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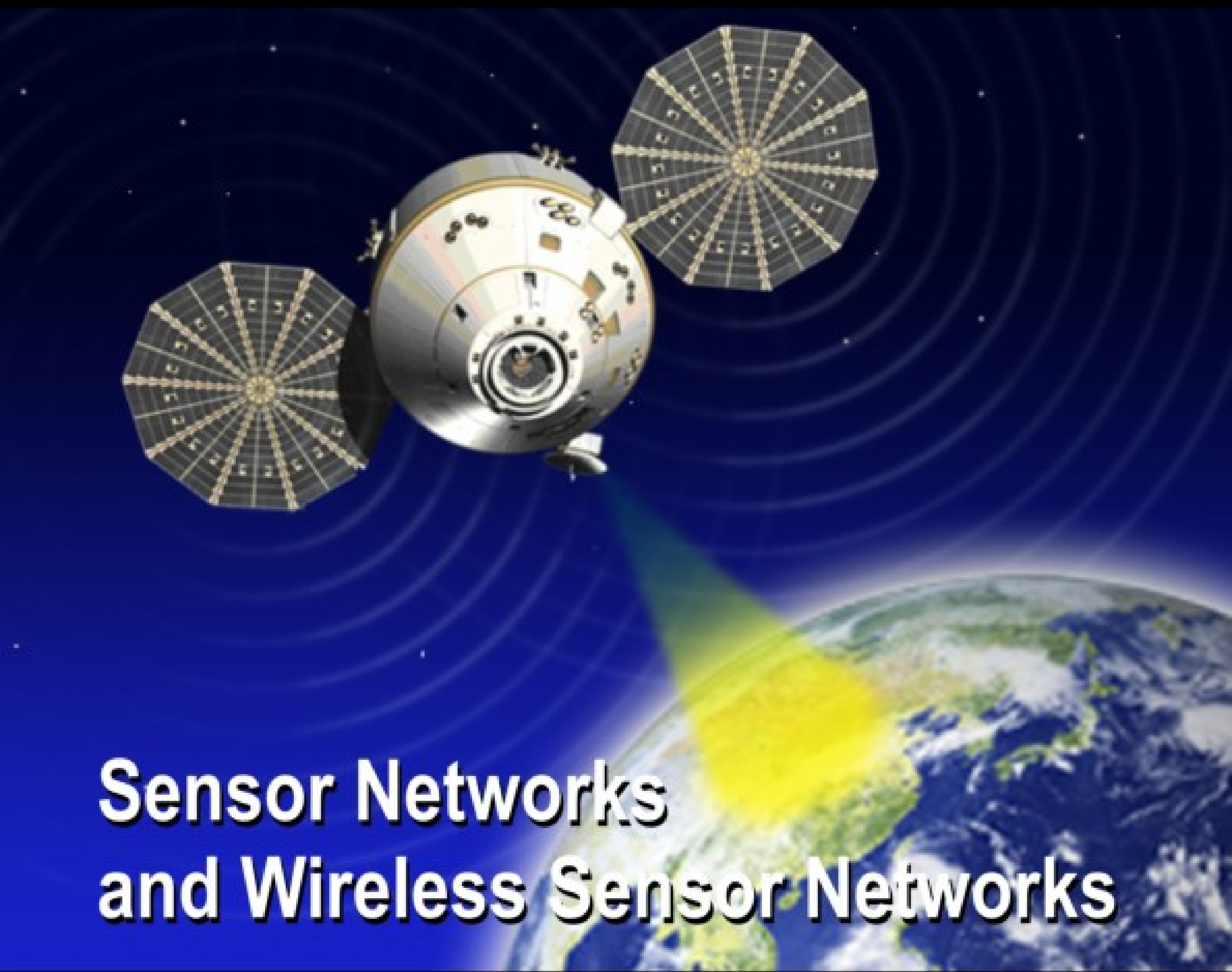

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Self-Adaptive Smart Sensors and Sensor Systems

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Abstract: Novel adaptive algorithms and practical examples of its realizations in various self-adaptive smart sensors and sensor systems with parametric adaptation are described in this article. The adaptive algorithms are based on novel methods of measurements such as modified method of the dependent count with programmable relative error and non-redundant time of measurement, and the method with non-redundant reference frequency. Equations of measurements for these methods are given and decision rules formulated. Some practical examples of self-adaptive smart sensor systems based on the Universal Frequency-to-Digital Converter (UFDC), Universal Sensors and Transducers Interface (USTI) integrated circuits, and ultra-low-power microcontroller are described in the paper. *Copyright © 2008 IFSA.*

Keywords: Self-adaptive smart sensors; Adaptive algorithm; Sensor systems; Universal-frequency-to-digital converter; UFDC-1; Universal sensors and transducers interface; USTI; Parametric adaptation

1. Introduction

According to Frost & Sullivan the forecast for North American smart sensors market is to reach $635.2 million in 2010 [1]. Strong growth expected for sensors based on MEMS-technologies, smart sensors and sensors with bus capabilities. Smart sensors' capability to have more intelligence built into them continues to drive their application in automotive, aerospace and defense, industrial, medical, and – most recently – homeland security applications [2]. Proprietary algorithms customized for specific applications analyze sensor data on key parameters to optimize machining, processing, and other component product or process quality.

