Smart Sensors Systems Design

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Acknowledgment

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Copyright Statement

Course Content

Part 1

- Introduction
- Modern sensor market trends
- Main definitions
- Sensors classifications
- Sensors architectures
- Informative parameters
- Advantages of frequency as informative parameter

Part 2

- Sensors types
- Six signal domains
- Smart sensors state-of-the-arts: temperature, pressure, accelerometers, rotation speed, optical, humidity, magnetic, chemical, gas, biosensors, multiparameters, etc.

Course Content (cont.)

Part 3

- Data acquisition methods (classification)
- Method with time-dividing channeling
- Method with space-division channeling
- Smart sensors architectures
- Main errors of DAQ systems
- Data transmitting and error protection

Part 4

- Classical frequency-to-digital conversion methods:

  direct, indirect, interpolation, combined
- Advantages and disadvantages
- Weight functions use to increase an accuracy
- Phase-shift – to – digital conversion methods

Course Content (cont.)

Part 5

- Advanced and self-adapted methods: ratiometric, M/T, reciprocal, CET, SB (DB), DMA
- Method of dependent count (MDC)
- Metrological performances
- Method with non-redundant reference frequency
- Advanced Phase-shift – to – digital conversion methods

Part 6

- Digital output smart sensors and program-oriented conversion method (PCM), definition, realization, optimal design; examples
- Adaptive PCM with increased speed
- PCM errors analyze and reduction
- Systematic errors correction

Course Content (cont.)

Part 7

- Smart sensor systems: one-channel sensor interfacing
- Multichannel sensor interfacing
- ABS example: sensor, encoder, self-adaptive method, sensor interfacing
- Multiparameter sensors systems

Part 8

- Virtual instrument definition
- Industrial DAQ boards for frequency-time parameters
- Virtual instruments examples: thermometer, data logger for pressure sensors, tachometer, videographic paperless recorder

Course Content (cont.)

Part 9

- Sensors buses and networks protocols
- I^2C, SPI, SMBus, Maxim/Dallas 1- and 3-wire bus, CAN bus, MODbus, SSI, Fieldbus
- Smart sensors buses, IS^2
- Wireless sensor networks, ZigBee and Bluetooth

Part 10

- Integrated frequency (time)-to-digital converters: USP-30, K512PS11, TDC, etc.
- Universal Frequency-to-Digital Converter (UFDC-1)
- Sensor interfacing integrated circuits: USIC, SSP1492/ 1493, UTI, UTI03

Course Content (cont.)

Part 11

- Smart sensor systems and digital sensors design
- Technologies and design methodology
- Sensors systems examples for optical parameters, temperature, acceleration, rotation speed, humidity, pressure, magmetic
- Multisensors systems

Part 12

- IEEE 1451 standards family
- IEEE 1451 and sensors from frequency-time domain
- TEDS example for frequency output sensors
- Mix-mode interface for frequency sensors (IEEE 1451.4)
- Virtual TEDS

Course Content (cont.)

Part 13

- Direct sensor-to-microcontroller interface
- Advantages and disadvantages
- Errors reduction measures
- Additional course materials and references

Part 14

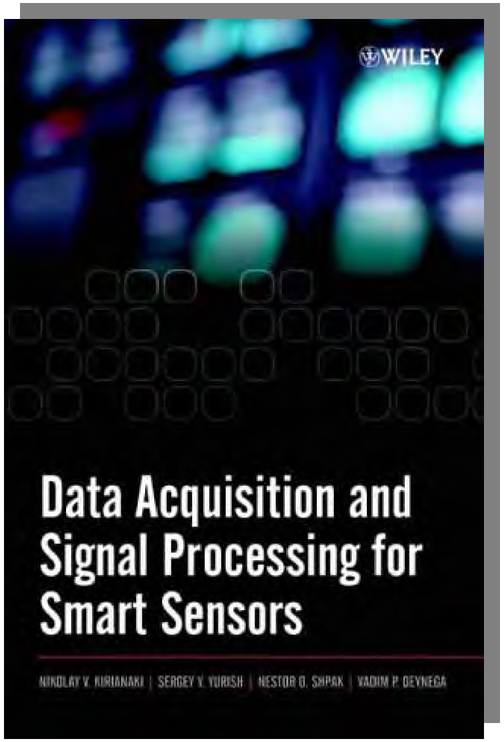
- Future trends
- Universal Frequency-to-Digital Converter (UFDC-2)
- Universal Sensors and Transducers Interface (USTI)
- Preliminary features and performances

Course Objectives

- To give practical knowledge in smart sensors and systems design; virtual instrumentation; sensors buses and interfacing circuits
- To help in evaluating and application of novel frequency-to-digital conversion methods in order to use it in smart digital sensors and data acquisition systems
- To show how to apply the Smart Transducer Interface standard IEEE 1451 to quasi-digital sensors
- To give ‘hints’ for software and hardware level smart sensors design

Reading

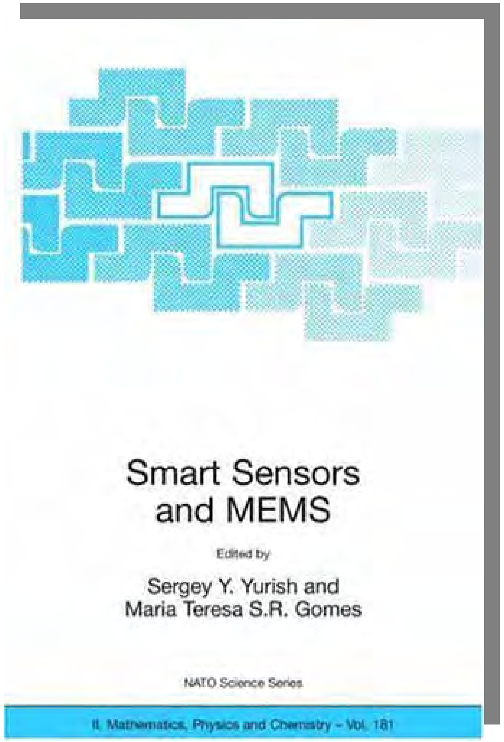
[1]. Kirianaki N.V., Yurish S.Y., Shpak N.O., Deynega V.P., Data Acquisition and Signal Processing for Smart Sensors, *John Wiley & Sons*, Chichester, UK, 2002



Reading (cont.)

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

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



Introduction

- Smart sensors are of great interest in many fields of industry
- Classical approach to DAQ systems - the information is in the amplitude of a voltage or current signal
- Another approach relies on resonant phenomena and variable oscillators: information is embedded in the frequency or a time parameters of signal
- Modern industrial sensor systems require novel advanced measuring technique

Sensors World Market Trends

According to INTECHNO CONSULTING:

- Sensor market will grow and is expected to reach US $ 50-55 billion by 2008
- Sensors on semiconductor basis will increase their market share to 43% in 2008
- Strong growth expected for sensors based on MEMS-technologies, smart sensors and sensors with bus capabilities

Smart Sensors Market

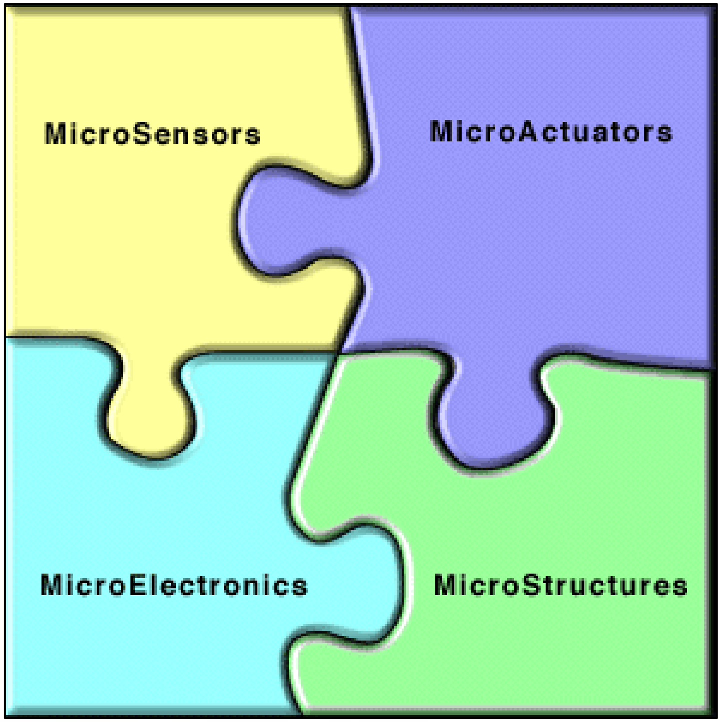
According to Frost & Sullivan:

- The forecast for North American Smart Sensors Market is to reach $635.2 million in 2010.

MST and MEMS

- Smart sensors are of great interest in many fields of industry
- Fast advances in microelectronics have brought new challenges in the physical design of integrated sensors, Micro-Electrical-Mechanical Systems (MEMS) and Systems-on-Chip (SoC)
- Microsystem technology (MST) offers new way of combining sensing elements, signal processing and communication circuitry in one chip

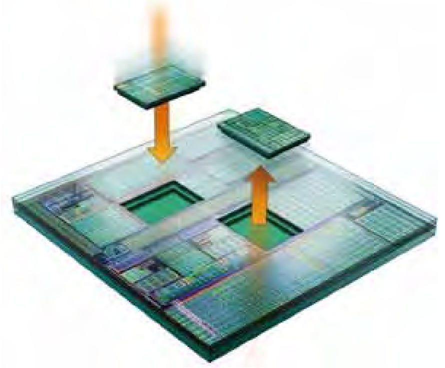
MEMS Definition



MEMS *- an IC chip that provides sensing and/or actuation functions in addition to the electronic ones*

System-on-Chip (SoC)

SoC is an idea of integrating all components of a computer system into a single chip. It may contain digital, analog, mixed-signal, and often radio-frequency functions

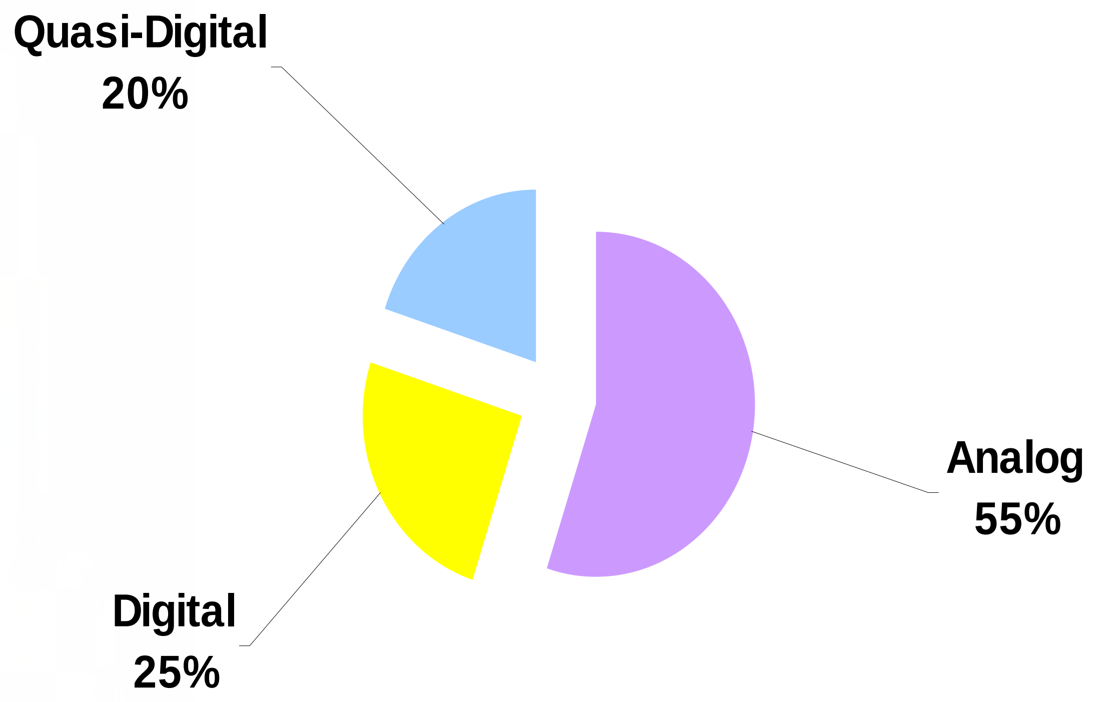


- A typical application - the area of embedded system
- SoC can include: μP, μC, DSP processor, memory, peripherals, different communication interfaces, ADC, DAC, etc.
- Technologies: full-custom, standard cell, FPGA

Unified Parameters

- Mechanical displacement (mercury thermometer, metal pressure gauge, pointer voltmeter, etc.)
- Amplitude of electric current (4-20 mA) or voltage (0.5 – 4.5 V)
- Frequency 2 – 22 kHz
- Duty Cycle 10-90 %

Sensors (IFSA study 2006)

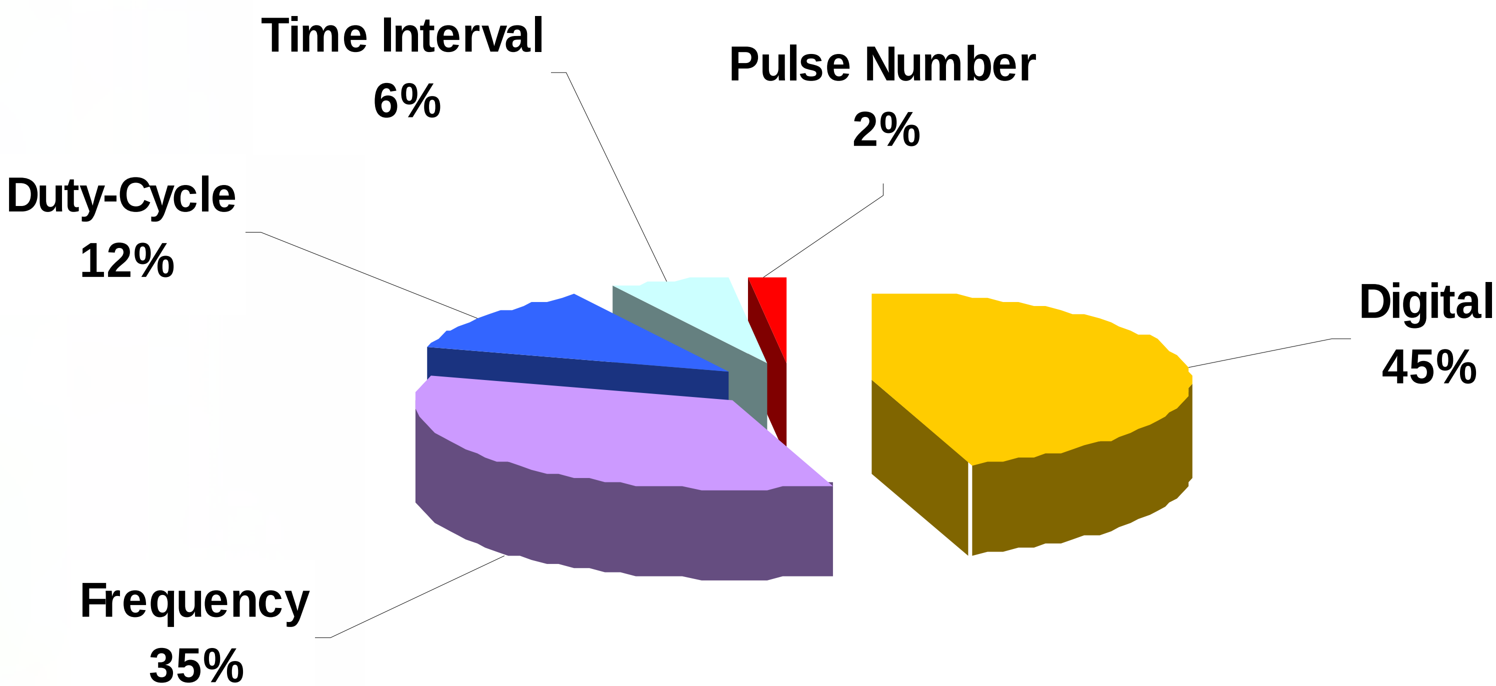


Quasi-Digital Sensors

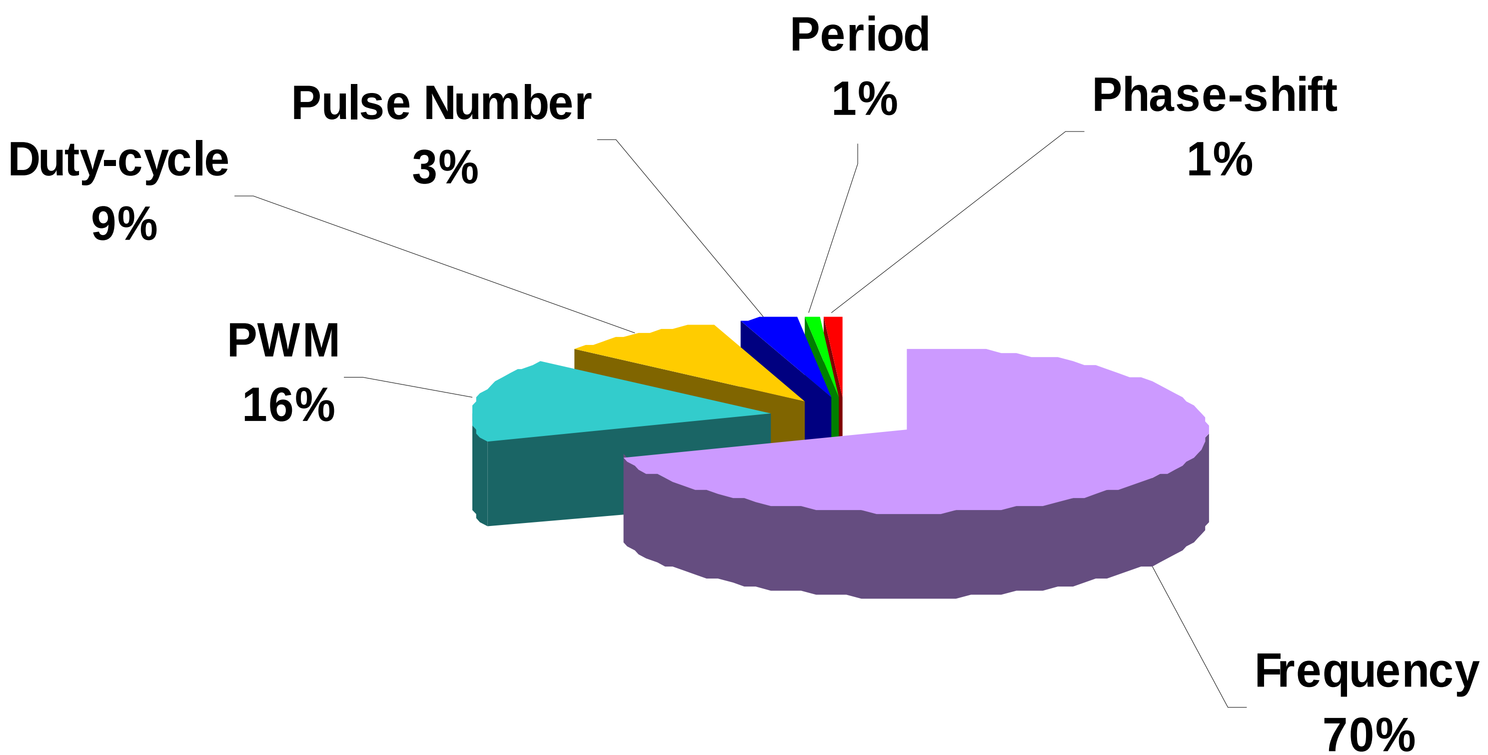
Quasi-digital sensors are discrete frequency-time domain sensors with frequency, period, duty-cycle, time interval, pulse number, pulse width modulated (PWM) or phase shift output

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

Discrete Sensor Groups



Quasi-Digital Sensors



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

Historical Facts

- **1930** - string distant thermometer (Pat. No.61727, USSR, Davydenkov N., Yakutovich M.)
- **1931** - string distant tensometer (Pat. No. 21525, USSR, Golovachov D., Davydenkov N., Yakutovich M.)
- **1941** - ADC for the narrow time intervals (Pat. No. 68785, USSR, Filipov V.N. and Negnevitskiy S.B.)
- **19XX** – Digital frequency counter

Digital Sensors

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

Frequency Output Sensors

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

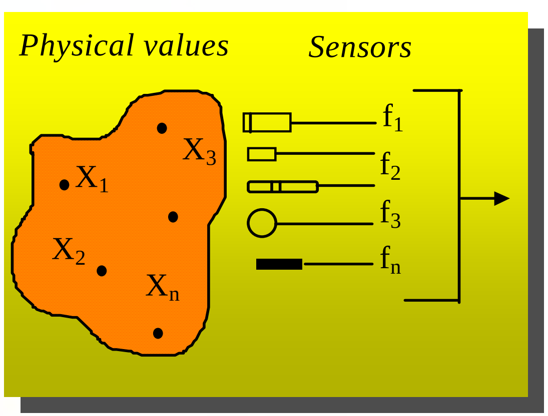
Although there are frequency output sensors practically for any physical, chemical, electrical and non-electrical variables, this prognosis has not been fully justified.

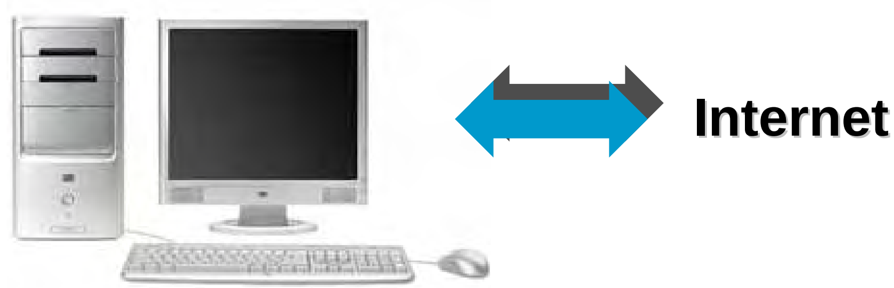
Some Subjective Reasons

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

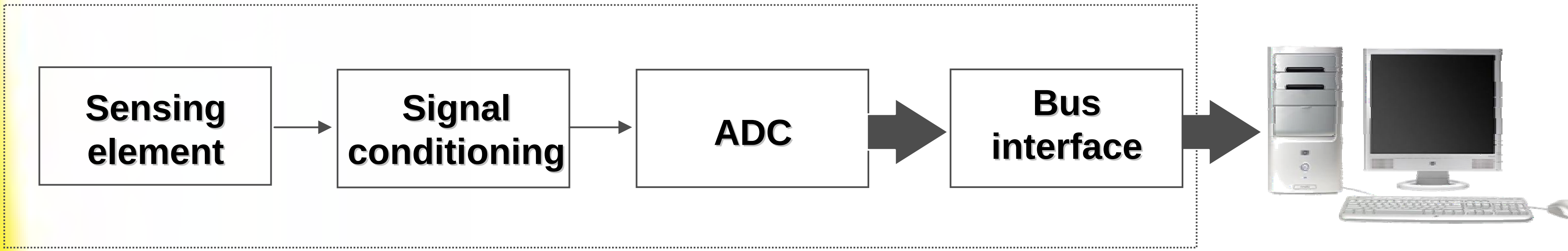
Data Acquisition (DAQ)

Data Acquisition (DAQ) *is collecting and measuring electrical signals from sensors and transducers and inputting them to a computer for processing*





Integrated Sensor



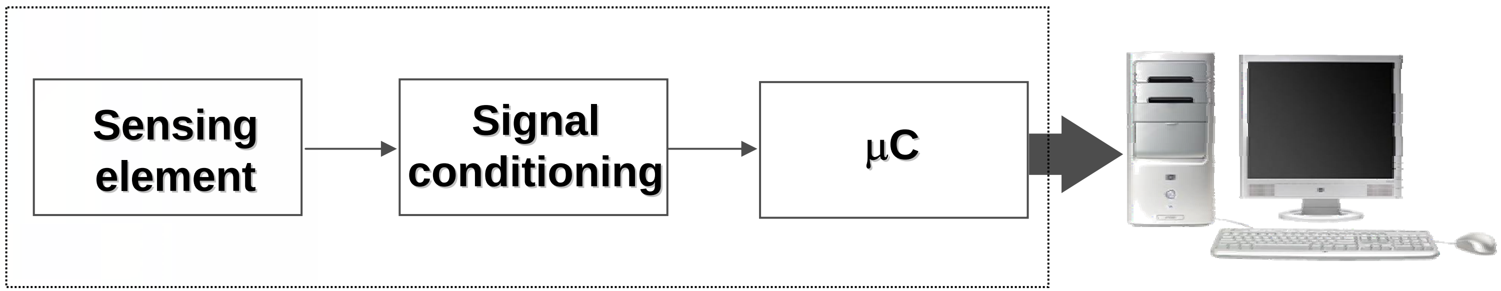
- resistor
- capacitor
- transistor
- piezo-electric material
- photodiode
- bridge, etc,

- amplification
- linearization
- compensation
- filtering, etc.

- ADC
- FDC

- RS-232/422/485
- SMBus
- IEEE 1451
- CAN bus
- I^2C
- SPI

Smart Sensor



- DSP
- FDC
- Communications

Smart Sensor Definition

Smart sensor *(or intelligent sensor) is one chip, without external components, including the sensing, interfacing, signal processing and intelligence (self-testing, self-identification, self-validation or self-adaptation) functions*

Main Smart Sensor Properties

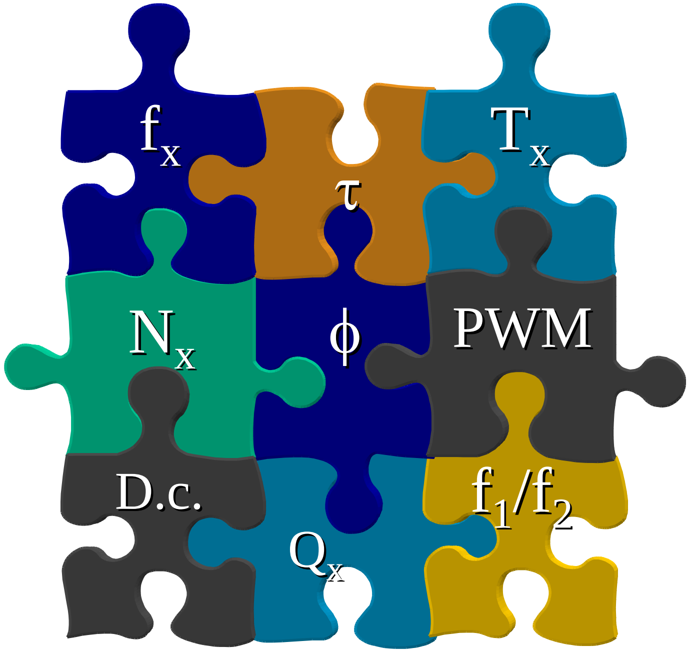
- **Adaptability:** exchange accuracy for speed and conversely; moderate power consumption by adjusting a clock crystal oscillator frequency
- **Accuracy:** measuring error should be programmable (statistical algorithms, weight average, etc.)
- **Reliability:** self-diagnostic is used to check the performance of the system and connection of the sensor wires

Technological Aspects

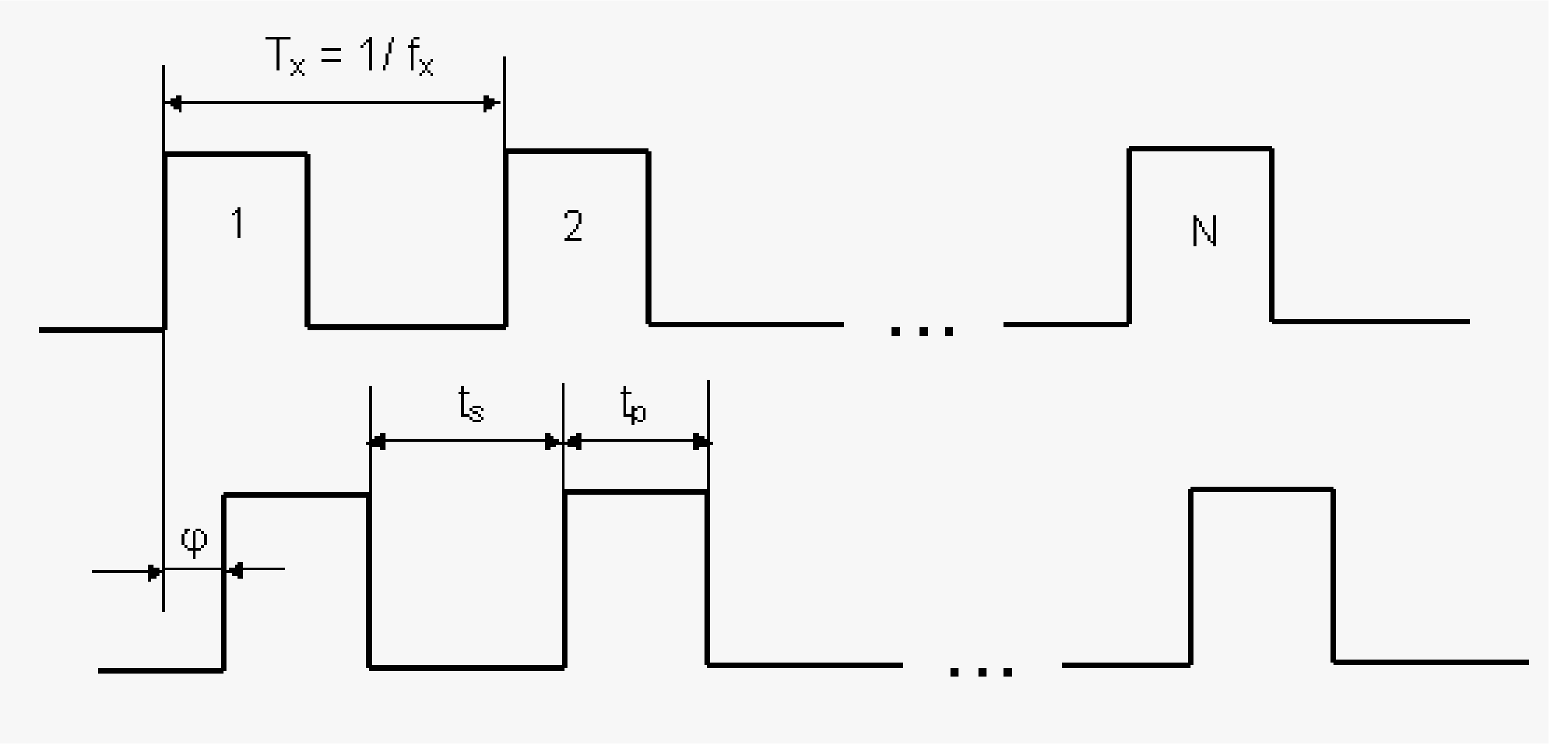
- For any type of silicon sensing element and read-out circuitry, a process can be developed to merge them on a single chip
- Only a huge production volume will pay off the development cost
- Successful integrated-sensor processes must have an acceptable complexity and/or applicability for a wide range of sensors
- Combination of monolithic and hybrid integration with advanced processing and conversional methods in many cases allows to achieve good results for a low cost

Frequency-Time Domain Parameters of Signal

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



Informative Parameters



Frequency Advantages

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

High Noise Immunity

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

High Power Signal

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

Wide Dynamic Range

- Dynamic range is not limited by supply voltage and noise
- Dynamic range of over 100 dB may be easily obtained

High Reference Accuracy

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

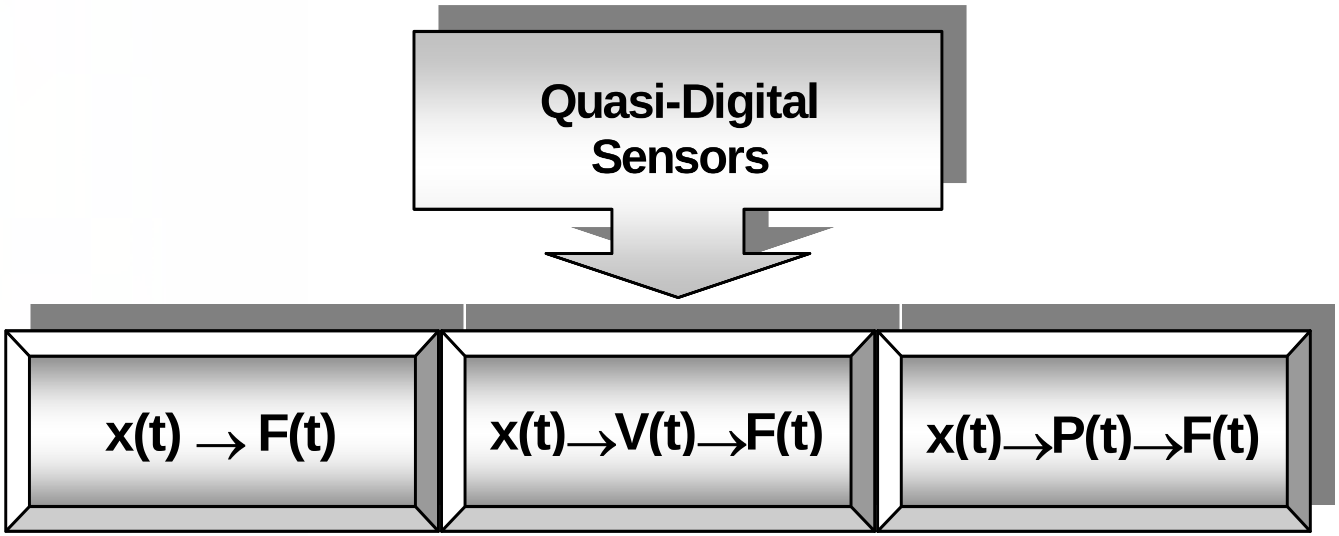
Simplicity of Interfacing

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

Simplicity of Integration and Coding

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

Quasi-Digital Sensor Classification



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

Sensors with $x(t) \rightarrow F(t)$ 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 $x(t) \rightarrow V(t) \rightarrow F(t)$ 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

Parametric (modulating) Sensors

Parametric (modulating) sensors *are devices producing a primary information by the way of respective alterations of any electrical parameter of some electrical circuit (inductance, capacity, resistance, etc.), for measuring of which it is necessary to have an external auxiliary power supply*

Examples: pressure sensors based on piezoresistive effect and photo detectors based on photoelectric effect

Self-Generating Sensors

Self-generating sensors *are devices permitting to receive a signal immediately by the way of a current i(t) or voltage V(t) and no require any source of power other than the signal being measured*

Examples: Seebeck effect based thermocouples and photo effect based solar cells

Self-generating sensors are also called in literature as “active” sensors, where as modulating sensors are called “passive” sensors

Frequency or Analog ?

- Voltage and current are used rather widely as unified standard signals
- Important role play the technological and cost factors
- Common statements what sensors are the best disregarding of concrete conditions of the usage are not correct enough
- Due to heady development of microsystem technologies, technological and cost factors were modified for the benefit of frequency sensors

Smart and Quasi-Digital Sensors Sate-of-the-Art

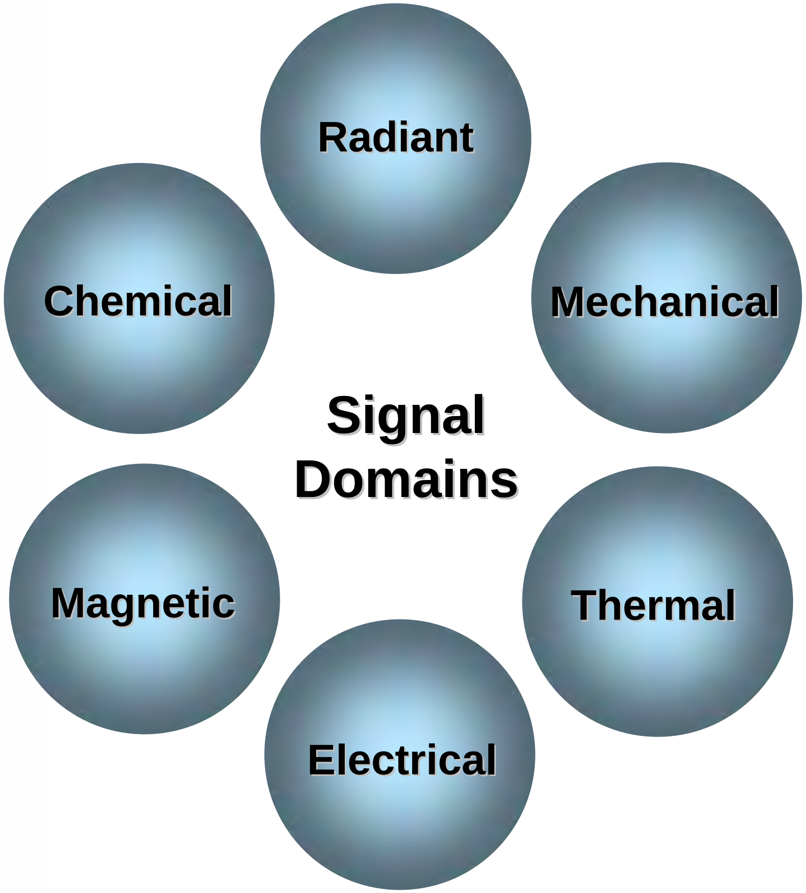
Sensor Types

Highest Demand	Fastest growing
• Temperature	• Rain
• Pressure	• Thickness
• Flow	• Navigation
• Binary position	• Tilt
• Chemical	• Photo detectors
• Filling	• Biosensors
• Rotation speed	• Magnetic
• Gas	• Motion
• Optical	• Glass breakage

Sensor Review

- Should reflect original and intelligent sensors solutions
- Will be focused on high metrology performances (sensor's error, quasi-digital output range, etc.)
- Aim: to formulate basic requirements to frequency-to-digital converters

Six Sensors Signal Domains



Temperature Sensors

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

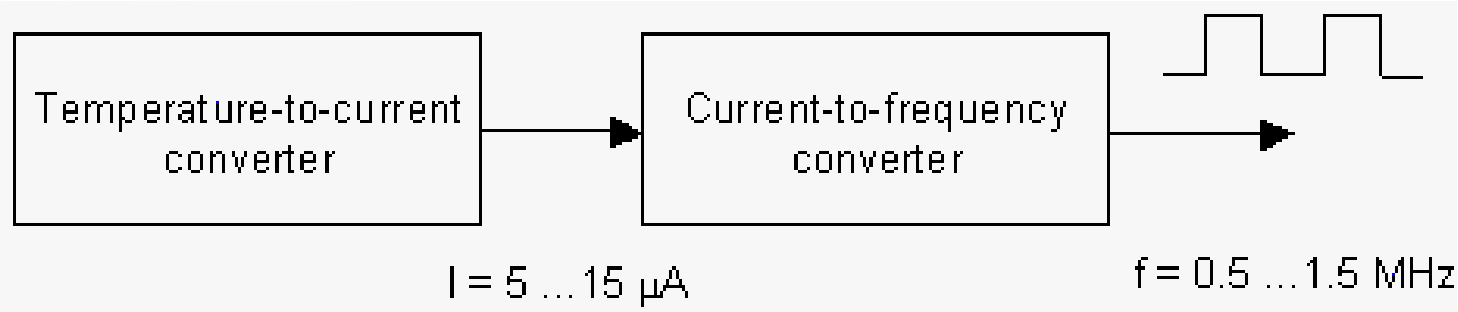
Main Requirements

- Minimum possible chip area
- Tolerances of device parameters
- Digital interference
- High-performance low-cost digital CMOS technologies is preferred

Integrated Temperature Sensors

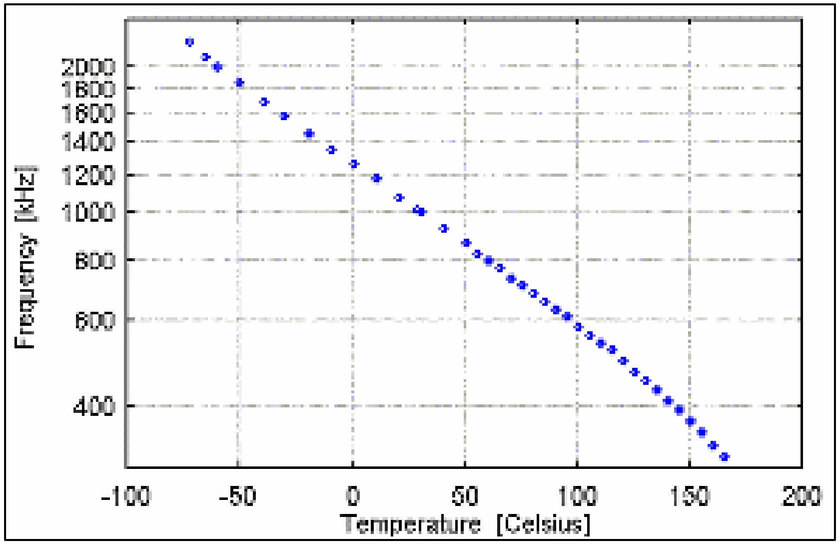
Sensor	Output type	Characteristic	Area, mm^2	IC technology
[1.11]	Digital	I→F converter + DSP	4.5	CMOS
[1.12]	Duty-cycle	Duty-cycle-modulated	5.16	Bipolar
[1.13]	Frequency	I→ F converter	6	Bipolar

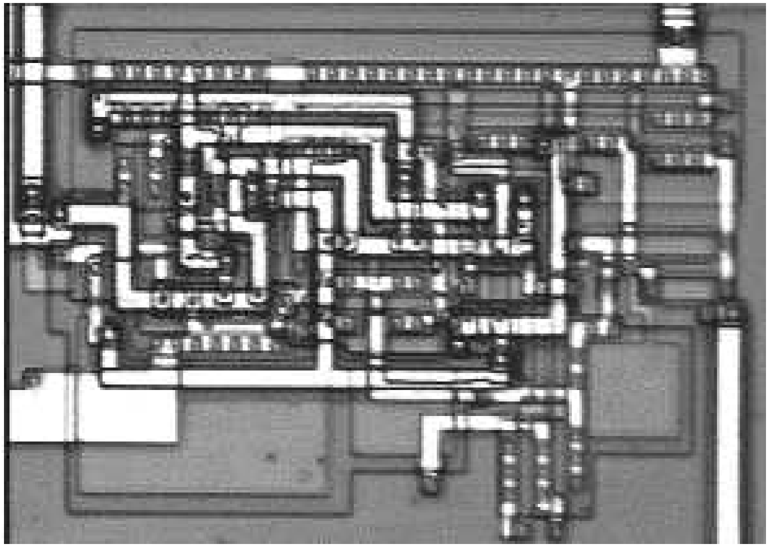
Sensor for Thermal Monitoring



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

THSENS-F





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

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

Thermal-Feedback Oscillator

- Sensor is based on the temperature dependence of the internal thermal diffusion constant of silicon
- Frequency-determining element is realized by a thermal delay line
- Frequency of oscillator is directly related to the thermal diffusion constant:

$$D_{th} = \lambda / c,$$

where λ is the thermal conductivity and c is the unit-volume heat capacitance

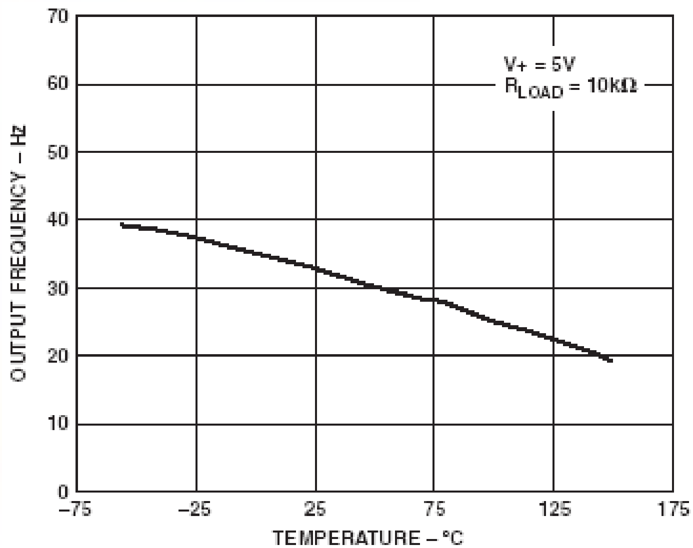
Temperature Sensors

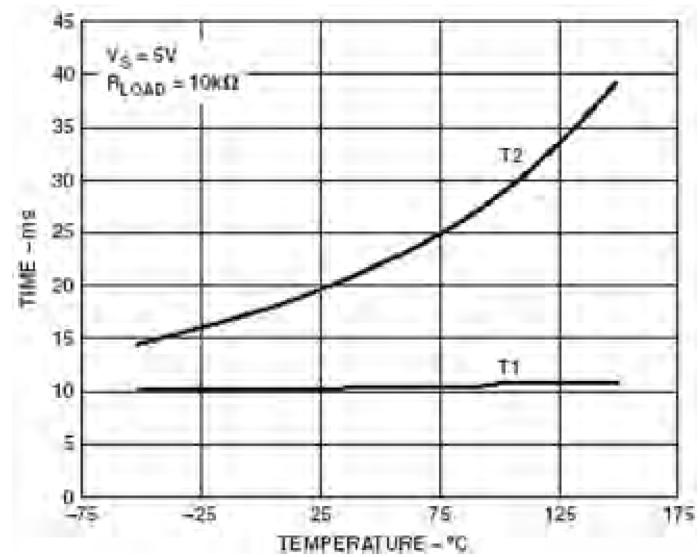
Sensor	Max. Temp. Error, °C	Temp. Range, °C	Resolution, Bits	Output	Output Range
Analog Devices					
TMP03	± 1.5	-40 to +100	16	PWM	-
TMP04	± 1.5	-40 to +100	16	PWM	-
TMP05	± 0.5	-40 to +150	12	PWM	-
TMP06	± 0.5	-40 to +150	12	PWM	-
Maxim Integrated Products					
MAX6576	± 3.0	-40 to +125	N/A	Period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

Temperature Sensors TMP03/TMP04

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

TMP03/04 Output





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

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

Temperature Sensors TMP05/TMP06

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

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

Temperature Sensors MAX6576/MAX6577

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

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

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

where *Ks* is the scalar multiplier

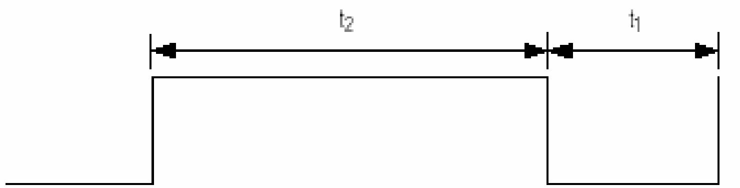
Temperature Sensors MAX6666/MAX6667

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

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

Temperature Sensors MAX6672/MAX6673

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

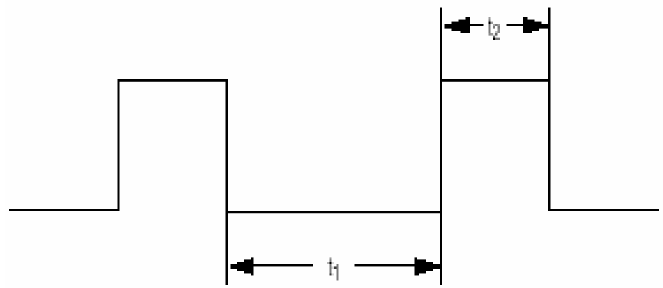


$$T(°C) = -200 \cdot \left(0.85 - \frac{t_1}{t_2}\right)^3 + \left(425 \cdot \frac{t_1}{t_2}\right) - 273$$

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

Temperature Sensors MAX6676/MAX6677

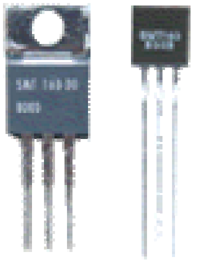
- High accuracy, low-power temperature sensors PWM output
- Accuracy is ±1.5 ^{0}C from –40 ^{0}C to +125 ^{0}C



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

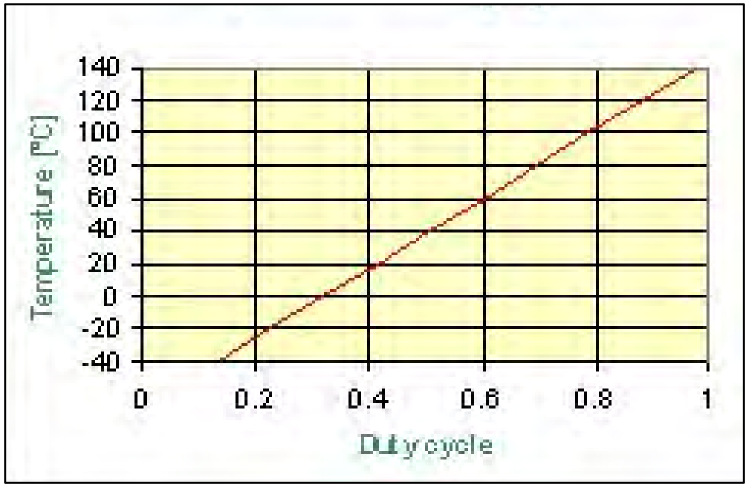
Temperature Sensor SMT 160-30

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



SMARTEC

SMT 160-30 Output



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

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

Temperature Sensor SBE 3F

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

Digital Temperature Sensor AD 74 / 78

Type	Description
AD7414	SMBus/I²C Digital Temperature Sensor in 6-Pin SOT with SMBus Alert and Over Temperature Pin
AD7415	SMBus/I²C Digital Temperature Sensor in 5-Pin SOT
AD7416	Temperature-to-Digital Converter, I²C, 10-Bit Resolution, -55^{0}C to +125^{0}C, ±2^{0}C Accuracy
AD7417	4-Channel, 10-Bit ADC with on-Chip Temperature to Digital Converter, I2C, ±1^{0}C Accuracy
AD7418	Single-Channel, 10-Bit ADC with On-Chip Temperature to Digital Converter, I2C, ±1^{0}C Accuracy
AD7814	10-Bit Digital Temperature Sensor in 6-Lead SOT-23
AD7816	10-Bit ADC, Temperature Monitoring

Dallas Semiconductor's Sensors

- DS16XX17XX 1-, 2-, 3- Wire® or SPI buses temperature sensors
- Accuracies ranging from ± 0.5 ^{0}C to ± 2.5 ^{0}C
- Temperature range of –50 ^{0}C to +125 ^{0}C
- Conversion time range is 750 ms ÷ 1.2 s
- Expandable from 9 to 13 bits or user configurable to 9, 10, 11, or 12 bits resolution
- Multi-drop capability, which allows multiple sensors to be addressed on the same bus

National Semiconductor's Sensors

- Temperature ranges from –55 ^{0}C up to +150 ^{0}C
- LM70 (10-bit), LM74 (12-bit), LM75 (±3 ^{0}C, I^{2}C™ Serial Bus)
- LM76 (±1 ^{0}C), LM77 (±1.5 ^{0}C) and LM92 (±0.33 ^{0}C) with two-wire interface
- Sensors LM70, LM74 and LM75 include delta-sigma analog-to-digital converter
- ACPI (Advanced Configuration and Power Interface) specification for PC due to Window-comparator architecture

National Semiconductor

Other Temperature Sensors

MAXIM	**MAX6575L/H - SOT Temperature Sensor with Multidrop Single Wire Digital Interface** **MAX6625/MAX6626 - 9-Bit/12-Bit Temperature Sensors with I^2C-Compatible Serial Interface in a SOT23**
+GF+ SIGNET GEORGE FISCHER +GF+ Piping Systems	**+GF+ SIGNET 2450 - temperature sensor with digital output**
Graftel, Inc.	**9401-ADM Smart Sensor - Temperature, RH and Dew/Frost Points**
READ GROUP.COM	**Combined Pressure and Temperature Sensor (WEPS) with analog, frequency or digital output**
SENSIRION	**AH31(Sensmitter) - Fully calibrated digital relative humidity sensor, temperature & dewpoint sensor**

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)

Technologies and Principles

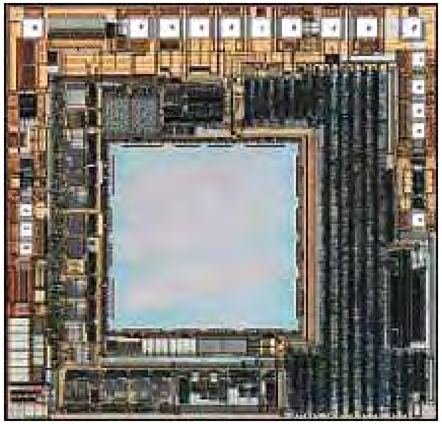
- Semiconductor micromachined pressure sensors use monolithic silicon diffused piezoresistors
- Advantages: high sensitivity, good linearity, minor hysteresis phenomenon, small response time
- Temperature error can be compensated due to the usage of built-in temperature sensors
- MEMS pressure transducers consist of a four-resistor Wheatstone bridge, fabricated on a single monolithic die using bulk etch micromachining technology

Architectures for Sensor Compensation

- Conventional analog sensor signal processing
- Digital sensor signal processing (fully digital compensation and error-correction scheme)
- Standard microcontroller or dedicated DSP can be used

Monolithic Pressure Sensor

- Digital calibration algorithm
- Digital communication interface
- IC contains a pressure sensor element that is coprocessed in a submicron, mixed-signal CMOS wafer fabrication step



VFC Based Pressure Sensor (I)

- Range of measuring frequencies 0 ÷ 2 kHz in the pressure range 0 … 40 MPa

$$p = (f - f_0)/K_p; \qquad K_p = K_F \cdot S_{eff},$$

where f_0 is the frequency at $p = 0$; f is the measurand frequency; K_p is the conversion factor of pressure-to-frequency; K_F is the force sensitivity factor; S_{eff} is the membrane's effective area

VFC Based Pressure Sensor (I)

ADZ Sensortechnik GmbH:

$$f_{out} = \frac{\left(V_{in} - V_{offset}\right) \cdot R6}{2.09V \cdot R4 \cdot R8 \cdot C6} \qquad V_{in} = P_{abs} \cdot 0.533 \frac{V}{bar} + 0.5V$$

- Measuring range is 0 ÷ 8.8 bar
- Frequency range is 1 ÷ 23 kHz

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

Other Pressure Sensor

- With strain-gage signal (Patriot Co.)
- Rugged crystalline quartz sensor (Amerada® Quartz Pressure Transducer from Geophysical Research Corporation
- High-accuracy (0.01 %) fibre-optic pressure transducers from ALTHEN GmbH

Quartz Crystal Pressure Transducers

- Digiquartz® Intelligent Transmitters (8DP, 8CDP, 8B, 8CB, 181KT) from Paroscientific Inc.
- Typical full scale (FS) accuracy 0.01 %
- RS-232 interface
- Fully thermally compensated using

Digital Pressure Transducers

- RS-232 or RS-485 interfaces (Druck)
- ± 0.01 % FS accuracy (Pressure Systems)
- Combined pressure and temperature sensors

Accelerometers

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

Quasi-Digital Accelerometers

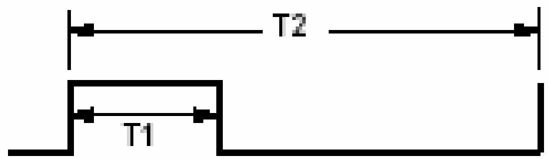
Device	Number of Axis	Range	Sensitivity Accuracy (%)	Max Bandwidth (kHz)
Analog Devices				
ADXL202	2	± 2 g	± 16	6
ADXL210	2	± 10 g	± 20	6
ADXL213	2	± 1.2 g	± 10	2.5
Honeywell				
RBA500	N/A	± 70 g	N/A	> 0.4
SA500	N/A	± 80 g	N/A	> 1
Kionix				
KXG20	2	± 2 g	N/A	< 0.5
MEMSIC, Inc.				
MXD2125	2	± 2 g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

N/A – no available information

ADXL202/210/213 Accelerometers

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

ADXL202/210/213 Output



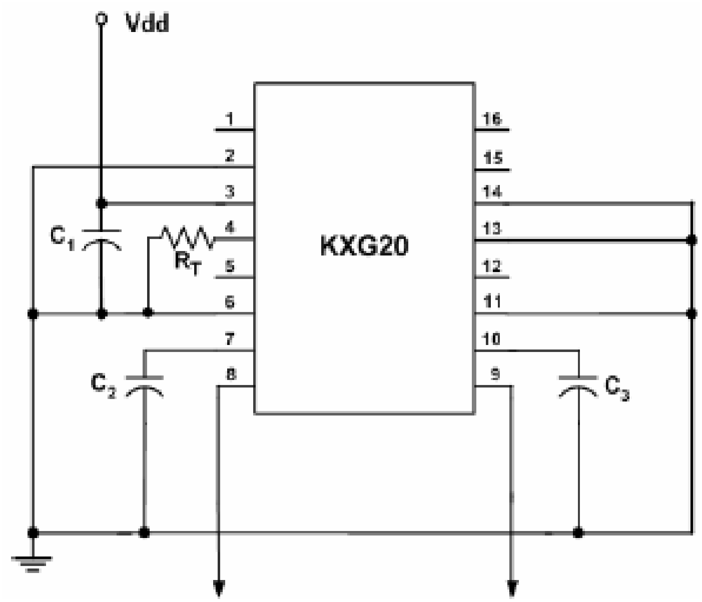
$$Acceleration\ (g) = \frac{(T1/T2) - 50\%}{12.5\%}$$ - for ADXL 202

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

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

KXG-20 Accelerometer

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



Other Accelerometers

- **RBA500** and **SA500** frequency output accelerometers (Honeywell)
- **MXD2125GL/HL/ML/NL** – CMOS accelerometers with duty-cycle outputs (MEMSIC)
- **Model 1010** - low-cost, integrated accelerometer (Silicon Designs). Output: density of pulses (number of pulses per second) proportional to acceleration

Digital Accelerometers

- Interfaces: RS-485, SPI, I^2C and IEEE 1451
- Dual- and Tri-axial models
- Wireless accelerometers (M9E-RF-1-50G smart accelerometer from TECHKOR Instrumentation)
- MEMS-based accelerometers (STMicroelectronics)

M9E-RF-1-50G

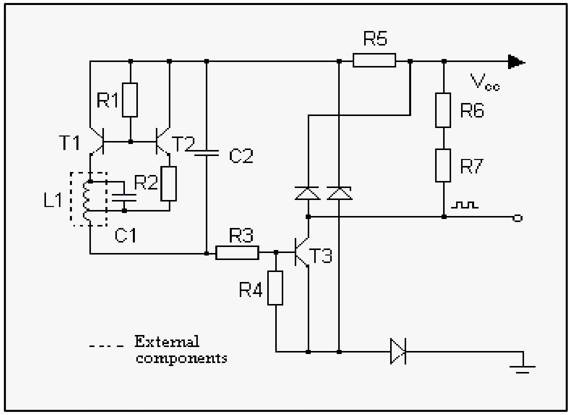
Rotation Speed Sensors

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

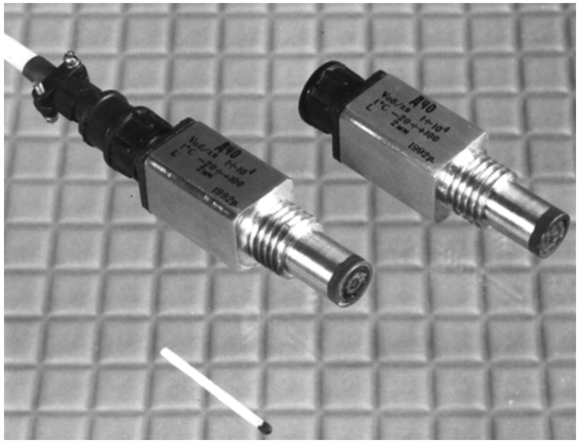
$$n_x = f_x \cdot \frac{60}{Z}$$

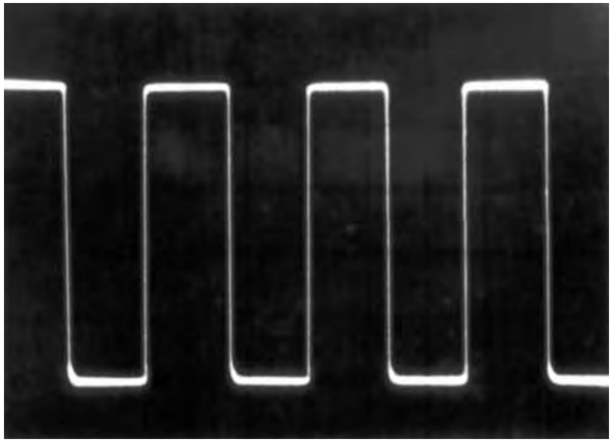
, where *Z* is the number of modulation rotor's (encoder's) gradations (teeth)

Active Sensor of Rotation Speed (ASRS)



