Approach of an Intelligent Sensing Instrumentation Structure Development

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Abstract

In the context of process towards advanced automated systems, an analysis of characteristics, requirements and modeling of an Intelligent Sensing Instrumentation Structure (ISIS) is being made. A structure that is capable of "intelligently" manipulating data from various sensing devices and perform a number of abstract actions depending on the application. Main attention is given to the data manipulation procedures to achieve a highly accurate and reliable system.

I. Introduction

The term Intelligent Sensing Instrumentation Structure (ISIS) is used, to describe an instrumentation system capable of performing a number of advanced "intelligent" tasks as it carries out the processing of information from multiple sensing devices of different kinds. Systems of this kind are intended for multi-sensor applications of advanced automated systems [1, 2]. The use of sensor systems in scientific, industrial and consumer equipment is very wide and it is strongly and continuously increasing. The coming revolution in automation, following the industrial and information revolutions, needs more and more sensors of every kind [3]. The problems of such multi-sensor systems are mainly focused at two levels: the sensors' capability to provide reliable and accurate input signals, and the system's capability to process and evaluate input information. The procedure of sensing in general and measuring more specifically is characterized by its accuracy and reliability [4]. Other additional requirements like measurement time, system complexity, cost, etc may strongly limit the final solution. Thus the high measurement accuracy of physical quantity but not the sensor signal should be provided in all cases. It requires usage both an initial error of each sensors and its individual drift in the operation conditions [5].

Nowadays "smart" sensors are widely developed [6]. These "smart sensing units" include a sensing element and proper signal conditioning functions within the same package. Systems of this kind usually include one or more of the following functions: sensing (one or more sensors), interfacing, calibration, and output communication (usually in a digital format). In such "smart sensing units" sensors interface and processing circuits placed in the same technological environment as the sensors and it is not always allowable. Therefore ISIS must maximal use traditional sensors as well as "smart" sensors.

There are two major reasons to consider new computational and modeling techniques in solving measurement problems. A new kind of instrumentation tools needs to be exploited in order to handle the new tasks. These new computational tools (the so-called soft computing techniques) include knowledge-based methods of artificial intelligence, fuzzy logic, neural networks and genetic algorithms [7, 8, 9]. This may also mean that higher accuracy and reliability could be achieved under the condition of limited execution (measurement) time. These new techniques are not widely used, however, since the study of their capabilities and of their overall performance evaluation in currently a state-of-the-art research subject. Using of means given above in universal ISIS is considered in this paper.

II. General characteristics and requirements

A preferable structure is of a distributed signal processing system, were sensor device(s) information is being processed in an intermediate level and only "useful" information is transmitted to a higher hierarchical level [10]. Considering the sensor devices as a sensors (actuators) and sensor interface circuits and the need of a human-machine interface, the general structure of a multi-sensory, multi-modal system is presented in Fig. 1. The realization of such structure is feasible [11] under the premise that the computational power hidden in the processing levels is adequate to perform the operations, which will give to the system three basic properties: accuracy, reliability and adaptability.

Accuracy. An accurate system must be able to compensate systematic (offset, gain, non-linearity, cross sensitivities), systematic drift and random errors originated from sensors characteristics or system parameters. The ability of dealing with missed data due to random (transient or intermittent) faults is also desirable;

Reliability. It is necessary to provide fulfillment of following operations: (i) data validation (detecting and compensating/eliminating undesired or corrupted data from each sensor device); (ii) self-testing (including determination of electrical path corrections); (iii) auto-calibration (automatic correction of sensors drift).

Adaptability. The joint fulfillment of the first three properties is possible only by using the system adaptability. The processing parameters of the each part of the system should be automatically established. They must adopted by high hierarchical level for optimize of measuring/ processing processes. This rule establishes the requirements to the databus structure and communication protocol between various levels of the system. Also, admitting the fact that, unlike processing procedures implemented by hardware, those implemented by software (computing) can be easily updated, an effort should be made to transfer as many operations as possible from sensor interface circuit to information processing level. This will also lead to sensor interface circuit simplicity and system extendibility. The software and hardware structure should provide: (i) using of ISIS for the solving of various problems. It means using of different kinds sensors and heterogeneous sensors for measurement of wide number of physical quantities; (ii) easy expandability of ISIS by using modular hardware and software. It provides the universality of ISIS.