Modern definition of smart or intelligent sensors based on two definitions given in [3] and [4] can be formulated now by the following way: '*Smart sensor is an electronic device, including sensing element, interfacing, signal processing and one- or several intelligence functions as self-testing, self-identification, self-validation or self-adaptation*'. The key word in this definition is "*intelligence*".

The self-identification function is closely connected to conception that is used in the IEEE 1451 standards family on smart transducer interface [5]. Self-testing, self-identification and self-validation functions mean a wide spectrum of different tasks from cable connection checking to self-calibration, metrology performance checking and monitoring, and conception, which is used in so-called soft sensors [6].

The self-adaptation is relatively new function of smart sensors. Novel designed self-adaptation smart sensor systems are based on so-called adaptive algorithms, which were used at the fist time in various digital measuring systems. Let consider such smart sensors systems and its algorithms below in details.

2. Adaptive Algorithms and Parametric Adaptation

Adaptive measurements are measurements in which measuring procedures can be changed at change of properties of a signal or measuring conditions [7]. An adaptation in smart sensors and sensor systems can be used for increasing of measurement accuracy, decreasing of measuring time, power consumption reduction, etc. A typical task of algorithmic adaptation is a control of inclusion in the measuring procedure of operations for increase of accuracy (improvement of metrological performance) at appropriate alterations of measuring conditions or properties of measurand. The necessity to control of operation usage for increase accuracy is caused by an opportunity of occurrence of situations when the application of this operation is inexpedient.

There are parametrical and algorithmic adaptations. The adaptation in smart sensors and sensor systems can be determined as a process of purposeful change of system's parameters, which means the determination of criterion of functioning and its fulfillment. If an overall performance of system to estimate by means of criterion of optimality, the adaptation will be a process to change of parameters by means of control influences on the basis of the current information with the purpose to achieve the optimal or required state of sensor system, according to a measuring algorithm at operating conditions changing. Hence, the process of adaptation consists in maintenance of the required (specified) quality of functional for a sensor system at change of operating factor U [8]:

$$U \in Y_i, \tag{1}$$

where Y_{i} is the i^{th} number of feasible controls.

In the case of parametrical adaptation

$$U = \langle P_1, P_2, ..., P_n \rangle, \tag{2}$$

where P_n are parameters of adaptation.

Parametrical adaptation consists in production of control signals supporting a smart sensor or sensor system in the required state by means of adopted parameters depending on measuring conditions and/or measuring algorithm. Here the parameter has a final number of values [8]:

$$U \in Y_i = D_i, \tag{3}$$

where D_i is the discrete number of control values.

Naturally, self-adaptive smart sensors systems should be based on novel methods of measurements and use of quasi-digital sensors (or sensing elements) with frequency, period, duty-cycle or PWM outputs [9]. First of all it means a novel patented modified method of the dependent count [10] with programmable relative error and non-redundant time of measurement, and method with non-redundant reference frequency and programmable relative error [11]. Both methods have so-called self-adaptive possibilities for change accuracy on speed of measurement, and accuracy on power consumption due to non-redundant time of measurement and non-redundant reference frequency respectively.

Being based on the approach described in [7] we shall result the equation of measurements for modified method of the dependent count in the operator form (for two possible algorithms of measurements: with maximal accuracy and maximal speed of measurement):

$$\lambda^*{}_j = T_s L\gamma_j(t) \vee \delta_s L\gamma_j(t), \tag{4}$$

where T_s and δ_s are operations of increase of speed and accuracy respectively, the introduction of which is made according to the established decision rule; L is the operator representing an algorithm of measurement; γ_j is the multivariate input action, generally, time-dependent [12, 13]. At ordinary direct measurements the input action correlated with that moment of time for which the result of measurement is fixed is used; $t \in [t_j, t_{j+T}]$, where T is the time of measurement cycle.

In turn, the equation of measurements for the method with non-redundant reference frequency in the operator form (at presence of two possible algorithms of measurements: with maximal accuracy and minimal power consumption) can be written by the following way:

$$\lambda^*{}_j = P_s L\gamma_j(t) \vee \delta_s L\gamma_j(t), \tag{5}$$

where P_s is the operation of power consumption reduction.

The choice of variants is made according to the current result of measurement β. So, for the modified method of the dependent count:

$$\begin{cases} \lambda^*{}_j = T_s L\gamma_j(t), & if \ \ F_x(\beta^*) \in I_f \\ \lambda^*{}_j = \delta_s L\gamma_j(t), & if \ \ F_x(\beta^*) \notin I_f \end{cases} \text{ at } I_f \in I, \tag{6}$$

where $F_x(\beta^*)$ is the characteristic of input action or measuring conditions, which value defines the decision for change of measuring algorithm (parameters of system); I_f is the subset of certain area I of possible values of characteristic $F_x(\beta^*)$, the set membership to which defines the necessity to change of system's parameters. Generally, the task of determination of area I_f for the resulted parameter arises.

