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Nikolay Kirianaki, Sergey Yurish, Nestor Shpak, Vadim Deynega

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PREFACE

Smart sensors are of great interest in many fields of industry, control systems, biomedical applications, etc. Most books about sensor instrumentation focus on the classical approach to data acquisition, that is the information is in the amplitude of a voltage or a current signal. Only a few book chapters, articles and papers consider data acquisition from digital and quasi-digital sensors. Smart sensors and microsensors increasingly rely on resonant phenomena and variable oscillators, where the information is embedded not in the amplitude but in the frequency or time parameter of the output signal. As a rule, the majority of scientific publications dedicated to smart sensors reflect only the technological achievements of microelectronics. However, modern advanced microsensor technologies require novel advanced measuring techniques.

Because data acquisition and signal processing for smart sensors have not been adequately covered in the literature before, this book aims to fill a significant gap.

This book is based on 40 years of the authors' practical experience in the design and creation of sensor instrumentation as well as the development of novel methods and algorithms for frequency–time-domain measurement, conversion and signal processing. Digital and quasi-digital (frequency, period, duty-cycle, time interval and pulse number output) sensors are covered in this book.

Research results, described in this book, are relevant to the authors' international research in the frame of different R&D projects and International Frequency Sensor Association (IFSA) activity.

Who Should Read this Book?

This book is aimed at PhD students, engineers, scientists and researchers in both academia and industry. It is especially suited for professionals working in the field of measuring instruments and sensor instrumentation as well as anyone facing new challenges in measuring, and those involved in the design and creation of new digital smart physical or chemical sensors and sensor systems. It should also be useful for students wishing to gain an insight into this rapidly expanding area. Our goal is to provide the reader with enough background to understand the novel concepts, principles and systems associated with data acquisition, signal processing and measurement so that they can decide how to optimize their sensor systems in order to achieve the best technical performances at low cost.

How this Book is Organized

This book has been organized into 10 chapters.

Chapter 1, *Smart sensors for electrical and non-electrical, physical and chemical quantities: the tendencies and perspectives*, describes the main advantages of frequency–time-domain signals as informative parameters for smart sensors. The chapter gives an overview of industrial types of smart sensors and contains classifications of quasi-digital sensors. Digital and quasi-digital (frequency, period, duty-cycle, time interval and pulse number output) sensors are considered.

Chapter 2, *Converters for different variables to frequency–time parameters of electric signals*, deals with different voltage (current)-to-frequency and capacitance-to-period (or duty-cycle) converters. Operational principles, technical performances and metrological characteristics of these devices are discussed from a smart sensor point of view in order to produce further conversion in the quasi-digital domain instead of the analog domain. The open and loop (with impulse feedback) structures of such converters are considered. (Figures 2.11, 2.12, 2.13, 2.14, 2.15 and some of the text appearing in Chapter 2, section 2.1, are reproduced from *New Architectures of Integrated ADC*, PDS '96 Proceedings. Reproduced by permission of Maciej Nowinski.)

Chapter 3, *Data acquisition methods for multichannel sensor systems*, covers multichannel sensor systems with cyclical, accelerated and simultaneous sensor polling. Data acquisition methods with time-division and space-division channelling are described. The chapter contains information about how to calculate the time-polling cycle for a sensor and how to analyse the accuracy and speed of data acquisition. Main smart sensor architectures are considered from a data acquisition point of view. Data transmitting and error protection on the basis of quasi-ternary cyclic coding is also discussed.

Chapter 4, *Methods of frequency-to-code conversion for smart sensors*, discusses traditional methods for frequency (period)-to-code conversion, including direct, indirect, combined, interpolation, Fourier conversion-based counting techniques as well as methods for phase-shift-to-code conversion. Such metrological characteristics as quantization error, conversion frequency range and conversion speed as well as advantages and disadvantages for each of the methods are discussed and compared.

Chapter 5, *Advanced and self-adapting methods of frequency-to-code conversion*, discusses reciprocal, ratiometric, constant elapsed time (CET), M/T, single-buffered, double-buffered and DMA transfer advanced methods. Comparative and cost-effective analyses are given. Frequency ranges, quantization errors, time of measurement and other metrological performances as well as hardware and software requirements for realization from a smart sensor point of view are described. This chapter is very important because it also deals with the concepts, principles and nature of novel self-adapting methods of dependent count (MDC) and the method with non-redundant reference frequency. The chapter covers main metrological performances including accuracy, conversion time, frequency range as well as software and hardware for MDC realization. Advanced conversion methods for frequencies ratio, deviations and phase shifts are also described. Finally, some practical examples and modelling results are presented.

