ISSN 1726-5479

SENSORS & TRANSDUCERS

12/09 vol. 111

Sensor Market Trends

International Frequency Sensor Association Publishing

IFSA

Sensors & Transducers

Volume 111, Issue 12
December 2009

www.sensorsportal.com

ISSN 1726-5479

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA).
Available in electronic and on CD.

Sensors & Transducers Journal

Contents

Volume 111
Issue 12
December 2009

www.sensorsportal.com

ISSN 1726-5479

Research Articles

Authors are encouraged to submit article in MS Word (doc) and Acrobat (pdf) formats by e-mail: editor@sensorsportal.com
Please visit journal's webpage with preparation instructions: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm

Sensors & Transducers Journal, Vol. 111, Issue 12, December 2009, pp. 10-17

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

cLite – A Capacitive Signal Conditioning IC

Krauss, GUDRUN
ZMD America, Inc. 201 Old Country Road, Melville, NY, 11747, USA
Tel.: 631.549.2666, fax: 631.549.2882
E-mail: gudrun.krauss@zmdi.com

Received: 16 November 2009 /Accepted: 22 December 2009 /Published: 30 December 2009

Abstract: The ZMD31210 cLite™ – a new member of the ZMDI's Lite™ family of low-cost sensor signal conditioner (SSC) integrated circuits – is described in this paper. The cLite™ is the first conditioner for capacitive sensors. Supporting sensor capacitances from 2 pF up to 260 pF, the new sensor signal conditioner covers a wide range of applications. An important aspect of conditioning a capacitance sensor input signal is the adaptation of the capacitive-to-digital converter (CDC) input range to the sensor signal span and offset values in order to maximize accuracy. All typical features of the Lite™ family including the digital calibration math based on EEPROM-stored coefficients and a variety of outputs (I^2C™ [1], SPI, PDM, and programmable alarms) are integrated in the cLite™ as well. Additional features including a sleep mode and low supply voltage range (down to 2.3 V) support the low power concept. The paper focuses in particular on the capacitance sensor adaptation and high precision sensor conditioning. *Copyright © 2009 IFSA.*

Keywords: Sensor signal conditioner, End-of-line calibration, Capacitive sensor conditioning

1. Introduction

Capacitive sensors are cost effective because they are simple to build or even exist as a parasitic in an application. They are also low power because no static current occurs. Tolerances of the design, nonlinearities, and unwanted environmental influences, for example temperature dependence, require sensor signal conditioning including signal amplification, error correction, and removal of temperature

[1] I^2C™ is a registered trademark of NXP.

dependency. The core of a capacitive SSC is the analog/digital signal path as shown in Fig.1. Blocks and features will be explained in details below.

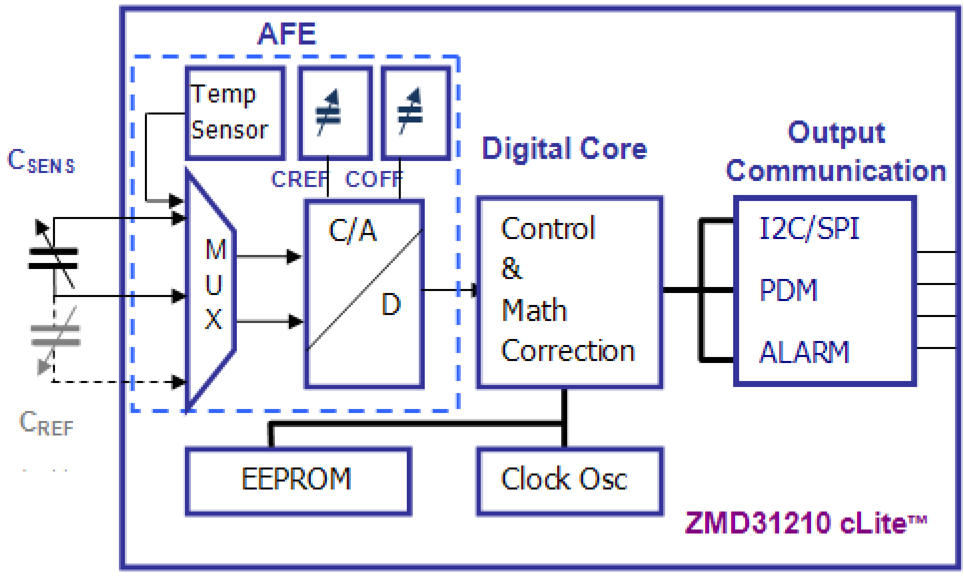


Fig. 1. Schematic for Capacitive SSC.