- Semiconductor active position sensor of relaxation type





Comparative Analyse

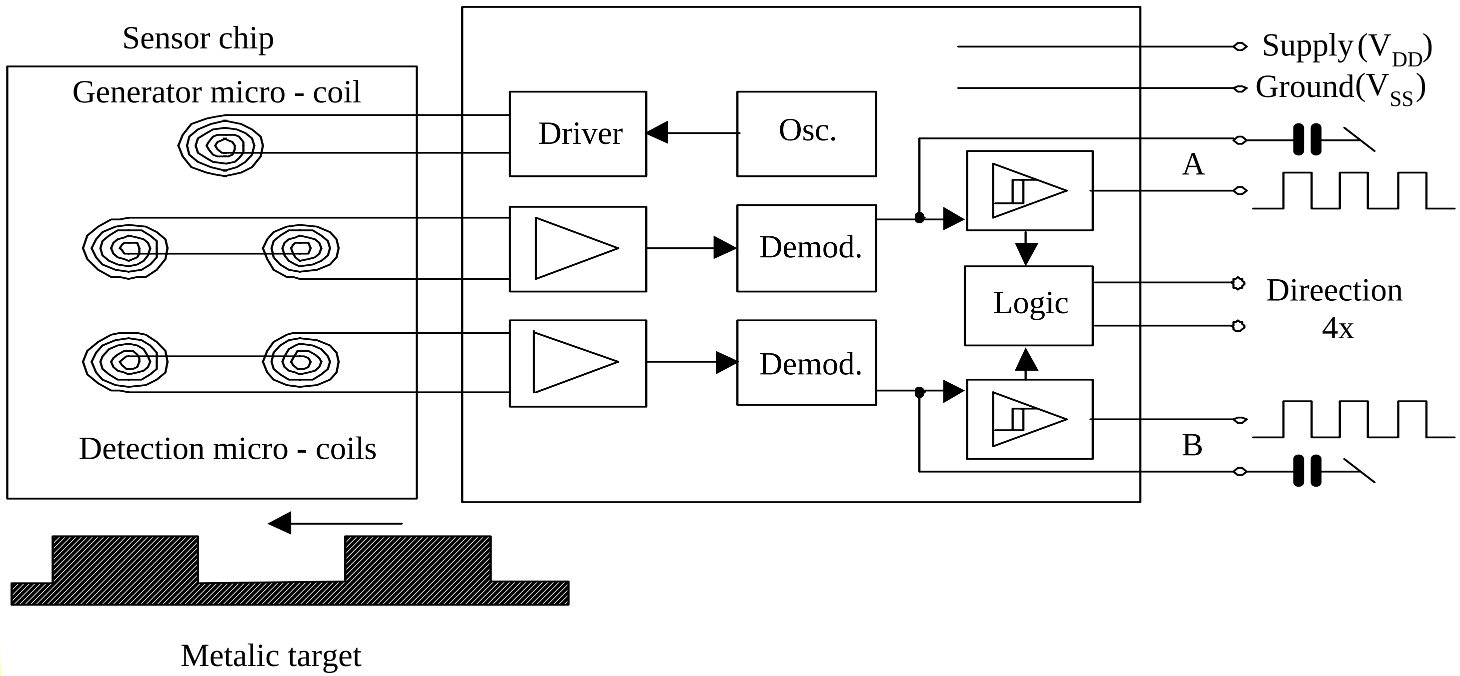
Sensors	Freq. Range, *kHz*	Supply Voltage, *V*	Current Consumption, *mA*	Type
ASRS	0 ÷ 50	4.5 ÷ 24	7 ÷ 15	active
A5S07	0.5 ÷ 25	8 ÷ 28	15 + load current	hall-effect
A5S08/09	0.5 ÷ 25	8 ÷ 25	15	hall-effect
DZ375	0 ÷ 5	4.5 ÷ 16	20 ÷ 50	magnetic
DZH450	0 ÷ 5	4.5 ÷ 30	20	hall-effect
DZP450	1 ÷ 10	4.5 ÷ 16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

Results

- Active, magnetic and Hall-effect sensors are more suitable for determination of object status “Stop”
- Active sensors can operate with non-magnetic modulating rotor’s teeth
- All sensors can be used like angular position sensor, position sensor, metallic targets counter and end-switch. Two such sensors can be used for rotation acceleration measurement
- Active semiconductor sensors are not influenced by run-out and external magnetic fields

Active Micro-sensor MS1200 (CSEM)

- Frequency range, kHz   0 ÷ 40
- Air-gap, mm   0 ÷ 3



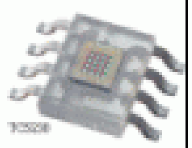
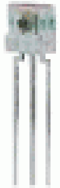
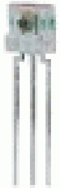
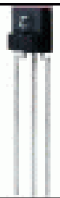
Intelligent Opto Sensors

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

Integrated On-chip Colour Sensor

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

TAOS Light and Color Sensors

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

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

where f_O is the output frequency; f_D is the output requency for dark condition ($Ee = 0$); *Re* is the device responsivity for a given wavelength of light given in kHz/(mW/cm2); *Ee* is the incident irradiance in mW/cm^2

Digital Opto Sensors

- **TSL2550, TSL2560, TSL2561, TSL2562, TSL2563** - light-to-digital converters (TAOS)
- **TSL3301** - optical sensor array (TAOS)
- **ISL29001, ISL29002** – integrated digital light sensors (Intersil)
- SMBus and I^2C interfaces
- Internal 8-15 ADCs

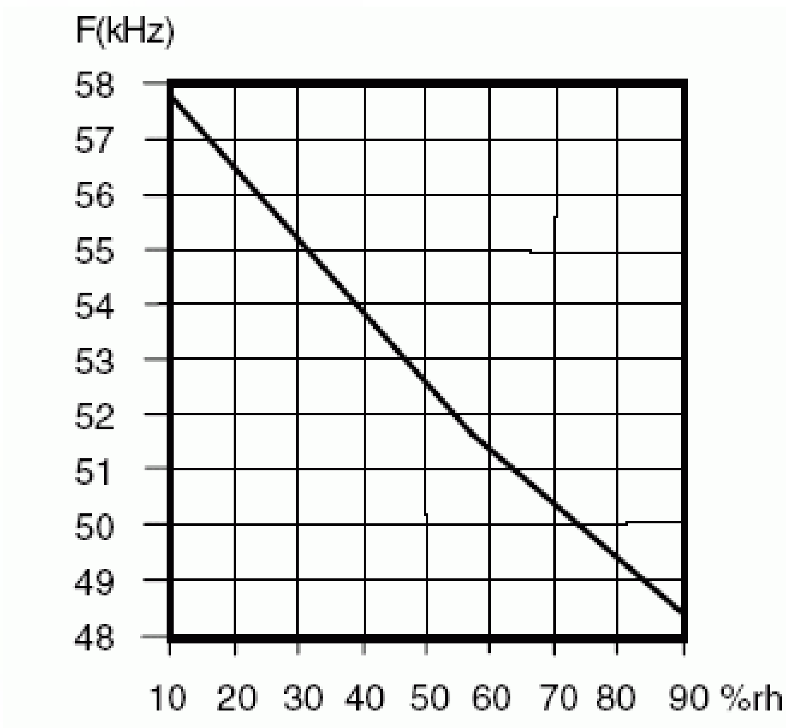
Humidity Frequency Output Sensors

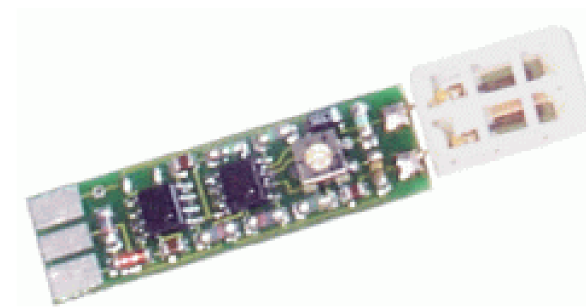
- Based on humidity–capacitance–frequency (time interval or duty-cycle) converters: $X(t) \rightarrow C(t) \rightarrow F(t)$
- Pulsed signal for both humidity and temperature
- Measuring range 0 ÷100% RH
- Frequency ranges from some kHz up to hundreds kHz
- Accuracy up to 1 %

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 20ºC	61.1…48.6
	Galltec+Mela, GmbH		
Humidity Frequency Converter	10…90	±3	57.9…48.4
	Humirel		
HTF3100	N/A	±3 at 55 %RH	N/A
HTF3130	10 … 95	±3 at 55 %RH	7.155…6.210
HTF3223	10 … 95	±5 at 55 %RH	9.560…8.030
HTF3225	N/A	±5 at 55 %RH	N/A
HTF3226	10 … 95	±5 at 55 %RH	9.44…8.070
HTF3226LF	10 … 95	±5 at 55 %RH	9.49…8.225
HTF3227	N/A	±3 at 55 %RH	N/A
	Kurabe		
KN-1050	0…95	±5	4.95…5

Humidity Frequency Converter (*Galltek +MELA*)



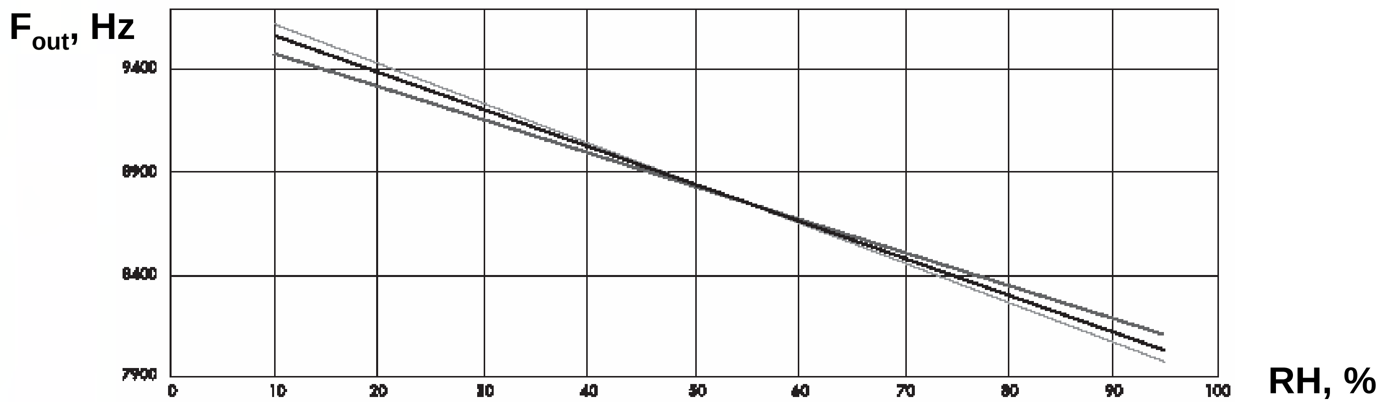


Galltec +mela

Dedicated Humidity Transducers from Humirel

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

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

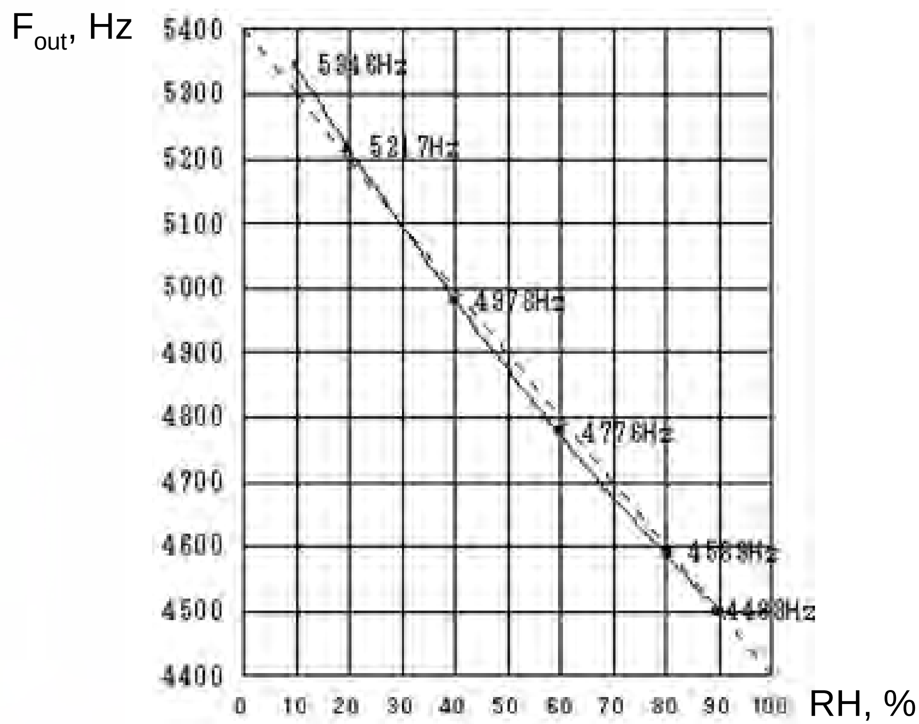


$$F_{out} = 9600 - 15.8 \cdot RH$$ - for **HTF 3226,** linear reference curve

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

Humidity-to-Frequency Converter KN-1050

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



Chemical, Gas and Biosensors

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

Mass Variation Sensors

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

Magnetic Sensors

- Hall effect sensors
- Magnetoresistors
- Magnetodiodes
- GMR
- SQUID
- Magnetometers
- Navigation compasses

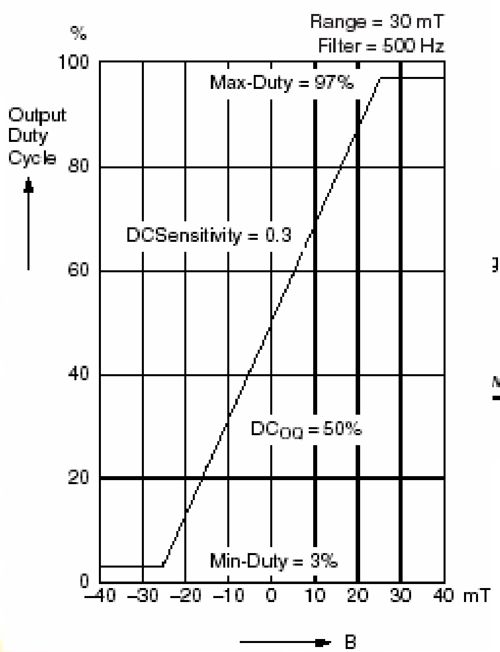
Magnetic Sensors (cont.)

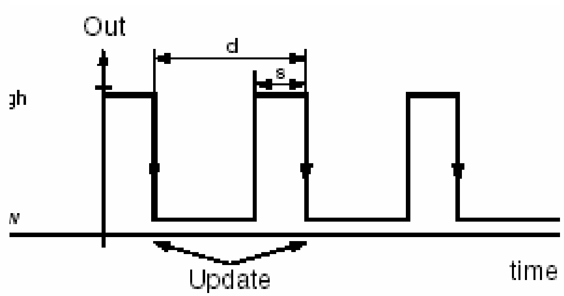
- HAL810, HAL819 – Hall sensors with duty-cycle output form *Micronas*;
- AKL Sensors Series from *Rhopoint Component Ltd.,*
- High resolution CMOS magnetic field to frequency converter with frequency difference on its output [1]

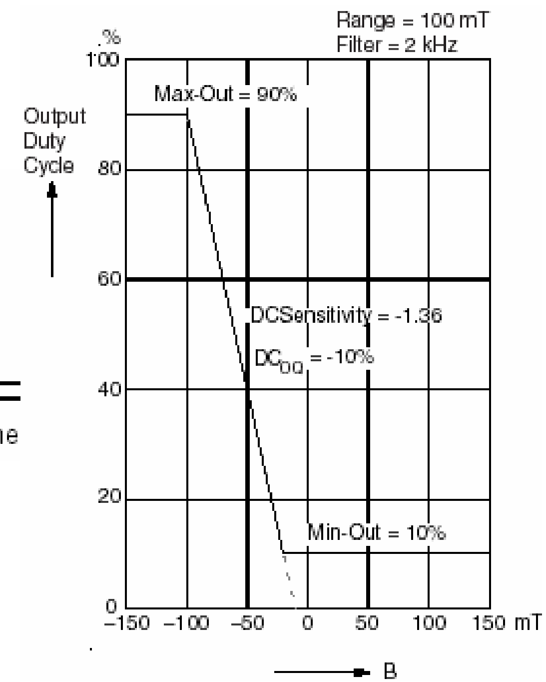
[1]. Shr-Lung Chen, Chien-Hung Kuo, and Shen-Iuan Liu, CMOS Magnetic Field to Frequency Converter, *IEEE Sensors Journal*, Vol.3, No.2, April 2003, pp.241-245

Programmable Magnetic Field Sensor HAL810

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





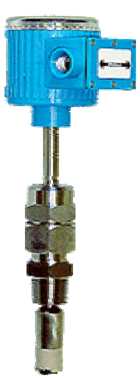


MICRONAS

Other Sensors

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






Multiparameters Sensors

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

Conclusions

- There are many quasi-digital and digital integrated sensors for any physical and chemical quantities
- The frequency range of such sensors is very wide (some parts of Hz to some MHz), relative error up to 0.01%
- Extension of its "intelligent" capabilities are observed
- Process of miniaturization boosts creation of multichannel, multifunction (multiparameter) one-chip smart sensors and sensors arrays
- The rapid development of microsystems promotes further development of different smart sensors

Data Acquisition Methods for Sensor Systems

Introduction

- Technological and manufacturing processes are sources of the initial data for multichannel sensor systems
- Multichannel DAQ systems are intended for transformation of initial parameters of processes and events into equivalent digital signals for the further processing
- Modern DAQ systems allow to supervise practically all physical and chemical quantities
- DAQ methods depend on solved tasks and directly influence to the structure and functionalities of multichannel data acquisition systems

Main Definitions

Acquisition Time *- The time required for the front end of a DAQ board to capture an input signal and hold it to within a specified error band after a sample command is received*

Background Acquisition *– Data is acquired by a DAQ system while another program or processing routine is running without apparent interruption*

Data Acquisition Board *- A data acquisition system incorporated on a PCB that is electrically and mechanically compatible with a particular computer system*

Main Definitions (cont.)

Data Acquisition System *- A system that processes one or more analog or quasi-digital signals and converts them into a digital form for the use by a computer system*

Data Logger *- A data acquisition system that incorporated a small computer, is typically portable, and is intended to collect data autonomously for extended periods of time. The data are afterwards downloaded into another computer for processing and analysis*

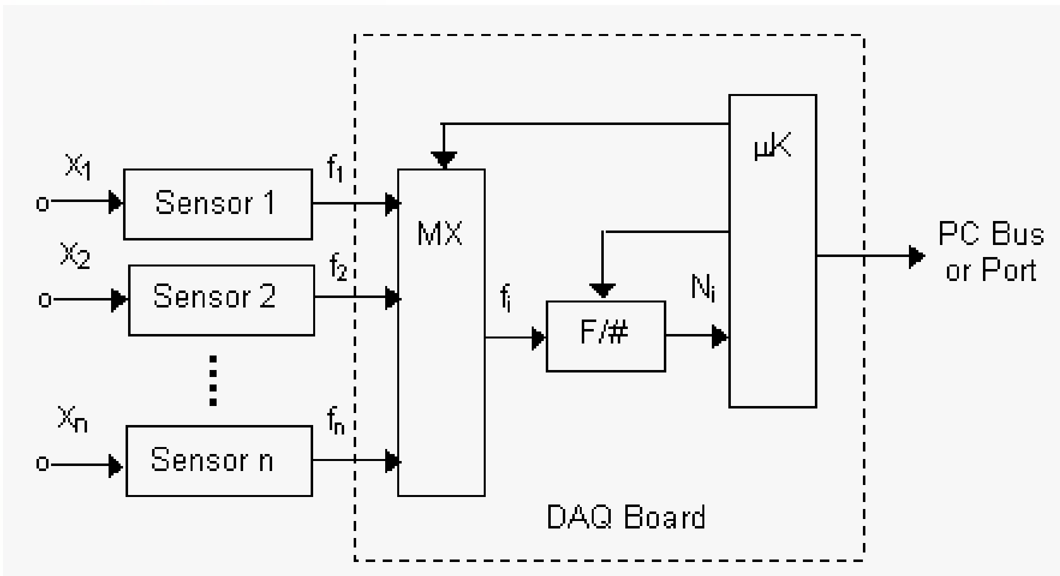
Real–Time Processing *- A procedure in which results of an acquired and computed value can be used to control a related physical process in real time*

DAQ Methods

- Methods with time-division channelling, based on the sensors multiplexing, i.e. on the time-shared data acquisition from each of them
- Methods with space- division channelling based on the simultaneous data acquisition from all sensors in the same time

The constancy of data sources, i.e. an opportunity of information access at any time depended on solved control and measuring tasks is used in both case.

Method with Time-Dividing Channelling



The frequency-to-digital conversion can be realized directly by microcontroller without any additional hardware

Sensors Polling and Data Input

Sensors polling:

- Cyclic synchronous
- Software controlled asynchronous (microcontroller chooses the required sensors depended on the task)

Data Input:

- System bus (ISA, PCI, PCMCIA, etc.)
- I/O port (USB, COM, LPT)

Polling Time

The cycle polling time: $\tau_0 = n \cdot (T_q + \tau_{delay1} + \tau_{delay2}),$

where T_q is the quantization time in frequency-to-digital converter;

- t_{delay1} is the time delay between the frequency conversion ending for the previous sensor and the command to poll the next sensor;

- t_{delay2} is the time delay of the frequency conversion starting after the sensor connection;

- n is the number of sensors in multichannel data acquisition system

Advantage and Disadvantage

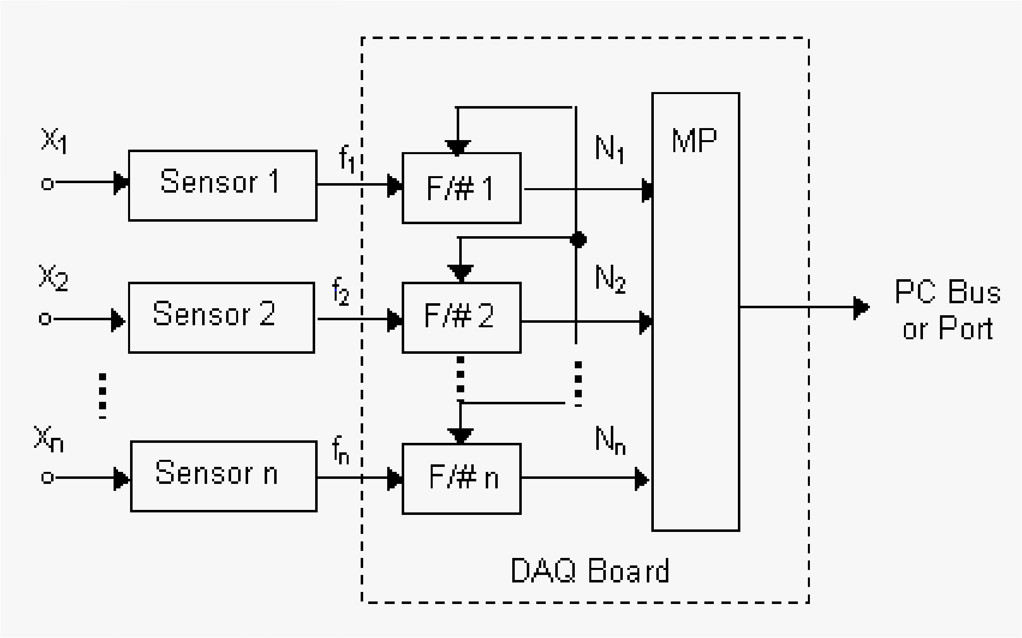
+ Method allows to create inexpensive multichannel data acquisition systems for quasi-digital sensors

− Constant sequence of sensor polling and the cyclicity, controlled by the microcontroller, is the reason of measuring information losses

Advanced Methods

- Method of accelerated polling for period output sensors: polling all channel during one cycle
- Method with increased polling frequency for channels with higher input frequency
- Method with time-shared polling of frequency sensors

Method with Space-Division Channelling



Conversion time: $\tau_0 = T_q + t_{readout}$

FDC to Microprocessor Interface

- By polling (software-controlled)
- By interrupt (2 000÷3 000 readings/s)
- DMA (300 000 ÷ 5 000 000 reading/s)

  - Continuously
  - Periodic synchronously
  - Software controlled asynchronously

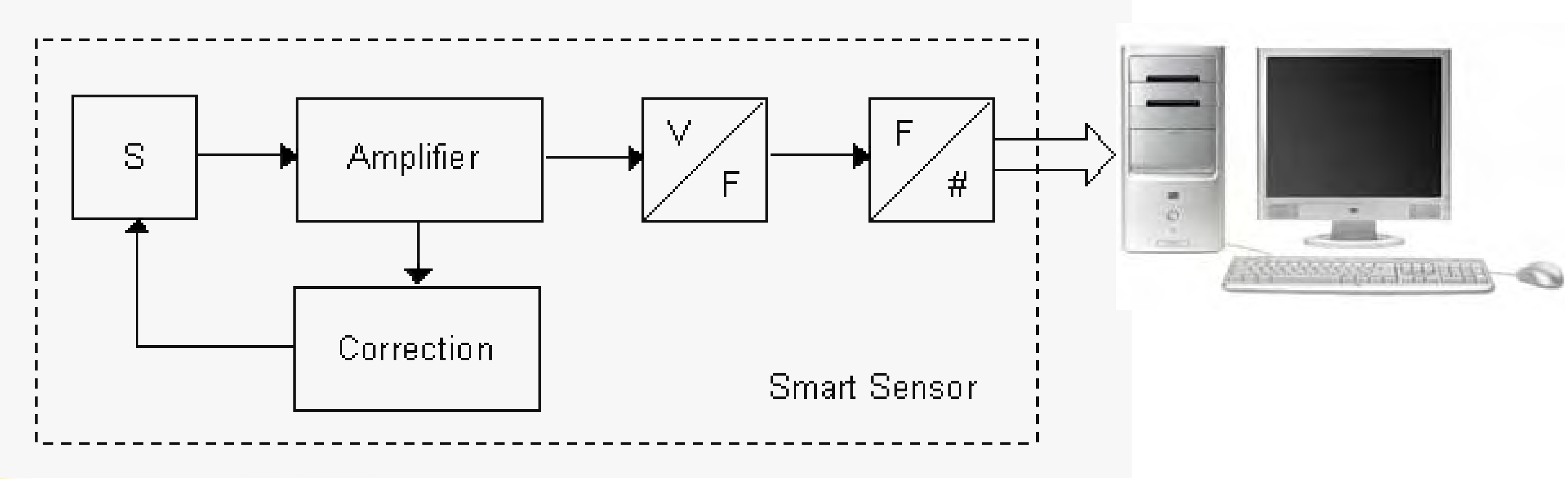
Advantage and Disadvantage

+ High speed (in *n* times more than in the previous method)

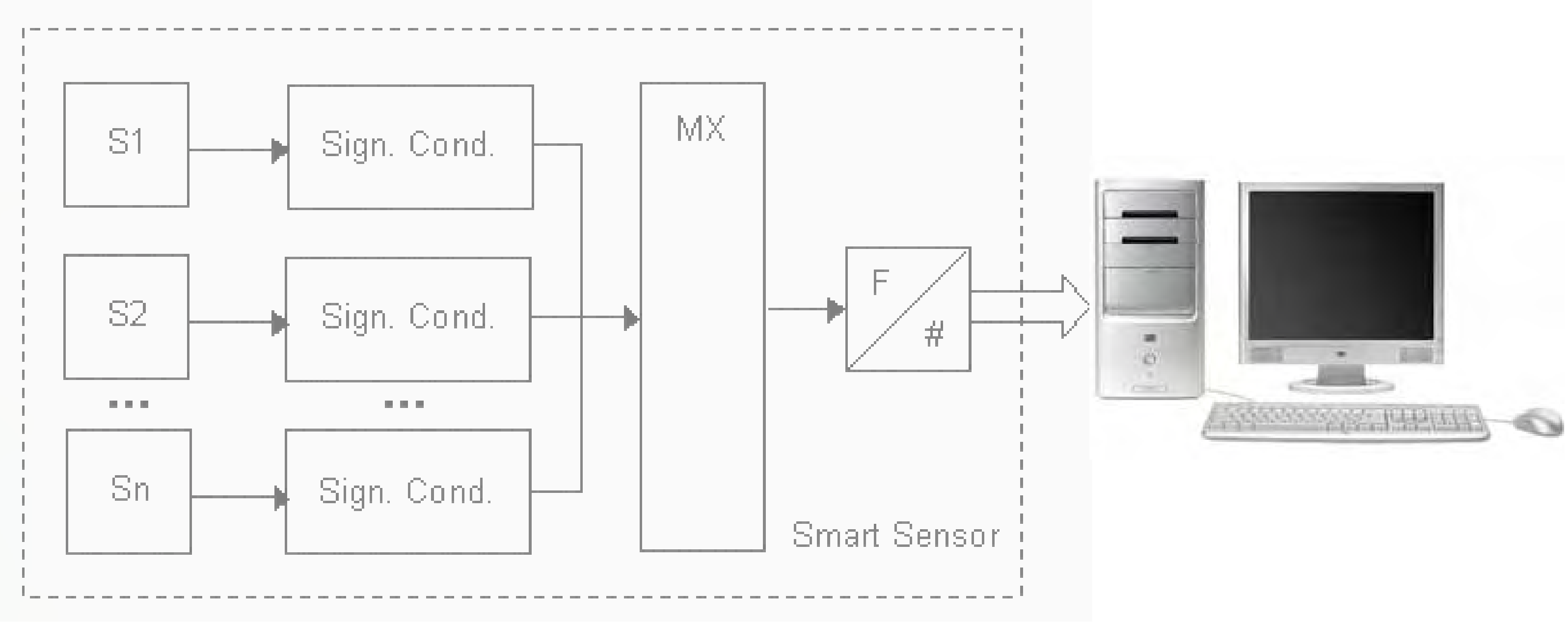
− Needs addition hardware and cost

Sensor Architectures and DAQ

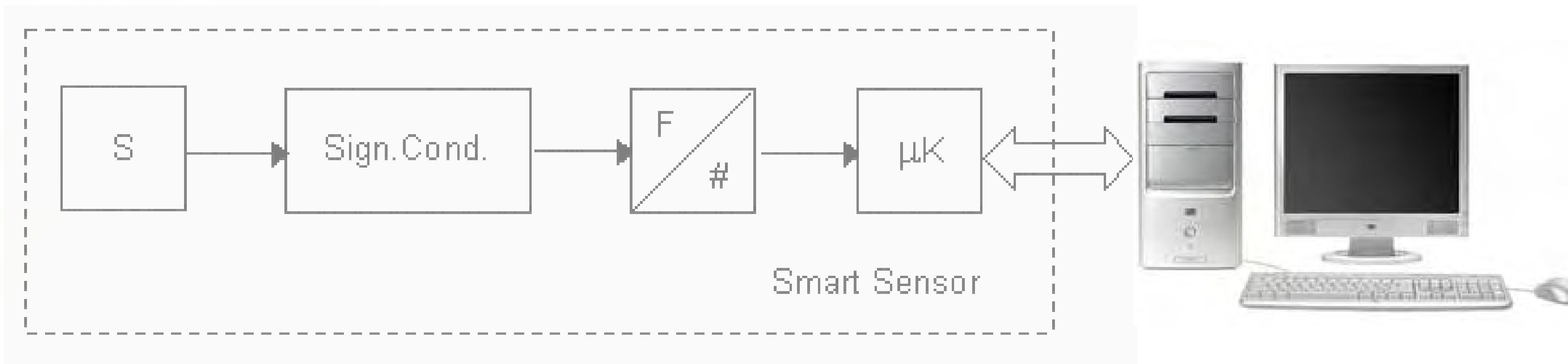
Smart sensor architecture with a preliminary correction in the analog signal domain and further conversion into frequency-time signal domain:

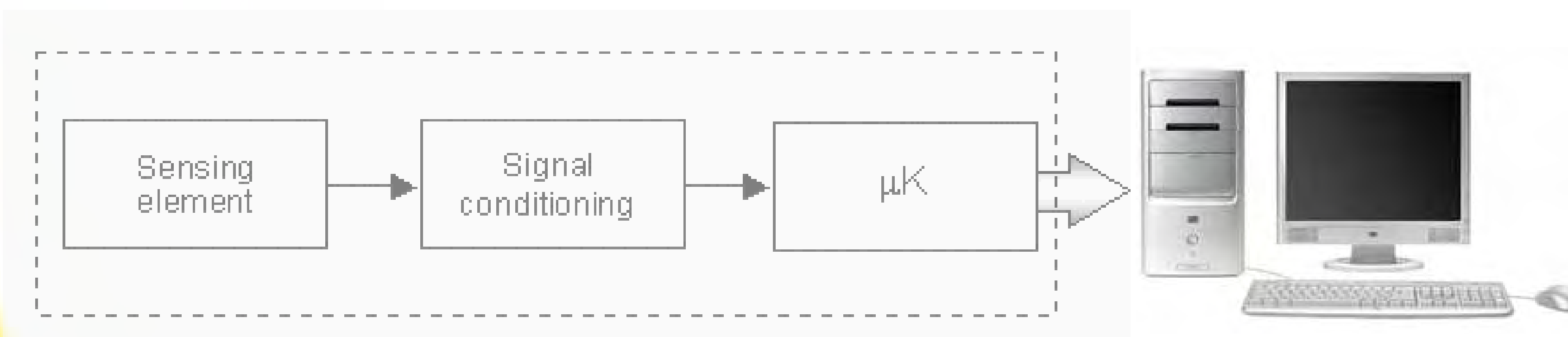


Sensor Array Architecture



Architectures with Microcontroller





DAQ Software

- Rapid application development
- Tight integration of software with a wide range of hardware
- Compatibility and flexibility with emerging computer and instrumentation technologies

Main Errors of DAQ Systems

- Full-scale sensor error - γ_D
- Analog-to-Digital conversion error (static and dynamic components)
- Calculation Error
- Multiplexers and communication lines between frequency output sensors and computer as rule do not influence on the sensor's output frequency

Static Error

- Reference error
- Trigger error
- Quantization Error

$$\delta_{T\max} = \delta_{Trigger\_error\_\max} + \delta_{0\max} + \delta_{q\max}$$

$$\sigma_T = \sqrt{\sigma^2_{Trigger\_error} + \sigma^2_0 + \sigma^2_q}$$

Quantization Error

Quantization Error is the inherent uncertainty in digitizing an analog (quasi-digital) value due to the finite resolution of the conversion process

- Main error of frequency-to-code conversion
- Strongly dependent on the used conversion method
- Equivalent to error of the method

DAQ Error

$$\sigma_{DAQ} = \sqrt{\sigma^2_{sensor} + \sigma^2_{F/C} + \sigma^2_{Calc}}$$

where $\sigma_{F/C} = \sigma_f$ or $\sigma_{F/C} = \sigma_T$ dependent on the used method of frequency-to-code conversion;

σ_{calc} is the root-mean square calculating error, carry out by a central computer

Data Transmission and Error Protection

The common coding algorithm:

$$f_{xi}(T_{xi}) \rightarrow N_{parallel} \rightarrow N_{serial} \rightarrow N_{cyclic\ code}$$

Taking into account features of chosen correction methods, transmission devices and specificity of system application, the developer of data acquisition system itself should solve, what is the coding algorithm meets by best way to requirements of designed by him systems

Conclusions

- Method with time-division channelling allows creating inexpensive multichannel DAQ systems for quasi-digital sensors
- Method with space-division channelling becomes increasingly attractive due to small cost of frequency-to-code converters
- Accuracy of modern industrial DAQ boards often does not allow to use it together with precision quasi-digital sensors
- Quantization error has essential influence to the DAQ system’s accuracy

Conclusions (cont.)

- It is desirable to have an opportunity to change both accuracy and time of measurement directly during the data acquisition
- Correct choice of a conversion method at creation of DAQ systems for frequency-time domain sensors is one of the main tasks at system design
- Sometimes the data transmission in digital form from sensor to a remote PC demands additional measures for error protection of transmitted data

Classical Frequency-to-Digital Conversion Methods

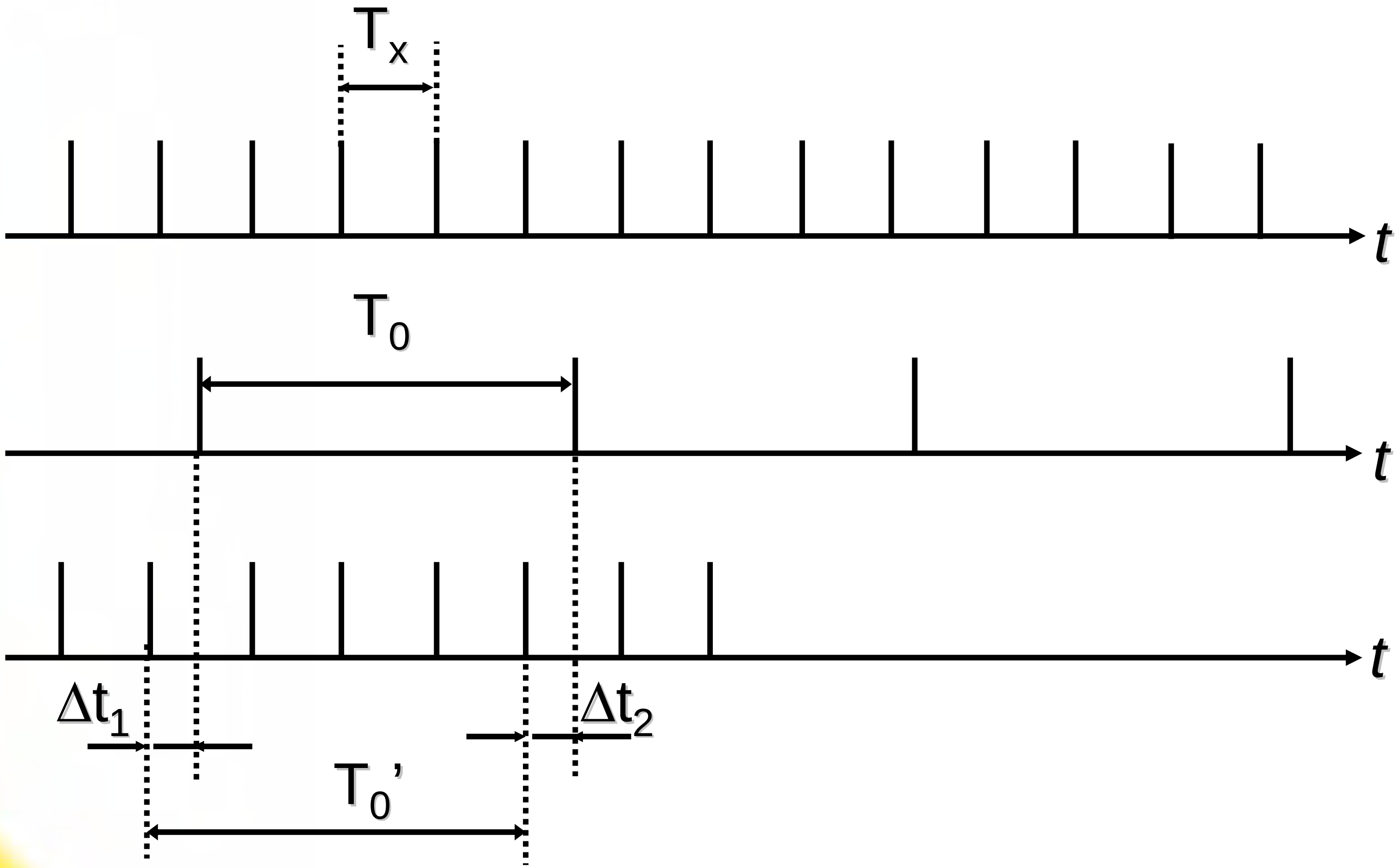
Introduction

- Frequency (period, duty-cycle or time interval)-to-code converter is one of the main parts of quasi-digital smart sensors
- This unit directly influences to metrological characteristics, as accuracy and conversion time as well as on power consumption
- Frequency-to-code conversion is not a trivial task of simple time-window counting
- There are more than 1 000 patents concerning various conversion methods and devices for frequency-time parameters

Conventional Methods

- Standard counting method (measurement of average frequency for a fixed reference gate time, for example, 1 s)
- Indirect counting method (measurement of instantaneous frequency $1/T_x$)
- Combined Method
- Interpolation method (with digital interpolation)

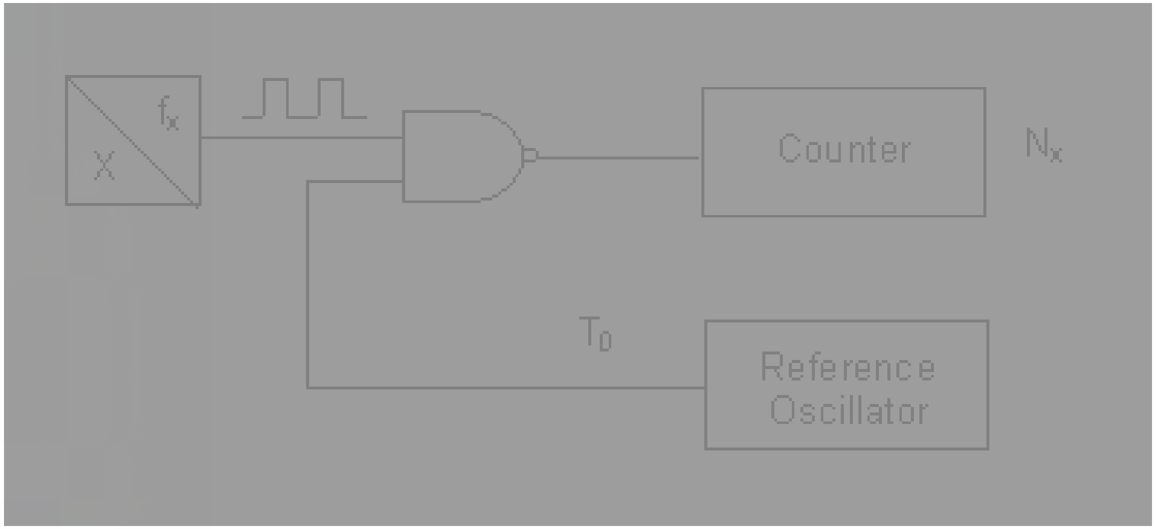
Standard Counting Technique



Frequency Counting Scheme

$$N_x = T_0 / T_x = T_0 f_x$$

$$f_x = N_x \cdot f_0 = \frac{N_x}{T_0}$$



Reason of Quantization Error

Actual time of measurement:

$$T_0' = N_x \cdot T_x = N_x / f_x = T_0 + \Delta t_1 - \Delta t_2$$

Therefore:

$$N_x = T_0 \cdot f_x + (\Delta t_1 - \Delta t_2)/T_x$$

$$T_0 = N_x T_x + \Delta t_1 - \Delta t_2 = N_x T_x + \Delta t = N_x T_x \pm \Delta_q$$

$\Delta t_1, \Delta t_2 \in [0, T_x]$; $\Delta_q = \pm 1$

Δ_q is distributed according to the triangular (Simpson's) distribution law:

$$W(\Delta_q) = \begin{cases} 0 & \text{, at } -1 > \Delta_q > 1 \\ 1 + \Delta_q & \text{, at } -1 \le \Delta_q \le 0 \\ 1 - \Delta_q & \text{, at } 0 \le \Delta_q \le 1 \end{cases}$$

$t << T_{xmin}$

Relative Quantization Error

$$\delta_q = \pm\frac{1}{N_x} = \pm\frac{1}{T_0 \cdot f_x}$$

- synchronization is absent

$$\delta_q = -\frac{1}{T_0 \cdot f_x}$$

- beginning of conversion is synchronized with f_x ($\Delta t_1 = 0$)

$$\delta_q = \pm\frac{1}{2T_0 \cdot f_x}$$

- half-period pulse shift ($\Delta t_1 = T_x/2$)

$$W(\Delta_q) = \begin{cases} 0, \text{at} -0.5 > \Delta_q > 0.5 \\ 1, \text{at} -0.5 \le \Delta_q \le 0.5 \end{cases}$$

- the quantization error is distributed according to the uniform symmetric (unbiased) law

$$M(\Delta_q) = 0;\ D = 1/12;\ \sigma(\Delta_q) = \pm\sqrt{D} = \pm 1/2\sqrt{3}$$

$\tau << T_{xmin}$

Main Error Components

- Frequency reference error δ_{ref}: systematic error, caused by inaccuracy of initial tuning and long-term instability of quartz generator frequency and random error due to the short-term instability [$(1 \div 50) \cdot 10^{-6}$ for non-temperature-compensated crystal oscillator; $10^{-6} \div 10^{-8}$ for oven-controlled crystal oscillator]
- Quantization error δ_q:

$$\Delta_q = \pm T_0 = \pm \frac{1}{f_0}$$

Limits of Error

$$\Delta_{max} = \pm\left(\delta_{ref} f_x + \frac{1}{T_0}\right)$$ - absolute error

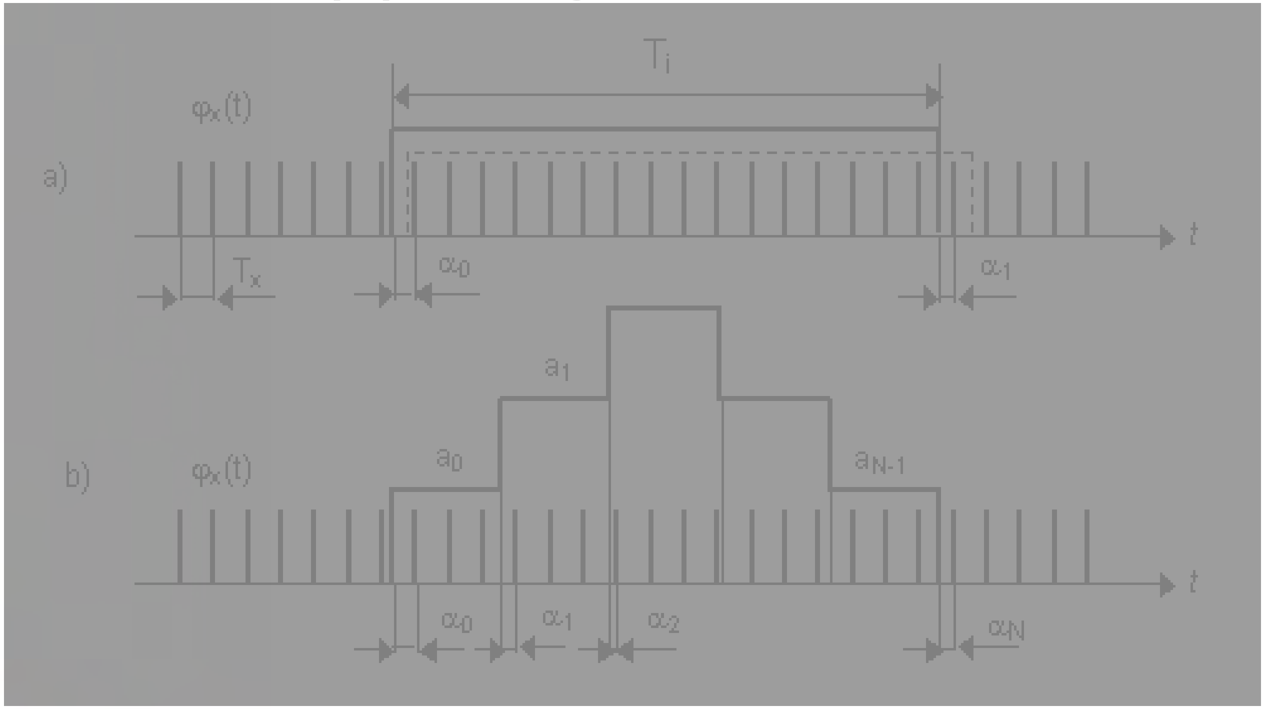
$$\delta_{max} = \pm\left(\delta_{ref} + \frac{1}{f_x \cdot T_0}\right)\cdot 100$$ - relative error, %

Methods of Error Reduction

- Multiplication of converted frequencies f_x in k times and subsequent measurement of frequency $f_x \cdot k$
- Statistical averaging
- Weight functions usage

Weight Functions Examples

Π - Shaped (Dirichlet) (a) and Graded-Triangular (b) Weight Functions:



Weight Functions Advantages

- Quantization Error Reduction. For triangular weight function

$$\delta_q = \frac{4}{T_0^2 \cdot f_x^2}$$

- Industrial noises influence reduction

Weight Functions Usage Restrictions

- Needs additional digital signal processing
- Chip area increasing in case of SoC
- Conversion time increasing
- Dynamic error increasing

Disadvantages of the Method

- High quantization error in low and infralow frequency range
- Quantization error dependents on frequency
- Redundant conversion time

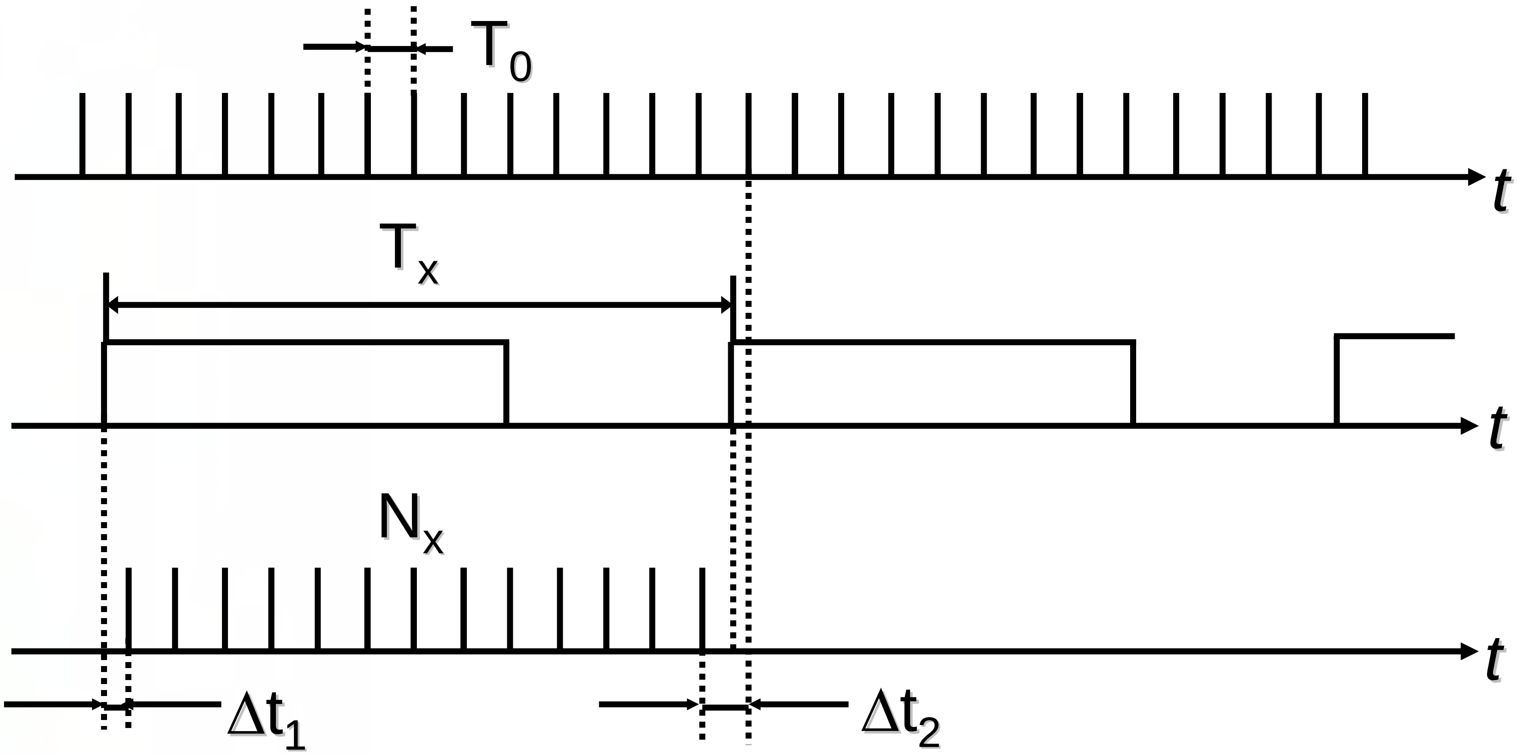
Redundant Conversion Time

Example:

1. Let us convert f_x = 20 kHz with quantization error δ_q = 0.01 %. In this case the conversion time should be chosen T_0= 0.5 s.

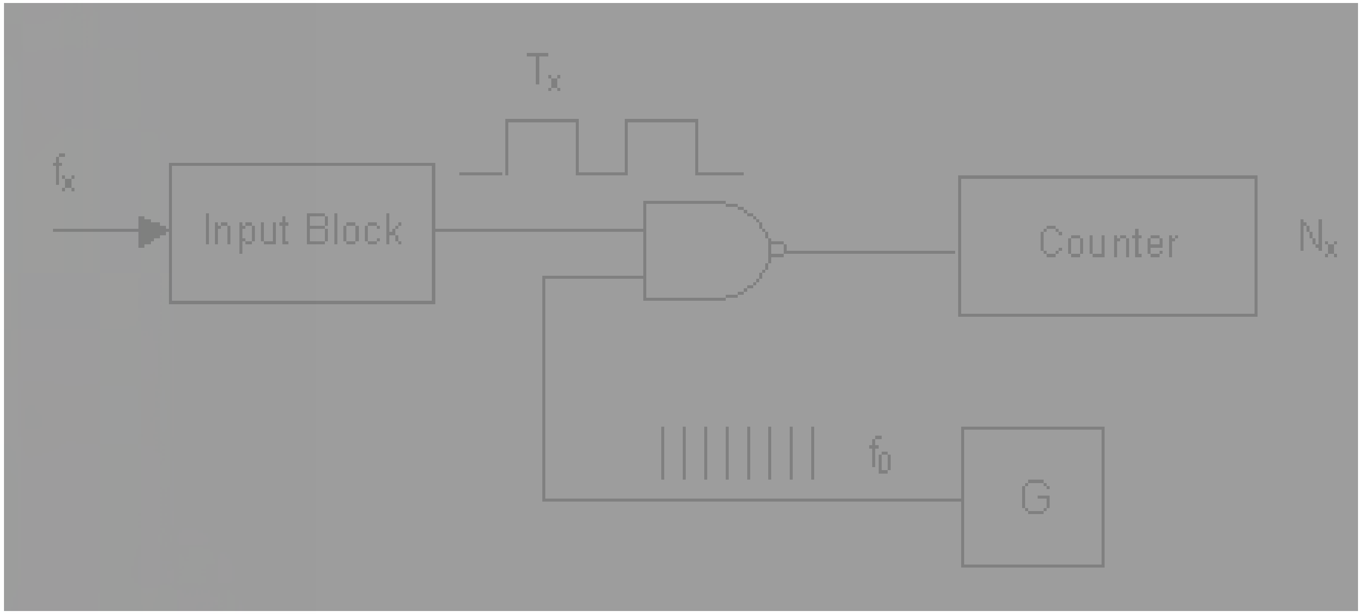
2. Now, let us convert f_x = 40 kHz with the same quantization error. In this case the conversion time can be 0.25 s. But it was already chosen T_0= 0.5 s in this design. Therefore, T_0 is redundant. It will be redundant for all frequencies $f_x > 20$ kHz except the nominal one f_{xnom} = 20 kHz.

Indirect Counting Method



$$N_x = n \cdot T_x / T_0 = n \cdot f_0 / f_x \, , \qquad T_x = N_x \cdot T_0$$

Period Counting Scheme



$$N_{fx} = \frac{1}{N_x}$$

Reason of Quantization Error

$$T_x = (N_x - 1)T_0 + \Delta t_1 + (T_0 - \Delta t_2) = N_x T_0 + \Delta t_1 - \Delta t_2 = N_x T_0 \pm \Delta_q$$

Distribution laws of errors $W(\Delta_{t1})$ and $W(\Delta_{t2})$ are equiprobable and asymmetrical with probability $1/T_0$ and mean:

$$M(\Delta t_1) = 0.5 \cdot T_0, \quad M(\Delta t_2) = -0.5 \cdot T_0$$

Quantization error δ_q is determined by the sum of independent and distributed according to the uniform distribution law random errors Δt_1 and Δt_2. The maximum value of error is $\Delta_{qmax} = \pm T_0$. It is distributed according to the triangular (Simpson's) law $W(\Delta_q)$ with mathematical expectation and dispersion:

$$M(\Delta_q) = M(\Delta t_1) + M(\Delta t_2) = 0 \qquad D(\Delta t_1) = D(\Delta t_2) = D(\Delta t) = \frac{T_0^2}{12}$$

Absolute Quantization Error

Synchronization of reference frequency f_0 with the beginning of converted interval T_x ($\Delta t_1 = 0$):

$$\Delta_{q\max} = \Delta t_2 = T_0;\ M(\Delta_q) = -0.5T_0;\ \sigma(\Delta_q) = \frac{T_0}{\sqrt{3}}.$$

Distribution law is uniform symmetric:

$$W(\Delta_q) = \begin{cases} 0 & \text{at } -0.5T_0 > \Delta_q > 0.5T_0 \\ \dfrac{1}{T} & \text{at } -0.5T_0 \le \Delta_q \le 0.5T_0 \end{cases}$$

Numerical characteristic:

$$M(\Delta_q) = 0;\ \ D = \frac{T_0}{12};\ \ \sigma(\Delta_q) = \pm\sqrt{D} = \pm\frac{T_0}{2\sqrt{3}}$$

Single-Cycle Methods

- Integrator with parallel carry, carrying out the pulse modelling of hyperbolic dependence simultaneously with the quantization of period T_x (or multiple time interval to its duration)
- Decoder based on a read-only memory (ROM), converting the number N_{Tx} proportional to period into the number N_{fx} proportional to frequency

Bicyclic Methods

- Two conversion steps: quantization of *n* periods and further $N_{Tx} \rightarrow N_{fx}$ conversion
- Decreased conversion speed

Main Error Components

- Instability of reference frequency
- Quantization error
- Trigger error due to internal and input signal noises

Trigger errors occur when a time interval of measurement starts or stops too early or too late because of noise on the input signal. There are two sources of this noise: noise on the signal being measured and noise added to this signal by the counter's input circuitry.

Limits of Relative Error

$$\delta_q = \frac{f_x}{n \cdot f_0} \cdot 100$$ - relative quantization error

$$\delta_{max} = \pm\left(\delta_{ref} + \frac{1}{f_0 T_x n} + \frac{\delta_{TriggerError}}{n}\right)$$ - limits of relative error

$$\delta_{TriggerError} = \frac{1.4\sqrt{\left(V_{noise-input}\right)^2 + \left(V_{noise-signal}\right)^2}}{S \cdot T_x},$$ - trigger error

where *S* is the signal slew rate (V/s) at trigger point.

At rectangular pulses with wavefront duration no more than $0.5T_0$ the trigger error is equal to zero. Just such output signals are used in majority of modern frequency output sensors.

Total Error for Time Interval Conversion

$$\delta_{max} = \pm\left(\delta_{ref} + \frac{1}{f_0 T_x} + 2\cdot\delta_{TriggerError} + \delta_{TriggerLevelTimingError}\right)$$

Trigger level timing error results from: the trigger level setting error due to the deviation of actual trigger level from the set (indicated) trigger level and amplifier hysteresis if the input signal have unequal slew rates:

$$\delta_{TriggerLevelTimingError} = \frac{\Delta V_{Level1}}{S_1 \cdot T_x} + \frac{\Delta V_{Level2}}{S_2 \cdot T_x}$$

Usually the inaccuracy of setting levels on the wavefront and tail are accepted equal (*ΔV = 20* ÷ 30 mV).

