Smart Sensor Systems Integration: New Challenges

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24 January 2011, The 6th International Conference on Systems (ICONS' 2011), St.Maarten, The Netherlands Antilles

Outline

1. Introduction
2. Modern Technologies
3. Smart Sensors Design
4. ADC vs. FDC
5. SoC and SiP
6. Conclusions

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Introduction

- **EPoSS** – The European Technology Platform on Smart Systems Integration (July 2006)
- **3SI** - The European Technology Platform on Smart Sensor Systems Integration (October 2003)

Smart Sensor Definition

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

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

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

Smart and intelligent sensors and systems ?

Modern Sensors

- $9.7 billion US sensors industry will rise 6.1 percent annually to 2014 *(Freedonia)*
- Sensors market in Europe estimates to reach revenues of $19.0 billion in 2016 *(Frost & Sullivan)*
- World smart sensors market is projected to reach $ 7.8 billion by 2015 (*Global Industry Analysts*, *Inc*.)
- Strong growth expected for sensors based on MEMS-technologies, smart sensors, sensors with bus capabilities and embedded processing

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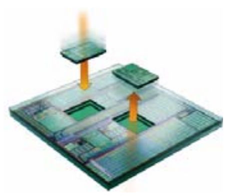
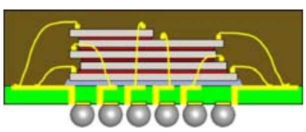
Smart Sensors Technologies



System-on-Chip (SoC)



System-in-Package (SiP)

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

Technological Limitations

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

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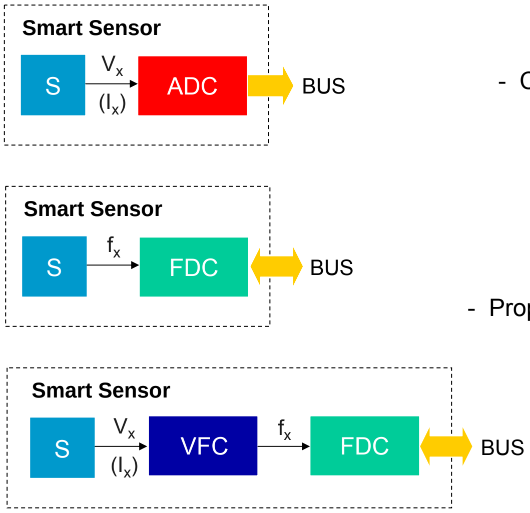
Smart Sensors Design

