Computational methods based on fuzzy control algorithms for operational control and identification of control systems in smart production

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Abstract. The problem of the functioning of complex technical systems is studied in this article. The authors consider the problem of structural and functional redundancy (the complexity of formalizing computational methods for dynamic and nonlinear systems used in modern industrial production). On the example of considering the structure of the climate control subsystem for a closed loop of an industrial unit, a fuzzy configurator model for controlling the operation of a refrigerator is formalized. It is reduced to: linearization of the reading of instantaneous temperatures from various loops of the considered control system, followed by fuzzification and antecedent analysis. Eventually this allows to implement a complex method of fuzzy control and calculation of structural redundancy in any configuration with a different probability ratio. The authors also raise the question of the comparability of the obtained data and application of the developed method as a tool for predictive analytics in technological processes of production management.

1. Introduction

The functioning of large and complex technical systems requires adherence to the demarcation line between the functional (declared) and structural apparatus for the studied or developed system, the ratio of their connections and the degree of controllability for various configurations.

In the theory of systems, structural redundancy, which is defined as R (formula 1), acts as a scalar parameter reflecting the excess of the total number of connections over the minimum number of connections that are necessary for a technical system:
\[ R = \frac{1}{2} \left[ \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} \right] - 1 \]  

(1)

This feature is used to indirectly assess the efficiency and reliability of computing systems [1,2]. For structures with maximum redundancy that have a "complete graph" structure \( R \geq 0 \); for systems with minimal redundancy \( R = 0 \); for disconnected systems \( R \leq 0 \); When there is structural redundancy, the system has a greater risk of failure and it is more difficult to predict its behaviour. And in combination with the inevitable occurrence of functional redundancy, this leads to an irrational use of resources in the process of work, lower efficiency of the control action, since part of the system's functionality is not simply used.

However, in practice, the above measure for determination of redundancy, is only at the design (synthesis) stage of the system by the developer or operator. The same cannot be said about already existing complex systems, where it is impossible to simply take and eliminate this or that unit, chain, during the operation of an automated control system or mechatronic complex (actuator, manipulator and other final device).

**Figure 1.** Hardware of the analysed system.

The closed loop of the workshop is a sealed isolated object, the model of which is defined as an orthogonal system with a volume of 4000 cubic meters.
2. Problem statement
In this study, the goal is to define and formalize the method of operational control and identification of control systems in intelligent industrial systems by solving a complex of problems of removing information entropy from structural redundancy for the object of analysis (control system for an industrial refrigerator).

As an implementation of the operational control subsystem, we mean a method for creation of an algorithm for tracking the behaviour of a functional group of a system's features with reduction to the basis of a formal model [3].

As an acquisition for the operational control subsystem of the function of identification of control systems, we mean a method or an algorithm for detection of structural redundancy in context of factor analysis.

3. Research questions
To solve the problem, a formal method has been applied. This method combines complex linearisation for a given nonlinear control system with a linear function of provision of an optimal algorithm for the system's response to the registered nature of events taken for attention.

The life support and temperature control system for the workshop of an industrial building will act as a nonlinear system taking into account the availability of an automated control system for the refrigerator.

4. Materials and methods
The purpose of this study is to create a mathematical model for ensuring the process of implementation of constant temporality. In other words process of implementation of the relationship between moments of time and temporal characteristics in the dynamics of changes in those phenomena and processes (it is due to the specifics of the existence of a dynamic system) [4].

The operational control subsystem has been implemented using a fuzzy modelling apparatus, in particular, on the basis of a fuzzy controller shown in figure 2.

![Figure 2. Flow chart for the use of a fuzzy controller in the PID controller of the climate control system of a closed loop.](image)

The configurator for a fuzzy controller is based on the study of three important values for the designated loop: loop temperature per unit time (temperature of refrigerator walls T1, loopwalls T2, air temperature in loop T3).
5. Results
Linearisation method shall be applied by determination of the weight coefficients of instantaneous temperatures in the form of a homogeneous system of a third-order linear equation (formula 2).

\[
\begin{align*}
\dot{x} &= a_{11} \cdot x + a_{12} \cdot y + a_{13} \cdot z \\
\dot{y} &= a_{21} \cdot x + a_{22} \cdot y + a_{23} \cdot z \\
\dot{z} &= a_{31} \cdot x + a_{32} \cdot y + a_{33} \cdot z
\end{align*}
\]

(2)

where \( x(t), y(t), z(t) \) are the required functions on the interval \((a, b)\), \( a_{ij} \) (\( i, j \) are real numbers from the range of temperature values accepted by the system of sensors (accuracy up to hundredths of a degree Celsius), in the form of values of linguistic measures of the temperature background (five levels: from Equal to Strongest in terms of from 1 to 9) \[2\].

