INFORMATION AND MEASUREMENT TECHNOLOGIES IN MECHATRONICS AND ROBOTICS

MODELING OF PROPERTY EVALUATION OF SYSTEM-ORIENTED MEASURING INSTRUMENTS

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Abstract. The main purpose of system-oriented measuring instruments (MI) is to ensure automated collection, processing, analysis and transmission of measurement data as part of complex information and measurement systems. Such MI are used in automated production systems, intelligent measuring systems, in the control of technological processes and in conducting scientific research, etc. The main properties of system-oriented MI are provided by a combination of modern hardware, powerful digital processing algorithms and integration into automated systems. They implement microprocessor systems with the implementation of self-diagnostic algorithms, built-in real-time controllers, etc. They have a modular architecture with the possibility of software configurability. In addition to the traditional MI testing methods, system-oriented MI is subject to mandatory testing of its software. To build a mathematical model of a system-oriented MI, a block-hierarchical approach was applied for different hierarchical levels. The mathematical modeling conducted allowed us to develop a multiple model of the system of indicators of the MI properties. The proposed model allows for the study of the influence of the MI properties and their evaluation at all stages of the MI life cycle. It also allows taking into account specific parameters of the MI properties and the corresponding methods for their determination. The model allows taking into account the features of system-oriented MIs, in particular, indicators of the MI's properties in terms of ensuring system functions and the corresponding methods for their determination. At each phase of the MI life cycle, both the appropriate verification for the sets of MI properties and their validation should be carried out. When implementing these procedures, it is necessary to use the established requirements of widely used international and regional metrology guidelines.

Key words: modeling, mathematical model, property evaluation, measuring instrument, system-oriented tool.

1. Introduction

The main purpose of system-oriented measuring instruments (MI) is to ensure automated collection, processing, analysis and transmission of measurement data as part of complex information and measurement systems. Such MI are used in automated production systems, intelligent measurement systems, in the control of technological processes and in conducting scientific research, etc. System-oriented MI have the following main properties: automation of measurements; the ability to integrate into industrial control systems for the automation of production processes; interactivity and data transfer with support for standard data transfer protocols; real-time data processing and analysis, in particular using digital signal processing; the ability to adapt to various tasks and environments with easy integration of new modules; high accuracy using error correction methods and reliability; resistance to environmental influences, etc.

The main properties of system-oriented MI are provided by a combination of modern hardware, powerful digital processing algorithms and integration into automated systems. They implement microprocessor systems with the implementation of self-diagnostic algorithms, built-in real-time controllers, etc. They have a modular architecture with the possibility of software configurability. In addition to the traditional methods of testing for MIs, such as determining the main metrological characteristics, testing functional characteristics, testing for reliability, durability and the influence of external factors, for system-oriented MIs, its software is subject to mandatory testing.

To take into account significant external influences on the properties of system-oriented MIs, comprehensive tests should be carried out. For this purpose, the following basic test methods should be used: calibration methods according to the requirements of the ISO/IEC 17025 standard [1]; functional, climatic and mechanical test methods; electromagnetic compatibility test methods; testing methods for MIs software, both built-in and external, according to the requirements of international and regional guidelines [2–4]. In this case, it is necessary to assess all significant risks that may affect the main properties of the MIs [5, 6].

2. Drawbacks

A fairly large number of scientific works are devoted to various methods of conducting MI tests. Multiple models of MI quality indicators and evaluation of their quality indicators, which allow studying the influence of these quality indicators and conducting their evaluation, are given in [5]. The results of studying the basis for establishing special MI quality indicators, the methodology for evaluating MI quality indicators and the algorithm for its implementation are given in [6]. The limitations of mathematical models, verification of models against scientific data, and the iterative nature of the model improvement process are shown in [7]. The only work that presents the results of mathematical modeling of system-oriented MI using the apparatus of general systems theory is presented in [8]. Such models with their graphical interpretation allow obtaining the necessary and useful information about the MI properties as a technical system. However, these models do not take into account the influence of the methods for evaluating their characteristics and their parameters on the MI properties. Therefore, the development of theoretical foundations for reliable assessment of the properties of system-oriented MIs, in particular, assessment of the properties of their software, remains a pressing issue.

3. Goal

The aim of the article is to develop theoretical basis for evaluating the indicators of the properties of modern system-oriented MIs, taking into account the most influential factors.

