

ADAPTIVE DATA COOPERATING METHODS

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Abstract: *Adaptive methods for data integration are proposed, which allow obtaining the maximum amount of available information with a limited number of channels. Instead of degree-of-freedom reducers, it is proposed to use the mechanism of degree-of-freedom discriminators, which makes it possible for all channels, to the extent of their information content in the current situation, to take part in the development of a cooperative solution.*

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Introduction

In developed information systems, data characterizing the state of the same object (process) is transmitted through several channels. The problem is to determine the relative degree of reliability of the data received through each of the channels at the current moment in time and to develop the most reliable assessment of the characteristics of the object (process) from the available set of data.

Considering the role of information systems in the construction of modern decision-making and management systems, the task of creating methods for solving the problem posed should be considered relevant.

Analysis of the problem status

The task of extracting maximum information from the available set of various data characterizing a process or object arises in a wide variety of subject areas. As an example, let us consider the problem of determining the altitude of an aircraft using the readings of barometric, airborne and ground radar altimeters and, possibly, using a visual channel. Each of these channels has its own advantages and disadvantages in different flight conditions. It is required to combine (integrate) the received data for the most reliable estimate of the height at the current time.

The monograph [1] poses the task of integrating the readings of instruments with different accuracy classes. In this case, each of the devices makes its contribution to the resulting reading in accordance with its accuracy class. Here the problem of integrating data from expert assessments is posed and solved, taking into account the varying degrees of competence of experts in the issue under consideration.

Article [2] describes a method for automatically classifying the state of forests based on aerospace survey materials based on the synergetic principle of data fusion. Here the most informative (dominant) spectral channels of the sensor are determined, and based on their readings the desired decision is made.

In [3], the task was set of integrating signals from navigation fields of various physical natures (radio navigation fields such as GPS, geophysical fields, the field of stars and bodies of the Solar System, etc.) for the most reliable assessment of the current coordinates of the spacecraft.

A method for combining signals for bistatic radar of small celestial bodies is described in [4]. To increase the accuracy of measurements when studying the parameters of the motion of small celestial bodies, a bistatic configuration of radar systems is used. Information from each of the receiving antennas, separated over considerable distances, is processed and compared with each other so that the resulting signal is the most reliable.

The examples given use the concept of synergetics [5,6] – the science of cooperative processes. In the hierarchy of system theories, synergetics occupies the top level. In contrast to the general theory of systems, synergetics

studies and organizes processes that develop not under centralized influences, but through the collective interaction of components in accordance with the set goal. Cooperation of components allows the use of reserve capabilities of the system and significantly increases the degree of emergence (system effect).

According to the definition of the creator of the theory of functional systems in biology, P.K. Anokhin, “a system can only be called such a complex of selectively involved components in which the interaction and relationship acquire the character of interaction of components to obtain a fixed useful result” [7]. The identified fundamental property of interaction is a clearly expressed and universally manifested synergistic process in biological systems [5].

When synthesizing a synergetic functional system, excess degrees of freedom are first created (Ashby's law [8] on necessary diversity), providing additional possibilities in the properties of the system. Then, in the process of adaptive interaction between the components, these degrees of freedom are overcome (reduced) according to the dominant mechanism in the process of system functioning. For this purpose, the system has “degrees of freedom reducers” [5].

The synergistic concept of data integration (fusion) is actively used to extract maximum information from the existing set of various data not only in biology, but also in other subject areas, as evidenced by the examples given.

Content analysis of the problem

Unlike biological and similar synergetic control systems, integration systems, as a rule, do not have an excessive number of data acquisition channels. The number of degrees of freedom is a priori limited and the essence of the problem is to extract the maximum amount of available information under these restrictions. In the above examples, the action of the “degrees of freedom reducers” led to the cutting off of less informative ones and to the selection of one or more of the most informative (dominant) channels for obtaining data in the current situation, on the basis of which the desired solution was formed.

With this approach, some useful nuances contained in the pruned channels do not take part in the solution search process, i.e. some information is lost. Figuratively speaking, from the entire ensemble of data, one or several dominant “soloists” are artificially singled out, whose sound lacks those overtones that give the performance special value.

When synthesizing a synergetic system for data integration, it is advisable to abandon the concept of a dominant and, instead of “degrees of freedom reducers,” include mechanisms that allow all channels of data acquisition to participate in the formation of a solution with weights corresponding to the degree of their information content in the current situation (“degrees of freedom discriminators”). As a result, all available information will be used properly, and the “sound” of the data ensemble will be coherent and voluminous.

