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NEW PROBLEMS OF INSTRUMENTATION DESIGN AND MEASUREMENT THEORY

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Abstract: The paper deals with a new approach to the measurement systems design. It contains the review of selected new problems of contemporary metrology related with the design. Main attention of the paper has been concentrated around possibilities of formalisation, development of mathematical apparatus and optimisation of a design of optimal analogue-digital, intelligent measuring systems (MS). The task of the discussed approach is analytical support for system-level decisions at the most responsible initial stages of MS design. Its takes into account all available prior information about objects, processes and environment, as well as about the way of observation including characteristics of sensors, noises, errors and disturbances accompanying the measurement process.

Keywords: measurement theory, optimal MS design, analytical synthesis

1 INTRODUCTION

Fast development of digital measuring technique creates a growing number of new important problems in measurement system theory and design. Up to now, these problems are solved mainly heuristically, on the base of experience and intuition of engineers-designers of MS, with only partial utilisation of analytic support of design process. In the last years, efficiency of their work has been improved due to advances in development of the MS computer design [1,2].

Modern analogue-digital measurement systems, especially produced in the silicon technology, belong to the general class of “embedded” systems [3,4]. These systems are characterised by mixed hardware, software and mechanical components with limited processing, input/output and storage resources. Their design requires the tools, which enable concurrent design, modelling, verification, and integration of hardware, software, mechanical and other subsystems before the fabrication.

All the quoted above works note a significant gap in the technology and methodology for this class of systems, which has been felt in metrology yet in 80th years [5,6]. As a most urgent, these works consider a problem of mathematically based system description to specify and model the hardware, software, and mechanical components. This description must enable designers to make well-argued system-level decisions as possible earlier in the design cycle, because these decisions are most responsible for the cost, performance and viability of the final product. Simultaneously, it should enable observable, predictable, and controllable transition to appropriate realisation technologies.

The aim of this paper is systematisation, analysis and formulation of the main problems appearing in design of the *optimal* (i.e. *best in the given conditions*) MSs, appraisal of possibilities and the ways these problems could be solved, advance of proposals for their solution.

Backgrounds of unified approach to analytical design of optimal and sub-optimal analogue-digital MSs (conventional, adaptive and intelligent) are considered. The discussed below material unites and develops ideas presented in various works, including results of own author’s investigations. We will note only some basic approaches and ideas, which have initiated the present investigation:

- methods and mathematical apparatus of optimal statistical synthesis [7,8] adapted to the specifics of measurement tasks;
- probabilistic models in measurements and some assumptions of the theory of MS accuracy [9,10];
- methodology of measurements and MS design, prior and posterior models [1,2,5,6,11,12];
- proposals following from the concept of “measurement metasystem” [5,6,12];
- Bayesian and non-Bayesian methods of complex optimisation of MSs [13,14] in conditions of statistically fitted observation of the process [15-17].

Optimal statistical synthesis [7,8] is a widely used and powerful tool for analytical support of the system-level decisions in design of various signal processing systems and receivers.
The delay in its applications to the MS design we explain by fantastic successes in the sensor technology and, on the other hand, by a lack of sufficiently adequate and general model of the sensor.

Now, let us discuss and put in order new, created by the practice of MS design problems. This clarifies main practical needs and shows directions of development of the approach.

2 METODOLOGICAL PROBLEMS OF MS DESIGN AND APPLICATIONS

Some terminology remarks: To exclude possible misunderstanding, we define the measurement as *estimation of measurands* - of unknown parameters, current values or other characteristics of the analysed input process. Estimates of measurands are formed in digital blocks of MS on the basis of *observations* of the analysed process (object, signal), in different works called also the "results of measurements", "experimental data"; "row" or "initial" measurements, "measured process (or signal}", etc.

Under words the "measuring device", "measurement system", we understand instruments designed for the measurands estimation. Physical elements of the measurement chain (sensors, receivers of different types, transducers, amplifiers, converters, and other elements), which deliver the empirical information to the blocks of measurands estimating, we call "*observers*", and refer them to the *analogue part* of the MS (for simpler chains we preserve the term "sensor").

