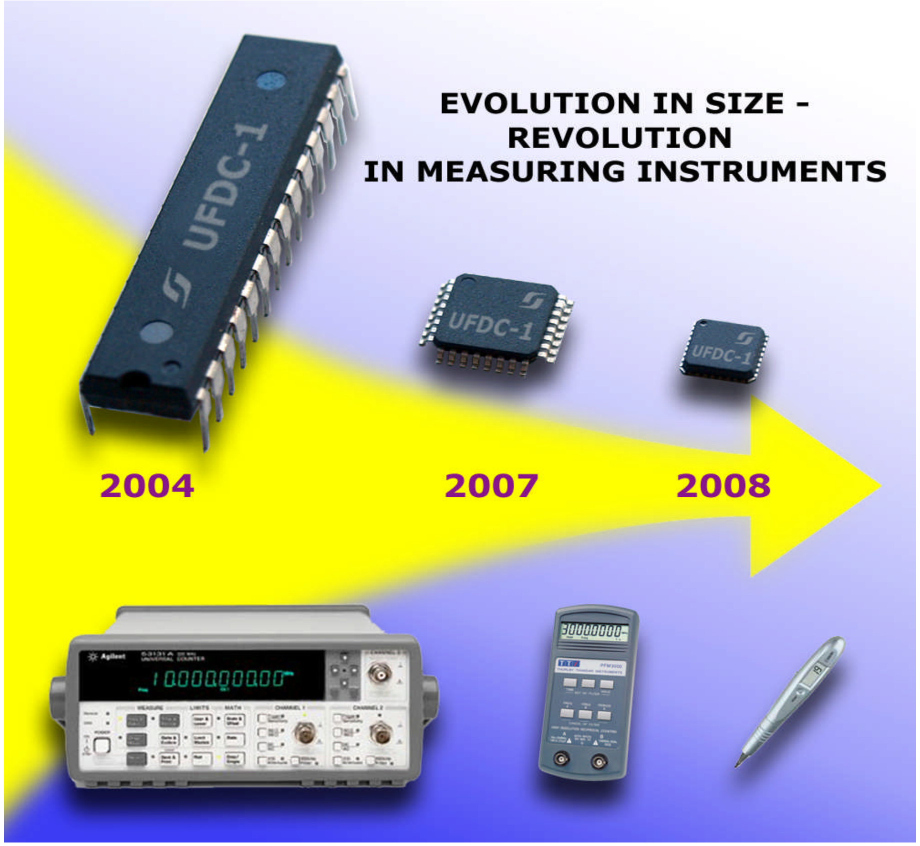


External Reference (Example)

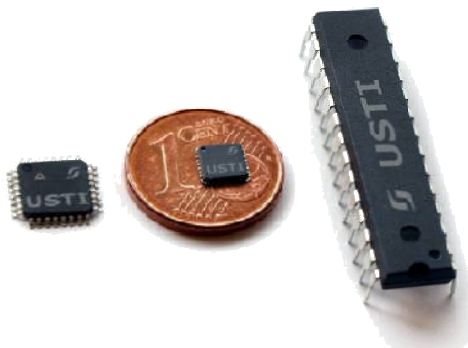


10 MHz to 51.84 MHz integrated generator from *Maxim* for highly accurate timing applications provides ±1 ppm (0.0001 %) frequency stability over the -40 ^{0}C to +85 ^{0}C industrial temperature range

UFDC-1 Packages

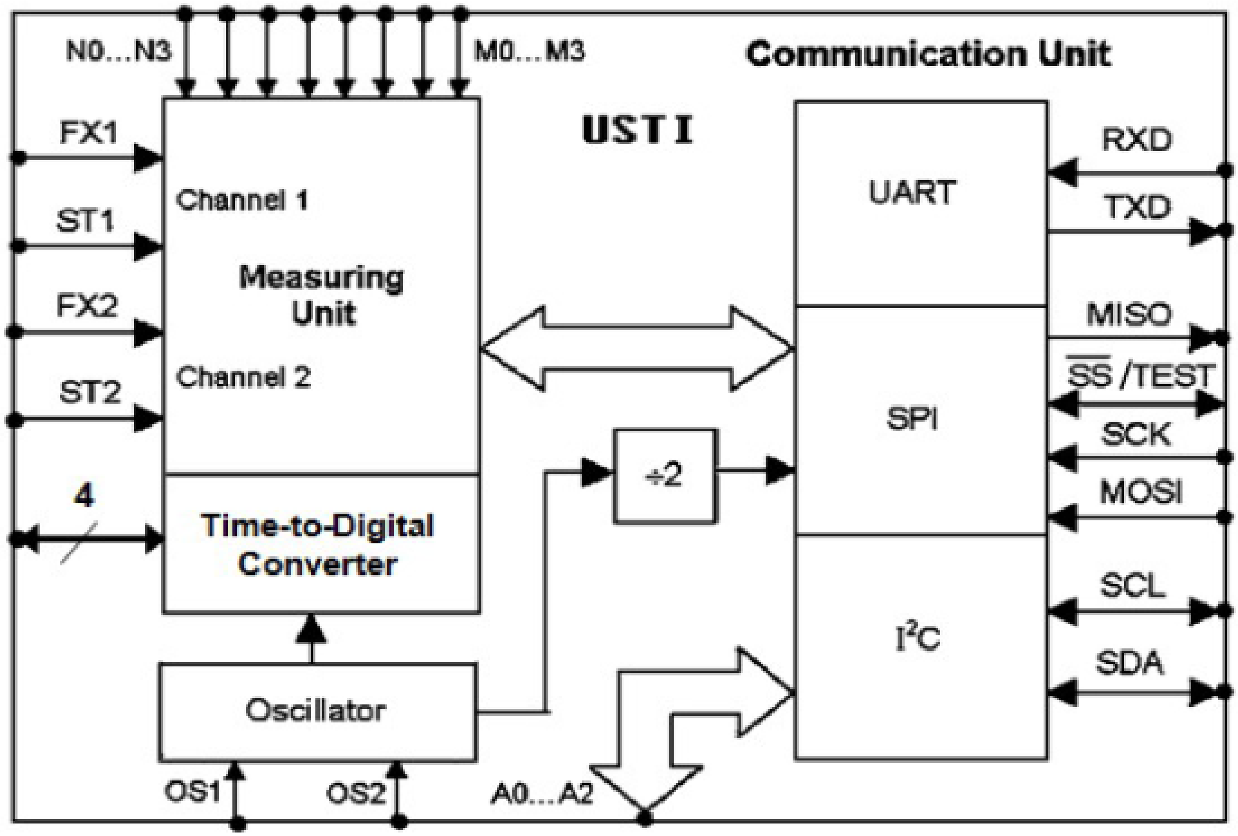


Universal Sensors and Transducers Interface (USTI)



- 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

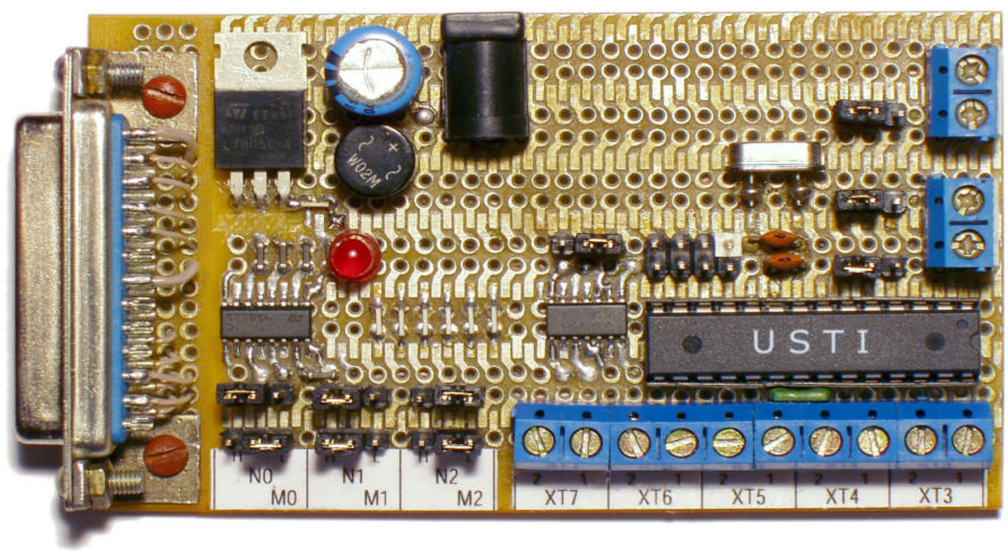
USTI Block Diagram



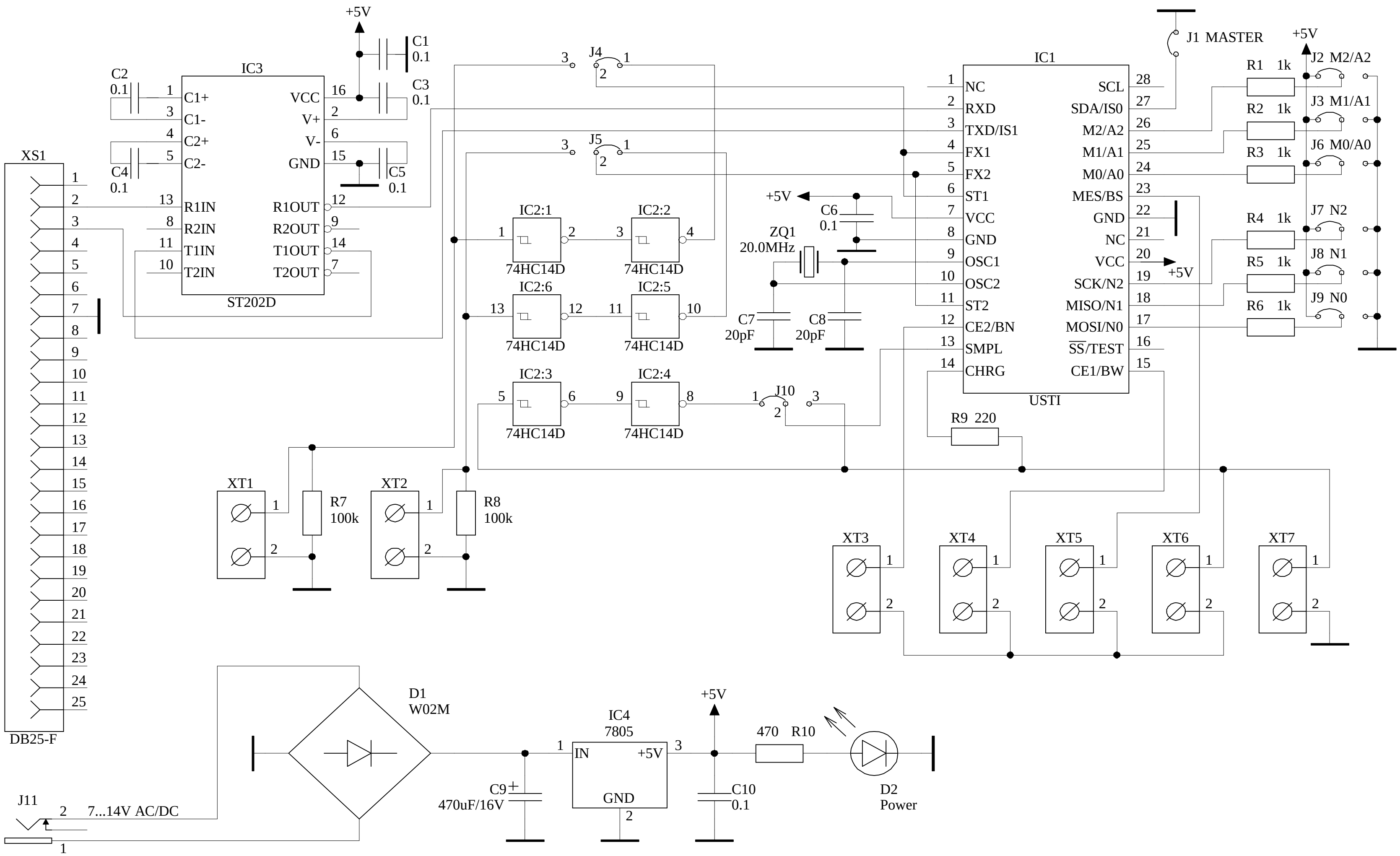
Comparison Performances of UFDC-1 and USTI

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

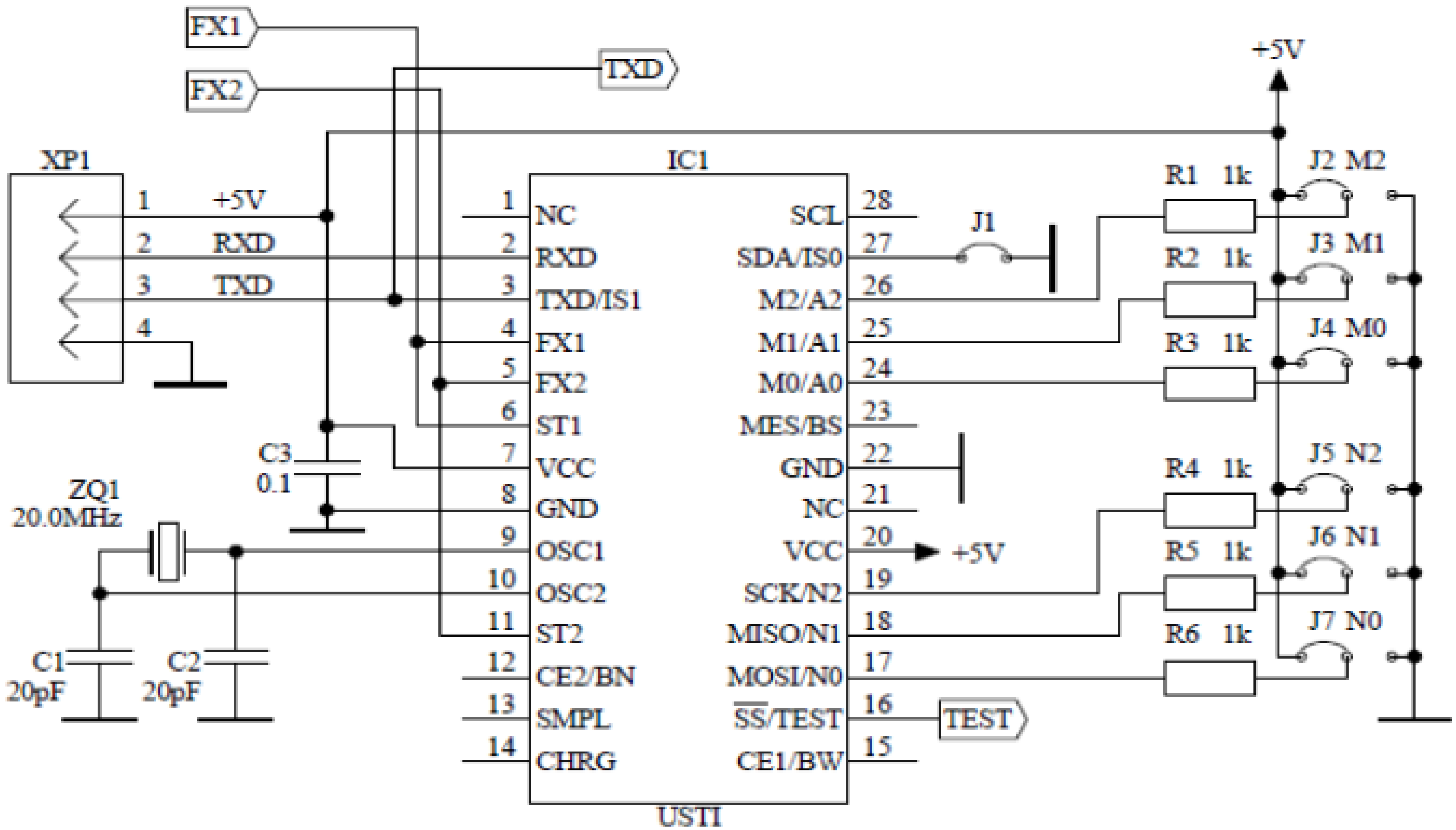
USTI Evaluation Board Prototype



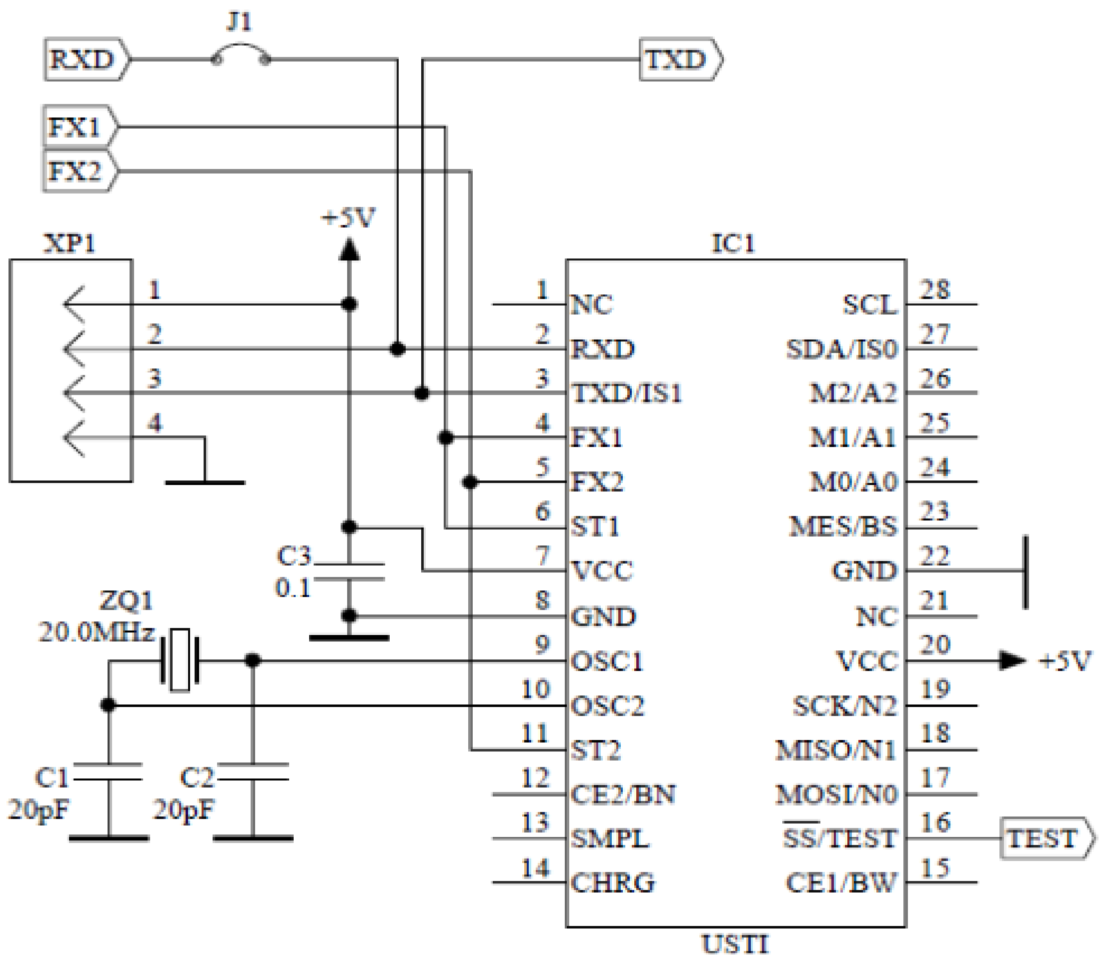
Evaluation Board Circuit Diagram



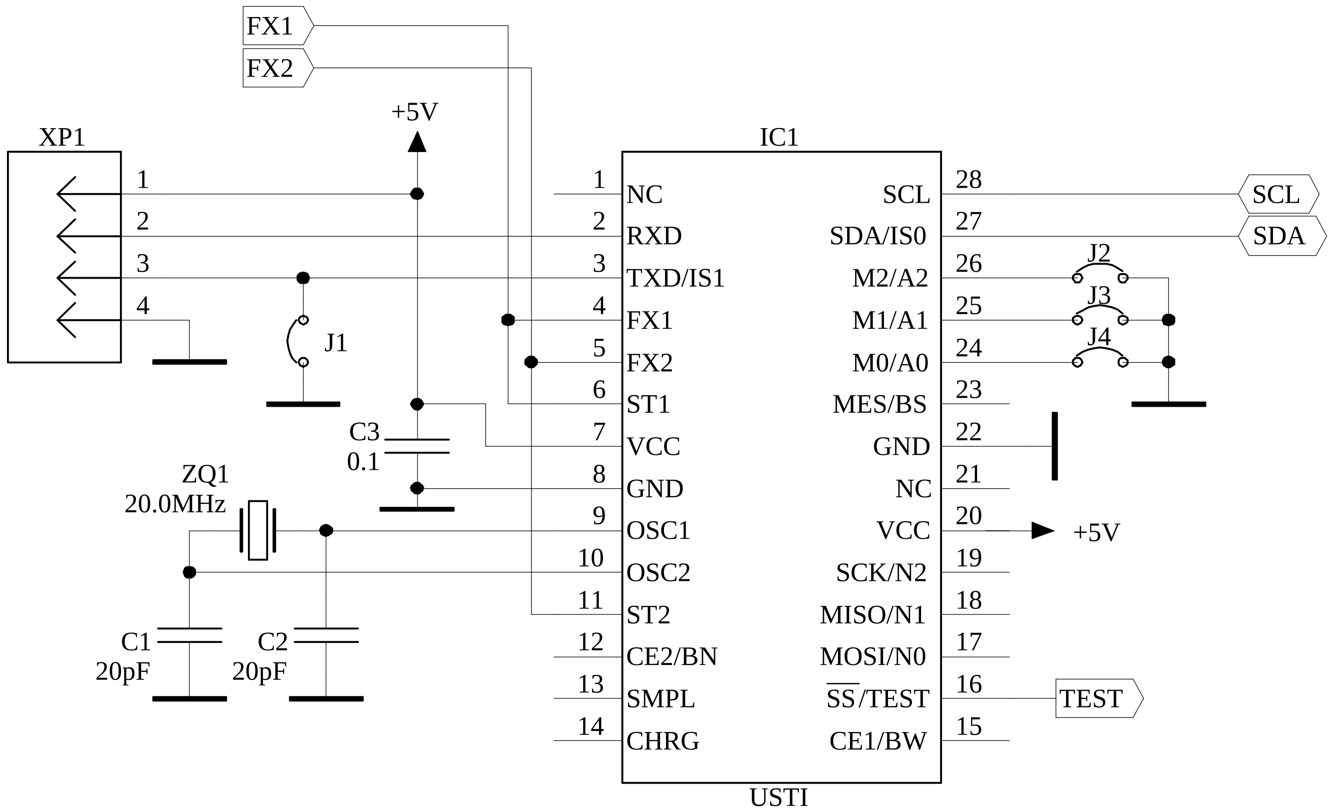
USTI RS232 Interface (Master)