In turn, for the method with non-redundant reference frequency we will have:

$$\begin{cases} \lambda^*{}_j = P_s L\gamma_j(t), & if \ \ F_x(\beta^*) \in I_f \\ \lambda^*{}_j = \delta_s L\gamma_j(t), & if \ \ F_x(\beta^*) \notin I_f \end{cases} \text{ at } I_f \in I, \tag{7}$$

The decision about inclusion in the measuring procedure of operation of accuracy or speed increase; or accuracy increase or decrease power consumption, is accepted on the basis of the set-up decision rule.

The decision rule is built on the basis of comparison of value of measuring results with the liminal value set in advance at which there is a change of system's parameters depending on the required measuring algorithm.

The common flowchart of adaptive measurement algorithm for smart sensor system based on the modified method of the dependent count at presence of two possible algorithms with parametrical adaptation is shown in Fig. 1.

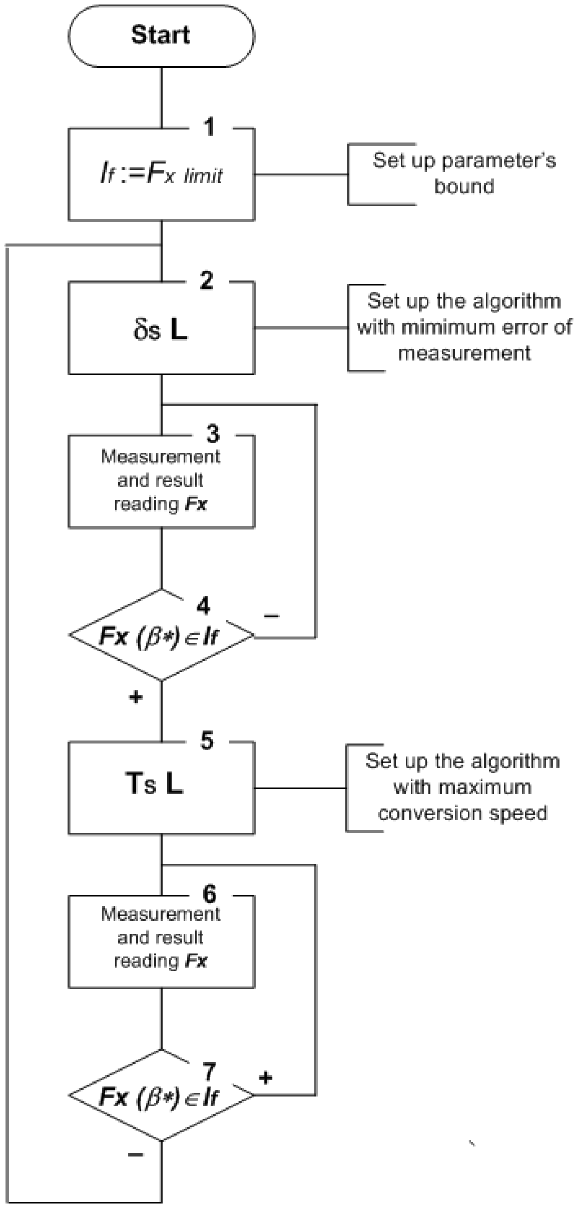

Fig. 1. Flowchart of adaptive measurement algorithm for smart sensor system based on the modified method of the dependent count.

The algorithm of adaptive measurement is realized by the following way. At the beginning, the boundary value of frequency $F_{x\ limit}$ is set-up at which the algorithm change should be made (Block 1). The subset I_f consists of only one value of boundary frequency belonging to the set I of all values of frequencies from the frequency measuring range. Then the programming of maximal accuracy for sensor system by means of the corresponding parameter is carried out (Block 2). After, the frequency measurement and reading of result of measurement F_x (Block 3) is carried out, which is compared to the boundary value $F_{x\ limit}$ (Block 4). If the result of current measurement does not exceed the set-up in advance the boundary value $F_{x\ limit}$, the measurement is proceed with the greatest possible accuracy (Block 3). Otherwise, the exchange of accuracy on speed (execution of operation for increase of speed due to accuracy decrease) should be made (Block 5), and system continues to function with the maximal speed, but with the lowered accuracy of measurements (Block 6), whether the checking measured parameter has returned to admissible limits (Block 7). In case $F_x \le F_{x\ limit}$, the measuring system returns back again in the mode of measurement with the increased accuracy by reprogramming (set up) of required error of measurement (Block 2).

The flowchart for adaptive measuring algorithm based on the method with non-redundant reference frequency is quite similar to the described above except that instead of operation of increase of speed, the operation of power consumption decrease P_s is used. Here, depending on the measuring algorithm, this operation can be carried out at the beginning, and then, if it is necessary to make one precise measurement, the exchange of power consumption on speed by increase (programming) reference frequency of system f_0 should be carry out. In this case, the subset I_f can contain one as well as some values of boundary frequencies belonging to the set I of all values of frequencies from the frequency measuring range for which it is necessary to carry out measurements with the increased accuracy, and values of time intervals or numbers of measurements when such measurements are necessary. For example, sometimes according to the measuring algorithm it is necessary to receive a value of measurand with the increased accuracy once per minute, or each tenth measurement should be made with the increased accuracy.