4. Structure and basic properties of measuring instruments

A system-oriented MI generally has the following main components: a primary converter of physical quantities (interacts with the measurement object); an Analog-to-Digital Converter (ADC) for converting the output signal of the primary converter into a digital code; a microcontroller for the necessary control of the MI components and processing of measurement data; a communication interface with external technical means; software that can be built into the MI or installed on a separate personal computer (PC); an MI display indicator, installed either on the MI itself or as a PC screen.

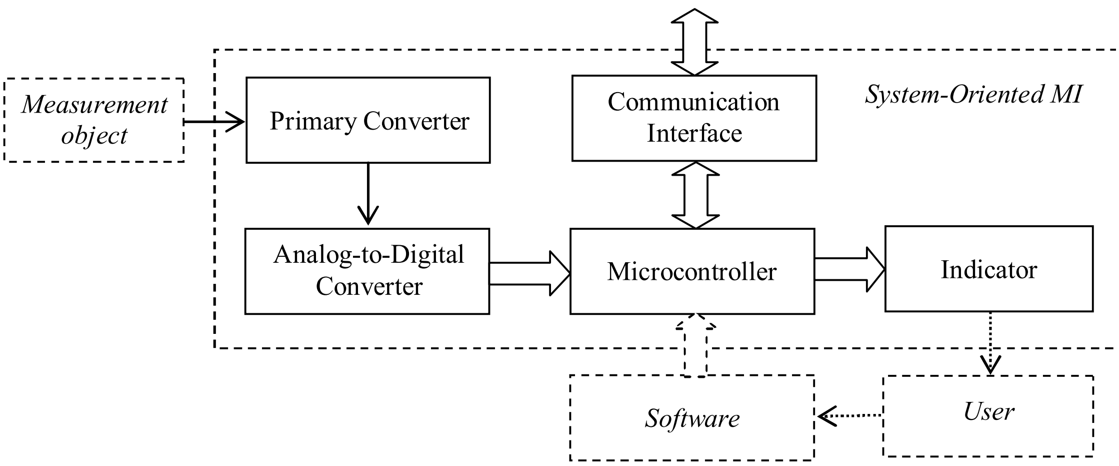
Figure shows a generalized structural diagram of a system-oriented MI.

The general properties of MIs include: the measurement range of a certain physical quantity; measurement error; sensitivity, stability and reproducibility of measurements; reliability indicators, etc. A large number of scientific works are devoted to the study of these properties, in particular [5, 6]. Almost all modern MIs contain software, therefore scientific works are also devoted to its study, in particular [9, 10].

A feature of system-oriented MI is that the software used in MI is intended not only for controlling it and processing data to obtain the measurement result with its indication on a special MI device, but also for ensuring the system functions of MI, such as ensuring external control of MI, transmission of measurement data to external technical tools, etc. Information and measurement complexes or systems can be created on the basis of individual system-oriented MIs. Such systems allow receiving measurement data from a large number of measurement objects and processing the obtained measurement data.

5. Features of mathematical models of measuring instruments

Mathematical models are used to design and describe various technical systems, in particular for measuring systems. The theoretical justification of the universal concept of modeling based on the idea of a classical measuring chain and practical procedures for its application are given in [11]. The generalized concept of measurement has limitations inherent in conventional object-oriented models of measuring systems [12].



Structural diagram of a system-oriented MI

A multivalued model for joint monitoring of quality indicators, which establishes a correlation between different indicators, is proposed in [13]. However, this model is general in nature and is not suitable for assessing the properties of the MI. Quality indicators with the same goals have contradictory and significantly different results of property evaluation, i.e. none of the properties of the object can have advantages over the other [14].

Mathematical modeling of system-oriented MI using the apparatus of the general theory of systems with their graphical and analytical interpretation was carried out in [8]. The theoretical set model of the formation of the information state of a cyber-physical system based on the sensor infrastructure model is given in [15]. This model can be used for mathematical modeling of system-oriented MIs.

To build a mathematical model of a system-oriented MI, a block-hierarchical approach can be applied for different hierarchical levels. The value of a certain MI property can be defined as a function of the measurement of an Element of a Property Indicator (EPI), which is determined using certain measurement methods. An indicator of one property is a Simple Property Indicator (SPI), and a property indicator that combines several simple indicators is called a Complex Property Indicator (CPI) [6, 15].