A very successful method for digitizing the sensor capacity is direct capacitance-to-digital conversion using the sensor as part of a switched capacitor network. By doing so, different state-of-the-art A/D conversion schemes are available such as sigma-delta or the charge-balancing converter. The latter, which is used in all other members of ZMDI's Lite™ family, is also employed for the capacitance-to-digital converter (CDC) of cLite™. The digitized signal is then conditioned using a set of polynomial ROM-programmed equations and the calibration coefficients stored in the cLite's EEPROM.

Two steps are necessary for receiving a precise calibration result:

1. An optimum range selection for the CDC in order to achieve the maximum resolution for the conversion.
2. The single-pass calibration including the selection of an optimized calibration method depending on the actual sensor behavior.

For the range requirement, the CDC inherits from the Lite™ family an "analog front end" that can be configured using gain and offset terms. The gain term is set by a programmable on-chip reference capacitor C_{REF} and defines the capacitive input span. The offset term is set by another programmable on-chip capacitor C_{OFF} and defines the base capacitance above which the span is located. Choosing the wrong front-end configuration can cause overdrive and saturation of the CDC, or it may result in a waste of resolution that cannot be recovered by the subsequent digital conditioning. The cLite™ also supports ratio-based (differential) capacitive sensors, where the reference capacitor is part of the sensor. For these types of sensors, two types of CDC transfer functions are available. Type 1 converts the ratio C_A/C_B of the two input capacitors; type 2 converts the ratio of one capacitor to the sum of the two capacitors $C_A/(C_A+C_B)$.

To optimize the calibration procedure, it is essential to know the sensor characteristics for non-linearity and temperature dependence because the cLite™ offers many different structural approaches (ROM-based formulas) from which the most appropriate one must be chosen in order to get best results.

2. Capacitance –Signal Adaptation

A single capacitive sensor C_A, for example a humidity sensor (Fig.2, can be split into two parts, a variable capacitance C_{AV} changing with the physical measurand, humidity in this example, and a base capacitance C_{AB}.

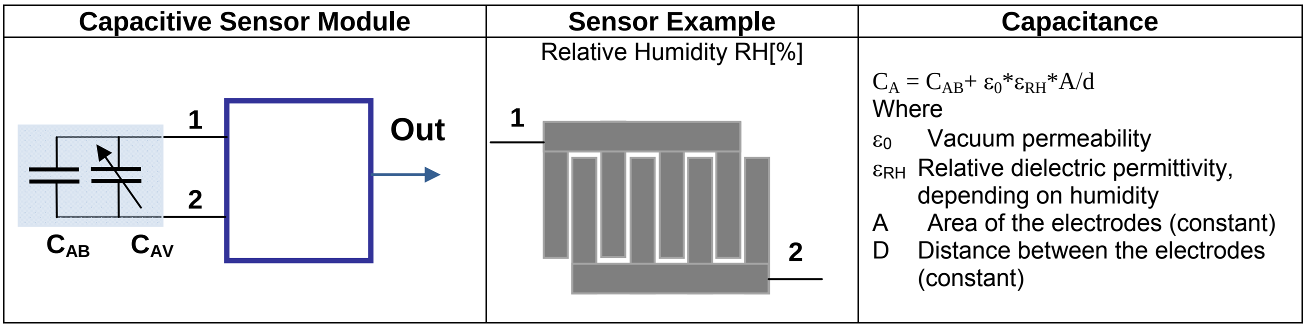


Fig. 2. Capacitive Sensor Module Consisting of a Single Variable Module.

The transfer function of the sensor can be described as

$$C_A = RH * C_{AV} + C_{AB}, \tag{1}$$

where RH represents the relative humidity in a range from 0 to 1 (0 % to 100 %).

The CDC must now be configured so that C_{AB} is compensated by an offset term and $RH^* \, C_{AV}$ is covered by an adequate gain term.

With the transfer function of the CDC,

$$Z_{SENSOR} = 2^{RES} * gain*(C_{IN} - offset) = 2^{RES} * (C_{IN} - C_{OFF}) / C_{REF} \, , \tag{2}$$

where
Z_{SENSOR} - CDC output number;
C_{IN} - Input sensor capacitance;
C_{REF} - Reference capacitance;
C_{OFF} - Offset capacitance;
RES - Resolution of the CDC.