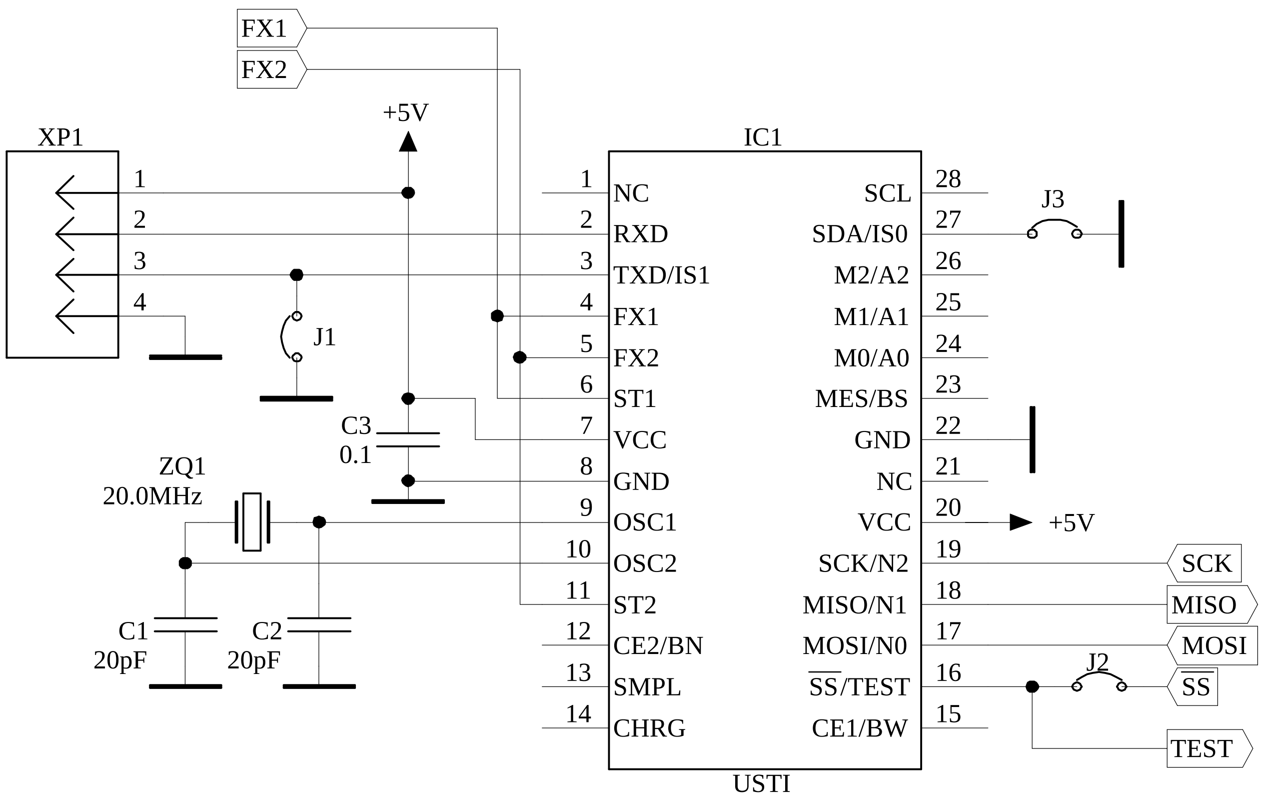
USTI RS232 Interface (Slave)



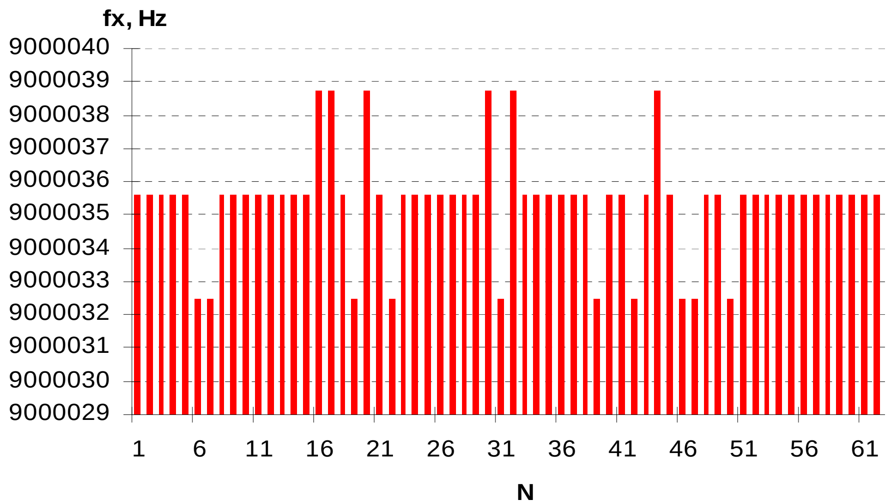
USTI I²C Interface

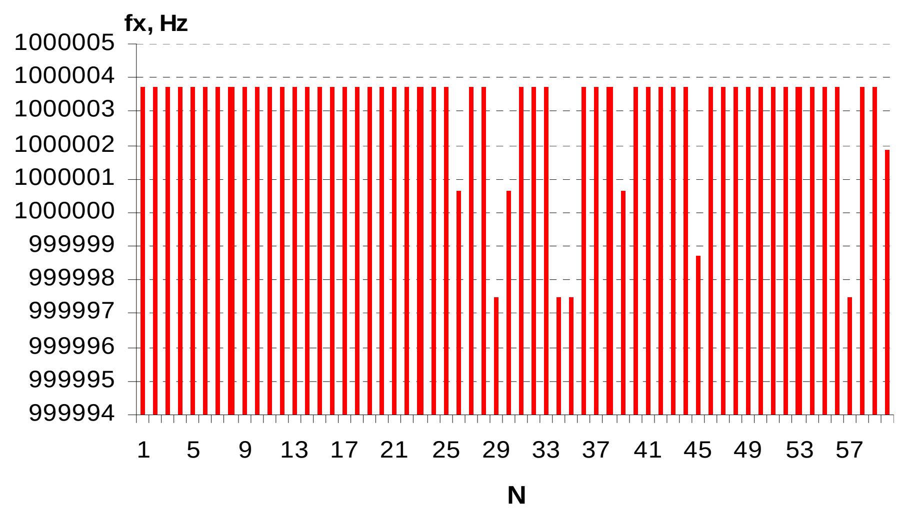


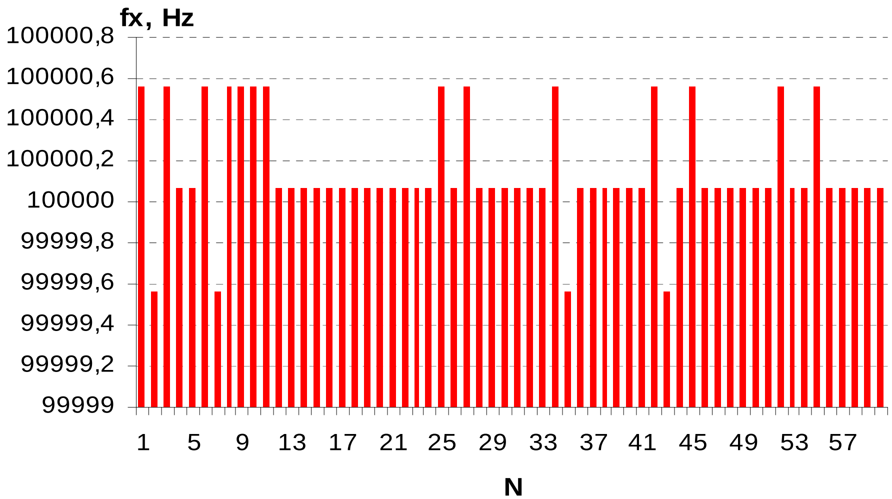
USTI SPI Interface



Experimental Results





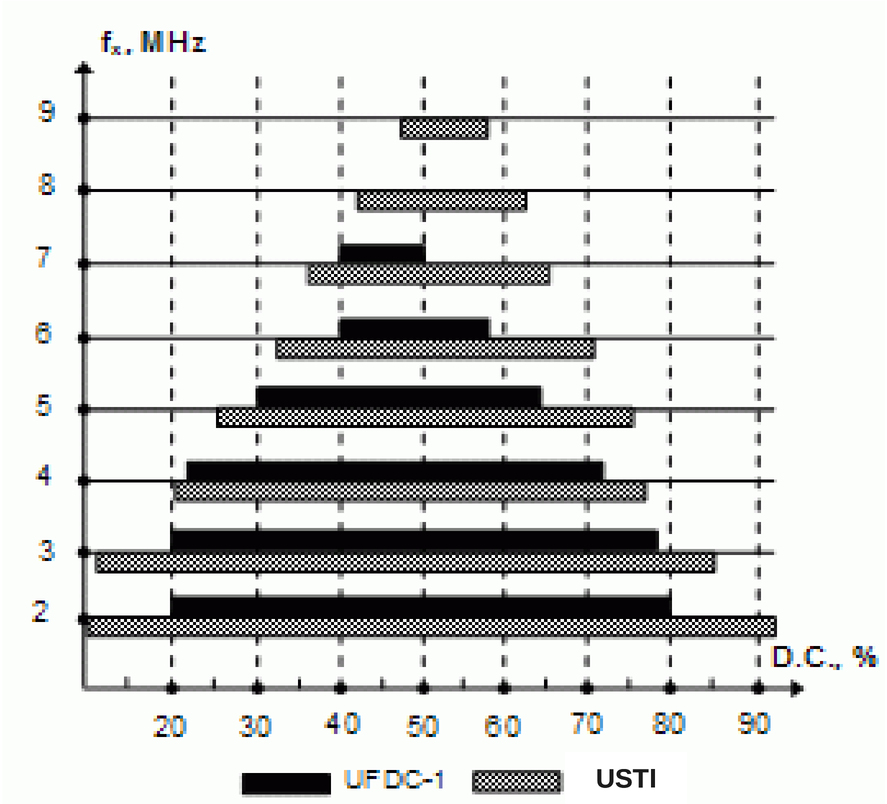


Statistical Characteristics

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 є [9000035 ÷9000035.83]	f_x є [1000002.55 ÷1000003.54]	f_x є [100000.073 ÷ 100000.22]
Relative error, %	0.00039 < 0.00050	0.00030 < 0.00050	0.00014 < 0.00050

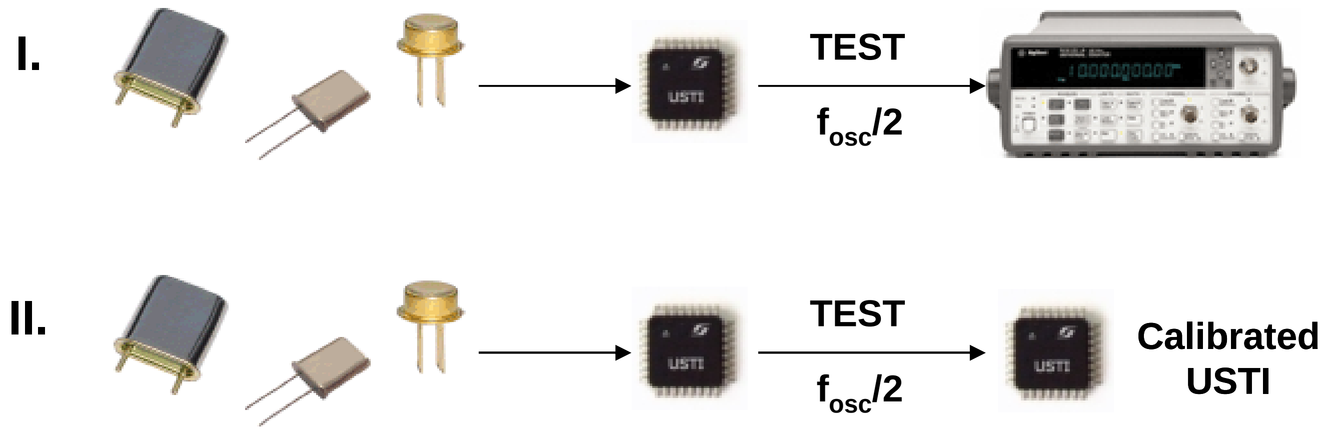
Duty-Cycle for Input Signal

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



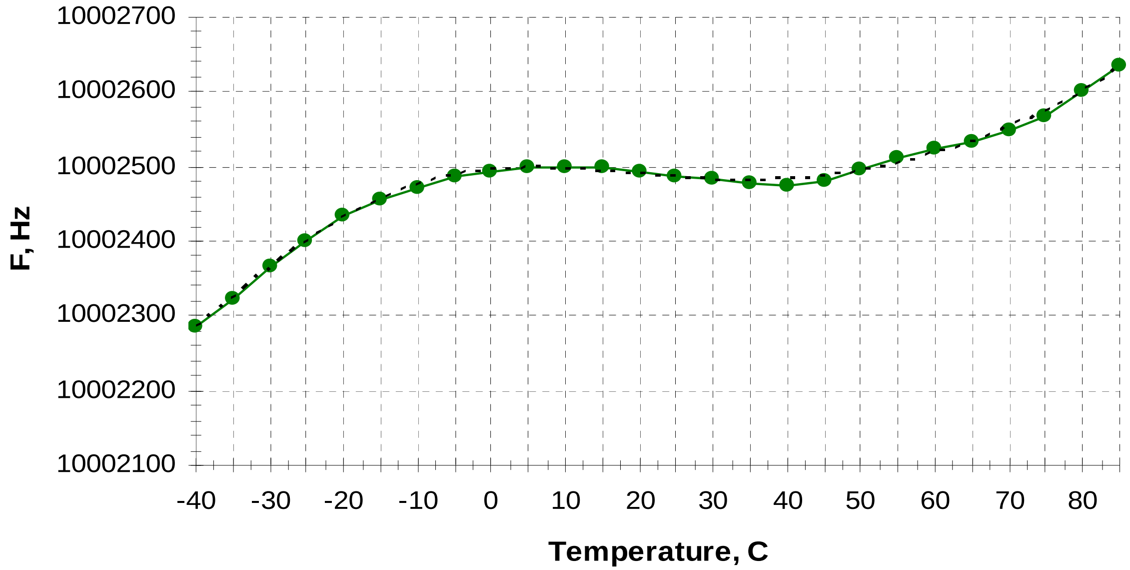
Temperature Drift Calibration

- 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:

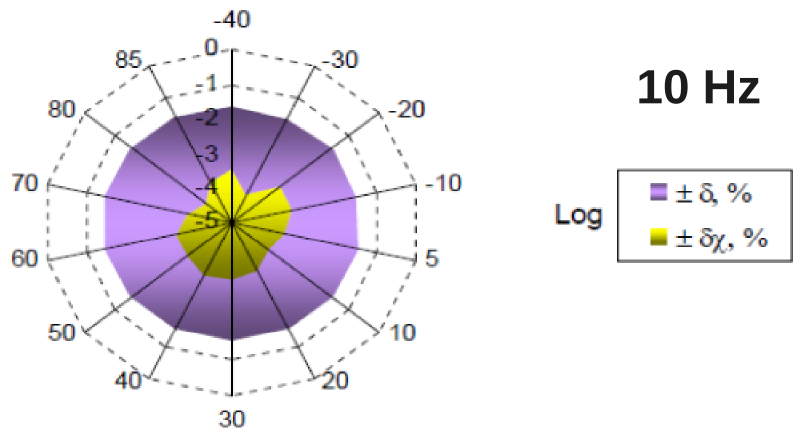
- Relative error of measurement > 0.026 %
- Use a precision temperature-compensated integrated generator ± 1 ppm frequency stability over the -40°C to +85°C, for example, DS4026 from *MAXIM*
- In this case a custom designed USTI should be ordered

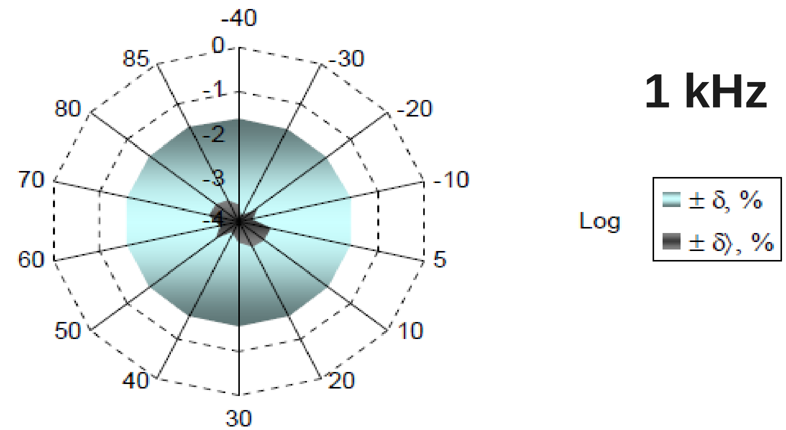
USTI Calibration Results

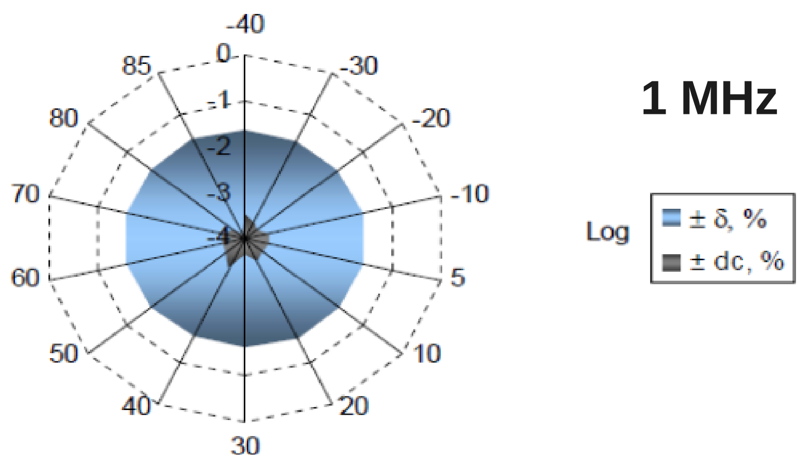


y = 3.10-5 x6 - 0,0025x5 + 0,0871x4 - 1,3113x3 + 6,3954x2 + 26,852x + 107;
R2 = 17,991 – squared value

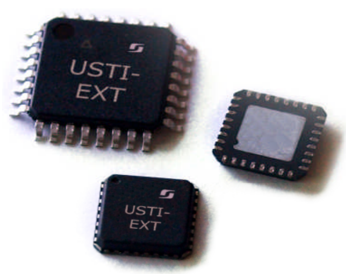
Calibration Results







USTI-EXT



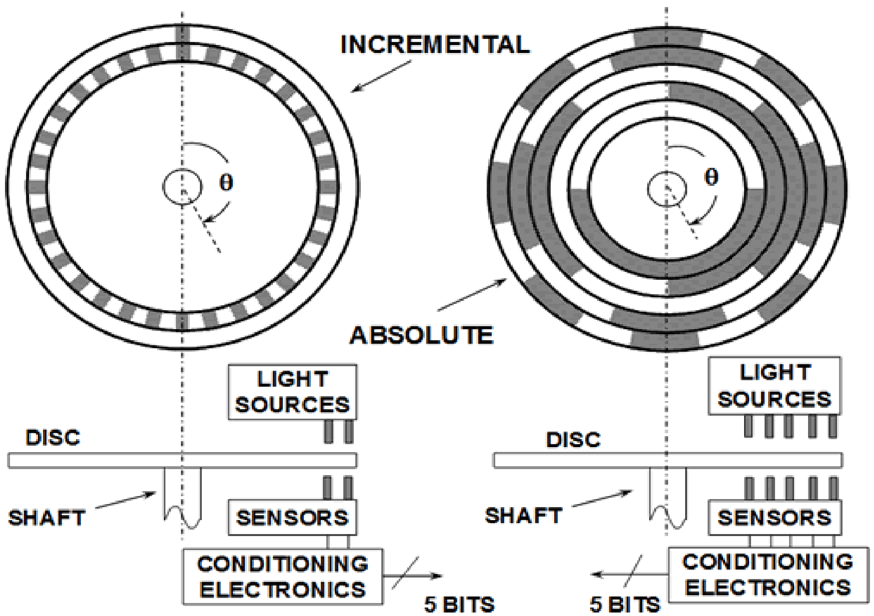
- Extended operation temperature range from - 55 ^{0}C to +150 ^{0}C
- Similar metrological performance as UFDC-1M-16
- Wide functionality as in USTI
- Increased baud rate for the RS232 serial interface: up to 76 800
- Active supply current <12 mA
- 32-lead, 7x7 mm TQFP and 32-pad, 5x5 mm (QFN/MLF)
-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

Outline

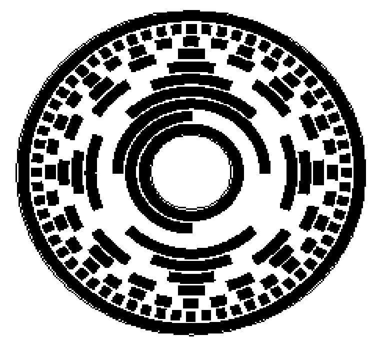
Digital Sensors

- 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.

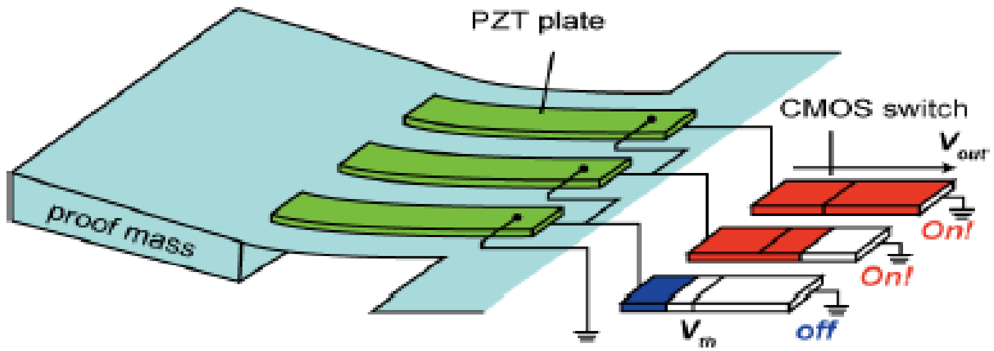
Angular-Position Encoder



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.



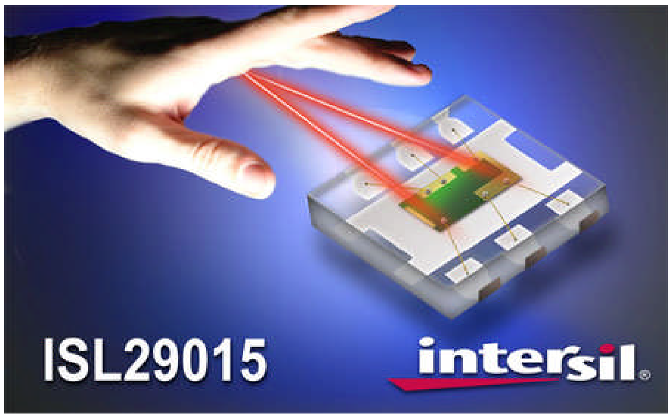
Digital Accelerometer

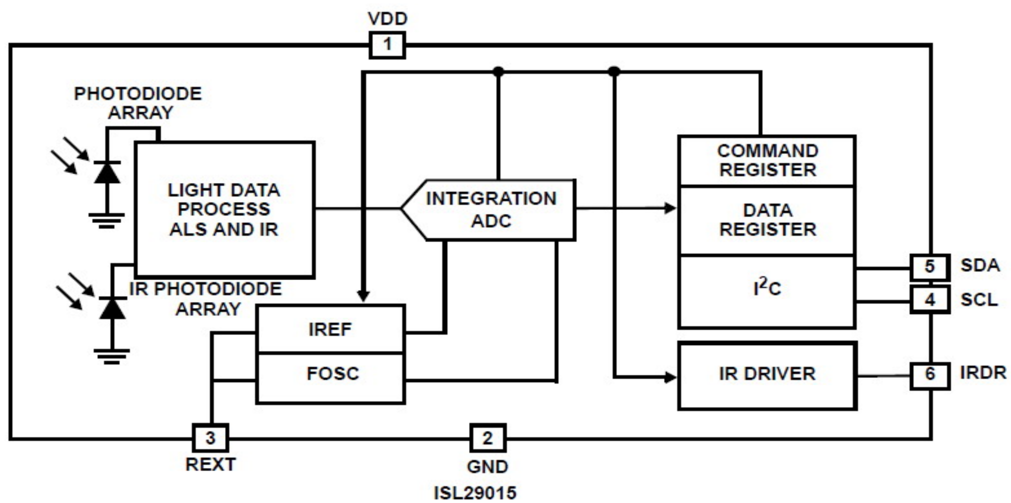


Toshihiro Itoh, Takeshi Kobayashi, Hironao Okada, A Digital Output Piezoelectric Accelerometer for Ultra-low Power Wireless Sensor Node, in *Proceedings of IEEE Sensors 2008*, 26-29 October 2008, Lecce, Italy, pp.542-545.