The mathematical model for evaluating MI properties can be given in the general form:

$$PI_{mi} = f\Big(f\big(\{(Par, Met), B\}\big), f\big(\{EPI, B\}\big), f\big(\{SPI, B\}\big), f\{CPI, B\}\Big), \tag{1}$$

where PI_{mi} is the indicator of the MI properties; (*Par, Met*) is set of tuples of parameters and measurement methods; $EPI=f(\{Par,\ Met\},B)$ is set of EPI of the MI; $SPI=f(\{EPI\},B)$ is set of SPI of the MI; $CPI=f(\{SPI\},B)$ is the set of indicators of the MI properties of a certain level

$$\begin{cases} CPI_{\substack{r\\(|l|-2)}} = f\big(\{SPI\}, B\big) \\ CPI_{\substack{r\\(|l|-3)}} = f\left(\left\{CPI_{\substack{r\\(|l|-2)}}\right\}, B\right) \\ \ldots \\ CPI_{\substack{r\\1}} = f\left(\left\{CPI_{\substack{r\\2}}\right\}, B\right) \end{cases};$$

$B=\left\{b_1,\ldots,b_i,\ldots,b_{|Q_l|}\right\}$ is characteristic vector of the corresponding sets $\left(PI_{\substack{r\\l}} \subset PI_{\substack{r\\l-1}} \middle| \forall PI_{\substack{r\\l}} \in PI_l, b_i = 1\right)$; PI_l is set of property indicators level l (l=(1|l|) is level indicator, |l| is lower level); (|l| – 1) and (1:|l| – 2) are levels of SPI and CPI property indicators, respectively; r is the index of the property indicator at the corresponding level.

The mathematical model for evaluating the performance of a MI at a certain phase of the MI life cycle (for example, design or operation) can be given in the general form:

$$PI_{miLC} = f\big(\{PhLC_{PI}\}\big), \tag{2}$$

where $PhLC_{CPI}$ is CPI of the generalized phase of a certain model of the property indicators of the MI, which, in turn, is equal to:

$$PhLC_{CPI} = f\big(VerCPI, ValCPI, LC_{PrCPI}, LC_{SubSysCPI}\big), \tag{3}$$

where *VerCPI* is CPI phase verification; *ValCPI* is CPI phase validation; LC_{PrCPI} is CPI phase process; $LC_{SubSysCPI}$ is CPI lower-level subsystems that belong to the phase.

The CPI verification and validation phases are defined as follows:

$$Ver_{PI} = f\Big(f\big(\{(Par, Met), B\}\big)_{Ver}, f\big(\{EPI, B\}\big)_{Ver}, f\big(\{SPI, B\}\big)_{Ver}, f\big(\{CPI, B\}\big)_{Ver}\Big), \tag{4}$$

$$Val_{PI} = f\Big(f\big(\{(Par, Met), B\}\big)_{Val}, f\big(\{EPI, B\}\big)_{Val}, f\big(\{SPI, B\}\big)_{Val}, f\big(\{CPI, B\}\big)_{Val}\Big). \tag{5}$$

The CPI of the phase processes is defined as:

$$LC_{PrPI} = \bigcup_b \{\Pr LCPI_b\}, \tag{6}$$

where b is index of phase process.

After some generalizations, we can obtain

($LC_{PrPI}=\varnothing$, $PrLC_{PrPI}=\varnothing$, $VerPI=\varnothing$, $ValPI=\varnothing$):

$$\begin{aligned} LC_{PrPI} &= f\big(\{PrLC_{PI}\}\big), \\ PrLC_{PI} &= f\big((VerPI), (ValPI)\big). \end{aligned} \tag{7}$$

The multiple model for evaluating the property indicators of the MI will take on the general form:

$$PI_{miLC}=\left\{\bigcup_{\substack{a=1\\g=1}}\left\{\bigcup_{b}\left\{\begin{array}{l}\left\{\bigcup_{c}\left\{\bigcup_{d}\left\{VerPI_{abcd},ValPI_{abcd}\right\}\right\}\right\},\left\{VerPI_{ab},ValPI_{ab}\right\},\\ \left\{\bigcup_{\substack{a\\g=2}}\left\{\bigcup_{b}\left\{\begin{array}{l}\left\{\bigcup_{c}\left\{\bigcup_{d}\left\{VerPI_{abcd},ValPI_{abcd}\right\}\right\}\right\},\left\{VerPI_{ab},ValPI_{ab}\right\},\\ \left\{\begin{array}{l}\ldots,\\ \left\{\bigcup_{\substack{a\\|g|}}\left\{\bigcup_{b}\left\{\begin{array}{l}\left\{\bigcup_{c}\left\{\bigcup_{d}\left\{VerPI_{abcd},ValPI_{abcd}\right\}\right\}\right\},\\ \left\{VerPI_{ab},ValPI_{ab}\right\}\end{array}\right\}\right\}\right\}\end{array}\right\}\end{array}\right\}\right\}\right\}\end{array}\right\}\right\}\right\},\tag{8}$$