Chapter 6, *Signal processing for quasi-digital smart sensors*, deals with the main frequency signal manipulations including multiplication, division, addition, subtraction, derivation, integration and scaling. Particular attention has been paid to new methods of frequency multiplication and scaling with the aim of frequency signal unification. Different wave shapes (sine wave, sawtooth, triangular and rectangular) of a sensor's output are considered. It is also shown how the weight function averaging can be used for noise and quantization error reduction.

Chapter 7, *Digital output smart sensors with software-controlled performances and functional capabilities*, discusses program-oriented methods for frequency-, period-, duty-cycle-, time-interval-, phase-shift- and pulse-number-to-code conversion and digital smart sensors. The design methodology for optimal program-oriented conversion methods, correction of systematic errors and the modified method of algorithms merging are considered. Examples are given. This chapter also describes specific errors and features.

Chapter 8, *Multichannel intelligent and virtual sensor systems*, describes smart sensor systems with time- and space-division frequency channelling. Both are based on the method of dependent count. Comparative analysis is given. Performances and features are illustrated by an ABS smart sensor microsystem example. Multiparameters sensors are also considered. The chapter includes information about virtual sensor instrumentation and how to estimate the total error of arranged system. Definitions and examples (temperature, pressure, rotation speed virtual instruments) are given.

Chapter 9, *Smart Sensor Design at Software level*, deals with embedded microcontroller set instruction minimization for metering applications (to save chip area) and low-power design techniques–optimal low-power programming (for power consumption reduction). Many practical 'hints' (e.g. instruction selection and ordering, jump, call and cycle optimization, etc.), recommendations and examples are given.

Chapter 10, *Smart sensor buses and interface circuits*, describes sensor buses and network protocols from the smart sensor point of view. Modern sensor interface circuits are discussed. Particular attention has been given to the Universal Transducer Interface (UTI) and Time-to-Digital Converter (TDC), which allow low-cost interfacing with different analog sensors elements such as Pt resistors, thermistors, potentiometer resistors, capacitors, resistive bridges, etc. and convert analog sensor signals to the quasi-digital domain (duty-cycle or time interval).

Finally, we discuss what the future might bring.

References. Apart from books, articles and papers, this section includes a large collection of appropriate Internet links, collected from the Sensors Web Portal launched by the authors.

LIST OF ABBREVIATIONS AND SYMBOLS

δ_q	program-specified relative quantization error
Δ_q	absolute quantization error
D_f	specified measuring range of frequencies
f_x	measurand frequency
f_0	reference frequency
F	greater of the two frequencies f_x and f_0
f	lower of the two frequencies f_x and f_0
f_{bound}	lower frequency limit
F_{bound}	upper frequency limit
m	counter capacity
N_δ	number, determined by the error $\delta = 1/N_\delta$
N_x	number of periods of lower frequency f
T	period of greater frequency ($T = 1/F$)
τ	period of lower frequency ($\tau = 1/f$)
T_q	quantization window
T_0	reference gate time interval
ABS	antilock braking system
ADC	analog-to-digital converter
ALU	arithmetic logic unit
ASIC	application specific integrated circuit
ASIP	application specific instruction processor
CAD	computer-aided design
CMOS	complementary metal oxide semiconductor
CT	counter
DAC	digital-to-analog converter
DAQ	data acquisition
DFT	discrete Fourier transformation
DSP	digital signal processor
FCC	frequency-to-code converter
FPGA	field-programmable gate array
FS	full scale
GUI	graphical user interface
LCF	Liapunov characteristic function

MDC	method of dependent count
μK	microcontroller
μP	microprocessor
MSM	multichip module
PCA	programable counter array
PCM	program-oriented conversion method
PWM	pulse width modulation
RAM	random access memory
ROM	read-only memory
VFC	voltage-to-frequency converter
VLSI	very large scale integration

INTRODUCTION

Rapid advances in IC technologies have brought new challenges to the physical design of integrated sensors and micro-electrical-mechanical systems (MEMS). Microsystem technology (MST) offers new ways of combining sensing, signal processing and actuation on a microscopic scale and allows both traditional and new sensors to be realized for a wide range of applications and operational environments. The term 'MEMS' is used in different ways: for some, it is equivalent to 'MST', for others, it comprises only surface-micromechanical products. MEMS in the latter sense are seen as an extension to IC technology: 'an IC chip that provides sensing and/or actuation functions in addition to the electronic ones' [1]. The latter definition is used in this book.

The definition of a smart sensor is based on [2] and can be formulated as: 'a smart sensor is one chip, without external components, including the sensing, interfacing, signal processing and intelligence (self-testing, self-identification or self-adaptation) functions'.

