Application of non-positional representation of information in the form of probabilistic mappings in control systems of unmanned vehicles

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Abstract. The paper considers the use of non-positional representation of information in the form of probabilistic displays in control systems of unmanned vehicles in order to solve the problem of ensuring the reliability and high bandwidth of information exchange channels (IEC) between unmanned vehicles (UMV) located in different environments and dispatch centers (DC). As shown in the paper, the use of probabilistic representation of information makes it possible to obtain combinations of the main characteristics of UMV control systems that are unattainable in a different form of information representation: speed, accuracy, reliability, and hardware volume.

1. Introduction

The high dynamism of the information exchange channels of unmanned vehicles (UMV) and their combinations, the change of their states (operational, failure, rollback, recovery), a wide range of parametric series, and multiple variations in the settings of hardware and software components make modeling, optimization, and decision-making tasks extremely complex both from system point of view and in the aspect of specific mathematical analytics [1-2]. In this work, we propose to build a set of mathematical models of vector programming with probabilistic criteria. The selected criteria firstly are due to the high criticality of the transmitted information in the information exchange channels (IEC) between the UMV and dispatch centers (DC), since the UMV itself can be the object of attack by a potential attacker with different goals, and become a potentially dangerous object in the event of loss of communication between the UMV and the DC. Thus, the development of a model of self-organizing adaptive IEC architecture between UMV and DC and special software for decision support for their control becomes potentially feasible within the framework of optimization solutions based on stochastic vector programming with probabilistic criteria [3 - 4].

As we know, intrusion detection systems (IDS) are one of the required components of the UMV security infrastructure [5]. A special role in the information security (IS) in the IEC between UMV and DC is occupied by the creation of preventive IS systems. The main methods of intrusion detection are usually divided into methods for detecting access rights violations and methods for detecting traffic anomalies [6-7]. The first direction involves searching for violators based on known attack signatures [5]. The second direction of intrusion detection methods is focused on controlling deviations of the specified values of traffic parameters from the established restrictions [7].
In this regard, research in the field of one of the development directions in parallel computing technologies, related to the development of methods, algorithms and devices of computer technology for digital signal processing using non-positional number systems, the most promising of which is the probabilistic form of information representation, is of particular relevance [8 - 11].

Along with the development of digital computing and simulation methods, the method of statistical testing has become widely used, the main idea of which is the relationship between the probabilistic characteristics of random processes and values that are solutions to mathematical analysis problems [8 - 11].

2. Problem statement
At the moment, in connection with the achievements of scientific and technological progress, the following trends in the development of control systems for UMV:

1. Switching to digital signal processing.
2. Import substitution of the element base in domestic microelectronics.
3. Implementation of the "network-centric" control principle.

These modern requirements, in turn, require developers and designers of control systems for UMV:
- decreasing the reaction time of the On-Board digital computer by orders of magnitude for real-time control;
- the need to increase the bandwidth and security of communication channels, which is expressed in:
  a) the need to implement new data transfer protocols;
  b) improving the noise immunity of existing and future data transmission channels;
  c) cryptographic stability of information transmitted over closed communication channels.
- need to increase the battery life of mobile devices (such as UMV);
- improving the reliability and resistance to external influences of circuit solutions, blocks and elements.

3. Methods and results
Methods for presenting information in the form of probabilistic mapping (PM) of information can be divided into: linear probabilistic transformation (PTr); nonlinear PT. Depending on the rule according to which the transformation takes place, all methods of presenting information in the form of PM information are divided into: one-line unipolar; one-line bipolar; two-line bipolar probabilistic representation and transformation of information (PRTI).

In the case of a single-line unipolar representation of information in the form of PM, the value of the converted value is either always positive or always negative [8, 11].

PM has the properties of synchronicity and independence of each member of mapping from any other. Using these properties and using the representation of information in the form of PM allows us to simplify the functional nodes for performing arithmetic and logical operations, in particular, addition, subtraction, multiplication, exponentiation, division, comparison, etc. and, thus, significantly reduce their hardware volume.

A single-line unipolar representation can be used in probabilistic information systems (PIS) only if the information without a sign being processed is either always positive or always negative. If the information processed in the PIS contains a sign, it is necessary to switch from a single-line unipolar representation to a single-line bipolar or two-line bipolar representation of information in the form of a PM.

To move to a two-line bipolar representation, it is sufficient to multiply logically the values of the PM \( y_g \) obtained in accordance with the probabilistic transformation rule for distribution on the "positive" or "negative" bus by the variable \( Z \), which takes only two values: +1 or -1.

In this case, the expression for a two-line bipolar representation will take the form:

\[ Y_i(t)z_i = \{ y_{i1}z_i; y_{i2}z_i; \ldots; y_{ig}z_i; \ldots; y_{ik}z_i \}. \] (1)
The third considered form of information representation in the form of PM is one-line bipolar. For it, the values of the signal parameter \( X(t) \), that change in the interval \([-1; +1]\), i.e. from \( x_{\min} = -1 \) to \( x_{\max} = +1 \), are implemented in hardware on a single bus, as for a single-line PTr.