Conversion Speed

- Determined by the time interval T_x and latency of new measuring cycle
- The last one can be reduced in two times in case of pulse signal or up to zero at the usage of two counters working alternatively
- Conversion time is non-redundant

Disadvantages of the Method

- High quantization error in all frequency range except low and infralow (for example, at conversion of frequency f_x = 10 kHz and reference frequency f_0 = 1 MHz the quantization error will be 1 %)
- Quantization error depends on frequency f_x

Weight Functions

- The term of “*weigh functions*” is known from the general statistics
- Weight functions are used also in ADCs for noise error reduction

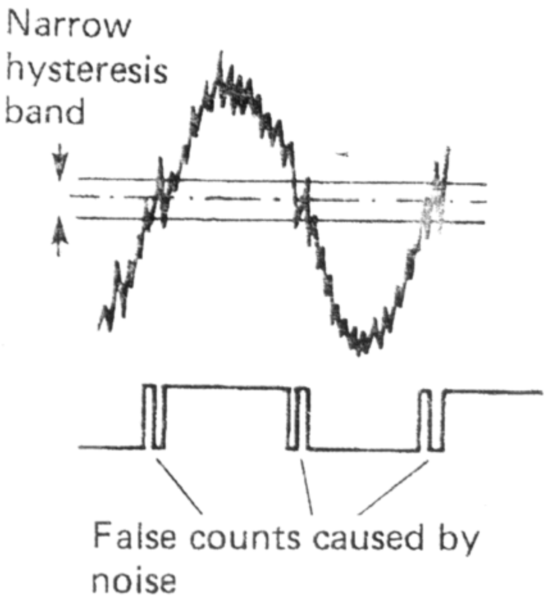
Definition: Weight functions are averaging windows of the finite duration impulse response (FIR) low frequency filter with the bandwidth, tending to zero

Historical Background

- Wight functions also can be used for period and frequency measurements
- First publications – 1976 (period), 1979 (frequency) - (Krasnoyarsk, Russia)
- Two patents (USSR) in 1981 (No. 842694 and No. 892410)
- D.Sc. Thesis, 2001 (Krasnoyarsk, Russia)
- No any publications in English up to 2002

Period Measurement

- Based on the zero-crossing algorithm, which is robust and fast but fails when signals have more than one zero crossing in the period



Dispersion Reduction

- The main task is to reduce the dispersion without increasing of conversion time T_{conv}
- Let there is measuring information about all averaged periods T_i and an estimation is

$$T^* = \sum_{\substack{i=-m \\ i \neq 0}} q_i T_i, \qquad (1)$$

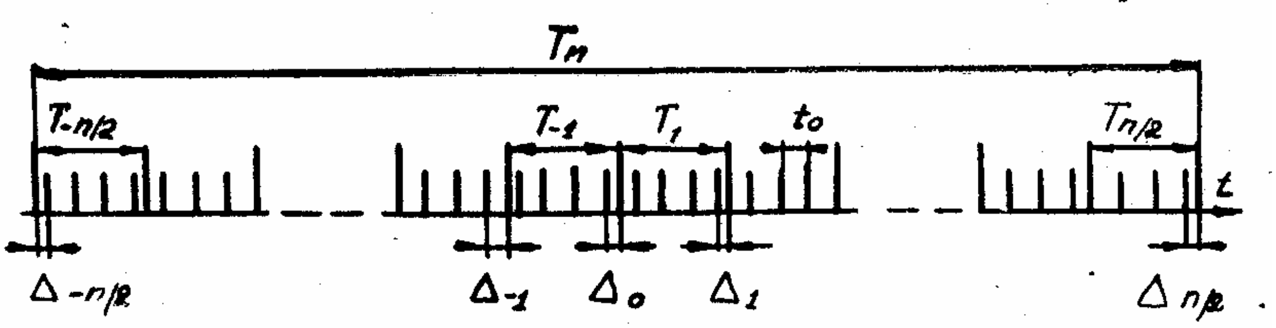
where q_i is weight coefficients of i-th measurement; $m=n/2$

Task Definition

- Task for error minimization is reduced to the weight coefficients optimization q_i giving the minimal dispersium for T^* at the constant conversion time

Method of Measurement

- There is a functional relation between error of beginning of *i-th* period and error of end (i-1) period



Resulting Error

- Taking into account this functional relation, the result error:

$$\Delta T^{*} = \Delta_0 (q_1 - q_{-1}) - \sum_{i=1}^{m-1} \Delta_i (q_i - q_{i+1}) + \sum_{i=-1}^{-m+1} \Delta_i (q_i - q_{i-1}) - \Delta_m q_m + \Delta_{-m} q_{-m}$$

- Dispersion can be calculated according to the common rule:

$$\sigma^2_{T^*} = \frac{\sigma_0^2}{2} \left[(q_1 - q_{-1})^2 + \sum_{i=1}^{m-1} (q_i - q_{i+1})^2 + \sum_{i=-1}^{-m+1} (q_i - q_{i-1})^2 + q_m^2 + q_{-m}^2 \right] \quad (2)$$

Weight Coefficients

- Weight coefficients that can minimize (2) can be determinated by the method of undefined Lagrange's multipliers after determination of the extremum for the following function:

$$\Phi(q_i) = \sigma_{T*}^2 - \lambda \sum_{\substack{i=-m \\ i \neq 0}}^{m} q_i \qquad (3)$$

Weight Coefficients (cont.)

- Taking the differential (3) by q_i and equating the derivative to zero, we shall receive the system of algebraic equations:

$$q_{i-1} = 2q_i - q_{i+1} - \lambda \quad \text{at } i = 2, 3, 4 \ldots m;$$

$$q_{i+1} = 2q_i - q_{i-1} - \lambda \quad \text{at } i = -2, -3, -4 \ldots -m;$$

Weight Coefficients (cont.)

- or, expressing q_i through q_1 and q_{-1} shall receive:

$$q_i = \begin{cases} iq_1 - (i-1)q_{-1} - i(i-1)\lambda / 2 & \textit{at } i > 0 \\ |i|q_{-1} - (|i|-1)q_1 - |i|(|i|-1)\lambda / 2 & \textit{at } i < 0 \end{cases} \qquad (4)$$

Weight Coefficients (cont.)

- For $i=\pm m$ and $i=\pm m\mp 1$ from (4) we shall write the system of equations:

$$q_m = (\lambda + q_{m-1})/2, \qquad q_{m-1} = 2q_m - \lambda,$$

$$q_{-m} = (\lambda + q_{-m+1})/2, \qquad q_{-m+1} = 2q_{-m} - \lambda$$

After its solution in relation to λ we shall receive: $q_1 = q_{-1} = m(m+1)\lambda/2,$ so $q_i = q_{-i}$

Hence, the weigh function must be symmetrical relatively of the middle of conversion time

Weight Coefficients (cont.)

- We shall determine the λ from the unbiased estimate condition of $T^*\left(\sum_i q_i = 1\right)$

and then shall receive the common equation for weight coefficients, that will minimize the dispersion (2):

$$q_i = \alpha_i \Big/ \sum_{i=-m}^{m} \alpha_i = \alpha_i / 4\sum_{i=-m}^{m} i^2,$$

where $\alpha_i = m(m+1) - |i|(|i|-1)$

Algorithm

The denominator can be transformed according to:

$$\sum_{i=1}^{m} i = m(m+1)/2 \quad \text{and} \quad \sum_{i=1}^{m} i^2 = m(m+1)(2m+1)/6$$

Substituting (5) in (1) we shall receive the algorithm for period-to-digital conversion with maximum accuracy:

$$T^* = \sum_{i=-m}^{m} \left[m(m+1) - |i|(|i|-1)\right] T_i \Big/ 4\sum_{i=-m}^{m} i^2 \quad (6)$$

Dispersion

- We shall to calculate the dispersion for estimation (6) according to (2):

$$\sigma_{T*}^{2} = 3\sigma_{0}^{2} / 2m\left(2m^{2} + 3m + 1\right) \qquad (7)$$

At *m >> 1* we can neglect by relatively small values in the denominator, and passing to the *n* shall receive:

$$\sigma_{T*}^{2} \cong 6\sigma_{0}^{2} / n^{3}$$

Results

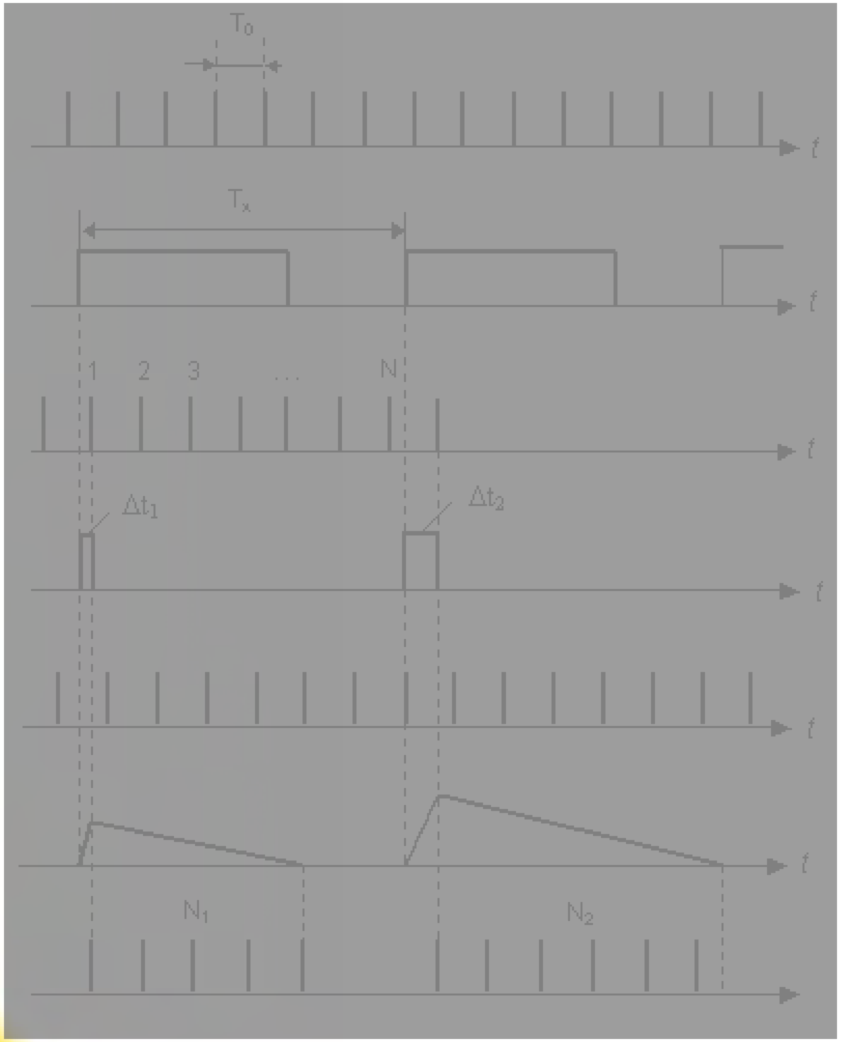
- At measuring time 1 s, f_0 = 10 MHz and T=10^{-6} s:

	Indirect Method	Weigh Functions
Dispersion	$\sigma_{ind}^2 = \sigma_0^2 / n^2$	$\sigma_{T*}^2 \cong 6\sigma_0^2 / n^3$
Mean Root Square	$10^{-7} / \sqrt{6}$	10^{-10}

Features

- An efficiency of weight function based method is higher in more than two orders in comparison with the classical indirect method
- The method lets to reduce the noise component of error as well as the quantization error

Interpolation Method

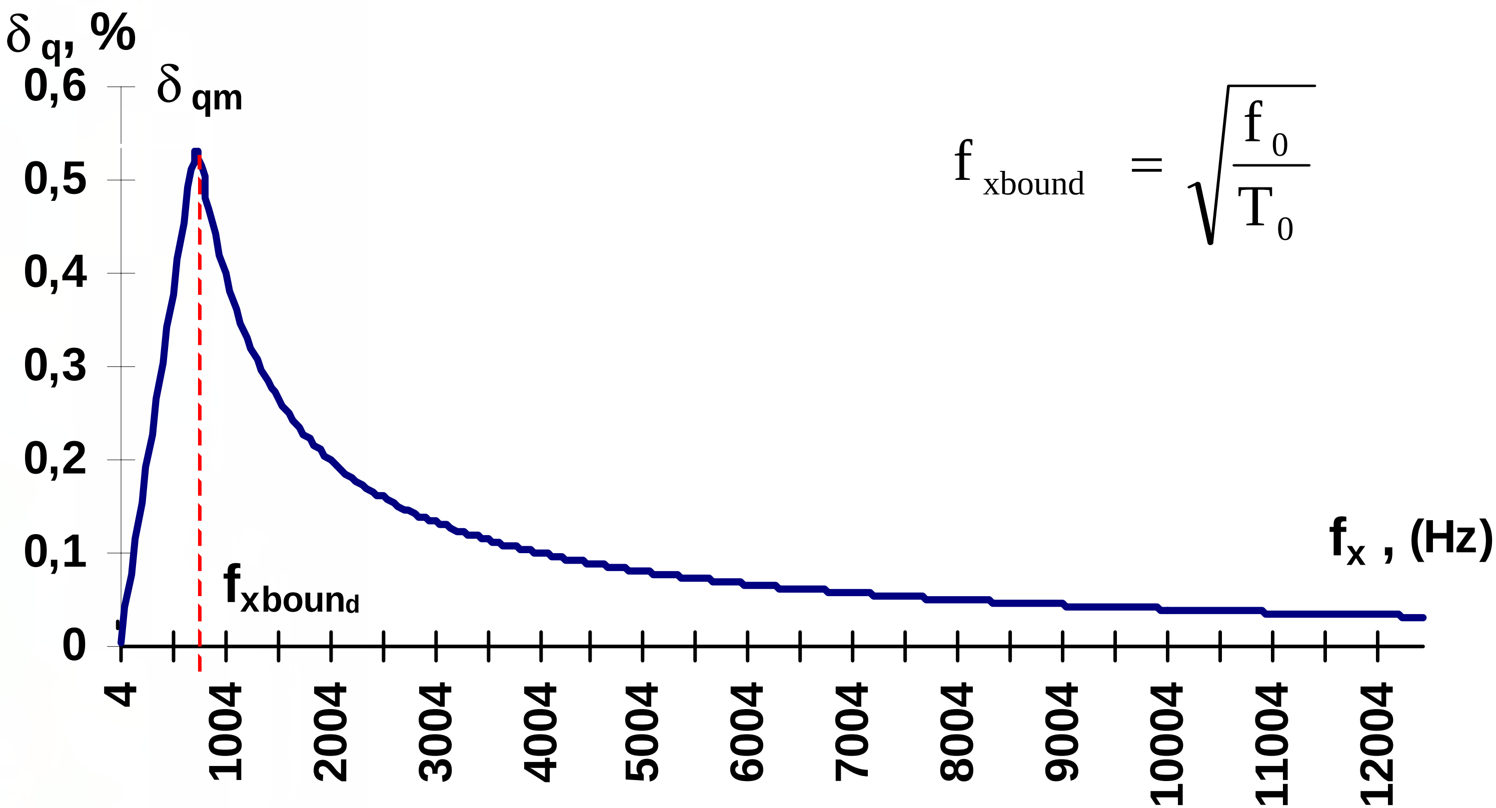


Conversion algorithm

1. During the time interval Δt_1 a capacitor is linearly charged, and then discharged in 1000 times slowly
2. This interval is filled out by the same counting pulses
3. The time interval Δt_2 is measured in the same way.

Absolute quantization error $T_0' = T_0/10^3$

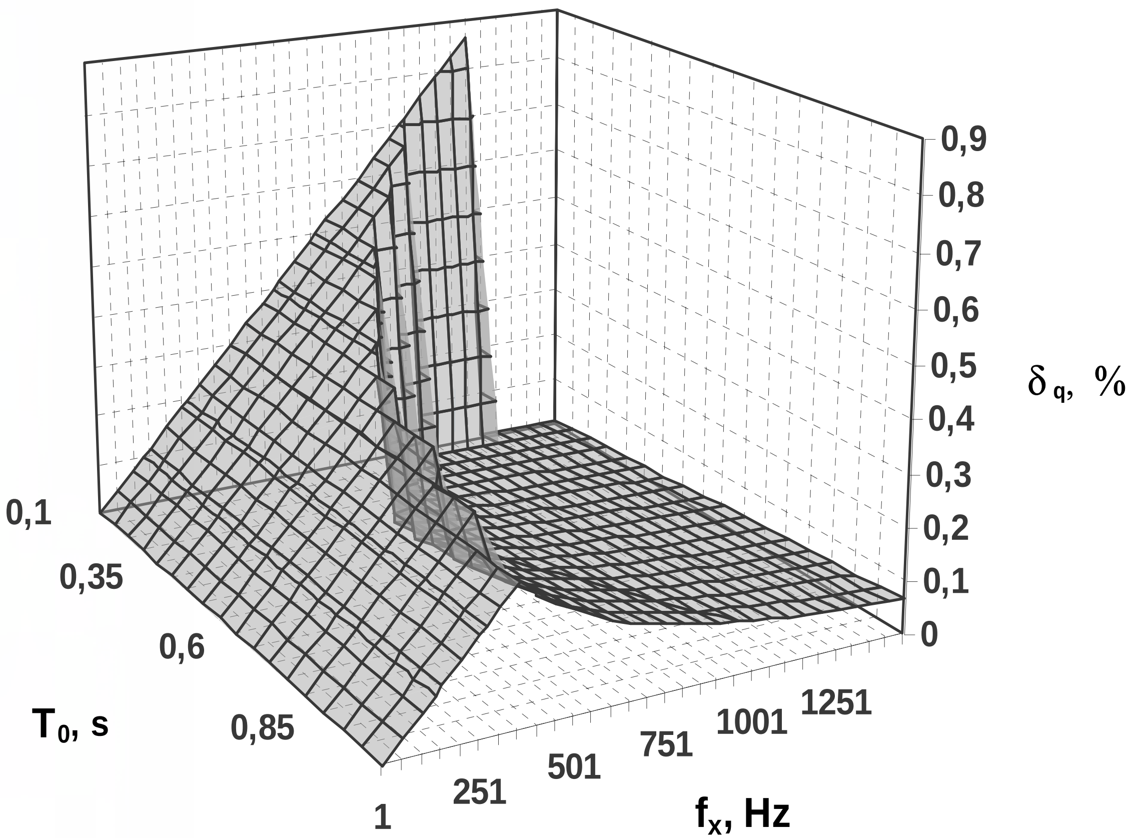
Combined Counting Method



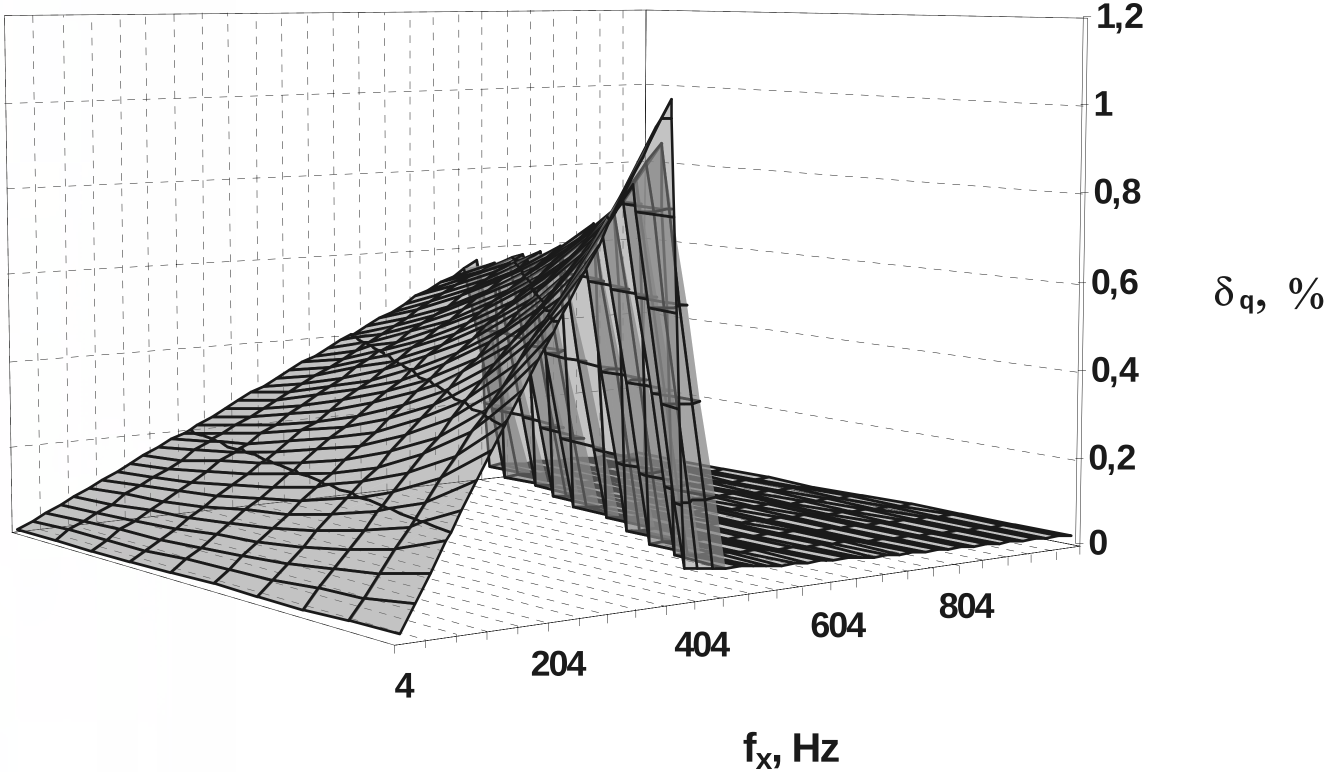
$$f_{xbound} = \sqrt{\frac{f_0}{T_0}}$$

(At f_0 = 133333.33 Hz and T_0 = 0.25 s, n=1)

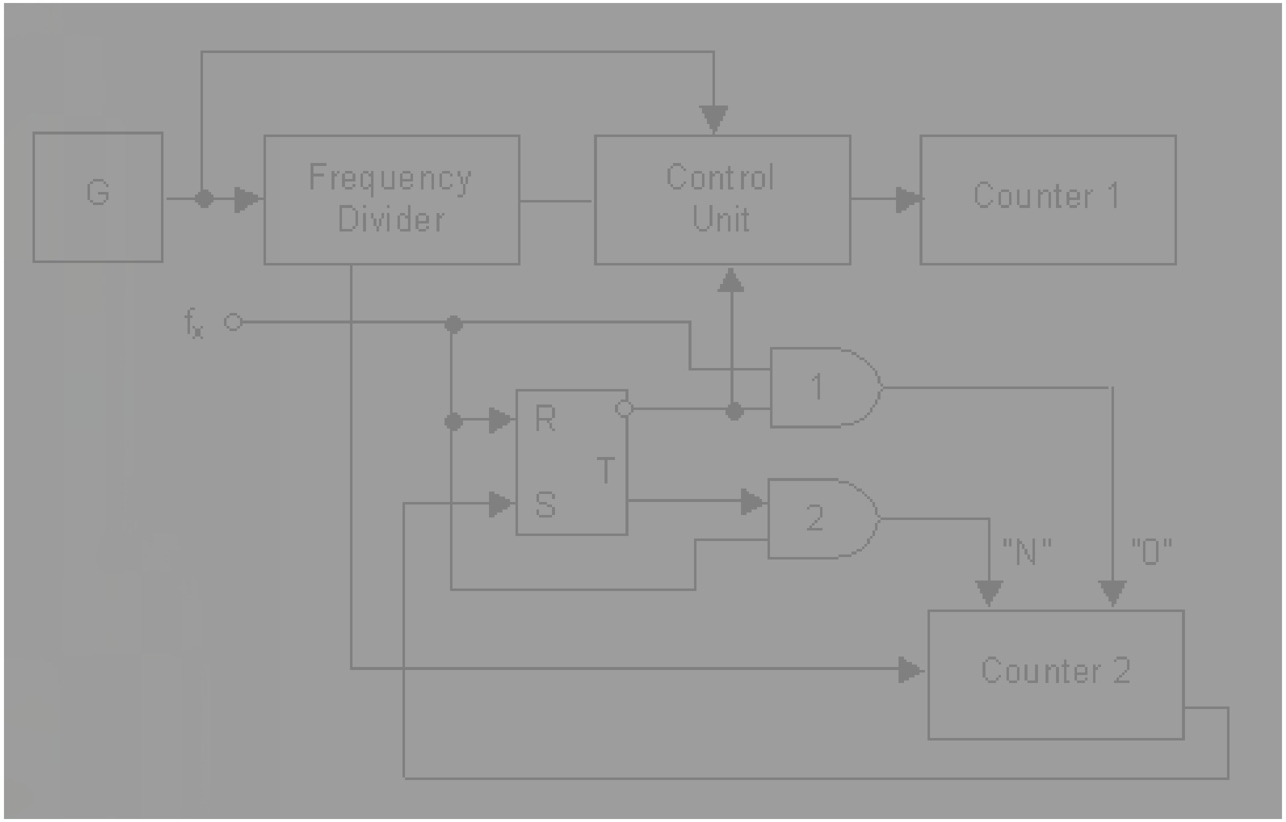
Graph of $\delta_q(f_x, T_0)$



Graph of $\delta_q(f_x, f_0)$



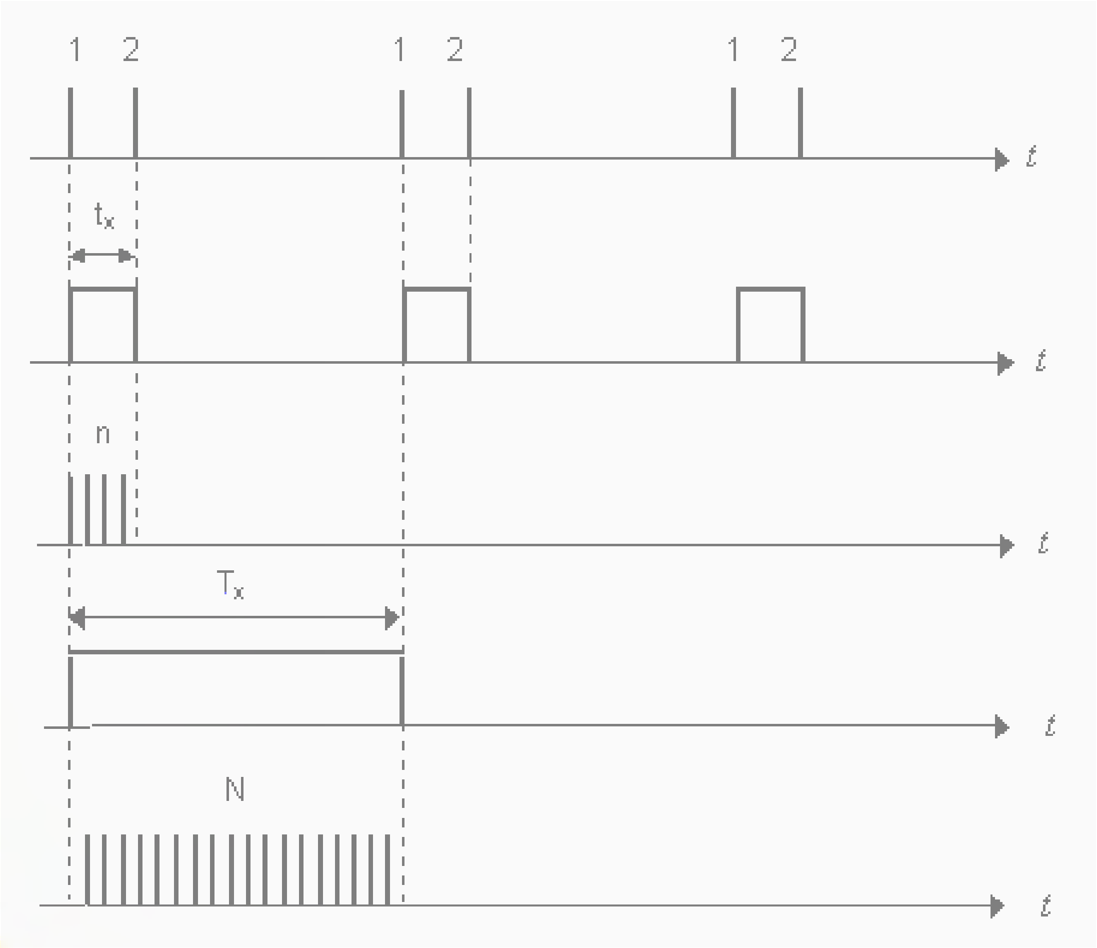
Hardware Realization



Phase Shift-to-Digital Conversion

- Can be reduced to the conversion of time interval t_x on which two periodic sequences of pulses with period T_x are shifted
- Method of average phase shift
- Method of instantaneous phase shift

Method of Instantaneous Phase Shift Measurement



$$n = f_0 \cdot t_x$$

$$N = f_0 \cdot T_x$$

$$\varphi = \frac{360 \cdot n}{N}$$

Components of Total Error

- Noise influence on conversion process
- Quantization error
- Trigger error
- Error caused by difference of form of converted signals from sine wave because of non-linear distortions
- Instrument error caused by non-identical channels

Metrological Performances

$$\sigma_q = \frac{\Delta\varphi_q}{\sqrt{6}}$$

- standard deviation of quantization error distributed according to the Simpson's distribution law

$$f_{x\,max} = \frac{\Delta\varphi_q}{360 \cdot T_0}$$

- maximum possible frequency at given absolute conversion error $\Delta\varphi_q$

Example: At $\Delta\varphi_q$ =0.1^0 and T_0 = 10^{-6} (f_0 = 1 MHz) the greatest possible frequency of converted signal should not exceed than f_{xmax}= 277.77 Hz. The low frequency is not limited.

Measures, Increasing Accuracy

- Interpolation
- Multiplication by f_x of time interval proportional to the converted shift
- Multiplication of reference frequency f_0 by f_x

Conclusions

- Choice of interface and conversion technique depends on the desired resolution and data-acquisition rate
- For maximum data-acquisition rate, indirect counting techniques can be used
- Maximum resolution and accuracy may be obtained using standard counting technique
- Further development of microelectronic technologies, microsystems and smart sensors stimulate perfecting the known and development of new advanced methods of frequency (period)-to-code conversion

Advanced and Self-Adapted Conversion Methods

Introduction

- Precise frequency-to-code conversion with constant quantization error in all frequency range (from 0.01 Hz up to some MHz) and non-redundant conversion time can be realized only based on the novel conversion methods
- There are some different design approaches

How to Improve Performances ?

- Technological methods
- Structural methods
- Structural-algorithmic methods

Technological Methods

- Means the technology perfection
- Received prevalence in the USA, Japan and Western Europe Countries
- Expensive

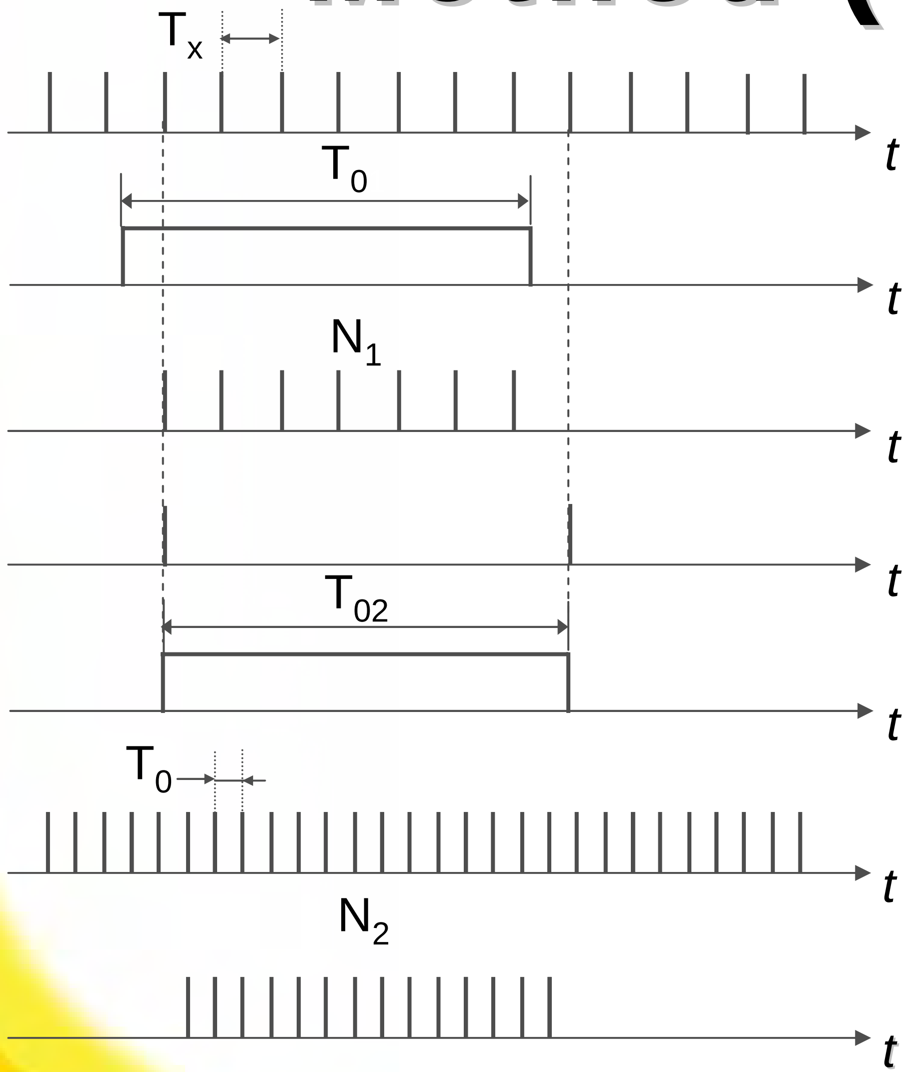
Structural and Structural-Algorithmic Methods

- Implementation of particular structures
- Structures are designed in most cases in heuristic way
- Use advanced calculations, algorithms and signal processing
- Broad development in the former USSR and continue developing in NIS countries

Advanced Methods

- Ratiometric Counting Method
- Reciprocal Counting Method
- M/T Counting Method
- Constant Elapsed Time (CET) Method
- Single- and Double Buffered Methods
- DMA Transfer Method
- Method of Dependent Count (MDC)
- Method with Non-redundant Reference Frequency

Ratiometric Counting Method (70's)



$$T_{02} = N_1 \cdot T_x$$

$$N_2 = N_1 \cdot T_x / T_0 = N_1 \cdot f_0 / f_x$$

$$f_x = \frac{N_1}{N_2} \cdot f_0$$

$$T_x = \frac{N_2}{N_1} \cdot T_0$$

Quantization Error

Maximum absolute error: $\Delta_2 = \pm T_0$

Maximum relative error: $\delta_2 = \pm \frac{T_0}{T_{02}} = \pm \frac{T_0}{N_1 \cdot T_x}$

$$N_1 T_x = T_{02} \rightarrow f_x = N_1 / T_{02}$$

$$\delta_q = \delta_2$$

According to the standard direct counting method:

$T_{01} = N_1 / f_x'$ $\quad$ $f_x' / N_1 = 1/T_{01},$

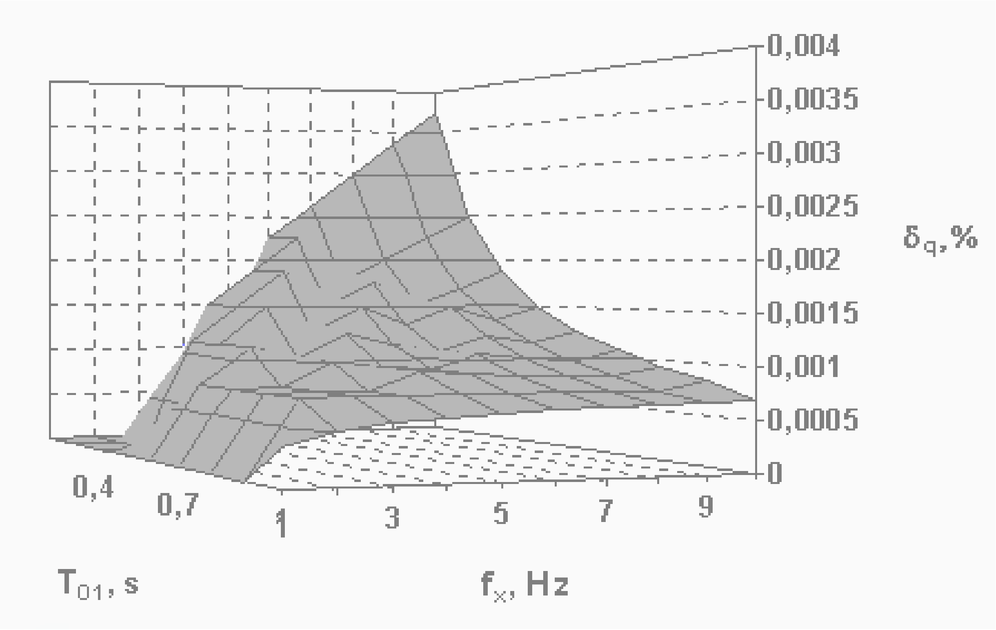
$$\delta_q = \pm \frac{T_0}{T_{01}} = \pm \frac{1}{f_0 \cdot T_{01}}$$

Refined Mathematical Model

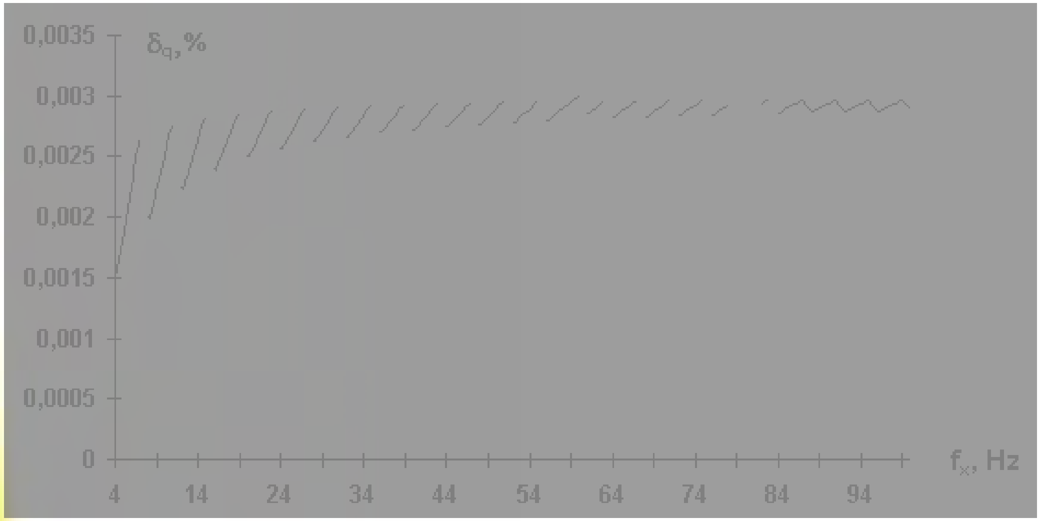
$$N_2 = \mathrm{ent}\left\{\frac{N_1 \cdot T_x}{T_0}\right\}$$

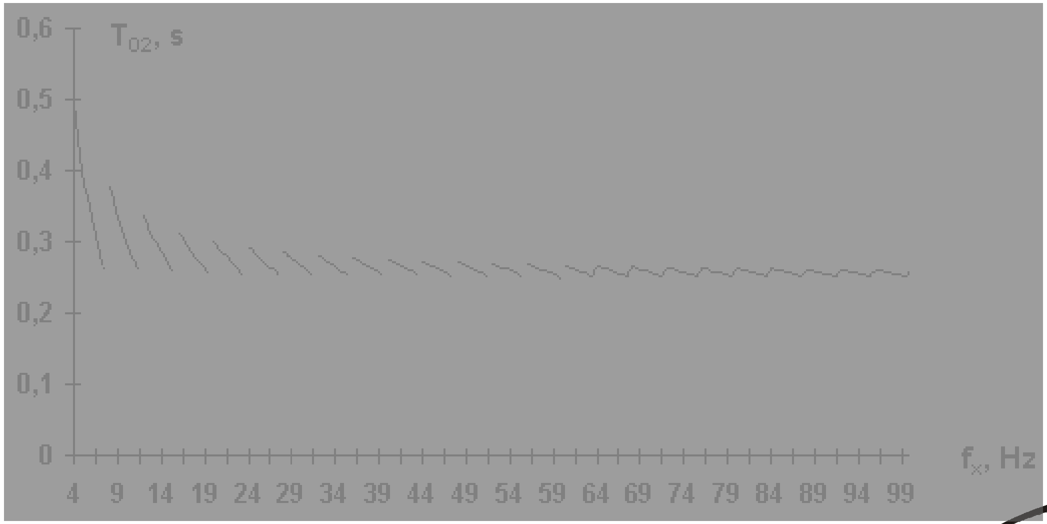
$$\delta_q = \pm\frac{f_x}{(N_1+1)\cdot f_o} = \pm\frac{T_0}{T_{01}} = \pm\frac{1}{N_2}$$

Modeling Results:

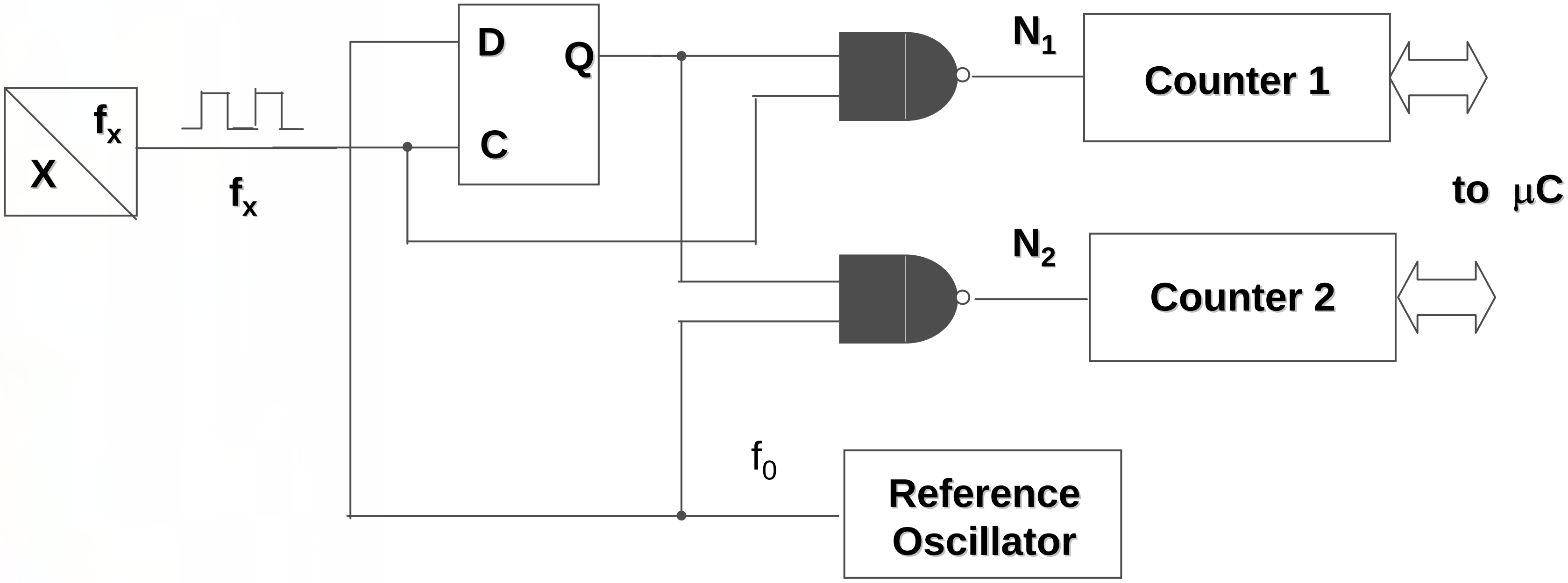


Modeling Results

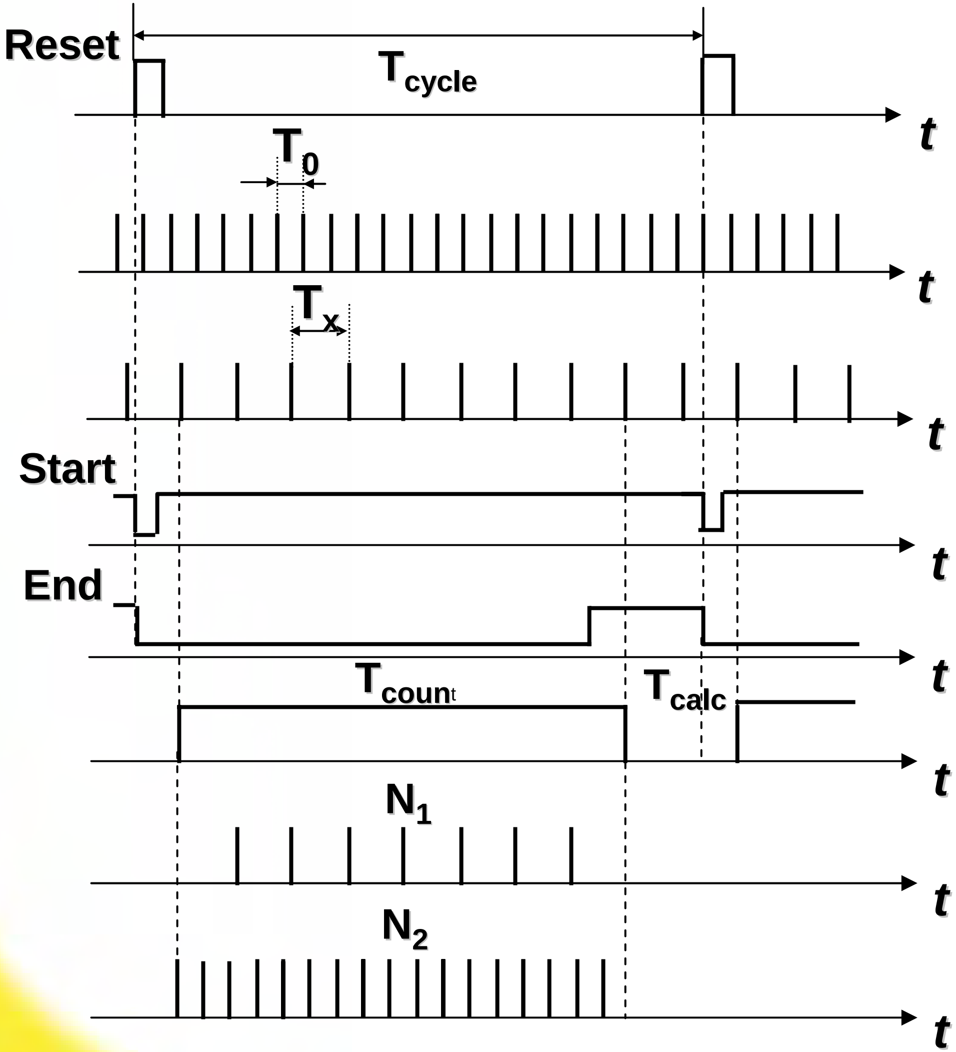




Simplified Diagram



Reciprocal Counting Method (70's)



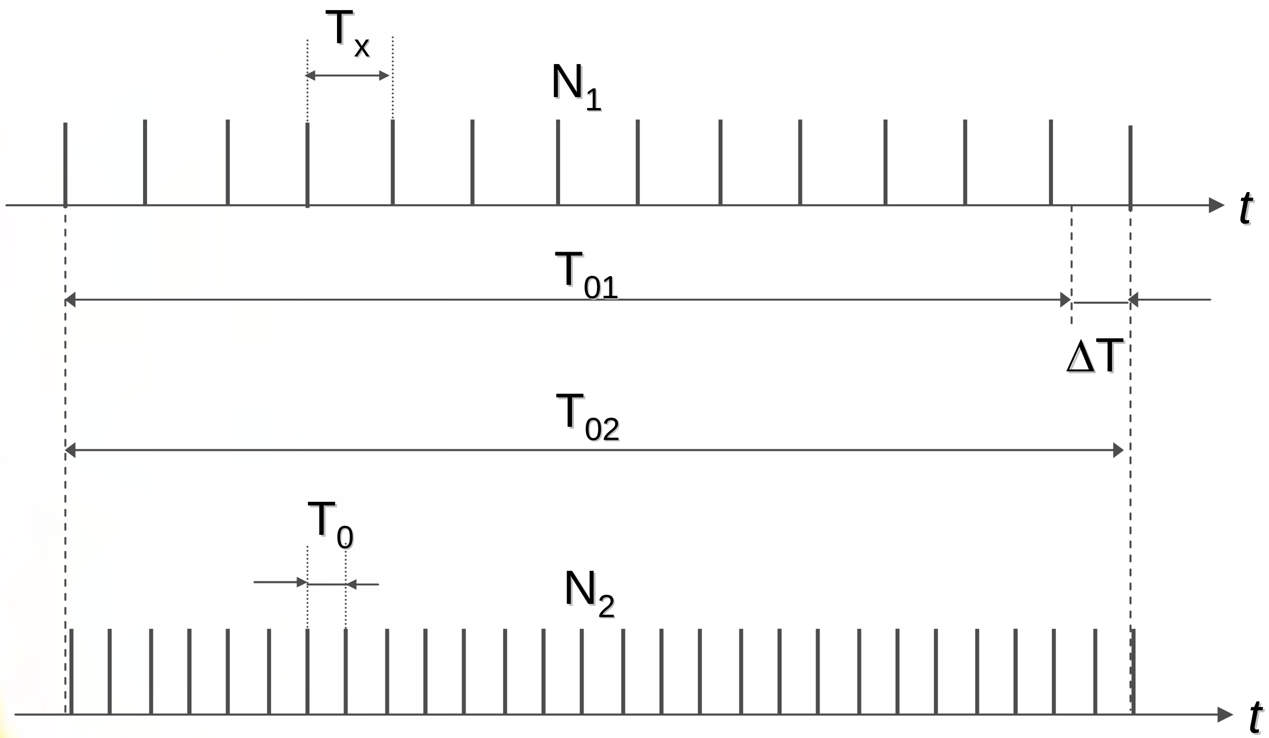
$$f_x = \frac{N_1}{N_2} \cdot f_0$$

$$T_x = \frac{N_2}{N_1} \cdot T_0$$

$$\delta_q = \pm \frac{1}{f_0 \cdot T_{count}}$$

Main demerit of both ratiometric and reciprocal methods is redundant conversion time.

M / T Counting Method (1982)



$$f_x = \frac{N_1}{N_2} \cdot f_0$$

$$T_x = \frac{N_2}{N_1} \cdot T_0$$

$$T_{02} = T_{01} + \Delta T$$

$$Q_N = f_0 \cdot N_1 \left(\frac{1}{N_2 - 1} - \frac{1}{N_2} \right) = \frac{f_0 \cdot N_1}{N_2 (N_2 - 1)}$$

Benefit and Demerits

Advantage:

Constant quantization error in all specified conversion range of frequencies

Disadvantages:

- Redundant conversion time due to prescribed conversion time
- Three hardware counters
- Two references (frequency and gate time)

Constant Elapsed Time (CET) Method

- Method was proposed in 1989
- It is very similar to the M/T counting method
- Uses two software timers and two hardware timer/counters
- Time counter is running continuously
- Redundant conversion time due to constant elapsed time
- Minimum converted frequency is limited by the maximum response time; maximum – by the sum of interrupt response time

Single and Double Buffered Methods

- Methods were proposed in 1991
- The same hardware as in the CET method
- Limited minimum frequency
- Redundant conversion time due to the prescribed conversion time
- Maximum converted frequency is limited by the software loop (for SB method)
- The higher error limit is twice as much as than the error limit of the M/T and CET methods

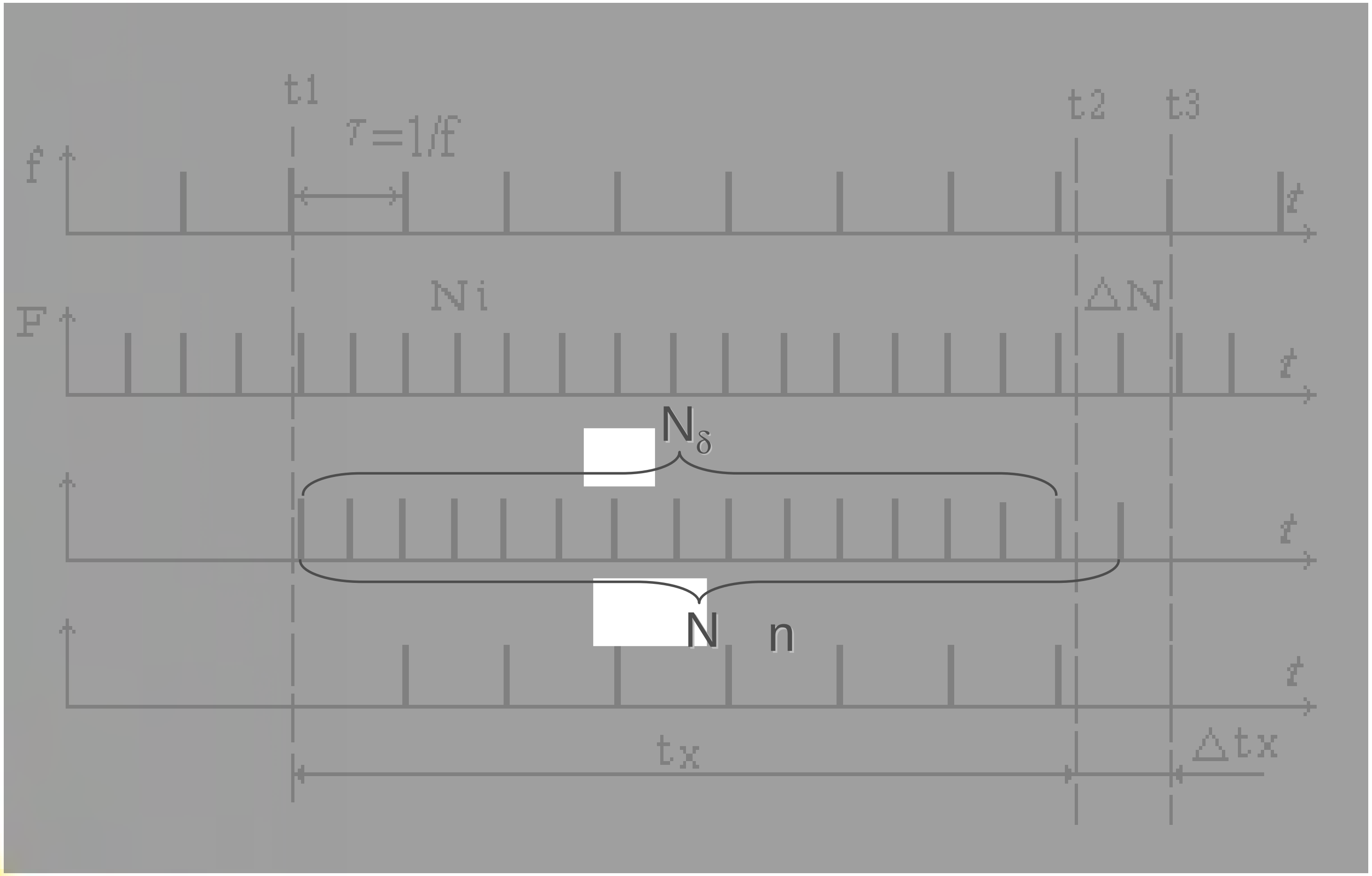
DMA Transfer Method

- Method was proposed in 1993
- Needs DMA integrated controller
- Maximum error is greater than the error of the all advanced conversion methods (some times more than 10 times greater)
- Redundant conversion time due to the constant sampling time

Method of Dependent Count (MDC)

- Method was proposed in 1980 (modifications: 1993 and 2006)
- Most advanced method: constant programmable quantization error in all frequency range; non-redundant conversion time; the possibility to convert frequency f_x higher, than the reference frequency f_0 ($f_x >> f_0$); self-adaptation capabilities
- The method has been developed for conversion of absolute, relative frequencies and periods
- Suitable for single channel as well as for multichannel synchronous frequency conversions

MDC Time Diagrams



Main Equations

$N = N_\delta + \Delta N$ is the number of pulses of higher frequency F

Conversion time:

$$t_x = \tau \cdot n = \frac{n}{f} = T \cdot N = \frac{N}{F} = \frac{N_\delta + \Delta N}{F} = \left(\frac{1}{\delta} + \Delta N\right) \cdot T$$

$$f_x = f_0 \cdot \frac{n}{N}$$ or $$f_x = f_0 \cdot \frac{N}{n}$$

$$\tau = \frac{N}{f_0 \cdot n}$$ or $$T = \frac{n}{f_0 \cdot N}$$

Quantization Error

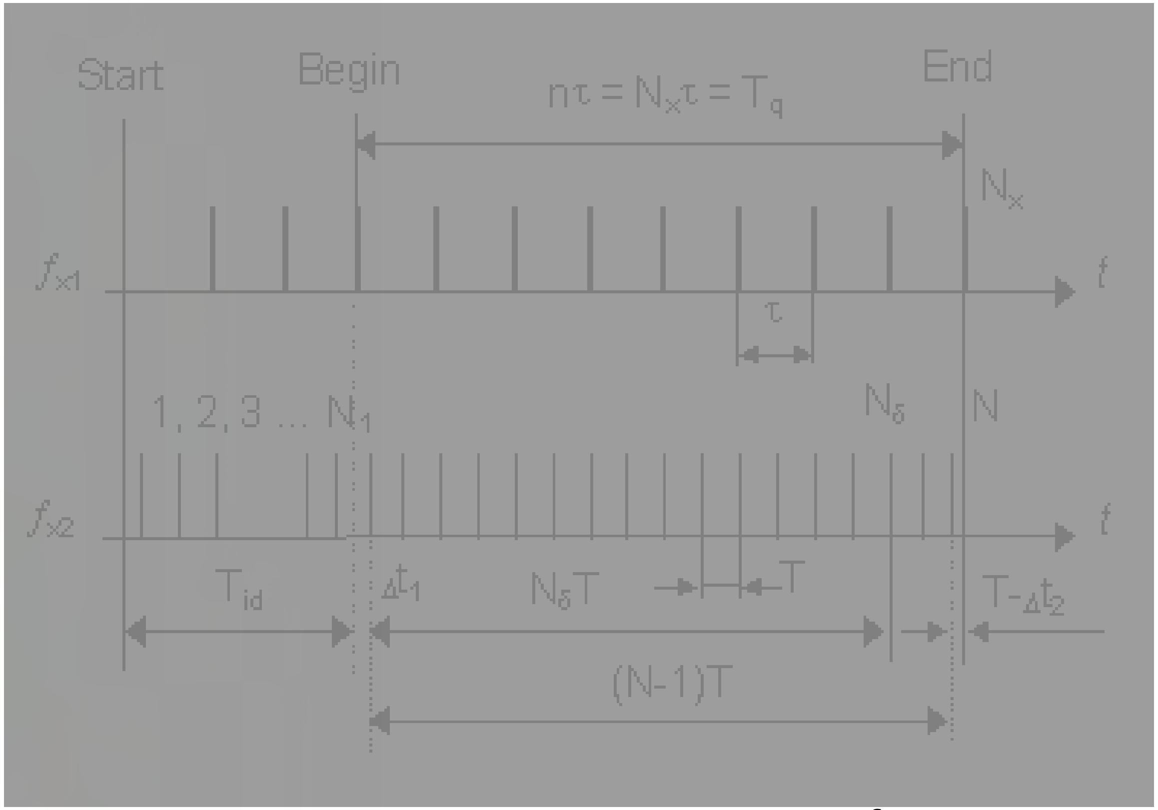
$$t_x \neq N \cdot T \neq N/F$$

$$\Delta N_{max} = \frac{\tau}{T} = \frac{F}{f}$$

$$\delta_{max} = \frac{1}{N_{min}} = \frac{1}{N_{\delta}}$$

$$\delta_{min} = \frac{1}{N_{max}} = \frac{1}{N_{\delta} + \Delta N_{max}}$$

Conversion Methods for Relative Values



$$\frac{f}{F} = \frac{n}{N} = \frac{N_x}{N_\delta + \Delta N}$$

or

$$\frac{\tau}{T} = \frac{N_\delta + \Delta N}{N_x}$$

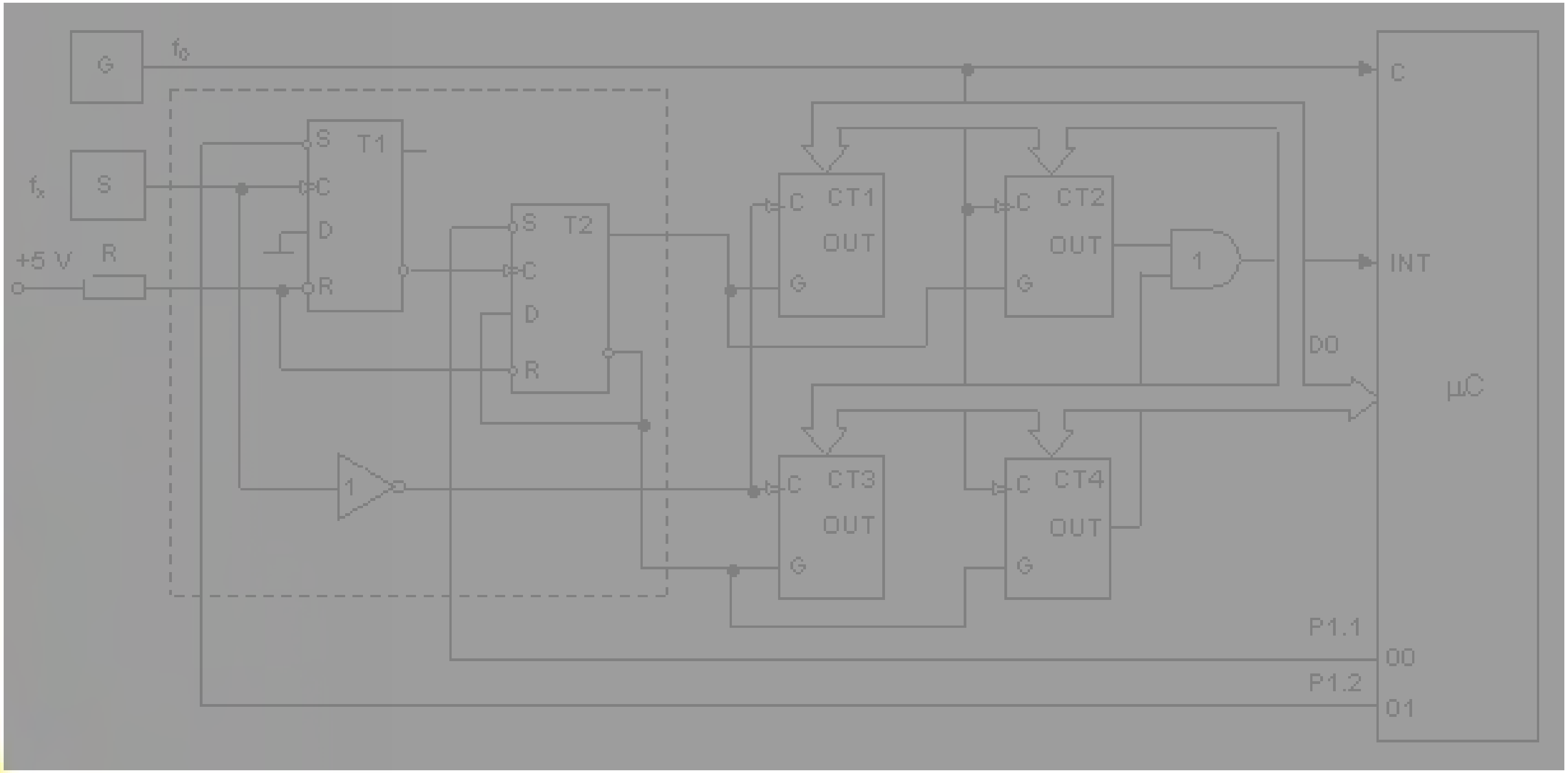
$$\frac{f_{x1}}{f_{x2}} = \frac{N_{x1}}{N_{x2} + \Delta N_2}$$ if $f_{x1} \leq f_{x2}$

$$\frac{f_{x2}}{f_{x1}} = \frac{N_{x2}}{N_{x1} + \Delta N_1}$$ if $f_{x2} \leq f_{x1}$