The main task of designing measuring instruments, sensors and transducers has always been to reach high metrology performances. At different stages of measurement technology development, this task was solved in different ways. There were technological methods, consisting of technology perfection, as well as structural and structural-algorithmic methods. Historically, technological methods have received prevalence in the USA, Japan and Western Europe. The structural and structural-algorithmic methods have received a broad development in the former USSR and continue developing in NIS countries. The improvement of metrology performances and extension of functional capabilities are being achieved through the implementation of particular structures designed in most cases in heuristic ways using advanced calculations and signal processing. Digital and quasi-digital smart sensors and transducers are not the exception.

During measurement different kinds of measurands are converted into a limited number of output parameters. Mechanical displacement was the first historical type of such (unified) parameters. The mercury thermometer, metal pressure gauge, pointer voltmeter, etc. are based on such principles [3]. The amplitude of an electric current or voltage is another type of unified parameter. Today almost all properties of substances and energy can be converted into current or voltage with the help of different sensors. All these sensors are based on the use of an amplitude modulation of electromagnetic processes. They are so-called analog sensors.

Digital sensors appeared from a necessity to input results of measurement into a computer. First, the design task of such sensors was solved by transforming an analog quantity into a digital code by an analog-to-digital converter (ADC). The creation of quasi-digital sensors, in particular, frequency sensors, was another very promising direction [3]. *Quasi-digital sensors are discrete frequency–time-domain sensors with frequency, period, duty-cycle, time interval, pulse number or phase shift output*. Today, the group of frequency output sensors is the most numerous among all quasi-digital sensors (Figure I). Such sensors combine a simplicity and universatility that is inherent to analog devices, with accuracy and noise immunity, proper to sensors with digital output. Further transformation of a frequency-modulated signal was reduced by counting periods of a signal during a reference time interval (gate). This operation exceeds all other methods of analog-to-digital conversion in its simplicity and accuracy [4].

Separate types of frequency transducers, for example, string tensometers or induction tachometers, have been known for many years. For example, patents for the string distant thermometer (Patent No. 617 27, USSR, Davydenkov and Yakutovich) and the string distant tensometer (Patent No. 21 525, USSR, Golovachov, Davydenkov and Yakutovich) were obtained in 1930 and 1931, respectively. However, the output frequency of such sensors (before digital frequency counters appeared) was measured by analog methods and consequently substantial benefit from the use of frequency output sensors was not achieved practically.

The situation has changed dramatically since digital frequency counters and frequency output sensors attracted increasing attention. As far back as 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...' [3]. Although frequency output sensors exist practically for any variables, this prognosis has not yet been fully justified for various reasons.

With the appearance in the last few years of sensor microsystems and the heady development of microsystem technologies all over the world, technological and cost factors have increased the benefits of digital and quasi-digital sensors. Modern technologies are able to solve rather complicated tasks, concerned with the creation of different sensors. Up to now, however, there have still been some major obstacles preventing industries from largely exploiting such sensors in their systems. These are only some subjective reasons:

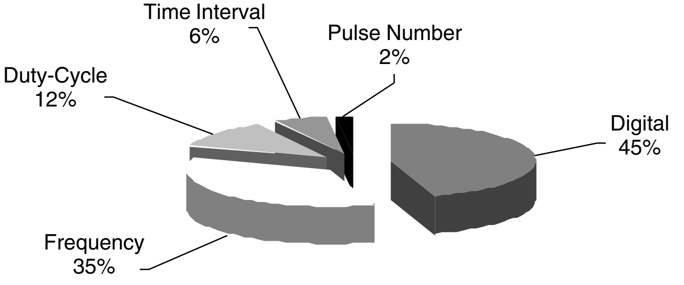

Figure I Classification of sensors from discrete group in terms of output signals (IFSA, 2001)

- The lack of awareness of the innovation potential of modern methods for frequency-time conversion in many companies, as processing techniques have mainly been developed in the former Soviet Union.
- The tendency of companies to return, first of all, major expenditures, invested in the development of conventional ADCs.
- The lack of emphasis placed on business and market benefits, which such measuring technologies can bring to companies etc.

Today the situation has changed dramatically. According to Intechno Consulting, the non-military world market for sensors has exceeded expectations with US$32.5 billion in 1998. By 2003, this market is estimated to grow at an annual rate of 5.3% to reach US$42.2 billion. Under very conservative assumptions it is expected to reach US$50–51 billion by 2008; assuming more favourable but still realistic economic conditions, the global sensor market volume could even reach US$54 billion by 2008. Sensors on a semiconductor basis will increase their market share from 38.9% in 1998 to 43% in 2008. Strong growth is expected for sensors based on MEMS-technologies, smart sensors and sensors with bus capabilities [5]. It is reasonable to expect that silicon sensors will go on to conquer other markets, such as the appliances, telecommunications and PC markets [6].

We hope that this book will be a useful and relevant resource for anyone involved in the design of high performance and highly efficient digital smart sensors and data acquisition systems.

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