THE PARAMETRIC DESIGN OF SONARS

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1. INTRODUCTION

A new approach for the parametric design of sonars as overall system is highlighted.
By means of a decomposition of the overall sonar system electronics one can select three loops : 1) signal forming and processing; 2) control; 3) supply. The goal of this paper is a formalization of the sonar design via description of its the most informative part - the signal forming and processing. Usually, the sonar subsystems (e.g. transmit, signal processing, display ones) are designed with different criteria of efficiency.

In this paper is used the one-parameter efficiency criterion with constraints for the overall signal loop. The last is termed as a system, which elements (subsystems, units and devices with software) is destined for the signals forming and processing in order to detection of underwater objects and measurement of their coordinates.

The signal loop may be introduce by means a several descriptions: algorithmical (functional), structural (morphological), parametric, data, statistical, equipment ones. The sequence of the descriptions depends on technical requirements to sonar and constraints. (E.g. technical requirements may consist structural and unit descriptions.) In this paper we start with the processing algorithmical description of the signal loop. The other descriptions will be giving later.

2. THE ALGORITHMICAL DESCRIPTION OF THE SIGNAL LOOP

It is based on multidimensional matrix description of the array signals and algebra operations with the convoluted multiplication of those matrices [1].

We suppose that signal processing is performed in digital form for output array signals. In this case the more suitable description of those signals is the matrix one. For the linear array it is usually (two-dimensional) matrix, but for the two-dimensional array it is three-dimensional one.

The multidimensional matrix is termed as a system of $N_1 N_2 \dots N_p$ elements of a numerical field P, placed in the points of p-dimensional space and determined by coordinates $i_1, i_2, \dots, i_p$

$$ {}_p\underline{U} = {}_p\underline{U}_{i_1, i_2, \dots, i_p} \qquad (i_\alpha = 1, 2, \dots, N_\alpha; \quad \alpha = 1, 2, \dots, p) \tag{1} $$

Underlined ${}_p\underline{U}_{i_1, i_2, \dots, i_p}$ with index p denotes p-dimensional matrix, right lower indices denote the matrix coordinates. According to this approach, the signal (data) from the output of the two-dimensional (surface) arrays, such as planar, cylindrical, spherical, conformal, is a three-dimensional matrix (with the time as third coordinate).

Associating multidimensional matrices with multilinear forms, one can determine the basic algebraic operations over those matrices. In [1] it was shown, that detection of the spatio-temporal signal may be described as a sequence of the convoluted multiplications : 1) the inverse correlation matrix of a noise field ${}_{2m}\underline{R}^{-1}$ on processing matrix ${}^{s}_{m}\underline{U}$ and 2) obtained product on a data matrix ${}^{sn}_{m}\underline{U}$

$$\ln \Lambda = {}^{m}({}^{sn}_{m}\underline{U} \circ {}^{m}({}_{2m}\underline{R}^{-1} \circ {}^{s}_{m}\underline{U})) \tag{2}$$

where m is the number of convoluted coordinates,

${}^{sn}_{m}\underline{U}$ is the signal–plus–noise (data) matrix,

${}_{2m}\underline{R}^{-1}$ is the inverse correlation matrix of the noise,

$\circ$ is the symbol of the multidimensional matrix multiplication,

${}^{s}_{m}\underline{U}$ is the processing matrix.

Let us consider the spatio-temporal processing of the signal from the circular array output. It may be described as

$${}_3\underline{U}_{f,\alpha,\beta} = {}^{\varphi_2}({}_3\underline{U}_{t,\varphi,z} \circ {}^{t_1,\varphi_1,z_1}({}_6\underline{S}_{t_1,f;\varphi_1,\alpha;z_1,\beta} \circ {}_6\underline{R}^{-1}{}_{t_1,t;\varphi_1,\varphi;z_1,z})) \tag{3}$$