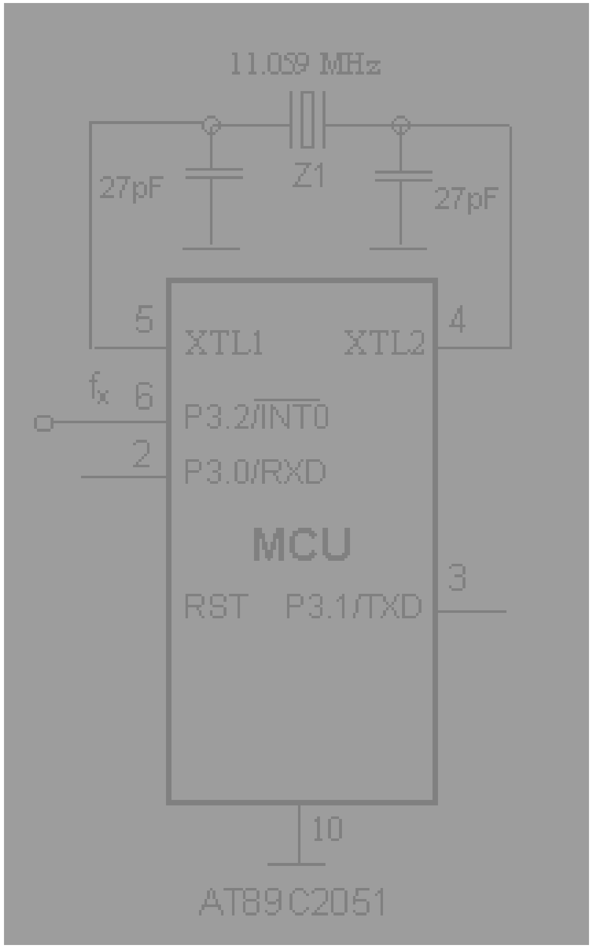
Realizations

- Hardware (integrated circuits, FPGA, PLD): maximum possible f_{xmax}
- Software (one-chip microcontrollers, ASIP): minimum possible hardware, unlimited $f_{xmin)}$
- Software-Hardware (one-chip microcontroller + high speed external counters or timer/counters)
- Any of these realization can be implemented like IC, ASIC or hybrid circuit

Hardware Realization



Software Realization



MDC Advantages

- Non-redundant Conversion Time
- A possibility to measure frequency $f_x >> f_0$
- Constant Quantization Error
- High Accuracy
- Only one reference: frequency base
- Self-adaptation Capabilities

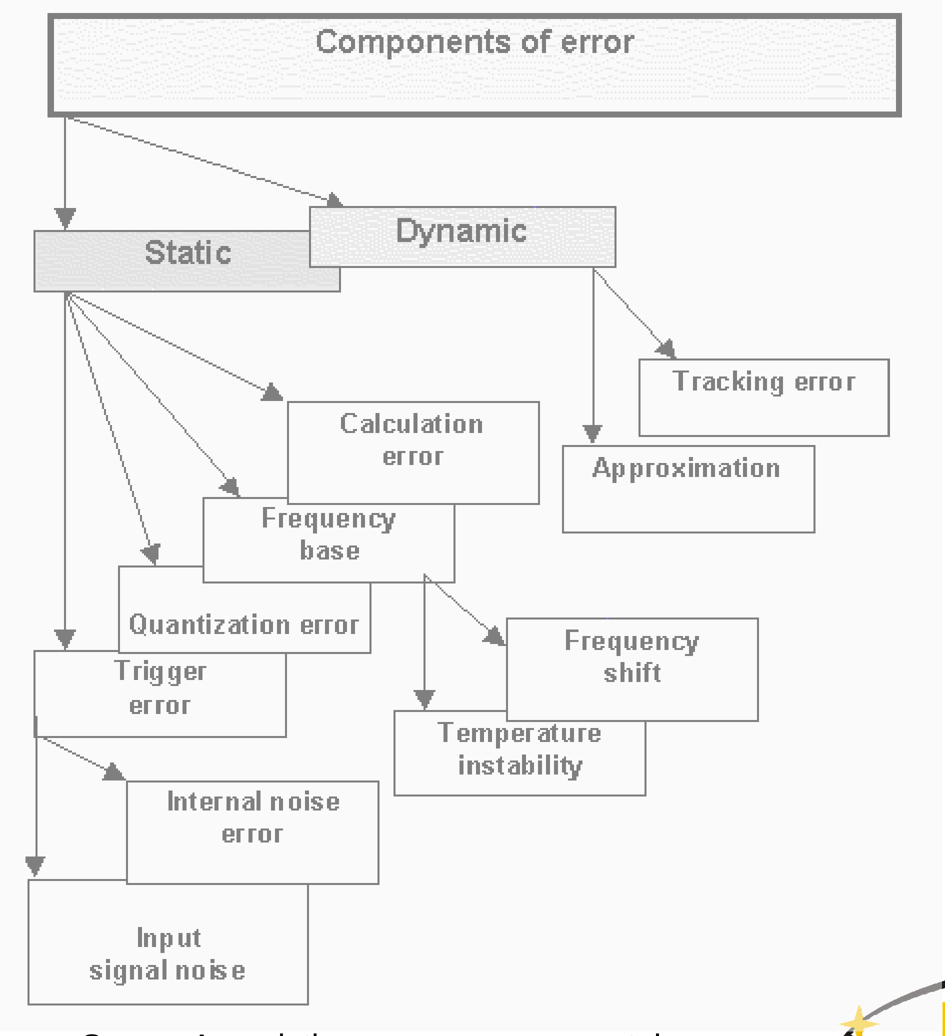
Main Components of FDC's Error

Calculation Error:

$$\delta_{\text{Calculation max}} << \delta_{\min}$$

Quantization Error:

$$\delta_{q\,max} = \frac{1}{N_\delta} = \delta$$



Frequency Base Error

Reference - A stable source for a physical quantity, such as voltage, frequency, etc. used in a measuring device to maintain measurement stability and repeatability

- Long-term instability. Depends on the systematic deviations of the frequency f_0 stipulated by the time drift ($10^{-9} \div 10^{-11}$ per day)
- Short-term instability. Depends on the frequency fluctuation because of temperature drifts ($10^{-7} \div 10^{-9}$, uniform distribution low

Error Reduction

- Systematic error can be reduced by correction up to the random level
- Random error can be reduced by the usage of temperature control and temperature compensation
- Usage of external generators with more stable reference frequency

Trigger Error (pulse signal)

$$\delta_{TriggerError} \approx \pm \frac{100 \cdot \Delta}{N_x S \cdot T_x} \%$$

where Δ is the set trigger level drift; S is the wavefront steepness

The error $\delta_{TriggerError}$ can also be neglected at the measuring frequency f_x of pulses with steep wavefronts

Dynamic Error

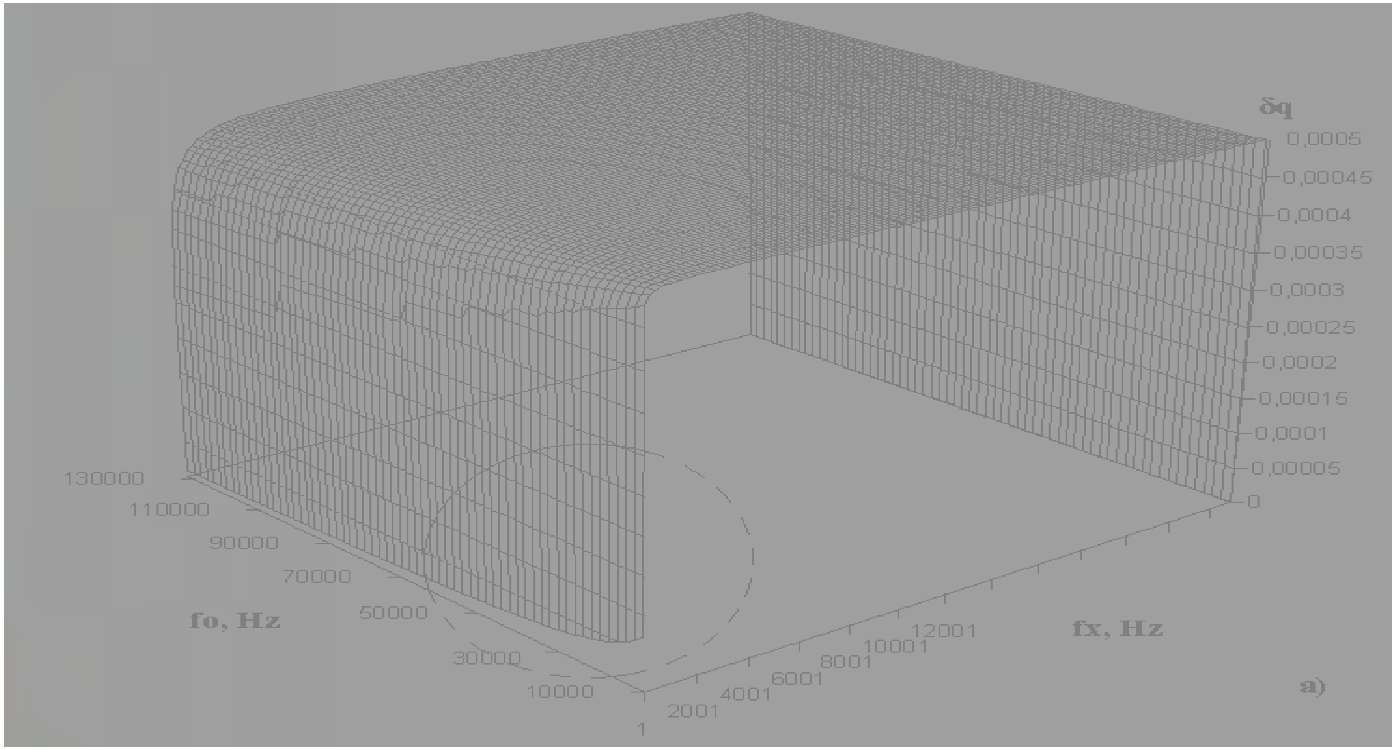
- Depends on dynamic properties of the researched process and speed of conversion method
- Tracking error. Depends on the conversion time T_q
- Approximation error. Determined by the digitisation interval and a kind of approximation

Dynamic Error (cont.)

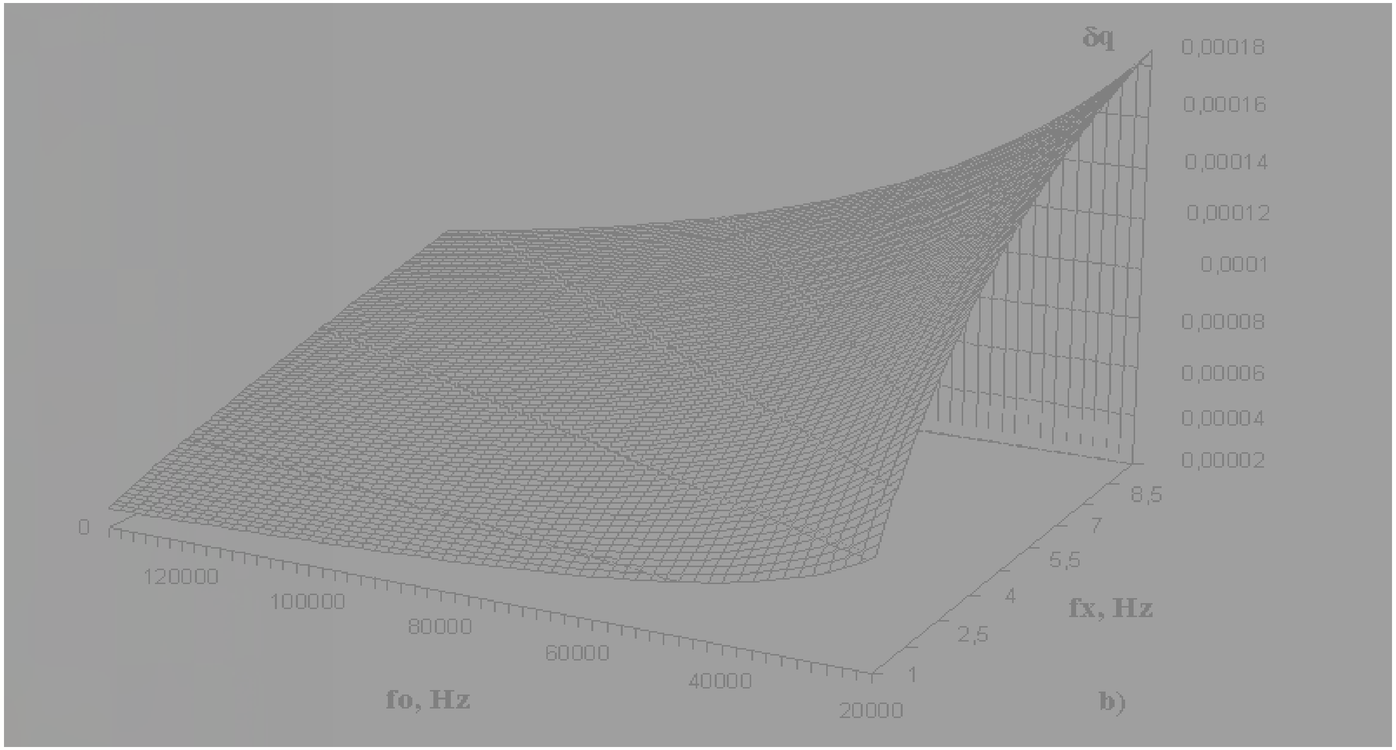
- Depends on dynamic properties of the researched process and speed of conversion method
- Conversion time T_q minimisation
- The usage of algorithms, eliminating latency time of the next conversion cycle

The dynamic error should not exceed the static error.

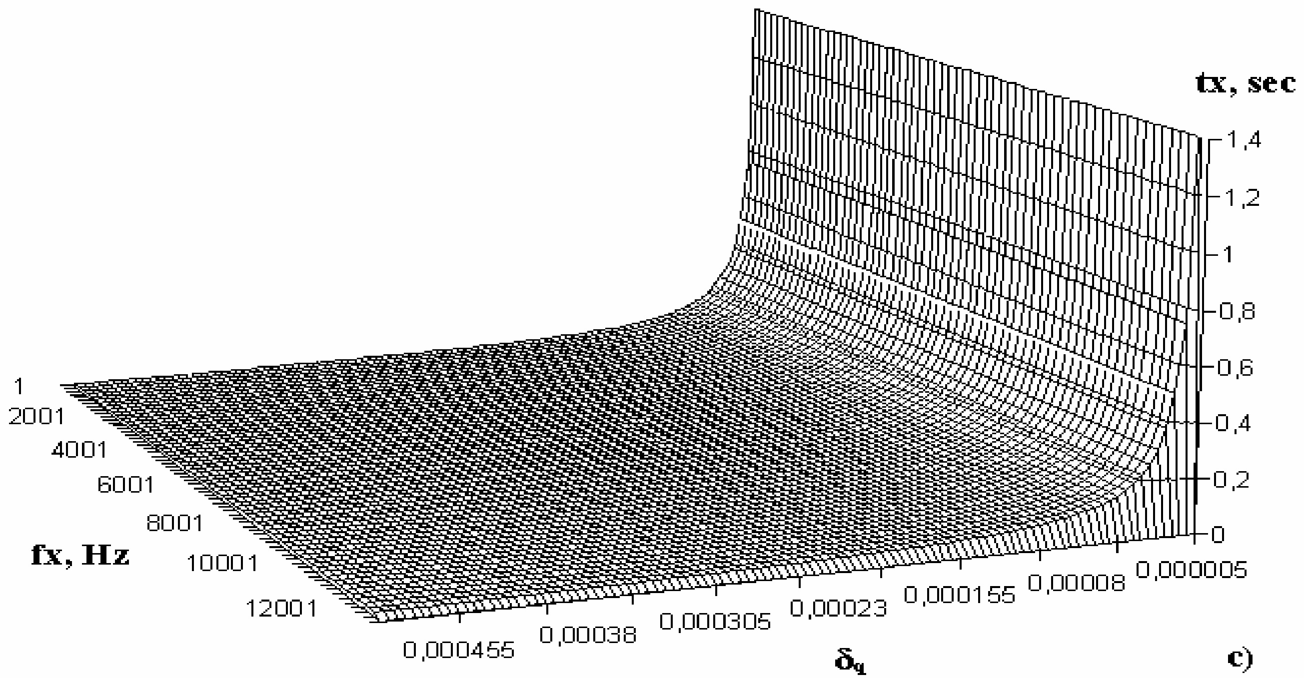
Simulation Results (I)



Simulation Results (II)



Simulation Results (III)



Conversion Time

$$t_x = \frac{N_\delta + \frac{f_0}{f_x}}{f_0} \quad \text{at } f_x \le f_0 \qquad\qquad t_x = \frac{N_\delta + \frac{f_x}{f_0}}{f_x} \quad \text{at } f_x > f_0$$

Initial ranges:

$f_x \in [0.1 \div 10\ 000\ 000]$ Hz;

$f_0 \in [100\ 000 \div 1\ 000\ 000]$ Hz;

$N_\delta \in [1\ 000 \div 10\ 000\ 000]$ (0.1 up to 10^{-7} %);

$\Delta N \in [0 \div \Delta N_{max}]$

Conversion Time (cont.)

- The conversion time t_x essentially depends on the reference frequency only in the area of infralow frequencies. This opens a prospect for the adaptive control of reference frequency during the conversion that results in reduction of power consumption in smart sensors
- The conversion time is non-redundant and can be changed during measurements according to the required accuracy of conversion (quantization error)

Example 1

Let us consider that it is necessary to convert the frequency f_x=2·10^4 Hz at f_0=10^6 Hz and N_δ=10^6 (δ=10^{-4}%):

$$t_x = \frac{10^6 + \dfrac{10^6}{2\cdot 10^4}}{10^6} \approx 1\text{s}$$

- for the method of dependent count

$$t_x = \frac{1}{\delta \cdot f_x} = \frac{N_\delta}{f_x} = \frac{10^6}{2\cdot 10^4} = 50\text{s}$$

- for the standard counting method

$$N_T = \frac{f_x}{f_0 \cdot \delta} = \frac{f_x \cdot N_\delta}{f_0} = \frac{2\cdot 10^4 \cdot 10^6}{10^6} = 2\cdot 10^4$$

$$t_x = N_T \cdot T_x = \frac{2\cdot 10^4}{10^4} = 2\text{s}$$

- for the indirect counting method

Coefficient of Variation for Error

$$\alpha = \delta_{q\,max} / \delta_{q\,min}$$

$$\delta_{max} = \frac{1}{N_{min}} = \frac{1}{N_{\delta}}$$

$$\delta_{min} = \frac{1}{N_{max}} = \frac{1}{N_{\delta} + \Delta N_{max}}$$

$$\alpha = \frac{N_{\delta} + \Delta N_{max}}{N_{\delta}} = 1 + \frac{1}{N_{\delta}} \cdot \frac{F}{f}$$

$$\alpha_1 = 1 + \frac{1}{N_{\delta}} \cdot \frac{f_0}{f_x} \quad \text{- at } f_x < f_0$$

$$\alpha_2 = 1 + \frac{1}{N_{\delta}} \cdot \frac{f_x}{f_0} \quad \text{- at } f_x > f_0$$

Example 2

Let's determine, in how many times the quantization error will be varied at measuring frequency f_x = 2 Hz, if f_0 = 10^6 Hz and $N_\delta = 10^6$ ($\delta = 10^{-6} \cdot 100\ \% = 0.0001\ \%$)

$$\alpha_1 = 1 + \frac{1}{10^6} \cdot \frac{10^6}{2} = 1.5$$

- for the method of dependent count

Using the standard direct counting method or the indirect method measuring period, the variation of the quantization error will be 500 000

Methods with Non-Redundant Reference Frequency (1998)

The dynamic average power of a circuit: $$P_{avr} = C_{eff} \cdot V_{DD}^2 \cdot f_{clc},$$

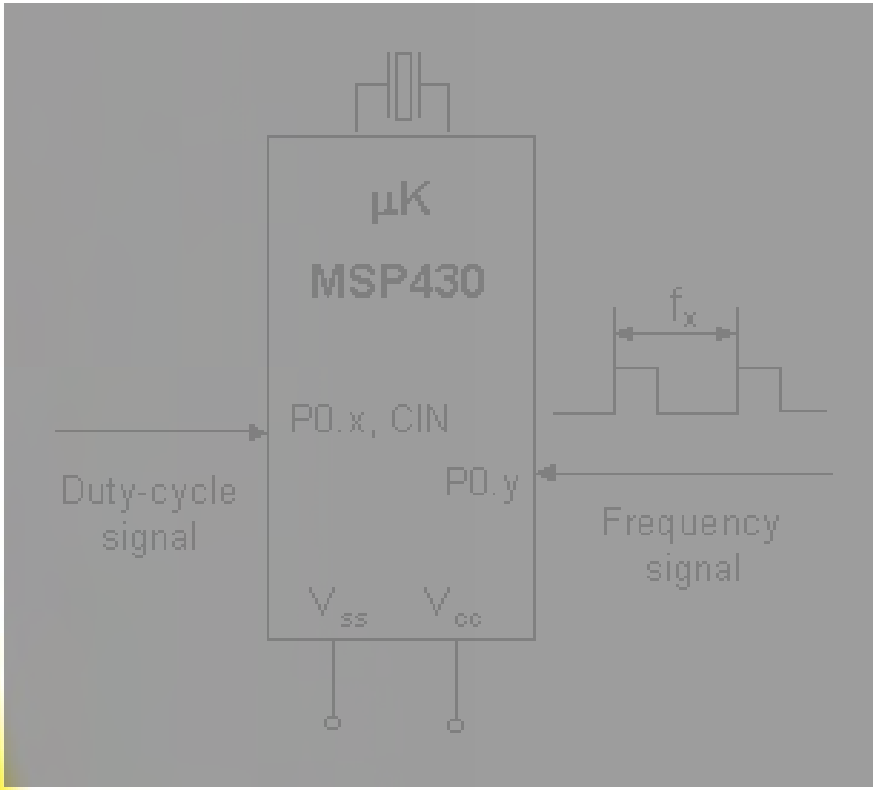
where V_{DD} is the supply voltage; f_{clc} is the clock frequency; C_{eff} is the effective capacitance of the circuit (V_{DD} = 2.8÷3.5 V, C_{eff} = const)

$$f_{0i} = \frac{k}{\delta_i},$$ where $k = 1/T_0 = const$ (T_o is the gate time)

$$f_x = \frac{N_1}{N_2} \cdot f_{0i}$$

$$\delta_i = \frac{1}{T_0 \cdot f_{0i}}$$

Realization

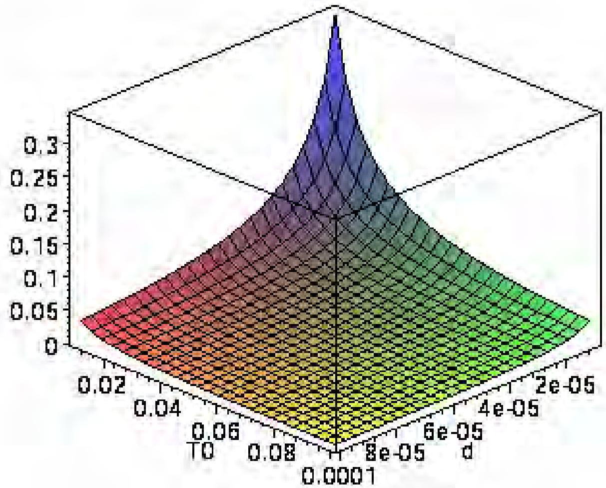


$$f_{system} = N \cdot f_{crystal},$$

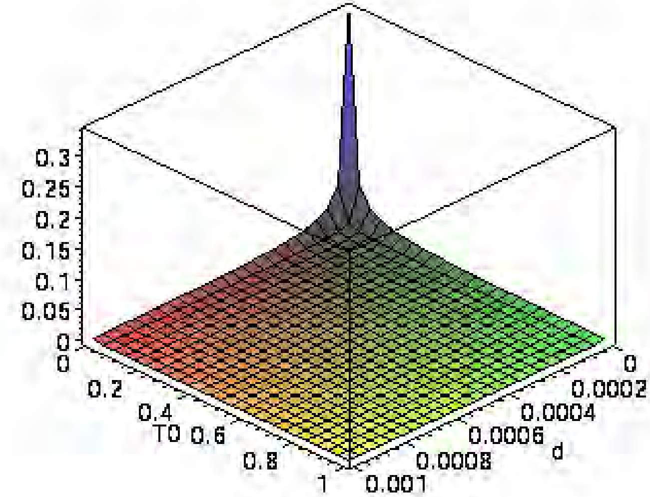
where *N (3÷127)* is the multiplication factor; $f_{crystal}$ is the frequency of the crystal (normally 32 768 Hz)

The reference frequency depends only on beforehand given error for each measurement.

Modeling Results

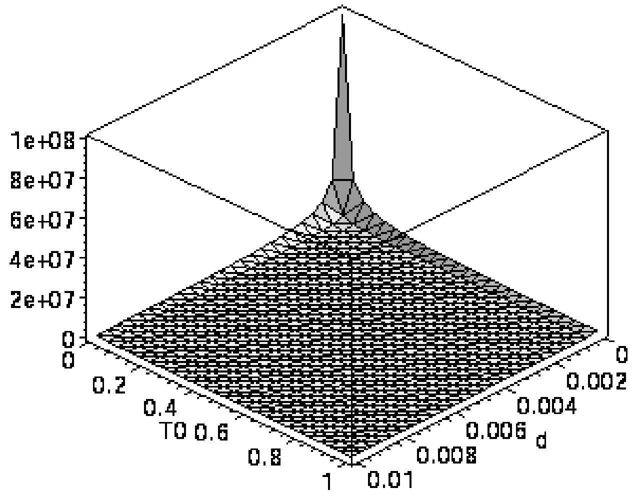


$P_{avg}=f(T_{0,}\delta)$ function at C=70pF,
$\delta_g \in [10^{-5} \div 10^{-4}]$ % and
$T_0 \in [0.01 \div 0.1]$ s.

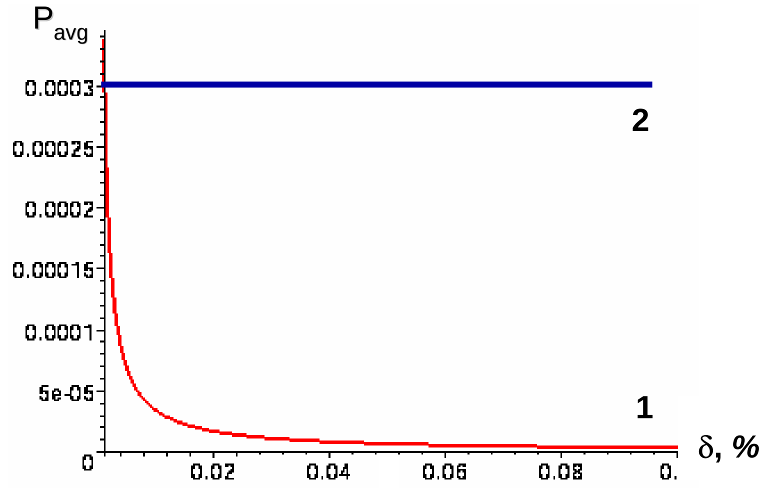


$P_{avg}=f(T_{0,}\delta)$ function at C=70pF,
$\delta_g \in [10^{-5} \div 10^{-3}]$ % and
$T_0 \in [0.01 \div 1]$ s.

Modeling Results (cont.)



The dependence of $f_{clc}=\varphi(T_0, \delta)$.



The dependence of $P_{avg}=\phi(\delta)$ for adaptive method with non-redundant reference frequency (1) and any of advanced method (2) at T_0=0.1s.

Features

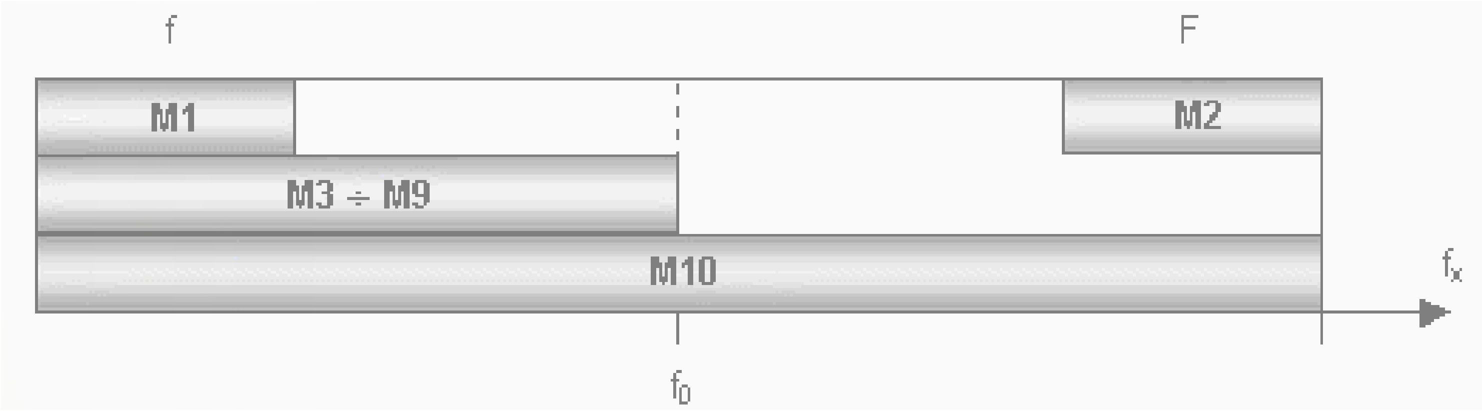
- Constant quantization error
- Non-redundant programmable reference frequency determined by the given quantization error δ_i
- Reduction of the power dissipation during the conversion (on the average by 1-2 order)
- Minimum possible hardware and easy realization

Disadvantages

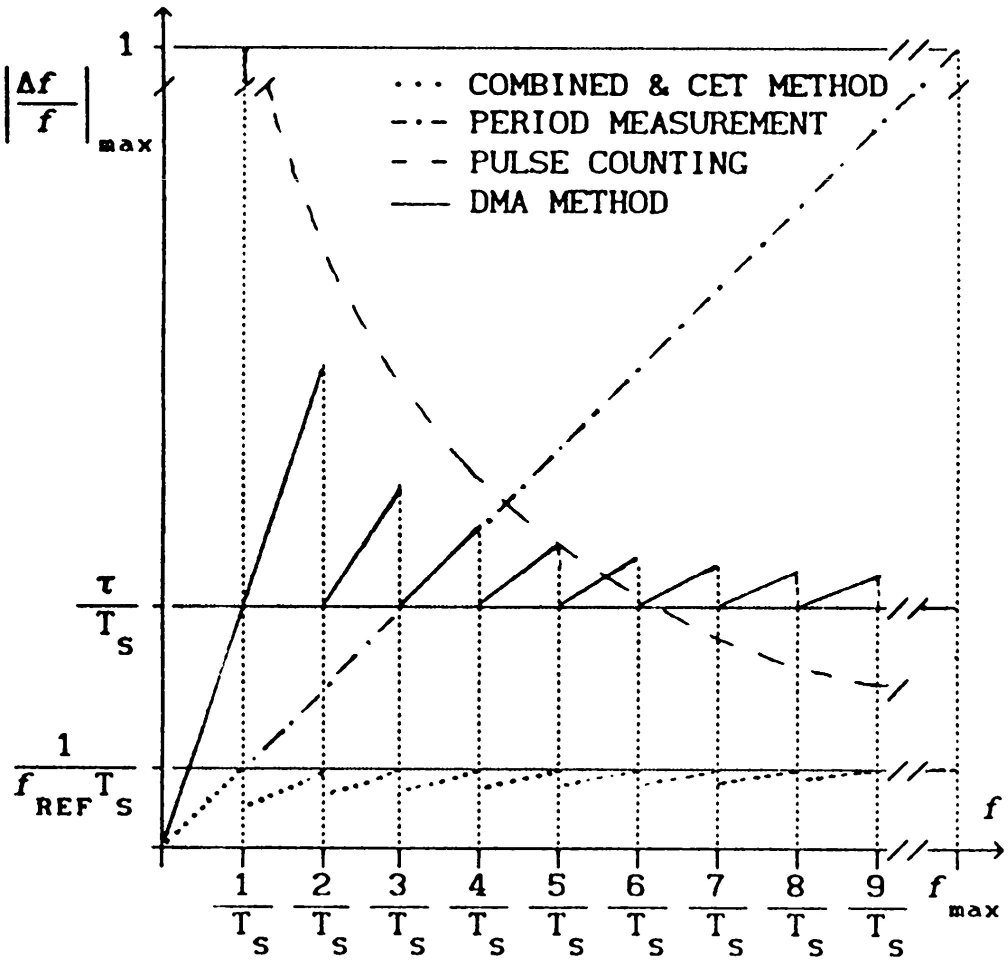
- Redundant conversion time
- Two references: frequency base and time base
- Needs software-controlled reference generator as it is in MSP430

Comparison of Methods

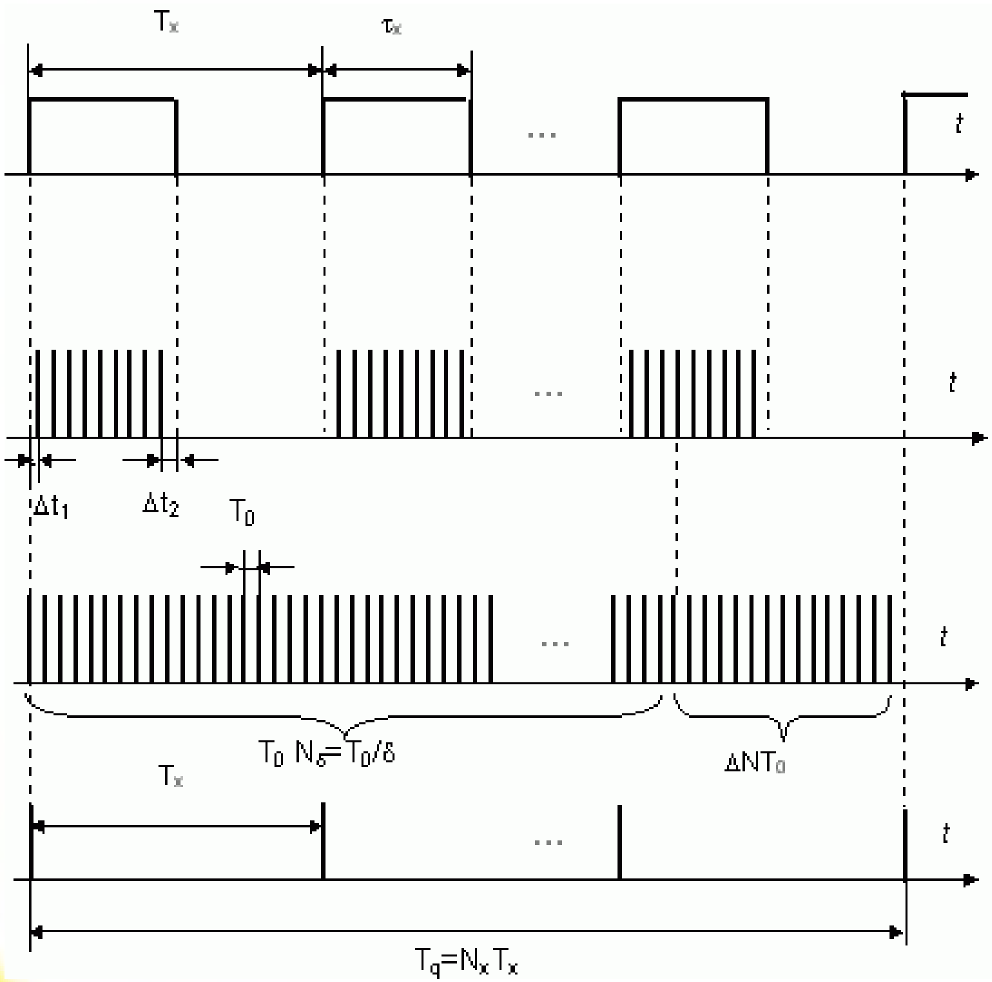
- Should have high metrological characteristics and simple realization at its universality



Relationship Between δ_q and f_x



Advanced Duty-Cycle Measurement Method



$$D.C. = \frac{N_{\bar{\tau}x}}{N_{\bar{T}x}} = \frac{\bar{\tau}_x}{\bar{T}_x}$$

$$K = \frac{N_{\bar{T}x}}{N_{\bar{\tau}x}} = \frac{\bar{T}_x}{\bar{\tau}_x} = \frac{1}{D.C.}$$

$$N_{\tau x} = (N_\delta + \Delta N)\tau_x / T_0,$$

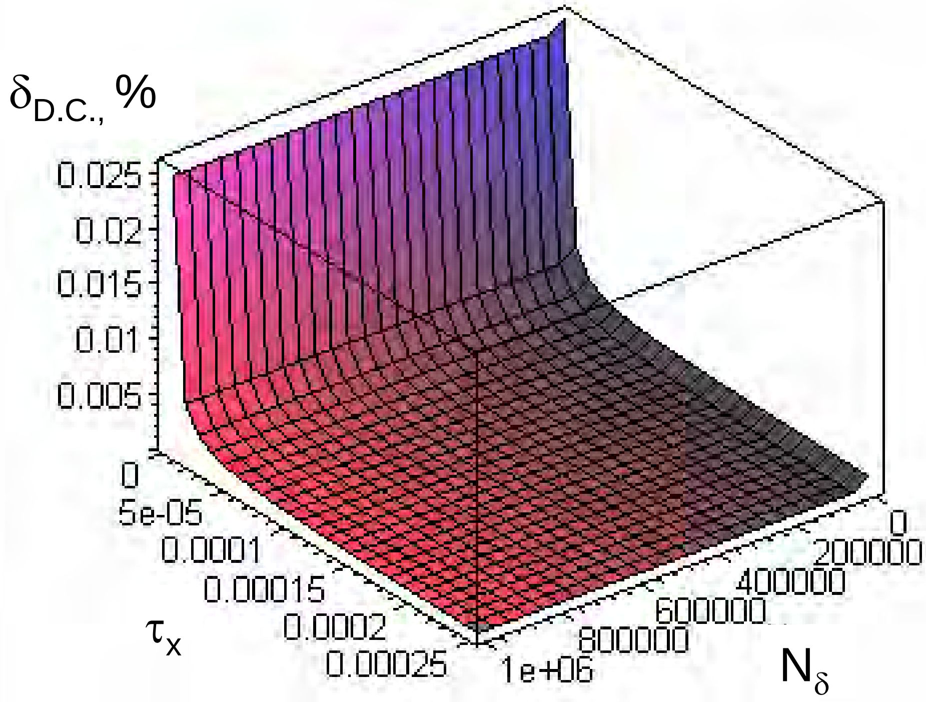
$$N_{Tx} = (N_\delta + \Delta N) T_x / T_0$$

Quantization Error

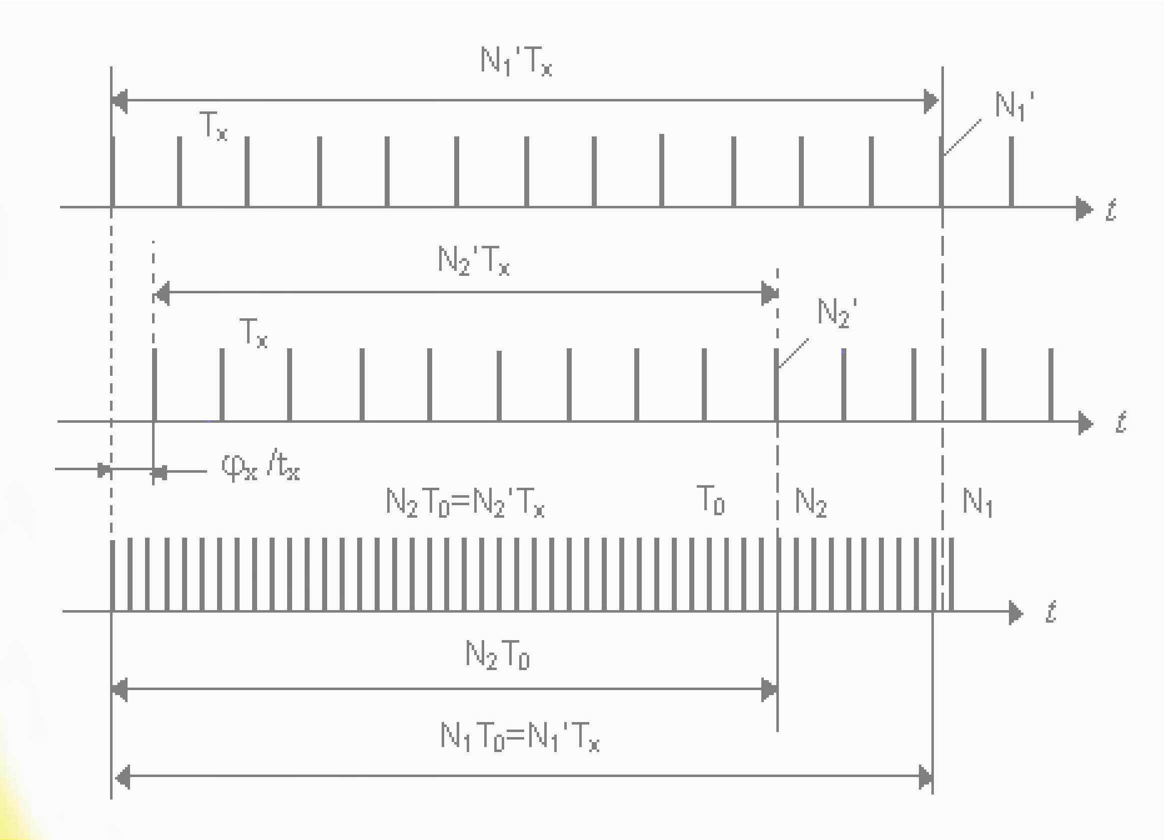
$$\delta_{D.C.} = \frac{N_\delta \cdot T_0 + \tau_x}{\tau_x \cdot N_\delta},$$ - at $\Delta N = N_{min} = 0$

$$\delta_{D.C.} = \frac{\left(N_\delta + \frac{T_x}{T_0}\right) \cdot T_0 + \tau_x}{\tau_x \cdot \left(N_\delta + \frac{T_x}{T_0}\right)}$$ - at $\Delta N = N_{max} = T_x/T_0$

Modeling Result



Advanced Method for Phase Shift-to-Digital Conversion



$$N_1 \cdot T_0 = N_1^{'} \cdot T_x$$

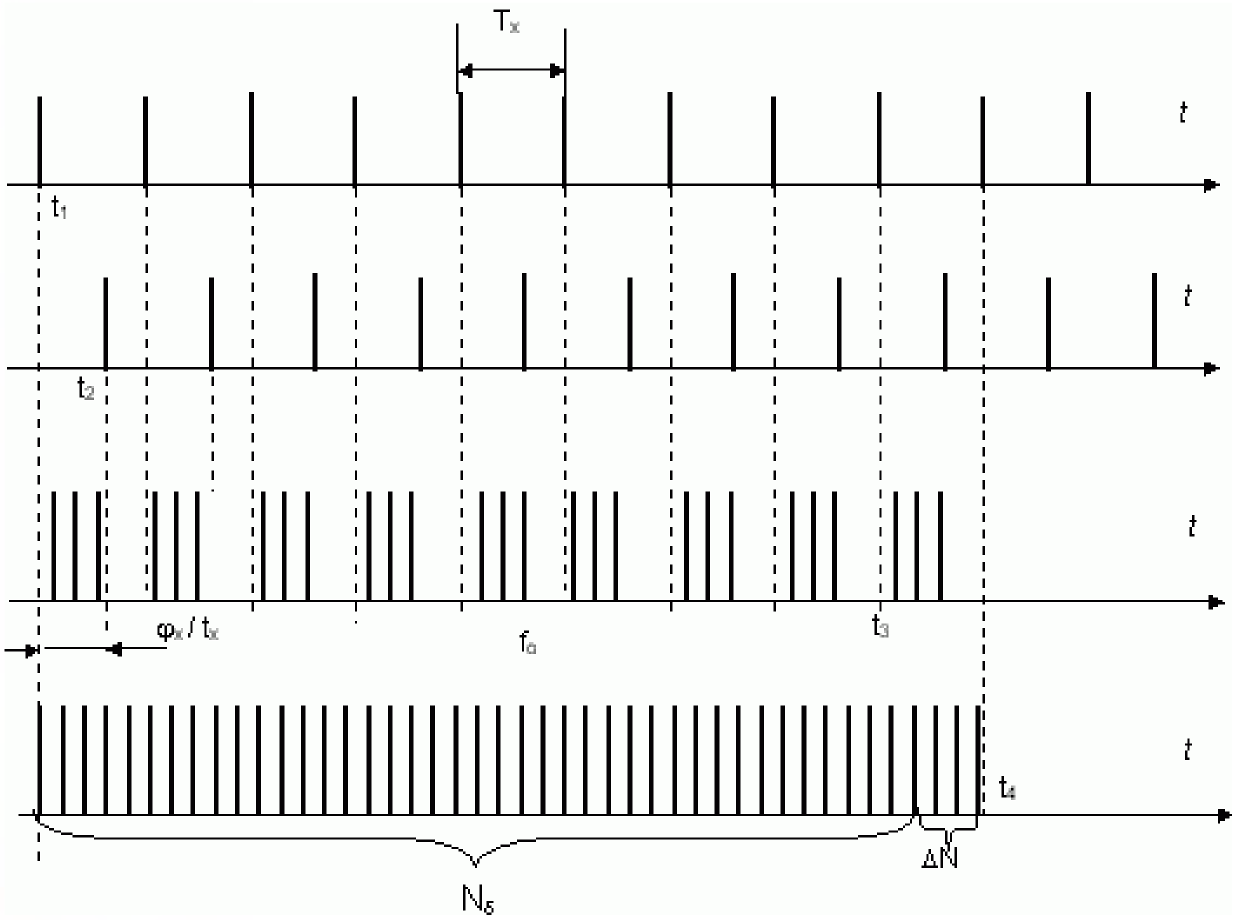
$$N_2 \cdot T_0 = N_2^{'} \cdot T_x + t_x$$

Main Equations

$$\varphi_x = \left(\frac{N_1^{'} \cdot N_2 - N_2^{'} \cdot N_1}{N_1} \right) \cdot 360 \qquad t_x = \left(\frac{N_1^{'} \cdot N_2 - N_2^{'} \cdot N_1}{N_1} \right) \cdot T_0$$

- φ_x and t_x do not depend on the period T_x
- Conversion errors is determined by pulses duration
- Reduction of these errors, the method of forming of pulse packets of coincidences can be used

Novel Method for Phase-Shift Measurements



Main Equations

$$N_{\varphi x} = 360\frac{N_{\bar{t}x}}{N_{\bar{T}x}} = 360\frac{\bar{t}_x}{\bar{T}_x} = \bar{\varphi}_x^{\,0}$$

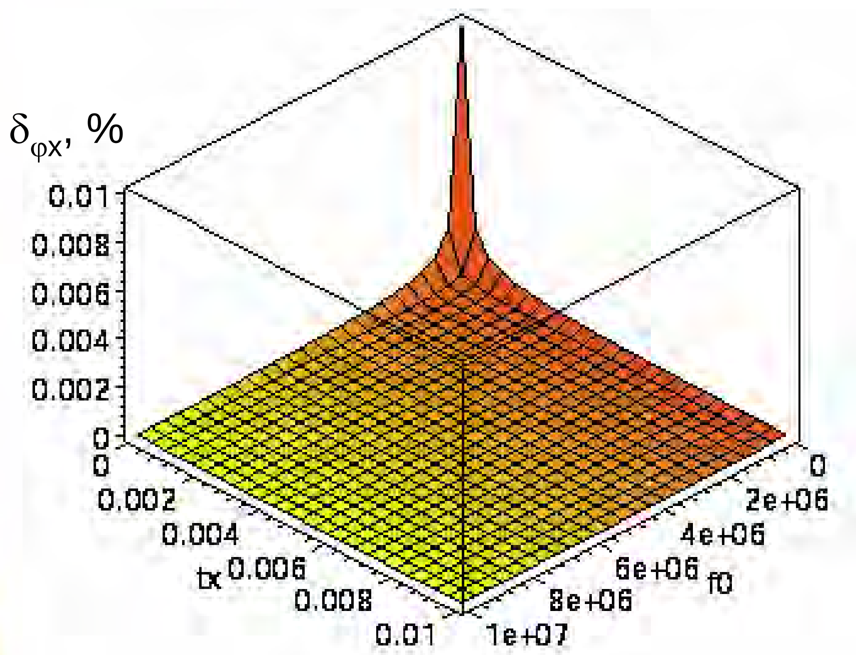
$$N_{\varphi x} = 2\pi\frac{t_x}{T_x} = \varphi_x(rad)$$

$$N_{tx} = N_\delta t_x / T_0$$

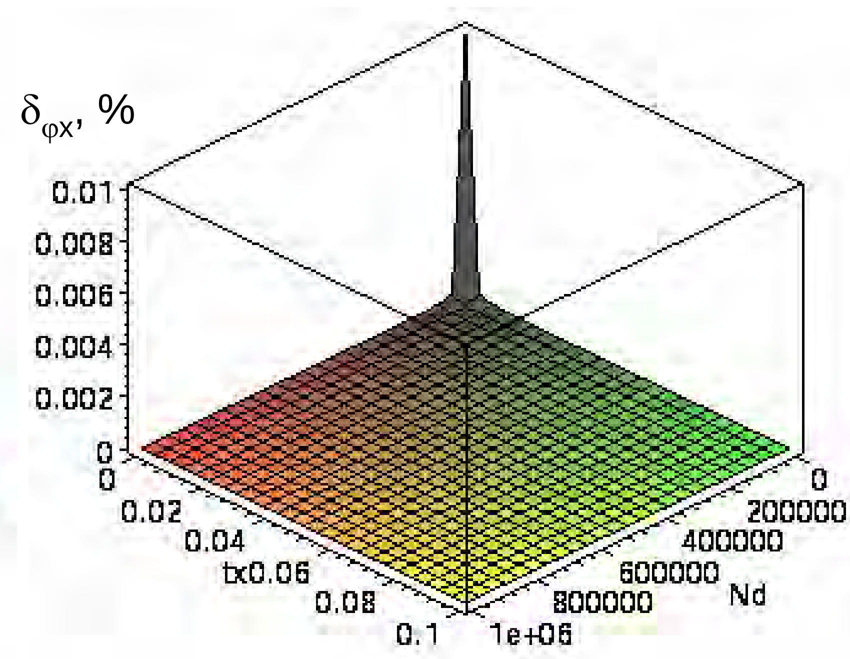
$$N_{Tx} = N_\delta T_x / T_0$$

$$\delta_{\varphi x} = \frac{f_0 \cdot t_x + N_\delta}{N_\delta \cdot f_0 \cdot t_x}$$

Modeling Results



$\delta_{\varphi x} = f(t_x, f_0)$ at $N_\delta = 10\ 000$



$\delta_{\varphi x} = \vartheta(t_x, N_\delta)$ at $f_0 = 100\ 000$ Hz

Conclusions

- The accuracy of conversion is one of the most important quality factors for smart sensors. Due to advanced methods it is possible to reach a constant quantization error
- Self-adapting method of dependent count and method with non-redundant reference frequency are very suitable for the usage in frequency-to-code converters of smart sensors
- They are optimal for microcontroller based frequency-to-code converters
- Due to advanced conversion methods precision and multifunctional smart sensor systems will be more available for customers

Digital Sensors and Program-Oriented Conversion Methods

Introduction

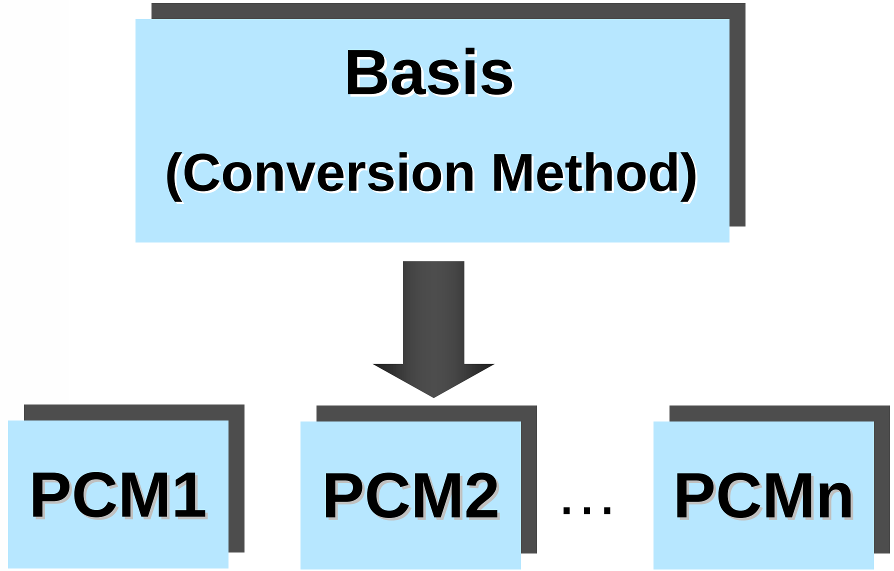
- Interface from the analog domain to the digital can be a mystifying design problem
- The hardware design and software must operate together to produce a complete, usable design
- Hardware and software needed to implement the bridge between analog and digital signals

Program-Oriented Conversion Methods

Program-Oriented Conversion Method (PCM) is a processor algorithm of measurement, implemented in the functional-logic architecture of computer or microcontroller at a virtual level through the software

- The conversion error is determined by the sensor's accuracy
- Hardware or chip area is minimum possible (microcontroller core and peripheral)
- Computing power is directly included into a converter as part of the measuring circuit and takes part in the conversion

PCM Design



There are two types of program model construction: compilating and interpreting

PCM Classification

- According to the program realization of frequency and time references:

- with program delays forming;
- with time intervals forming by means of built - in timer/counters (T/C)

- Depending on realization of events counting:

- with counting on polling (synchronous or asynchronous);
- with counting on interruptions (single-level or multilevel);
- with counting with the help of timer/counters

PCMs Based on Ratiometric Method

- Contains critical time-dependent pieces of programs
- Demands a high multisequencing degree of elementary measuring procedures of processor algorithms
- There is a multiway at PCM realization based on the ratiometric counting method

Main Design Steps

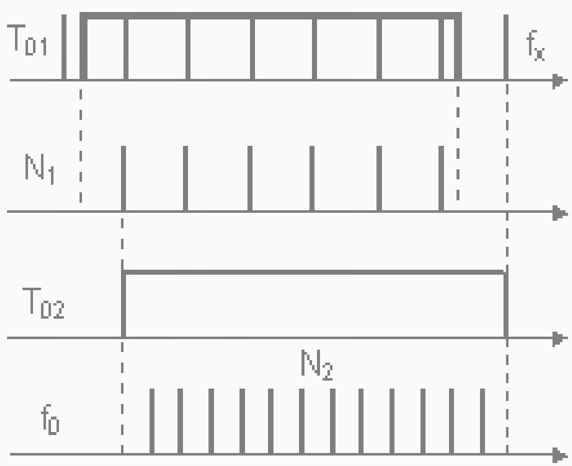
- Careful analysis of processor algorithms' structures
- Usage of necessary resources of microcontrollers' architectures
- Correct determination of software part, which requires an optimization

PCM Realization

Concurrent execution of four elementary procedures:

- First gate time T_{01} forming
- Second gate time T_{02} forming
- Counting of reference f_0 and measurand f_x frequencies

PCM Decomposition



Elementary Procedures	Variants of Realization			
	By delay	By T/C	By interrupt	By pooling
T_{01}	●	●	—	—
N_1	—	●	●	●
T_{02}	—	—	●	●
f_0	—	●	●	●

Ranges of Possible T/C Delays

Type of µC	Minimum Time Delay	Maximum Time Delay
MCS - 51	$12/f_{osc}$	$12/f_{osc} \cdot 2^n$
MCS - 251	$4/f_{osc}$	$4/f_{osc} \cdot 2^n$
MCS – 96/196	$4/f_{osc}$	$4/f_{osc} \cdot 2^n$
MSP430CXX (at MCLK=1 048 MHz)	$1.5 \cdot 10^{-5}$ sec	2 sec

where f_{osc} is the frequency of crystal oscillator; n is the number of bits of timer/counter.

There is the error Δt_{int} caused by the time of instruction execution necessary for control transfer to the interrupt vector of internal interruption and "stop" instruction for a timer/counter. It is a systematic error and should be corrected.