3. Examples of Self-Adaptive Smart Sensors Systems and Its Realizations

Let's consider some examples of sensors systems where adaptive measurements are necessary, for example, antilock braking system (ABS) for automobiles; pressure sensor system for gas pipelines; sensors systems based on different sensing elements, having a various error of measurement in different parts of a measuring range; and sensor system for fail-safe cooling with fan speed control based on current temperature measurements.

3.1. Self-Adaptive Antilock Braking System (ABS)

According to the self-adaptive ABS algorithm based on the modified method of the dependent count for rotation speed, at the beginning, the critical value of rotation speed for wheels at its blocking is set-up. When wheels are not blocked, the measurement of rotation speed is made with the maximal accuracy with the aim to receive information for engine, gear set and other car's systems optimization. At the moment when wheels are blocked, the sensor system is adopted for the changed measuring conditions by an exchange of accuracy on speed with the aim to receive information necessary for wheels unblocking and the prompt generating of corresponding control signals. At the moment when wheels are unblocked again and rotation speed of wheels lays outside of critical values, the sensor system adapts again for measurement of rotation speed with the increased accuracy by reprogramming the required relative error for rotation speed - to - digital conversion.

Naturally, the use of such adaptive algorithms means the presence of computing power (microcontroller or embedded computer) in a sensor system. However, especially developed for such self-adaptive sensors systems the Universal Frequency-to-Digital Converters (UFDC-1, UFDC-1M-16, UFDC-2) [14-17] and Universal Sensors and Transducers Interfaces (USTI, USTI_1M-20) [18] integrated circuits essentially simplify realization of such smart sensors and sensor systems at minimal possible hardware and low cost.

All ICs are based on the modified method of the dependent count, working in a broad frequency range from 0.05 Hz to 7.5 MHz (9 MHz for UFDC-2 and USTI) without prescalling, have constant programmable relative error from 1 to 0.001 % (0.0005 % for UFDC-2 and USTI) in all frequency range and non-redundant conversion time. These ICs are ideally suited for rotation speed measurements. They can measure a rotation speed and indicate the results in *rpm* units. The number of gear teeth Z (1…255) must be set up in advance [19]. Any rotation speed sensor with frequency output can be connected directly to the UFDC or USTI.

Relative errors and appropriate conversion times for the mentioned ICs are shown in Table 1 and Fig. 2. Based on an appropriate adaptive measuring algorithm, a trade-off between required relative error and time for rotation speed-to-digital conversion or frequency (period)-to-digital conversion can be chosen.

A self-adaptive smart sensor system for rotation speed based on the mentioned ICs should contain an appropriate frequency output sensor for rotation speed, for example [20]. A smart sensor system example is shown in Fig. 3. Any from UFDC or USTI ICs have three popular sensor systems interfaces such as SPI, I^2C and RS-232, and can be controlled by an external microcontroller or computer (slave communication mode).

Table 1. Relative errors and appropriate conversion times.

Relative error, δ_x %	UFDC-1 (at f_0=500 kHz)	UFDC-1M-16 (at f_0=16 MHz)	USTI, UFDC-2 (at f_0=625 kHz)	USTI-1M-20 (at f_0=20 MHz)
	t_{conv}, s			
1	0.0002	0.00000625	0.00016	0.000005
0.5	0.0004	0.0000125	0.00032	0.00001
0.25	0.0008	0.000025	0.00064	0.00002
0.1	0.002	0.0000625	0.0016	0.00005
0.05	0.004	0.00125	0.0032	0.0001
0.025	0.008	0.0025	0.0064	0.0002
0.01	0.02	0.00625	0.016	0.0005
0.005	0.04	0.0125	0.032	0.001
0.0025	0.08	0.025	0.064	0.002
0.001	0.2	0.0625	0.16	0.005
0.0005	-	-	0.32	0.01

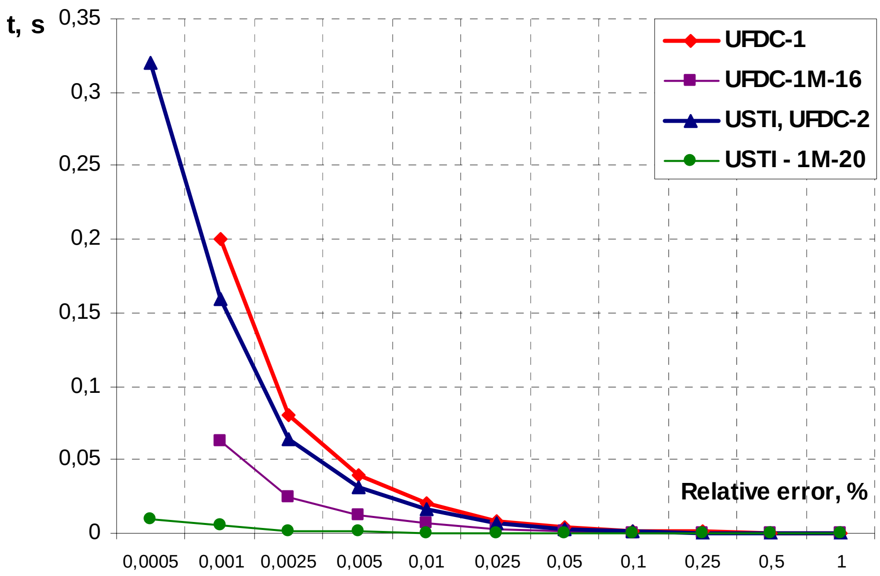

Fig. 2. Conversion times vs. relative error.