The "hardware", i.e. microprocessors and elements (ADC, DAC, etc.) which link their inputs/outputs with the analogue elements of the MS, analysed object, or other MSs, as well as the "software"-estimating, adjusting, testing, controlling and other algorithms - belong to the *digital part* of the system. In the applied calculations, usually performed in the discrete time, it is more convenient to consider linking elements as the input-output blocks of corresponding analogue subsystems of the MS.

2.1 Connections between the MS software and full model of measurement process

Definition: „Measurement system is the complete set of measuring instruments and other equipment assembled to carry out the specified measurement task" [18] is too restrictive for the aims of modern MS design. To show this, let us consider the extremely generalised structure of the measurement experiment presented in Fig. 1.

It is easy to see that analogue-digital MS is a part of this structure, and the quoted definition seems to be satisfactory good. However, and this is very important, final quality of measurements depends not only on characteristics of the analogue part and hardware, but in no less degree, on the quality of software. (Such valuable properties of contemporary MS as multi-functionality, adaptability, and flexibility are also best realised just in software [4]). The latter, in turn, depends on information not only about the MS, but also about conditions, in which it works, and on the characteristics of the analysed process. Thus, the advanced software is an important component of contemporary MSs and depends on the information about *all the components* of the measurement experiment including models of the analysed process, observer, and digital part as well. This is not taken into account in the quoted definition that makes it insufficient for the MS design.
Claim 1: *The sequential approach to MS design should be based on the analysis of the full model of the measurement experiment.*

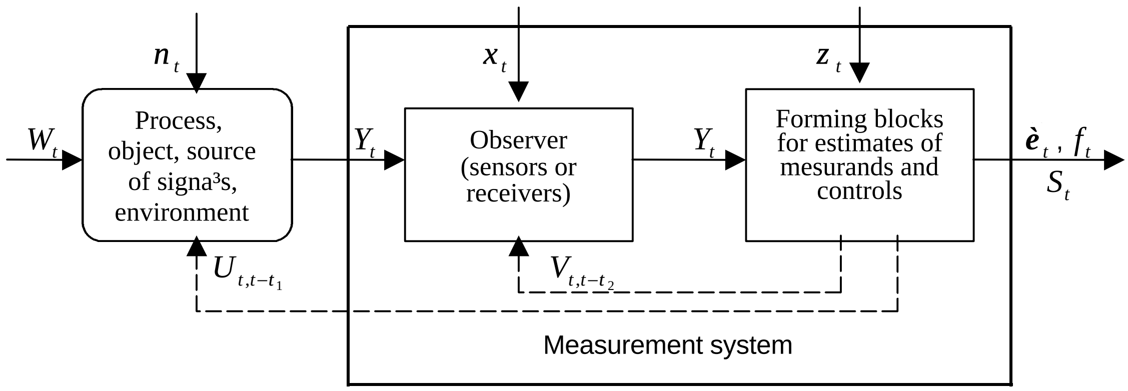

Figure 1. General structure of an advanced measurement experiment.

Notations in Fig. 1: $\ddot{\mathbf{\grave{e}}}_t$ are estimates of the measurands $\mathbf{\grave{e}}$ related with the analysed process Y_t.Variable $\ddot{f}_t$ denotes the estimates of more complex measurands $f_t = f_t(\mathbf{\grave{e}})$; Y_t is the signal at the observer output;
$v_{t,t-t_2}$ is the predictive adaptive control adjusting observer; S_t is the current measure of estimates quality. Time-delay t_2 describes the time necessary for the adjusting controls could be formed. $u_{t,t-t_1}$ are the controls actuating the object with time-delay t_1; variable W_t denotes possible deterministic or programmed external control; n_t, x_t z_t are random noises and disturbances of different nature and intensity.