C_{REF} and C_{OFF} must be chosen as small as possible given the configurability of the on-chip capacitors C_{REF} and C_{OFF} but large enough that the CDC input range is never saturated at maximum input signal including possible sensor tolerances and temperature influences. In a subsequent step, the transfer function will be corrected in the digital domain of the SSC during calibration.

The second main type of capacitive sensors is the differential sensor; e.g., the linear position sensor in Fig.3. Rotating types (angular position) are also feasible. Typically for this type of sensor, the sum of the two parts remains constant.

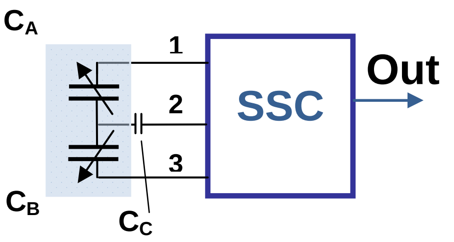
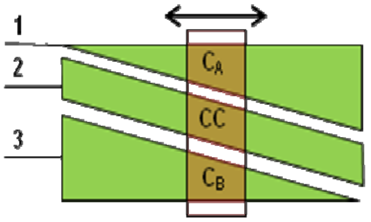
Capacitive Sensor Module	Sensor Example	Capacitance
	Angular or Linear Position (pos) Sensor 	$C_{A\_pos}=\varepsilon_0*\varepsilon_{rel}*A/d$ $C_{B\_pos}=\varepsilon_0*\varepsilon_{rel}*(A_0-A)/d$ Where ε_0 Vacuum permeability ε_{rel} Relative dielectric permittivity of the surrounding air A Area covered by CA A_0 Area covered by CA and CB d Distance between the electrodes (constant)

Fig. 3. Capacitive Sensor Module – Differential Structure with Equal Slope of 2 Capacitors.

The sensor includes two capacitors that are captured as a ratio. This “self-referencing” has the advantage of compensating environmental influences; e.g., humidity or temperature. The sensor is built so that one capacitance is increasing and the other is decreasing over the input signal range but the total sum always remains constant. The transfer function of this sensor can be described by the equation

$$C_A/(C_A+C_B) = X\ , \tag{3}$$

where X represents the position in a range from 0 to 1 (0% to 100%).

For such a sensor, the CDC transfer function would be set to type 2, which results in a digital output of

$$Z_{SENSOR} = 2^{RES} * C_A / (C_A + C_B) \tag{4}$$

In an actual sensor, there are always small parasitic capacitors in parallel to C_A and C_B, which prevents the output from being completely symmetric and varying from 0 to full scale. The correction for those deviations must be done as part of the digital conditioning. The goal of the sensor design for this sensor type should be to provide as much span as possible by keeping the parallel parasitic capacitors small (parasitics to ground are tolerable).

The capacitor C_C shown in Fig. 3 does not appear in any equation and has no influence on the transfer function. It could also be replaced by a short circuit. However, this capacitor is fortunate in two respects:

- In positioning sensors, it prevents the need for direct contact with moving parts and makes the sensor very robust against wearing.
- C_C could also be used to lower the overall capacitance level to a value that is supported by the cLite™ IC because it limits the maximum capacitance seen by the cLite™ input to C_C even if C_A and C_B have higher values.

The sensor in Fig.3 is the special case of the single variable capacitive sensor. An external capacitor is part of the sensor construction and acts as a reference capacitor that adds some self-compensation for environmental influences such as temperature and aging. A level sensor is shown as an example. Here also the tolerance of ε_{rel} of the liquid is compensated. The transfer function of the sensor would be

$$C_A/C_B = L\ , \tag{5}$$

where L represents the fluid level in a range from 0 to 1 (0 % to 100 %).