Smart Sensor Example I

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

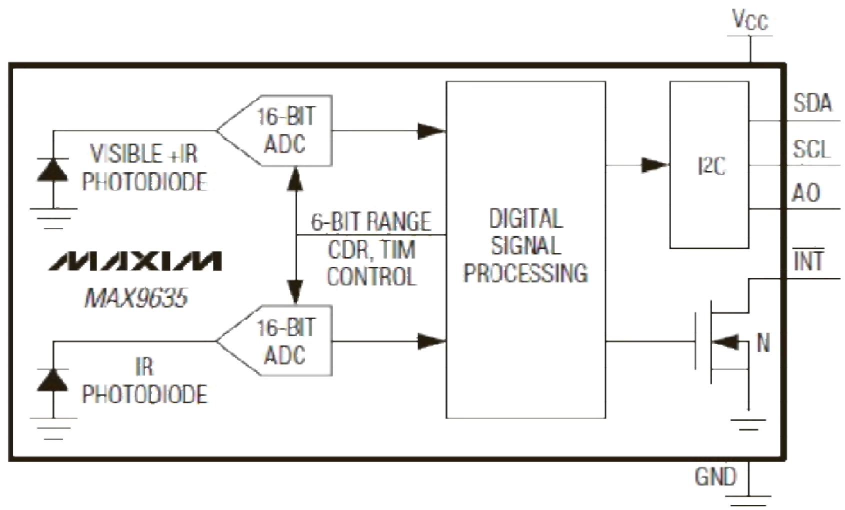




Integration time of 16-bit ADC: 45 … 90 ms

Smart Sensor Example II

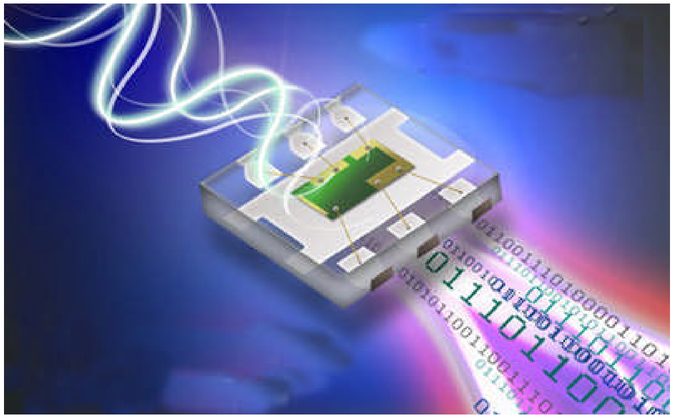
Ambient Light Sensor MAX9635 with ADC (*Maxim*)

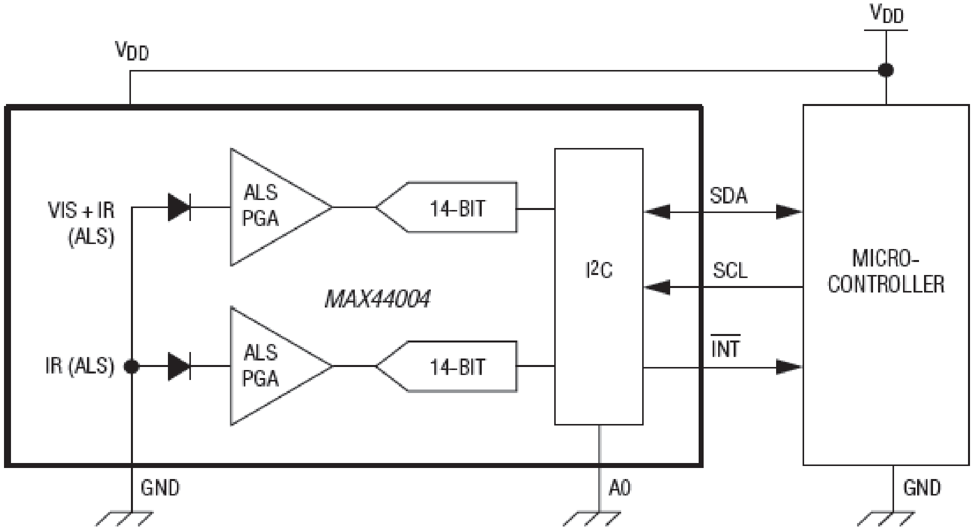


ADC's conversion time: 97 … 100 ms

Smart Sensor Example III

Digital Ambient Light Sensor MAX44004 with ADC (*Maxim*)

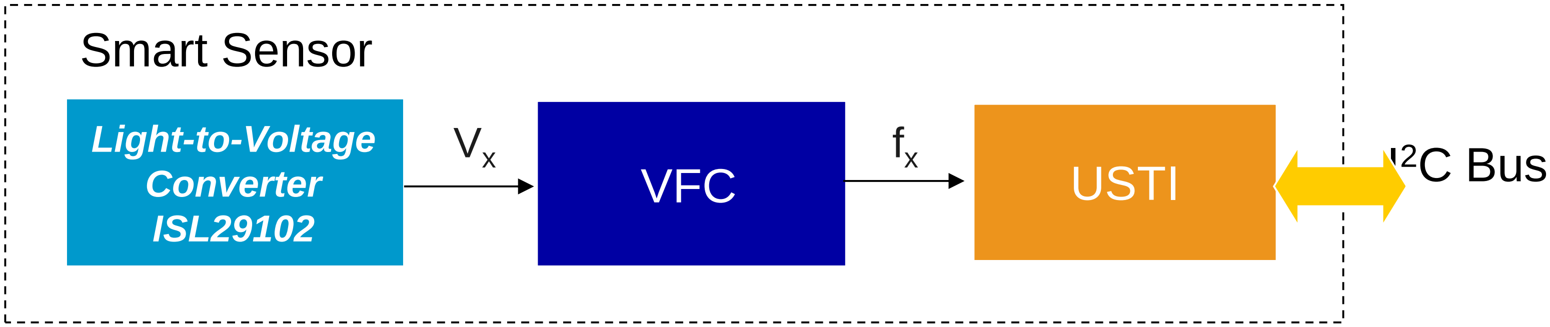




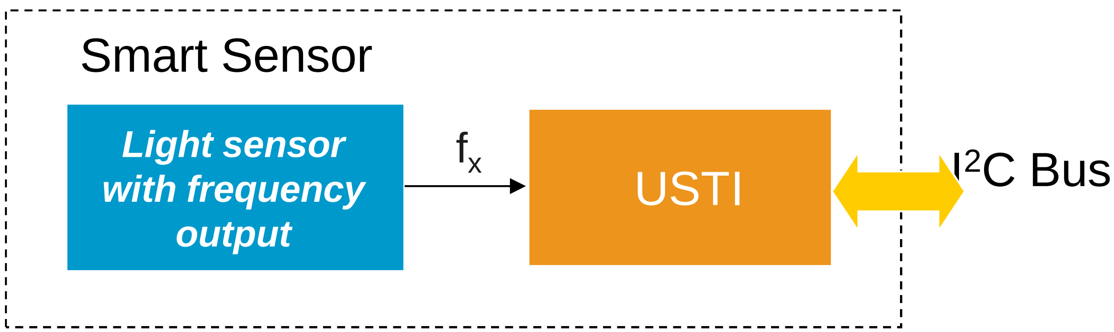
ADC's conversion time (14-bit): 100 ms

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

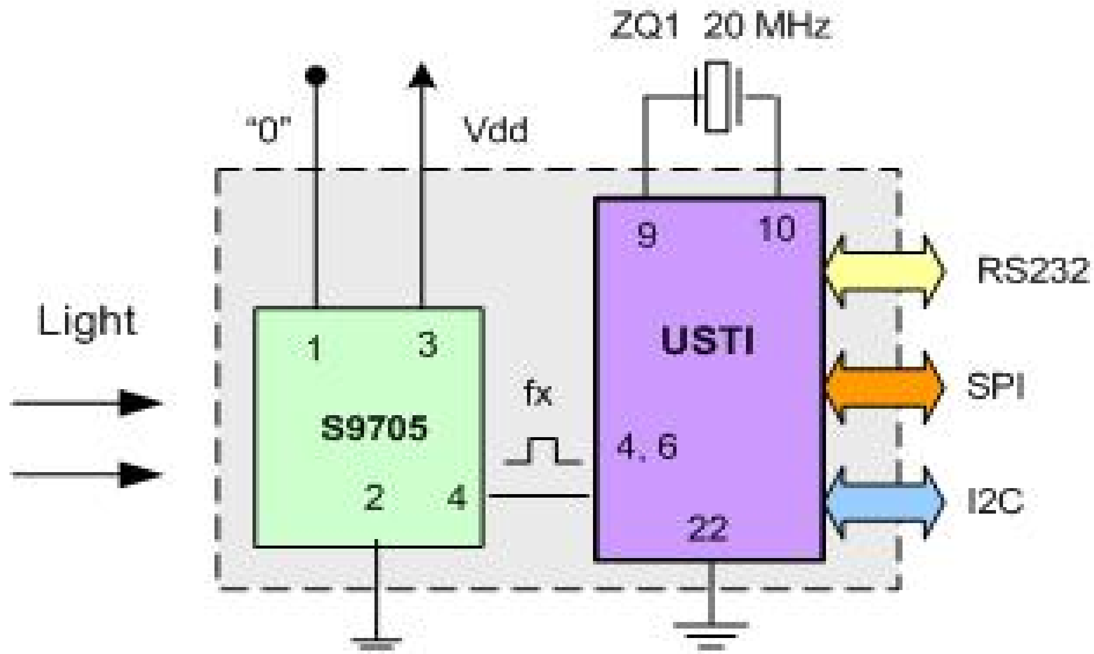
Modern VFCs

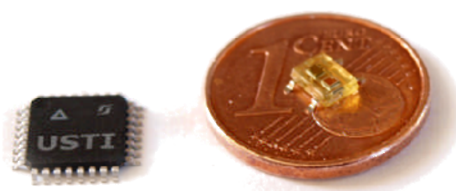
- There are a lot of commercially available types of integrated VFCs to meet many requirements (0.012 % integral nonlinearity)
- Ultra-high speed 1 Hz-100 MHz VFC with 0.06 % linearity
- Fast response (3 μs) 1 Hz-2.5 MHz VFC with 0.05 % linearity
- High stability quartz stabilized 10 kHz – 100 kHz VFC 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

Optoelectronic Sensor System



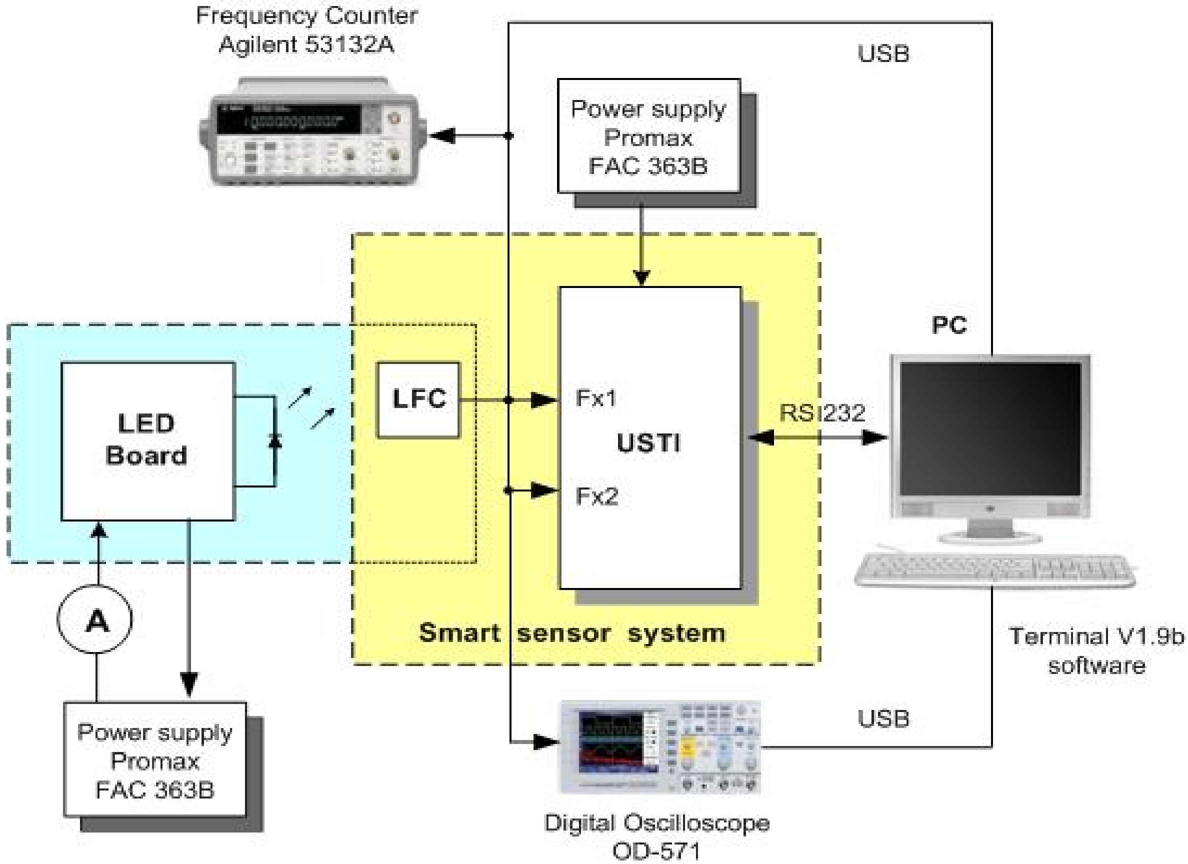


Commands for RS232 Communication Mode

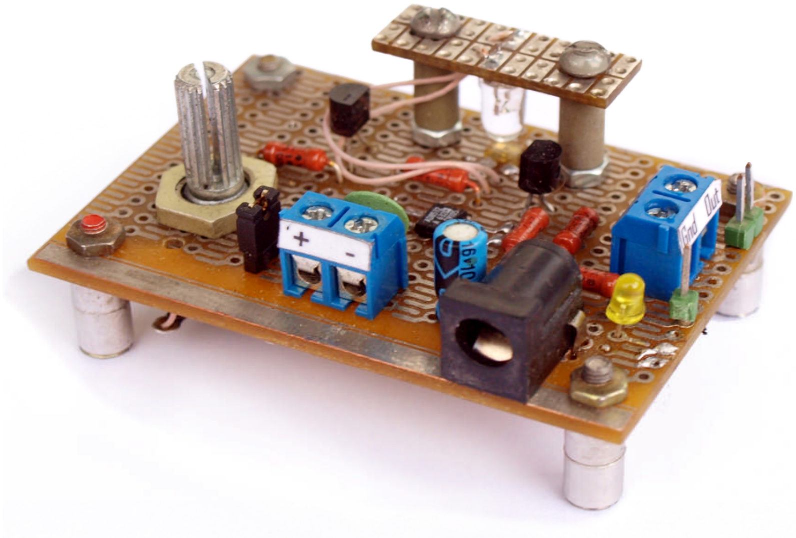
>A02 ;Set the relative error 0.25 %
>M00 ;Set up a frequency measurement mode in the 1st channel
>S ;Start a frequency measurement (light sensor)
>C ;Check the measurement status (‘r’-ready, ‘b’ -in progress
>R ;Read a result of frequency measurement in Hz
>462987.345

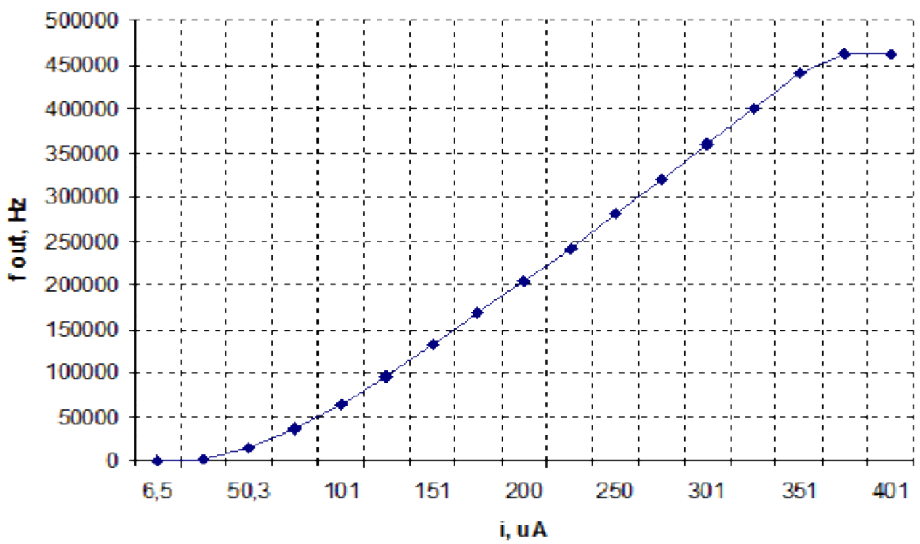
>M0E ;Set up a frequency measurement mode in the 2nd channel
>S ;Start a frequency measurement (colour sensor)
>C ;Check the measurement status (‘r’ -ready, ‘b’-in progress
>R ;Read a result of frequency measurement in Hz
>37005.0119

Measuring Set-up

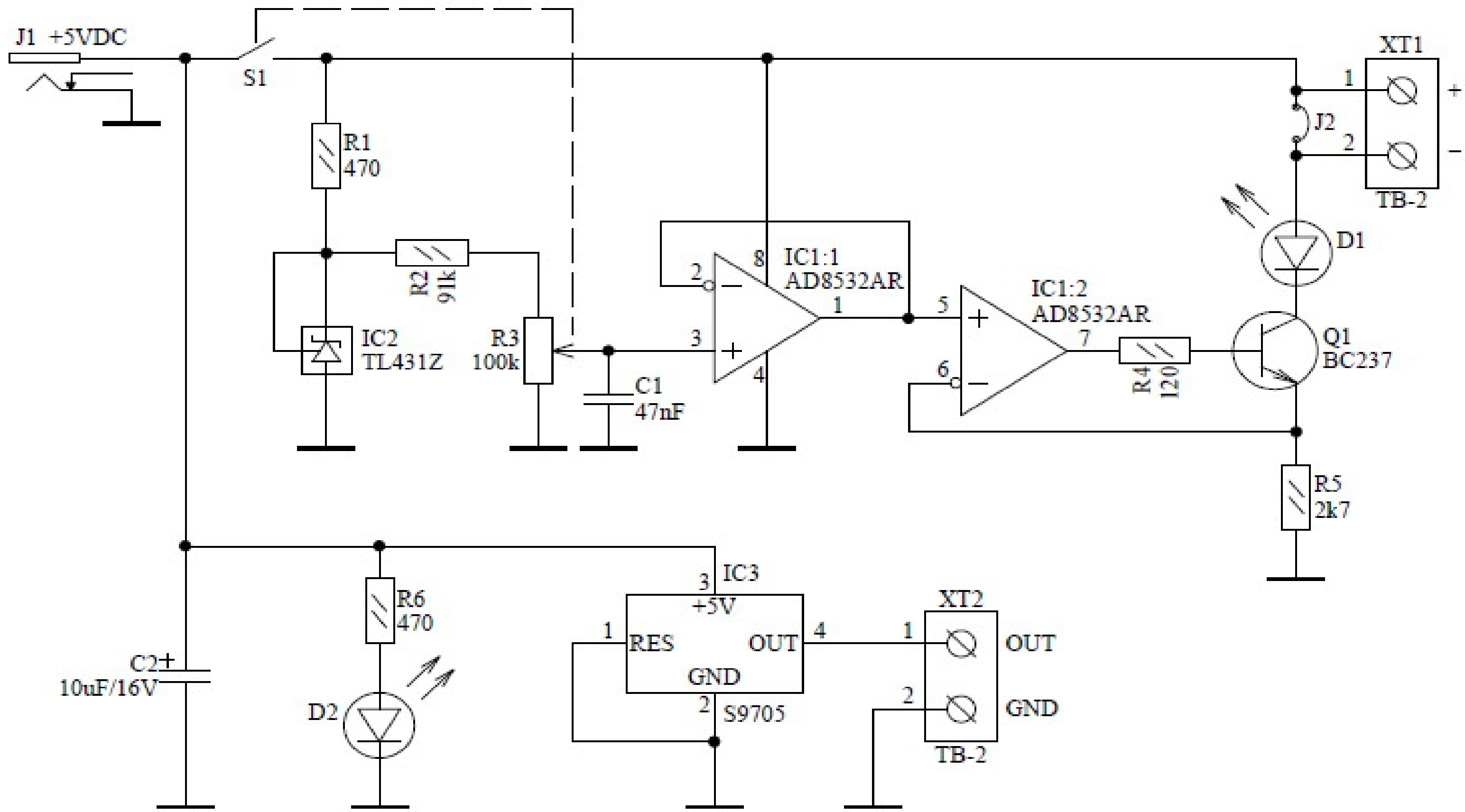


LED Evaluation Board

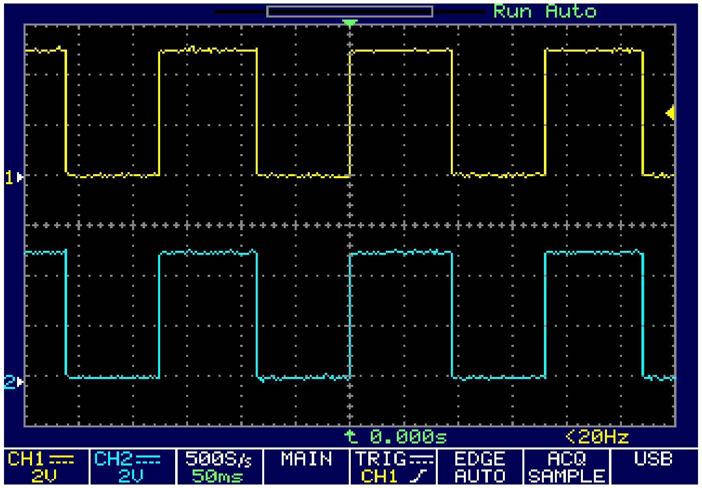


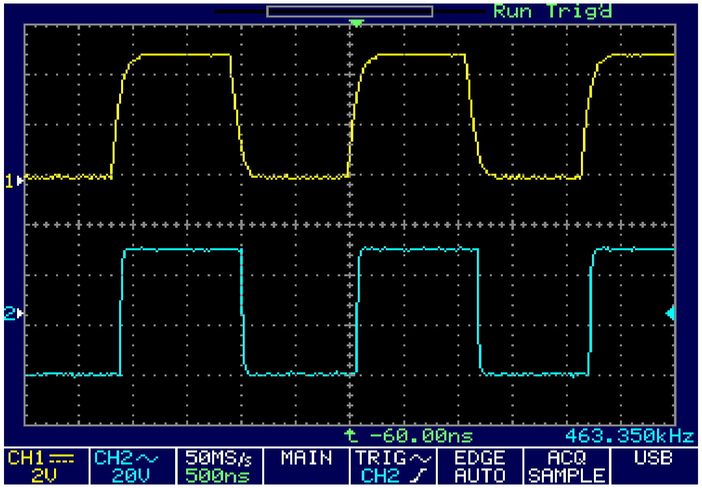


LED Evaluation Board Circuit Diagram



LFC's Oscillograms





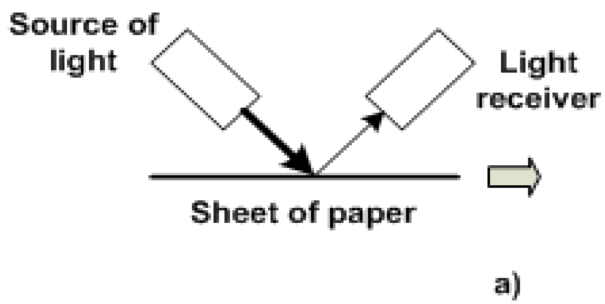
Statistical Characteristics (~ 463 kHz)