To convert the discrete information into a single line bipolar representation in the form of PM for positive and negative numbers the expression is transformed to the form:

\[
y'_y = \begin{cases} 
0, & \text{npu } x_{(up)} + z_i \leq r_y \\
1, & \text{npu } x_{(up)} + z_i \geq r_y
\end{cases}
\]

\[
y'_y = \begin{cases} 
0, & \text{npu } x_{(down)} + z_i \leq r_y \\
1, & \text{npu } x_{(down)} + z_i \geq r_y
\end{cases}
\]

where \( x_{(up)} \) – the direct code of the number \( x_i \), \( x_{(down)} \) – additional.

If we consider that the mathematical expectation (ME) PM is defined through a distribution series for a discrete random variable as follows:

\[
M[Y(t)] = \sum_{j=1} y_j P_j = P(y_i, j = 1) = P[R(t) < x_i = r] = F_{x_i}(R),
\]

that of (3), PM of the converted signal value will correspond to the converted parameter (without taking into account the methodological error) only in the case of an infinite number of independent statistical tests \( K \). Since the \( K \) value is selected based on either the specified speed or the frequency range of the converted signal when working in real time, a PTr error occurs.

ME PE (2) and its estimate, which is asymptotically effective, in accordance with (3), are determined by the equations:

\[
M[Y_i(t)] = F_{x_i}(R), \quad \left[M[Y_i(t)]\right]' = \frac{1}{K} \sum_{j=1}^K y_j = x_i^*.
\]

To fulfill the unbiased criterion, we define ME of estimation \( x_i^* \):

\[
M\left[x_i^*\right] = M\left[\frac{1}{K} \sum_{j=1}^K y_j\right] = \frac{1}{K} \sum_{j=1}^K M(y_j) = F_{x_i}(R) = x_i.
\]

The variance of the estimate is determined to calculate the error of the PTr:

\[
D[x_i^*] = \frac{1}{K^2} \sum_{j=1}^K \sum_{j=1}^K [y_{ij} - M(y_{ij})]^2 P_{ij} = \frac{[F_{x_i}(R) - F_{x_i^2}(R)]}{K}.
\]

The expression for standard deviation according to formula (6) will take the form:

\[
\sigma[x_i^*] = \sqrt{\frac{F_{x_i}(R) - F_{x_i^2}(R)}{K}}.
\]

Based on formula (7), the number of tests \( K \) required to achieve the allowable error is as follows:

\[
[K] = \left(\frac{\sqrt{2} \Phi^{-1}(P)}{\Delta} \sqrt{x_i(1-x_i)}\right)^2.
\]

Analysis of expression (8) shows that the number of tests \( K \) depends largely on the specified conversion error, as well as on the value \( x_i \), and, all other things being equal, is the maximum at \( x_i = 0,5 \).
This implies that sequential transformation of information in a probabilistic form, when PIS operates in real time, leads to a noticeable narrowing of their frequency range in the case of choosing a sufficiently large $K$ and, consequently, limits the applications of PIS data.

As is known, the main advantages of probabilistic computing devices that process information presented in non-positional form in the form of probabilistic mapping are: simplicity of circuit solutions; high noise immunity; low hardware volume compared to similar digital devices [11].

As an example, to analyze the advantages obtained from using a probabilistic form of information representation, we propose to consider a typical example of a probabilistic computer. As shown in [11], the total hardware volume of the probabilistic arithmetic device as a whole is less than 150 times compared to its digital counterparts.

For processing analog and discrete information in the PIS in all cases, a preliminary conversion to a non-positional probabilistic display is required. The developed probability converters: "frequency-probability", "phase-probability", "voltage-probability", have an undeniable advantage: the input signal is integrated at the conversion interval, so that the probability converters are very resistant to failures, for example, as a result of exposure to ionizing radiation (IR).

While PRTI in PIS, the developed analog-probability converters, regardless of the location of the interference on the time axis, integrate it and add it to the average value of the useful signal amplitude (figure 1).

![Figure 1. Effect of pulse interference on the analog-to-probability converter operation.](image)

The effect of interference is less, the more statistical tests have been carried out for the probabilistic transformation. If the interference is bipolar and symmetrical, its effect will not affect the value of the useful signal at all.

4. Conclusion
As a result, the primary converters (PrC) proposed for use in PIS have the ability to integrate random interference and can be structurally executed in the form of integrated circuits (IC). This, in turn, makes it possible to place the PrC in close proximity to the sensors, which is currently very popular when implementing IEC between UMV and DC, located in different environments with high reliability and bandwidth. As the analysis shows, the main advantage of using non-positional probabilistic representation of information is a multiple reduction in the hardware volume of computing devices while maintaining the remaining performance indicators.

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