Program Asynchronous Polling

$$\left.\begin{aligned} T_{x\max} &\geq n \cdot \tau_{cycle} \\ \tau_{Jump} \leq \tau_x &< n \cdot \tau_{cycle} \end{aligned}\right\},$$

where T_{xmax} is the period of converted frequency; τ_{cycle} is the duration of machine cycle; n is the number of machine cycles necessary for realization of polling program; τ_{Jump} is execution time for conditional jump instruction according to a high logic level "1" in microcontroller's inputs

Count by Interrupt

$$T_{x\max} \geq T_{INT},$$

where T_{INT} is execution time of interrupt subroutine

$$T_{INT} \geq t_{clc} \cdot n,$$

where *n* is the number that is determined for each type of microcontroller

Frequency Range

Maximum possible frequencies on T/C's inputs:

Type of µC	Maximum Frequency on T/C input
MCS - 51	$f_{osc}/24$
MCS - 251	$f_{osc}/8$
MCS – 96/196	$f_{osc}/4$
MSP430C33x (for MCLK)	3.8 MHz

Minimum possible frequency:

$$f_{x\,min} = \frac{1}{N_{2\,max} \cdot T_{clc}},$$

where $N_{2max}=2^k=const$; k is the capacity of virtual counter

Reference Frequency

- Frequency output Clock-Out mode for three timer/counters architectures:

$$F_{clock-out} = \frac{F_{osc}}{4 \cdot (65536 - RCAP2H, RCAP2L)}$$

The increasing of reference frequency f_0 up to $F_{clc}/4$ is possible due to the PCM realization based on microcontrollers containing a programmable counter array (PCA)

It is a good internal device for measurement of period, pulse duration, phases differences, etc., in 5 channels at the same time

Main Features of PCM

- Open character of converters functionalities
- Self-adapting capabilities
- Not limited range of low and infralow converted frequencies
- A high degree of multisequencing operations of conversion algorithm
- Essential complication of processor algorithms
- Growth of relative density and complication of methodical and algorithmic component of error

General Number of PCM Variants

$$S^* = S_1 \cup S_2 \cup S_3 \ldots \cup S_p \qquad \left(S_1 \cap S_2 \cap S_3 \ldots \cap S_p \neq 0\right)$$

$$V^n = \left\{V_i^n\right\} = \prod_{i=1}^{p} C_{N1}^{ki} - q = C_{N1}^{k1} \cdot C_{N2}^{k2} \cdot C_{N3}^{k3} \cdot \ldots \cdot C_{Np-1}^{kp-1} \cdot C_{Np}^{kp} - q,$$

where *q* is the number of incompatible realizations of PCM

$V^n = \left\{V_3^n\right\} = C_3^1 \cdot C_3^1 \cdot C_2^1 - 8 = 10$ - for one-timer architectures

$V^n = \left\{V_3^n\right\} = C_3^1 \cdot C_3^1 \cdot C_2^1 - 1 = 17$ - for two-timers architectures

$V^n = \left\{V_3^n\right\} = C_3^1 \cdot C_3^1 \cdot C_2^1 = 18$ - for three-timers architectures

Optimization Criterion

$$\nabla_i K_i = \min_{\{B_{ij}\}} F_i(\delta_{ij}, T_{xij}, V_{ROMij}, P_{ij})$$

where δ_{ij} is the quantization errors, $T_{ijx} \leq T_{ijaccept}$ ($T_{ijaccept}$ is the allowable conversion time; $T_{xij} = 1/f_{xij}$), V_{ROM} is the memory sizes, P_{ij} is the power consumption

Weight-average geometrical complex parameter: $\prod_{i=1}^{m} \left(\frac{k_i^{min}}{k_i} \right)^{\nu_i}$,

where k_i^{min} is the minimum values of appropriate parameters of quality on all allowable variants of PCM; ν_i is the normalized weight factors of proportionality for appropriate parameters, and

$$\nabla_i \nu_i \geq 0, \qquad \sum_{i=1}^{m} \nu_i = 1 \ \ (i = \overline{1, m})$$

Integrated Criterion of Efficiency

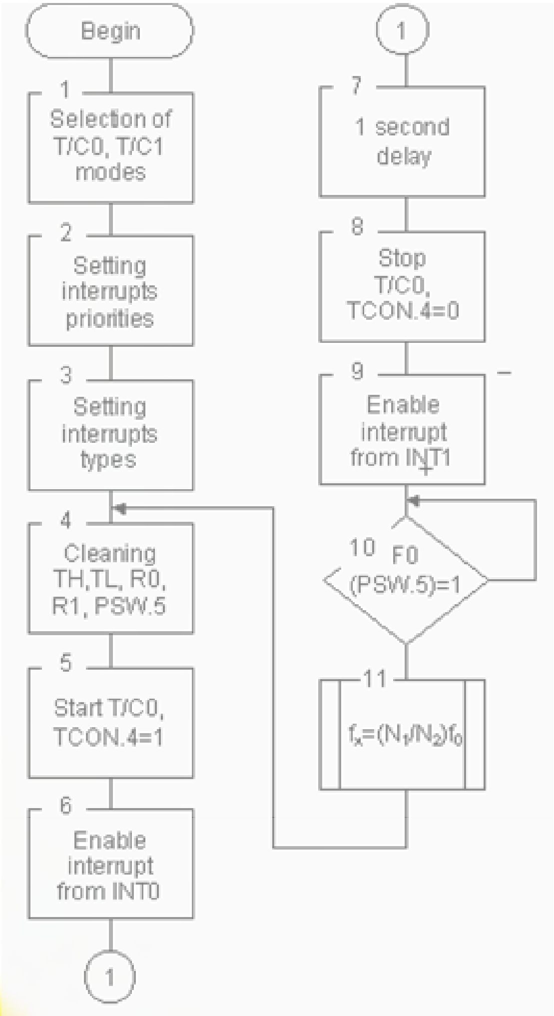
$$K_{ij} = \left(\frac{\delta_{i\,min}}{\delta_{ij}}\right)^{\nu_i\delta} \cdot \left(\frac{T_{xi\,min}}{T_{ij}}\right)^{\nu_{iT}} \cdot \left(\frac{V_{ROMi\,\,min}}{V_{ROMij}}\right)^{\nu_{iROM}} \cdot \left(\frac{P_{i\,min}}{P_{ij}}\right)^{Pi},$$

where δ_{imin}, T_{ximin}, $V_{ROMimin}$, P_{imin} are the minimum values of the appropriate parameters; $\nu_i\delta$, ν_{iT}, ν_{iROM}, ν_{iP} are the weight factors of priority

$$\nabla_i 0 \le \{\nu_i\delta, \nu_{iT}, \nu_{iROM}, \nu_{iP}\} \qquad \left(\nu_{i\delta} + \nu_{iT} + \nu_{iROM} + \nu_{iP}\right) = 1$$

$$K_{ij} = \left(\frac{\delta_{i\,min}}{\delta_{ij}}\right)^{\nu_i\delta} \cdot \left(\frac{T_{xi\,min}}{T_{ij}}\right)^{\nu_{iT}}$$

PCM Example

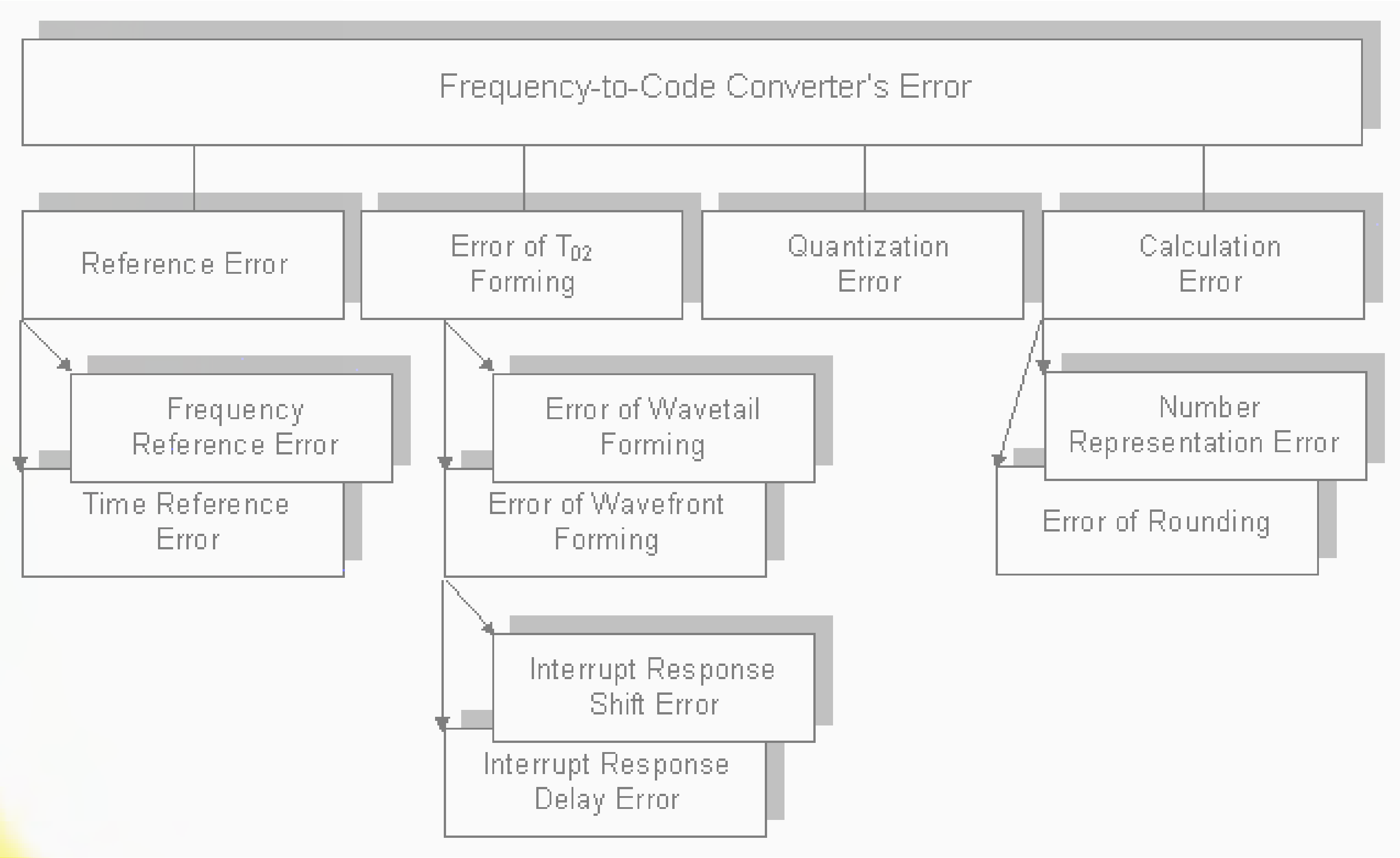



```
         ORG     03H
         JMP     CINT0
         ORG     0BH
         JMP     TIMER0
         ORG     13H
         JMP     CINT1
         ORG     1BH
         JMP     TIMER1
         ORG     26H
INTF0:   BIT     D0H.5
         MOV     TMOD,#01010101B     ;GATE=0,COUNTER,16-BITS
         MOV     IP,#00000101B       ;INT0,1 - HIGH PRIORITY
         SETB    TCON.0              ;INT0 - BY WAVETAIL
         SETB    TCON.2              ;INT1 - BY WAVETAIL
REPR:    CLR     A                   ;0 -> A
         MOV     TH0,A               ;CLEANING T/C0
         MOV     TL0,A
         MOV     TH1,A               ;CLEANING T/C1
         MOV     TL1,A
         MOV     R0,A                ;0 -> R0
         MOV     R1,A                ;0 -> R1
         CLR     INTF0               ;PSW.5=0
         SETB    TCON.4              ;START T/C0
         MOV     IE,#10001011B       ;ENNABLE INT0
         CALL    DELEY               ;1 SECOND DELAY
         CLR     TCON.4              ;STOP T/C0
         SETB    IE.2                ;ENNABLE INT1
WAIT:    JNB     INTF0,WAIT          ;WAITING FOR PSW.5=1
         CALL    MATH                ;fx CALCULATION
         JMP     REPR
```

Subroutines

```
;                  *** INTERRUPT HANDLING SUBROUTINES ***

CINT0:      SETB        TCON.6                      ;START T/C1
            CLR         IE.0                        ;DISABLE INT0
            RETI

CINT1:      CLR         TCON.6                      ;STOP T/C1
            CLR         IE.2                        ;DISABLE INT1
            SETB        INTF0                       ;SETTING PSW.5=1
            RETI

TIMER0:     INC         R0
            RETI

TIMER1:     INC         R1
            RETI
```

Error Analysis



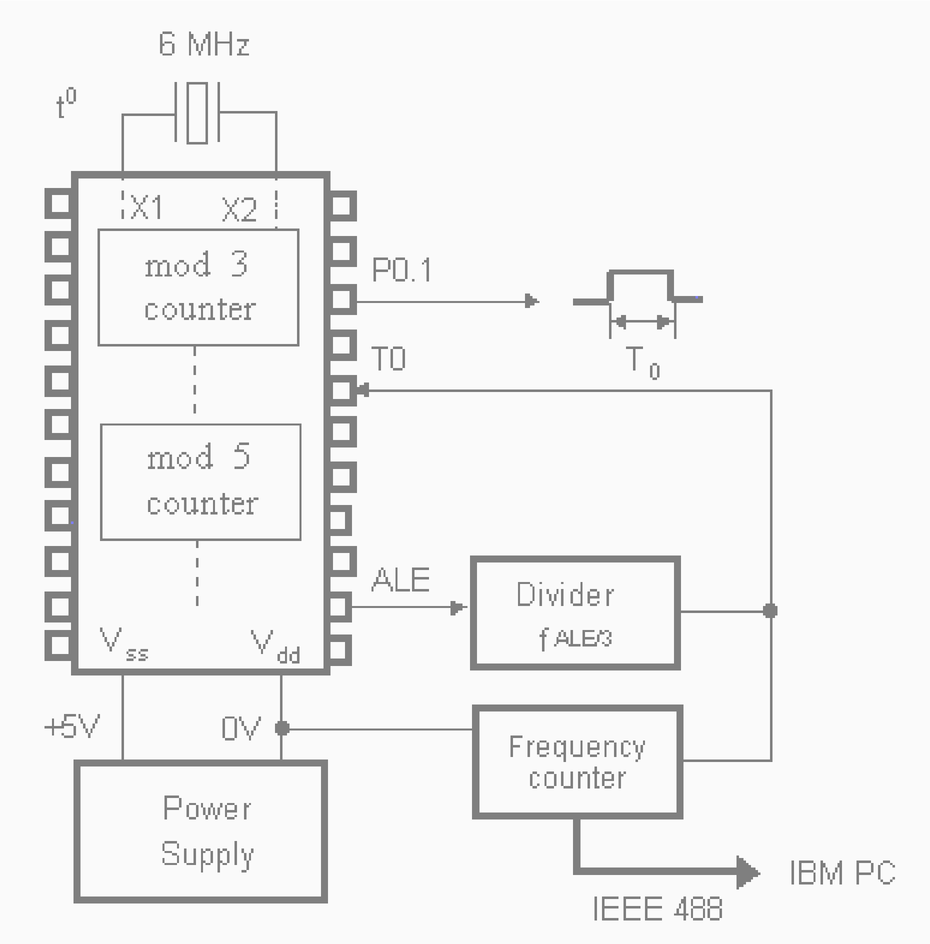
Reference Error

- Frequency base error
- Time base error

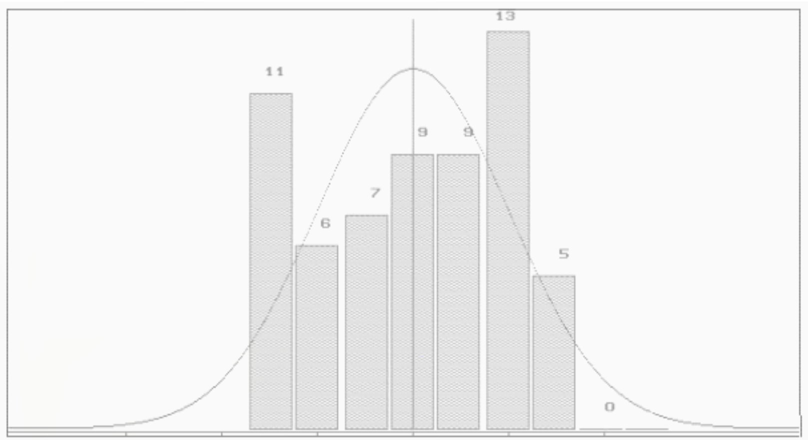
Temperature instability:

$$\frac{\Delta f}{f} = \frac{2 \cdot (f_{max} - f_{min})}{f_{max} + f_{min}}$$

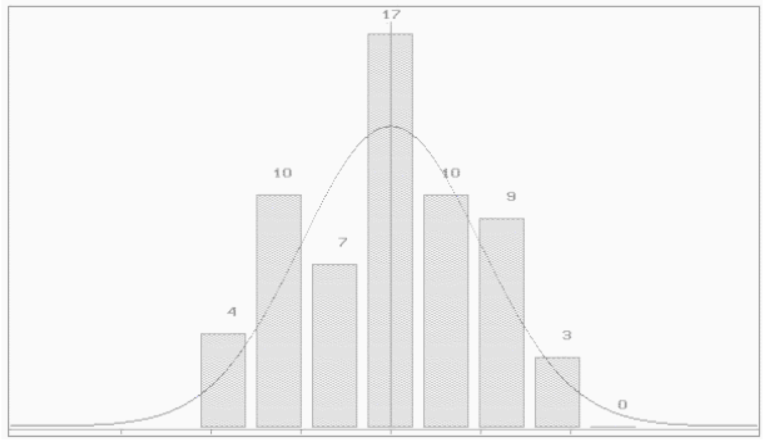
Experimental Setup



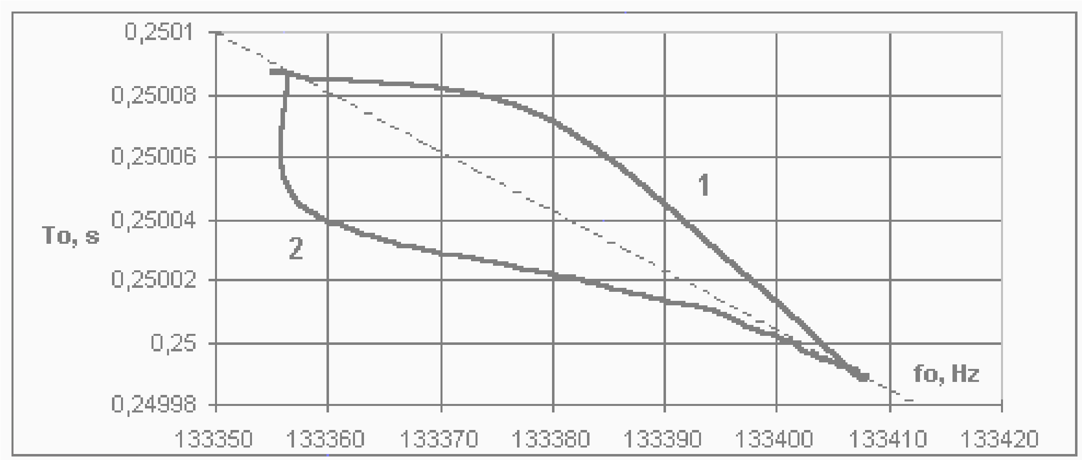
Experiment Results



Frequency base $\pm 11.5 \cdot 10^{-6}$



Time base $\pm 0.38 \cdot 10^{-6}$



Total Error of Reference

$$\sigma\sum_{m} = \sqrt{\sigma_{To}{}^{2} - 2\sigma_{To}\sigma_{fo}\rho + \sigma_{fo}{}^{2}},$$

where is the correlation factor *r* = - 0.981 ± 1.291·10^{-6}

Total Error: ± 10.9 · 10^{-6} (at the probability of 97 %)

Quartz Generator Stability Improvement

- The usage of oven-controlled crystal oscillator
- The usage of MSP430 microcontroller:

$$\Delta f = -0.035 \cdot (t - 19)^2,$$

where Δf is the frequency deviation in *ppm; t* is the crystal temperature in ^0C, $t_0 = + 19\ ^0C$ - turning point

Calculation Error

$$\sigma_{Number\_Representation\_Error} = \frac{1}{2} k^{-n_o},$$

where n_0 is the number of bits for *X* numeration; *k* is the base of system of numeration

- Truncation error: rejection and rounding
- Arises as the result of word length reduction after multiplication, division, right shifts and algebraic summation in view of scaling variables

Numeration Ranges for N_1, N_2

$$N_{1max} = ent\{T_{01} \cdot f_{x\,max}\}$$

$$N_{2\,max} = ent\left\{\frac{N_1 \cdot f_o}{f_{x\,min}}\right\}$$

- The usage of fixed point format
- Multibyte operands are stored in the packed format in microcontroller's memory

Arithmetic Methods

- Multiplication method with the exact multiplication scheme by low-order digit forward with shift to the right of partial product
- Division method with shift to the left and residue restoration
- In order to increase computing operations accuracy, it is expediently to use the scaling by multiplication of numerator and denominator to scale factor k_m

Arithmetic Operations Order

$$f_x = \frac{N_1 \cdot (f_0 \cdot k_m)}{N_2 \cdot k_m}$$

As $f_0 \cdot k_m = K = const$, that the final equation will be:

$$f_x = \frac{N_1 \cdot K}{N_2 \cdot k_m}$$

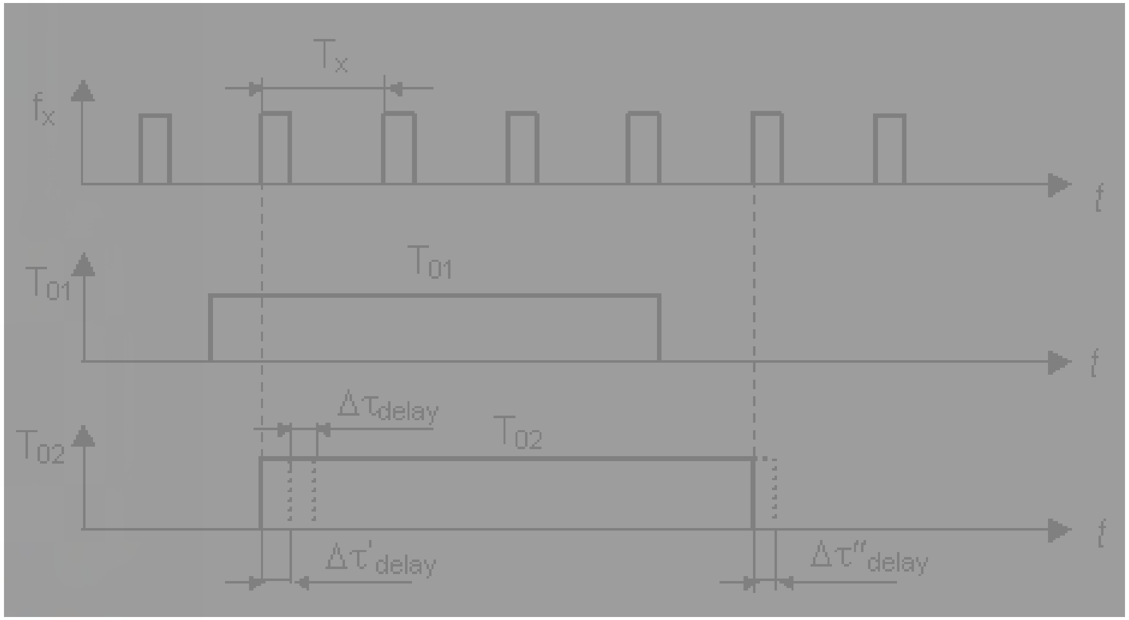
1) $N_1 \cdot K = k_1$

2) $N_2 \cdot k_m = k_2$

3) $f_x = k_1 / k_2$

Error of T_{02} Forming

- Error of wavefront forming
- Error of wavetail forming (includes the error due to delay of reaction to interruption, and the error of shift in time of response for interruption)



Delay of Reaction to Interruption

It is the time interval between the pulse of frequency f_x on the interrupt input and timer/counter start. It is determined by execution time for three instructions:

1) CALL to the interrupt vector;
2) Unconditional jump (JMP) to the interruption subroutine;
3) Start timer/counter:

$$\Delta\tau_{delay} = \tau_{CALL} + \tau_{JMP} + \tau_{STRT} \geq 1/f_0$$

Shift in Time of Response for Interruption

The reason of this component is that the time used by microcontroller for the response to interruption can be varied.

$$\tau_{cmax} = 2 \cdot \tau_{cycle},$$

$$\Delta\tau_{delay}' \in \,]0;\, \tau_{cmax}]$$

Error of Wavetail Forming

It is determined by the delay $\Delta t''$, connected with the execution of instruction of logic polling for the last pulse of frequency f_x. Its value is in the interval $\Delta t''\ [3t_{cycle}, 5t_{cycle}]$.

$$T_{02\ real} = T_{02} - \Delta\tau_{delay} - \Delta\tau_{delay}' + \Delta\tau_{delay}''$$

Error Reduction

- Error of shift in time of response for interruption and errors because of T_{02} wavetail forming can be mutually compensated as the first component reduces the gate time T_{02} and the second increases it
- The first component can be reduced due to the usage of more high-speed microcontroller core or increased clock frequency

Systematic Errors Correction

- Can be reduced at the design stage of PCM software
- Possible at high conversion speed and without an essential algorithmic complication

$$\Delta t_{correction} > 1/f_0$$

Correction Method

To change the rigidly established (by service protocol for external interruptions) the instruction order for interrupts subroutine from external sources (converted frequencies f_x). For delay Δt_{delay} reduction, the interruptions subroutine is modified so the instruction to start timer/counter was executed as soon as possible.

$$\Delta\tau_{delay} = t_{CALL} + t_{STRT} = 3 \cdot \tau_{cycle}$$

Conclusions

The usage of PCMs for frequency-to-code conversion in digital output smart sensors with embedded microcontrollers allows essentially:

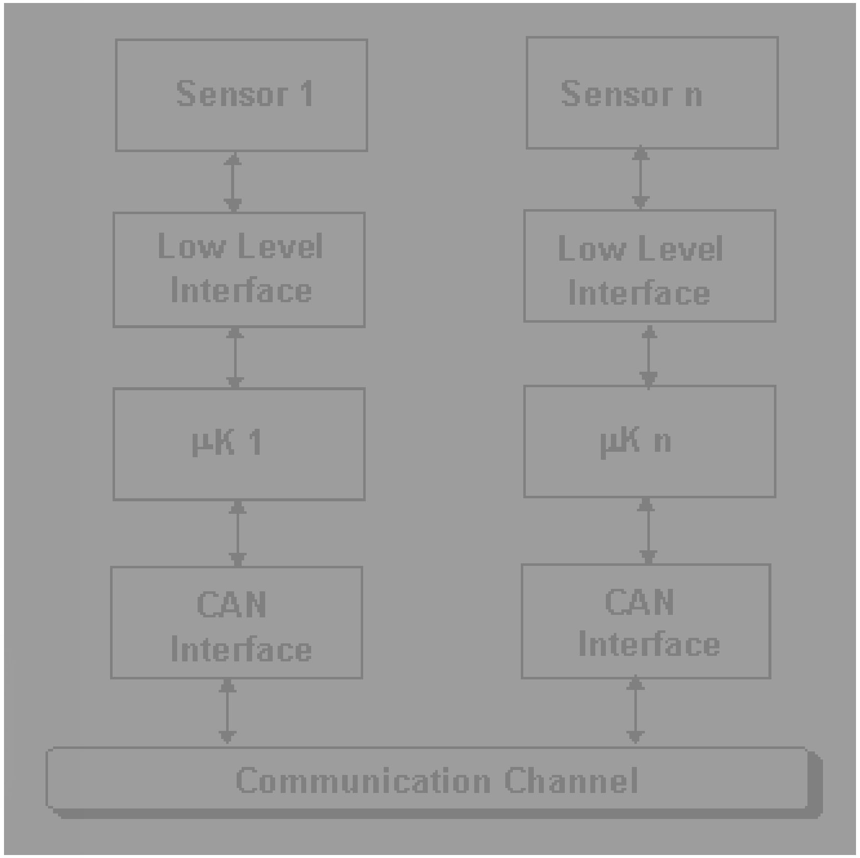
- To reduce hardware (die size)
- To increase reliability
- To lower the time-to-market at sensor design due to the reusing software components
- To realize in full sensor's self-adaptive capabilities (software-controlled performances and functional capabilities).

Smart Sensor Systems

Introduction

- In most measuring and control systems, a large number of sensors are connected to a central computer or microcontroller
- The number of frequency time-domain sensors is continuously increasing in different applications of sensor networks
- Sensors networks are widely used in systems with distributed intelligence

Multilayer Sensor Network Architecture



Architecture Advantages

- High layers use the information ensured with lower layers and do not pressing in detail of operation the last ones
- Interfacing functions: low level hardware and software interface (sensor - microcontroller), secondly - high level Controller Area Network (CAN) interface

Controller Area Network – A serial bus that finds the increasing use as a device-level network for the industrial automation. CAN was developed by Bosch to address the needs of in-vehicle automotive communications

One-Channel Sensor Interfacing

- Modern frequency-time domain sensors are microcontroller compatible and designed to drive a standard TTL or CMOS logic input
- Some of frequency-time domain sensors can be placed in a high impedance state when not required
- It is useful for applications where input devices share a microcontroller
- Hardware interface is solved rather easily

Software Interfacing

- It is necessary to ensure standardizations of the information interchange procedure with allowance of required speed
- Data exchange methods: Interruption, DMA, polling
- Interface productivity depends on a selected type of connection
- Depends on the desired resolution and data-acquisition rate

Software Interfacing (cont.)

- Program-oriented approach allows to achieve the universality
- Software interfacing module realises the frequency (period, duty-cycle, time interval)-to-code conversion on the virtual level inside the functional-logical architecture of the microcontroller

Multichannel Sensor Interfacing

- Simultaneous multichannel measurements are necessary for connection of some frequency-time domain sensors to the same microcontroller
- Needs multisequencing of execution of elementary measuring procedures
- Conversion of sequential algorithms into quaziparallel in order to use standard microcontrollers

ABS System

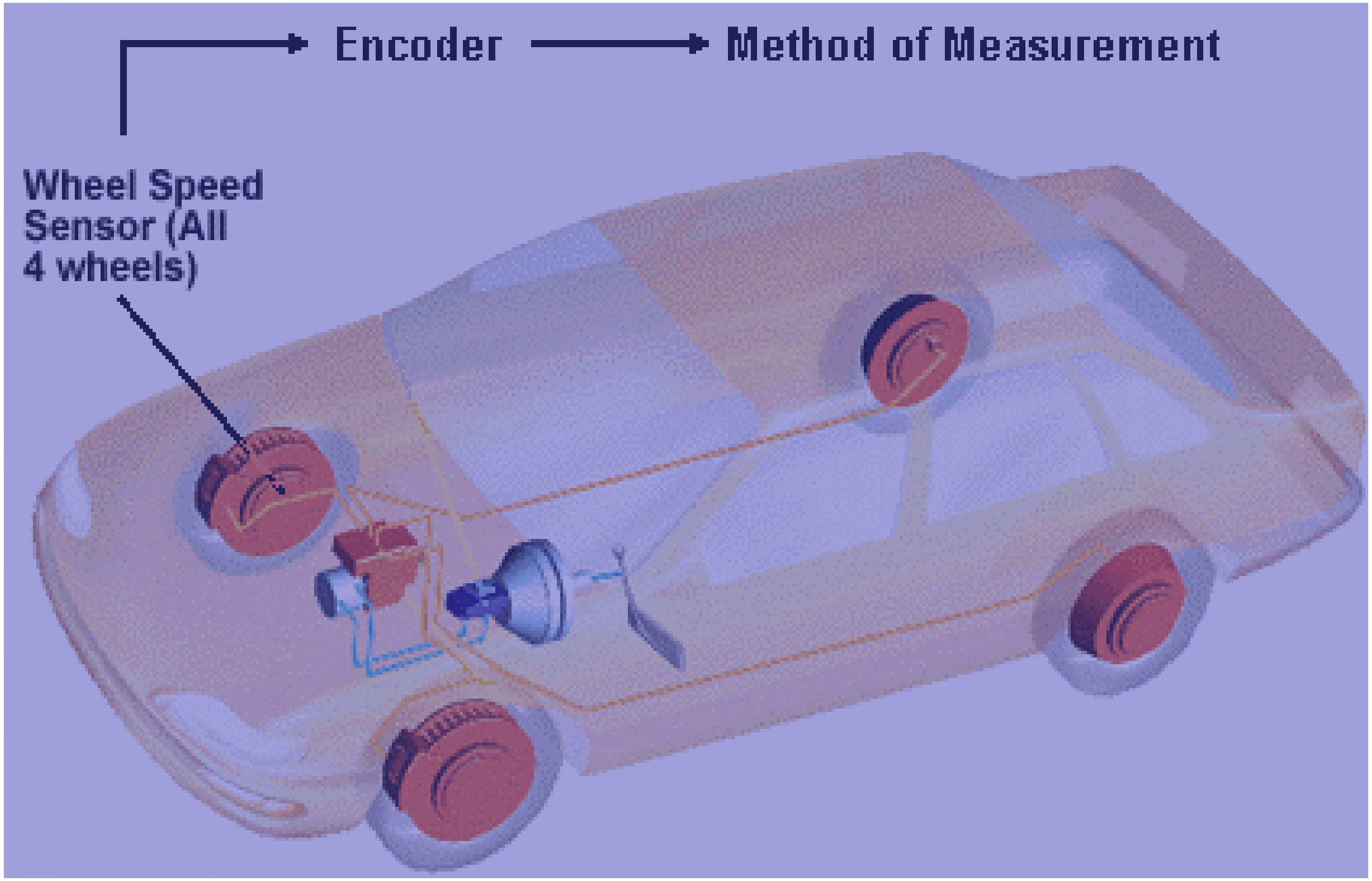
System	Abb.	Sensors	System	Abb.	Sensors
Distronic	DTR	3	Common-rail diesel injection	CDI	11
Electronic transmission control	EGS	9	Automatic climate control	KLA	13
Roof unit	DBE	7	Active body control	ABC	12
Automatic brake control	ABS	4	Tire pressure monitoring	RDK	11
Power lock	ZV	3	Electronic stability programme	ESP	14
Dynamic light regulation	LWR	6	Parktronic system	PTS	12

Sensor systems of W220 (source DaimlerChrysler)

Anti-Lock Braking System (ABS)

- Reliability of the ABS is determined by speed of processing of measuring information and solution made by the control system
- Must work in harsh environment and wide temperature range
- Price should not be excessively high in conditions of large production volumes

Three Main Components of ABS



Smart Rotation Speed Sensor

- Sensor technology is playing a critical role
- Three types of rotation speed sensors can be used in ABS:

- Hall sensors;
- active semiconductor sensors;
- passive self-generating inductive sensors.

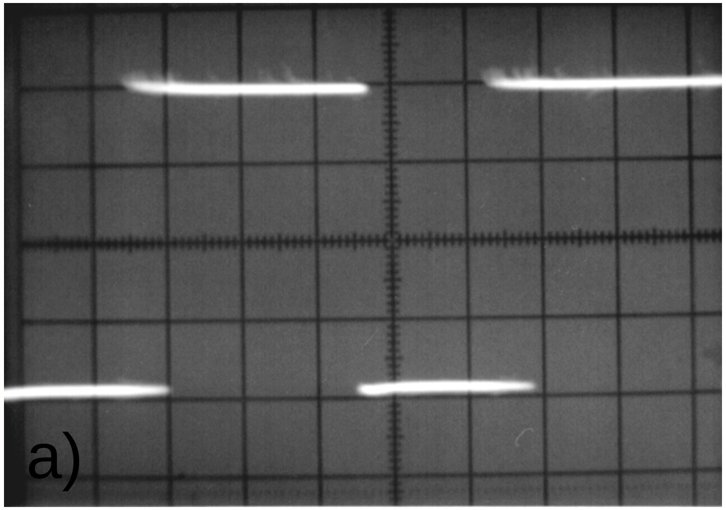
Hall Sensors Disadvantages

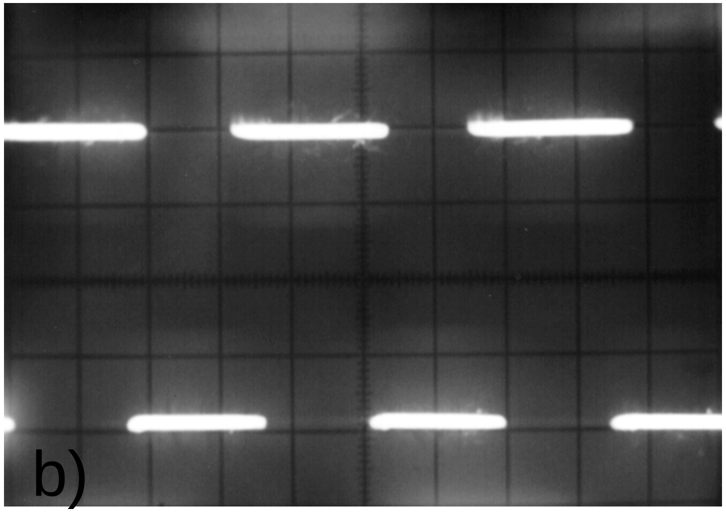
- Needs magnetic pole teeth in the encoders
- It is influenced by run-out and external magnetic fields
- It is also necessary to take into account the availability of the initial level of the output signal between electrodes of the Hall's element at absence of magnetic field and its drift
- Critical to low temperatures

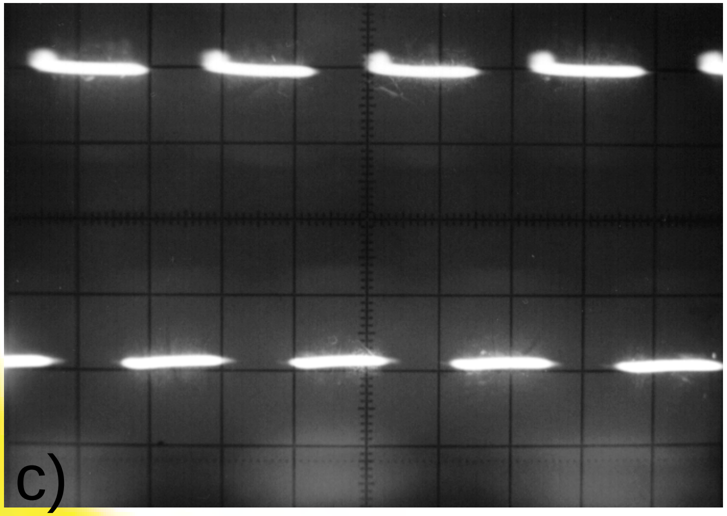
Active Sensor Advantages

- No magnets
- Any metallic target: steel, copper, brass, aluminium, nickel, and iron
- Wide temperature range
- Sensor is not influenced by run-out and external magnetic fields

Experimental Results





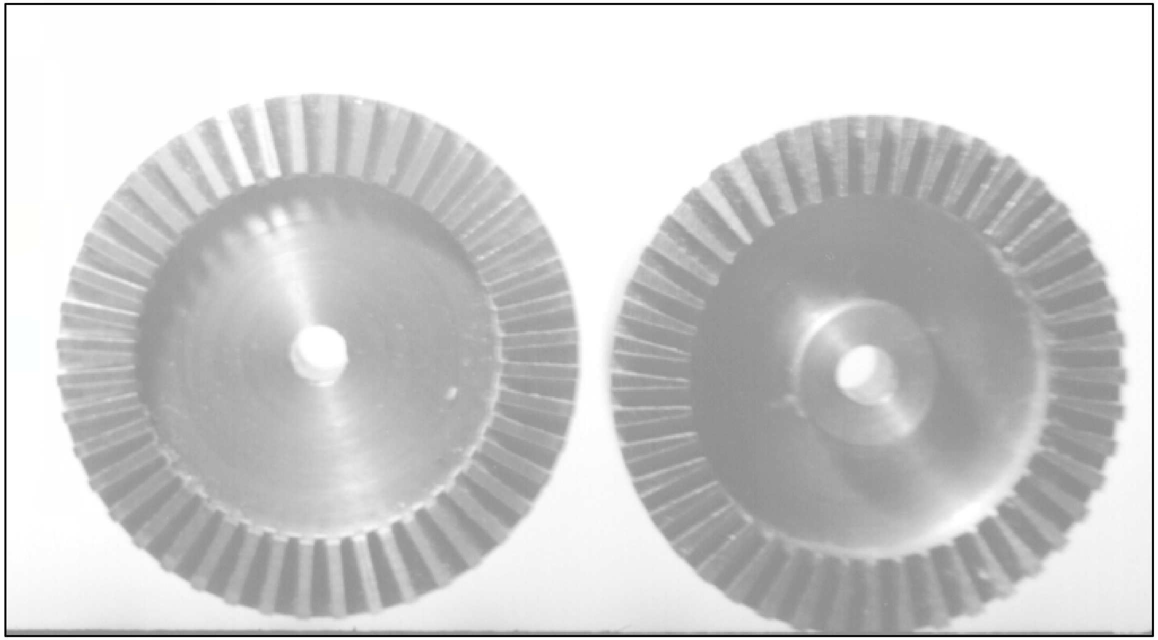


a) 200 rpm

b) 1500 rpm

c) 3000 rpm

Encoders



Example


Henkel
Mobil
Mercedes-Benz
SCHÜCO
Hilton
MICHELIN
JOHNNIE
WALKER
SIEMENS
Mobil

Conversion Method

- Method with non-redundant conversion time (method of dependent count)

Example: Let automobile be driving with speed of 240 km/h (67 m/s), and the time of measurement should not exceed 0.1 sec. (i.e. for this time the automobile will drive no more than 8.7 m at the maximum speed). Let us determine the time of quantization having set the relative error from 0.05 % up to 0.5 % and reference frequency $f_0 = 1/T_0$ = 1 MHz:

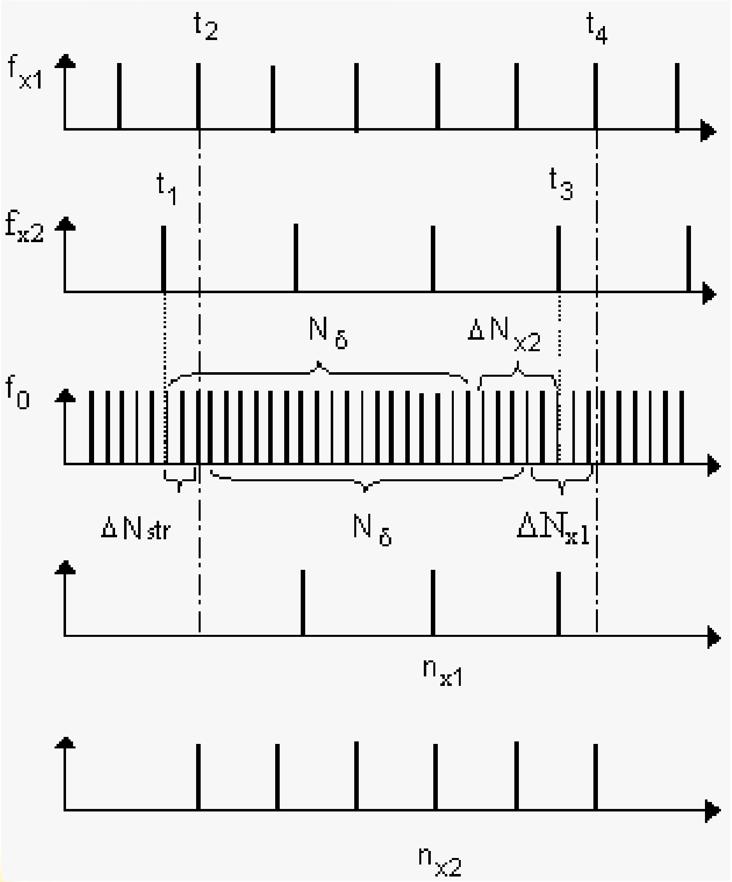
$$T = (1 \div 2) \cdot T_0 N = (1 \div 2)\frac{T_0}{\delta},$$

This time will be varied within the limits 2 ÷ 4 ms at δ = 0.05 % and 0.2 ÷ 0.4 ms at δ = 0.5 %. In case, when f_0 = 10 MHz this time can be reduced in 10 times. Therefore, during 0.1 sec there will be carried out 25 ÷ 50 measurements per second at δ = 0.05 % and 250 ÷ 500 at δ = 0.5 %.

Advanced ABS Algorithm

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

Sensors Interfacing



- Four measuring channels are subdivided conditionally into two groups pairwise channels each
- Each from two groups functions absolute identically
- Hardware sensor interfacing can be realised with the help of four external interrupts and two built-in timers/counters

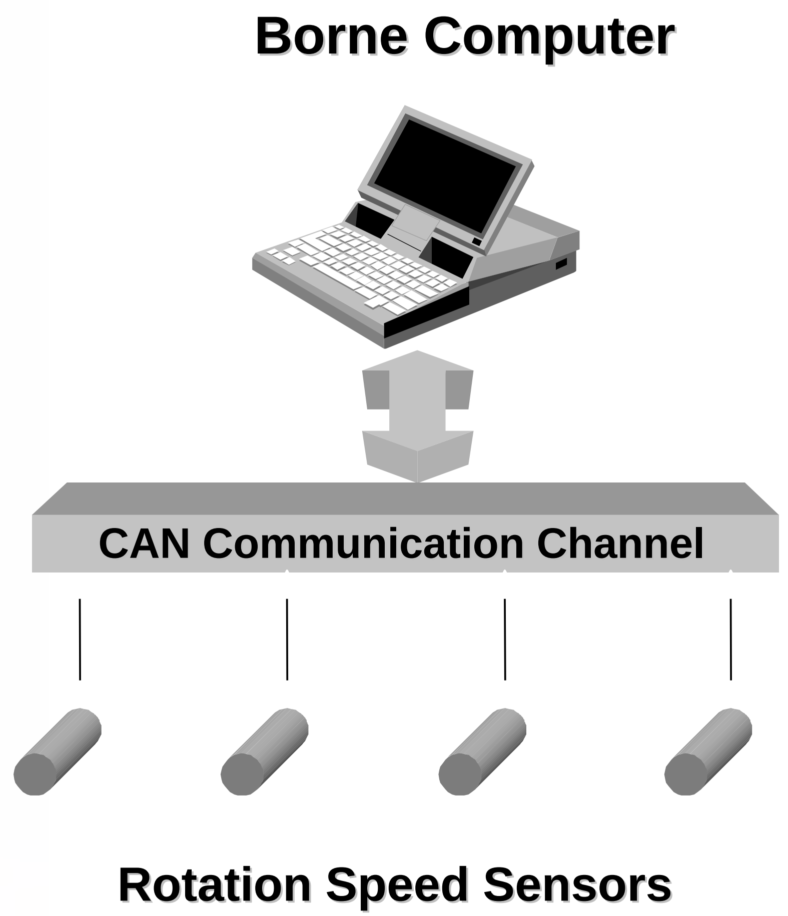
Main Equations

$$f_{x1} = \frac{n_{x1}}{N_\delta + \Delta N_{x1}} \cdot f_0 \qquad f_{x2} = \frac{n_{x2}}{N_\delta + \Delta N_{x2}} \cdot f_0$$

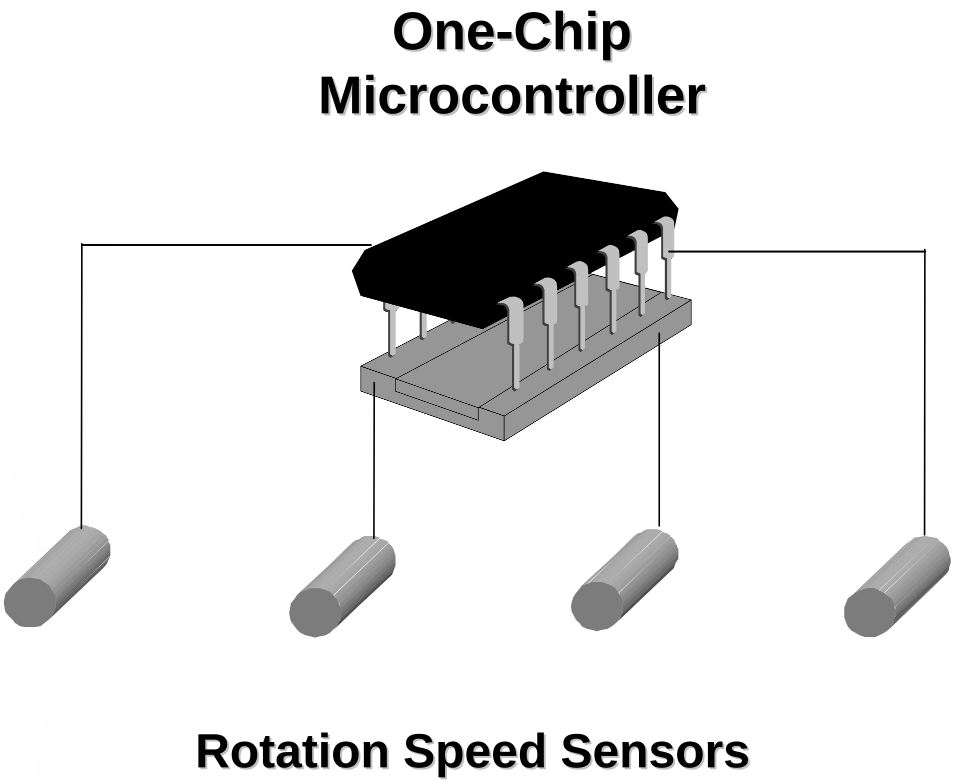
$$t_{x1} = \frac{n_{x1}}{f_{x1}} = \frac{N_\delta + \Delta N_{x1}}{f_0} \qquad t_{x2} = \frac{n_{x2}}{f_{x2}} = \frac{N_\delta + \Delta N_{x2}}{f_0}$$

$$\delta_1 = \frac{1}{N_\delta + \Delta N_{x1}} \qquad \delta_2 = \frac{1}{N_\delta + \Delta N_{x2}}$$

Architecture for High-end ABS



Architecture for Mid-Range ABS



Advantages

- Minimum hardware for realisation
- More simple and cheap encoders
- High economic performance (greater efficiency in the ratio productivity / manufacturability / cost
- Adaptive possibilities allow to use the advanced ABS algorithm (the accuracy can be selected depending on the current rotation speed. It allows to reduce the conversion time for critical rotation speeds
- Possibility to measure the rotary acceleration, in other words, to use the advanced control method for ABS

Multiparameters Sensors

Multiparameters sensors are multifunctional sensor arrays fabricated on silicon substrates for detecting different kind of chemical and physical parameters, which action is concentrated in a small, local area

- It is not simple unit of one-functional sensors
- It is structurally advanced combination with the aim to reduce chip area and sharing usage of digital or quasi-digital output
- Modern silicon technologies offer many advantages in the design of multifunctional (multiparameters) smart sensors

Sensors Examples

- Electronic noses, tongues and gas sensors
- Medical implemented sensors
- Join temperature, pressure and humidity detection in one multiparameters sensor for different environmental tests
- **MPS-D** sensor from SEBA Hydrometrie GmbH for simultaneous measurement of six parameters: pH-value, redox-potential, conductivity, temperature, water level and dissolved oxygen

Conclusions

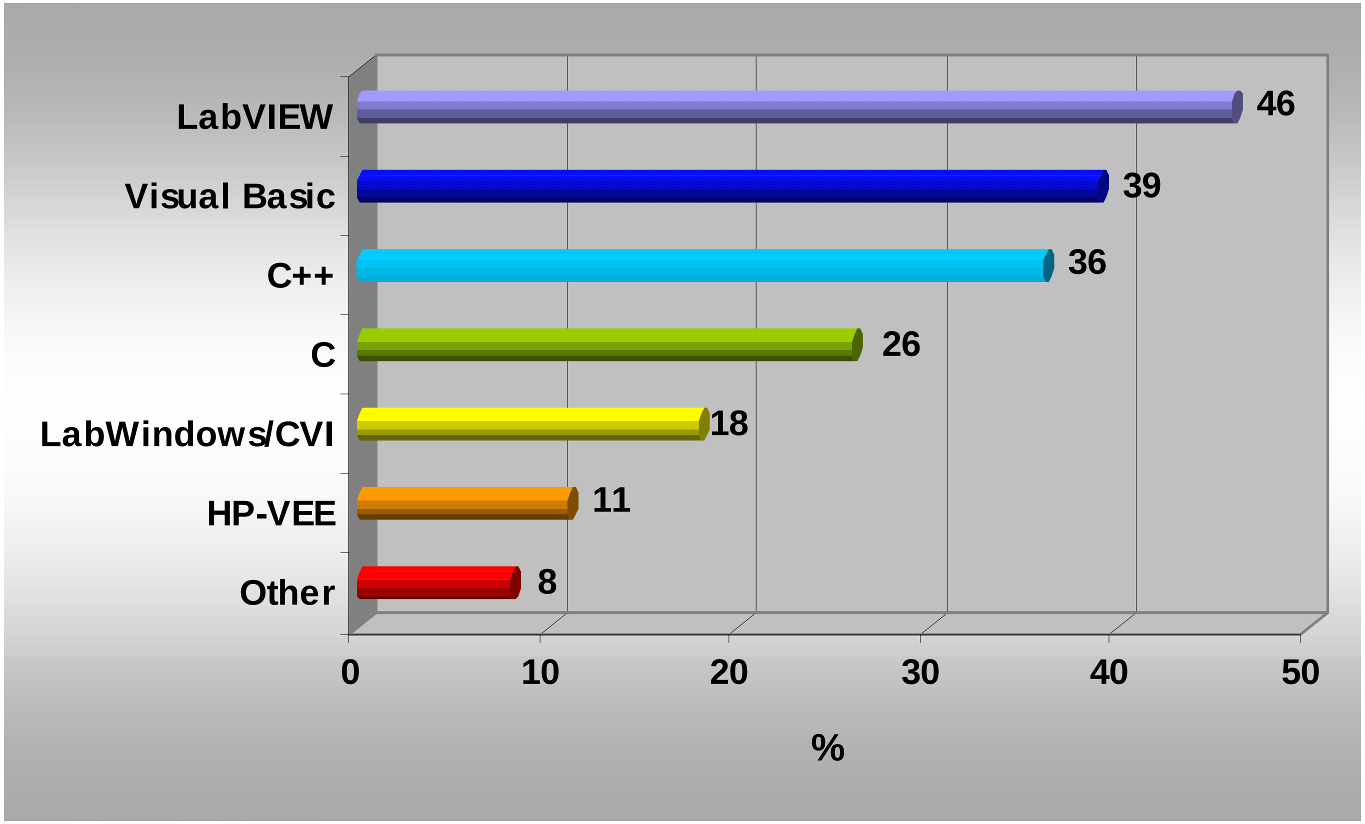
- Smart sensors need smart interface with increased productivity and minimum component on application layer
- Low level software interface can be realized with the help of the program-oriented conversion methods
- In common case, signal processing and conversion for multiparameters sensor signals are the similar to the processing used in multisensor systems

Virtual Instruments

Introduction

- Virtual instrumentation revolution
- "*DAQ hardware without software is useless - and DAQ hardware with poor software is almost as useless*".
- *"The Software is the Instrument"*
- There is an obvious lag of algorithms and software development from progress in microelectronics

Software Used for DAQ



(According to Cahners Research)

Historical Facts

1983 – LabVIEW project has been started

1986 – LabVIEW for Macintosh

1990 – two patents and LabVIEW 2.0, two patents

1992 – LabVIEW for Windows and Sun

1993 – LAbVIEW 3.0

1994 – LabVIEW for Windows NT, Power Mac and HP-UX, new two patents

1995- 2000 LabVIEW for Windows 95/98, LabVIEW 5.0

2001 – LabVIEW 6i for Windows 2000/NT/ME

2003– LavVIEW 7.0 for Windows XP

2006 - LavVIEW 8.0 for Windows XP

Problem Definition

- Distinction between the virtual instrument, intelligent measuring instruments and measuring systems with Graphical User Interface (GUI) becomes slightly fuzzy
- Generally accepted terminology related to the virtual instrumentation did not exist up to 1997/98

NI and HP Definitions

Virtual Instrument (NI) – (1) A combination of hardware and/or software elements, typically used with a PC, that has the functionality of a classic stand-alone instrument; (2) A LabVIEW software module (VI), which consists of a front panel user interface and a block diagram program

According to HP, capability of using graphical software and a personal computer for the processing and displaying of measurement results has been referred to as *“virtual instrumentation”*

VI: Instrument System; Software Graphical Panels; Graphical Programming Technique; Reconfigurable Building Block as VI.

Definitions' Disadvantages

- Rather broad
- Include the measuring systems with GUI
- The second definition from NI includes only LabVIEW software modules

Virtual Instrument Definition (1997)

Virtual Instrument can be described as an instrument composed of a general-purpose computer equipped with cost-effective measurement hardware blocks (internal and/or external) and software, that perform functions of traditional instrument determined both by hardware and software, and operated by means of specialized graphics on the computer screen (*Prof. Winiecki, 1997)*

It means that equipment can be qualified as a virtual instrument, when its hardware part and software part cannot operate separately as a measuring instrument.

Mathematical Definition (1998)

The *necessary condition* of Virtual Instrument existing is the software realisation of the user interface, performed by general-purpose computer and *the sufficient condition* is that hardware and software part of Virtual Instrument do not exist separately as an instrument.