Parameter	463 kHz
Number of measurements, *N*	53
Minimum f_x (min)	461653.265
Maximum f_x (max)	463991.336
Sampling Range, f_x (max) - f_x (min)	2338.0705
Arithmetic Mean	462788.685
Variance	234229.738
Standard Deviation	483.9729
Coefficient of Variation	956.2286
Confidence interval for arithmetic mean at *P*=97 %	$462644.42 < f_x < 462932.95$
Relative error, %	0.014
χ^2 – test (S) at: k=6; *P* = 97 % χ^2_{max} = 8.9	1.7272
Hypothesis about Gaussian distribution	Accepted

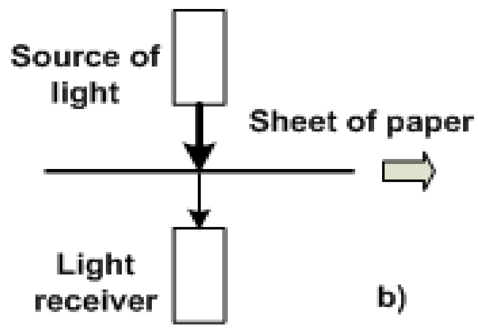
Statistical Characteristics (~ 5 Hz)

Parameter	5 Hz
Number of measurements, *N*	60
Minimum f_x (min)	5.2014
Maximum f_x (max)	5.6466
Sampling Range, f_x (max) - f_x (min)	0.4452
Arithmetic Mean	5.3899
Variance	0.0109
Standard Deviation	0.1045
Coefficient of Variation	51.577
Confidence interval for arithmetic mean at *P*=97 %	$5.3606 < f_x < 5.4192$
Relative error, %	0.54
χ^2 – test (S) at: k=6; *P* = 97 % χ^2_{max} = 8.9	6.6726
Hypothesis about Gaussian distribution	Accepted

Paper Type Detection

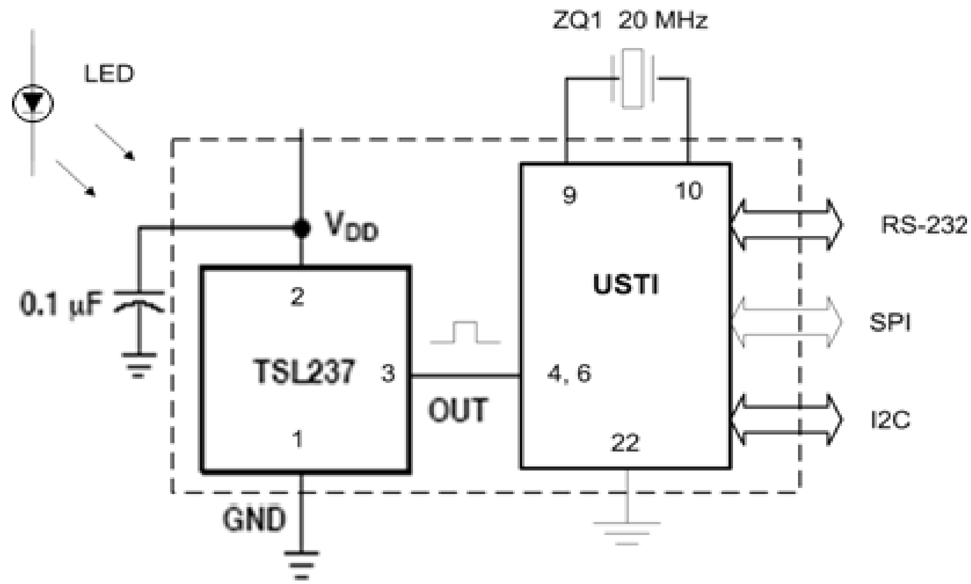


- Reflective type sensor



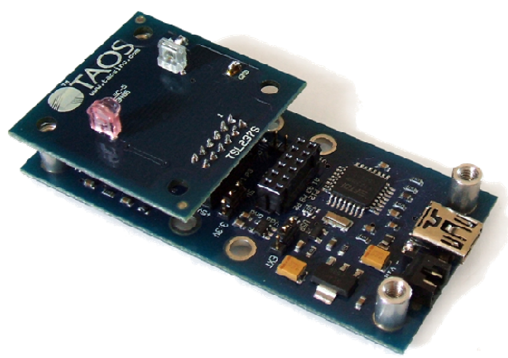
- Transmission type sensor

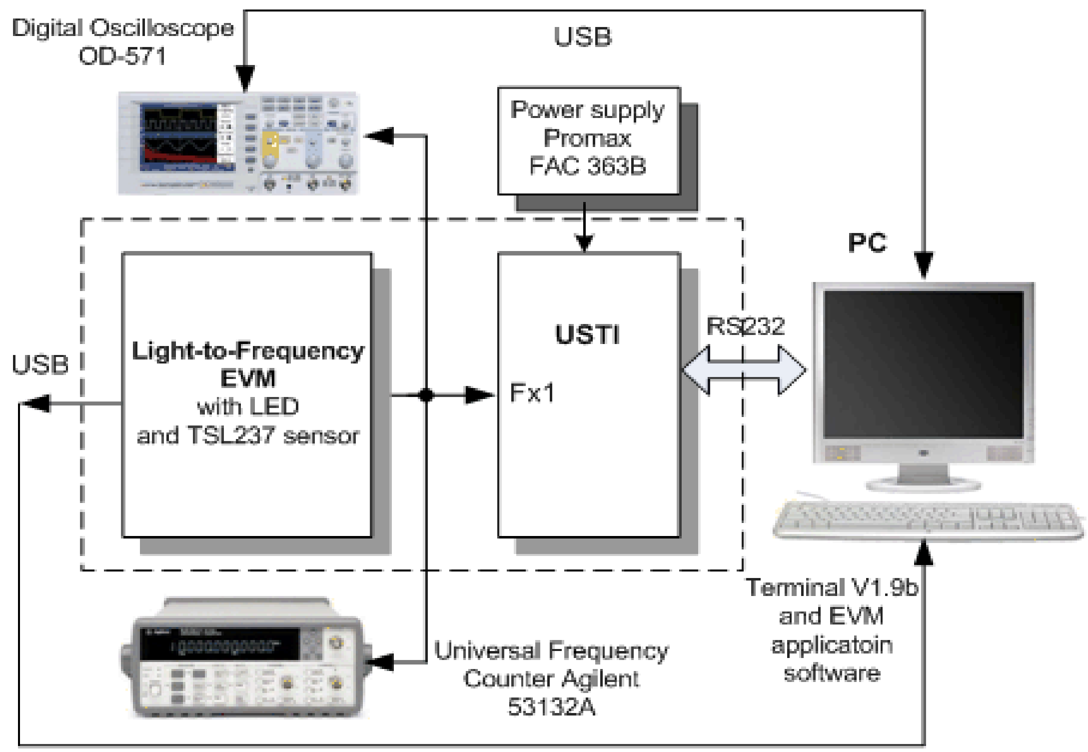
Paper Thickness Sensor System



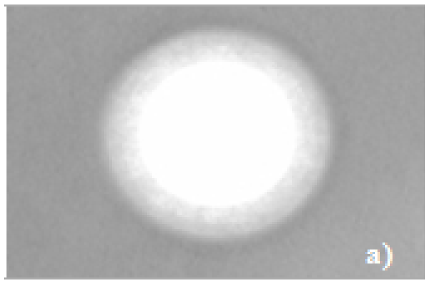
1. Light sensor TSL237
2. LED
3. USTI

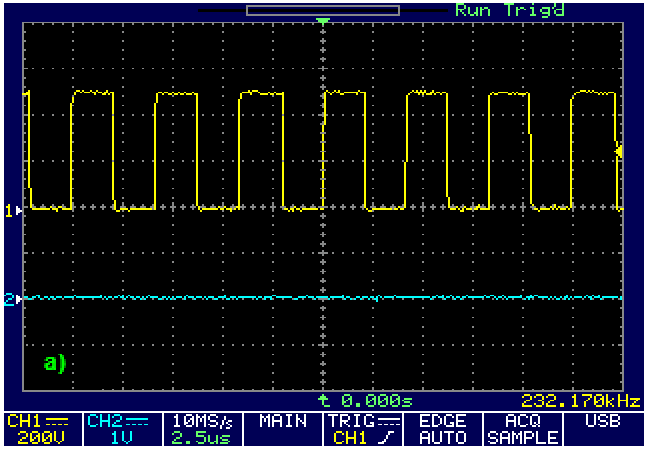
Measurement set-up for Sensor System Investigation

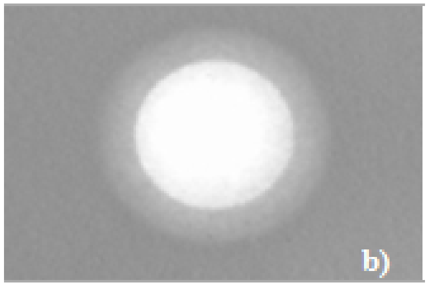


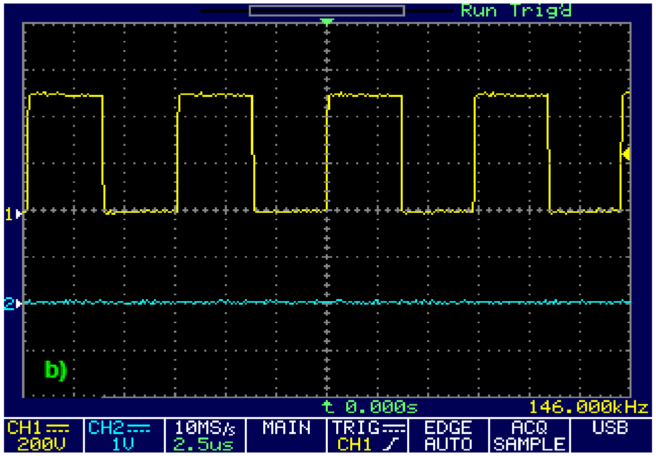


Sensor Output Signals at 0.086 mm (a), and 0.217 mm

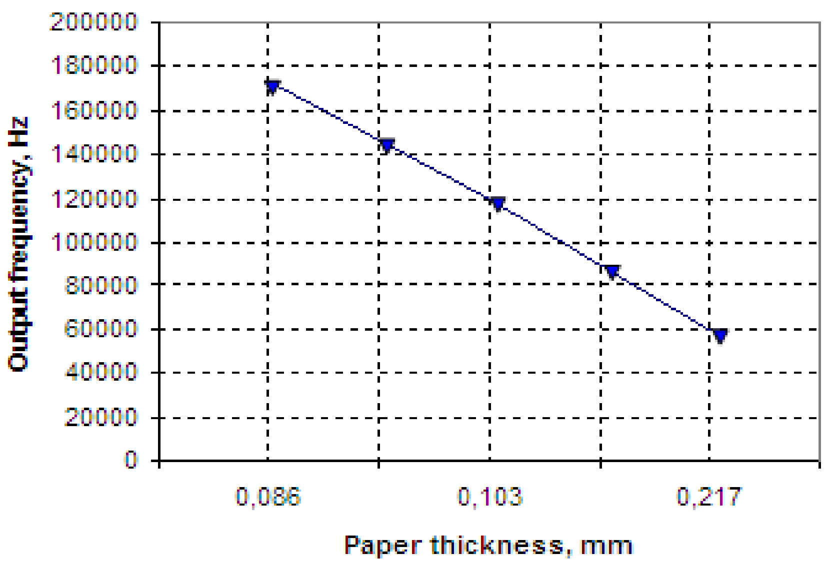


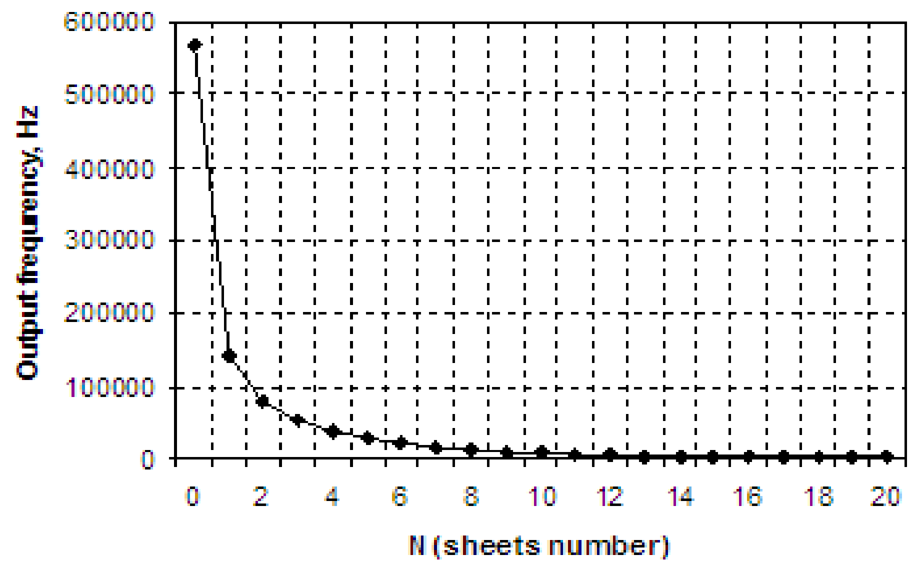






Experimental Results

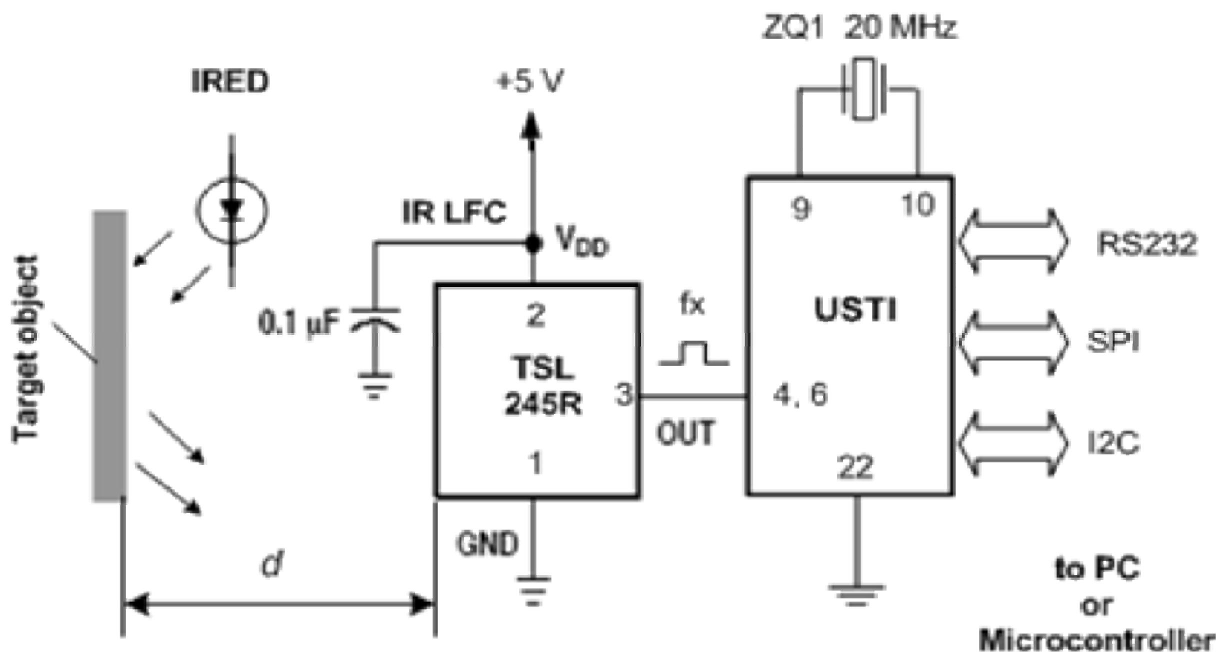




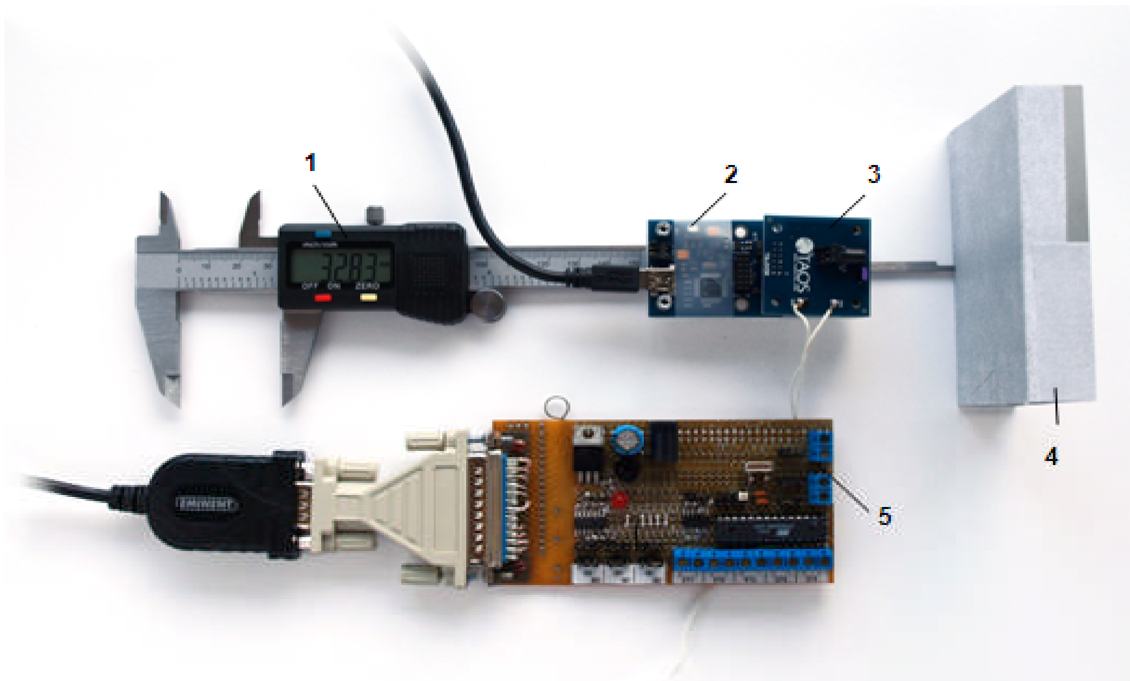
N	1	2	3	4	5	6	7	8	9	10
f_x, Hz	143000	81100	55500	39400	29500	22400	17350	12600	10350	8300

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

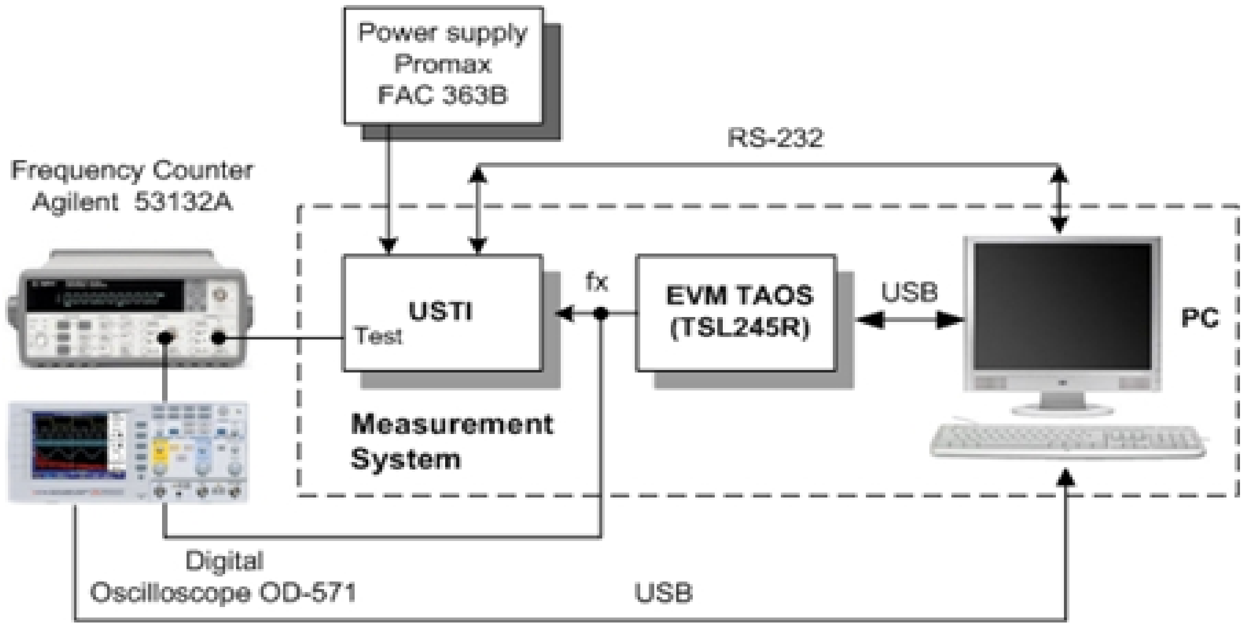


Sensor System Prototype

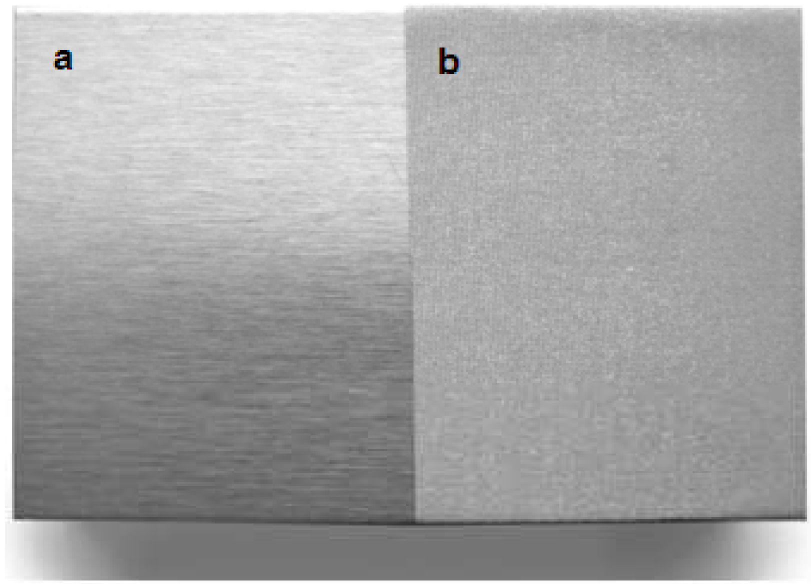


1-Electronic digital caliper Z22855 Powerfix; 2-LTF EVM motherboard
3-TAOS LTF EVM TSL245R daughterboard; 4-Target object;
5-USTI Evaluation Board