Many important details such as internal noises, stochastic and quasi-deterministic disturbances of a measurement process and others, are not shown in the Fig. 1. Measurands, estimates, controls, noises, as well as the observer inputs and outputs can be multidimensional.

2.2 General problems of contemporary MS and instrumentation design

Problems of contemporary MS and instrumentation design can be split into three groups. The first grope concerns a development of the tools which enables formalisation and optimisation of MS design in the way ensuring, under given conditions, the best characteristics of the final product.

The second group includes the problems of optimal, in extended sense, planning and control of the experiment. The latter means maximal improvement of the measurements quality by proper application of the given, not necessary optimal MS. This can be done using its adaptation to initially unknown or changing conditions of experiment. Another possibility is a controlled by the MS, programmed or adaptive acting at the analysed process. In general case, both these possibilities should be used.

The third group joins two previous groups of problems into the united problem of optimal MS design, planning and control of the measurement experiment. These systems should not only provide the best estimation of measurands. Simultaneously, they should additionally improve these estimates using locked with estimation, adaptive adjustment of own parameters, and controlling the state of the analysed objects or processes.

Main difficulties in solution of the listed problems are:

In the first group: separated, weakly correlated design of analogue and digital parts of MSs, lack of developed mathematical tools for support and optimisation of the system-level decisions. In particular:

a) Design and optimisation of the *analogue part* (physical part of measuring chain) are based on intuition and experience of engineers-designers. Objective of their work is to satisfy the requirements of initial specification in the part, which concerns them. Designers of measuring chain minimally, if ever, take into account the data-processing software and work of data-processing blocks.
b) Similar situation prevails in design of the *digital part* of MS. Optimal data-processing algorithms are derived using methods of optimal signal processing without or minimally taking into account of the measurement chain functioning.

It is worth to remind that a separate or weakly correlated design of analogue and digital parts of MS reduces a quality of measurements in comparison with the potentially attainable under complex, interconnected design of both parts of MS. However, up to now, this form of design has no methodological and mathematical basis.

Notice: In the last years, digital blocks of MS all the more frequently used also for calibration and correction of the measuring chain parameters ([19,20] and others). Nevertheless, there remains a big gap between the software, hardware and measuring chain design.

In the second group: methods of well-developed theory of optimal planning of the experiment solve many problems, including of identification kind. However, this theory is not related with the models of real processes, observing devices, and omits the structure of MS as a whole. For this reason, planning of experiment results in noticeable improvement of the measurement quality only in relatively narrow set of the measurement problems. Some questions of optimal situating and movement of the sensors in distributed parameter measurements were considered in [21]. Derived from the another assumptions, general rules of the sensor adaptation to the characteristics of the input process are given in [17].

The problems of the third group are not investigated completely.

Resume: there exists a group of unsolved problems of a great importance for MS design, production and application, as well as for general development of the field. They are:

1) *General differentiation of main stages of design, argued selection and development of methods and tools for their formalisation and optimisation.*

2) *Development of mathematical apparatus enabling complex analysis and synthesis of optimal MS, numerically argued system-level decisions and optimal decomposition of initial design task into particular tasks for the main components of analytically found optimal structure of the MS.*
3) *Generalisation of approach for the case of intelligent MSs. To this class, we refer the systems which realise their aims restoring* (*in digital blocks*) *all the more complete and adequate models of the analysed processes or environment, can analyse them and find the best or better conditions for measurements, adjust themselves to these conditions, and communicate with other systems.*
4) *Similar problem, but the improvement of measurements is achieved by optimal adaptive actuating the analysed process or a state of the analysed object.*

The listed problems are very complex and require a comprehensive analysis. Below we will present the main principles of approach enabling formalisation of these problems and development of mathematical apparatus necessary for their solution.

2.3 Optimal statistical synthesis as a basis for formalisation of a design process

First of all, we should separate properly the main stages of design and corresponding research tools. Most natural gradation seems to be as follows:

1) Forming of the *initial specification* containing all the main requirements to MS.
2) Definition of optimal structure of the MS and partial specifications for its main components.
3) Optimal or sub-optimal decomposition of the main design task, forming of the optimal program and schedule of the engineering works, their following realisation.
4) Realisation, experimental analysis and debugging of the MS prototype (physical, virtual or mixed).
5) Preparing of final documentation and transition to the serial production.