Measuring Channel Parts

- Input data acquisition (F_1)
- Data processing (F_2)
- Output data presentation (user interface) (F_3)

$$R_1 = F_1(H) + F_2(H) + F_3(H) \Rightarrow TI$$

$$R_1 = F_1(H) + F_2(H) + F_3(S) \Rightarrow MS/VI$$

$$R_1 = F_1(H) + F_2(S) + F_3(S) \Rightarrow VI$$

μC Based Traditional Instruments

$$R_{1A} = F_1(H) + F_2(S) + F_3(H)$$

- typical microprocessor instruments of the first generation

$$R_{1B} = F_1(S) + F_2(S) + F_3(H)$$

- measuring instruments with virtual channel

$$R_{1C} = F_1(S) + F_2(H) + F_3(H)$$

- measuring instruments with increased processing speed

- Software is the key
- Low cost
- Reusable
- Flexible functionality

Additional Basic Models

$$R_{2A} = F_1(S) + F_2(H) + F_3(S)$$

$$R_{3A} = F_1(S) + F_2(S) + F_3(S)$$

- virtual instrument or a measuring system with GUI, composed of the modern microcontroller based measuring instruments

In these cases the measuring instrument can be qualified as a VI, when its hardware part and software part cannot operate separately as measuring instruments

Complete Set of Base Models

$$\left.\begin{aligned}
R_1 &= F_1(H) + F_2(H) + F_3(H) \\
R_{1A} &= F_1(H) + F_2(S) + F_3(H) \\
R_{1B} &= F_1(S) + F_2(S) + F_3(H) \\
R_{1C} &= F_1(S) + F_2(H) + F_3(H)
\end{aligned}\right\} \Rightarrow \mathrm{TI}$$

$$\left.\begin{aligned}
R_2 &= F_1(H) + F_2(H) + F_3(S) \\
R_{2A} &= F_1(S) + F_2(H) + F_3(S) \\
R_3 &= F_1(H) + F_2(S) + F_3(S) \\
R_{3A} &= F_1(S) + F_2(S) + F_3(S)
\end{aligned}\right\} \Rightarrow \mathrm{MS/VI}$$

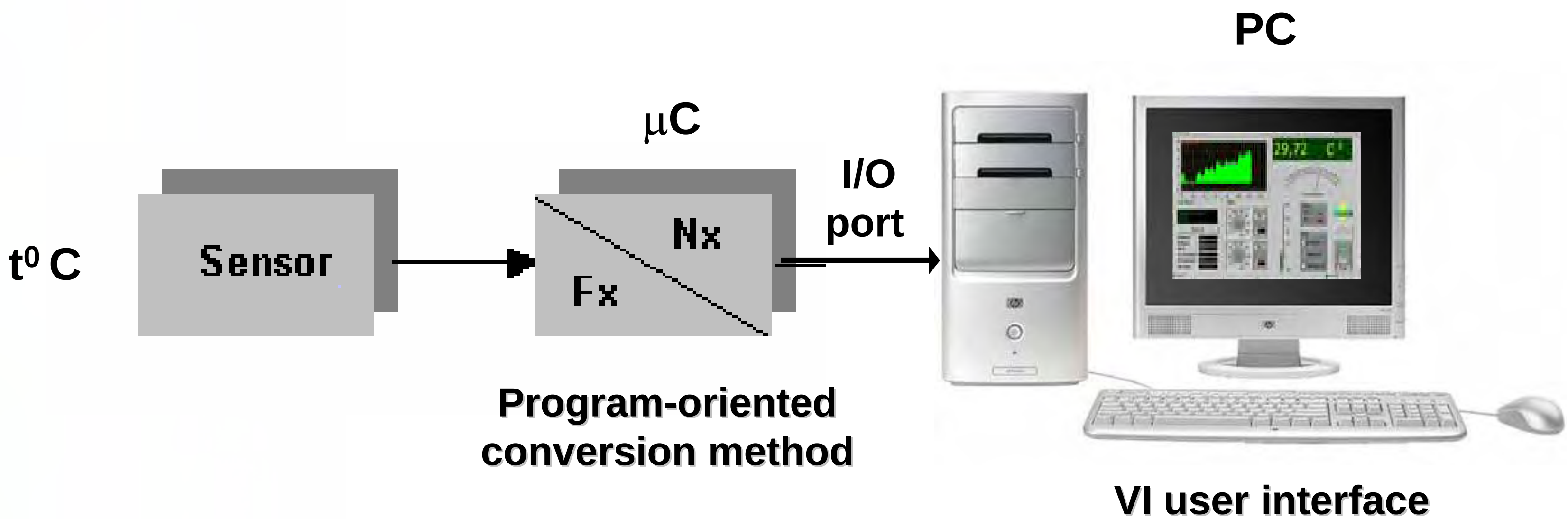
Industrial DAQ Boards

Type	Maximum Source Frequency, MHz	Number of Channels	Base Clock Accuracy, %
Timing I/O Boards, *National Instruments* (USA)			
PC-TIO-10	7	10	0.01
NI 660X	20 ÷ 80 (60 ÷125)	4 ÷ 8	0.005
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 (error of measurement)
Digital I/O and Timing Board, *Mielhaus Electronic (Germany)*			
ME-1400A/B	10	3 ÷ 6	0.01
Module of Time-to-Digital Cnverter, *Acqiris*			
TC840	20 s	13	0.0002
DAQ System, Intelligent Instrumentation *(США)*			
UDAS-1001E	10	1	N/a
Multifunctional Timer/Counters Boards, *ADLINK Technology* (*Taiwan)*			
ACL-8454/X	10	6 ÷ 12	N/a
PCI-8554	10	16	N/a
Timer/Counters Boards, *OMEGA (USA)*			
CIO-CTR10HD	7	10	N/a
CIO-CTR20HD	7	20	N/a
Timer/Counters Boards, *Contec (Japan)*			
CNT16-32S	0.2	32	N/a
CNT24-4	1	4	N/a
TCR-10	7	10	N/a
Module for Frequency Measurements, *Mera (Russia)*			
MC-451	0.01 Hz ÷ 400 kHz	8	0.001 ÷ 0.01 (FS error)
Digital I/O and Counter Board, *Advantech (USA)*			
PCL-720	2.6	3	N/a
Timer/Counetrs Boards, *Axiom (Taiwan)*			
AX5216	7	5	N/a
AX5218	7	10	N/a
AX5220	10	3	N/a

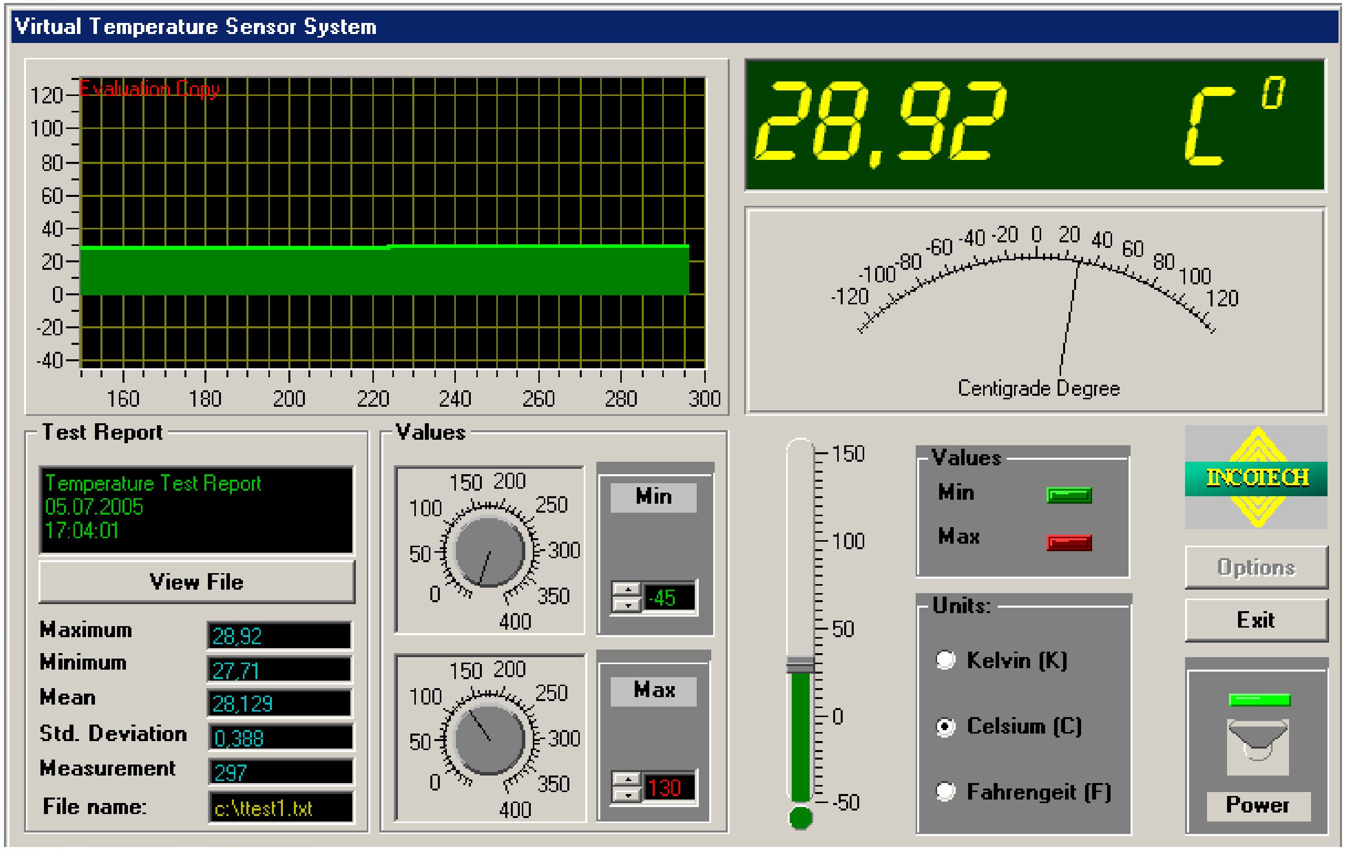
DAQ Boards Features

- 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

Virtual Thermometer



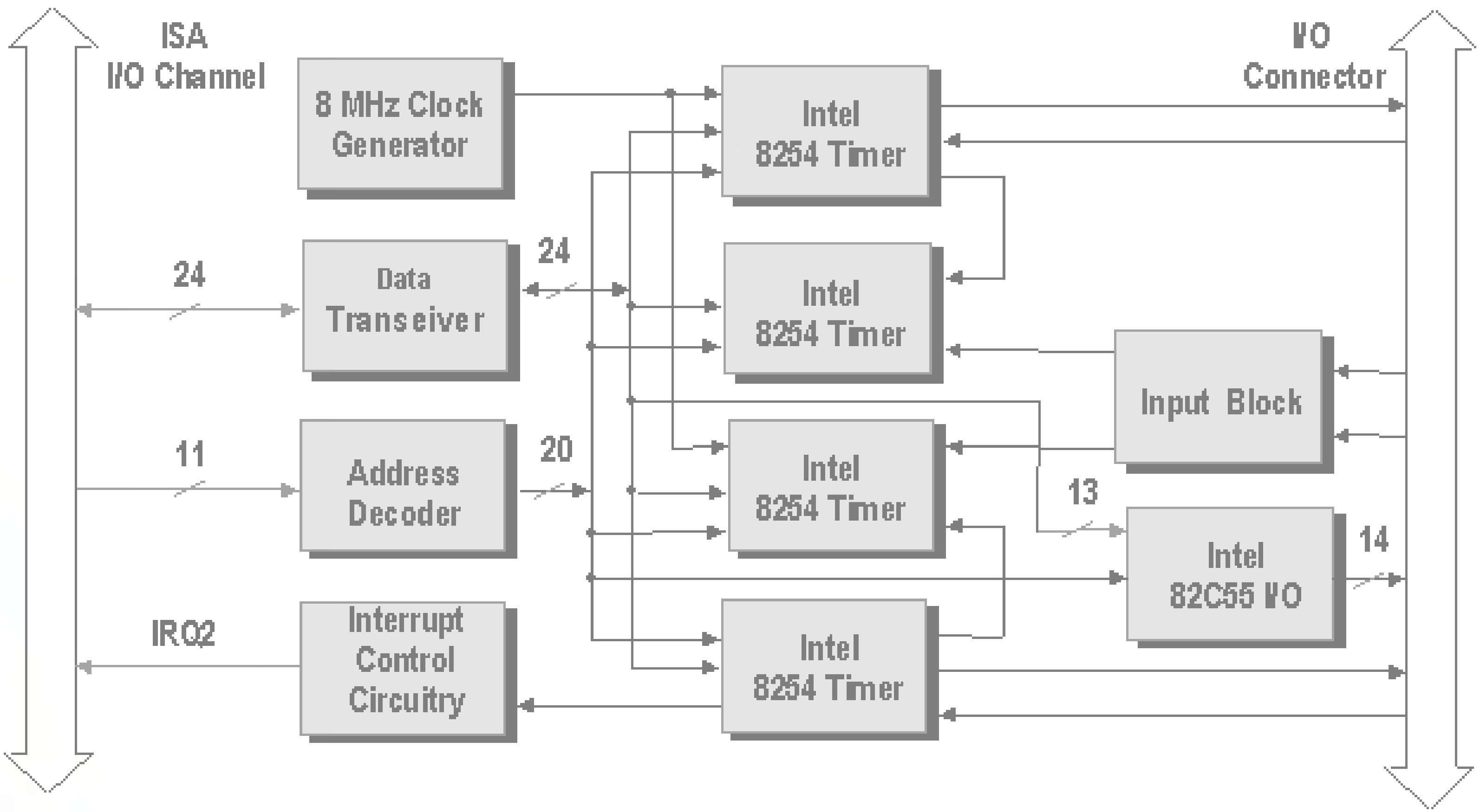
User Interface



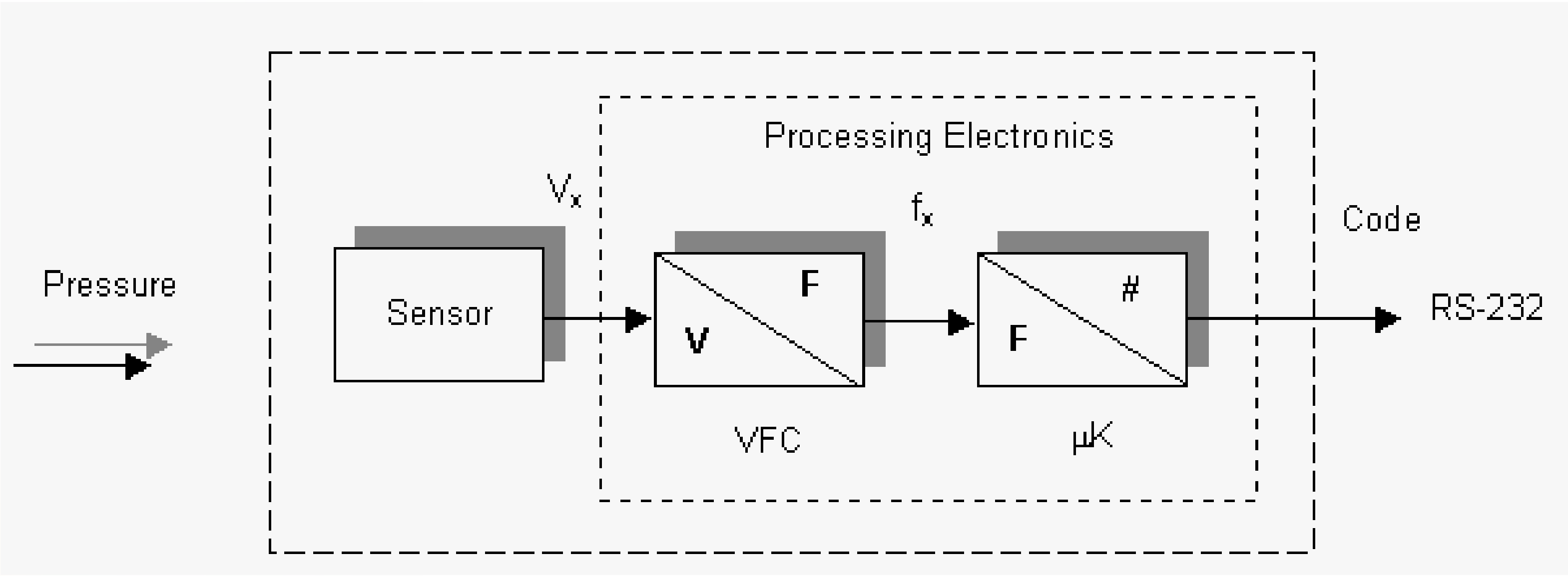
Technical Performances

- Temperature range, ^{0}C - 45 ... + 130
- Absolute accuracy, ^{0}C ± 0.7
- Relative error, % ± 0.54
- Linearity is better than 0.2 ^{0}C
- Directly connectable to LPT port
- Cable length up to 20 m
- Statistics calculation
- File of results
- Digital, analog and sound indications

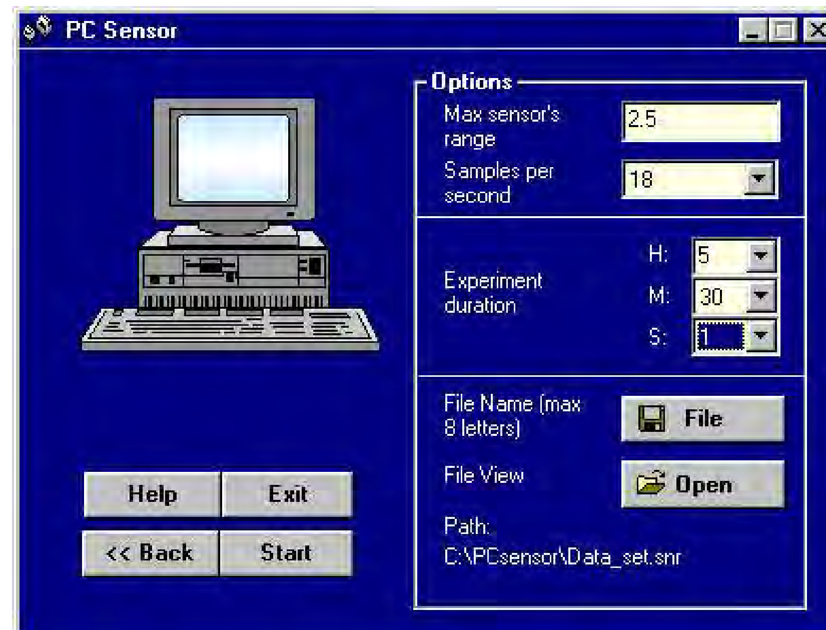
DAQ Board


ISA
I/O Channel
8 MHz Clock Generator
Intel 8254 Timer
I/O Connector
24
24
Data Transeiver
Intel 8254 Timer
Input Block
11
20
Address Decoder
Intel 8254 Timer
13
Intel 82C55 I/O
14
IRQ2
Interrupt Control Circuitry
Intel 8254 Timer

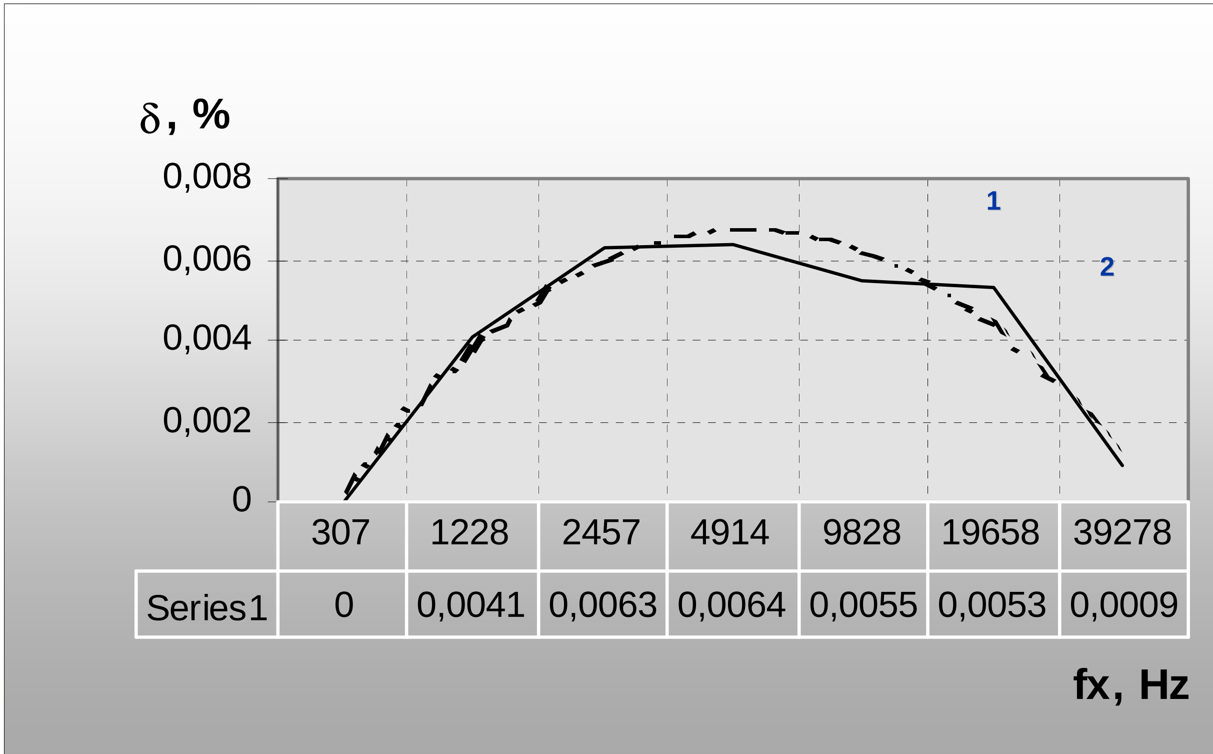
Data Logger for Pressure Sensors



User Interface



Experimental Results



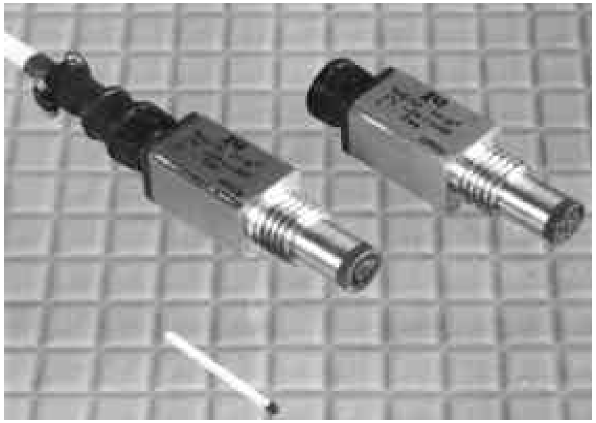
	307	1228	2457	4914	9828	19658	39278
Series1	0	0,0041	0,0063	0,0064	0,0055	0,0053	0,0009

Technical Performances

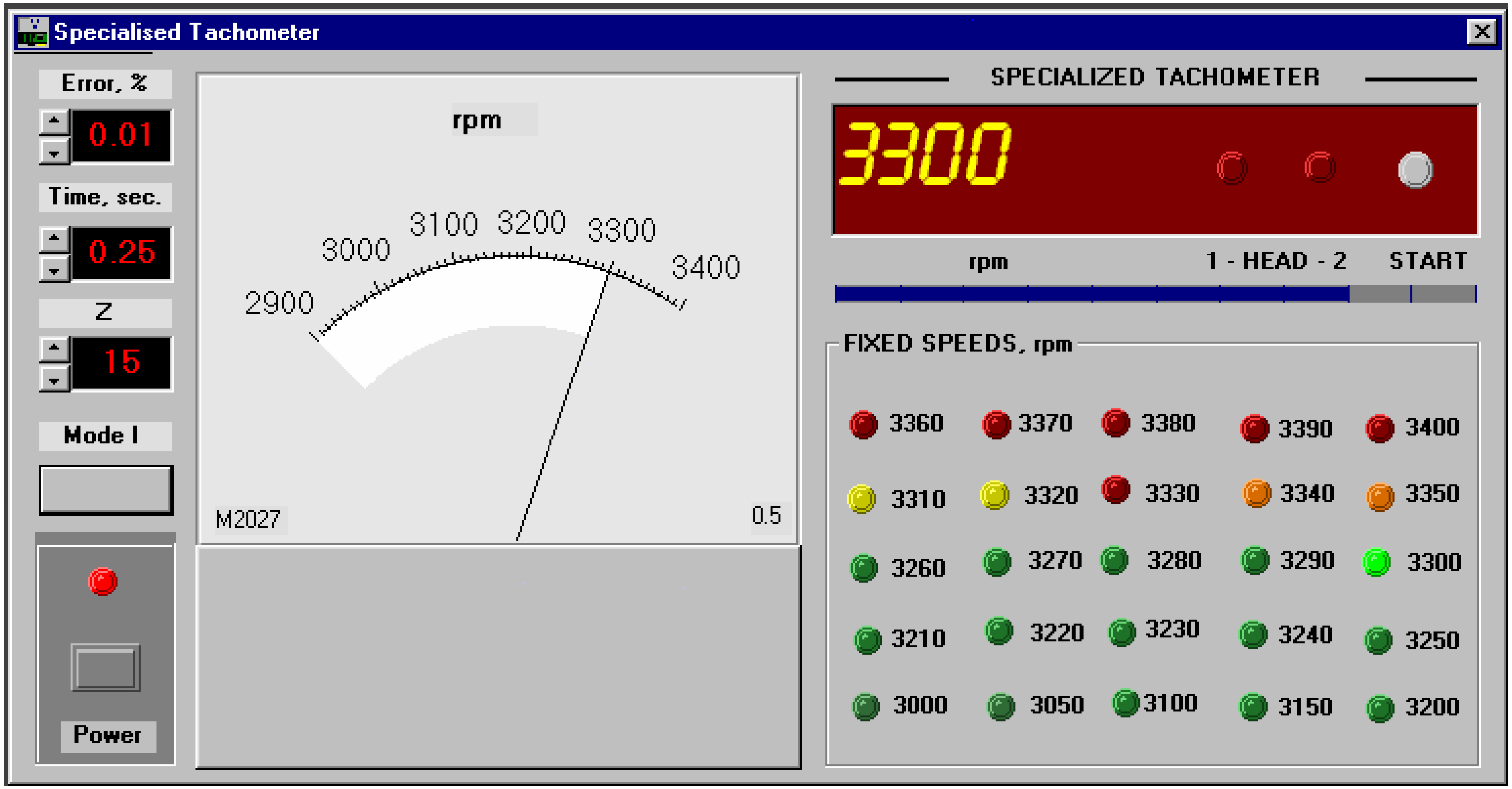
- Specified measuring range of frequencies from 400 up to 40 000 Hz
- With probability 97 % the total error does not exceed 0.0064 % in all range of frequencies
- Conversion error can be neglected, as it is in 2 orders less than the nonlinearity error of used voltage-to-frequency converter and in three-four orders less than sensor's error
- Dependence of total error of measurement against frequencies is explained by calculation error. It depends on the features of arithmetic with floating point, namely, from the operands

Tachometric System

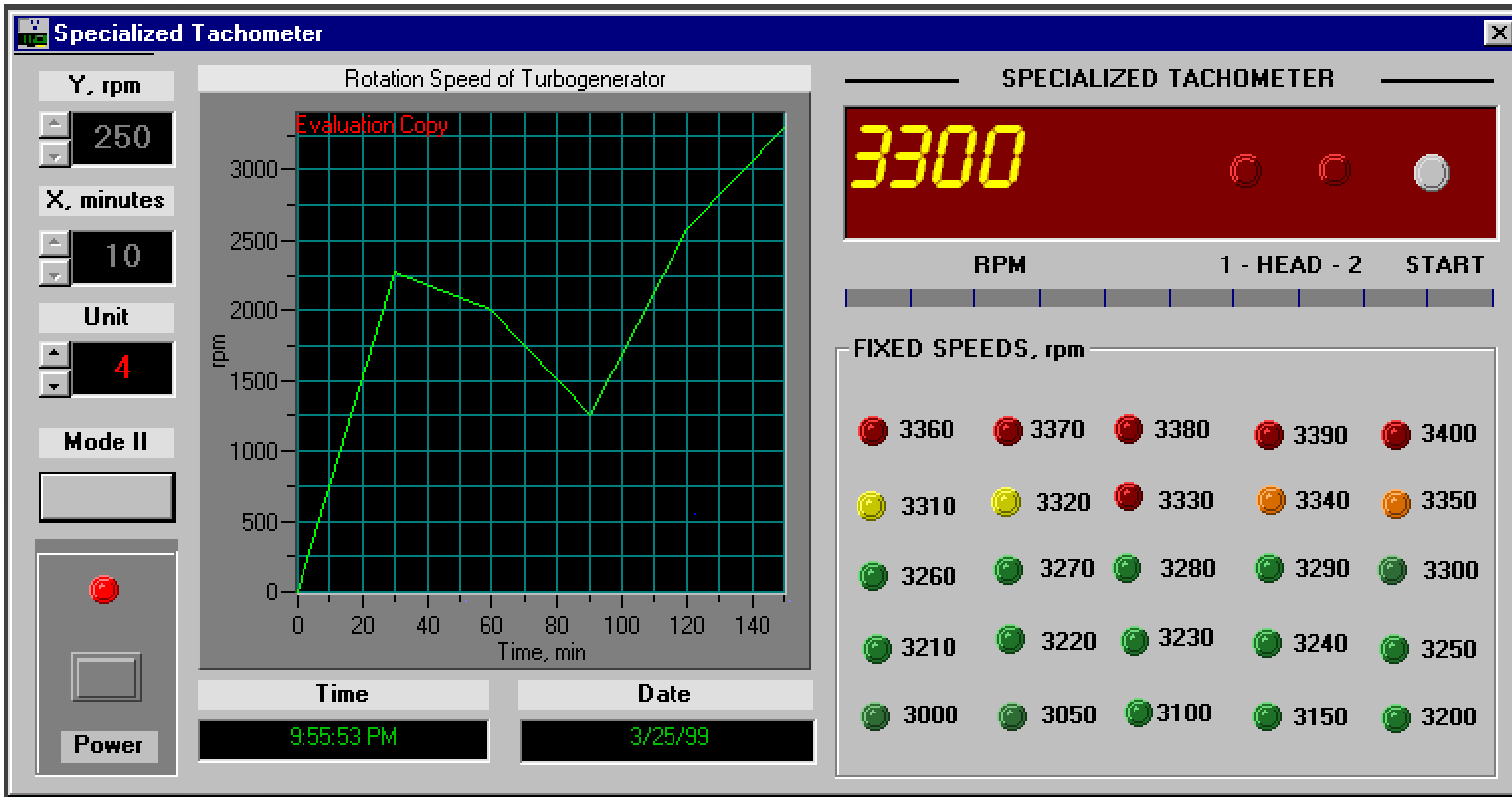
- Semiconductor active sensor of rotation speed
- Two sensors of circuit-breaker's firing-pins
- Interfacing block for sensor of rotation speed with the turbogenerator's shaft



Virtual Tachometer (Mode 1)



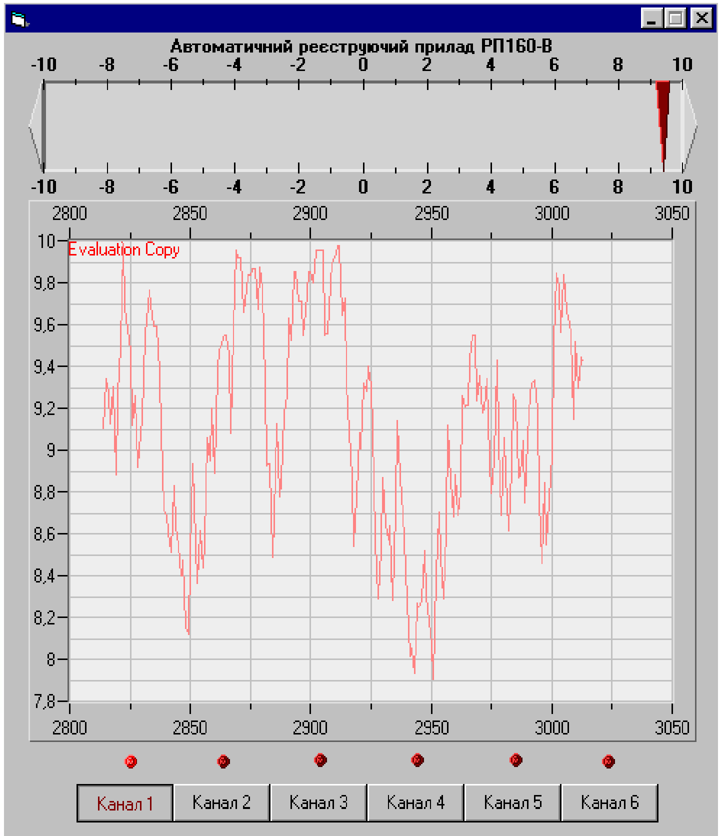
Virtual Tachometer (Mode 2)



Advantages

- Increased accuracy of measurement and operating speed
- Extended functionality
- Full automatization of the tuning process for the control system
- Universality
- Minimum possible hardware and high adaptability to manufacture of such instrument

Videographic Paperless Recorder



Number of channels	16
Capacitive sensors, pF	0÷2, 0÷12, up to 300
Platinum resistor	Pt100, Pt1000
Thermistor, kΩ	1÷25
Resistive bridges with max imbalance ±4% or ±0,25%	250Ω÷10kΩ
Potentiometers, kΩ	1÷ 50
Frequency input, Hz	0,01÷ 2000000
Frequency sensor accuracy	up to ± 0.0001%
Resolution, bits	14
Linearity, bits	11÷13
Measurement time, ms	10÷100

Sensor Buses, Protocols and Networks

Sensors Buses

- There are hundreds sensors communication between a central computer and smart sensors in a modern car and thousands sensors communication in space shuttles
- Sensors are produces by different manufacturers
- Sensors' outputs have different formats
- Data transfer should be organized in an orderly and reliable fashion

Network Protocols

- There are a lot of different protocols coupled with its application field
- Each protocol having its own interface requirements
- Requirements stipulate following parameters:

- headers;
- data-word length and type;
- bit rate;
- cyclic redundancy check;
- others

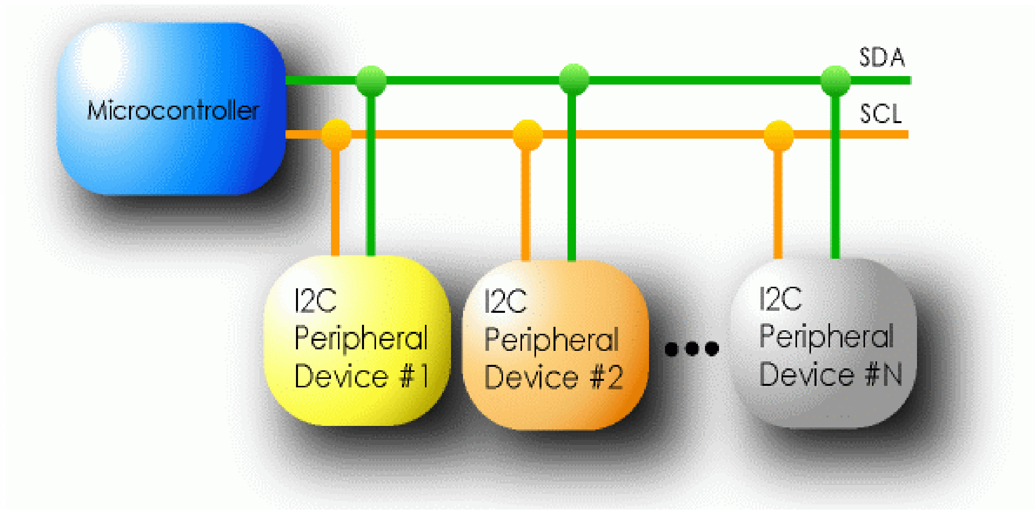
Sensor Buses

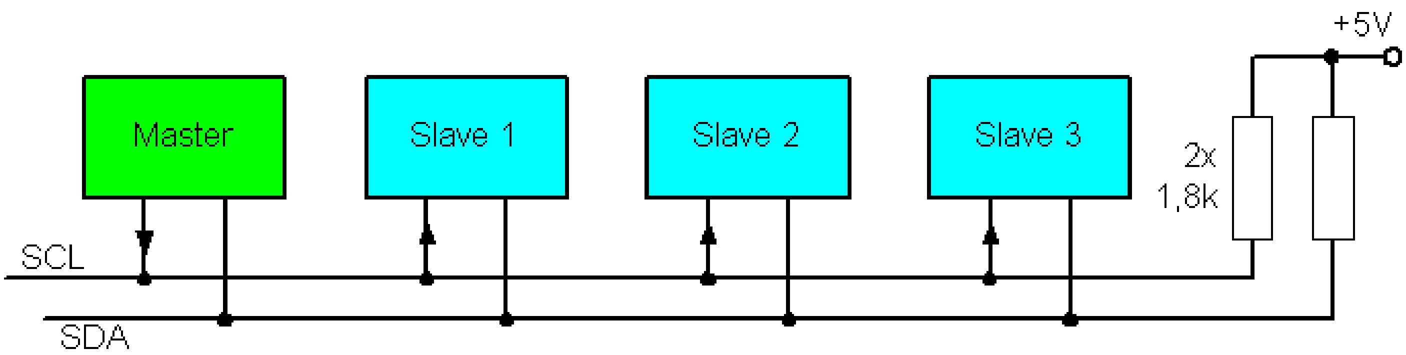
- I^2C
- SPI
- SMBus
- Maxim/Dallas 1-Wire and 3-Wire buses
- CAN Bus
- MODBus (protocol)
- SSI (bus and protocol)
- FieldBus

Integrated Circuit Bus (I^2C)

- 2-wire serial interface standard defined by Philips Semiconductor in the early 1980's
- Only two active lines - clock Serial CLock line (SCL) and data Serial DAta line (SDA) are required for full duplexed communication
- Simple master/slave type interface
- 100 kHz to 400 kHz transmission speed
- Each sensor on the bus has a unique address (127 maximum)
- In most sensor systems a microcontroller is the master and sensors are slaves
- There are many different variations of I^2C in use

I²C Diagram


Microcontroller
SDA
SCL
I2C Peripheral Device #1
I2C Peripheral Device #2
I2C Peripheral Device #N

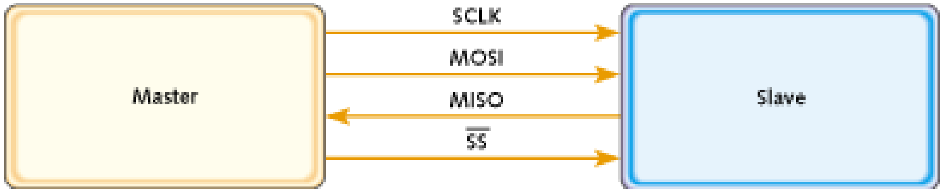

+5V
Master
Slave 1
Slave 2
Slave 3
2x 1,8k
SCL
SDA

Serial Peripheral Interface (SPI)

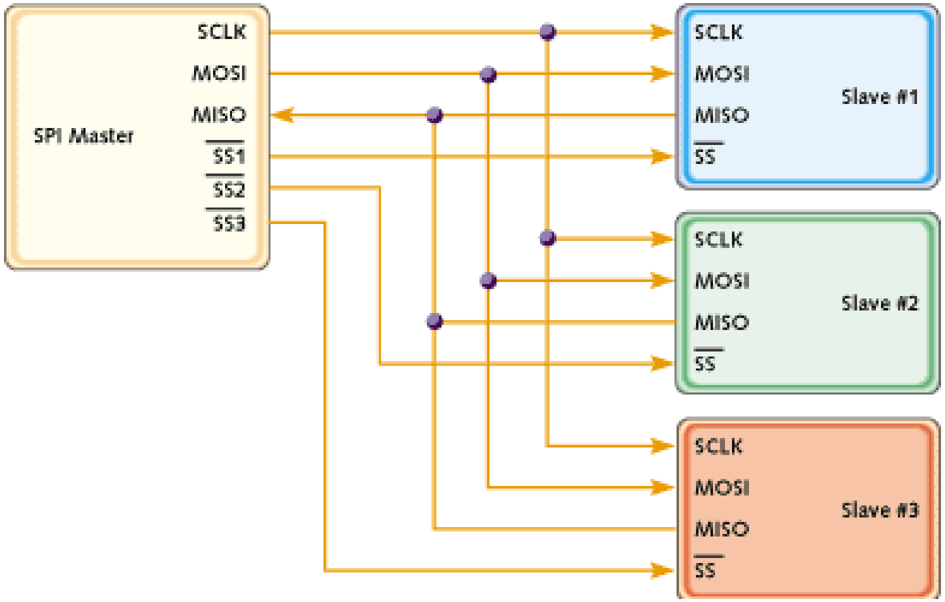
- 4-wire serial communications master/slave interface defined by Motorola
- It is a simple synchronous serial interface for connecting low speed external devices
- Full-duplexed protocol is used in SPI
- SPI specifies four signals: clock (SCLK); master data output, slave data input (MOSI); master data input, slave data output (MISO); and slave select (SS)
- A chip-select input is required to enable the sensor that makes possible to connect many sensors to same SPI bus in parallel

SPI Diagrams

Single master, single slave:



Single master, multiple independent slaves:



SPI vs. I^2C

- Both SPI and I^2C offer good support for communication with low-speed devices, but SPI is better suited to applications in which devices transfer data streams
- SPI is simple and efficient for single master, single slave applications but it can be troublesome to implement for more than one slave, due to its lack of built-in addressing
- SPI can achieve significantly higher data rates than I^2C. Its often range is up to 10 MHz

System Management Bus (SMBus)

- 2 – wire interface which is based on the I^2C bus
- Defined by Intel in 1995
- SMBCLK and SMBDAT bidirectional lines, pulled high via a resistor
- Operate at a frequency of 100 KHz
- SMbus link may have multiple masters and slaves devices on the bus

SMBus and I^2C Comparison

	I^2C	SMBus
Timeout	No	Yes
Minimum Clock Speed	DC	10 kHz
Maximum Clock Speed	100 kHz (400 kHz and 2 MHz)	2.1 V
V_{HIGH}	0.7 * V_{DD}, 3.0 V Fixed	0.8 V
V_{LOW}	0.3 * V_{DD}, 1.5 V Fixed	0.8 V
Max I	3 mA	350 µA
Clock Nomenclature	SCL	SMBCLK
Data Nomenclature	SDA	SMBDAT
General Call	Yes	Yes
Alert #	No	Yes

Maxim / Dallas 1-Wire Bus

- 1-Wire® is a simple control network system developed by Dallas/Maxim
- It is similar in concept to I^2C, but with lower data rates and a much lower cost
- It allows one signal wire to carry both operating power and signal
- The system is quite sensitive to the right timing to operate well

Maxim 3-Wire Bus

- The data flow to and from the sensor (DS1620) is multiplexed on only one pin (DQ) while SPI needs two separate signals (MOSI, MISO)

CAN Bus (1980, Bosh)

- **Controller Area Network Bus** Suitable for industrial applications, building automation, railway vehicles and ships
- It is the basis of several sensor buses
- Extensive error detection and correction features of CAN can easily withstand the harsh physical and electrical environment
- Many semiconductor manufacturers propose microprocessor with embedded CAN controllers

Examples: pressure transducer of COP series with FS accuracy up to 0.15 % (Trafag GmbH); CO_2 sensor based on infrared light absorption from Madur Electronics (Austria).

MODBus

- Serial communications protocol published by Modicon in 1979 for use with its programmable logic controllers (PLCs)
- De facto standard communications protocol in industry
- Restricted to addressing 254 devices on one data link
- It is a protocol that doesn't insist on voltage levels, connection pins, etc.
- Modbus devices can use a variety of cables or networks, including RS485 or RS232

Synchronous Serial Interface (SSI)

- SSI bus consists of 4 signals; SCLK, SDATA, SDEN0, and SDEN1
- It is a bi-directional (3-state) data line which requires a pull-up or pull-down resistor
- Data is sent in 8 bit bytes, LSB first.

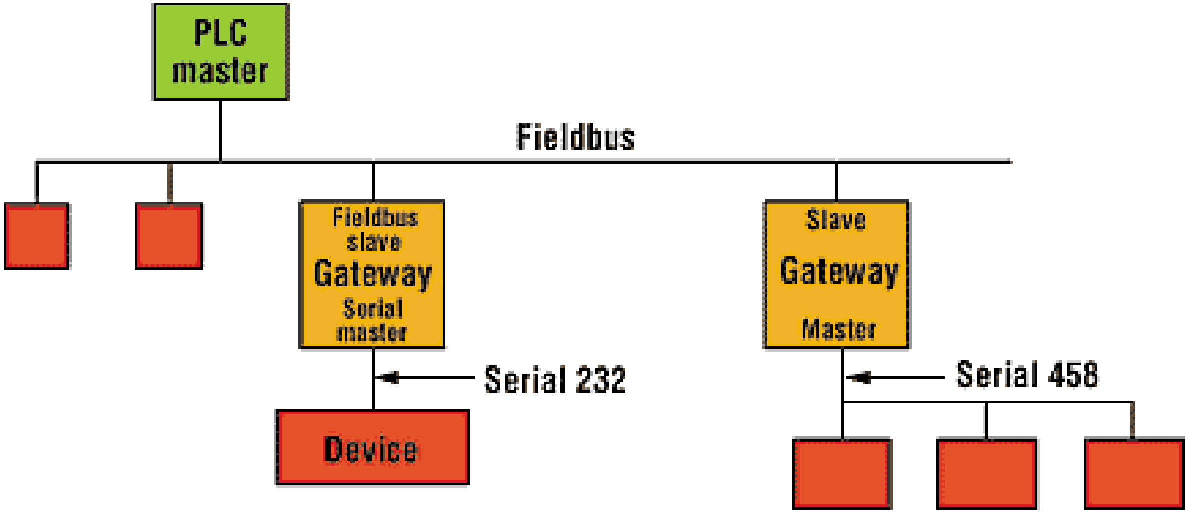
Simple Sensor Interface Protocol

- SSI (Simple Sensor Interface) protocol is a simple communications protocol designed for data transfer between computers or user terminals and smart sensors
- SSI protocol is used in point-to-point communications over UART and networking nanoIP applications. SSI also provides polling sensors and streaming sensor data. For RFID sensor tags SSI specifies memory map for sensor data

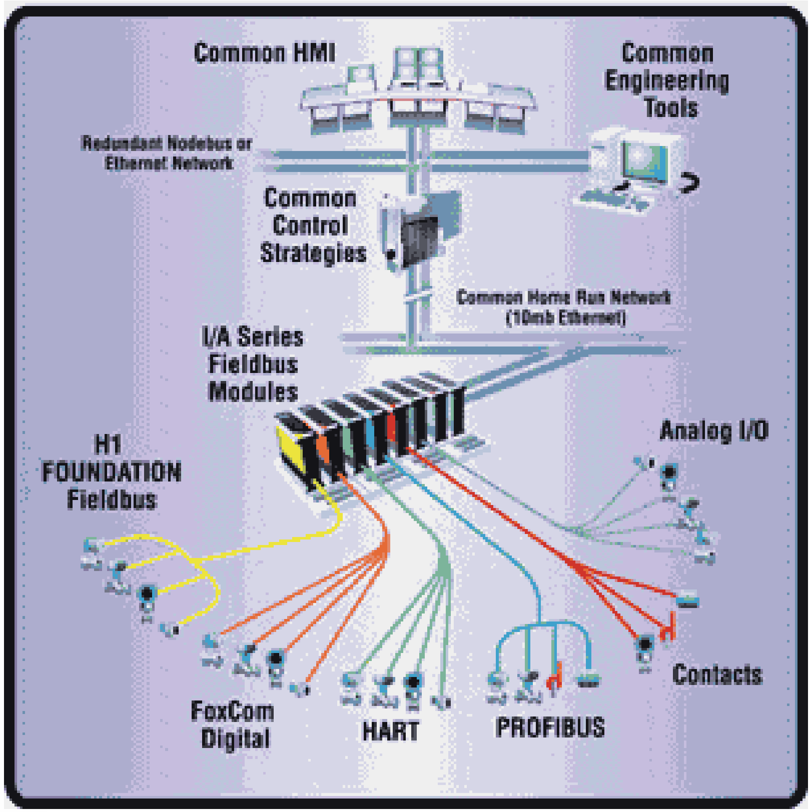
Fieldbus

- A **Fieldbus** is an industrial network system for real-time distributed control
- This is typically linked to a middle layer of programmable logic controllers (PLC) via a bus system (e.g. Ethernet)
- The network is a digital, bi-directional, multidrop, serial-bus, communications network used to link isolated field devices, such as controllers, transducers, actuators and sensors
- Each field device has low cost computing power installed in it.

FieldBus Architecture



FieldBus Example



Smart Sensors Buses

- Smart sensors are a new kind of application
- Majority of existing digital bus systems can not be directly applied for smart sensors networks
- I^2C (topology is rather simple and it has minimum hardware requirements but the communication protocol is too rigid)

IS^2 Bus

- IS^2 *(Integrated Smart Sensor)* is similar to the I^2C bus but with a highly simplified protocol
- Like to I^2C it requires two lines for communication: clock line and data line
- Data field length is not determined
- Transmission can be terminated either by data master or data sensor

Wireless Sensor Networks

- WSN is a computer network consisting of spatially distributed autonomous sensors
- Each sensor module (node) in a sensor network consists of sensors, data converters, a small microcontroller, radio transceiver or other wireless communications device, power management circuitry and battery
- Main standards: ZigBee, Bluetooth. Both are types of IEEE 802.15 wireless personal-area networks but with different modulation technique

Bluetooth vs. ZigBee

	Bluetooth	ZigBee
Frequency Band	2.4. GHz	2.4. GHz
Network Range	1 or 100 m	Up to 70 m
Data Rate	0.8 - 1.0 Mb/s	0.02 – 0.2 Mb/s
Protocol Stack Size	250 Kbyte	28 Kbyte
Network Join Time	3 s	30 ms
Cost	Low	Lower
Power	Low	Lower
Application Focus	Cable replacement	Monitoring & control
Problems	Speed and Interference issues	Very less communication range, low data-rate

Sensor Interface and FDC Integrated Circuits

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*
- SSP1492 - Sensor Signal Processor from *Sensor Platforms, Inc. (USA)*

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 Interval Measurements (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
- RS-232/485 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-F1:** 8-channel; resolution 60-120 ps; measurement range is 5 ns ÷ 7.8 μs; 24-bit parallel bus; reference frequency 1 MHz ÷ 40 MHz; 160-pin PQFP package
- **TDC-GP2:** resolution 50 ps; SPI interface; measurement range 3.5 ns ÷ 1.8 μs
- **TDC-GPX:** resolution 10 – 81 ps; measurement range 10 ns ÷ 10 μs

2-Channel TDC-GP1

- Resolution of approx. 250 ps; 2 measuring ranges: 2 ns - 7.6 µs and 60 ns-200 ms
- 4 ports to measure capacities, coils or resistors with 16 bit precision and up to 20 000 measurements per second
- Internal ALU for the calibration, 8-bit processor-interface
- Power consumption (10 µA), fully battery operation is possible
- Ranges for R, L and C measurements: 100 Ω ÷1 MΩ, 10 µH ÷ >10 H, 10 pF ÷ 1 mF accordingly

8-Channel TDC-F1

- 8 channels with approx. 120 ps resolution
- Optional 4 channels with approx. 60 ps resolution
- Optional 32 hit-channels with approx. 5.7 ns resolution
- Measuring range: approx. 7.6 µs
- 8-Bit I/O Interface

Time-to-Digital Converter (TDC)

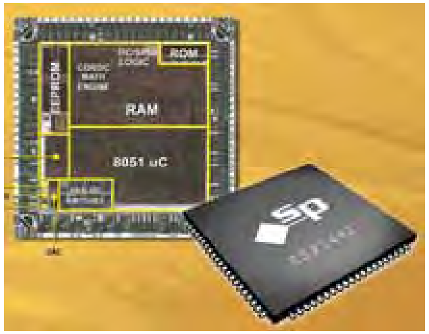
- Ultrasonic-based flow and density measurements
- Temperature measurements (Pt100, Pt500)
- Nuclear and high-energy physics
- Laser distance measurement
- Ultrasonic position feedback devices
- Capacitance and resistance measurement
- Frequency and phase measurement (in a few ranges)

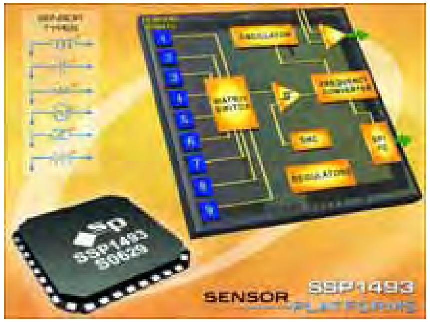
TDC (cont.)

- Used the modified method of delayed coincidences
- Limited low frequency range
- Relatively high price
- Only slave communication mode
- Narrow functionality

Sensor Signal Processor SSP1492/1493

- 80/32-pin IC (SoC)
- Includes a frequency-time mode converter with scalable resolution and conversion time
- SPI and I^2C interfaces
- Reference frequency 18 MHz/ 150 MHz)
- Based on the classical conversion method
- Low functionalities for frequency-time domain signals (period and pulse width)





IFSA

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.

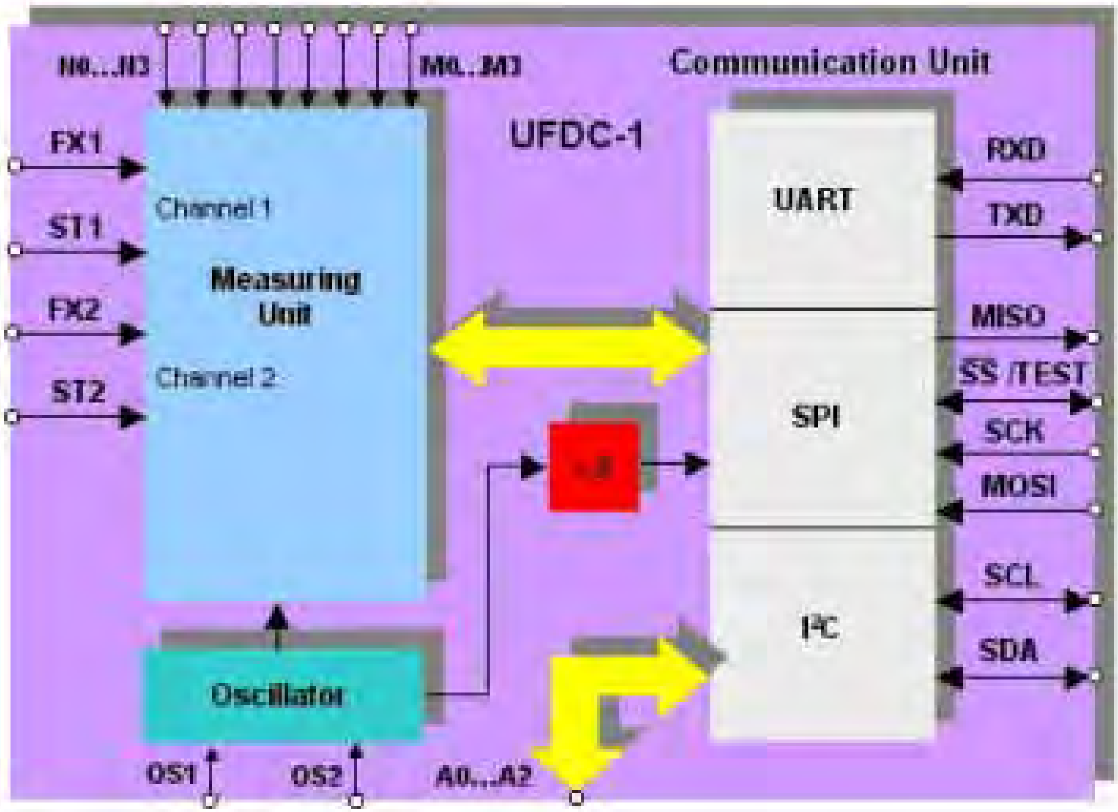
Universal Frequency-to-Digital Converter (UFDC-1)

- 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

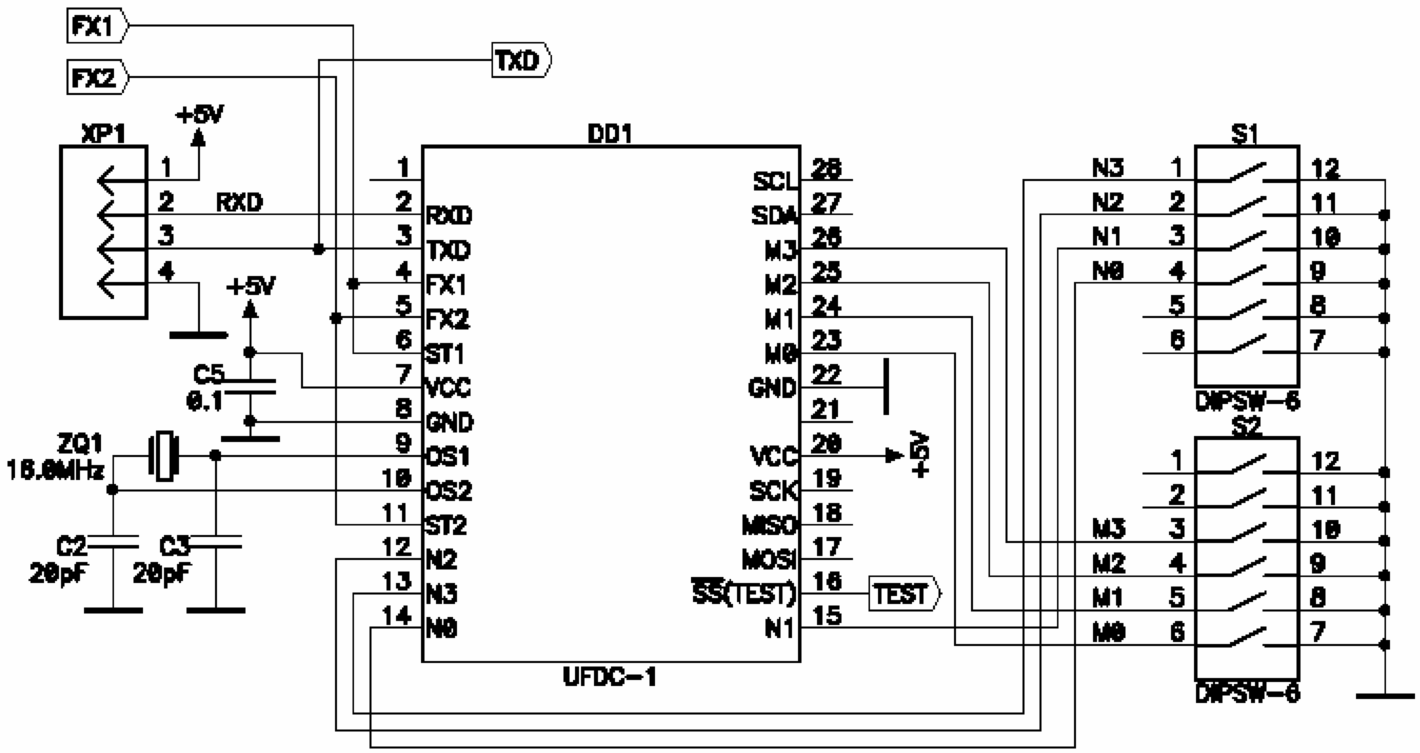
UFDC-1 Block Diagram



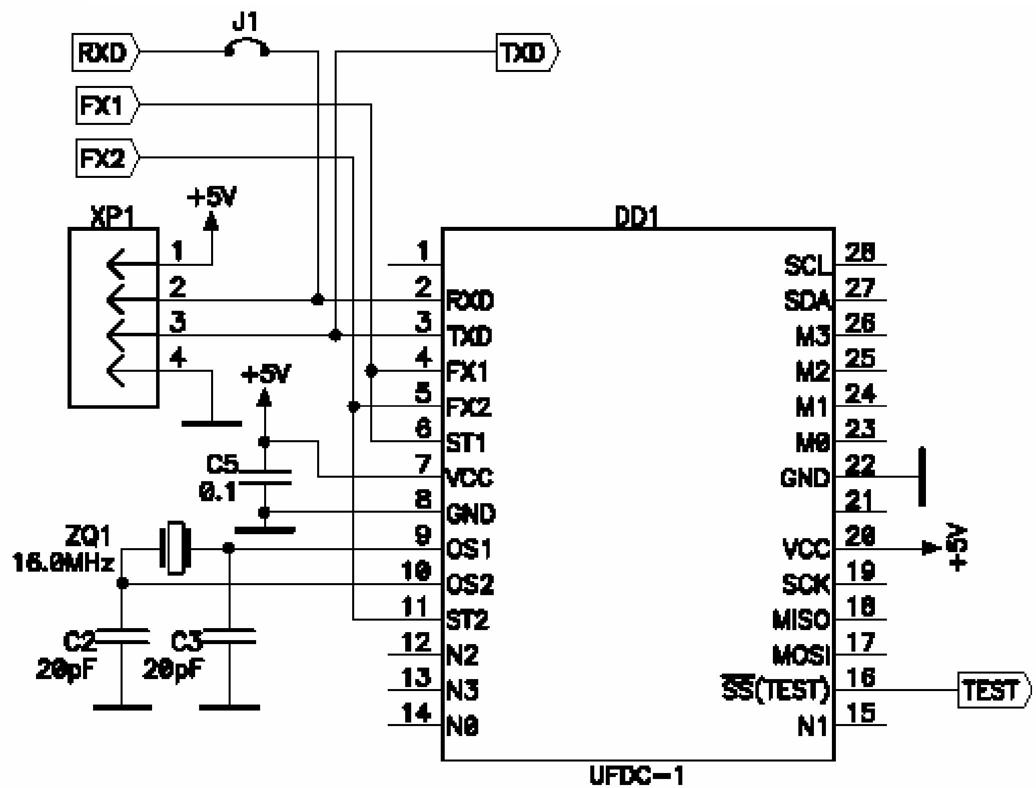
Measuring Modes

- 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 $0 - 4 \cdot 10^9$

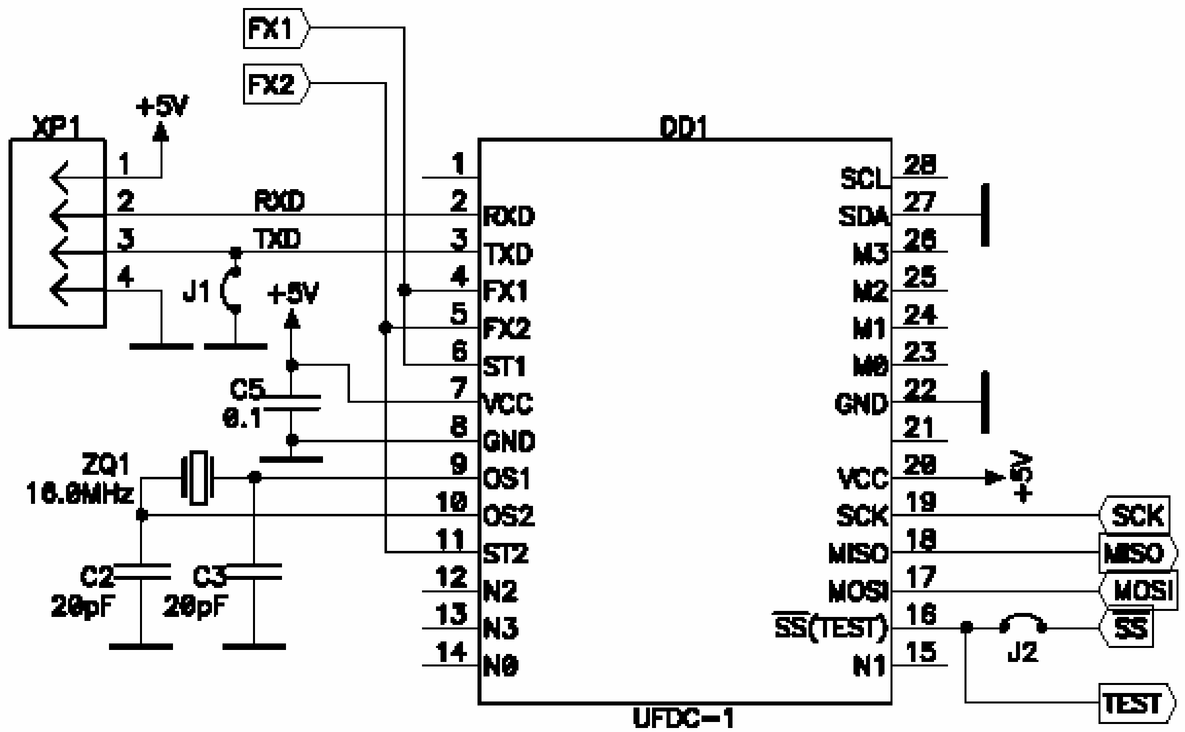
UFDC-1 Master Mode (RS-232)



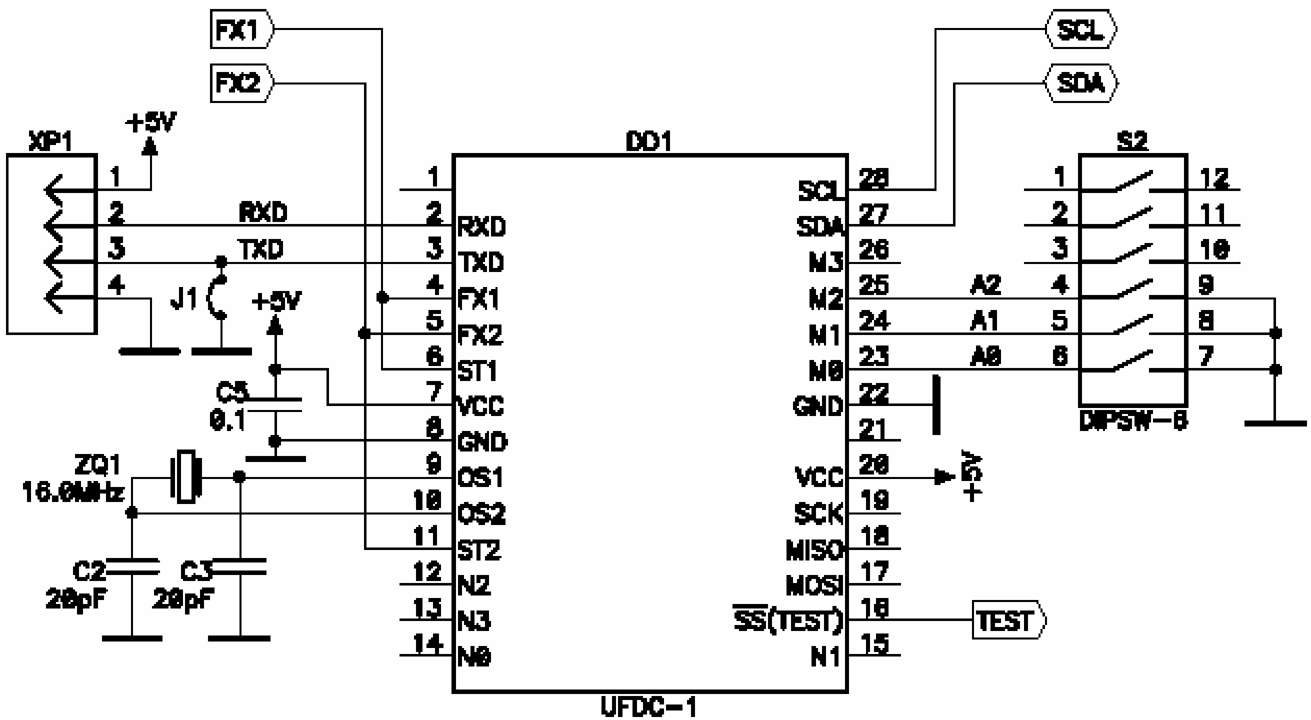
UFDC-1 Slave Mode (RS-232)