Measurement set-up for Experimental Investigation



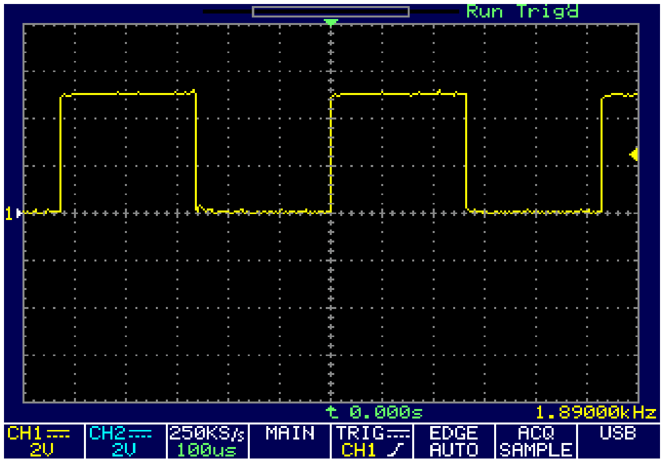
Targeted Objects

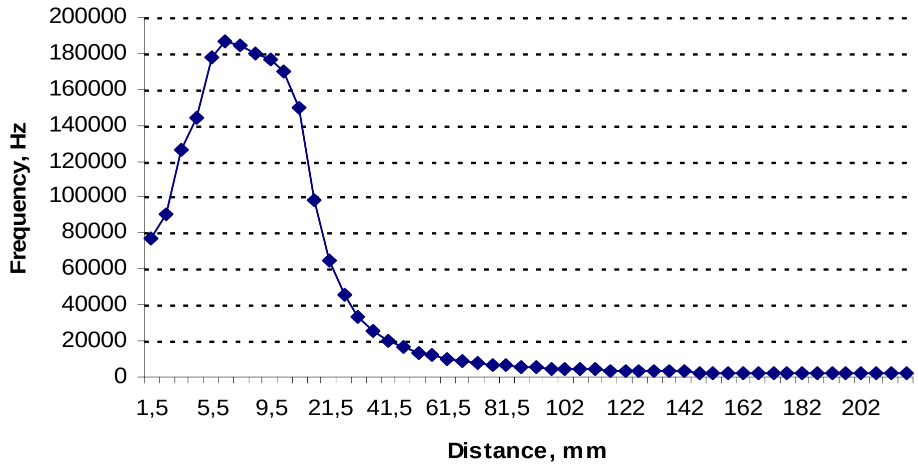


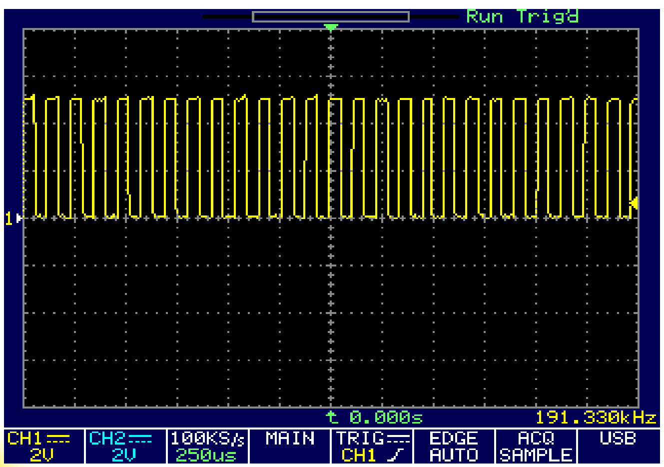
a) Duraluminium surface

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

Experimental Results





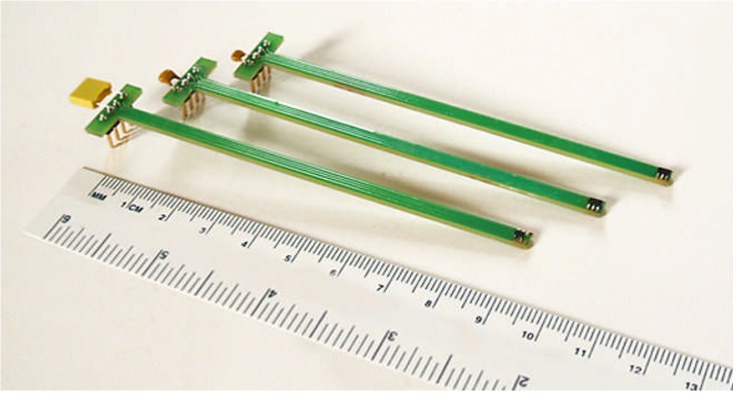


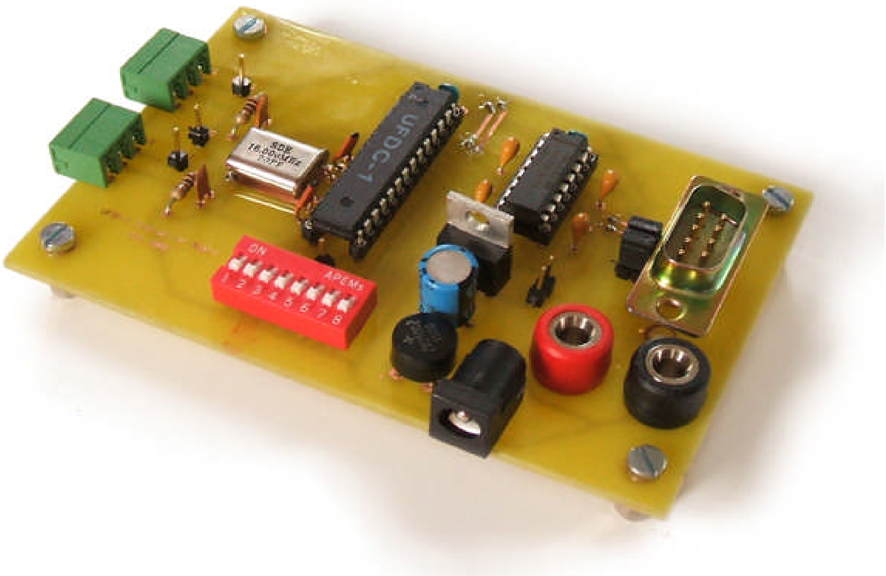
- Measurement range, 1.5 to 215 mm
- Frequency output ~1.8 to 190 kHz
- Resolution 0.01 mm
- Response 34 Hz/0.01 mm at 75 mm
- Decreased in 9.5 …38 times measuring time in comparison with 0.25 to 1 s in standard systems

Opto Sensors Systems Applications

- Proximity detection
- Color classification systems
- Oximeters
- Light parameters monitoring and control
- Water turbidity measurement
- Flame control
- Fluid absorption measurement
- Paper handling
- Exposure control
- General visual process control, etc.

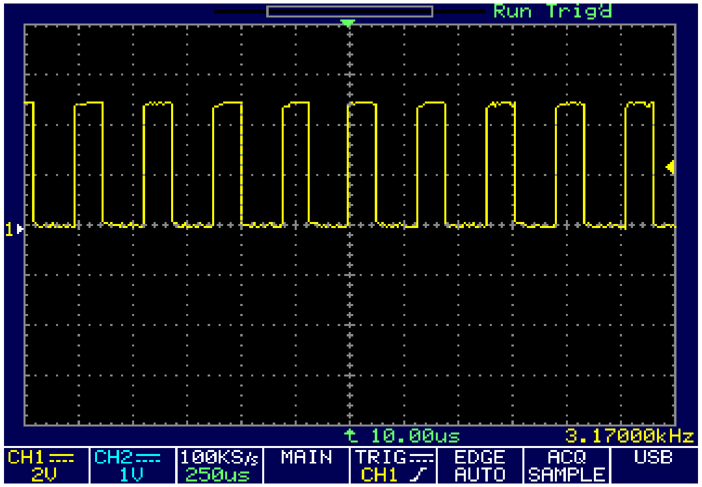
Low Cost Temperature Sensor System

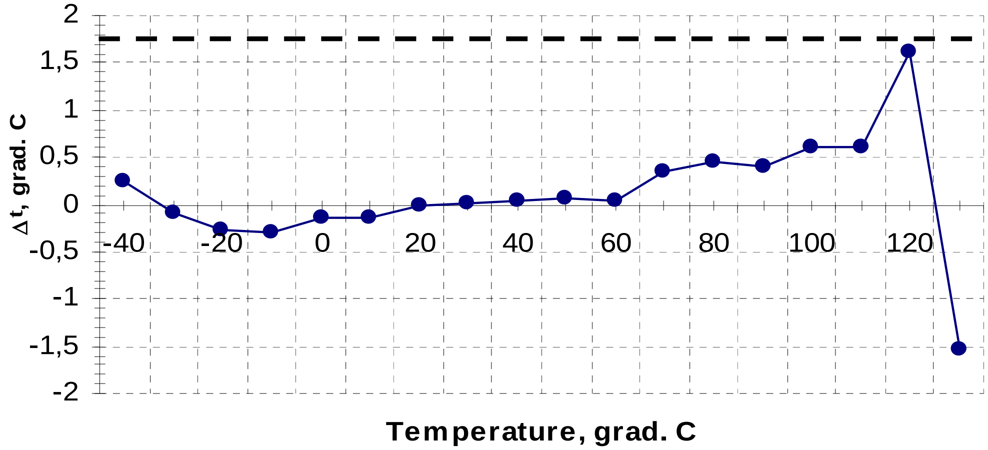


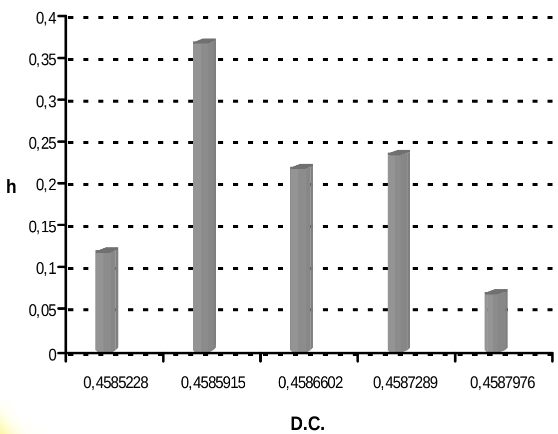


Experimental Setup and Temperature Chamber CTS T-40/50

Experimental Results

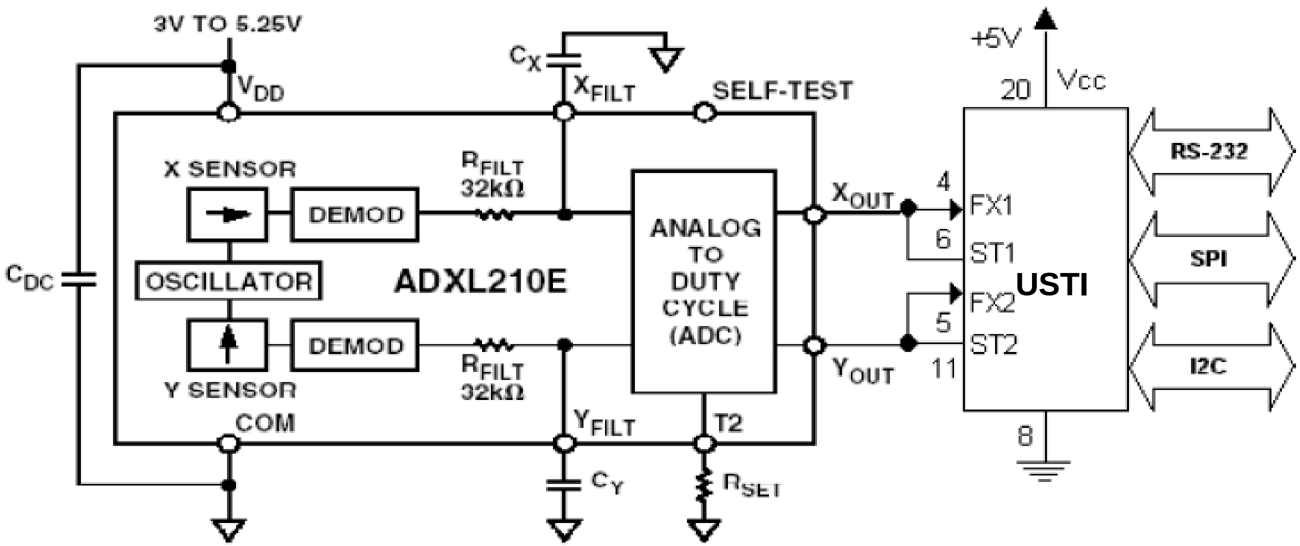


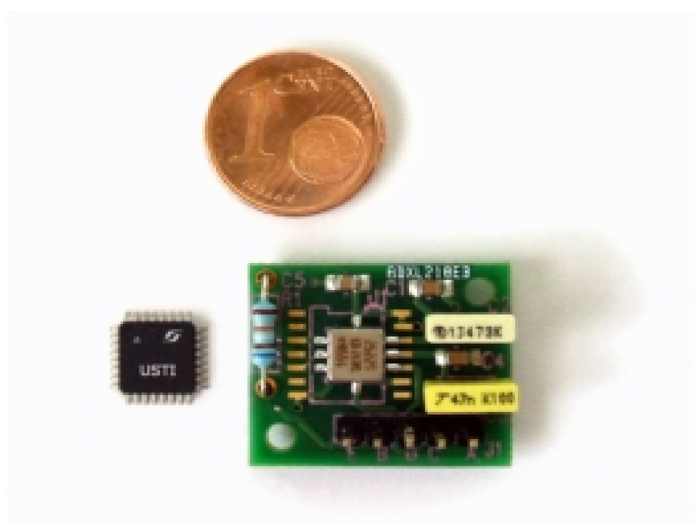




Parameter	Duty-cycle, %
Number of measurements, *N*	60
Minimum *D.C.* (min)	0.4585
Maximum *D.C.* (max)	0.4588
Sampling Range, *D.C.* (max)- *D.C.* (min)	0.0003
Median	0
Arithmetic Mean	0.4586
Variance	6.6E-0009
Standard Deviation	0.0001
Coefficient of Variation	5666.7026
Relative error, %	0.044
Confidence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

Dual-Axis Inclinometer



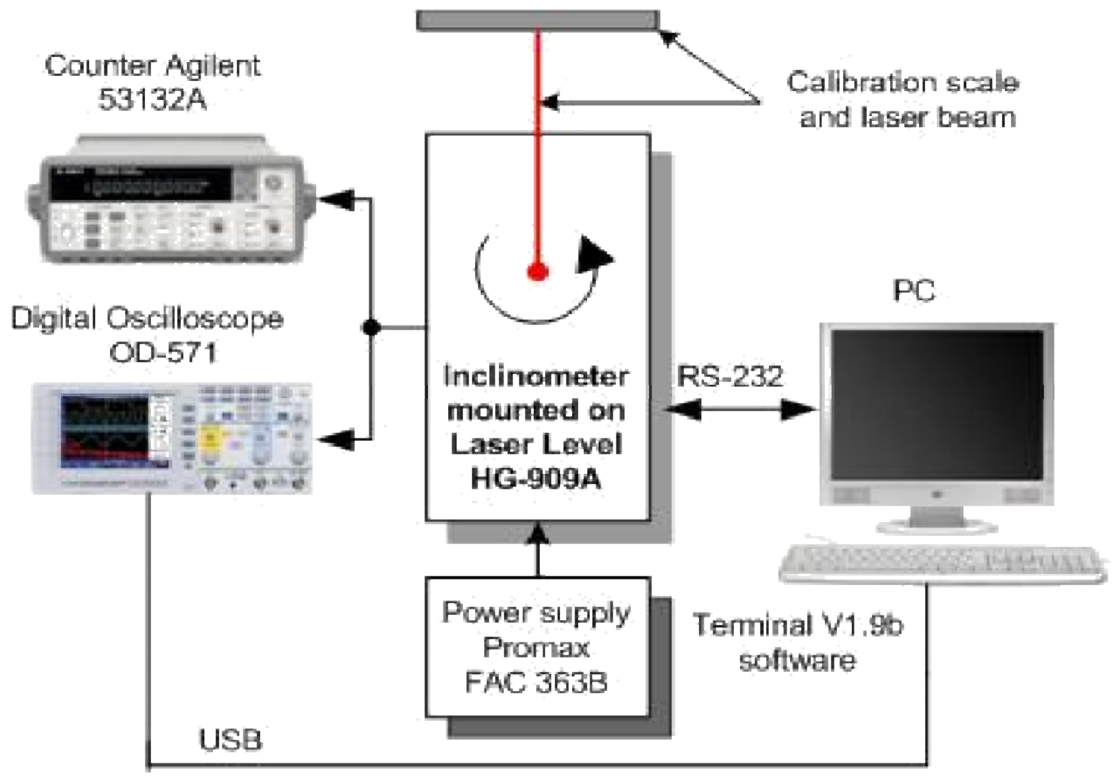


Commands for USTI

> 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

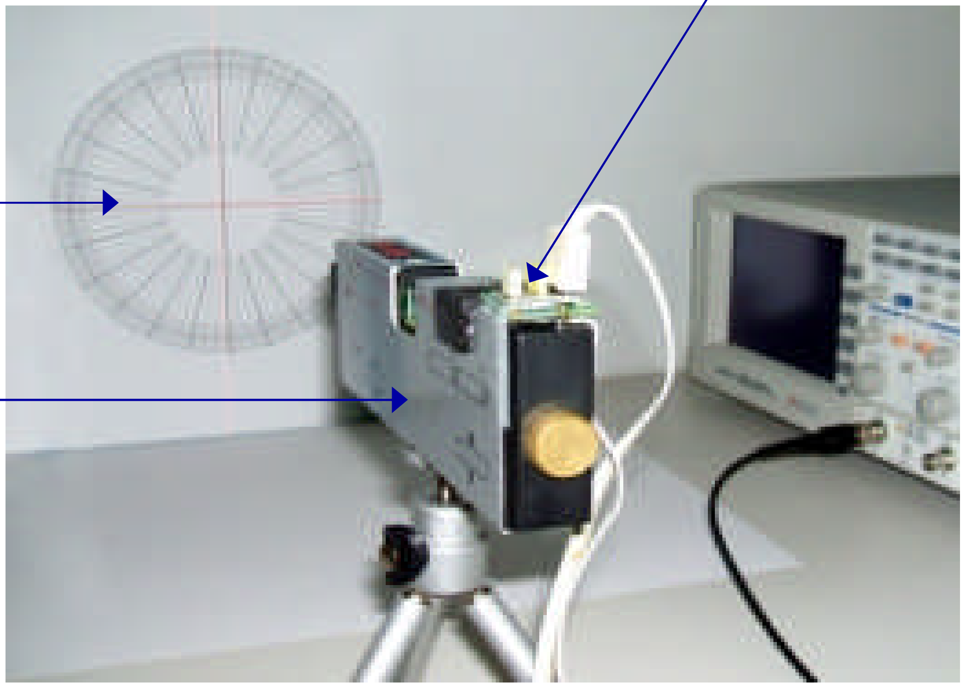


Calibration Set Up

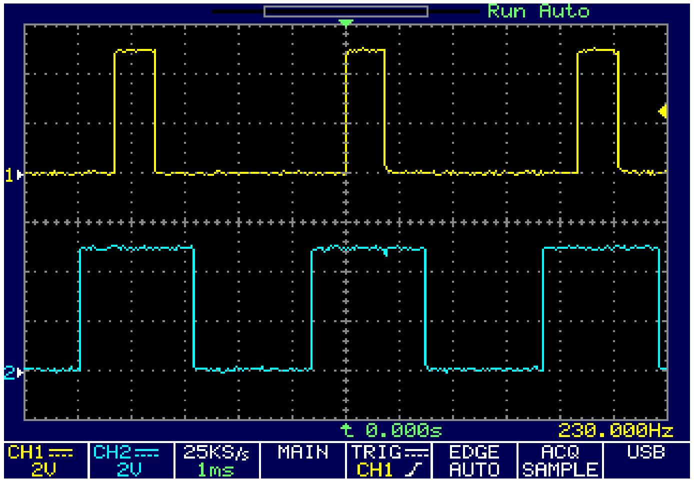
Inclinometer

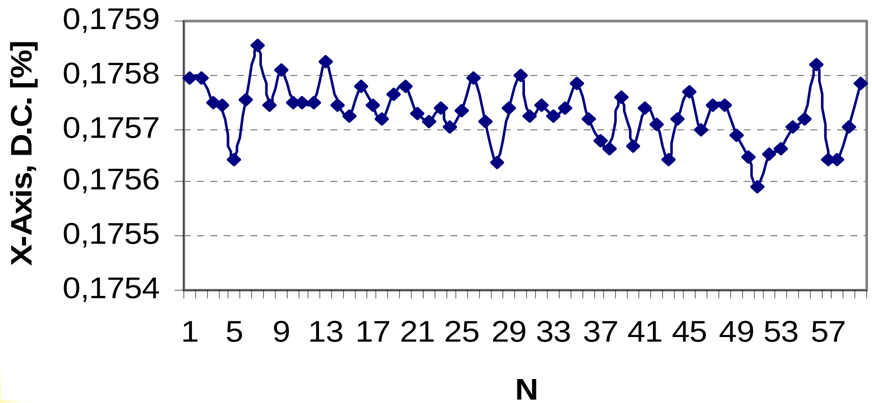
0-360^0 calibration scale-disc

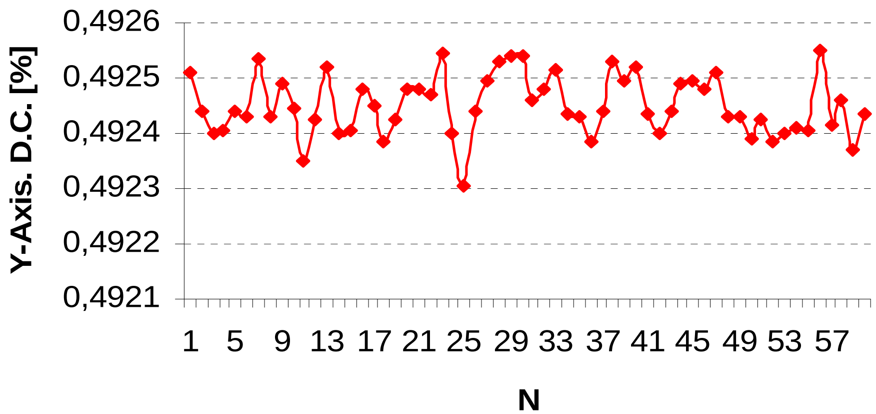
Laser level HG 909A



Experimental Results



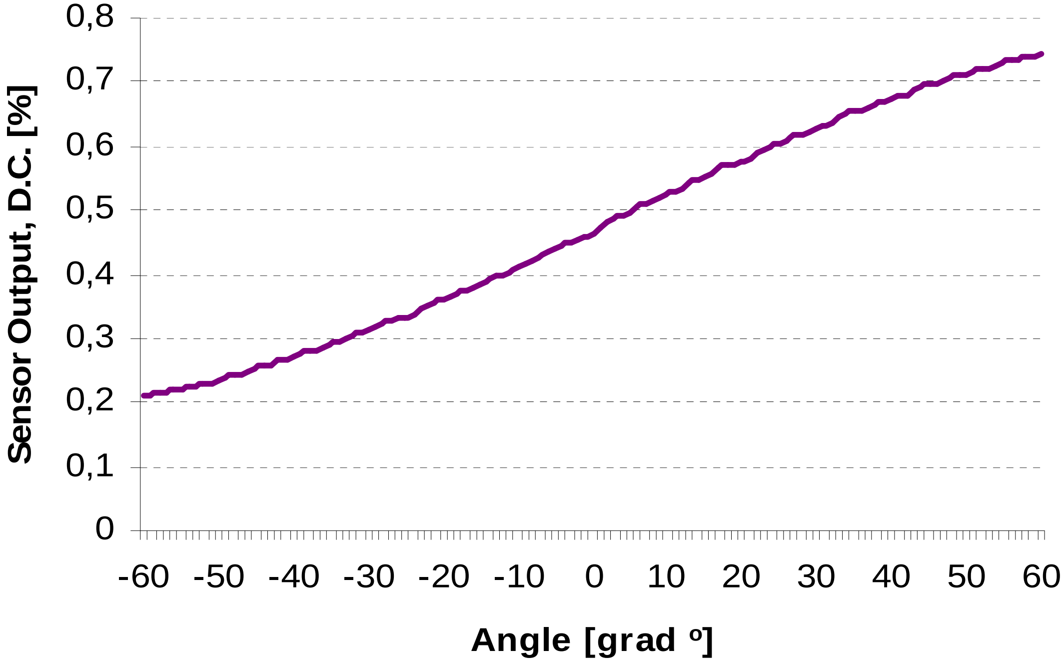


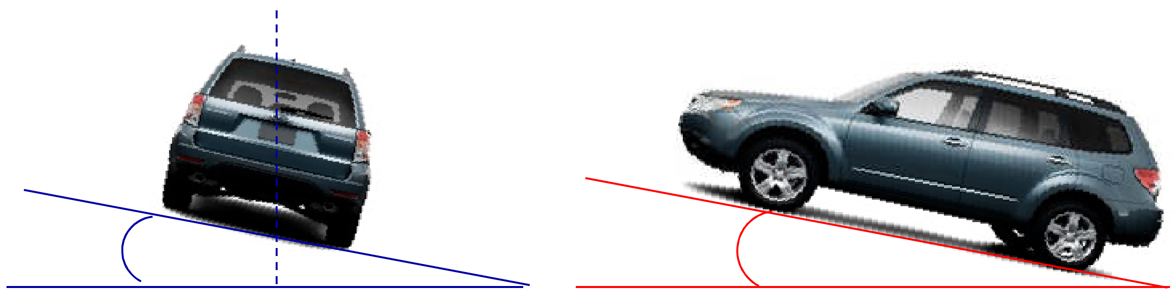


Statistical Characteristics

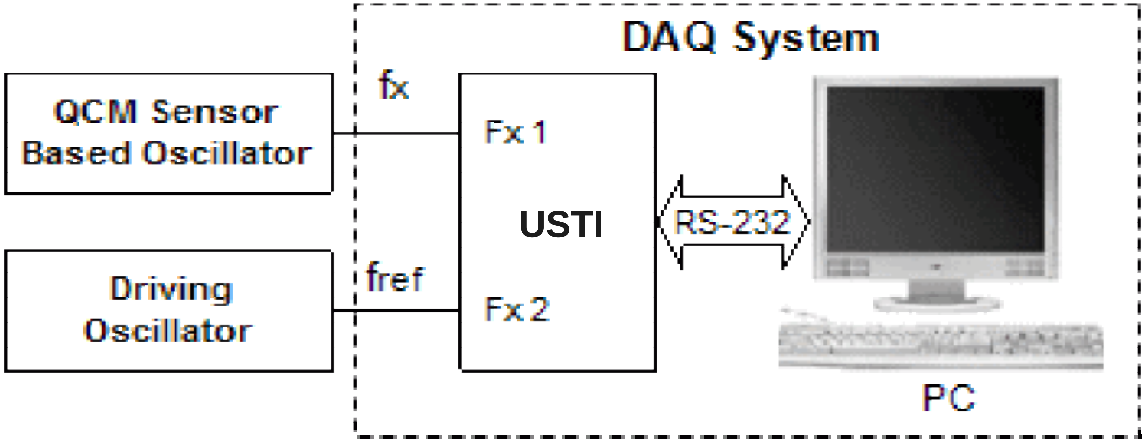
Parameter	Value	
	X-Axis	Y-Axis
Number of measurements, *N*	60	60
Minimum *D.C.* (min)	0.1756	0.4923
Maximum *D.C.* (max)	0.1759	0.4926
Sampling Range, *D.C.* (max)- *D.C.* (min), Hz	0.0003	0.0002
Median	0	0
Arithmetic Mean	0.1757	0.4925
Variance	2.8E-9	2.9E-9
Standard Deviation	0.0001	0.0001
Coefficient 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