Formulation of the problem

Given: the number of data transmission channels (the number of degrees of freedom in a synergetic integration system) $m \geq 3$. The source data array is represented as a column matrix

$$A^T = \left\| \alpha_1 \alpha_2 \dots \alpha_m \right\|, \quad (1)$$

where $\alpha_j, j \in [1, m]$ are obtained through the j -th channels data on a certain numerical value α (components of the integration system).

The task is set: to obtain the most reliable estimate α^* of the value α .

Solution method

If the number of channels is large enough and it is known that the degree of their information content is approximately the same, then the problem is solved by simple averaging over the channels:

$$\alpha^* = \frac{1}{m} \sum_{j=1}^m \alpha_j.$$

The problem of increasing the reliability of the assessment arises when the number of data transmission channels is small, and the relative degree of confidence in them is different and is not known in advance.

In this case, to solve the problem, we will use the mechanism of “degrees of freedom discriminators” and organize an iterative synergetic process of adaptive interaction between the components of the data integration system.

Since at the beginning of the process it is not known which of the channels to trust more, we first assume that the degree of trust in all channels is the same and when averaging their data is accepted with the same weighting coefficient $k_j^I = 1, j \in [1, m]$.

As a result of averaging at the first iteration, the average estimate is obtained

$$\alpha^I = \frac{1}{m} \sum_{j=1}^m k_j^I \alpha_j = \frac{1}{m} \sum_{j=1}^m 1 \cdot \alpha_j = \frac{1}{m} \sum_{j=1}^m \alpha_j.$$

Let's call it the estimate of the first iteration. The averaging operation in matrix form is the multiplication of the data column matrix on the left by a unit m -row matrix (summing vector)

$$E = \begin{bmatrix} 1 & 1 & \dots & 1 \end{bmatrix}$$

and dividing the product by the number of channels:

$$\alpha^I = \frac{1}{m} EA.$$

Now we have information about the average estimate α^I , with which we can compare estimates for individual channels α from matrix (1). Naturally, the difference between the average rating (majority opinion) and the rating received on a given channel can serve as a basis for changing the weighting coefficient with which the rating on a given channel is perceived. For those channels whose assessment at the first iteration is closer to the average, it is advisable to increase the coefficient k_j and, conversely, for channels whose assessments are far from the average, it should be lowered. Our procedure omits those

relatively rare cases in which the “truth” turns out to be on the side of the minority.

Let us introduce a measure (“degrees of freedom discriminators”)

$$\delta_j^{II} = |\alpha^I - \alpha_j|, j \in [1, m],$$

which serves as a quantitative expression of the degree of trust in the j -th channel at the second iteration. It is advisable to select coefficients k_j^{II} that would represent functions inversely proportional to δ_j^{II}

$$k_j^{II} = a / \delta_j^{II}, a = \text{const}, \quad (2)$$

given that

$$\sum_{j=1}^m k_j^{II} = m. \quad (3)$$

Solving the system of equations (2) and (3), we eliminate the unknown proportionality coefficient a and obtain

$$k_j^{II} = \left(\frac{m}{\delta_j^{II}} \right) / \sum_{t=1}^m \left(\frac{1}{\delta_t^{II}} \right).$$

After this, averaging is performed at the second iteration, taking into account the trust in the channels based on the results of the first iteration

$$\alpha^{II} = \frac{1}{m} \sum_{j=1}^m k_j^{II} \alpha_j. \quad (4)$$

By introducing the row matrix

$$K^{II} = \left\| k_1^{II} \quad k_2^{II} \quad \dots \quad k_j^{II} \quad \dots \quad k_m^{II} \right\|,$$

we present expression (4) in matrix form

$$\alpha^{II} = \frac{1}{m} K^{II} A.$$

The third iteration process begins with establishing the measure

$$\delta^{III} = \left| \alpha^{II} - \alpha_j \right|, j \in [1, m],$$

etc.

Iterative procedure

$$\alpha^{(g)} = \frac{1}{m} K^{(g)} A, g \in [1, h], K^l = E$$

continues until a stop condition is met

$$\left| \alpha^{(h)} - \alpha^{(h-1)} \right| \leq \varphi,$$

where φ is a given small value. The result of the described iterative procedure is to obtain a refined estimate $\alpha^* = \alpha^{(h)}$, determined taking into account the heterogeneity of channels. In practical cases, the iterative process converges in 3-4 iterations. Note that in this case, with a decrease in the value φ the estimate based on the principle of “degrees of freedom discriminators” asymptotically degenerates into an estimate based on the principle of “degrees of freedom reducers.”