If the spatio-temporal processing is factorable on spatial and temporal ones, then at the first stage we obtain the delay-samplings matrix:

$${}_2\underline{U}_{\varphi,\tau(\alpha)} = {}^{t_1}({}_2\underline{U}_{\varphi,t_1} \circ {}_3\underline{H}_{\varphi/(\alpha),t_1}), \tag{4}$$

Where ${}_2\underline{U}_{\varphi,t_1}$ is a data matrix over time interval, that is sufficient for forming the delays for the α bearings,

${}_3\underline{H}_{\varphi(\alpha),t_1}$ - the matrix of the impulse responses for signal delays for bearings α. Then, if necessary, the rearrangement of the data is followed

$${}_2\underline{U}_{\alpha,\tau(\varphi)} = {}_2\underline{U}_{\tau(\alpha),\varphi} \circ {}_2\underline{H}_{\varphi,\alpha} \tag{5}$$

where ${}_2\underline{H}_{\varphi,\alpha}$ is the permutation matrix,
and then the summing of the delayed samplings

$${}_1\underline{U}_{\alpha} = {}^{\tau}({}_2\underline{U}_{\alpha,\tau(\varphi)}) \tag{6}$$

Then follow data accumulation in each beam

$${}_1\underline{U}_{\alpha}(t) \Rightarrow {}_2\underline{U}_{\alpha,t}, \qquad t = t\,mod(N_t) \tag{7}$$

and temporal processing

$${}_2\underline{U}_{\alpha,f} = {}_2\underline{U}_{\alpha,t} \circ {}_2\underline{S}_{t,f} \tag{8}$$

where ${}_2\underline{S}_{t,f}$ is a temporal processing matrix (in particular case it may be FFT one). If the signal is coded, e.g. over frequency and time, then the accumulation its energy over each possible Doppler channel with accordance the frequency-time coding is performed

$${}_2\underline{U}_{\alpha,f_{dp}} = {}^{f}({}_2\underline{U}_{\alpha,f} \circ {}_2\underline{P}_{f,f_{dp}}) \tag{9}$$

The next stage is the accurate target coordinates measurement (calculation). It compare the maximal amplitude, which corresponds to the target, and its maximal immediate neighbour one. The radiate velocity is obtained from comparing this pair over frequency, the bearing - over beams, the distance - over successive time interval

$${}_1\underline{U}_{(\alpha_{ac},f_{ac})}(d_{ac}) = Compar(maxmax_3\underline{U}_{\alpha,f,t}, maxngb_3\underline{U}_{\alpha,f,t}) \tag{10}$$

The target trajectory analysis with Kalman and Wiener filtering over the data (10) is performed to observe many targets simultaneously and to improve theirs detectability and coordinates measurement accuracy. Its output (as well as input) data with the data (7) and (8) may be used for classification, adaptation and high-resolution.

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THE STRUCTURAL DESCRIPTION OF THE SIGNAL LOOP

The previously described algorithms are used for a structural description signal loop. Making use the matrix designations one may presents the sonar structural scheme as on Fig. 1

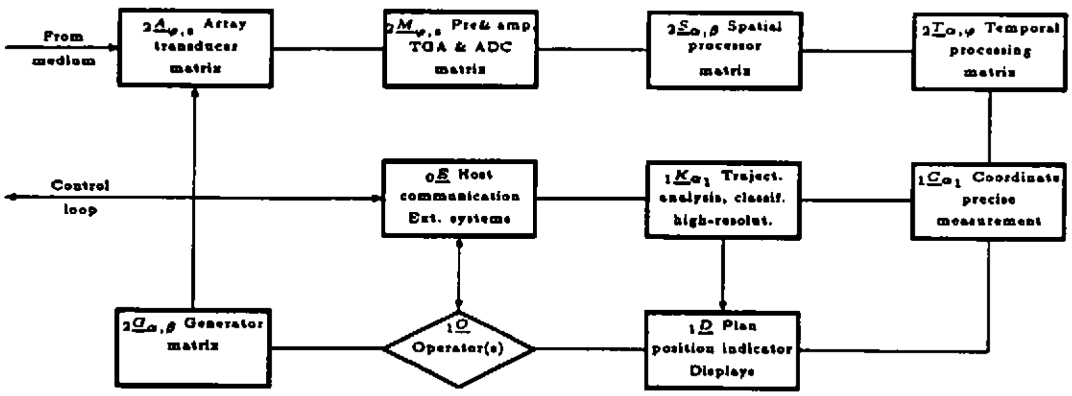

Figure 1. The structural scheme of the signal loop

This description allows to define signal loop morphology and to point out the number of devices at the loop elements (suit subsystems).