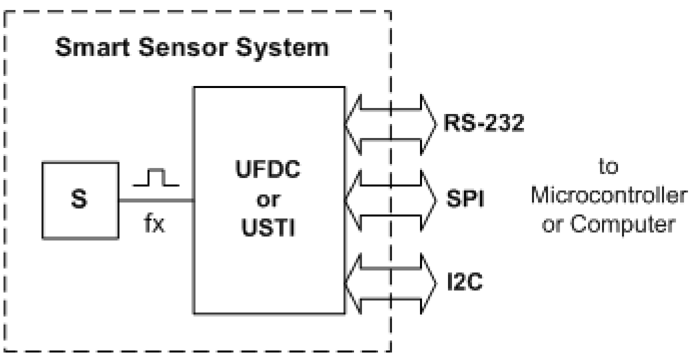

Fig. 3. Block diagram of self-adaptive smart sensor system based on UFDC or USTI integrated circuit (S - frequency (period) output sensor).

A microcontroller or computer can change accuracy or conversion time by sending an appropriate command to the UFDC or USTI based on the current measurement result and measuring algorithm. An example of such commands for RS-232 communication mode is shown in Fig. 4.

```
>M0A; Rotation speed measurement initialization in the 1st channel
>Z30; Set up the modulation rotor teeth number Z=48(10)=30(16)
>A09; Choose the relative error of frequency measurement 0.0005 %
>S;   Start a measurement
>R;   Read a result of measurement in rpm

; Here microcontroller or computer should check the condition for an algorithm changing and prepare
  the USTI to measure with highest speed (maximum relative error) if a critical rotation speed has
  been achieved:

>A00; Choose the relative error of measurement 1 %
>S;   Start a measurement
>R;   Read a result of measurement in rpm
```

Fig. 4. Commands for RS-232 communication mode at adaptive rotation speed measurements by the USTI.

It is also expediently to use the additional command "C" between "S" and "R" commands to check the measurement status especially at near zero rotation speed. It returns "r" if the result is ready and "b" if the measurement is in a progress.

The described above low cost, smart adaptive sensor system lets choose the minimum possible conversion time at critical rotation speed of wheels and maximum possible accuracy for the best engine optimization at nominal rotation speed of wheels.

3.2. Self-Adaptive Smart Pressure Sensor System for Gas Pipeline

The UFDC and USTI integrated converters works well with all frequency ranges of modern quasi-digital pressure sensors and transducers [21]. The ICs based sensor systems are extremely cost-effective. The level of sensor intelligence that can be obtained for only a few percents of the total cost has made the UFDC-1 or USTI the element of choice for MEMS based pressure sensors and transducers. The UFDC-1 interfacing with various quasi-digital pressure sensors is described in [22]. The self-adaptive smart sensor system block diagram is the same as adduced in Fig.3. Two frequency output sensors can be connected to each of ICs.

At quick pressure drop and achievements of critical values of pressure in a gas pipeline, the smart adaptive pressure sensor system automatically increases a relative error of measurement of frequency in UFDC-1 or USTI, providing with that a high speed and reaction of sensor system for monitoring of current situation and produce appropriate control signals. At the returning of values of pressure in a nominal range, the accuracy of sensor system is increased up to the level, at which it is possible to neglect this error in comparison with a relative error of pressure sensor.

The commands for RS-232 communication mode at adaptive measurement of pressure by the UFDC-1 are shown in Figure 5.

```
>M0;  Frequency measurement initialization in the 1st channel
>A9;  Choose the relative error of frequency measurement 0.001 %
>S;   Start a measurement
>R;   Read a result of measurement

; Here microcontroller or computer should check the condition for an algorithm changing and prepare
  the UFDC-1 to measure with highest speed (maximum relative error) if a critical value of pressure
  has been reached:

>A0;  Choose the relative error of measurement 1 %
>S;   Start a measurement
>R;   Read a result of measurement
```

Fig. 5. Commands for RS-232 communication mode at adaptive measurement of pressure by the UFDC-1.

Thus, the parametrical adaptation allows to reduce the measuring time for the UFDC-1 in 3 orders, and in view of communication and calculation times [16], the frequency-to-digital conversion time can be reduced in 23 times in average for critical values of pressure.

3.3. Temperature and Humidity Self-Adaptive Smart Sensors Systems

Various quasi-digital sensors, for example, temperature and humidity sensors with frequency (period) outputs have different errors in various parts of measuring range [23, 24]. For example, temperature sensors with period (MAX6576) and frequency (MAX6577) output from *Maxim* have error, which is changed in different part of working temperature range (- 40^0C to + 125^0C) in 2.2 times [25]. The temperature and humidity module HTF3130 from *Humirel* with frequency output proportional to a relative humidity has an error that is changed in 1.7 times in the whole working range (from 0 to 99 % RH) [26]. The interfacing of such sensors with the UFDC-1 is described in [27, 28].