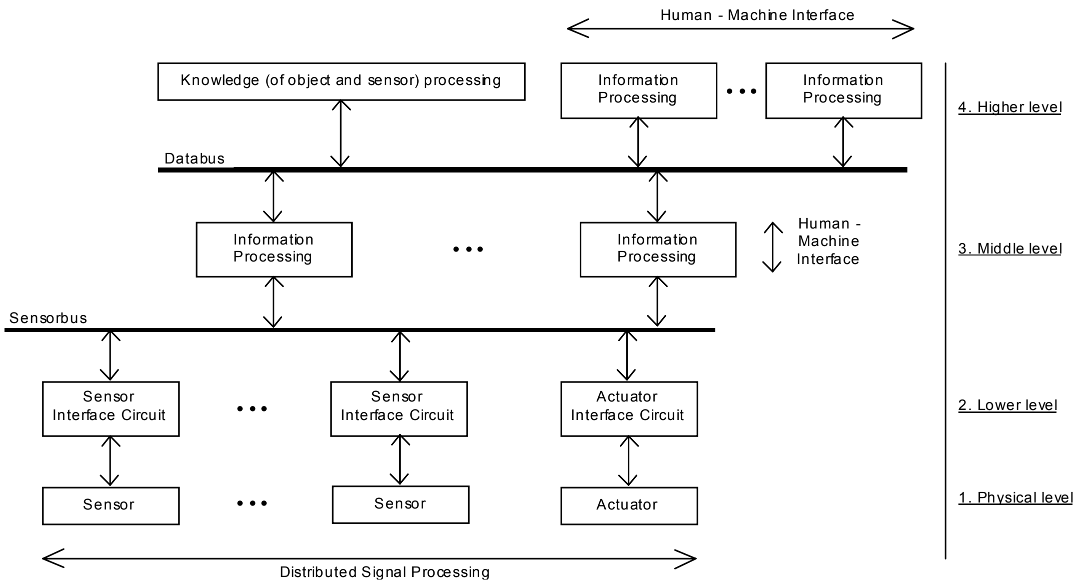

Fig. 1. General Structure of ISIS

The information about sensors is the initial data for maintenance of all three properties: for the lower level – information about sensor's output signals, for middle level – information about the conversion characteristic and for the higher level – information about sensor's drift. Using of this information permits to formulate the main rules of ISIS designing:

1. The hardware of the lower level should provide conversion the majority sensors signals to code. The analysis of different kinds and heterogeneous sensors has shown that their output signals in the majority cases (for example, more than 95% for the power station) are limited by following kinds and values: (i) direct voltage or current (or their relation) in ranges from 10 mV to 10 V and from 1 μA to 20 mA; (ii) alternating voltage or current (or their relation) in ranges from 100 mV to 10 V and from 100 μA to 20 mA; (iii) frequency or period in range from 10 Hz to 1 MHz and from 1 μs to 100 ms. The allowable measurement error changes in wide ranges from 0.05% to 1%. It is necessary to note, that sensor auto-calibration in ISIS should be executed with maximum using of network means. At comparison sensor with standard sensor the last one should be connected to ISIS measuring modules. Thus the measurement error of sensor signal should correspond to standard sensor but not working sensor;
2. At the hardware level any signal processing should be excluded. Each sensor type requires individual processing algorithms and their replacing at the hardware level requires large recourses;

3. The traditional signals processing algorithms of different sensor types include similar procedures: censoring, zero setting and calibration, functional conversion. However, the functional conversions should be executed with using of a very wide class of various functions. At the same time, the correction algorithms of different sensor errors are very strongly different. Thus the ISIS software should be based on universal means of functional conversion. As such means it is expediently to use neural networks [12].

Let us consider the fulfillment of these rules on lower, middle and high levels of ISIS (Fig. 1).

III. Lower level

For sensor signals measurement at the lower ISIS level it is enough to use analog-to-digital converters (ADC) of three kinds:

1. Precision ADC of low level voltage [13]. It will provide connection of: temperature sensors; sensors of linear and angular values; sensors of mechanical forces, stress, pressure, moment; sensors of liquid or gas flowmeters; all types of humidity sensors; all types of sensors, provides of output signal norming means which have on output the signal of direct current (using additional shunts), voltage and resistance (using additional reference resistors). This ADC should correspond the following requirements: voltage measurement range of direct current – from 10..15 mV up to 1...1.5 V; maximum sensitivity – 0.5..1 μV; measurement error – 0.02 %; digit capacity – 15...16; number of channels – 8; average measurement time of one channel – not more than 0.1s.
2. High-speed ADC of average level voltage with high accuracy. It will provide connection of: sensors of the linear and angular values; sensors of mechanical forces, stress, pressure, moment; sensors of liquid or gas flowmeters; all types of vibration sensors; ultrasonic sensors for various application which have on output the signal of alternating current (using additional shunts), voltage and resistance to alternating current (using additional reference resistors). This ADC should correspond the following requirements: voltage measurement range of direct current – from 100 mV up to 10 V; maximum sensitivity – 3 μV; measurement error – 0.05 %; digit capacity – 15...16; number of channels – 8; average measurement time of one channel – not more than 10 μs.
3. ADC of frequency-time signals. It will provide connection of: temperature sensors; sensors of mechanical forces, stress, pressure, moment; sensors of liquid or gas flowmeter; all sensor types, using of resonance and which have on output the signal of frequency, period or number of pulses. This ADC should correspond the following requirements: range of frequency measurement – from 10...15 Hz up to 10...15 MHz; range of period and pulse duration measurement – from 100 μs up to 50 ms; maximum sensitivity – 0.1..0.2 μs; measurement error – 0.002 %; digit capacity – not less than 16; number of channels – 8.

The accuracy and reliability properties on the lower level are provided by automatic ADC self-testing and prediction of their errors using neural network [14]. Zero setting in the first two ADC kinds requires of shorting of one of the measurement channels. For its calibration it is necessary to use an appropriate source of calibrating voltage. Such source provides some calibration points with error not more than 0.01% on each ADC range. ADC of frequency-time signals does not require calibration, as its error is determined by reasonably small error of quartz resonator non-stability. Thus its self-testing is reasonably simply organized by short circuit of inputs of program-controlled counters and measurement of pulse duration which is set by the software.

The important element of lower level sensor interface circuits is switchboard. In ISIS for first two kinds of ADC is not expediently to use multi-channel structure (each sensor is connected to the individual measuring amplifier). Such structure does not permit self-testing procedure. Considerably more perfect is the multi-point structure where sensor outputs are connected to sensor signals switchboard. Despite complicating of switchboard construction the self-testing requires only switchboard additional channel and software support. The ADC of frequency-time signals has not additive error and it is expedient to use multi-channel structure for it.

Heterogeneous and other kinds of sensors require different ADCs as well as different switchboards. Correlation dependence between the requirements to ADC and to switchboard is observed. It permits to unite the ADC and switchboard in one construction. The switchboard of ADC of low level voltage should provide: maximum switched voltage – not more than 10 V; maximum switched current – not more than 20 мA; error – not more than 0.5..1 μV; number of channels– not less than 8; average time of one channel signal establishment – not more than 20 ms. The switchboard of high-speed ADC of average level voltage should provide: maximum switched voltage – not more than 10 V; maximum switched current – not more than 20 mA; error – 3..10 μV; number of channels – 8; average time of one channel signal establishment – not more than 2 μs.

The analysis of requirements has shown, that the ADC switchboard of low level voltage should be executed on contact elements (reed relay) [15] and the switchboard of high-speed ADC of average level voltage should be executed on MOS-transistors.

IV. Middle level

Taking into considerations rules of ISIS designing formulated in chapter II the basic sensor signal processing procedures should be executed at the middle level. Thus, the requirement to middle level nodes can be conditionally divided on internal and external. The main purpose of internal functions is providing of high measurement quality by self-training and adaptation to the measurement conditions. The solving of this problem is rather difficult. It can be solved only using of an Artificial Intelligence methods. As the main criterion of measurement quality is its error in ISIS measurement result should be presented together with its error. Thus the error should be the individual characteristic of each measurement result and the self-training and self-adaptation procedures should provide required accuracy of each measurement channel [11]. For fulfillment of these requirements at the lower ISIS levels the following procedures should be stipulated:

1. The error correction of electrical path;
2. Calculation of residual error of electrical path;
3. The sensor correction factor prediction on individual mathematical model of drift taking into account current as well as previous conditions and also changes of influencing quantities and operation time;
4. Calculation of corrected measurement result and its current storage;
5. Prediction of the prognosis error of the sensor correction factor individual mathematical model;
6. Determination of total individual measuring channel error and it comparison with the allowable error;
7. Sending the message to the high level at excess by individual error of measuring channel of the allowable value;
8. Transfer (under the high level initiative) of the channel which have the higher error than the norm in the auto-calibration mode under reference sensor or special calibrator, and transfer the calibration results to the high level;
9. Correction of mathematical models of sensor drift and prognosis error of the sensor correction factor by receiving of the correspondent messages from the high level;
10. Determination of object condition and formation on its basis of the messages for knowledge base of the high level.