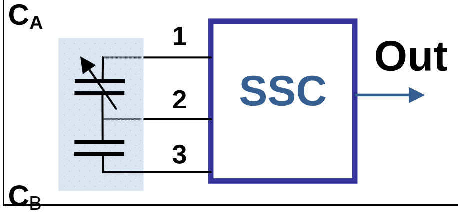
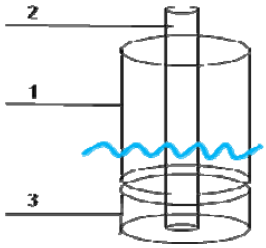
Capacitive Sensor Module	Sensor Example	Capacitance
	Liquid Level Sensor 	$C_{A\_LV} = 4\pi \cdot \varepsilon_0 \cdot \varepsilon_{rel} / \ln(r_2/r_1)$ Where C Capacitance depending on fill level ε_0 Vacuum permeability ε_{rel} Relative dielectric permittivity, depending on liquid r_1,r_2 Radius of the external, internal cylinder

Fig. 4. Capacitive Sensor Module Consisting of a Single Variable and Reference Capacitor.

Normally for the sensor transfer function (5), the CDC should be set to the transfer function type 1 in order to provide a linear output of the converter that would need very little additional signal conditioning. To do this, the simple sensor design shown in Fig.4 must be modified to ensure that C_B is always equal to or bigger than the maximum value of C_A. In some cases, this could cause difficulties in the construction of the sensor or disadvantages in the application such that another method must be chosen.

Using the type 2 transfer function of the CDC results in a digital output of the converter of

$$Z_{SENSOR} = 2^{RES} * C_A / (C_A + C_B) = 2^{RES} * L / (L + 1) \tag{6}$$

when combined with the sensor's transfer function. The resulting non-linearity, though it is not a parasitic influence but systematic, can be corrected in the digital domain to an overall linear response.

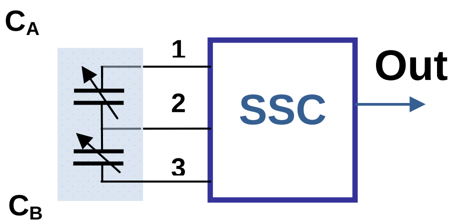
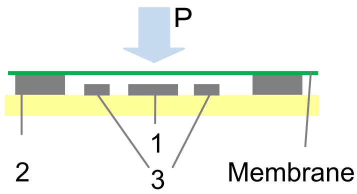
Capacitive Sensor Module	Sensor Example	Capacitance
	Pressure Sensor 	$C_{A\_P} = \varepsilon_0 * \varepsilon_{rel} * A/d$ Where C Capacitance depending on the pressure ε_0 Vacuum permeability ε_{rel} Relative dielectric permittivity of the surrounding air A Area of the electrodes (constant) d Distance between the electrodes changing depending on the pressure

Fig. 5. Capacitive Sensor Module – Differential Structure with Different Slope for the 2 Capacitors.

A very common type of pressure sensor is shown in Figure 5. Here again the membrane carries two capacitors that can be seen as the "input" capacitor and "reference' capacitor. Both of the capacitors change in the same direction with pressure but with a difference in slope. Usually the output signal of such a sensor is defined as

$$(C_A - C_B)/(C_A + C_B) = f(P) \tag{7}$$

This type of transfer function is not implemented in the cLite™. However, since equation (7) is not a linear function of the pressure because of the physics of the membrane deflection, it does not make a significant difference to use the Type 1 (C_A/C_B) transfer function instead. In any case, the result must be corrected for linearity in the digital domain.

3. Capacitive Sensor Data Validation

The adjustment of cLite's equation system to the individual sensor behavior takes place during the calibration, presuming that the configuration of the CDC (Type 1 / 2, C_{REF}, C_{OFF}) was done appropriately. Calibration coefficients are determined and stored in the EEPROM. Finally, depending on the sensor input signal (and the temperature input signal, if the temperature dependency is also conditioned), a corrected output signal can be calculated based on the equations and the stored coefficients.

Although the calibration as part of the mass production process is a fully automated procedure, the sensor module consisting of the sensor and a conditioner IC must be carefully designed in order to achieve optimal results in terms of accuracy and calibration time. Prerequisite therefore is the knowledge of the sensor characteristics. The most effective approach is the measurement of the sensor capacitance as a function of the input signal (e.g. pressure or humidity) and the temperature. With this data, one can estimate what type of correction (only linear or higher order) would fulfill the targeted accuracy. Knowing that capacitive measurements sometimes cause problems, the raw data collection function of the cLite™ can be used to capture that data. Very useful for this estimation is a nonlinear optimization tool like the EXCEL-Solver. The following strategy has been proven of value in order to get familiar with the potential correction results, which can be achieved with cLite's conditioning algorithm.