Synergetic aspects of mathematical statistics

The synergetic principle of data integration has much in common with the ideas of mathematical statistics [9]. Indeed, if the synergetic concept of data integration (merging) is used for the most reliable assessment of the characteristics of processes (objects) from the available set of data, then mathematical statistics studies methods for the most reliable assessment of the moments of distribution of random variables from the available set of sample elements. The commonality of the problems of both theories makes the task of

studying the synergetic aspects of mathematical statistics relevant both for synergetics and for the development of statistical methods.

Let us consider the problem of information processing with a limited number of data transmission channels as the calculation of a refined estimate θ^* of the parameter θ of the distribution $f(x|\theta)$ of a random variable X based on statistical material of a limited volume $x=x^{(n)}=(x_1, x_2, \dots, x_n)$ as an analogue of the degrees of freedom of a synergetic data integration system.

To solve the problem, we apply the Bayesian approach [9]. A priori information is used that the unbiased estimate of the parameter θ , considered as a random variable, is distributed according to the same law as X . Minimizing the risk function with a quadratic loss function gives an expression for the optimal estimate as the posterior expectation of the parameter θ , calculated from a given vector observations:

$$\theta^* = \int_{-\infty}^{+\infty} \theta f(\theta|x) d\theta \Big|_{x=x^{(n)}}. \quad (5)$$

Let's use the definition of posterior density according to Bayes' theorem [9]:

$$f(\theta|x) = \frac{f(x|\theta) f_a(\theta)}{f(x)},$$

where the marginal distribution $f(x)$ is expressed by the formula

$$f(x) = \int_{-\infty}^{+\infty} f(x|\theta) f_a(\theta) d\theta.$$

Then expression (5) is transformed to the form

$$\theta^* = \frac{\int_{-\infty}^{+\infty} \theta f(\theta|x) f_a(\theta|\theta') d\theta}{\int_{-\infty}^{+\infty} f(\theta|x) f_a(\theta|\theta') d\theta} \Big|_{\bar{x}=\bar{x}^{(n)}}. \quad (6)$$

Since the required estimate $\theta^* = \theta^*(x_1, x_2, \dots, x_n)$ must be calculated from a given vector of observations, we must move in expression (6) from integrals to summation over the elements of a given sample and replace the unknown constants with their estimates:

$$\theta^* = \frac{\sum_{i=1}^n x_i f(x_i | \theta^*) f_a(x_i | \theta^*)}{\sum_{i=1}^n f(x_i | \theta^*) f_a(x_i | \theta^*)}. \quad (7)$$

Formula (7) expresses the dependence

$$\theta^* = \varphi(x_1, x_2, \dots, x_n; \theta^*).$$

As is known [10], an equation in this form can be solved using the iterative method. The iterative procedure is organized in accordance with the recurrent formula

$$\theta^*[l] = \varphi(x_1, x_2, \dots, x_n; \theta^*[l-1]), l \in [1, L],$$

and the iterative process ends when the condition is met

$$\theta^*[L] - \theta^*[L-1] \leq \lambda_\theta$$

where L is the number of the current iteration; λ_θ – specified accuracy of calculation of the estimate θ^* . If it is necessary to analyze issues of convergence, then we can apply the well-known theorem [10], according to which for the convergence of the iterative process it is sufficient so that on the considered interval of refinement of the estimate θ^* the inequality holds

$$|d\varphi(x_1, x_2, \dots, x_n; \theta^*)/d\theta^*| < 1$$

The general expression for the refined estimate (7) fully corresponds to the following idea of Gauss [11]. The most likely value of the estimated parameter is one that minimizes the sum of squared differences between the actually

observed and calculated values, multiplied by a weighting coefficient k_i reflecting the relative confidence in the observations:

$$\theta^* = \arg \min_{\theta^*} \sum_{i=1}^n k_i (x_i - \theta^*)^2. \quad (8)$$

In [12,13] it is shown that expression (7) is indeed obtained from (8) if the posterior probability distribution density (“degrees of freedom discriminators”) is introduced as a measure of relative confidence in observations.

Conclusion

Thus, the proposed technique provides for an individual approach to each realization of a random variable (weighting in accordance with the posterior probability of its occurrence), which allows [14] to eliminate information loss when calculating the required estimates from a small sample.

It is important to note that the development of the most reliable estimate is carried out through the organization of an iterative process in which the sample elements at each iteration adaptively interact with each other. Likewise, synergetics involves a process characterized by self-organization in accordance with a set goal. Adaptation processes develop through the collective interaction of components. Cooperation of components includes the reserve capabilities of the system and significantly increases the degree of emergence (system effect).

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