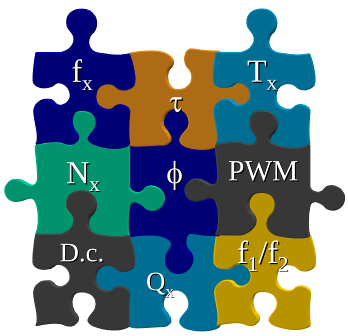


- Classical approach

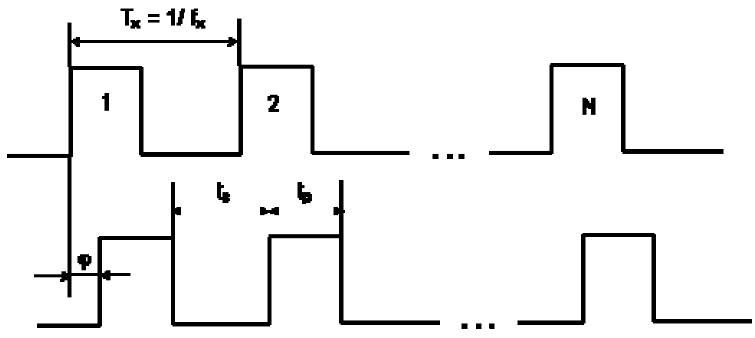
- Proposed approaches

Frequency-Time Domain Parameters of Signal

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



Informative Parameters



Frequency Advantages

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

High Noise Immunity

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

High Power Signal

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

Wide Dynamic Range

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

High Reference Accuracy

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

Simplicity of Interfacing

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

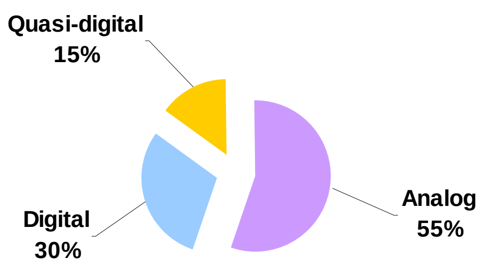
Simplicity of Integration and Coding

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

Multiparametricity

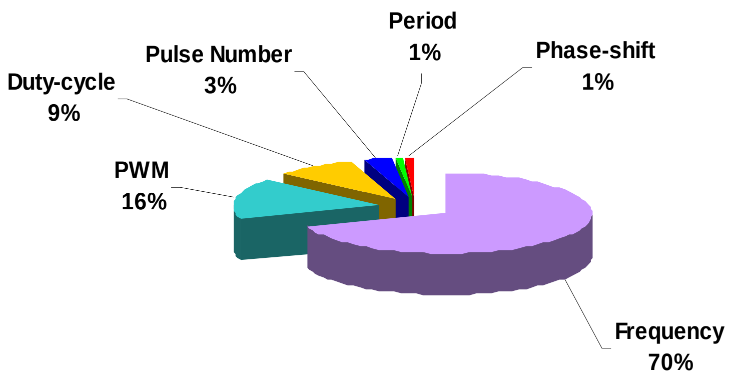
- One sensor's output - two informative parameters: a frequency is proportional to the physical quantity X and duty-cycle at the same output is proportional to the physical quantity Y
- Today there are some examples
- It is the future of multiparametric, multichannel and multifunctional sensors systems

Global Sensor Market



Global sensor market (IFSA, 2010)

Quasi-Digital Sensors



Classification of quasi-digital sensors in term of output signal (IFSA, 2010)

Historical Facts

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

Frequency Output Sensors

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

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

Some Subjective Reasons

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

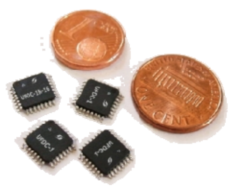
Some Objective Reasons

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

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

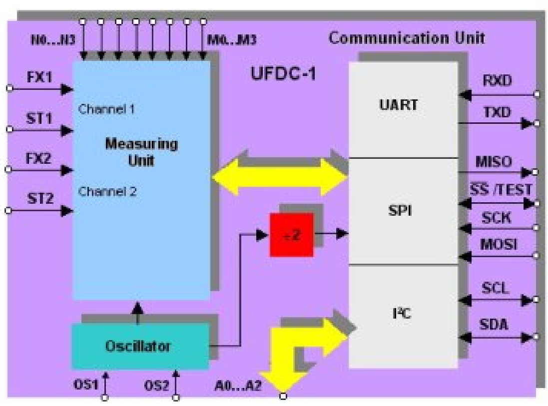
- Low cost digital IC with programmable accuracy
- 2 channels, 16 measuring modes for different frequency-time parameters and one generating mode ($f_{osc}/2$ = 8 MHz)
- Based on four patented novel conversion methods
- Should be very competitive to ADC and has wide applications

Features



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

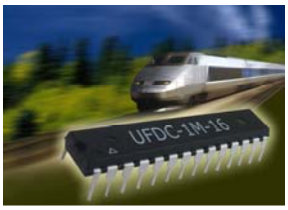
UFDC-1 Block Diagram



Measuring Modes

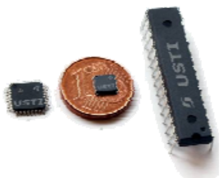
- Frequency, f_{x1} 0.05 Hz – 7MHz directly and up to 112 MHz with prescalling
- Period, T_{x1} 150 ns – 20 s
- Phase shift, φ_x 0 - 360^0 at $f_x \leq 300$ kHz
- Time interval between start- and stop-pulse, τ_x 2.5 μs – 250 s
- Duty-cycle, D.C. 0 – 1 at $f_x \leq 300$ kHz
- Duty-off factor, Q 10^{-8}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

Fast IC UFDC-1M-16



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

Universal Sensors and Transducers Interface (USTI)

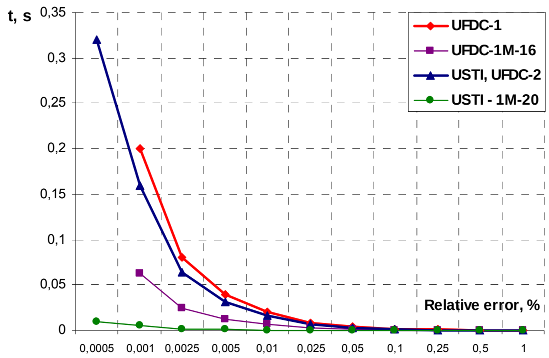


- All UFDC's modes plus a frequency deviation (absolute and relative) measuring mode
- Improved metrological performances: extended frequency range up to 9 MHz (144 MHz with prescaling), programmable relative error up to 0.0005 %, etc.
- Two channel measurements for every parameters
- Improved calibration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