- Taking one characteristic (5 to 10 data points) versus the input sensor signal at room temperature. With this data, the required correction equation can be estimated. It must be considered that not only is the order limited to 3rd order in cLite™, but there are also limitations in the amount of correctable nonlinearity.
- Taking one characteristic (4 to 8 data points) versus temperature with no (zero) input signal. With this data, the TCO (temperature coefficient for offset) or a potential second order TCO can be estimated again by a linear or second order fit of the characteristic.
- Taking one characteristic (4 to 8 data points) versus temperature at full scale input signal. Based on this data, the TCG (temperature coefficient of gain) or a potential second order TCG can be estimated. In order to do that, the temperature data at zero input must be included to clearly separate the TCG from TCO.
- Finally it is worthwhile to make a full fit over the captured data by letting the EXCEL-Solver find optimized values for all coefficients.(For the previous fittings, the trend line feature of EXCEL could also be used.) The exact correction equations that are prerequisite for this step can be taken from the cLite™ specification. The result can provide a very good estimation of the achievable accuracy. Also one can estimate the penalty in accuracy when using fewer data points in order to save calibration time in volume production. (Note that the values of the coefficients are not the same as the values of the real calibration because of normalizations that go together with the fixed point math of the cLite™ processor.)

4. Capacitive Sensor Calibration

Using a polynomial to model the sensor behavior, calibration is a process of determining the coefficients of the equation system by using a best fit approach. If *n* coefficients are needed to reach the required accuracy of the calibration, then *n* data points are necessary. The target values of the calibrated output signal are usually given as percentage ratios related to the full scale output (2^{RES} for digital outputs). For example, the target value 10 % for a 14-bit CDC is 1638 counts. The CDC resolution is programmable in cLite™ to 14, 12, 10 or 8 bits. A lower resolution allows for faster conversion time.

The calibration itself is characterized by three main steps. These steps are supported and guided by the software included in ZMDI’s cLite™ Development Kit.

1. The configuration data including a unique ID is written to the EEPROM of the device. The ID is subsequently used to identify all data connected with the specific device which is stored in a data base on the PC. The data stored on the PC includes target values, raw capacitances and raw temperatures used to calculate the coefficients at the end of the calibration process.
2. With the selection of the calibration method, the minimum number of the data points required for calibration can be determined. There are several criteria for the optimum location of those points; however, they must also be chosen by the user with consideration for the calibration environment. Because ZMDI’s software uses the nonlinear optimization for calculating the coefficients, tolerances in reproducing temperature or sensor input values will not influence the accuracy as long as they are captured as a change of the target value by the measurement equipment. Furthermore it is possible to consider more than the minimum number of data points resulting in a best-fit calibration, which can help to “over-weigh” important areas of the input range. The raw values are then stored in the data base.
3. After the total number of calibration points is collected, the calibration coefficients are calculated by the ZMDI’s software and written to the EEPROM.

This “single-pass” calibration method does not require any iteration steps or adjustment of external components. Using the bi-directional digital interface (I^2C, SPI), an end-of-line calibration of the packaged sensor module is possible.

An option for reducing calibration time while still maintaining reasonable accuracy is the use of a default value for a coefficient that has a narrow statistical distribution. An option for increasing the accuracy of the calibration is to “over-determine” the equation system by collecting more measured points than the minimum required number. In most cases, the accuracy improvement does not justify the additional effort to obtain the higher number of data points.

For a transfer function (e.g. for humidity sensors) as shown in Fig. 1, a special equation system is implemented in the cLite™ mathematics.

The transfer function is characterized by a break point at a programmable input value, where the gain is changing. For such sensors, a piece wise calibration is necessary for achieving minimum errors via different coefficients (gain, nonlinearity) for the two parts of the transfer function.

5. Output / Communication Block

The ZMD31210 cLite™ supports the most common digital standard protocols I^2C and SPI to process commands (“command mode”) for the "end of line" calibration, which allows calibrating the module after the manufacturing process is finished and prevents calibration influences resulting from sensor parameters changing due to mechanical or thermal stress.