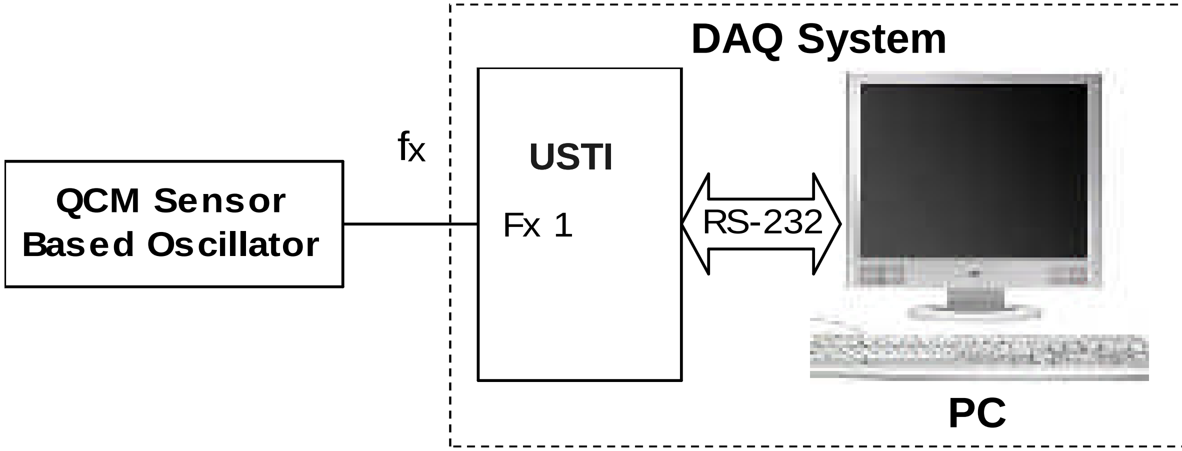


QCM Sensor System: Example 1



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

QCM Sensor System: Example 2



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

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

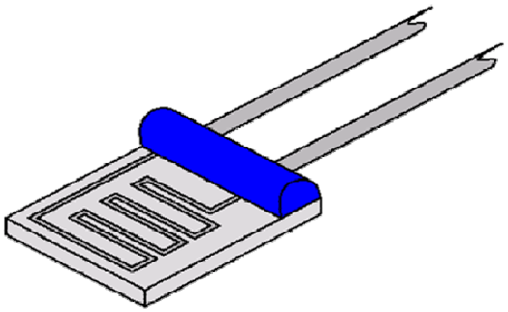
$$M_{off} = M_{off}$$

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

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

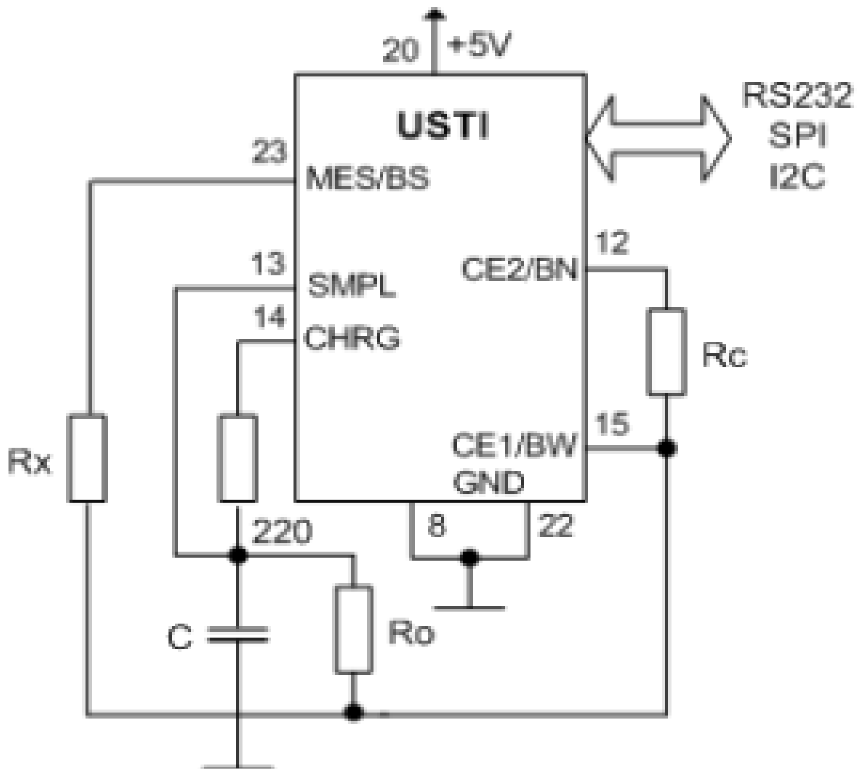
- USTI operates in condition of auto-calibration, that is base on a 3-phase differential method of measurement
- Three signals: $S_1 = 0$, $S_2 = S_{ref}$ and $S_3 = S_x$ (zero, reference and measurand) during one cycle

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

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

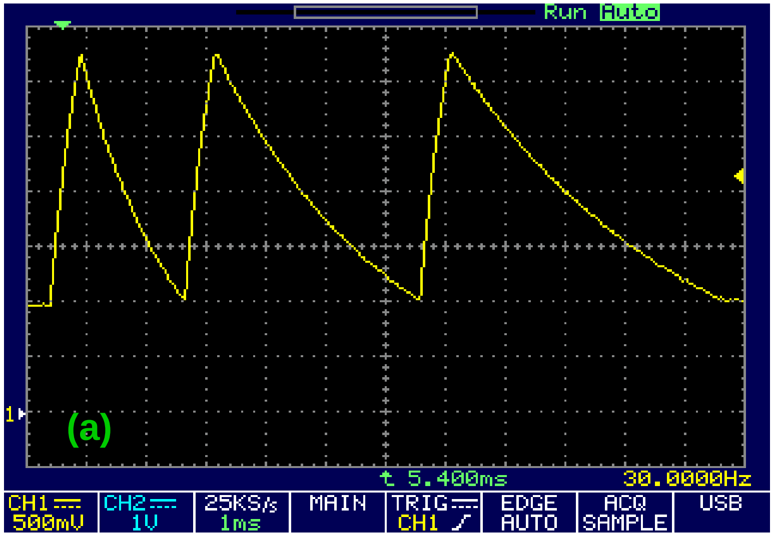
No.	Command "Wnn"	Charging Time
1	00	100 μs
2	01	200 μs
3	02	300 μs
4	03	400 μs
5	04	500 μs
6	05	600 μs
7	06	700 μs
8	07	800 μs
9	08	900 μs
10	09	1 ms
11	0A	2 ms
12	0B	3 ms
13	0C	4 ms
14	0D	5 ms
15	0E	6 ms
16	0F	7 ms
17	10	8 ms
18	11	9 ms
19	12	10 ms
20	13	20 ms
21	14	30 ms
22	15	40 ms
23	16	50 ms
24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

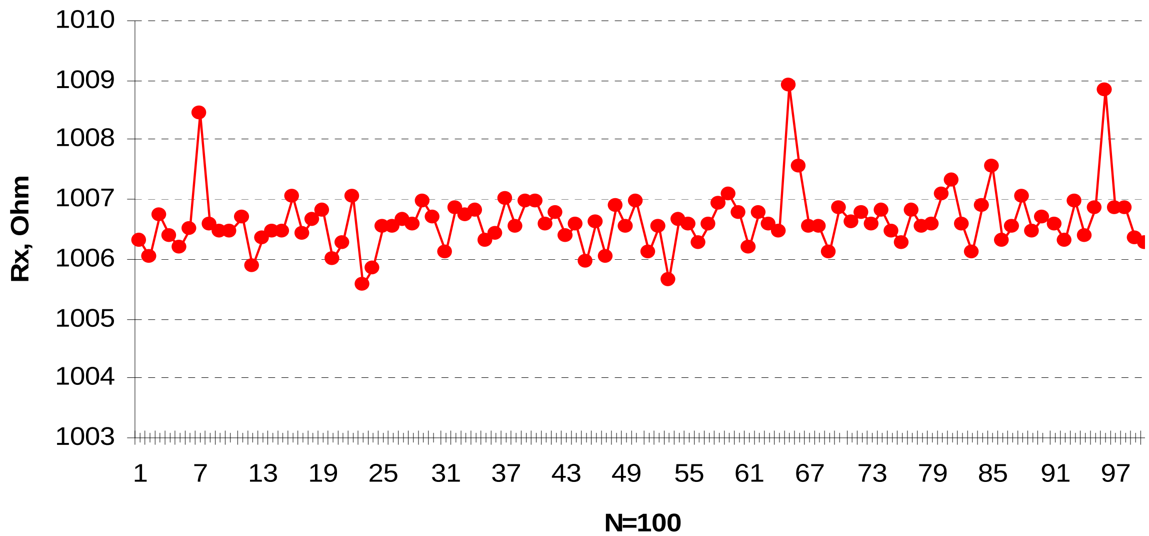


R_x=1006.5 Ω; R_c=604.02 Ω; C= 3 µF and R_0=328.63 Ω (a); and R_x=10 237 000 Ω (b)

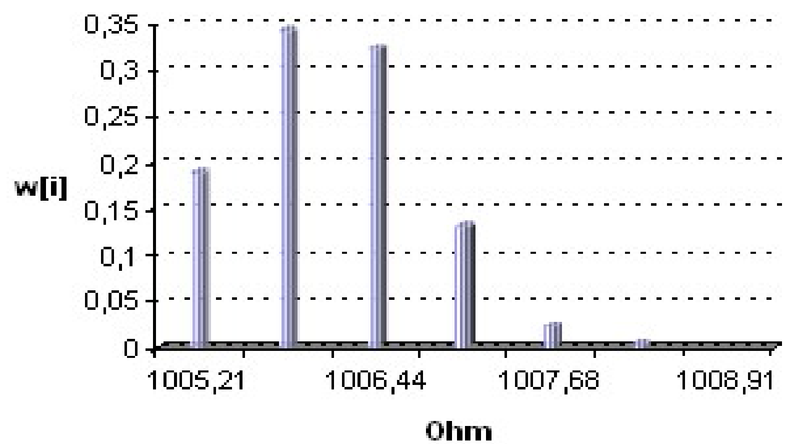
USTI Commands for Resistive Measurement (RS232 Interface)

>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



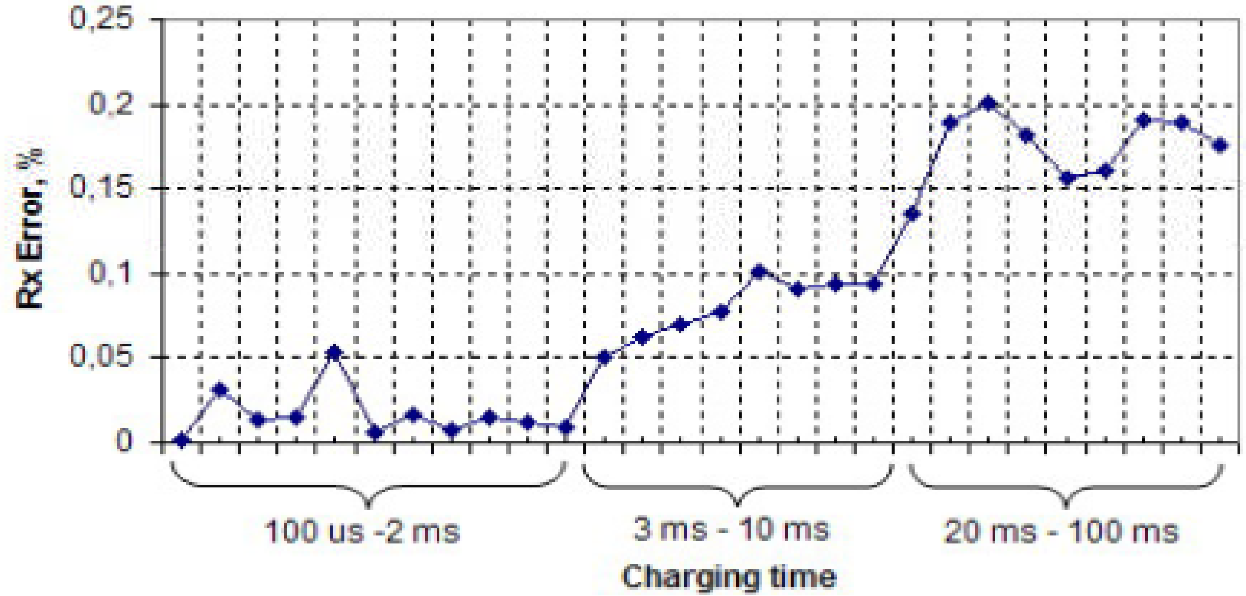
Parameter	Value
Number of measurements, N	100
Minimum R_x (min), Ω	1004.5897
Maximum R_x (max), Ω	1008.9129
Sampling Range, R_x (max) - R_x (min), Ω	4.3232
Median	0
Arithmetic Mean, Ω	1005.7816
Variance	0.4172
Standard Deviation	0.6459
Coefficient of Variation	1557.1612
Confidence interval for arithmetic mean at P=97 %	$1005.6414 \le R_x \le 1005.9218$
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