Relative Error vs. Conversion Time

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

Conversion Times vs. Relative Error



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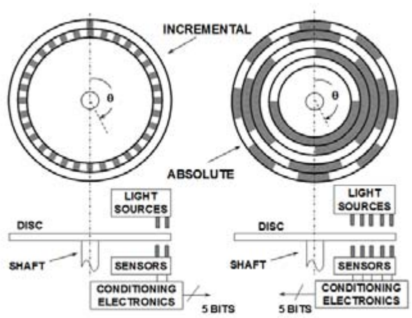
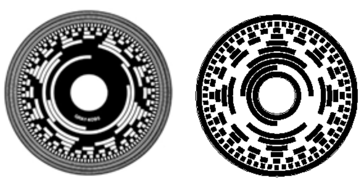
Digital Sensors

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

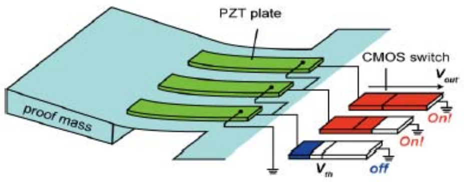
Angular-Position Encoder



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



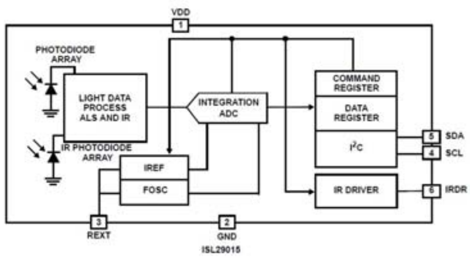
Digital Accelerometer



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

Smart Sensor Example I

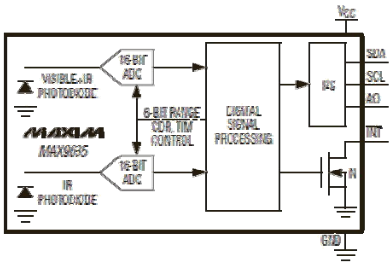
ADC – based digital light sensor ISL29015 (*Intersil*)



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

Smart Sensor Example II

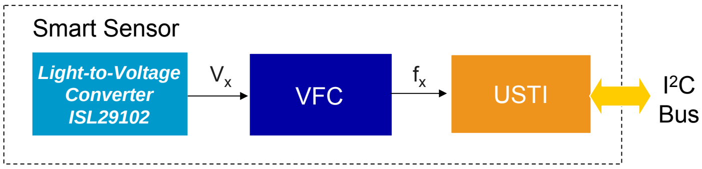
Ambient Light Sensor MAX9635 with ADC (*Maxim*)



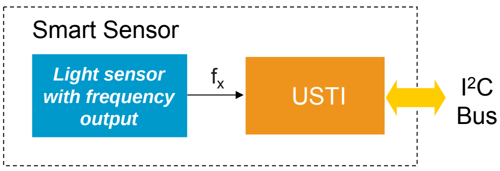
ADC's conversion time: 97 … 100 ms

Smart Sensor Example III

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



FDC – based digital light sensor (II):



Conversion time in both cases at 0.01 %

relative error: 0.5 … 16 ms

VFC Advantages in ADC Conversion Scheme

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

Modern VFCs

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

A / D Converter Types

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

SoC and SiP

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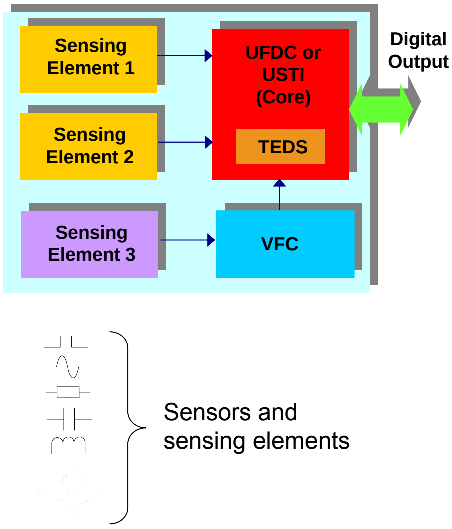
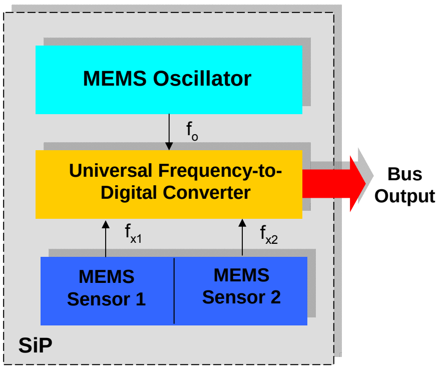
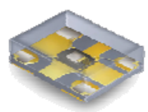
System-on-Chip (SoC)



System-in-Package (SiP)



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



Conclusions

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

Questions & Answers