Based on sensors systems design considerations, in order to be neglected, the relative error of frequency (period) – to – digital conversion should be chosen in one order (or at the least in 3 times) less than the relative error of sensor. For example, in the case of maximum possible 5 % full scale relative error for HTF3130 humidity module, the programmable relative error for UFDC-1 should be chosen equal to 0.5 %. But from 0 to 10 % RH and from 90 to 100 RH % the module has maximum error only 3 %. It means 0.25 % programmable relative error for the UFDC-1. If we use this relative error for all humidity range (0 – 90 % RH), the time for frequency measurement in such sensor system will be redundant at the beginning (0 – 10 % RH) and at the end (90 – 100 % RH) of this range.

Based on the parametric adaptation, it is possible to reduce the conversion time in a self-adaptive smart humidity sensor system. In this case, the programmable relative error for frequency-to-digital conversion should be changed dependent on the current measuring range of humidity. According to considerations about the parametric adaptation described above, the lowest and highest parts of working measuring range (0 – 10 % RH) and (90 – 100 % RH) will represent the subset I_f of I set of all possible values (0 – 90 % RH) of characteristic $F_x(\beta^*)$. The commands for RS-232 communication mode at adaptive measurement of humidity by the UFDC-1 are shown in Fig. 6. At this, the total conversion time in view of communication and calculation times will be decreased on 0.5 ms. Obviously, if the range of sensor's error is changing in wide limits, the effect of measurement time reduction will be greater.

```
>M0; Frequency measurement initialization in the 1st channel
>A2; Choose the relative error of frequency measurement 0.25 %
>S;  Start a measurement
>R;  Read a result of measurement

; Here microcontroller or computer should check the condition for an algorithm changing and prepare
  the UFDC-1 to measure frequency with 0.5 % relative error if a value of humidity is in the 0 – 10 %
  RH or 90-100 % RH relative humidity range.

>A1; Choose the relative error of measurement 0.5 %
>S;  Start a measurement
>R;  Read a result of measurement
```

Fig. 6. Commands for RS-232 communication mode at adaptive measurement of humidity by the UFDC-1.

3.4 Self-Adaptive Smart Sensor System for Fail-Safe Cooling with Fan Speed Control

In various fail-safe cooling systems the UFDC and USTI integrated circuits families can be used for low-cost realization of adaptive temperature and fan rotation speed measurements. For example, any frequency output rotation speed sensor can be connected to the 1st channel of USTI and temperature sensor with frequency, period, duty-cycle or PWM output – to the 2nd channel of IC.

At the optimal conditions, the relative errors for each of channel should be chosen (programmed) in one order less then the sensors' relative errors. In critical conditions, for example, increased temperature or sudden decreasing of fan rotation speed (this can be an evidence of fan fail), the self-adaptive sensors system will automatically to decrease time of rotation speed and/or temperature measurement due to temporary accuracy reduction in appropriate channel in order to produce appropriate control signals as soon as possible by controller (master). The master initiates communication with the USTI (slave) according to I^2C, SPI and RS-232 serial interfaces in order to send appropriate commands, read results and produce control signals. All these make such sensors systems ideal for intelligent fan control in a wide range of cooling applications with fan failure detection in communication, networking, high-end consumer and test equipments.

4. Self-Adaptive Sensors Systems Based on the Method of Measurement with Non-redundant Reference Frequency

Main applications for the frequency-to-digital converters based on the method with non-redundant reference frequency are different self-adaptive autonomous, embedded and wireless sensors and sensor systems, where power consumption is a critical parameter. In such systems, the reference frequency f_0 for a frequency-to-digital conversion can be increased for a short time in order to obtain a precision measurement, and then it can be reduced to the minimum possible for power saving and indicating rough results of measurements.

The dynamic average power of a CMOS circuit can be given as

$$P_{avr} = C_{eff} \cdot V_{DD}^2 \cdot f_{clk}, \quad (8)$$

where V_{DD} is the supply voltage; f_{clc} is the clock frequency; C_{eff} is the effective capacitance of the circuit. The V_{DD} and C_{eff} are constant for the specific integrated circuit and technology. For many smart sensor systems the V_{DD} can be reduced up to 2.8 - 3.5 V. The power consumption is directly proportional to the system clock. If clock speed doubles, the current doubles. Obviously, power can be saved by operating the device at the lowest possible clock speed [4].

Self-adaptive sensor systems with low power consumption can be easy realized on ultra-low-power microcontrollers with programmable clock frequency, for example, MSP430 microcontroller family form Texas Instruments [29]. These microcontrollers have multiple oscillators driven directly from a common 32 kHz watch crystal. The system clock frequency f_{system} in MSP430 microcontroller family can be calculated as:

$$f_{system} = k_N \cdot f_{crystal}, \tag{9}$$

where k_N *(3÷127)* is the multiplication factor; $f_{crystal}$ is the frequency of crystal (normally 32 768 Hz). The normal way to change the system clock frequency is to change the multiplication factor *N*. The System Clock Frequency Control register SCFQCTL should be loaded with $(k_N\text{-}1)$ to get the new frequency.