4. THE PARAMETRIC DESCRIPTION OF THE SIGNAL LOOP

The parameters of the signal loop that have one-to-one correspondence with the efficiency of the sonar on physically measurable criterion are denoted as parametric description of the signal loop.

We have selected the one-parameter efficiency criterion for the signal loop with constraints over the other parameters. This criterion is sufficient for sonar on account of the efficiency is obtained for the maximum values of the constrained parameter.

The problem of the selection the signal loop parameters may be formulate as follows. There are given
d_m a main parameter for optimisation,
ΔR the space domain, which limits the array sizes,
$\Delta\alpha$ an angular coverage,
ΔT a time interval for target detection,
δ_i permissible errors of coordinate measurements,
Δv_t a range of a target velocity,
Δv_p a range of a platform velocity,
ξ parameters of a platform pitching and rolling,
c_i a set of hydrological-acoustical conditions,
MS the mass, size and the other constraints.

It is required to find the signal loop parameters, that satisfy the selected criterion.

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The selection of optimisation parameter is connected with the sonar main assignment and e.g. for the safety sonar may be formulated as maximal range detection with constraints, included the precise coordinate measurement and the other technical requirements.

$$Eff. = max(Range)_{\delta_i, MS, \ldots} \tag{11}$$

Let us consider the signal loop parameter selection according to a scheme on Fig.2. At first and second block the technical requirements are analysed and efficiency criterion is selected.

At the third block either active or passive sonar mode is preferred, to depend on a relation of an intensity of radiated and returned acoustic fields.

At sixth block panoramic scan method is selected. For many search modes a multi-beam receiving and a non-directional radiation are used. For safety sonar a multi-directional radiation may be useful [2]. The scan method is selected with moving platform design constraints (block 32) and angular coverage requirements (block 51).

A carrier frequency selection is iterative process with an optimisation of the relationship (11). For the Gaussian noise the efficiency criterion may be lead to maximization of the signal-to-noise ratio functional at the output of the signal loop processing

$$_n\underline{Q}^2{}_{f,r,f_t,f_p,\Delta F,\ldots}(f) = max \frac{_n\underline{E}_{f,r,f_t,f_p,\Delta F,\ldots}(f)_1\underline{H}_f}{L_2(\sum_{i=1}^{K} w_i \sigma_i^2(f))} \tag{12}$$

where E is the energy of the signal,

H is a coefficient, that takes in the account processing performance loss,

L_2 is a transformation operator of the signal-plus-noise over frequency,

σ_i is mean-square-error of i-th noise component. The arguments of the functional are the frequency-depending parameters (range r, target and platform velocity v_t *and* v_p, passband ΔF, sonar conditions, etc.).

It follows from (12) that for the selection optimal frequency one must know the other parameters of the signal loop. Initially they are selected by designer from a previously experience. Since the dependence of the signal-to- noise ratio from the frequency is weak and has a plane maximum, the choosing frequency is sufficient for many cases. If the accuracy of the coordinate measurements is not adequate, or other parameters are over constraints, then correction is followed (blocks 18, 45, 7, 21).

At the block 8 transducer specific acoustic power is selected. It has requirements on a life and a duty continuity (block 52). The acoustical pressure on beam axis is depended from both transducer specific radiated power and array directivity factor by given geometry and transducer connections (block 33).