Analysis of the question shows great potential possibilities of the optimal statistical syntheses [7,8,10] as a tool for formalisation and analytical support of the MS design at the most difficult and responsible initial stages 2 and 3.

On the one hand, statistical syntheses enables strict analytical definition of theoretically best version of the system, which possesses the highest, “potentially achievable” characteristics of quality in the given conditions. This solves simultaneously a problem of *theoretically optimal decomposition* of initial design task into the set of simpler individual tasks for the MS components with determined by calculations optimal characteristics and forms of interaction.

On the other hand, if theoretically optimal version of MS cannot be realised in conditions of specification, its structure and characteristics may serve as the pattern and initial point for ordered search of sub-optimal - nearest to the optimal version of the MS, which satisfies all the requirements of specification. Solution of this problem, as above, enables *the sub-optimal decomposition* of the project task.

Thus, the results of optimal synthesis application give the designers well-grounded analytical basis for the most appropriate system-level decisions before a transition to the direct engineering design. This allows them not only to be sure in the properties of the final product, but to optimise and synchronise the program and schedule of engineering design works and debugging the MS prototype.

Claim 2: *Being adapted to the metrology tasks, optimal statistical synthesis* [7,8] *may become the effective tool for formalisation and optimisation of design of the analogue-digital (embedded) measurement systems, especially at the initial, system-level stage of design. Its application determines the MS with “potentially achievable”, theoretically best characteristics, and enables further sub-optimal decomposition*

The design of MS starts with forming the *initial specification* (“pre-design” stage 1). This specifications is individual for each MS and should contain [4,6,10]:

1 General and technical part: predestination of the MS, aim of measurements, measurands, acceptable or required operational parameters and characteristics of the MS (range, accuracy, etc.).
2 Marketing and technological part: requirements connected with realisation of the MS (price, complexity, consumed power, reliability, technological constrains, sizes, weight, service, etc.).
3 Analytical part: all the available prior information about each element of the measurement chain and metasystem (see Claim 1 and Sect. 3.1 below).

Many authors [5,11,12] consider the inclusion of mathematical models as a necessary element of the initial specification. However, up to now, the role of analytical part in specification was not too significant - there were no analytical tools for its efficient utilisation.

Conditions in items 1,2 of specification play a role of additional constraints on the set of possible variants of MS after transition to the third stage of design – to sub-optimal decomposition of the system.

3 GENERAL PRINCIPALS OF THE MS DESIGN FORMALISATION

The above discussion shows a special role of the statistical synthesis in the MS design. *For its methods could be efficiently applied in new conditions, it should embrace the models of all main participants of the measurement experiment, including software. The result of synthesis is one or several (theoretically equivalent) optimal or sub-optimal versions of the MS.*

3.1 Prior information and metasystem

The results of statistical synthesis depend on the completeness of the prior information about each participant of the measuring process. Our earlier investigations show that this information should include:

1) Field and aim of measurements – type of the analysed processes Y_t and measurands $\grave{\boldsymbol{e}}_t$.
2) Class (thesaurus [10]) of mathematical models of the analysed process with one or some unknown parameters or a given discrete set of possible states. Relation "measurand - model of the process" should be determined. The models should include the prior distribution of possible values of measurands and unknown parameters, statistics of possible random disturbances.
3) Mathematical model of the observer (measurement chain)– formalised description of its reaction on the input excitations, which takes into account all meaningful deterministic and random factors.
4) Mathematical model of the observations – sample sequences $Y_1^n = \{Y_1, ..., Y_n\}$ or realisations Y_0^t of the signal at the sensor output.
5) Class of admissible mathematical models of the digital blocks functioning – determined for each data-sequence Y_0^t sets of possible estimates of measurands $\hat{\boldsymbol{e}} = \hat{\boldsymbol{e}}(\tilde{Y}_0^t)$, as well as controls for adjusting the observers and analysed object actuators.
6) Analytical measure of quality of the current estimates of measurands – function of difference between the estimated and real values of measurands, or between the model of the analysed process and its analogue restored on the basis of observations.