An example of self-adaptive smart sensor systems based on MSP430, which realize the frequency-to-digital conversion according to the method with non-redundant reference frequency is shown in Fig. 7.

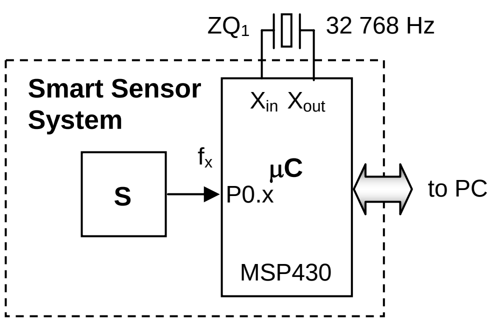

Fig. 7. Block diagram of self-adaptive smart sensor system based on MSP430 microcontroller.

Any quasi-digital sensors with frequency (period), duty-cycle, PWM, time interval, phase shift or pulse number output [30] can be directly interfaced to the any microcontroller's eight inputs of Port0 and counted via interrupt. If frequencies to be measured are above 30 kHz then the Universal Timer/Port or the 8-bit Interval Timer/Counter may be also used for counting. The first reference gate time according to the method with non-redundant reference frequency is formed by the Basic Timer.

The signal to be converted is connected to one of eight inputs of Port0. Each one of these I/Os allows interrupt on the trailing and on the leading edge. With the Basic Timer an appropriate timing is selected for the needed resolution and the conversion made. The Universal Timer/Port may be used for this purpose too: the pulse to be measured is connected to pin CIN and the time measured from edge to edge. Even better resolution is possible with the Timer_A. The input signal is connected to one of the TA-inputs and Capture Register is used for the time measurements.

In spite of the fact that as a rule, the timer functions independently of central processor core CPU, the speed of timer is based on the clock frequency of microcontroller CLCOUT. The current consumed by the timer depends on its activity. If timer is overloaded frequently, it consumes more energy.

4.1 Modeling Results

The relative quantization error for the method with non-redundant reference frequency [11] can be determined according to the following equation:

$$\delta_{qx_i} = \frac{1}{T_o \cdot f_{oi}} \times 100,\ \%, \tag{10}$$

where T_0 is the fist reference gate time; f_{0i} is the programmable reference frequency.

Having determined the clock frequency from the equation (10) and substituted it in the equation (8) we shall receive the formula, suitable for the power consumption modeling in CMOS ICs:

$$P_{avg} = \frac{\mathrm{V}_{\mathrm{DD}}^2 \cdot C \cdot 100}{\delta_{gi} \cdot T_0}. \tag{11}$$

With the aim to scope of wider nomenclature of various sensors, the following ranges of change for variables have been chosen at modeling: average capacity C=70 pF; supply voltage V_{DD} = 2.2 V; the first gate time $T_0 \in [0.01 \div 10]$ s; quantization error $\delta_g \in [10^{-5} \div 0.1]$ %. The modeling results for dependence $P_{avg} = f\,(T_0, \delta)$ are shown in Fig. 8.

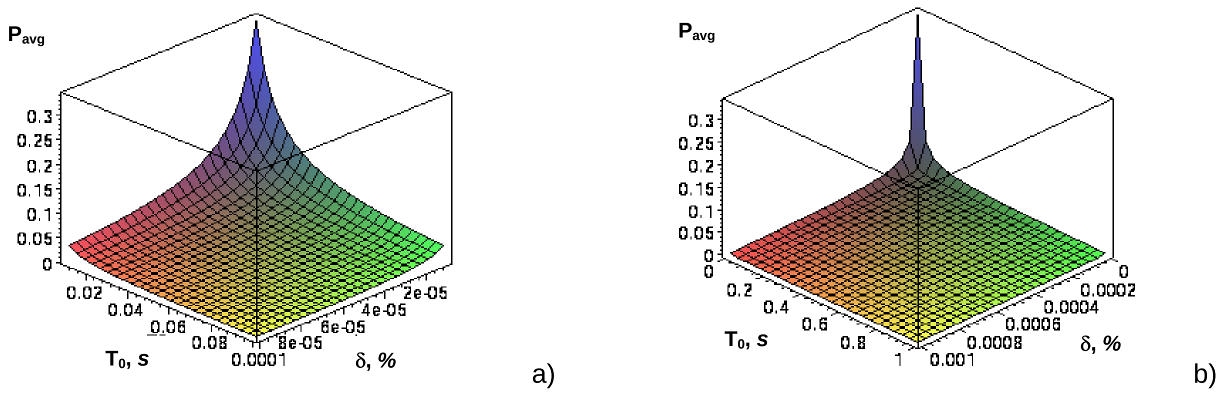

Fig.8. Modeling results for $P_{avg} = f\,(T_0, \delta)$ at: (a) C = 70 pF, $\delta_g \in [10^{-5} \div 10^{-4}]$ % and $T_0 \in [0.01 \div 0.1]$ s; (b) C = 70 pF, $\delta_g \in [10^{-5} \div 10^{-3}]$ % and $T_0 \in [0.01 \div 1]$ s.