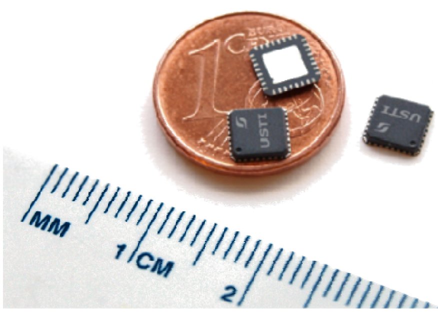
USTI Commands for Frequency Measurement, RS232, Slave Mode

```
> 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

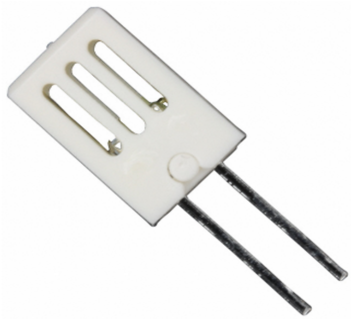
Relative Resistance Error			
Marked Value	PICMETER [4] Error, %	USTI Error, %	Measurement conditions
0.10 K	N/a	0.24	R_c=329.66 Ω; C=2μF R_0=609.86 Ω
0.30 K	N/a	1.58	R_c=432 260 Ω; C=2μF R_0=609.85 Ω
0.82 K	N/a	1.31	
1.0 K	N/a	0.026	R_c=604.02 Ω; C=3μF R_0=328.63 Ω
1.2 K	1.3	1.17	
5.1 K	1.0	1.067	
8.2 K	2.0	0.92	
10 K	2.0	0.918	
15 K	1.7	0.860	
20 K	1.5	0.805	
30 K	1.4	0.759	
51 K	1.0	0.641	
75 K	1.0	0.566	R_c=432 260 Ω C=2 μF R_0=609.85 Ω
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_c=563 960 Ω
2.0 M	N/a	0.063	R_c=432 280 Ω C=2.1 nF R_0=464 240 Ω

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

Capacitive Sensing Elements

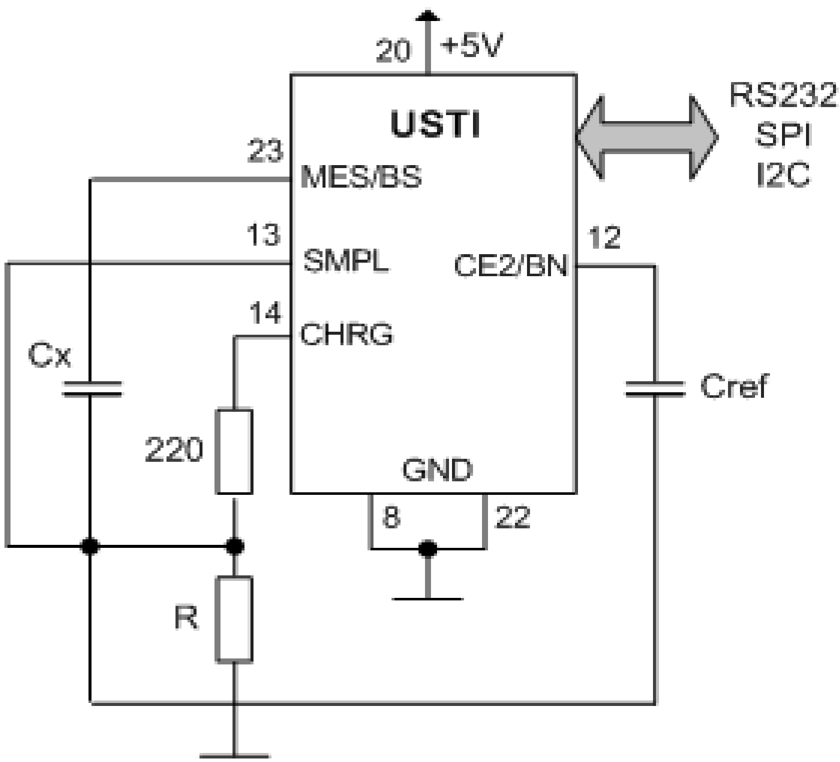


- Capacitive sensing elements are widely used in humidity, level, pressure, acceleration, position, proximity, chemical sensors, biosensors and transducers
- They have a wide measurement ranges: from tens pF to hundreds pF
- Existing ICs, ASICs or µC-based solutions have low accuracy or/and narrow measurement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

Integrated Capacitance-to-Digital Converters

IC	Capacitance Range	Relative Error, FS %	Interfaces	Communication Mode
		ZMDI		
ZSSC31210	2 pF to 260 pF	± 0.25	I^2C, SPI	Slave
ZSSC3122	< 10 pF	± 0.25	I^2C, SPI	Slave
ZSSC3123	< 260 pF	± 0.25	I^2C, 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	I^2C, SPI	Slave
		Technology Assistance BCNA 2010, S. L.		
USTI	50 pF to 100 μF	*±0.036 %	I^2C, SPI, RS232	Slave and master (RS232)

Direct Capacitance Sensing Element Interfacing



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

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

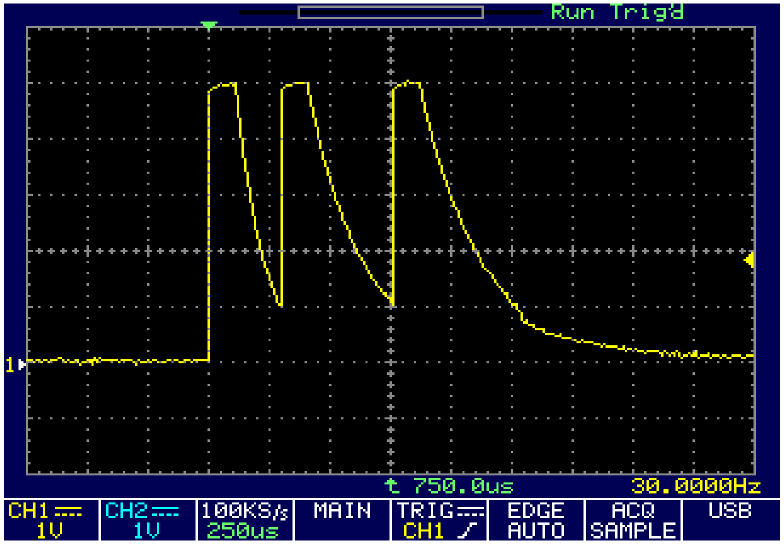
$$T = 2200 \times C$$

USTI Commands for Capacitance Measurement (RS232 Interface)

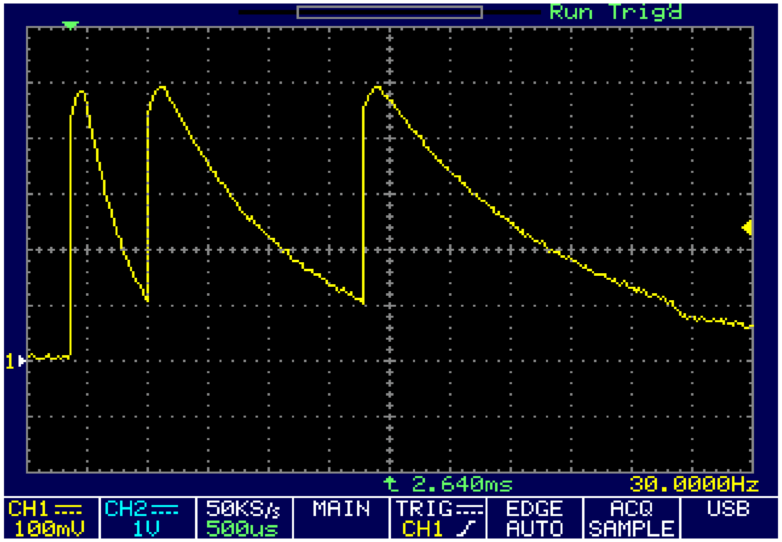
> **M11**; Capacitance measurement mode
> **E0.00000000012543**; Reference set up C_{ref} =125.43 pF
> **W00**; Set up the charging time constant number (100 μs)
> **S**; Start Measurement
> **C**; Check the measurement status: b-in progress; r-ready
> **R**; Get the result

0.00000000015222; Measuring result C_x = 152.22 pF

Oscillograms of Three-point Calibration Technique

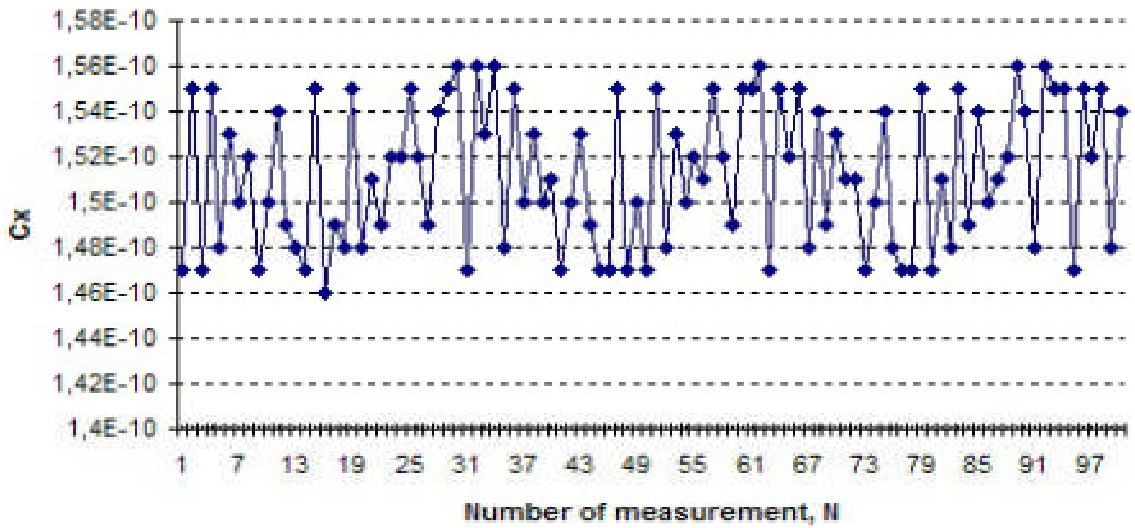


152.22 pF measurement

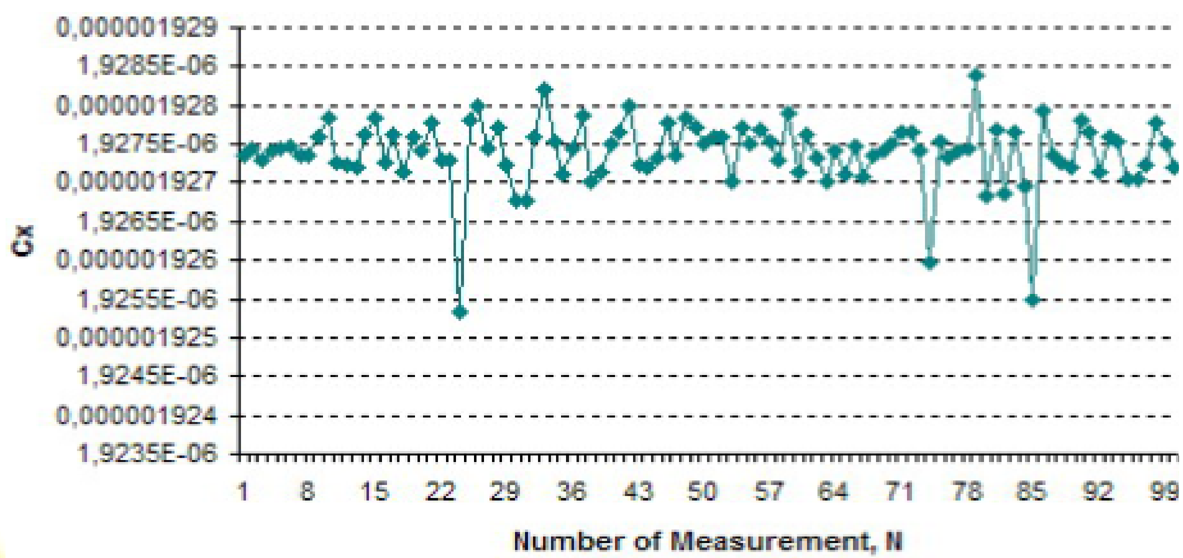


257 pF measurement

Experimental Results



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

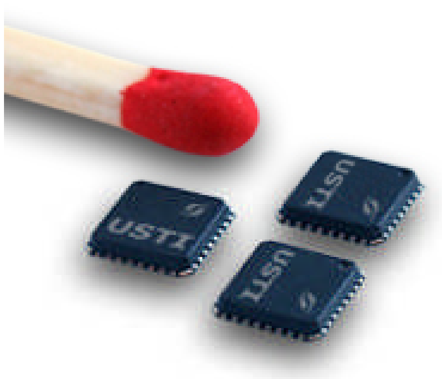


C_x=1.9279 μF at C_{ref}=1.9286 μF and R=99 Ω

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



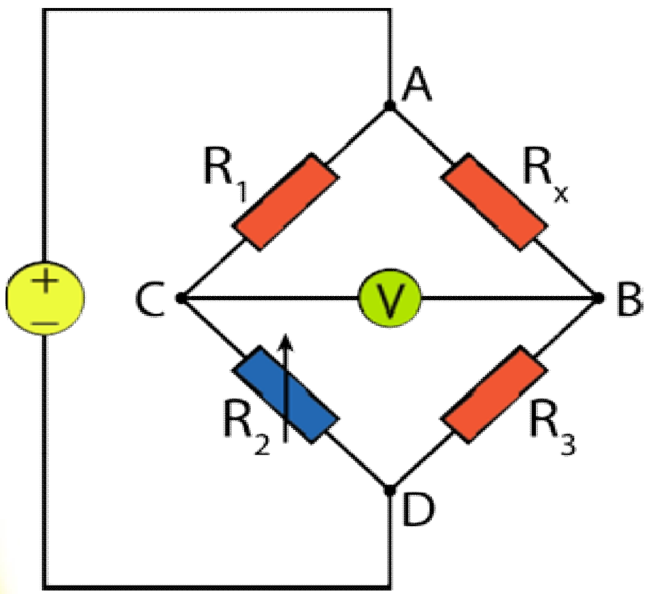
- Capacitance measurement range from 50 pF to 100 μF.
- Average relative error ± 0.036 %
- Worst case relative error for reported results is not more than ± 0.7 %
- Can work with any known capacitance-to-frequency converters

Resistive-bridge Sensors

Charles Wheatstone
(1802-1875)

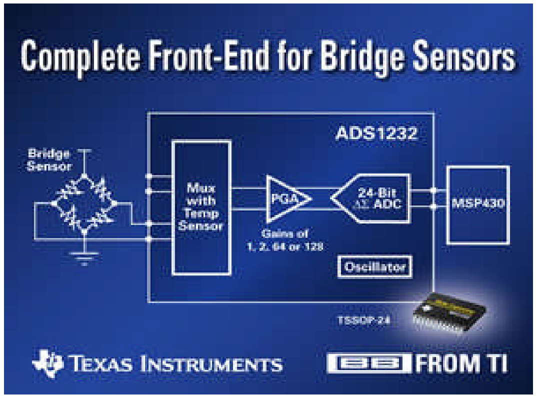
- A Wheatstone bridge is widely used to convert the resistance variation of sensors, related to the physical quantity, into a voltage or current
- A lot of manufacturers produce resistive-bridge sensors
- In such sensors systems output bridge voltages should be converted into digital

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

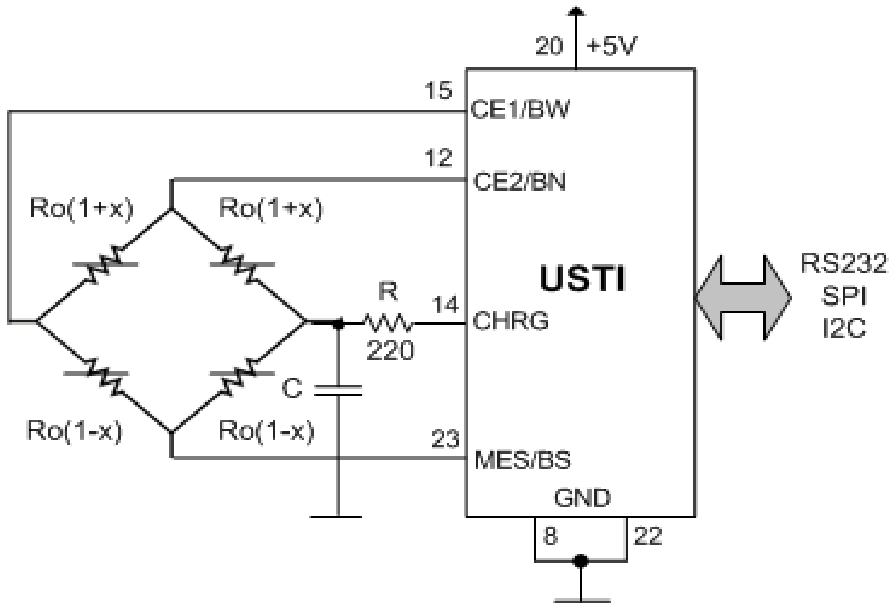
No one existing integrated converter for resistive bridge sensors can work with both: resistive-bridge sensing elements, frequency and duty-cycle signal conditioners' outputs

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

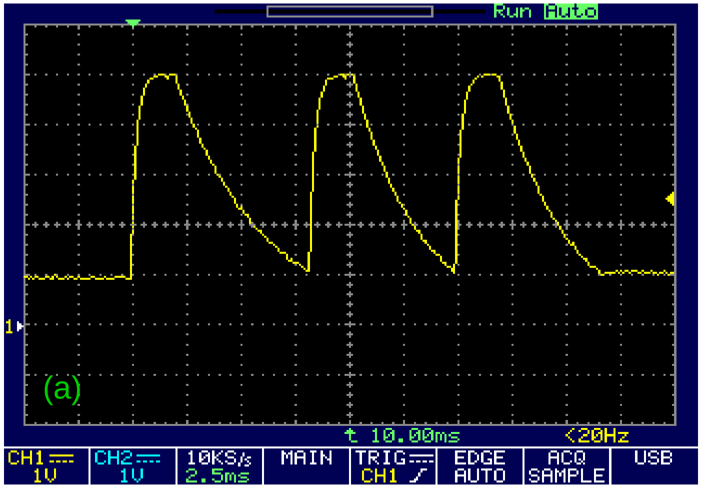
>C ; Check the measurement status:

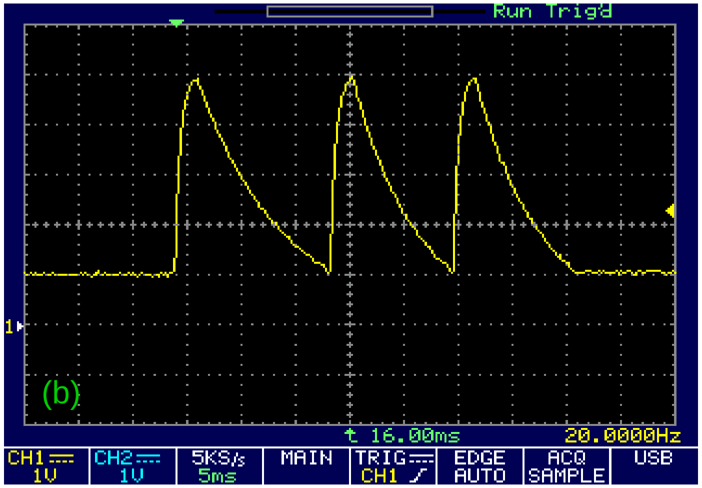
r ; Returns ‘b’-if in progress; ‘r’-if ready

> R ; Read result

0.006005379986

Oscillograms at CHRG Output Pin

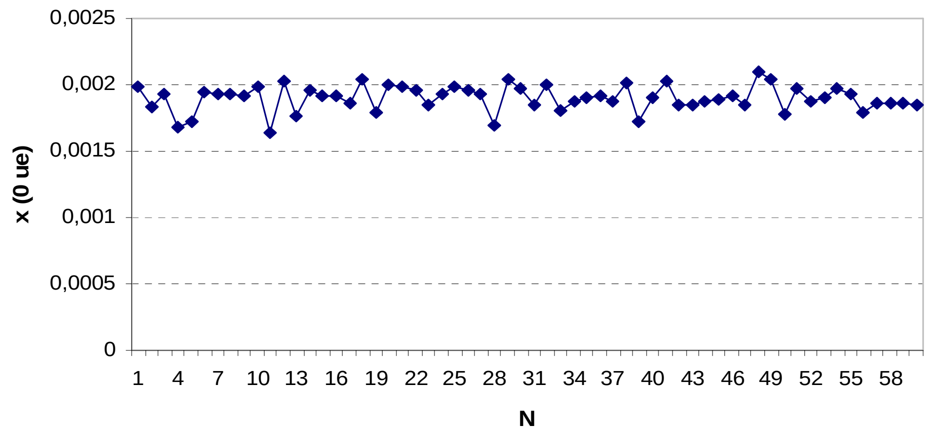


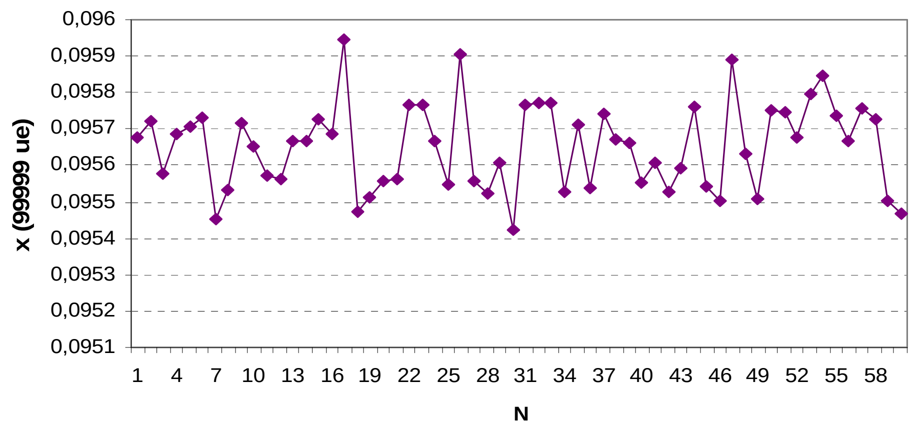


C=1 μF , charging time 2 ms (a)   C=2 μF , charging time 4 ms (b)

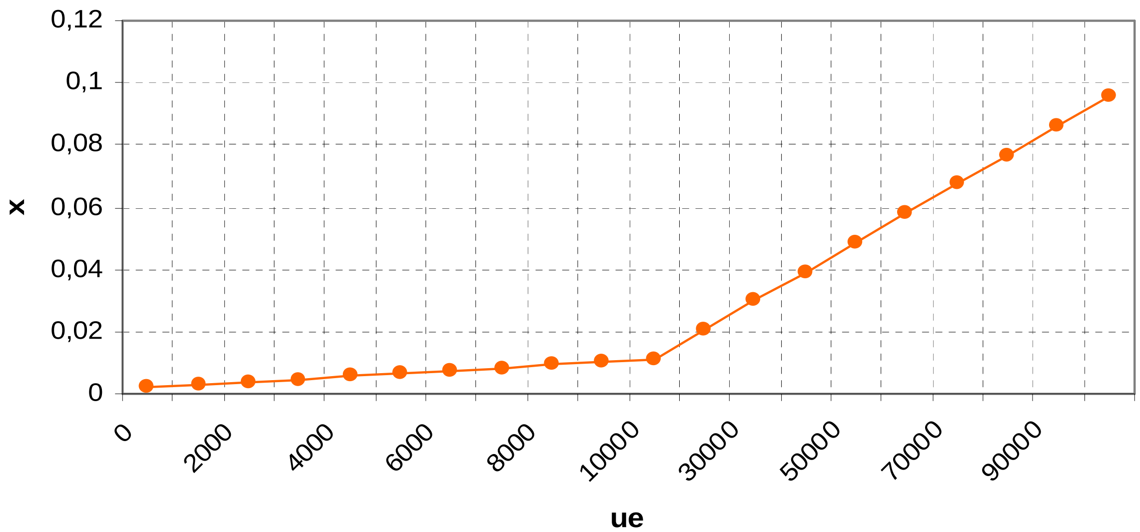
Experimental Results I: Strain Gauge Emulator

1550A Strain Indicator Calibrator
(VISHAY)





X Changes Through the Strain Gage Measuring Range



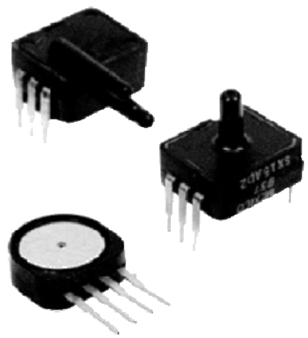
Relative quantization error for time interval measurement:

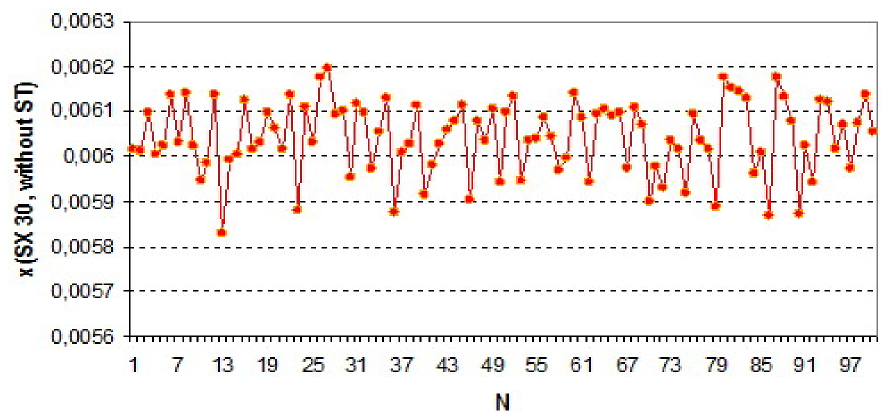
$$\delta_x = \frac{1}{f_0 \times t_x} \times 100$$

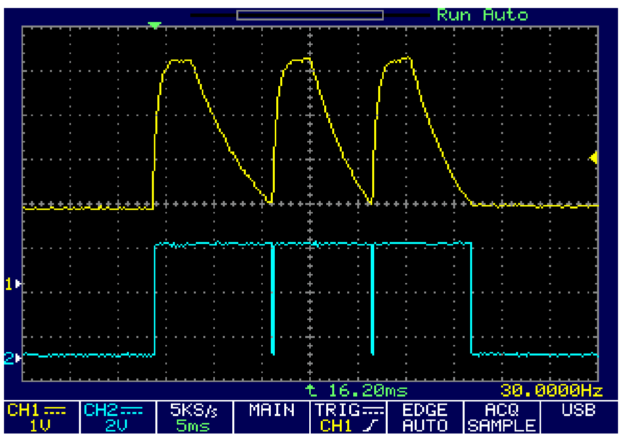
Statistical Characteristics

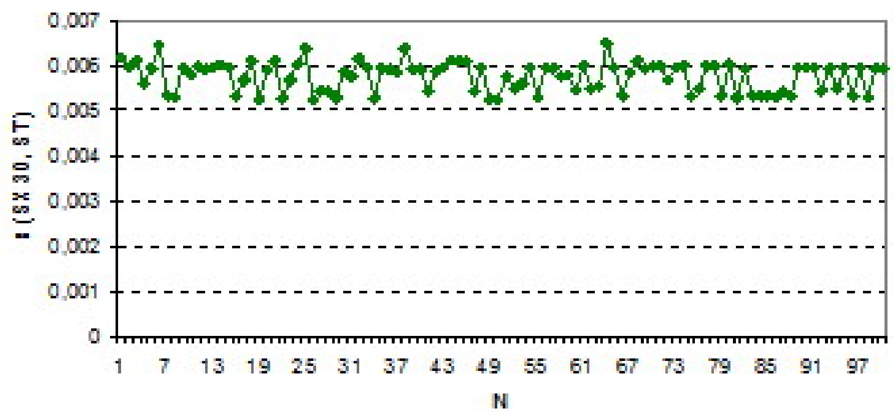
Parameter	Value	
	x (0 με)	x (99900 με)
Number of measurements, *N*	60	60
Minimum R_x (min)	0.0016	0.0954
Maximum R_x (max)	0.0021	0.0959
Sampling Range, R_x (max) - R_x (min)	0.0005	0.0005
Median	0	0
Arithmetic Mean	0.0019	0.0957
Variance	9.5E-0009	1.4E-0008
Standard Deviation	0.0001	0.0001
Coefficient 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*)









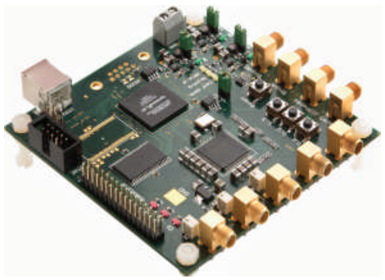
Statistical Characteristics

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

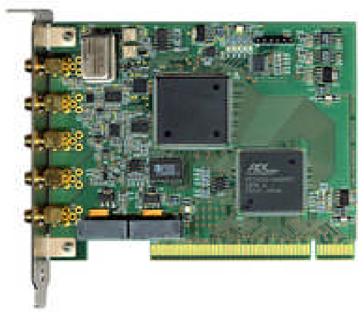
USTI Features

- 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

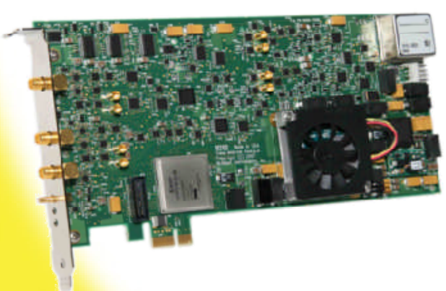
DAQ Systems and Modules



Picosecond Timing System (EOS Optronics, GmbH, Germany)



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



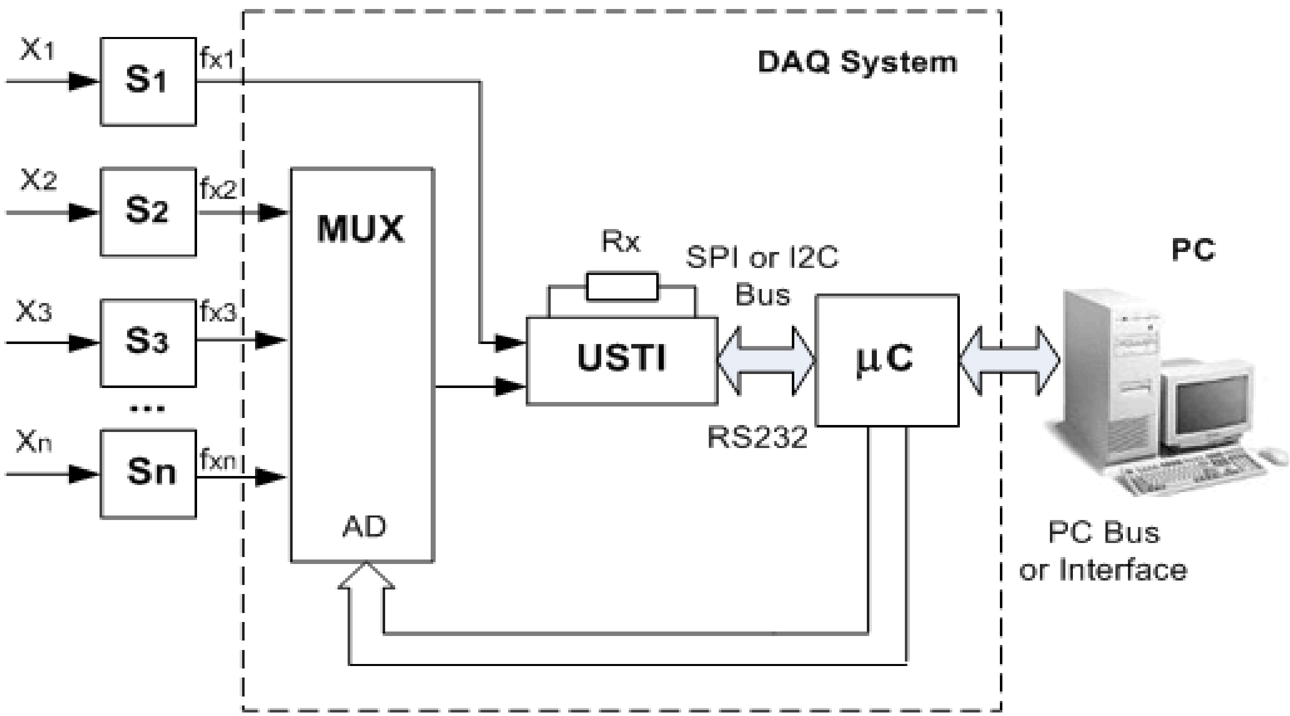
BI200 Time Interval Analyzer (Brilliant Instruments, Inc., USA)

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

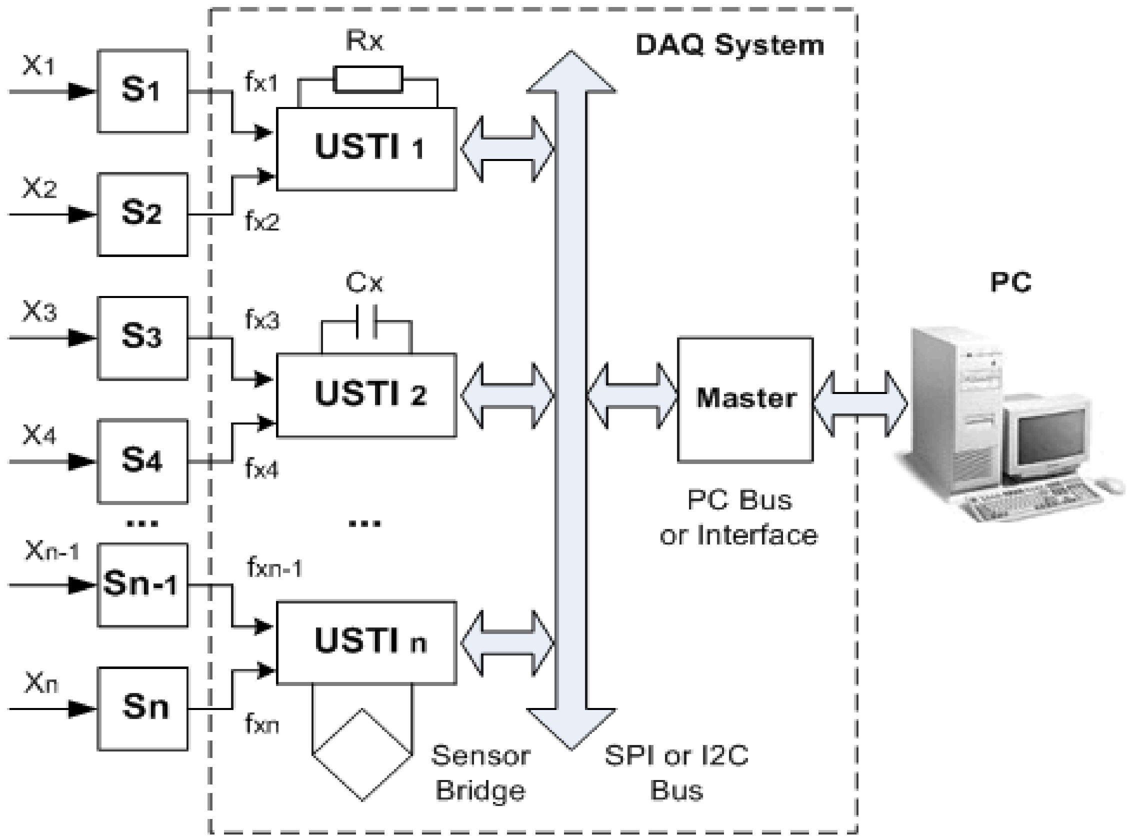
- More or less good maximum frequency range f_{xmax}
- Excellent number of channels (up to 32)
- Low accuracy due to use of classical methods for frequency measurement
- Mostly satisfy programmers (due to software and drivers) but not metrologist

DAQ System with Time-Division Channeling



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

DAQ System with Combined Space- and Time-division Channeling



USTI Commands for Frequency Measurement, RS232, Slave Mode

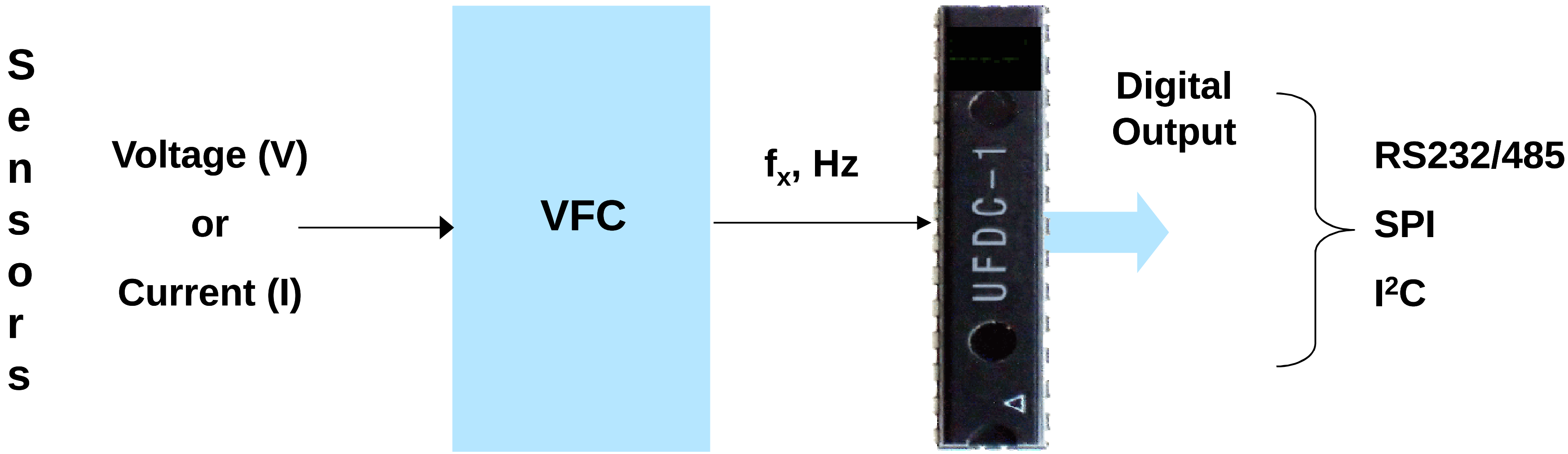
```
> A0A   ; Set up the relative error 0.0005 %
> M00   ; Frequency measurement in the 1st channel
> S     ; Start measurement
> C     ; Check in the result is ready
r       ; Returns ‘b’-if in progress; ‘r’-if ready
> R     ; Read result
100000.07507