UFDC-1 SPI Interface Connection

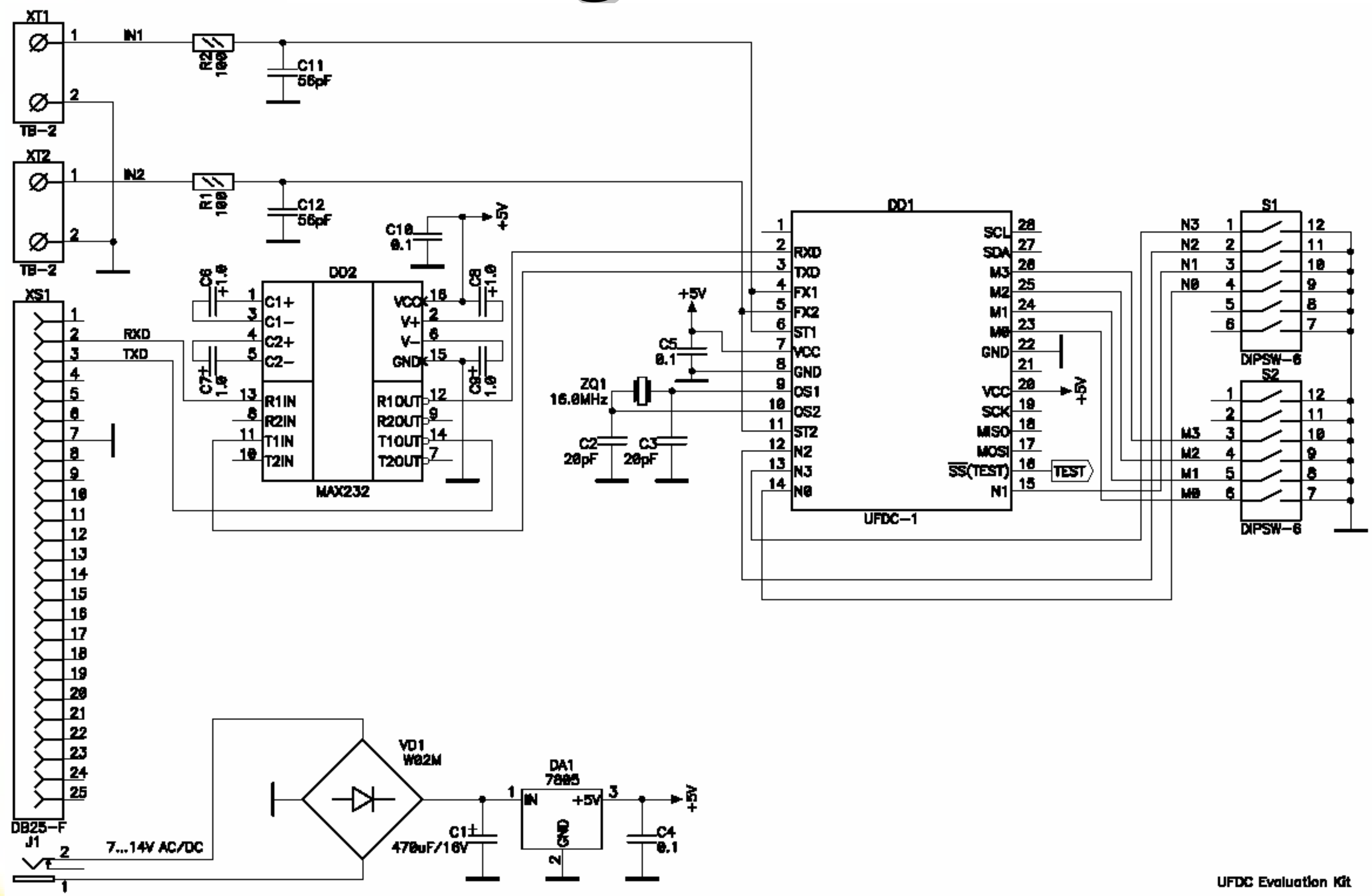


UFDC-1 I^2C Bus Connection



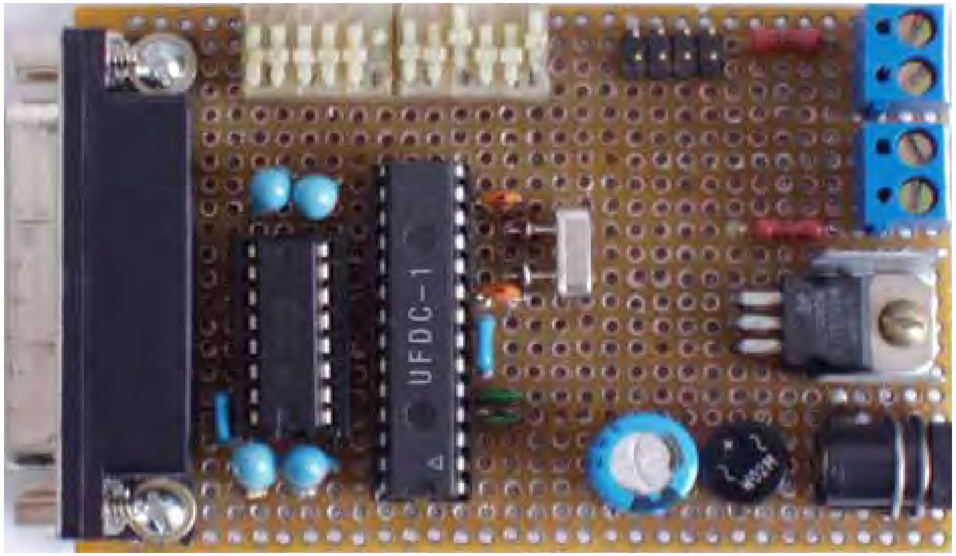
IFSA

Evaluation Board Circuit Diagram

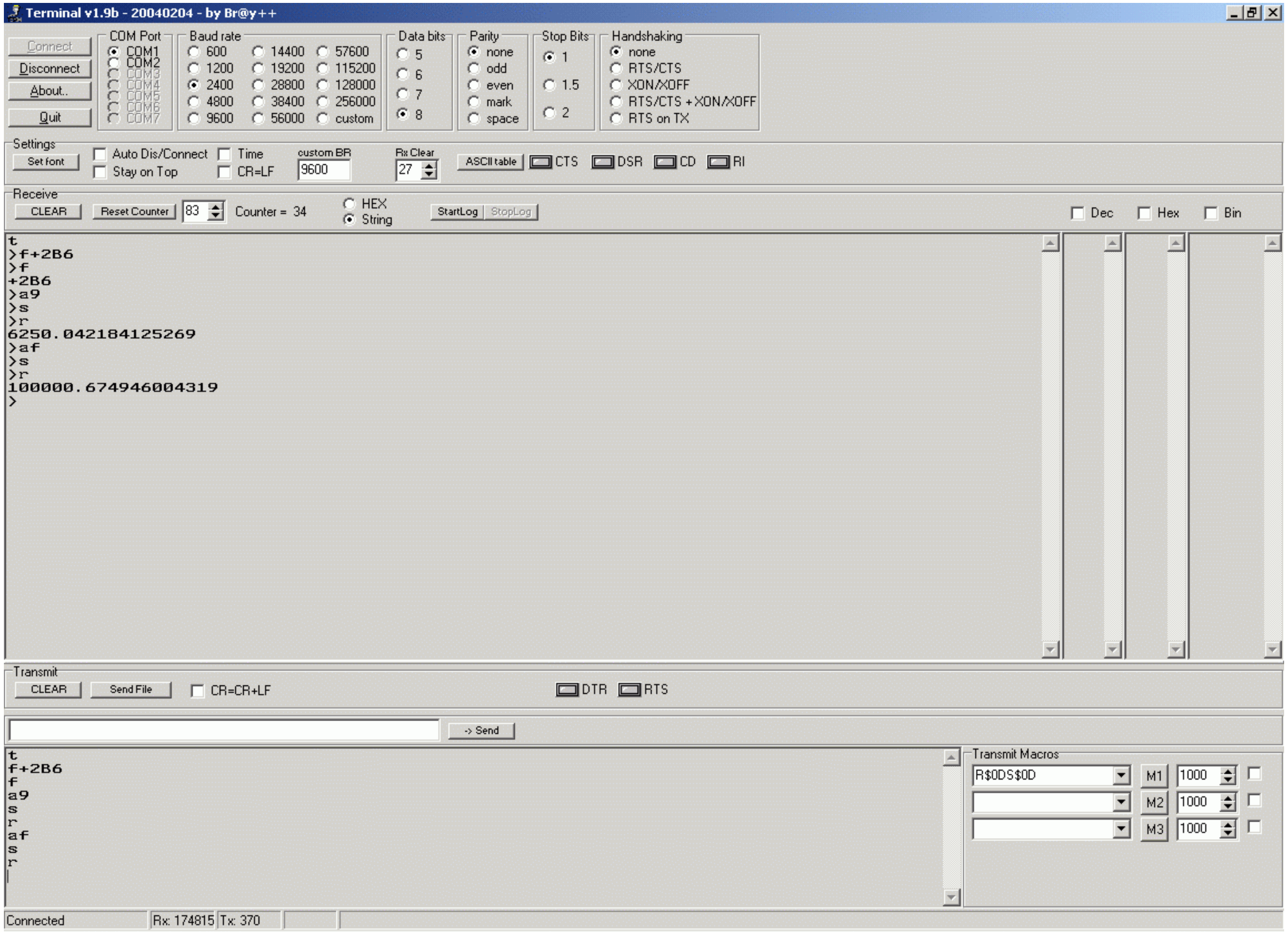


UFDC Evaluation Kit

UFDC-1 Evaluation Board



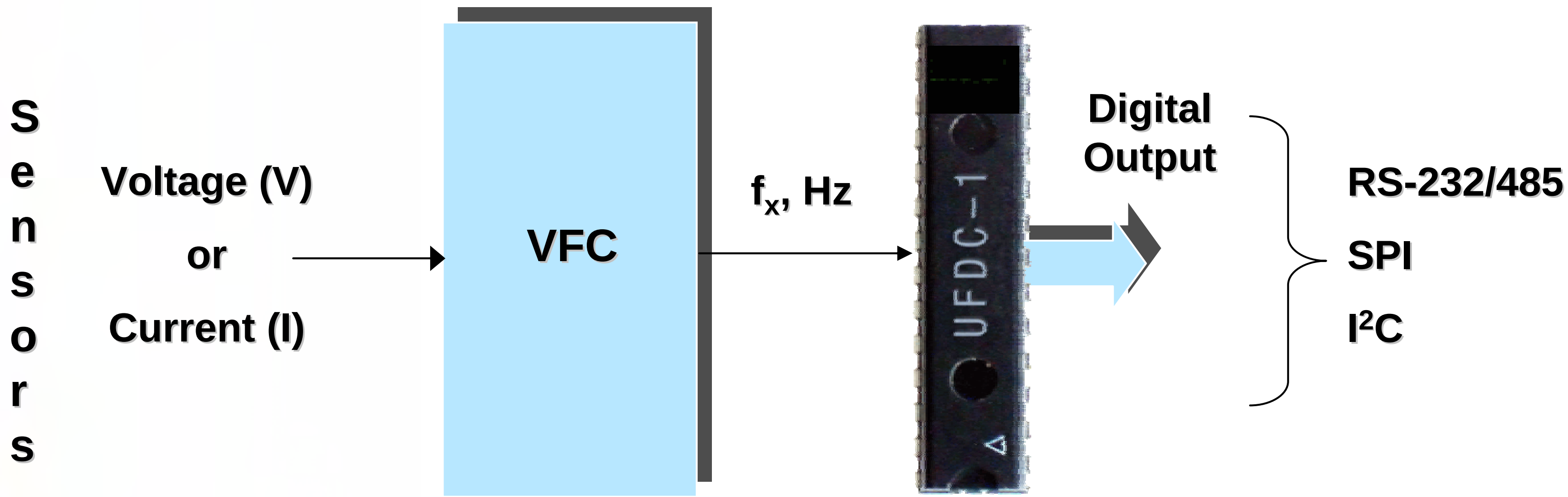
Software (Terminal V1.9b)



Applications

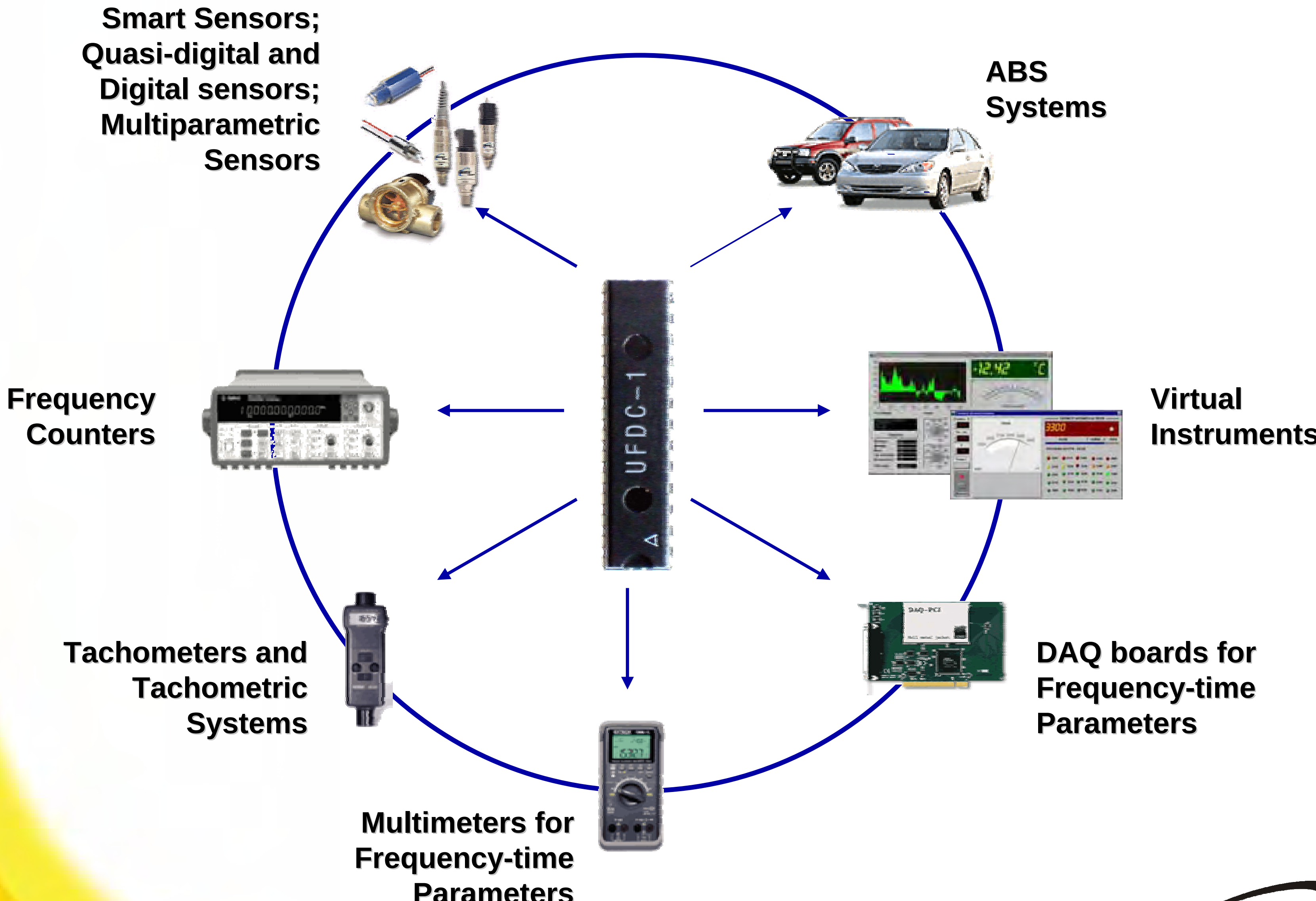
- Any frequency, period, duty-cycle, time interval, phase-shift, pulse number output sensors
- Digital sensors and sensor systems design
- Smart (self-adaptive) sensors
- Multifunctional and multiparamters sensors for simultaneous detection various parameters
- Data acquisition (DAQ) boars and systems for frequency-time parameters
- Virtual instruments
- Desktop multifunctional frequency counters
- Tachometers and tachometric systems
- Handheld multimeters for frequency-time parameters
- High-end, mid- and low-range ABS

UFDC-1 and Analog Signal Domain



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

Where to use the UFDC-1 ?



What Calibrate ?

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

Why Calibration ?

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

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

When Calibrate the UFDC-1 ?

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

How to Calibrate ?

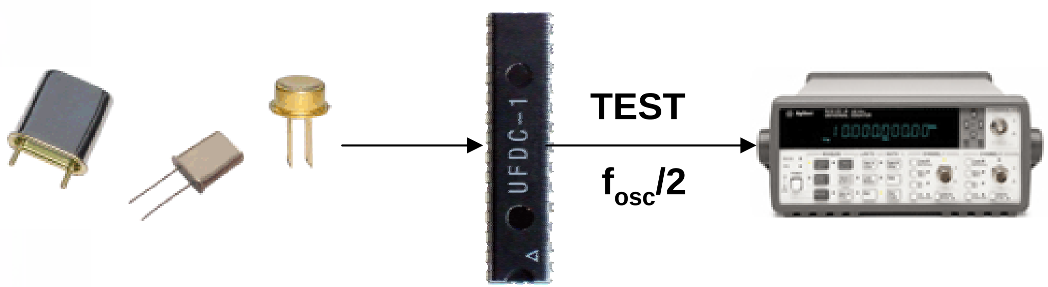
- Should be made in real working conditions with the 16 MHz crystal oscillator
- Connect the UFDC-1 to PC through the serial interface RS-232
- Use the test command "T“
- Measure the frequency at the TEST pin by any external frequency counter with accuracy not worse than 0.0001 % or at least 0.0005 %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

Calibration Procedure Example

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

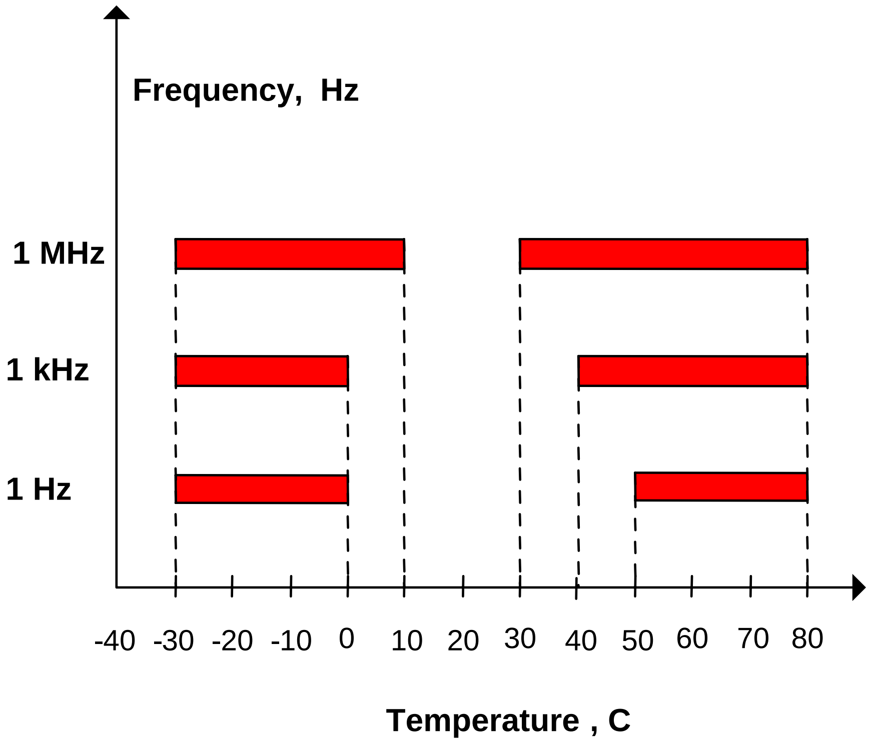
UFDC-1 Calibration Commands

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



Temperature Drift Calibration

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



Integrated Circuits

- A common disadvantage of many digital interfaces is that a lot of analog sensors can not be read out in a low-cost way
- Universal Transducer Interface (UTI) from Smartec (The Netherlands)
- Time-to-Digital Converter (TDC) from Acam-Messelectronic GmbH

Universal Transducer Interface (UTI)

- It is a complete analog front end for low frequency measurement applications, based on a period-modulated oscillator
- Sensing elements can be directly connected to the UTI without extra electronics
- Provides an intermediate function between low-cost sensor elements and microcontroller
- Only a single reference element, of the same kind as the sensor is required

Sensors Elements

- Pt resistors (Pt100, Pt1000)
- Ni resistor
- Thermistors
- Potentiometers resistors
- Capacitors
- Resistive bridges

With some extra electronic circuitry, it can be used to measure voltage (two ICs MAX4560) and currents, which makes them suited to interface also thermopiles, thermocouple and other type of voltage- or current-output analog sensors

Mode of Functioning

- UTI converts low-level signals from an analog sensor to a period-modulated (duty-cycle) microcontroller-compatible time domain signal
- Signal conversion is carried out according to the linear law:

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

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

Method of Measurement

- UTI operates in condition of auto-calibration, that is base on a three-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:

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

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

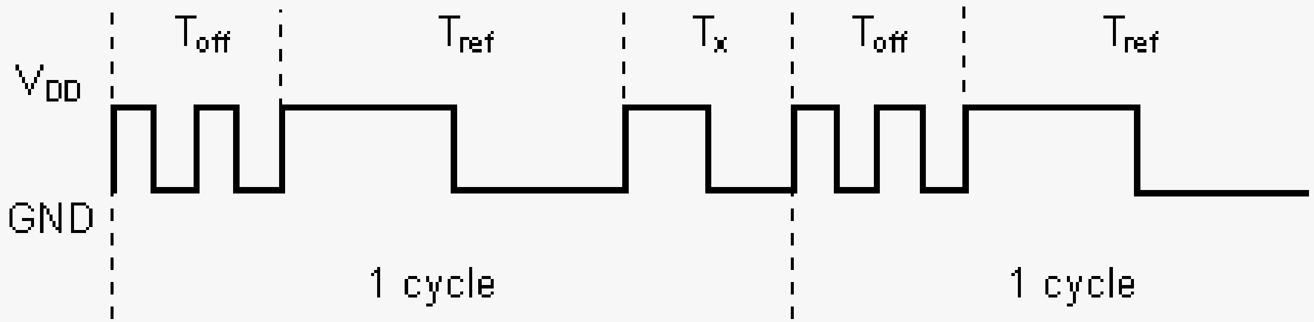
$$M_x = k \cdot S_x + M_{off}$$

3-Signal Calibration Technique

100 g m_x

The scale is linear. Calculate m_x

Output Signal of UTI



$$M = \frac{T_x - T_{off}}{T_{ref} - T_{off}} = \frac{C_x}{C_{ref}} \quad \text{or} \quad = \frac{R_x}{R_{ref}} \quad \text{or} \quad = \frac{V_x}{V_{ref}}$$

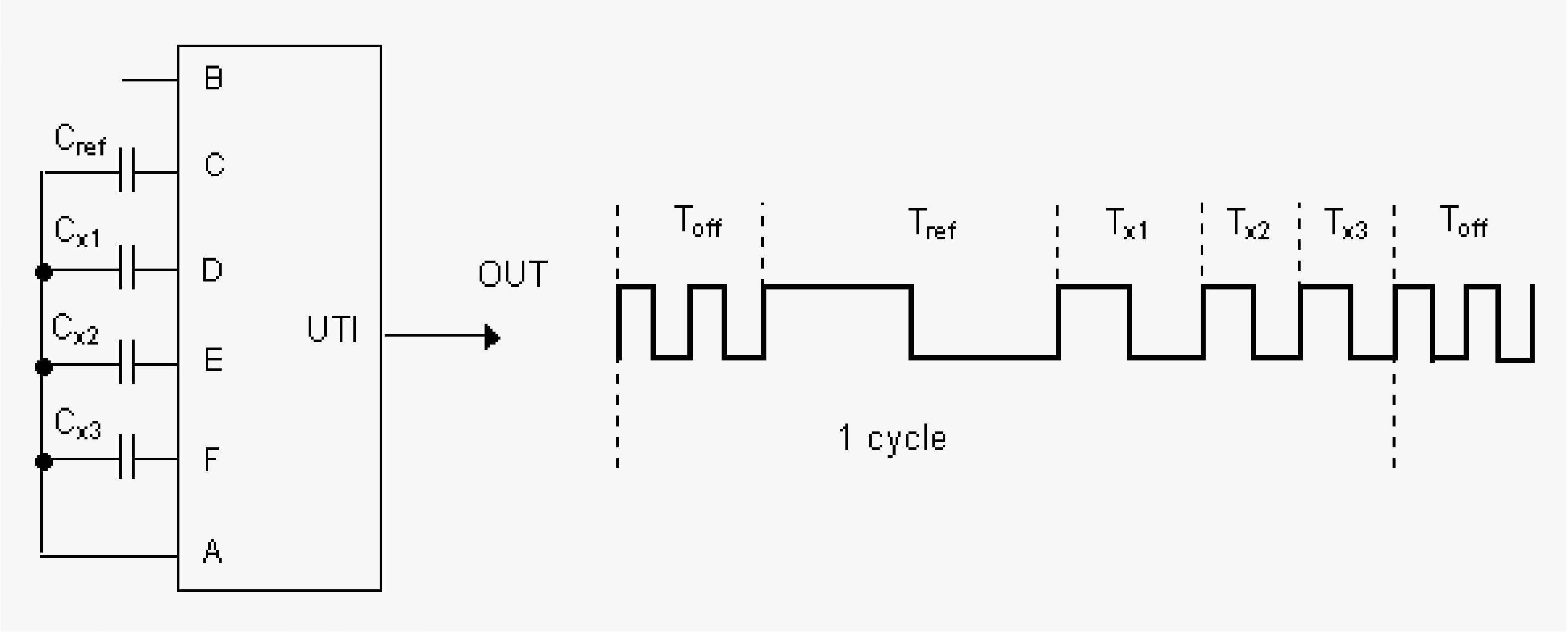
UTI modes

- There are 16 different modes with 3 ÷5 phases within one cycle
- Linearity of the UTI has values between 11 bits and 13 bits, depending on the mode
- Mode's parameters are: the accuracy, the resolution, the number of phases, the specified signals in the various phases

Technical Performances

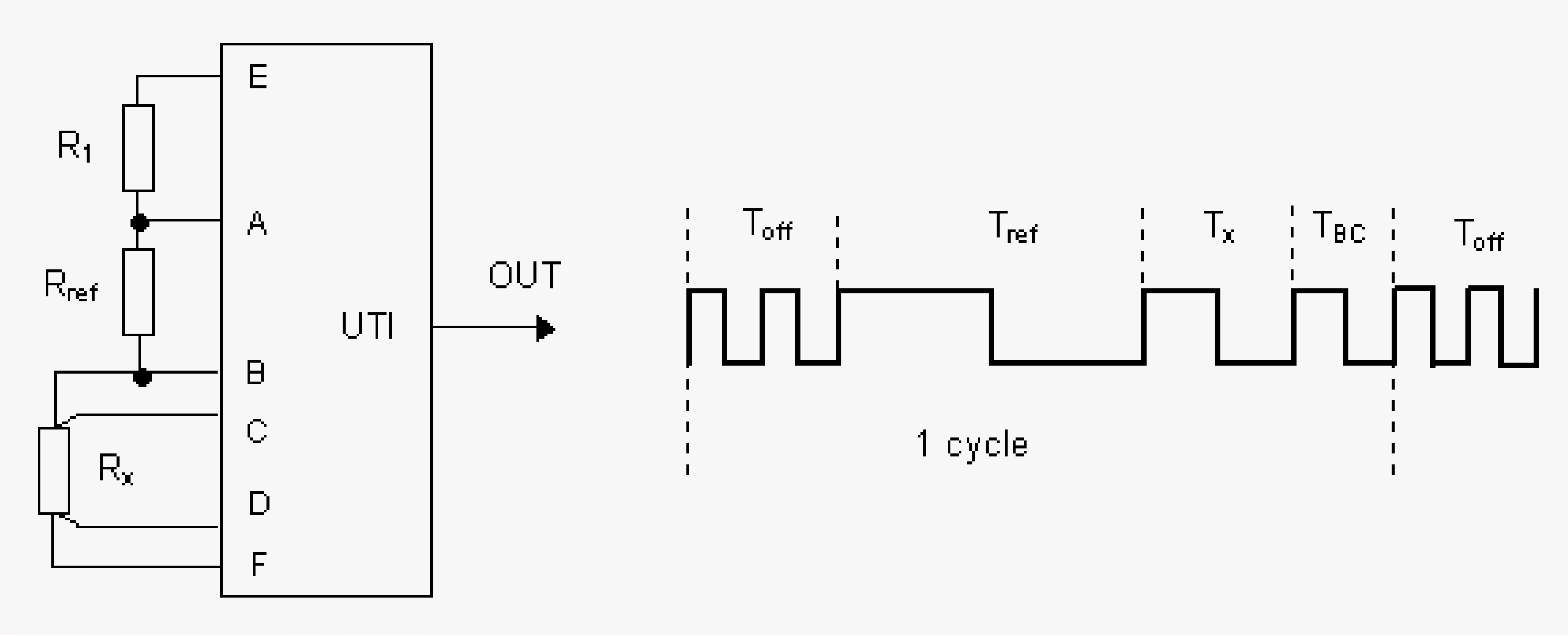
Parameter	Range
Capacitive sensors, pF	0 ÷ 2, 0 ÷ 12, up to 300
Platinum resistor	Pt100, Pt1000
Thermistor, kΩ	1 ÷ 25
Resistive bridges with max imbalance ± 4% or ± 0,25%	250 Ω ÷ 10 kΩ
Potentiometers, kΩ	1 ÷ 50
Resolution, bits	14
Linearity, bits	11 ÷ 13
Measurement time, ms	10 ÷ 100
Suppression of interference, Hz	50/60
Temperature range, ^{0}C	- 40 ÷ + 85
Power supply, V	2.9 ÷ 5.5
Current consumption, mA	< 2.5

Capacitance Measurement



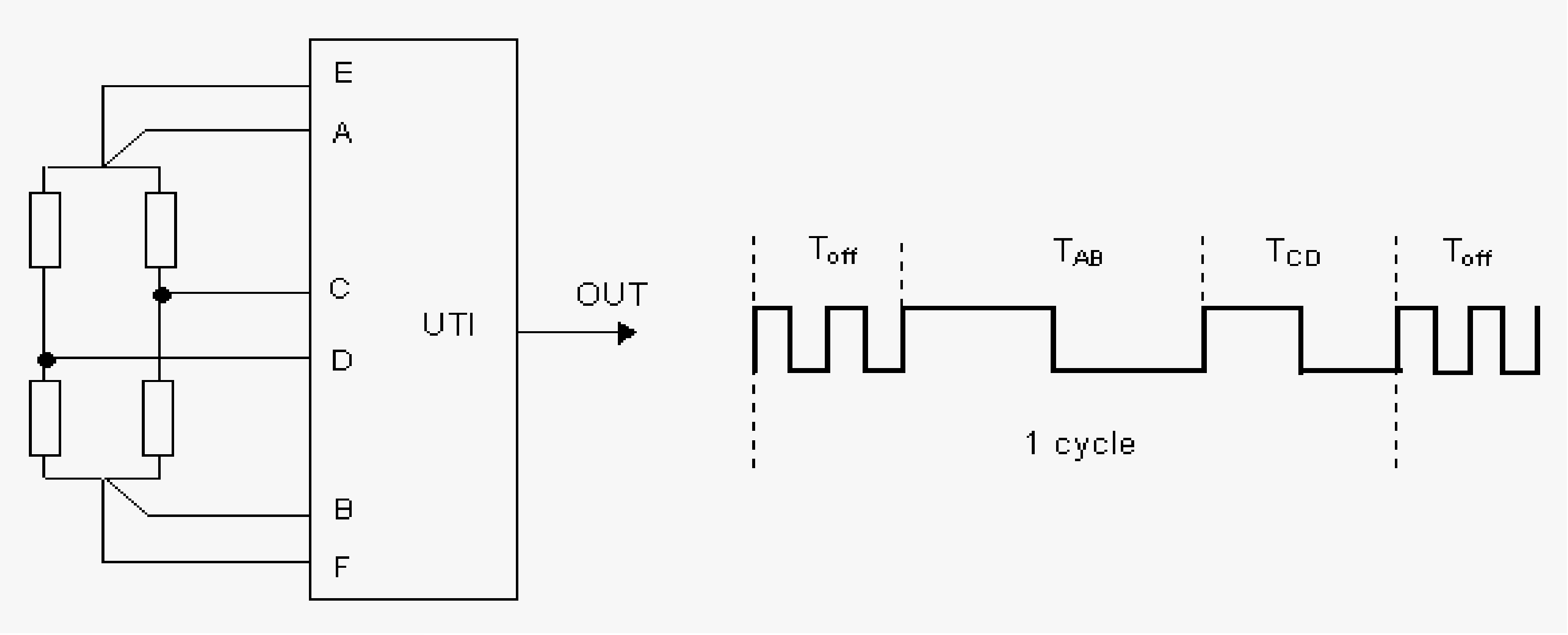
$$M_i = \frac{T_{xi} - T_{off}}{T_{ref} - T_{off}} = \frac{C_{xi}}{C_{ref}}$$

Thermistor Measurement



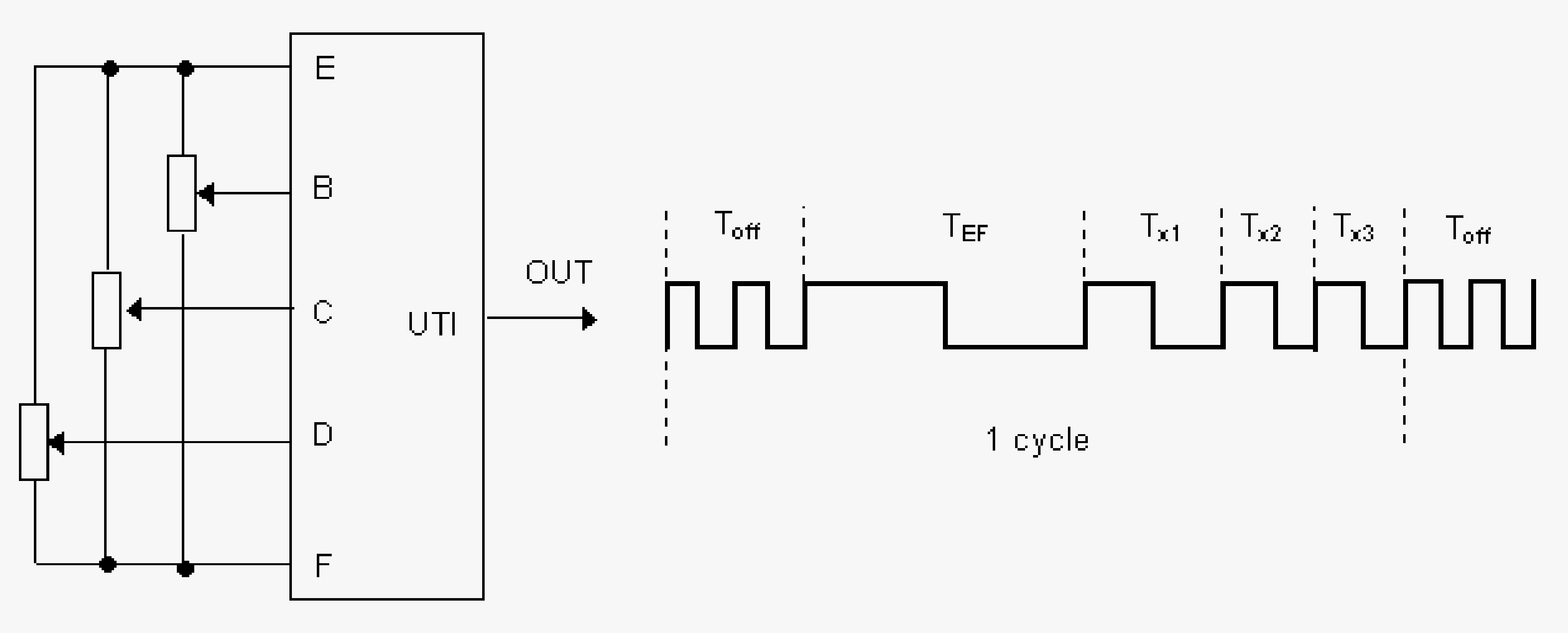
$$M = \frac{T_x - T_{off}}{T_{ref} - T_{off}} = \frac{R_x}{R_{ref}}$$

Resistive Bridge Measurement



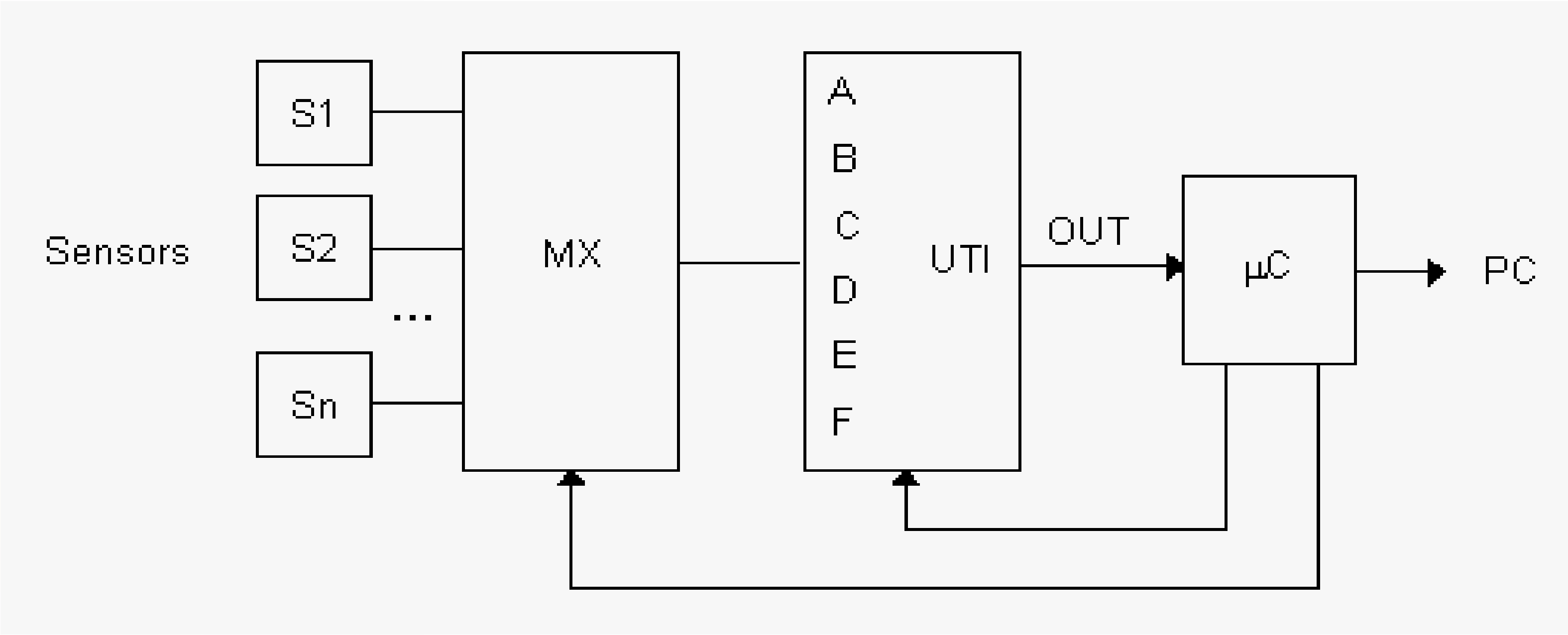
$$M = \frac{1}{32} \cdot \frac{T_{CD} - T_{off}}{T_{AB} - T_{off}} = \frac{V_{CD}}{V_{AB}}$$

Potentiometer Measurement

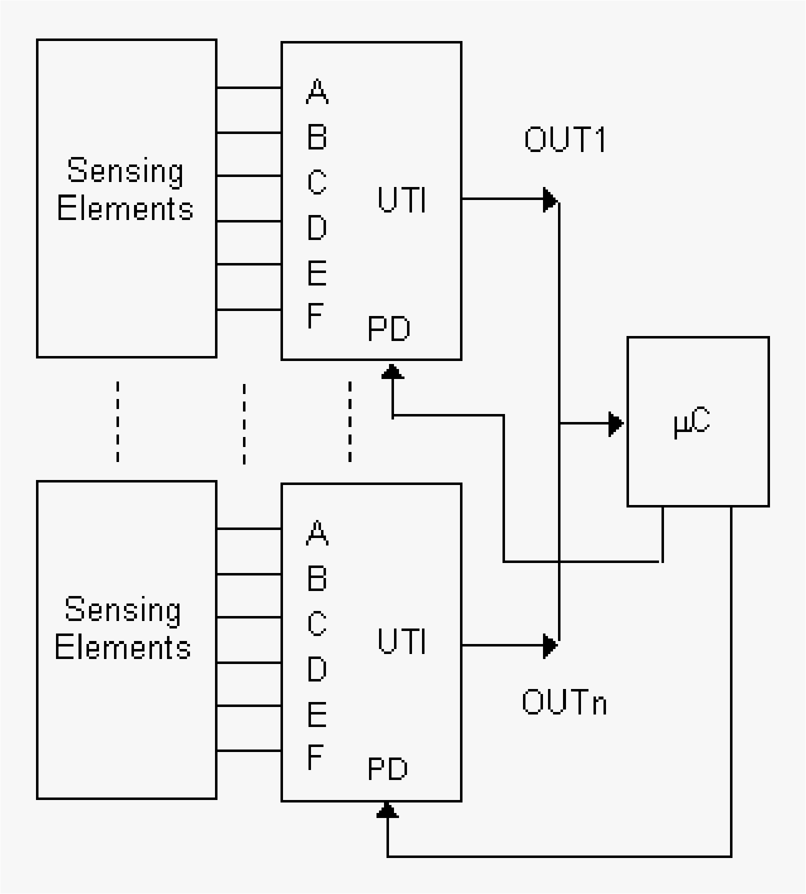


$$M_i = \frac{T_{xi} - T_{off}}{T_{EF} - T_{off}} = \frac{R_{xi}}{R_{pi}}$$

Multiple Sensing Elements Measurement



Multiple Channel Signal Measurement



High-Performance UTI03

- Capacitive sensors, 0 pF …300 pF
- Single or multiple platinum resistors, Pt100, Pt1000
- Thermistors, 1kΩ ~ 25kΩ
- Resistive bridges, 250 Ω ~ 10kΩ with maximun imbalance +/- 4 % or +/- 0.25%
- Thermocouples
- Thermopiles
- Conductivity sensors, 0.1 μS ~ 100 mS
- pH sensors

UTI03 (cont.)

- Temperature effect compensation
- Resolution and linearity up to 14.8 bits and 13.5 bits with a measurement time of 100 ms
- Can be controlled via SPI bus

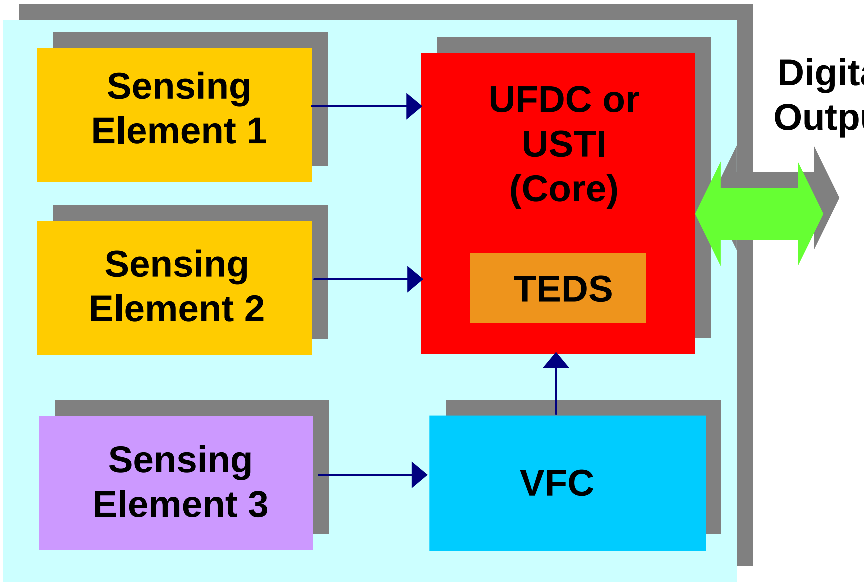
Conclusions

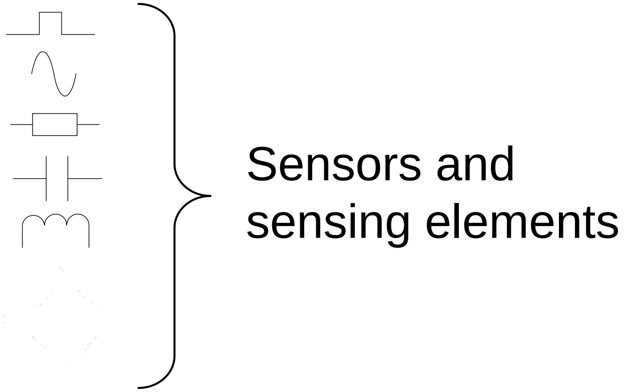
- Due to “virtual instrumentation revolution”, it is possible to create a measuring system of any required configuration and functionality
- Owing to the non-redundant conversion time MDC can be used in different time critical applications, for example, ABS
- Industrial interface circuits let easily to convert analog sensors signals to quasi-digital domain and change the accuracy and speed by software-controlled way

Digital Sensors and Smart Sensors System Design

Technologies

- IC, ASIC
- Hybrid
- MEMS
- System-on-Chip (SoC)
- Discrete components





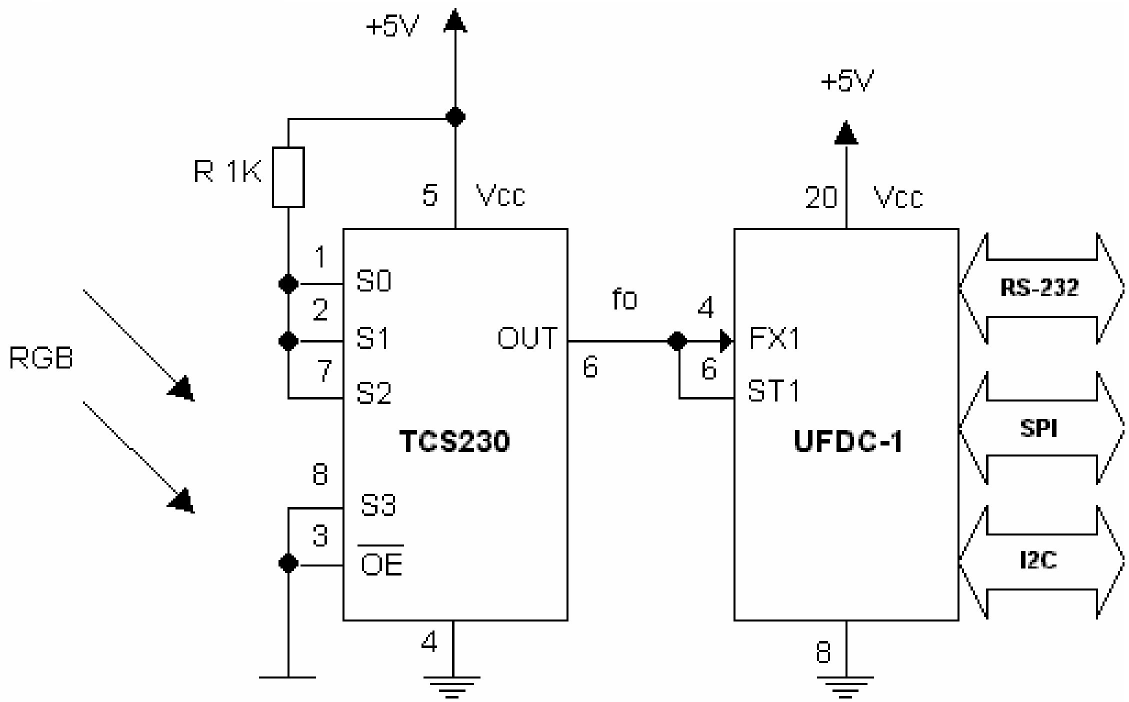
Design Methodology

- Suitable for digital sensors, DAQ systems, data loggers and smart sensor systems
- Based on novel integrated universal frequency-to-digital converters and interfacing circuits
- Task oriented

Optical Sensor Systems

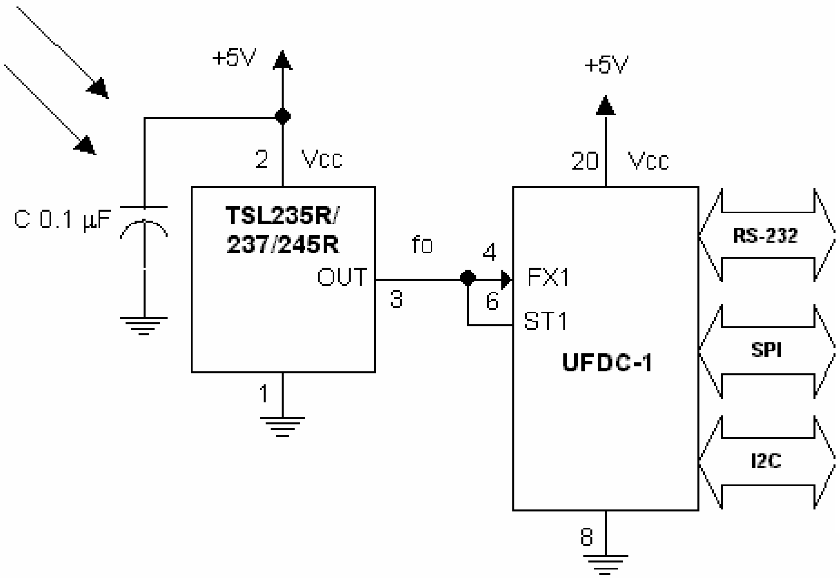
- The direct use of a microcontroller in the measurement chain offers simple, low-cost solutions
- Taking into account a wide output frequency range of light-to-frequency converters an advanced conversion method should be used
- Microcontroller based solution introduces additional error components due to so-called program-dependent or software-related effects
- The UFDC-1 should be used in systems design in order eliminate mentioned problems

Color-to-Digital Converter

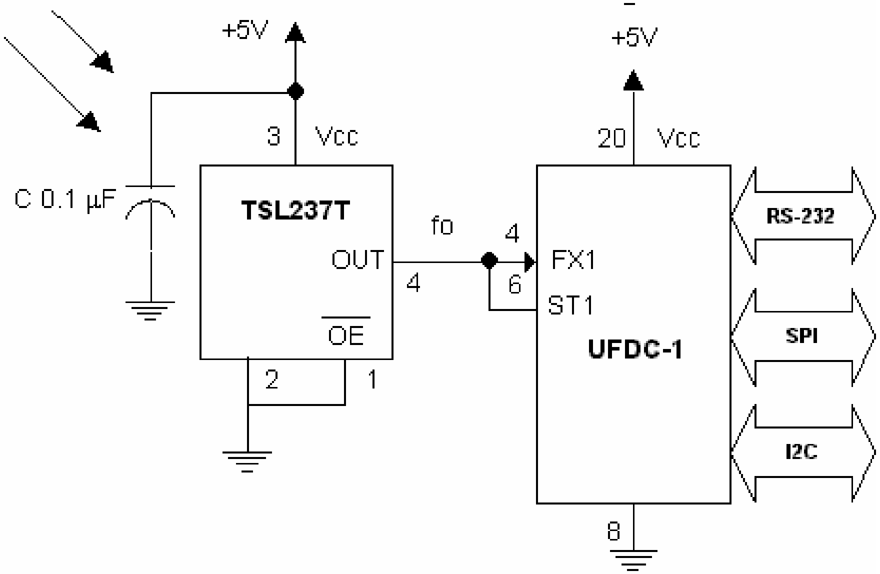


Design notes: 100 % scaling mode for TCS230 (S0, S1 =1) and clear photodiode type (no filter, S2=1, S3=0). Power-supply lines must be decoupled by a 0.01-µF to 0.1-µF capacitor with short leads mounted close to the device package.

Light-to-Digital Converters



(a)

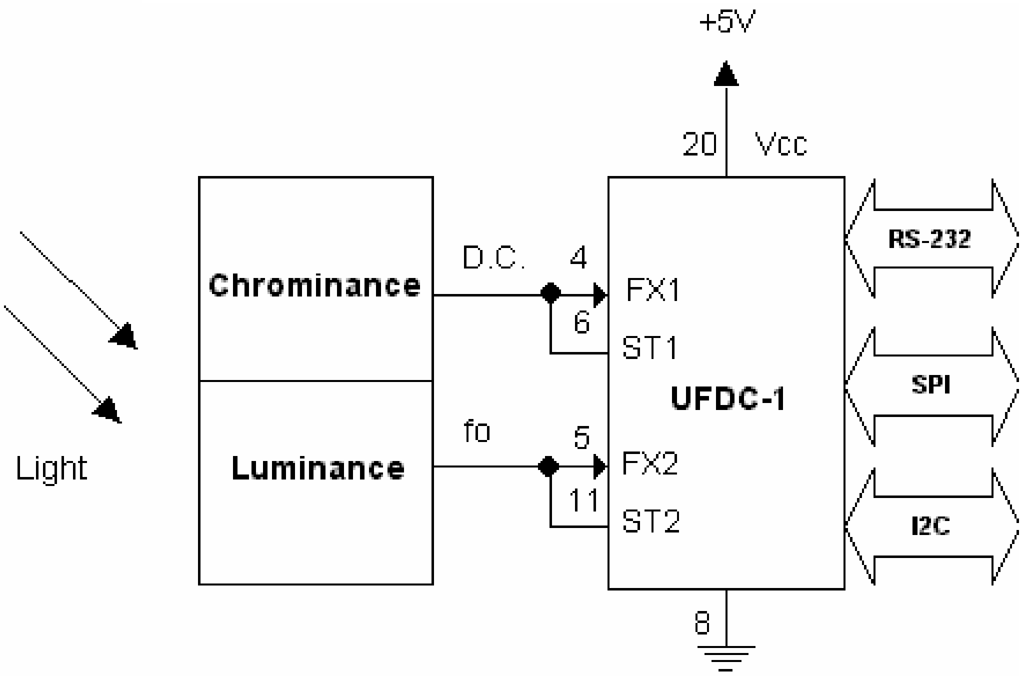


(b)

Commands Example (RS-232 interface)

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

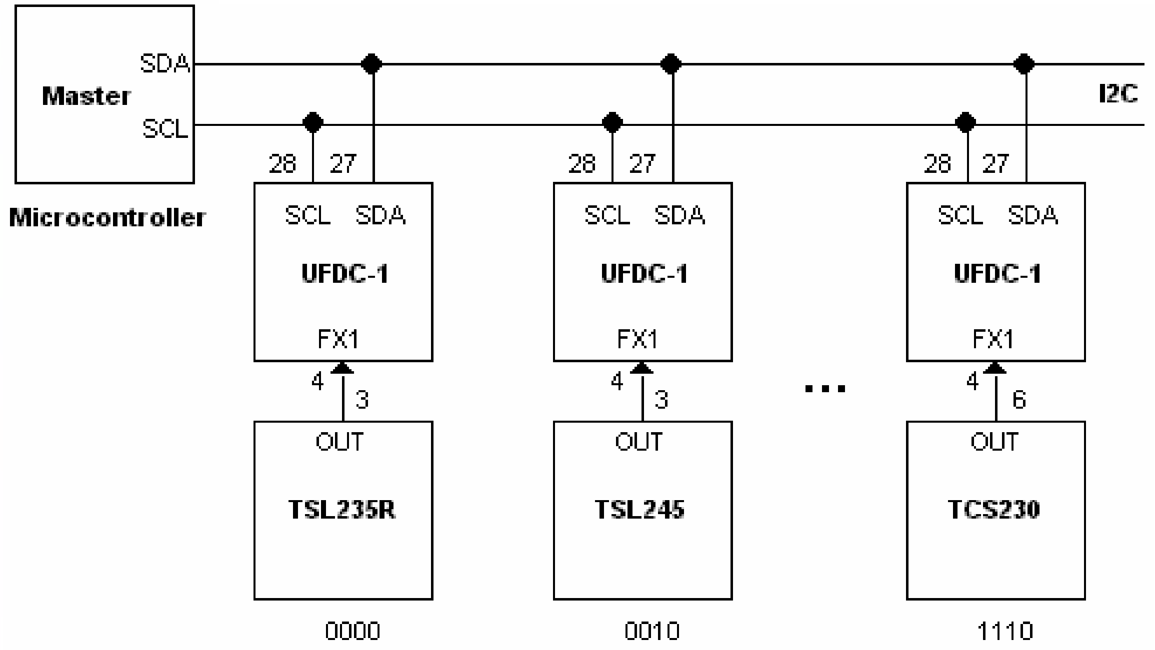
Multiparameters Sensor Interfacing



Multiparameters Sensor Interfacing (cont.)

>M4	; Duty-cycle measurement initialization
>S	; Start a measurement
>R	; Read a result
60.9786	; Duty-cycle measurement result indication
>ME	; Frequency measurement initialization on the 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



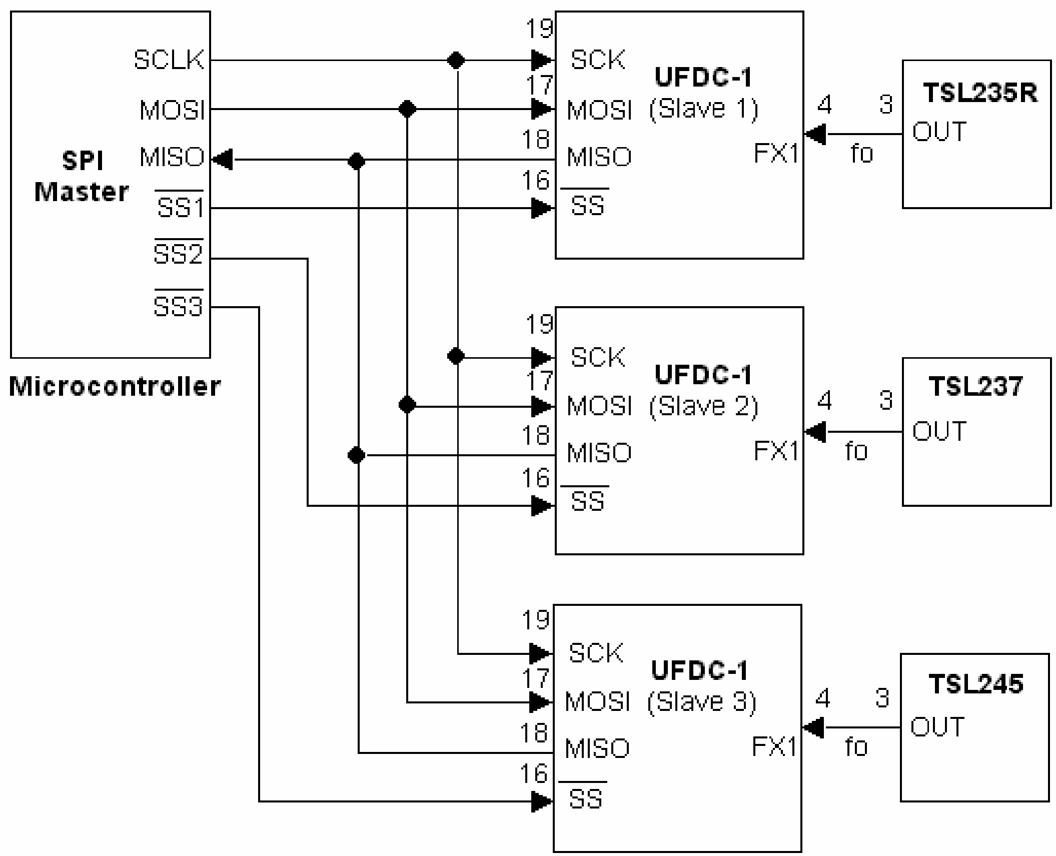
<06><00> ; Frequency measurement initialization

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

<09> ; Start a measurement

<07> ; Get measurement result in BCD format

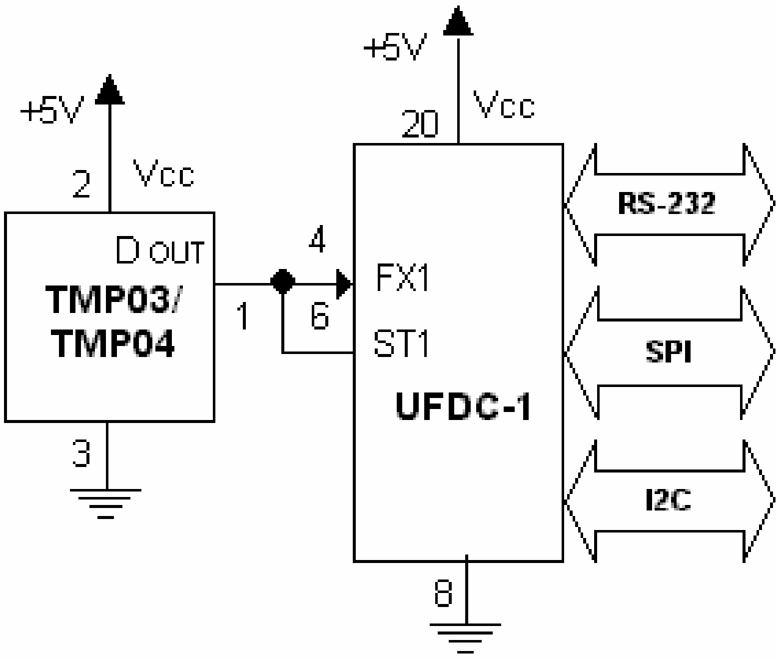
SPI Interface to TAOS Opto Sensors



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.