As it is visible from the charts, the power consumption can be in two orders higher, in case of precision frequency-to-digital conversion with the quantization relative error 0.00001 % at the gate time less, than 0.04 s. With increasing of the first gate time, the power consumption can be reduced at the same quantization error. Thus, due to adaptive features of the method with non-redundant reference frequency, the parametrical adaptation of measuring according to two parameters is possible: to the gate time (directly influences on the measuring time) and quantization error. From the point of view of reduction of power consumption at the use of the given method, the gate time should be chosen greater as it is possible. So, for example, at the use of inert sensitive elements with big time constants for measurement of slowly varying values, for example, temperatures, the first gate time can be chosen equals to 0.5 s. If according to measuring conditions the high accuracy is not required, the reference frequency also can be automatically reduced. Such adaptive measuring procedure allows to reduce essentially (by some orders) the power consumption in self-adaptive smart sensors and sensor systems.

The maximal power consumption will be only at critical measuring conditions, namely when fast and precise measurements are required. As a rule, in real technological processes this necessity arises extremely rarely, and it is connected with measurements in breakdown or critical situations. Hence, sensor systems can work for a long time with the minimal power consumption without deterioration of metrological characteristics.

The chart for $f_{clc}=\varphi(T_0, \delta)$ at the same values of V_{DD} and C is shown in Fig. 9. For comparison purpose, the dependence $P_{avg} = \phi(\delta)$ for the adaptive method of measurement with the non-redundant reference frequency (1) and any of methods for frequency (period) measurements with the constant reference frequency f_0 (2) at the same gate time $T_0 = 0.1$ s are shown in Fig. 10.

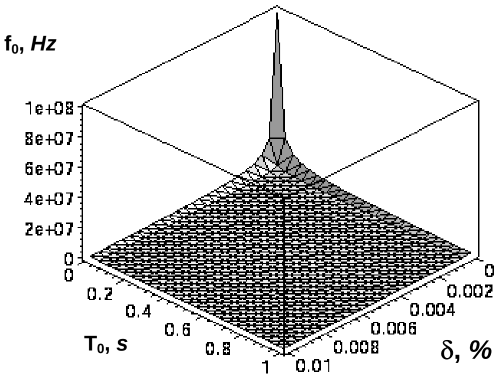

Fig.9. Dependence of $f_{clc}=\varphi(T_0, \delta)$ at $V_{DD} = 2.2$ V and $C_{eff} = 70$ pF.

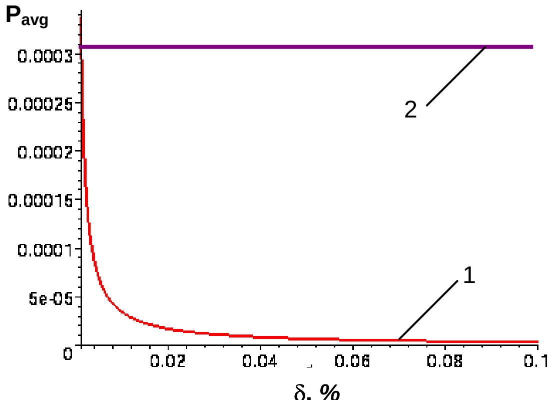

Fig.10. Dependence of $P_{avg} = \phi(\delta)$: (1) for the method with non-redundant reference frequency; (2) for any method with constant f_0.

Due to redundancy and constancy of reference frequency, the power consumption in the second case is essentially greater. The further decrease of power consumption (on 10 - 30 %) is possible at software level owing to the use of special measures at designing for microcontrollers' software and cores of built in microcontrollers used in measuring channels [31-33].

Thus, self-adaptive smart sensors and sensor systems using the method with non-redundant reference frequency for frequency (period)-to-digital conversion of sensor's output signal allow to reduce the dynamic power consumption in one-two order due to adaptive control of reference frequency during measurements.

5. Conclusions

Self-adaptive smart sensors and sensor systems based on novel modified method of the dependent count for frequency (period)-to-digital conversion of sensor's outputs can be easy realized on UFDC and USTI integrated circuits well-suited for such kind of applications. Smart sensors systems using the method with non-redundant reference frequency for any quasi-digital sensors can be based on modern ultra-low-power microcontroller with software driven system clock frequency, for example, the MSP430 microcontroller family from Texas Instruments.

All described self-adaptive smart sensors systems are based on parametric adaptation. Simple decision rules lets chose one of two possible adaptive algorithms: with a high accuracy or speed of measurement, or with a high accuracy and low power consumption dependent on measuring algorithm.

The use of such sensors systems allows to change flexibly accuracy on speed and contrary when it is necessary to receive information about measurand in critical points, and also to reduce the power consumption of sensor system in the whole, using the measuring algorithm with programmable reference frequency in depend on the accuracy of measurement.

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Guide for Contributors

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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.

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