The next four schemes blocks (11-14) are concerned to the signal parameter selection. The signal duration (block 11) is selected under conditions the range measurement accuracy (block 54), sound emission duty ratio (block 35), dead range (block 36), target velocity measurement accuracy (block 56), etc. The problems of the signal type and their processing algorithms synthesis may be solved by means variational methods (see e.g. [3])

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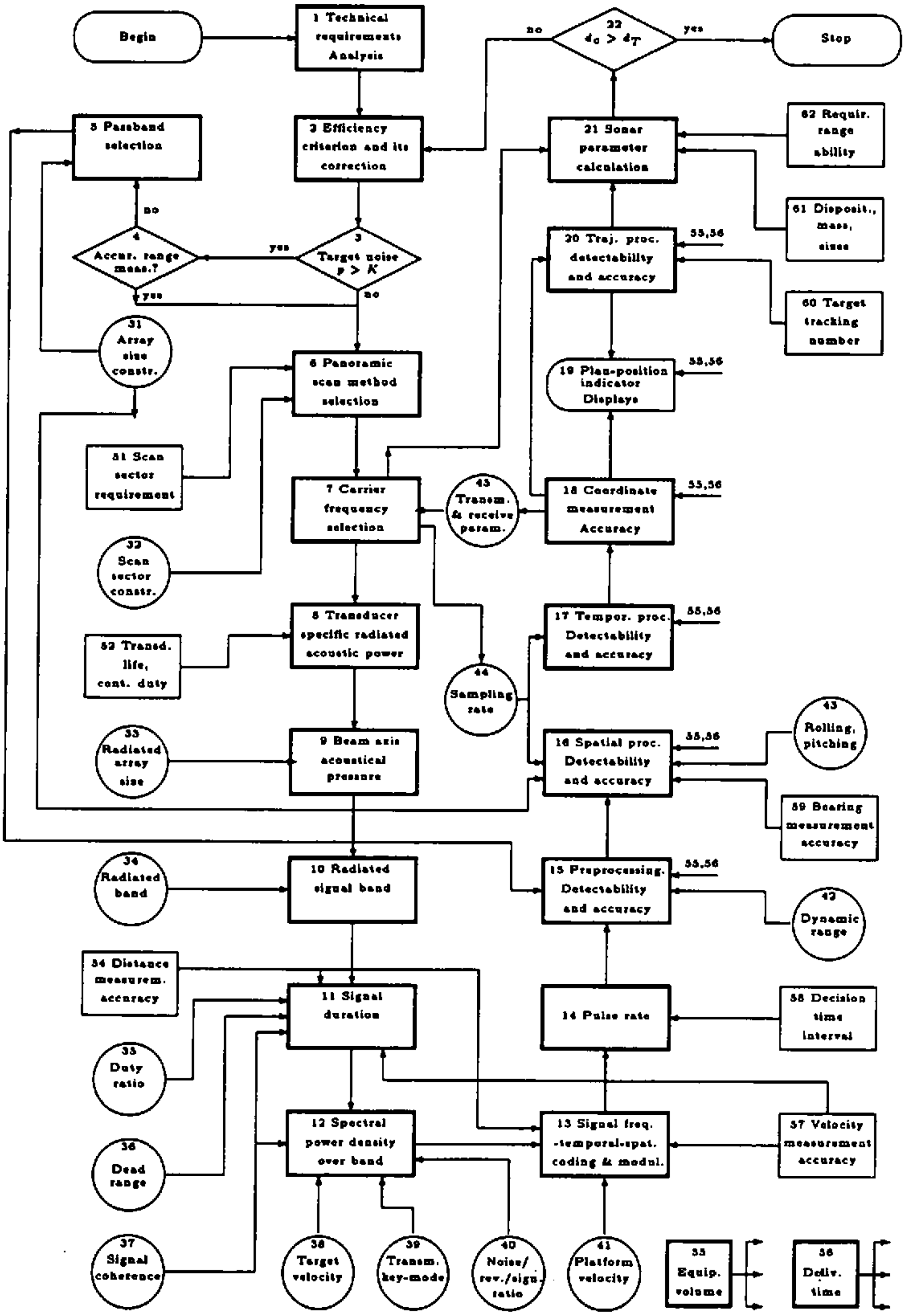

Figure 2. Block-scheme of the sonar parameter design

The maximisation of the functional (12) ought to calculate optimal signal band and its coding, with taking in account the requirements (54) and (57). For the safety sonar the optimal bandwidth-time product $\Delta FT = 30$.