> M0E   ; Frequency 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
0.0500085968
```

USTI Commands for RC Measurement, RS232

> M11 ; Capacitance measurement mode
> E0.00000000012543 ;Set up C_{ref} =125.43 pF
> W00 ; Set up the charging time (100 μs)
> S ; Start Measurement
> C ; Check the measurement status:
r ; Returns ‘b’-if in progress; ‘r’-if ready
> R ; Read result
0.000000000155

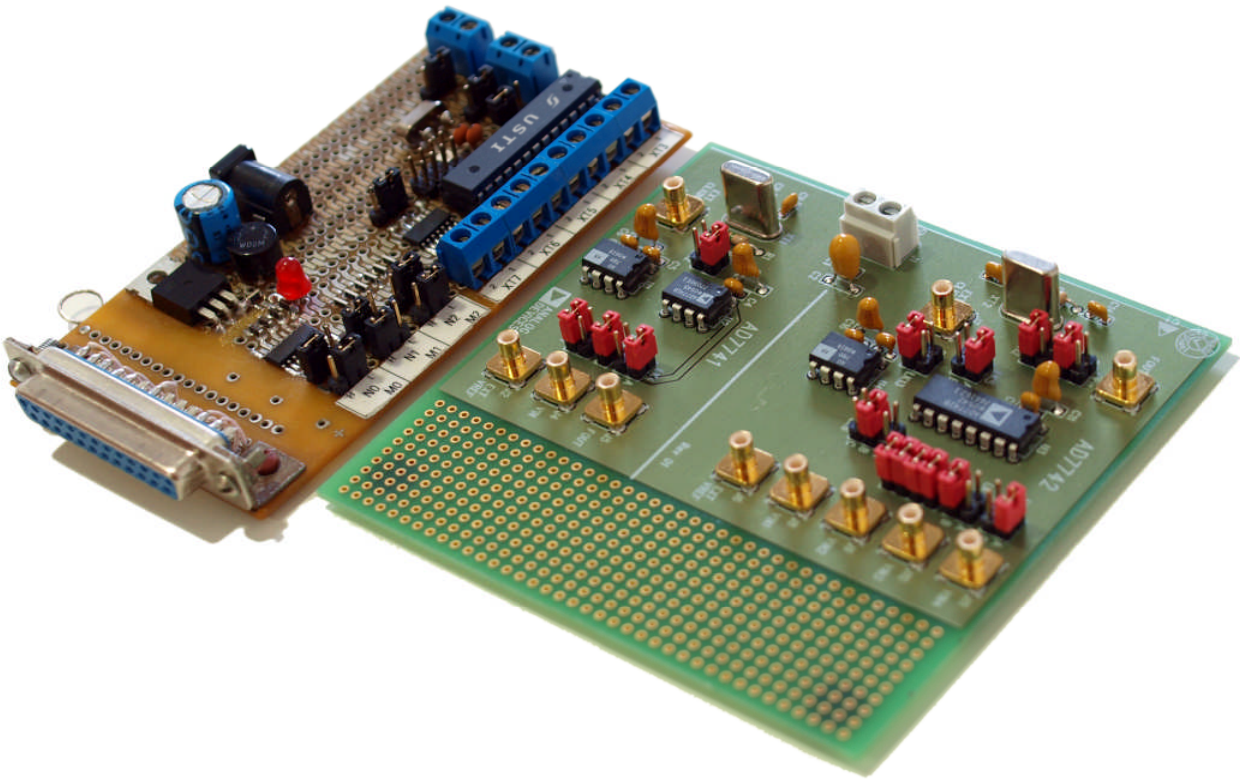
>M10 ; Set up a resistance R_x measurement mode
>E263000.0; Set the reference value R_c =263 kΩ
>W1B ; Set the charging time 100 ms
>S ; Start measurement
>C ; Check the measurement status:
r ; Returns ‘b’-if in progress; ‘r’-if ready
> R ; Read result
569001.008956

UFDC-1/USTI and Analog Signal Domain

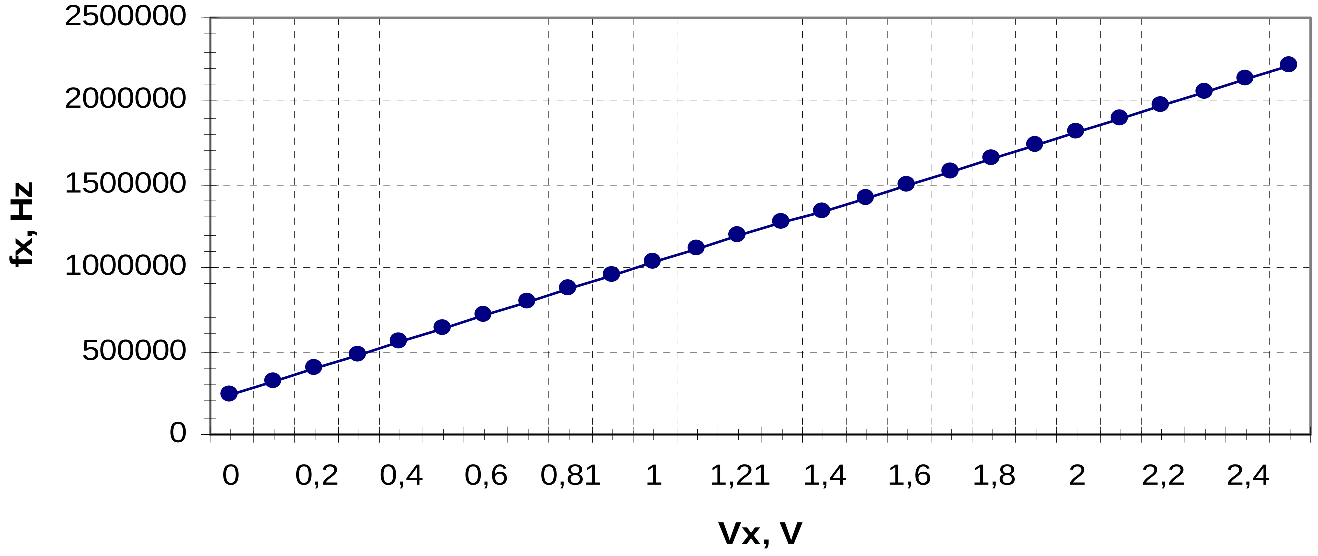


Any Voltage-to-Frequency Converter (VFC) can be used to convert an analog signal to quasi-digital (frequency) signal

DAQ Board Prototype



Experimental Results



Outline

1. Introduction: Definitions and Markets
2. Modern Technologies
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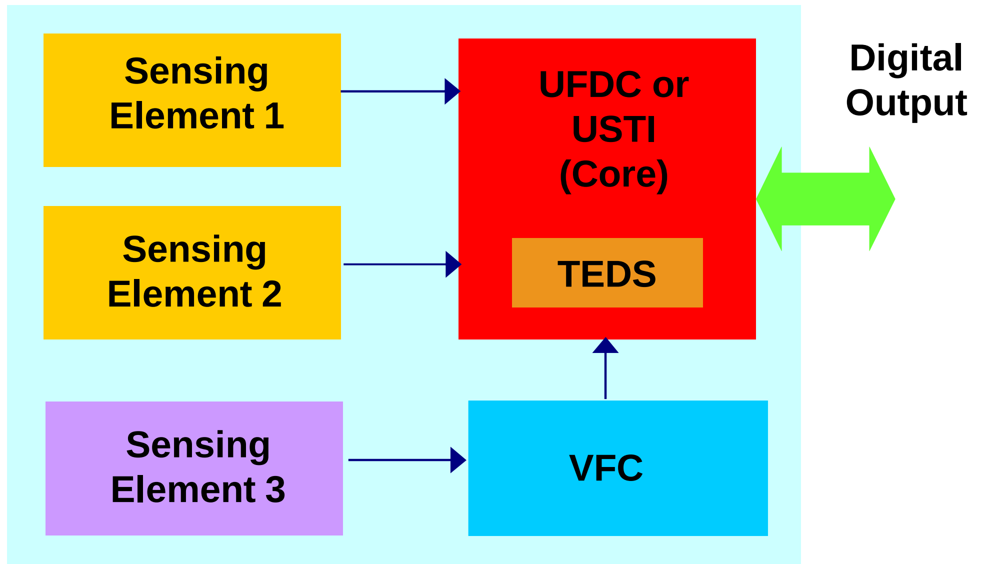
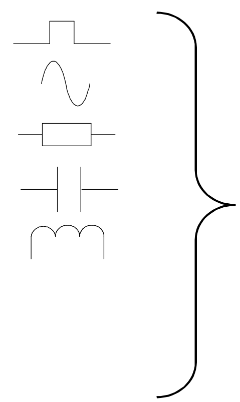
Smart System Integration

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

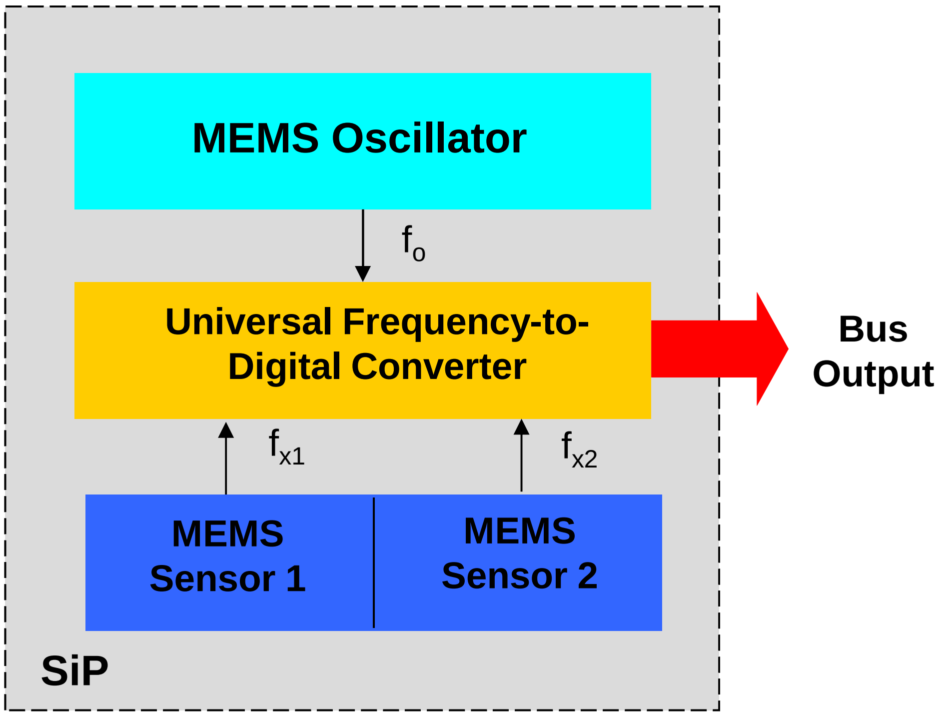
SoP and SiP



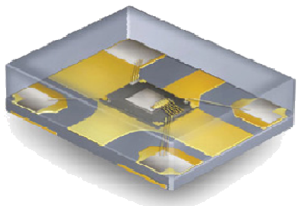


Sensors and sensing elements

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



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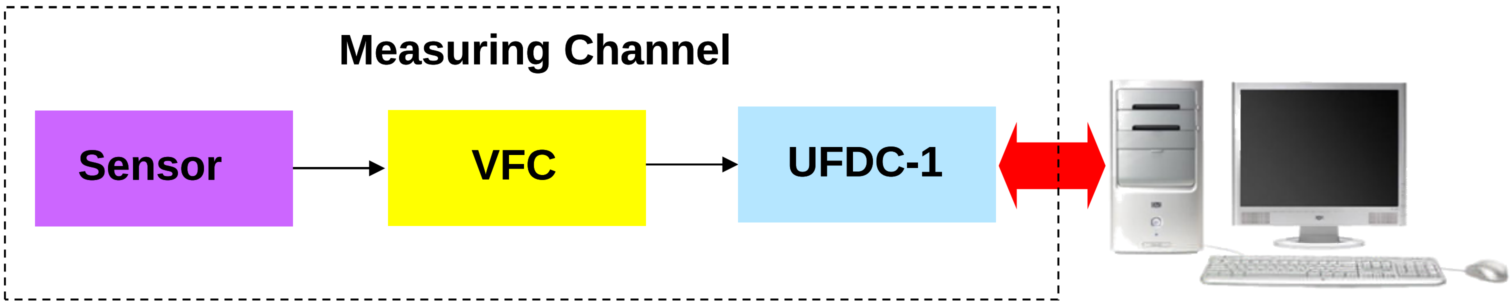
Measuring Channel



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	$\delta_s{}^*$	Normal (Gaussian)	$\sigma_s = \frac{\delta_s}{2.3}$
VFC's error	$\delta_{VFC}{}^*$	Normal (Gaussian)	$\sigma_{VFC} = \frac{\delta_{VFC}}{2.3}$
Quantization error	$\delta_q{}^{**}$	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 with the voltage output (0-10 V) and full scale error δ_s = ±0.1 % ; a voltage-to-frequency converter (µ 2.0 Series from *Canopus Instruments*), with the relative error δ_{VFC} < ±0.1 %, and non-calibrated UFDC-1 IC with the 30 ppm (δ_{fo} = ±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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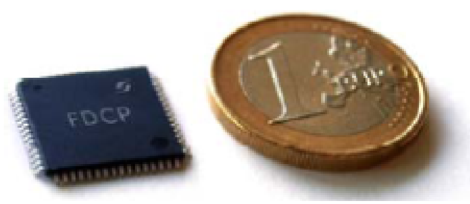
Frequency-to-Digital Converter with Parallel Interface (FDCP)



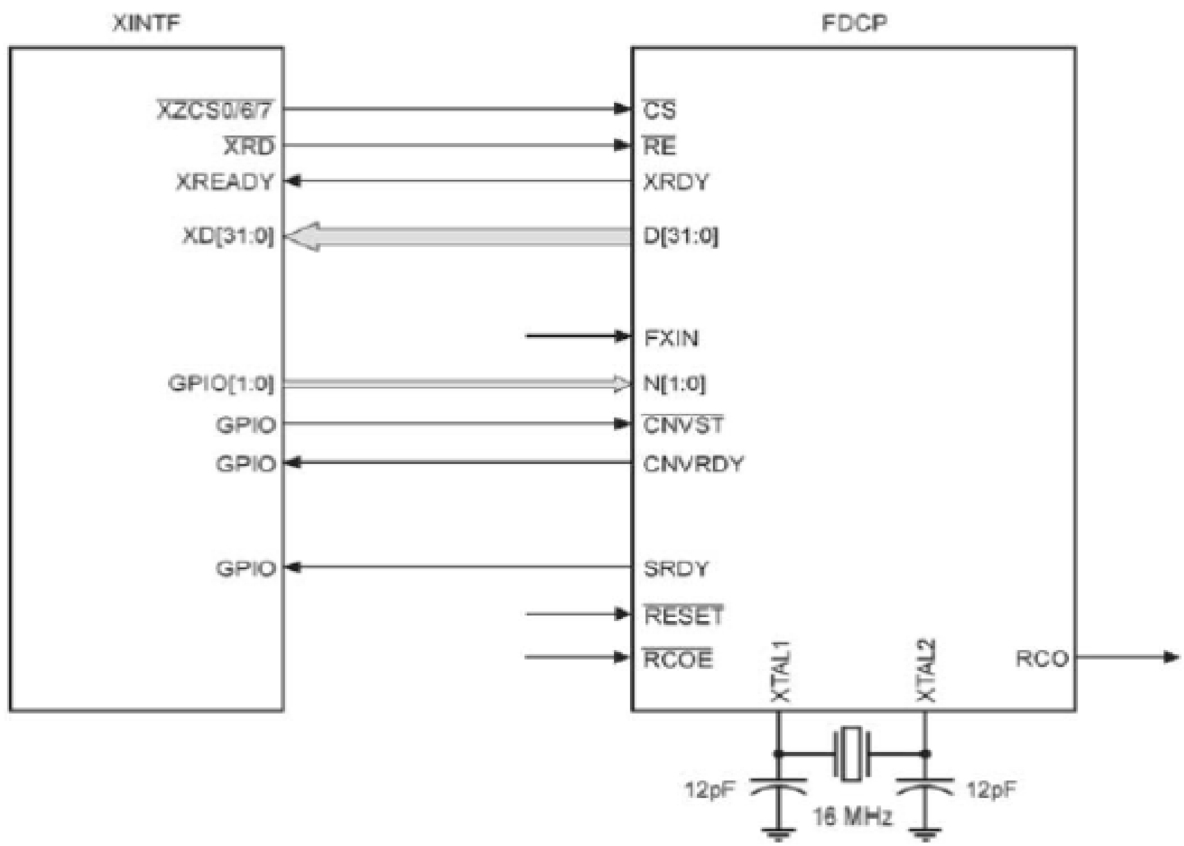
- Fully digital, low-power CMOS IC
- Non-Redundant conversion time 6.7 μs to 1.6.ms
- One generating output (fo=32 MHz
- 64-lead TQFP package 14 × 14 mm
- Parallel output: two 16-bit words N_x and N_r
- Slave communication mode

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

FDCP Metrological Performance and Electrical Characteristics

Parameter	Value
Minimal converted frequency, Hz	$\geq$ 500
Maximal converted frequency, MHz	$\leq$ 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



USTI-WSN

Cost-effective Sensor Nodes for Wireless Sensor Networks

SENSORCOMM 4: Tuesday, 21 August, 10:30 - 12:15

Summary

- In order to overcame technological limitations it is necessary to move from traditional analog (*V*, *I*) informative parameters to frequency-time parameters, and implement as much system components as possible in digital or quasi-digital form
- Digital and intelligent sensors and sensor systems with high metrological performances can be designed based on on-shelf electronics components and low cost

Reading

[1]. Yurish S.Y., Digital Sensors and Sensor Systems: Practical Design, *IFSA Publishing*, 2011.

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

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

Questions & Answers