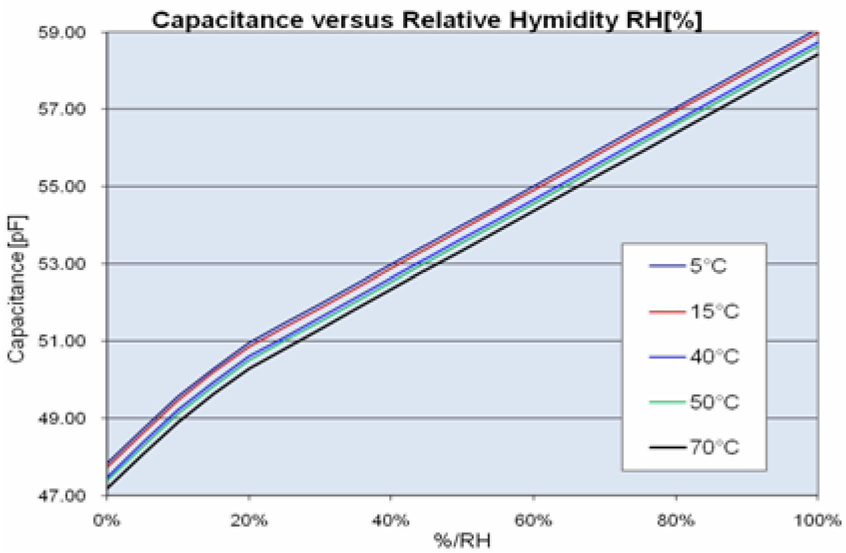


Fig. 1. Transfer Function with Breakpoint.

After calibration, the EEPROM contents can be locked.

The cLite™ provides two PDM outputs for the conditioned capacitance and temperature values. Those outputs are intended to be used together with an external 1st order RC-low pass filter as analog ratiometric outputs.

In addition, two alarm outputs can be selected, which are programmable separately including hysteresis.

6. Summary

With the addition of the ZMD31210 cLite™ signal conditioner with a capacitive front end, ZMDI addresses a new type of sensors, retaining high functionality and meeting low cost requirements for high volume applications. The large variety of applicable sensor types complemented with digital and analog output methods characterizes the high flexibility of this new SSC. Optimization for low power/ low voltage applications and support for a wide range of capacitive sensors are key parameters of ZMDI's cLite™.

___

Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

Topics Covered

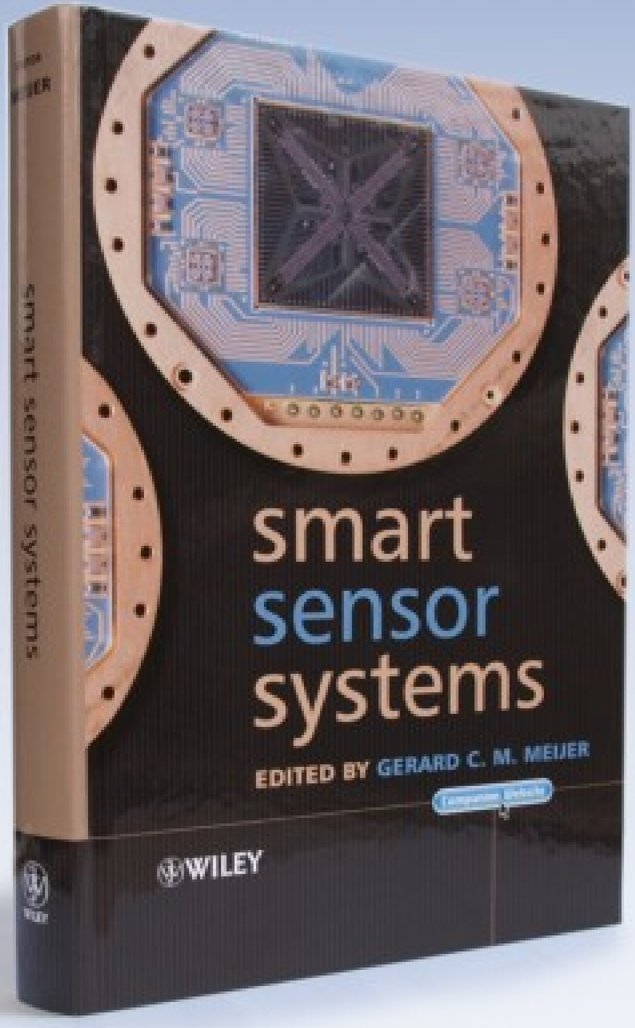
Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 8-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm Authors must follow the instructions strictly when submitting their manuscripts.

Advertising Information


smart
sensor
systems
EDITED BY GERARD C. M. MEIJER
WILEY