The interpulse period (block 14) depends from an emitting signal band and the target velocity and decision time requirements (blocks 34, 10 and 57). For high-frequency sonars and high-speed targets it is useful to employ a multi-pulse multi-frequency technique (more than one pulse at conventional period, [2]). The preliminary, spatial, temporal and trajectory processing algorithms (blocks 15-18) are synthesized by efficiency criterion (11) under constraints (31, 42, 43), taking account requirements on coordinate accuracy measurements (blocks 54, 57, 59), on delivery time (56) and equipment volume (55). If the calculated errors of the coordinate measurements are over satisfactory level (block 18), then correction of the transmitting and receiving subsystem parameters (block 45) is followed and the carrier frequency may be changed (block 7).

At the block (21) sonar parameters is calculated. If the technical requirements (blocks 22, 61, 62) are satisfied, the calculation is ended, at the other case efficiency criterion (11) is corrected (block 2) and new iteration is performed. If there is no way to satisfy technical requirement, then the upper system efficiency criterion must be analysed and technical requirements or (and) constraints must be reduced.

5. OTHER SIGNAL LOOP DESCRIPTION

Let us briefly consider other description of the signal loop.

5.1 Statistical description

Statistical description contains the distribution function of the random fields, processes and values at the inputs of the signal loop blocks. By matrix description of the the input data, they also may be described as multidimensional matrices or their section as conventional two-dimensional matrices. Statistical description must be precede to algorithmical one. The searching the distribution functions is the separate problem and we don't consider it here.

5.2 Data stream description

The data stream are described by addition numbers to Fig.1, which characterized the channel numbers and the data rate. The last is depended from the sampling rate. It is the one of the important parameter of the preliminary processing. For the active sonar the sampling rate connects with the bandpass and aliasing, leakage and other digital effects have an influence on filter parameters and a noise level and therefore the sampling rate must be select carefully.

5.3 Equipment description

Equipment description bases on algorithmical, data stream and structural ones. It differ from the last more detailed connections and points out physically addresses of the inputs and outputs in sonar units. Since inputs and outputs ought not to have a direct connections, then connections of signal loop may be presents square matrix $N_s \times N_s$, where N_s is the number of the units or suit subsystems. The elements of this matrix is the $N_i \times N_o$ submatrices of the connections subsystems, where N_i is a number of the inputs, N_o is a number of the outputs.

6. APPLICATION

The previously described technique and algorithms were used for some sonar designing. One of them was the safety navigation sonar. The input data were represented as a three-dimensional matrix.

The signals for the dominate reverberation noise were synthesized. The transmitted signals were coded over frequency and time to obtain more echoes, than in conventional transmitting-receiving time interval (multi-pulse multi-frequency technique). The optimal processing algorithms, based on multidimensional matrix operations, were developed. In the spatio-temporal processing subsystem the matrix of the TMS320 digital signal processors was used that allowed to obtain real-time processing, survey and indication. The R&D project stage with positive sea trial was performed.

7. CONCLUDING REMARKS

In this paper we have attempted to describe a sonar design process at its the most informative part - signal forming and processing. For the sonar designing must be make:
1) signals and noises statistical description at inputs suit subsystem, e.g. their distribution functions and energy relations;
2) algorithmical description - synthesis of the forming and processing algorithms (including detection and coordinate measurements ones);
3) structural description - basically connections of the suit subsystems;
4) parametric description - the searching of the signal loop parameters, that give it optimality;
5) data stream description;
6) equipment description.

The conception of the signal loop allows separate the problem of the forming and processing signals - one of the important part of design - from the overall sonar design. The signal loop descriptions may be employed for the design automatization under the unified efficiency criterion and signal loop parameter optimization.

References

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