where

$$VerPI_{n}=\left\{CPI_{\substack{nr\\1}}\left\{\ldots\left\{CPI_{\substack{nr\\(|l|-2)}}\left\{SPI_{\substack{nr\\(|l|-1)}}\left\{EPI_{\substack{nr\\|l|}}\left\{\left(Par,Met\right)_{\substack{nrp\\|l|}}\right\}\right\}\right\}\right\}\right\}\right\}-$$

is set of property indicators of the MI for the verification process;

$$ValPI_{n}=\left\{CPI_{\substack{nr\\1}}\left\{\ldots\left\{CPI_{\substack{nr\\(|l|-2)}}\left\{SPI_{\substack{nr\\(|l|-1)}}\left\{EPI_{\substack{nr\\|l|}}\left\{\left(Par,Met\right)_{\substack{nrp\\|l|}}\right\}\right\}\right\}\right\}\right\}\right\}-$$

is set of property indicators of the MI for the validation process;

b, *c*, *d*, *g* are indices of the phase of the MI life cycle, the process of the MI life cycle phase, the process phase, the level, respectively; *n* is index of the verification and approval processes at the stages of the MI life cycle; *p* is index of the tuple of the set of parameters and measurement methods $p = (1{:}|p|)$.

The binary relations between the set of EPI and the parameters and measurement methods have the following form:

$$\left(Par,Met\right)_{\substack{nrp\\|l|}}\subset EPI_{\substack{nr\\|l|}}\left|b_{i}=1,\right.\tag{9}$$

where $B=\left\{b_{1},b_{2},\ldots,b_{|p|}\right\}$ is characteristic vector $EPI_{\substack{n\\|l|}}$, $i=(1{:}|p|)$.

6. Discussion of practical aspects of the proposed model

In general, the indicators of the properties of any technical system include: purpose indicators; functional indicators; resource-saving indicators, etc. For a measuring instrument as a technical system, it is necessary, first of all, to consider the purpose indicators, which include metrological characteristics. The main metrological characteristics include, in particular: measuring interval or measurement range; maximum permissible error; sensitivity of a measuring system; instability of a measuring instrument; instrument drift, etc. [6, 16, 17].

To determine the specified metrological characteristics of all measuring instruments, as well as some additional functional indicators, such as metrological reliability, serviceability, failure, intercalibration interval [18], it is necessary to use appropriate methods of calibration and testing of measuring instruments. For system-oriented MI, one of the important elements is the establishment of requirements for MI software and the use of special methods for testing MI software, both embedded and third-party [2–4].

A feature of the proposed model, when compared with a mathematical model based on general systems theory, is the ability to take into account specific parameters of MI properties and corresponding methods for their determination. Based on metrological characteristics and corresponding methods for their determination, a set of tuples of parameters and measurement methods (*Par*, *Met*) for EPI, SPI and CPI is formed. Another feature of the model is the establishment of MI CPI for the generalized phase of the MI life cycle $PhLC_{CPI}$ (for example, the operation phase). For each phase of the MI life cycle, it is necessary to establish both a set of MI property indicators for the *VerCPI* verification process and a set of MI property indicators for the *ValCPI* approval process.

7. Conclusions

The mathematical modeling conducted allowed us to develop a multiple model of the system of indicators of the MI properties. The proposed model allows for the study of the influence of the MI properties EPI, SPI and CPI, and their evaluation at all stages of the MI life cycle.

It also allows taking into account specific parameters of the MI properties and the corresponding methods for their determination. The model allows taking into account the features of system-oriented MIs, in particular, indicators of the MI's properties in terms of ensuring system functions and the corresponding methods for their determination. At each phase of the MI life cycle, both the appropriate verification for the sets of MI properties and their validation should be carried out. When implementing these procedures, it is necessary to use the established requirements of widely used international and regional metrology guidelines.

Conflict of interest

The authors declare that there are no financial or other potential conflicts of interest regarding this work.

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