This information is sufficient for the analytic synthesis of the optimal MSs could be performed (certainly, assuming that possible mathematical difficulties in calculations can be successfully settled). Let us remind that the result of synthesis – the model of optimal MS is only a part of the model of the bigger system (set of systems) presented in Fig. 1. By analogy with [5,6], we preserve for this system, together with information from items 1) - 6), the term *measurement metasystem* (megasystem in [12]).

3.2 Principals of optimal statistical synthesis of MS

The objective of optimal synthesis is the analytical support of decision and choice of optimal versions of designed systems at the most difficult [12] for analysis *initial* stage of design. In turn, the main stages of calculations during the statistical synthesis and their sense are as follows [7,8,17]:

1) The fundamental postulate is: "the synthesis of optimal algorithms is always connected with establishment of conditions ensuring extremum of the given criterion of quality. Without formulating a criterion of quality, any task of the system synthesis has no sense" [7, p.314].

2) Really – among a practically infinite set of different versions of data processing systems, there exist only one (ore a small number of the equivalent ones) which forms the estimates of measurands in the best way with respect to the given criterion of quality of the Bayesian or non-Bayesian type [9]. Objective of optimal synthesis is definition of these, optimal systems which ensure the extremum of given analytical measures of quality. This explains - why analytical synthesis is necessary connected with the solution of corresponding extremum problem.

3) To formulate this problem, the analytical measure of quality should be introduced, which takes into account adequately all the details of measurement process included into the analytical part of specification (Sect. 3.1, items 1-6).

4) The solution of the extremum problem – functionals, equations or discrete-time algorithms for optimal estimates of the measurands, determine the sequence, type and parameters of operations which should be performed with each sample of observations for these estimates were optimal. Processing of the samples according to this sequence ensures theoretically highest quality of measurements.

5) On the other hand, this sequence determines a set, types, optimal parameters, characteristics, the way of interaction of the technical elements and blocks, which are needed for corresponding operations could be realised. *Thus, the derived relationships for optimal estimates determine the best version of the designed MS including optimal connections, the way and sequence of interactions of its analogue and digital elements, locked and driven by optimal algorithms* (*software*) *installed in digital data processing blocks of the system* (*hardware*).

This completes the statistical synthesis and simultaneously solves the problem of optimal decomposition. The next stage of design - suboptimal decomposition can be developed starting from this result.

CONCLUSIONS

A number of new problems of contemporary design of the analogue-digital (embedded) measurement systems are discussed together with possible ways of their solution. The frameworks of new approach to formalisation and optimisation of the MS design are considered. The approach should be based on the methods of optimal statistical synthesis adapted to the aims of metrology. Importance of joint, complex consideration of all components of the measurement experiment is emphasised.

Optimal synthesis provides the MS designers with analytical tools for an argued choice of the best in the given conditions versions of MS including their structure, parameters and characteristics. It may become a source of systematic development of analytic and computer tools for efficient support of engineering decisions at the most difficult and responsible initial stages of MS design. Calculated analytically, optimal versions of MS can be used for development of efficient formal methods of optimal or sub-optimal decomposition of initial design task according to the specification.

Being properly developed and applied to the MS design, statistical synthesis may supply the engineers with mathematical representation of the design process, enabling its formalisation and optimisation. This gives an answer on the remark [11, p. 78]: „That is badly missing is means to formalise the design process with mathematical representation. This seems to be impossible to do but...”

We completely agree with the point of view that „Measurement theory should be concerned at its core not with the description and analysis of measurement and instrumentation systems, but with their design” [1]. Just this is an objective of the approach discussed in the paper.

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