DAQ System for Temperature Sensors (I)



>MB; Pulse interval T1 measurement

>S; Start a measurement

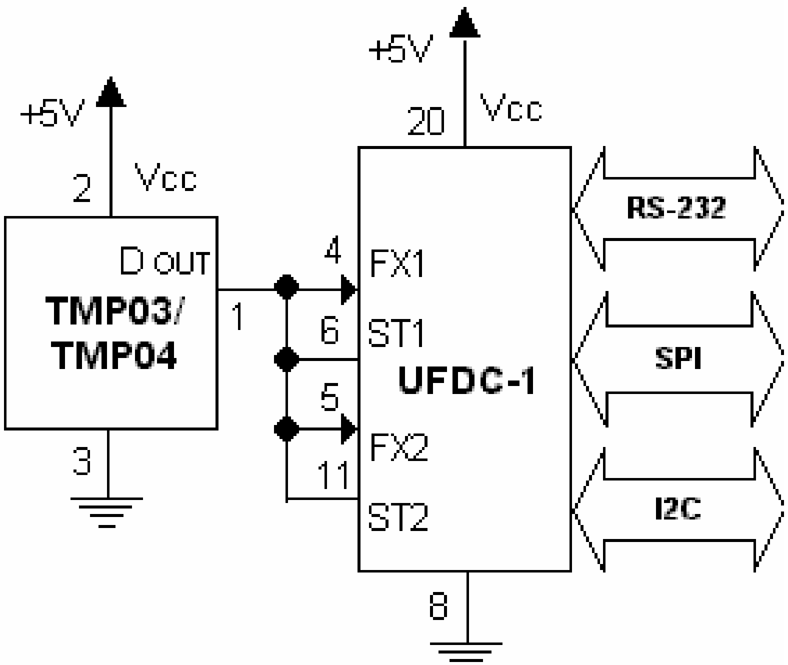
>R; Read a result for T1

>MC; Space interval T2 measurement

>S; Start a measurement

>R; Read a result for T2

DAQ System for Temperature Sensors (II)



>MF; T_x=T1+T2 measurement

>A3; 0.1 % T_x conversion error

>S; Start a measurement

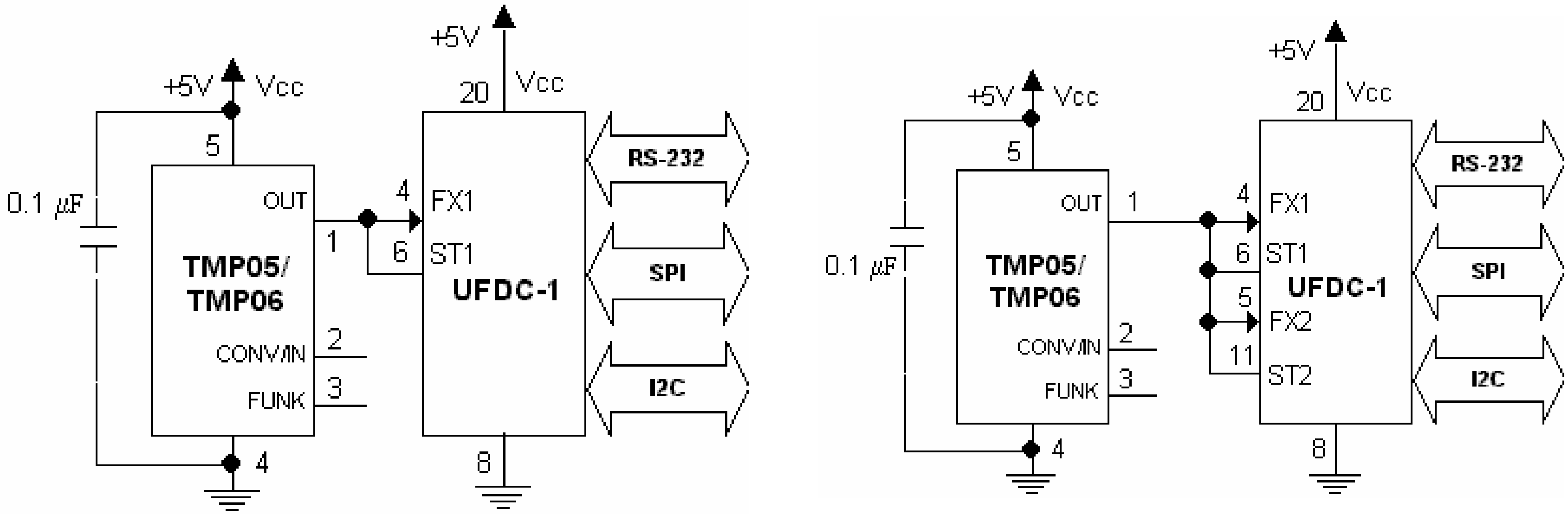
>R; Read a result for T1

>MC; Space interval T2

>S; Start a measurement

>R; Read a result for T2

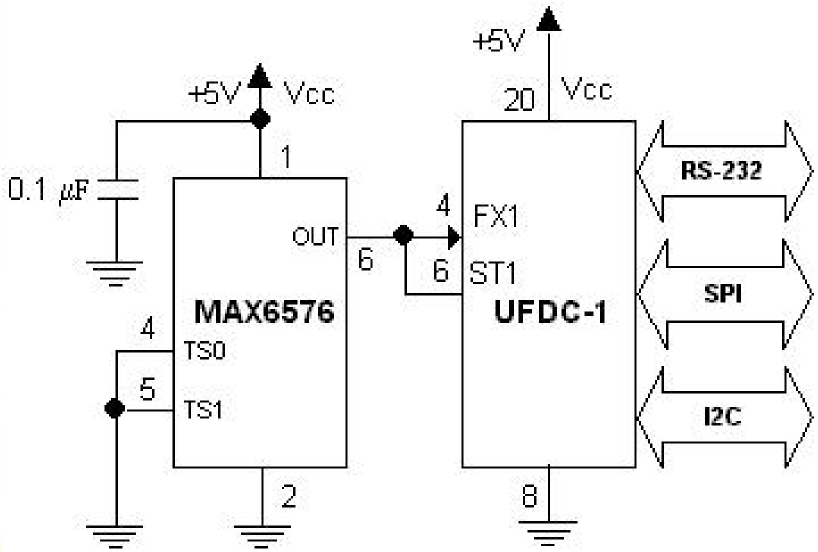
TMP05/TMP06 Sensors Interfacing



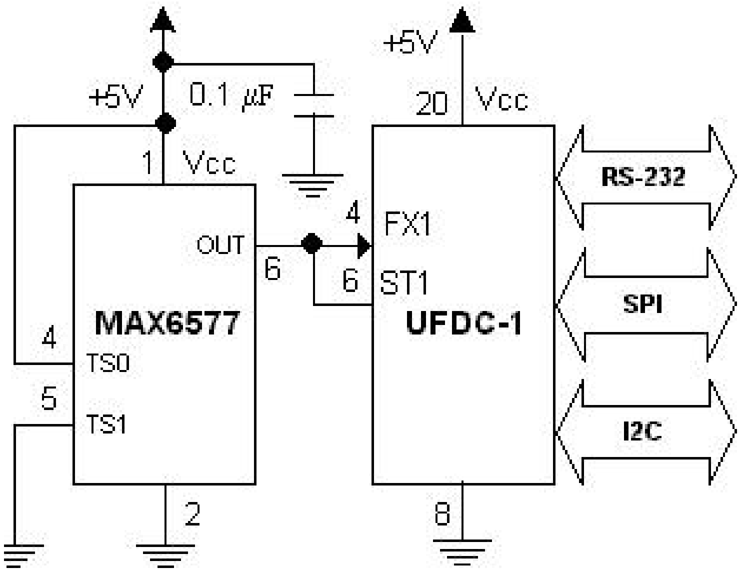
(a) (b)

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)



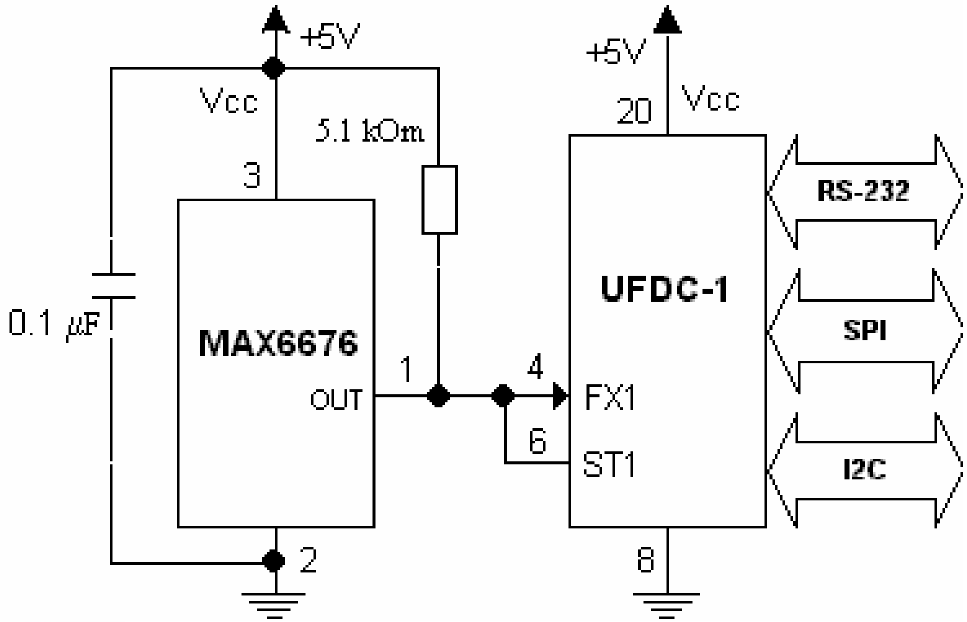
(a)



(b)

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

MAXIM Temperature Sensors Interfacing (II)

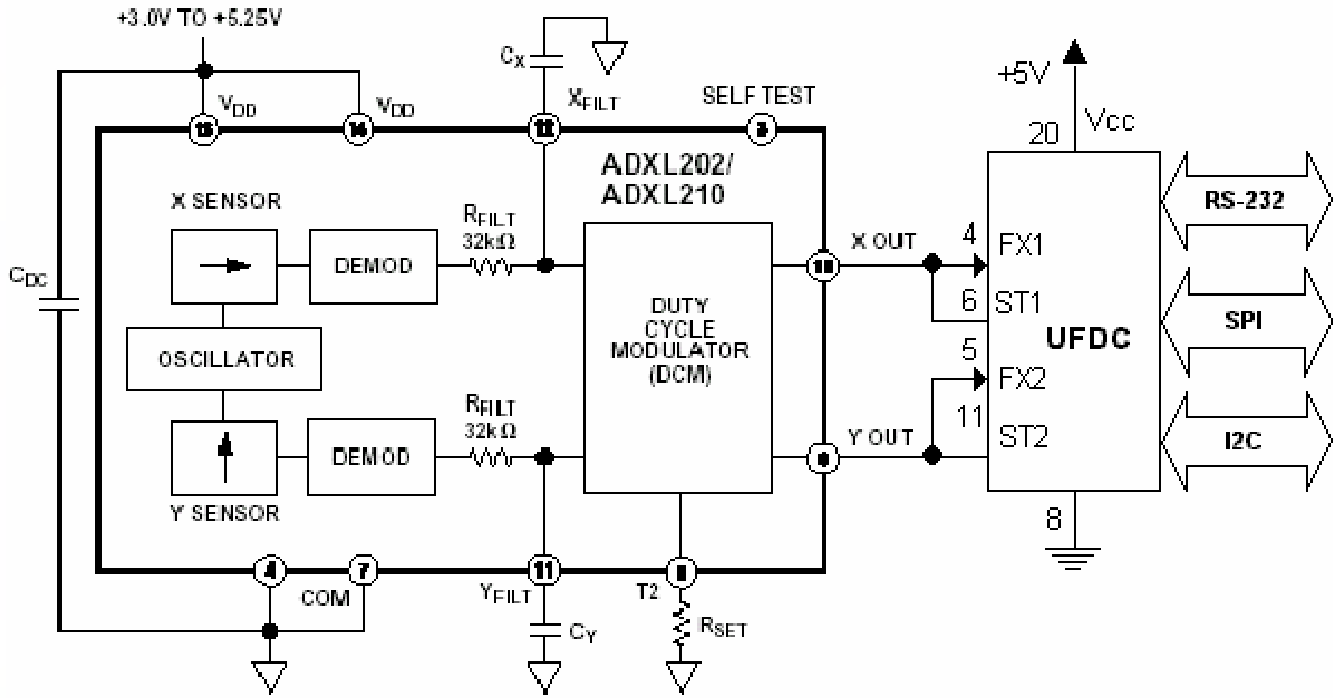


MAX6676 to UFDC-1 interfacing functional diagram

Temperature Sensor Systems Applications

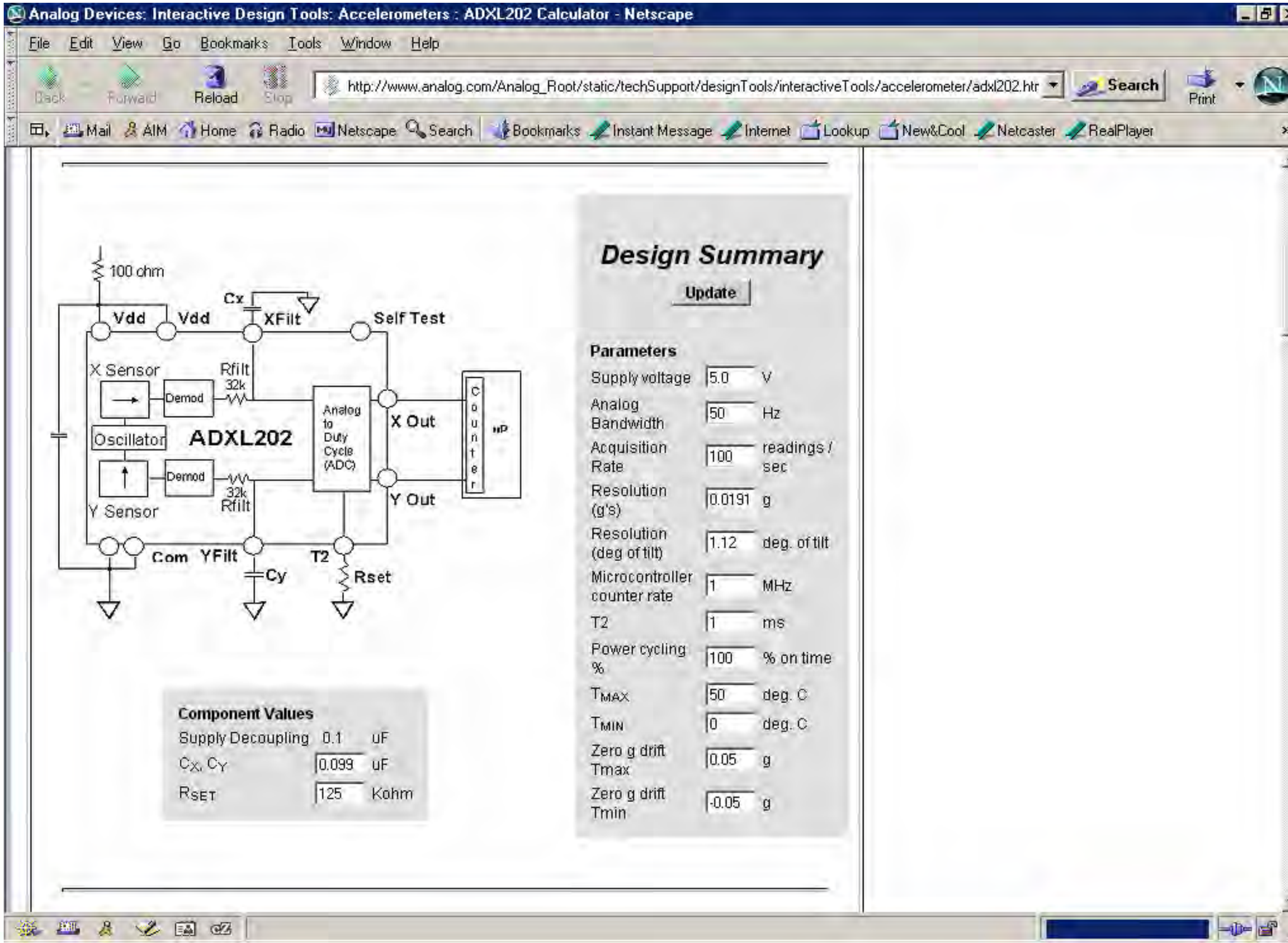
- Temperature monitoring
- Remote temperature measurements
- Environmental control systems
- Industrial process control
- Thermal protection, etc.

Accelerometers Based Systems (I)

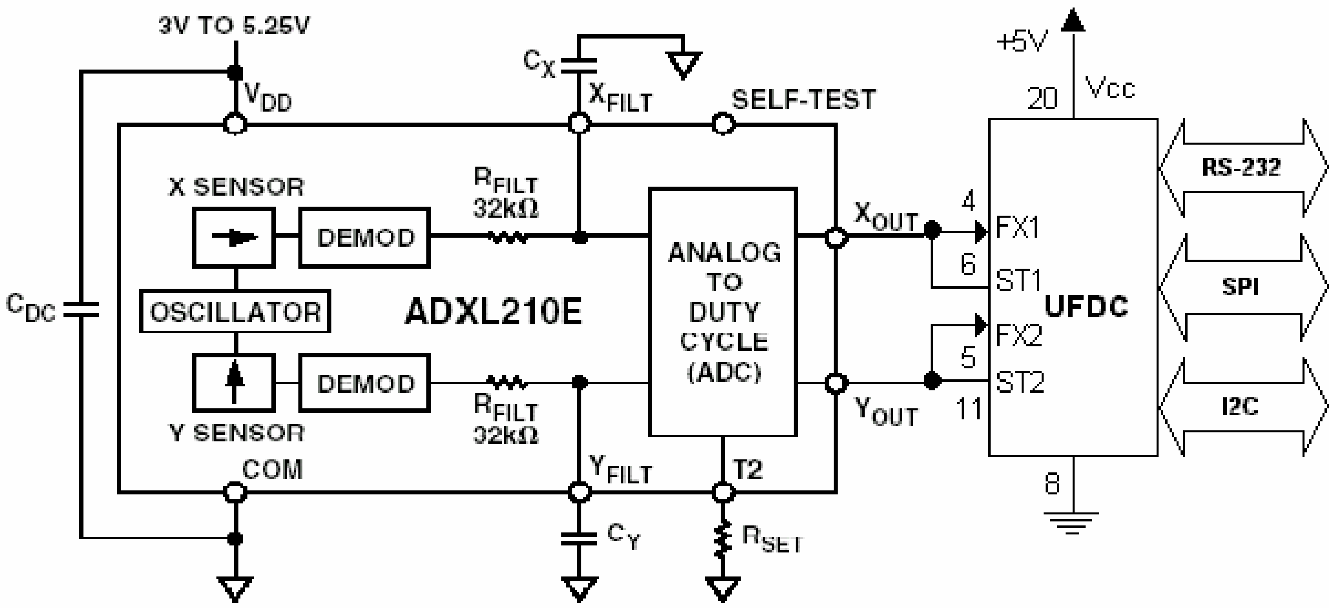


ADXL202 to UFDC-2 interfacing functional diagram

Interactive Design Tools

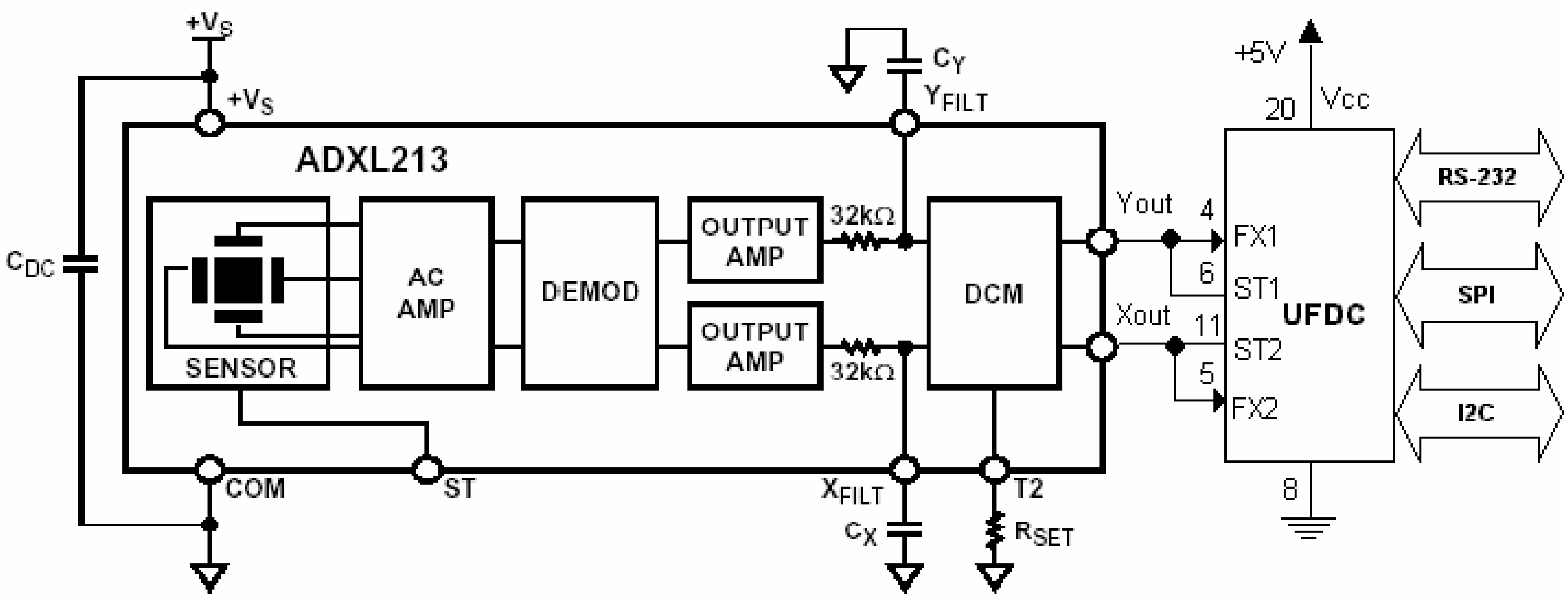


Accelerometers Based Systems (II)



ADXL210 to UFDC-2 interfacing functional diagram

Accelerometers Based Systems (III)

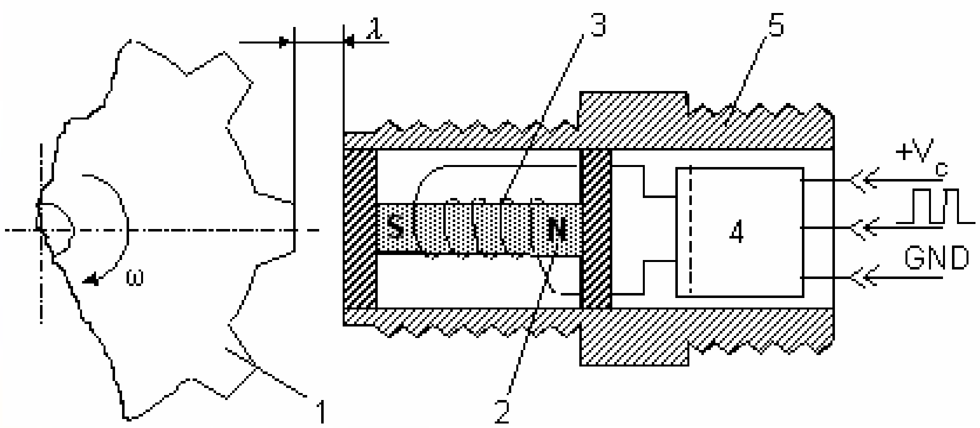


ADXL213 to UFDC-2 interfacing functional diagram

Acceleration to Frequency Circuits

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

Rotation Speed Digital Sensors and Systems



1 - gear tooth

2 - constant magnet

3 - inductance coil

4 - integrated circuit

5 - package

Commands Example (RS-232)

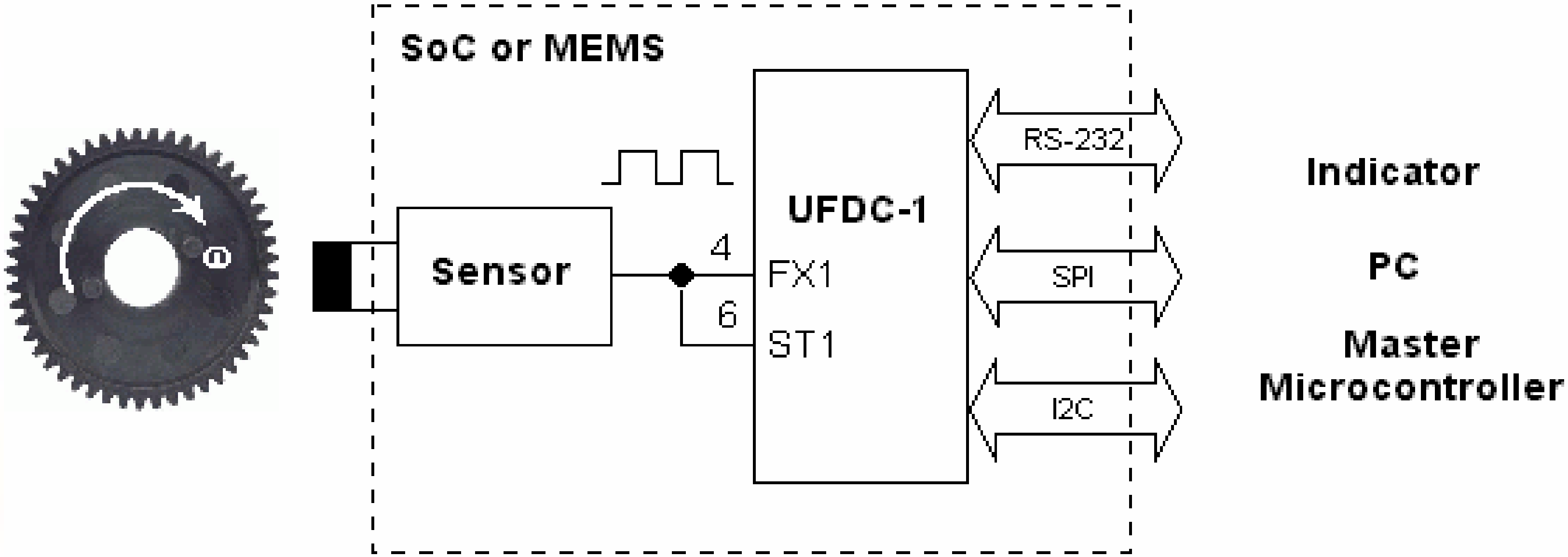
>MA	;Rotation speed measurement initialization
>Z0C	; Set up $Z=12_{(10)}=C_{(16)}$
>A9	;Choose the conversion error 0.001 %
>S	;Start a measurement
>R	;Read a result of measurement in *rpm*

Rotation Acceleration Measurement

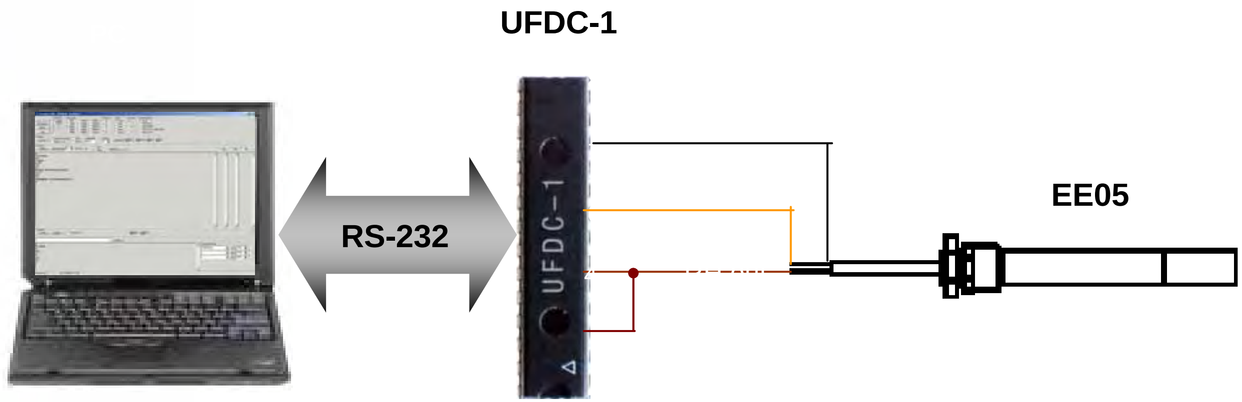
$$\varepsilon_x = \frac{n_1 - n_2}{t_2},$$

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

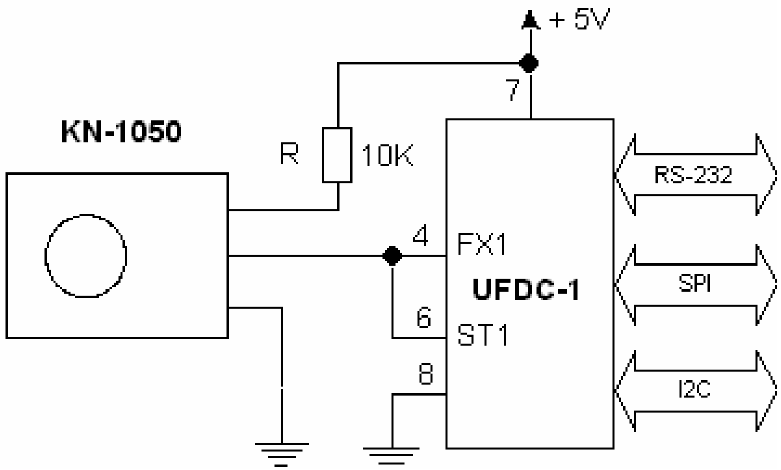
SoC for Rotation Speed Measurement



Digital Humidity Sensors and Data Loggers

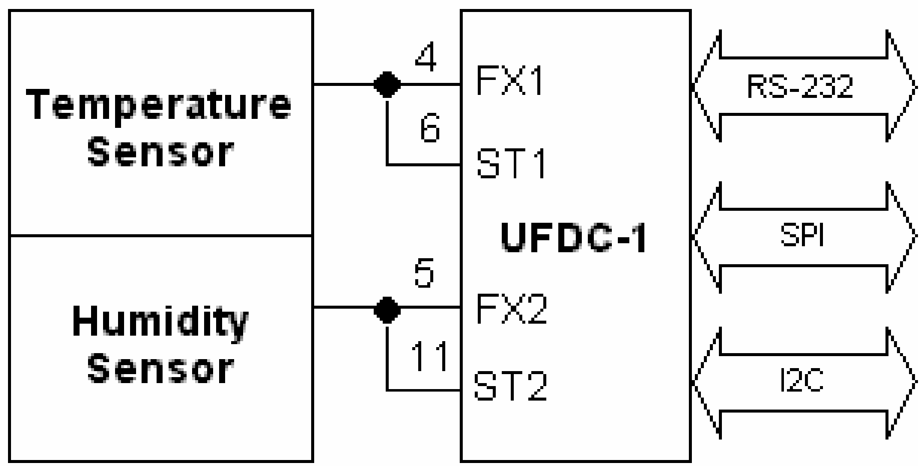


(a)



(b)

Temperature and Humidity Multisensors System



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

Commands Example (RS-232)

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

>A2; Choose the conversion error 0.25 %

>S; Start a measurement

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

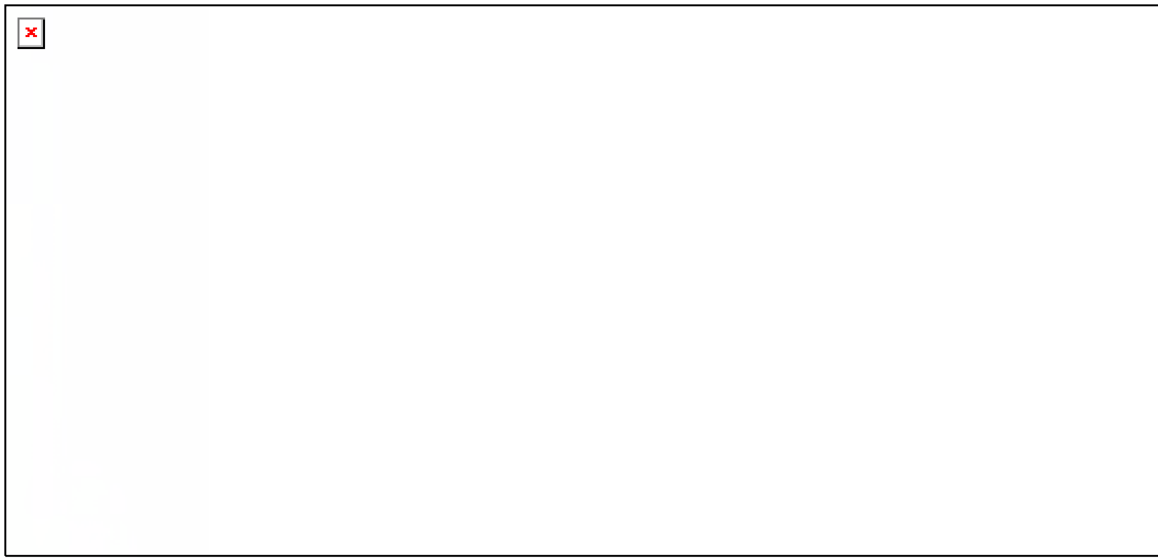
>ME; Frequency measurement, 2nd channel, HTF3130 humidity sensor

>A2; Choose the conversion error 0.25 %

>S; Start a measurement

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

Pressure Sensors Interfacing

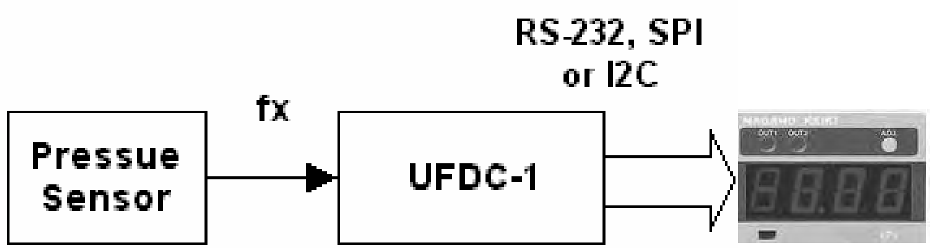


Connection diagram for 8000 Series of frequency output depth sensors from Paroscientific, Inc.

Commands Example (RS-232)

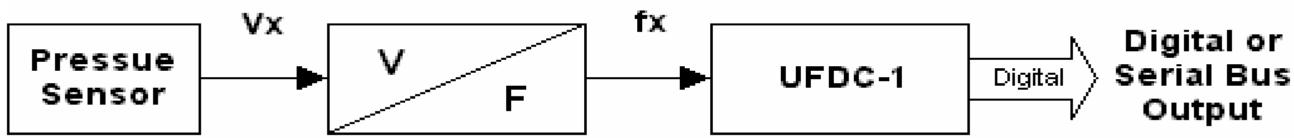
>M0	; Frequency measurement initialization in the first channel
>A0	; Choose the conversion error 0.001 %
>S	; Start a measurement
>R	; Read a result proportional to temperature
>ME	; Frequency measurement initialization in the second channel
>A0	; Choose the conversion error 0.001 %
>S	; Start a measurement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

Pressure Gauges



LCD pressure gauge based on UFDC-1

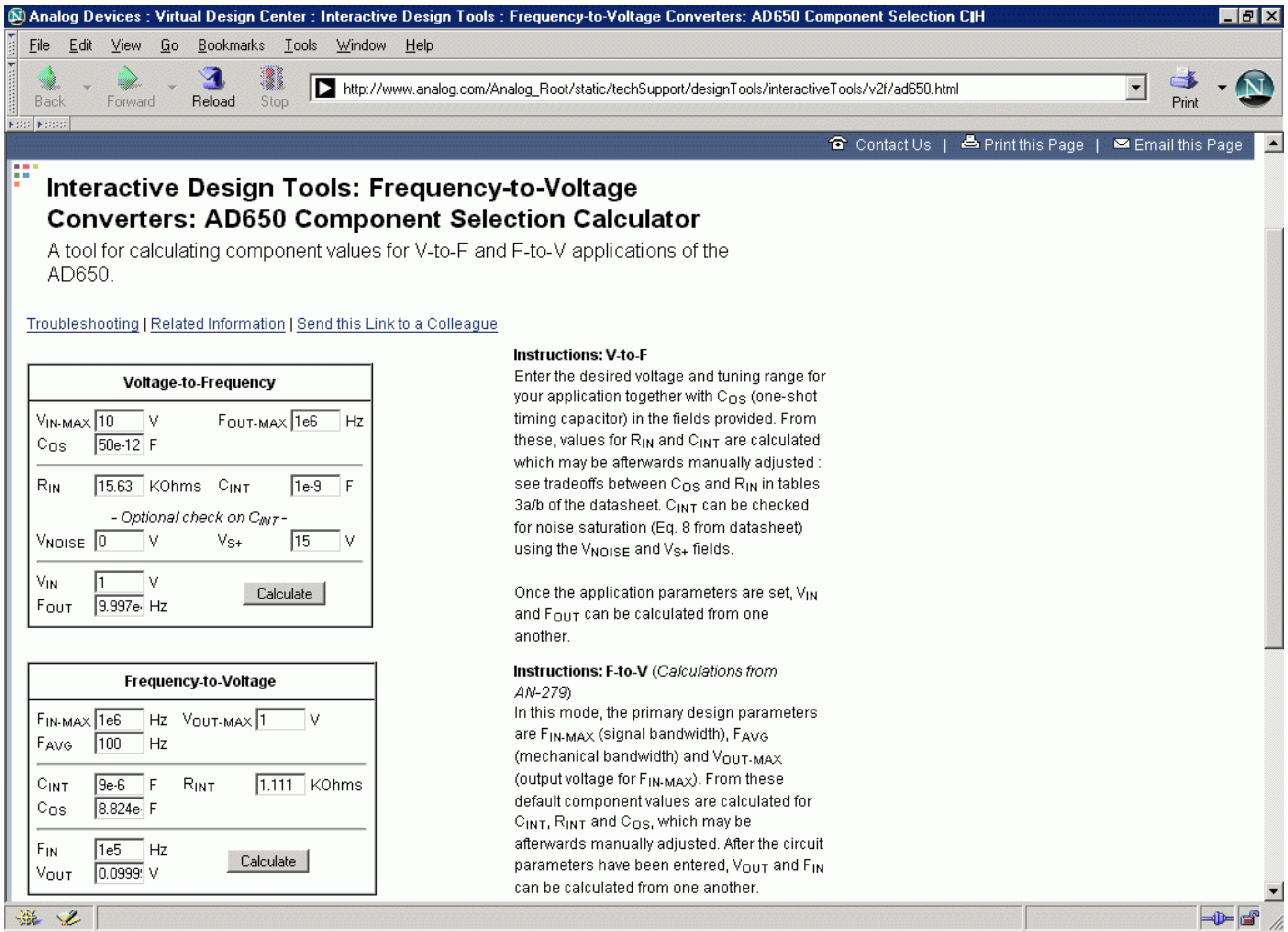
Digital Pressure Sensors with VFC



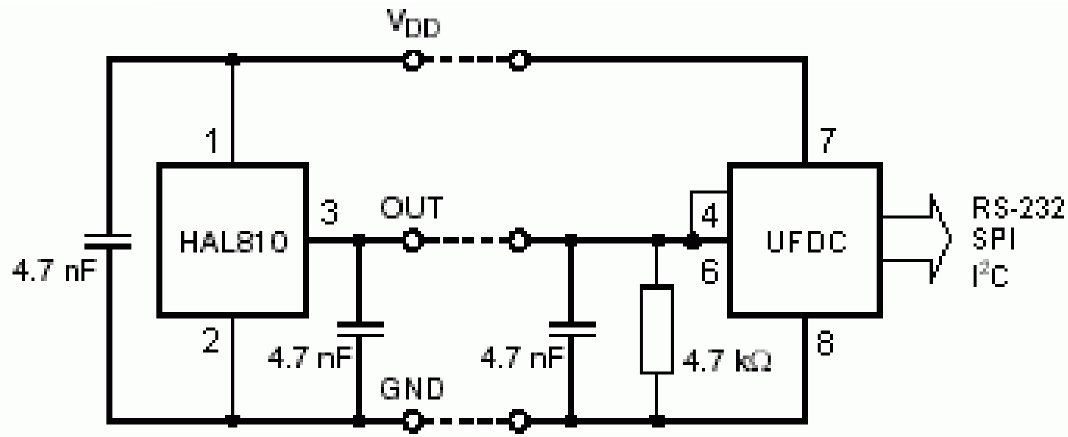
Precision VFCs:

- AD650 and AD652 (Analog Devices)
- AD7740, AD7741 and AD7742 (Analog Devices)
- LM231 and LM331 (National Semiconductors)
- VFCs on discrete components: Jim Williams, Designs for High Performance Voltage-to-Digital Converters, Application Note 14, March 1986, Linear Technology

Interactive Design Tool for VFC



Digital Magnetic Sensors and Systems



HAL819 to UFDC-1 interfacing circuit

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

Conclusions

- The design approach based on the UFDC-1 lets significantly simplify the design process, reduce time to market and production price
- It can be used for both aims in the same time: for maximum resolution and accuracy as well as for maximum data-acquisition rate
- In comparison with the direct microcontroller interfacing this design methodology lets eliminate many design problems connected with the use of advanced measurement methods, microcontroller choice, its Assembler programming and additional error components due to program-dependent and/or software-related effects

IEEE 1451 Standard and Frequency Sensors

IEEE 1451 Standard

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

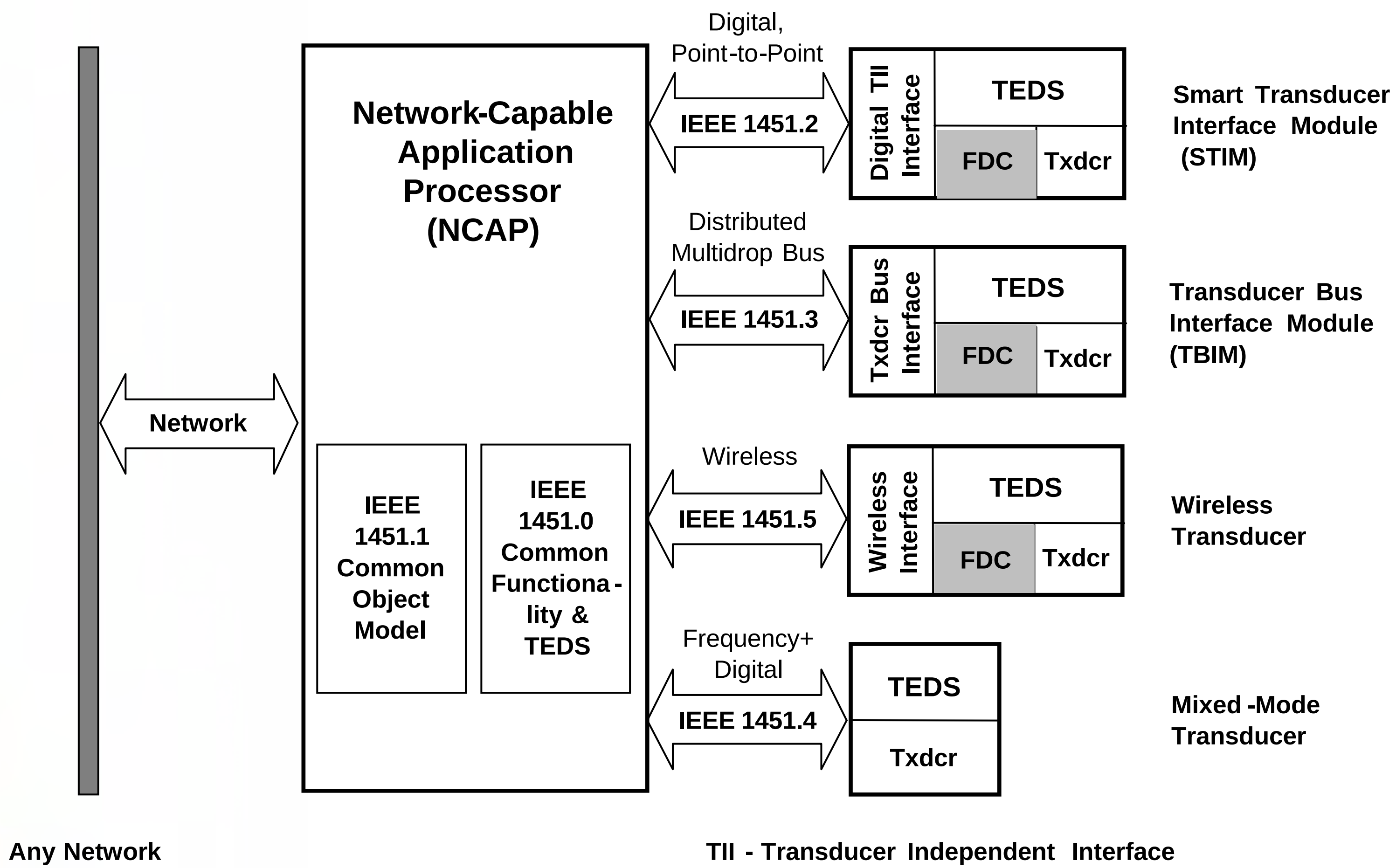
IEEE 1451 Standard Family Members

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

IEEE 1451 Standard and Frequency Sensors

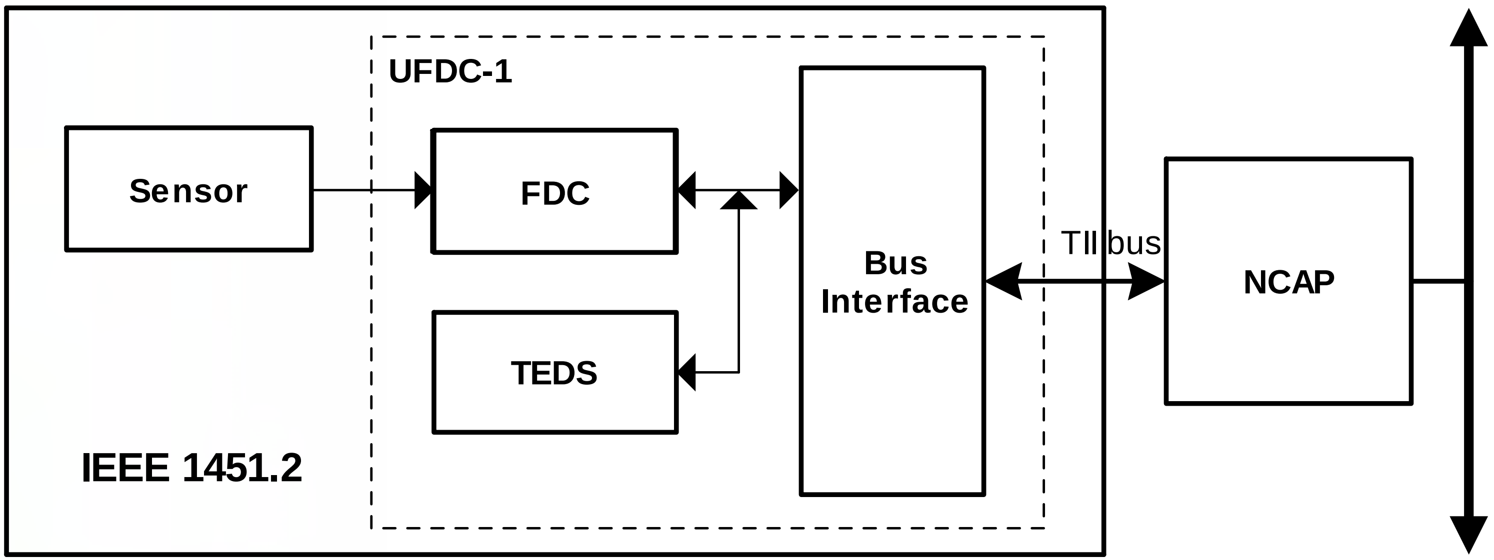
- Frequency sensors also mentioned in some documents, articles and papers about this standard
- Real results are not observed
- No exist any TEDS example for frequency-time domain sensors
- Reasons: (a) there is no any standardized frequency-to-digital conversion method; (b) sensor’s error depends on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

Standard Extension



TII - Transducer Independent Interface
Txdcr - Transducer

Physical Representation of IEEE 1451.2

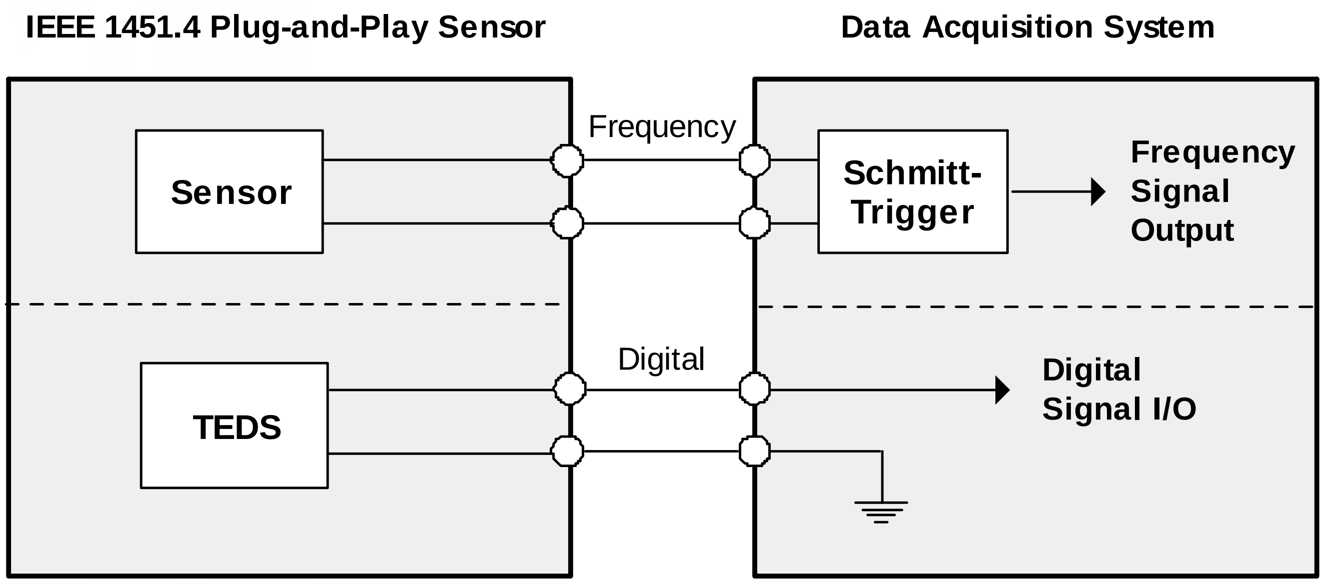


TEDS Example

A POSSIBLE STRUCTURE OF IEEE 1451.4 TEDS FOR PRESSURE FREQUENCY OUTPUT SENSOR

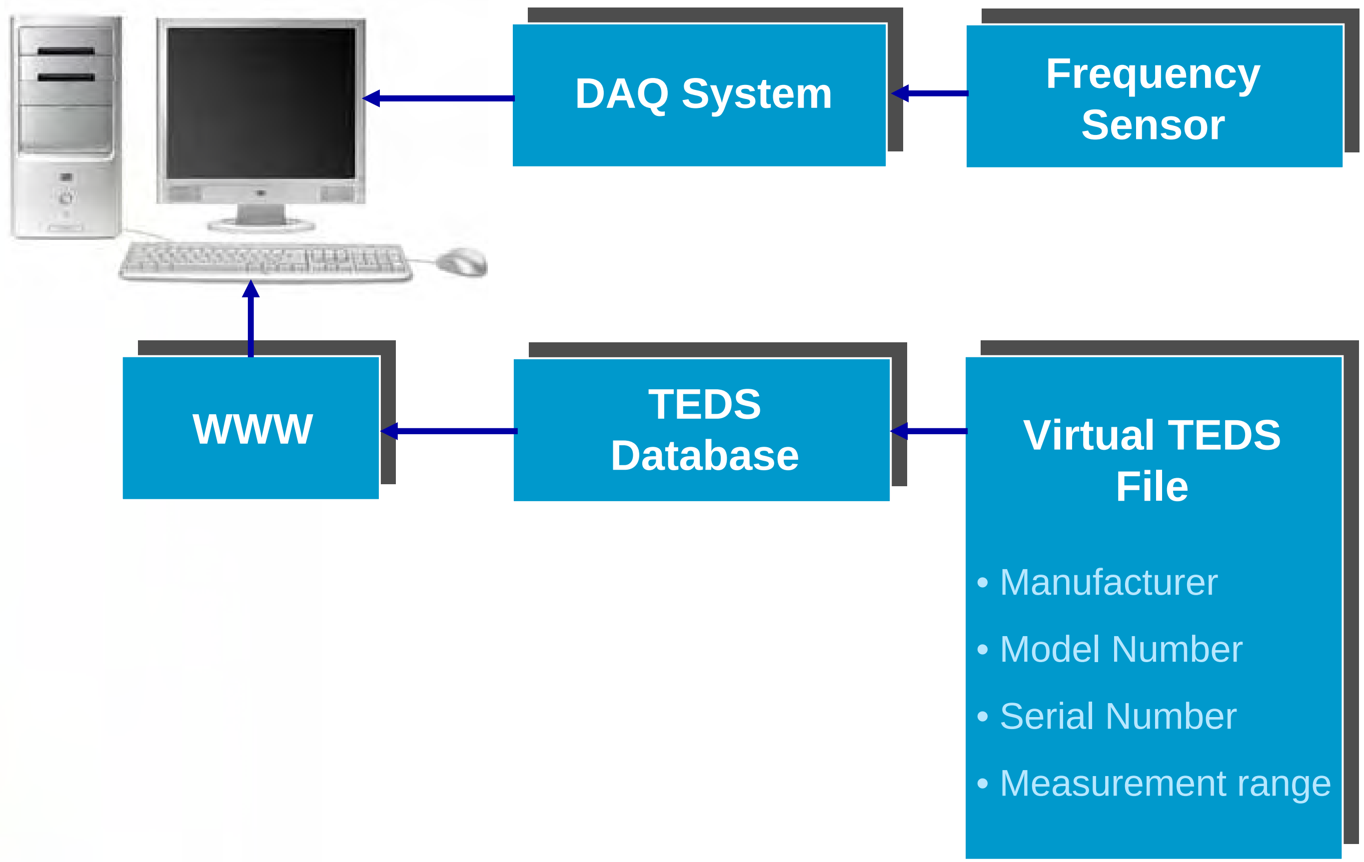
TEDS Structure	Example of Pressure Frequency Output Sensors	
Basic TEDS	Manufacturer ID	19
	Model ID	5300
	Version letter	A
	Serial number	00639F
Standard and Extended TEDS (fields will vary according to transducer type)	Calibration date	21 September 2006
	Measurement range	1000 psia
	Frequency output minimal	30 kHz
	Frequency output maximal	42 kHz
	Relative FS error	0.01 %
	FDC quantization error	0.001 %
	Thermal Sensitivity	±0.005 %/°C
	Response time	3 ms
User Area	Sensor location	B35-2
	Calibration due date	21 September 2009

Mix-Mode Interface for Frequency Sensors



Class II multiwire interface

Virtual TEDS



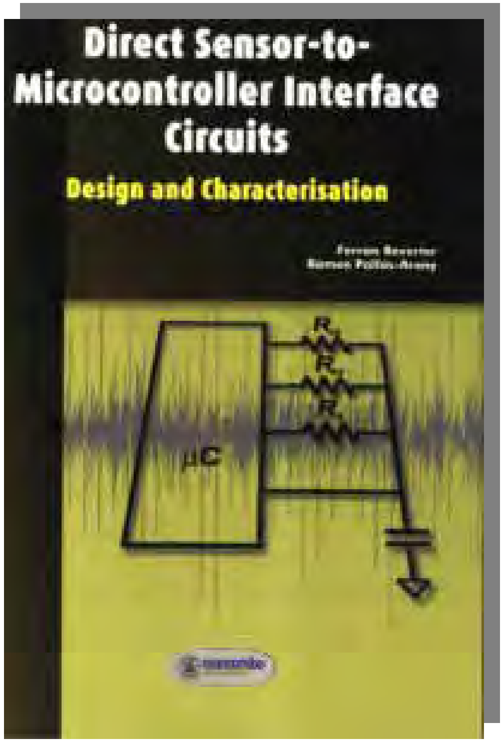
Conclusions

- Simple extension of IEEE 1451 standards family for quasi-digital sensors will manufactures with the ability to produce different IEEE 1451 compatible smart sensors, transducers and systems
- The design approach needs only one of universal component - the UFDC-1, UFDC-2 or USTI

Direct Sensor-to-Microcontroller Interface

Reading

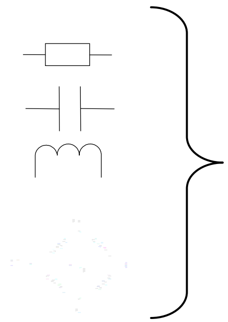
[1]. Ferran Reverter, Ramon Pallas-Areny, Direct Sensor-to-Microcontroller Interface Circuits: Design and Characterisation, *Marcombo S.A.*, 2005



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

Direct μC Interfacing

- Capacitive sensors
- Inductive sensors
- Resistive sensors
- Resistive bridges



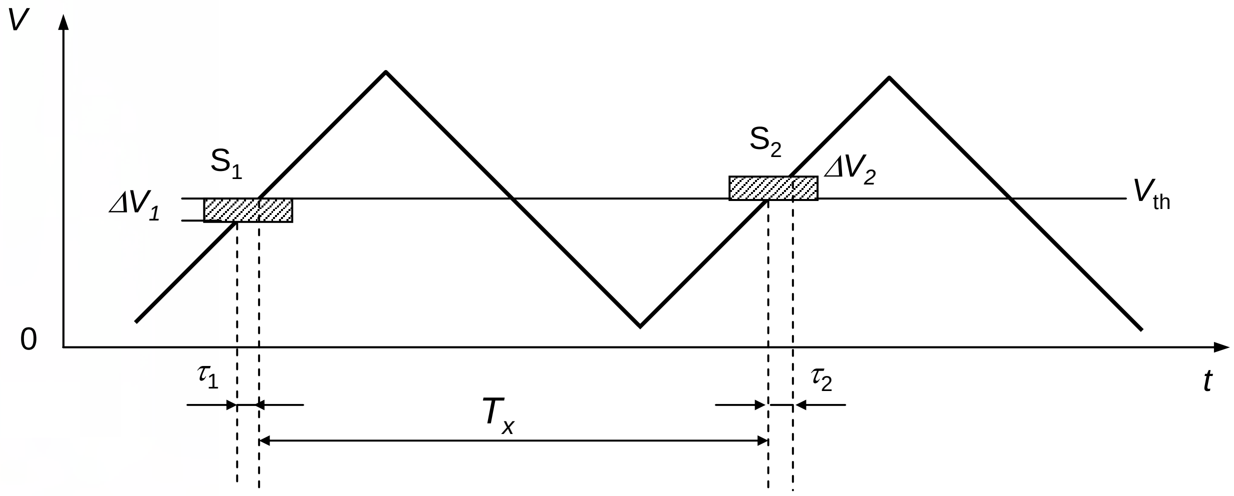
Sensing elements

Advantages

- Minimum possible hardware
- No any ADC
- Low cost
- High reliability
- Simple digital sensors design
- Applications: digital humidity sensors, temperature sensors, pressure sensors, etc.

Disadvantages

- Additional components of error due to software related quantization effects and power supply interference effects
- Related to single time interval measurement for slow slew rate signals:



How to Reduce Errors ?

- Use an external forming devices, for example Schmitt trigger
- Use a capture or sleep mode of microcontroller at interrupt handling
- Use an internal voltage comparator
- Three-signal measurement method should be used

Additional Readings

[1]. A. Custodio, R. Bragos, R. Pallas-Areny, A Novel Sensor-Bridge-to-Microcontroller Interface, in Proceedings of IEEE Instrumentation and Measurement Technology Conference, Budapest, Hungary, 21-23 May, 2001

[2]. S. Y. Yurish, F. Reverter, R. Pallas-Areny, Measurement error analysis and uncertainty reduction for period-and time interval-to-digital converters based on microcontrollers, *Measurement Science and Technology*, Vol.16, No.8, 2005, pp.1660-1666.

[3]. S.Y. Yurish, R. Pallas-Areny, Precise frequency and period measurements for slow slew rate signals based on the method of the dependent count, *Measurement* (in Press).

Future Trends

UFDC-2

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

Universal Sensor and Transducer Interface

- **USTI** – it is the UFDC-2 + resistance, capacitance and resistive bridge measuring modes
- Can contain a TEDS in its flash memory

Future Directions

- Task of creation of different smart digital sensors and systems for various physical and chemical, electric and non electric quantities is one of the most perspective and urgent task
- Accuracy increasing of frequency-time domain sensors as well as the increasing distribution of multiparameters smart sensors are expected
- Integrating all components of sensor system into a single SoC with advanced processing and conversion methods in many cases allows to achieve magnificent technical and metrological performances

Finish

Questions ?

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