The external requirements are determined by nodes place in the Fig. 1. and realized by the following procedures:

1. Support of sufficient number of input/output channels for which it is difficult to determine beforehand the requirements of their exchanging protocols;
2. The processing of preliminary value of the physical quantity which corresponds to the sensor signal;
3. Output of the measurement results according to the higher level requests;
4. The human-machine interface support (limited by its level functions).

It is necessary to note, that the external procedures depend on varying channel structure and components used in it. The internal procedures depend on mathematical models ensuring calculations of correction factors and errors which are individual for each channel. Thus it is possible to use one mathematical model with individual parameters or individual mathematical models. Therefore, the requirements to middle level nodes are difficult to determine before the designing stage of particular variant of ISIS realization. Also it is necessary to have the possibility to change the internal procedures during normal operation of the middle level nodes (during ISIS adaptation and self-training). It can be provided at the expense of remote software reprogramming (reconfiguration) of middle level nodes [16].

The general structure of information processing node [17] of the middle level is shown on Fig. 2. The microcontroller MC is its central element. The speed of microcontroller should be defined by most complex signal processing algorithm. The creation of mathematical models is executed on the high level and MC executes only lower level control and uses of prepared mathematical models [18]. Thus the high requirements to MC speed are not demanded.

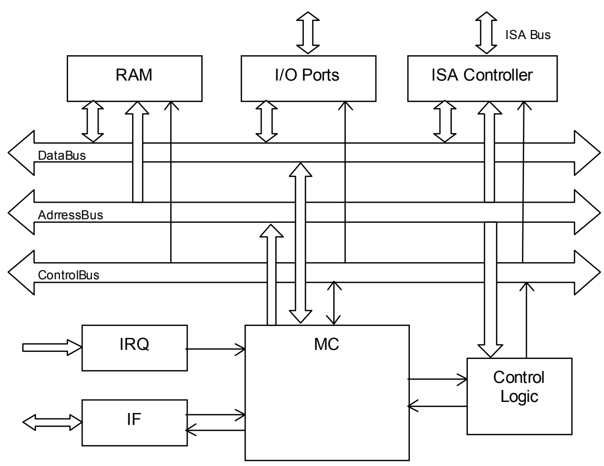

Fig. 2. General Structure of Information Processing Node

The RAM should provide the storage of: (i) system control program of the node; (ii) arrays of current measuring information; (iii) set of individual processing programs for these arrays, including mathematical models loaded from the high level. The digit capacity of input-output (I/O) ports should be not less than 16, their number should be sufficient for connection of sensor interface circuit set and own peripheral devices. For information exchange with wide set of high-speed devices a parallel interface with enough throughput is necessary.

Control logic controls of internal nodes components and provides remote reprogramming mode. Interfaces (RS-232C, RS-485, IEEE 1451) must support the interaction with the higher level. Interruptions circuit should support following interruption types: internal and external, masked and non-masked. The internal interruptions are used for node functioning organization and service of critical situations. The external interruptions are used for providing of remote reprogramming mode and interaction with elements both of the high and lower levels.

V. Higher level

All functions providing three ISIS properties at the higher level should be divided on two groups: common functions and intelligent functions. The common functions provide:

1. The human-machine interface realization;
2. The interaction with middle level information processing nodes;
3. Remote reprogramming of the middle level information processing nodes;
4. Data compressing and data protection from unauthorized use.

The intelligent functions mean use of Artificial Intelligence methods for improvement of measurement result as well as measurement process. As the measurement result at middle level is presented as value of the physical quantity with its error, the main purpose of intelligent functions fulfillment at the higher level is adaptation (by self-training) of all system to constantly varying measurement conditions with the purpose of the accuracy property fulfillment. Thus the intelligent functions can be described by following set of procedures:

1. Receiving of measurement results in the form of knowledge about measurement object condition;
2. Messages receiving about excess by individual error of measuring channel of allowable value;
3. Sending the decision about chosen method of accuracy increasing and necessary data for its fulfillment (using reprogramming mode) and also receiving periodic testing or calibrating results;
4. Correction of individual mathematical model of sensor drift;
5. Correction of temporary limits of individual mathematical model of sensor drift by estimation of the previous prognosis of correction factor;
6. Correction of individual mathematical model of prognosis error of sensor correction factor by training of appropriate neural network;
7. Correction of temporary limits of individual mathematical model of prognosis error of sensor correction factor by estimation of the previous prognosis of correction factor error;
8. Sending of the corrected mathematical models of sensor drift and prognosis error of sensor correction factor, as well as temporary limits of their using to certain information processing node.

The fulfillment of listed above procedures provides individual adaptation of ISIS measuring channels to sensor drift and its self-training during operation for providing of required measurement accuracy.

The central computer (CC) software consists of two levels: the base software level (BSL) and user software level (USL) [11]. The software components (modules) interact between themselves using client-server technology. The BSL modules as a rule execute the function of modules-servers and the USL modules are the clients. Each module-server should have standardized and completely determined external specification, due to which any software module can generate the command request to it. Let us consider purpose and functions of each BSL module.

Supervisor is the main program of base level. It functions invisibly for user and executes the majority of ISIS system functions: controls of ISIS by sending the appropriate command requests, remote reprogramming of middle level nodes, operating with ISIS database and knowledge base of recourses and configuration and also controls of executing improvement accuracy functions listed above.

The knowledge base of resources and configuration is intended for storage and effective using of information about all possible ISIS resources and configurations. The knowledge of ISIS resources consist of following attributes: ISIS components types, their characteristics (excluding metrological) and rules of its construction/ accordance. The knowledge of ISIS configuration are stored as set of attributes which completely describing of measuring channel as the sequence of its hardware and software components and used rules of their uniting.

The main purpose of *the expert system* using is providing of the required measurement accuracy of each physical quantity by realization of intelligent functions listed above (points 3..8). Thus it forms the requests to the neural network manager and base knowledge of metrological characteristics and answers of the USL program requests - manager of middle level information processing nodes and accuracy manager. The requests on transfer of corrected mathematical models of sensor drift and prognosis error of correction factor to the supervisor, as well as temporary limits of their using to the appropriate information processing node are also formed.

The knowledge base of metrological characteristics of ISIS components serves for effective providing of measurement accuracy of all measuring channels. On the basis of these knowledge mathematical models of sensor drift and other ISIS components are build. Using of neural networks is the main method of mathematical models construction for sensor drift prediction. Therefore the data for neural network training are one of the attributes of the knowledge base. At neural network training for its application as mathematical model in concrete measuring channels three groups of sensor drift data are used: the real, historical and hypothetical data [18, 12]. Besides the knowledge base of metrological characteristics contains the following attributes: sensor types (names, physical effects and characteristics); instrumental and methodic errors of working and standard sensors and calibrators; the mathematical models and their parameters on which errors correction of each channel was made and temporary limits of their using; testing or calibration results on each channel; rules of creation of individual adaptive mathematical models for sensor error prediction and prognosis error (on the basis of the knowledge about testing or calibrating results).

The manager of neural networks on expert system request fulfills scheduling and dispatching of neural networks training (some set simultaneously) with the purpose of their further use as drift mathematical models in appropriate measuring channels. It executes choice from knowledge base of metrological characteristics of neural network architecture (network model: number of layers and neurons, types of activation functions etc., and training algorithms) which corresponds to certain measuring channel. In neural networks database are stored initial typical structures of predicting neural networks with their binding to some set of hypothetical drift functions.

The user software level consists of the programs of ISIS management and programs of object management. Let us to consider the programs of ISIS management.

Manager of information processing nodes of middle level is the main program providing human-machine interface with ISIS and executes the majority of system functions. This program is a client in architecture client-server. The main functions of this program are: initialization of the network and connected middle level nodes; setup of measuring channels of middle level nodes; organization of interaction between the user (expert) and expert system; organization of access to all data and knowledge bases of ISIS.

Main function of accuracy manager is the purpose analysis (using knowledge base of metrological characteristics) and giving to the user the tendency of accuracy reduction on chosen measuring channel of certain middle level node. The accuracy manager offers set of strategies on accuracy increasing of chosen measuring channel of this node and forms appropriate command requests according to points 3..8 of intelligent functions of ISIS higher level.

VI. Conclusions

The ways of Intelligent Sensing Instrumentation Structure as a distributed hierarchical measuring system are considered in this paper. The formulated designing principles and the requirements to ISIS components have allowed to offer a structure which provide fulfillment of accuracy, reliability and adaptability properties by using of Artificial Intelligence methods.

Acknowledgment

The authors would like to thank for support by INTAS, grant reference number INTAS-OPEN-97-0606.

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