![Figure 3. Model of fuzzy granulation for the temperature range for a 10-bit analogue-to-digital converter of the temperature sensor.](image)

6. Findings
Solving the problem by drawing up a characteristic equation of the type (Formula 3), after obvious iterations, we obtain a general solution (Formula 4), which for convenience is represented in the form of a system of equations (formula 5).

\[
\begin{bmatrix}
a_{11} - A & a_{12} & a_{13} \\
a_{21} & a_{22} - A & a_{23} \\
a_{31} & a_{32} & a_{33} - A
\end{bmatrix} = 0, \quad E = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}
\]

(3)

\[
\dot{X} = C_1 \begin{pmatrix} -1 \\ 1 \\ 1 \end{pmatrix} e^t + C_1 \begin{pmatrix} -1 \\ 1 \\ 2 \end{pmatrix} e^{-t} + C_1 \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} e^{2t}
\]

(4)

\[
\begin{align*}
x &= -C_1 e^t - C_2 e^{-t} \\
y &= C_1 e^t + C_2 e^{-t} + C_3 e^{2t} \\
z &= C_1 e^t + 2C_2 e^{-t} + C_3 e^{2t}
\end{align*}
\]

(5)

The target values for the equations \( x, y, z \) shall be expanded. For convenience, the system of constraints in the canonical form of the problem is denoted as a fuzzy matrix with the coefficients \( C_x \), which defines fuzzy logical rules in tabular form (by a probabilistic criterion).

These rules usually take two variables as input, clearly mapping them into a two-dimensional matrix, although a matrix of any number of dimensions is theoretically possible \[5, 6\].
To speed up the search for a solution, avoiding enumeration of "unpromising" options, two types of estimates can be used in program calculus: lower bounds for the values of the objective function on a subset of feasible solutions and upper bounds for the optimal value of the objective function [7]:

Moreover, the implementation of this solution is demonstrated at the level of reading of the analogue signal by the temperature sensor located on the analogue pin A0, on any of the specified groups of parameters T1..T3 (below there is a fragment of the program code in C ++ for the subsystem of operational accounting of input values)

```c++
A_0=analogRead(A0);
for(int i=0;i<=8;i++){
    if (tuning_RW[i]!="'1'") {continue;};
    if (d_val[i] != d_val_old[i])
    {
        if (d_val[i]) {outputM[i]='1';}else{outputM[i]='0';};
        send_cito++;
        d_val_old[i]=d_val[i];
        if (tuningSIGN[i]!="!'") {digitalWrite(d_name[i], d_val[i]);}else {digitalWrite(d_name[i], !d_val[i]);};
    };
}; // end for
for(int i=0;i<=8;i++){
    if (tuning_RW[i]=='1') {continue;};
    d_val[i]=digitalRead (d_name[i]);
    if (d_val[i] != d_val_old[i])
    {
        if (tuningNOW[i] != '!') {send_cito++;}; // a fast changing vars don't send by changing
        d_val_old[i]=d_val[i];
    };
}; // end for
for(int i=0;i<=4;i++){
    if (s_val[i] != s_val_old[i])
    {
        if (tuningNOW[i+9] != '!'') {send_cito++;}; // a fast changing vars don't send by changing
        s_val_old[i]=s_val[i];
    };
}```
Having implemented the process of bringing the entered values into the form of a fuzzy matrix (having determined the fuzzyfication stage) for the control group of temperature values, the developed apparatus of fuzzy regulation rules will be applied for the operational control system.

The ultimate goal of introduction of fuzzy control is to ensure the constancy of measurements for all four types of sensors (T1 ... T3), and processing in real time based on attendant analysis to identify the truth of the entire group of events (the rules have been formalized empirically):

The optimum temperatures for a working cooling system are levels corresponding to 1-3 for the fuzzy granulation model for T1 .. T3.

RULE <1>: antecedent - "temperature T1 within the" 1 of 9 "position OR" temperature T1 within the "2 of 9" position OR "temperature T1 within the" 3 of 9 "position; the degree of truth of the antecedent С min {0.75; 1.00} = 0.99.

RULE <2>: antecedent - "temperature T2 within the" 1 of 9 "position OR" temperature T2 within the "2 of 9" position OR "temperature T2 within the" 3 of 9 "position; the degree of truth of the antecedent C min {0.75; 1.00} = 0.99.

RULE <3>: antecedent - "temperature T3 within the" 1 of 9 "position OR" temperature T3 within the "2 of 9" position OR "temperature T3 within the" 3 of 9 "position; the degree of truth of the antecedent C min {0.75; 1.00} = 0.99.

For all other options, it is necessary to develop an apparatus of fuzzy rules with decreasing antecedent coefficients:

RULE <4>: antecedent - "temperature T1 within the" 4 out of 9 "position OR" temperature T1 within the "5 out of 9" position OR "temperature T1 within the" 6 out of 9 "position; the degree of truth of the antecedent C min {0.49; 1.00} = 0.50.

... For rules 5 and 6 it is the same as for rule <4>.

And so on up to 0.01 for the values of all T1-T3 groups with the values of the sensors taken in the range of the 9th level of the fuzzy model.

7. Discussion

Determining the probabilistic nature of the application of certain probabilistic rules (the number of which is defined as n), the particular problem of structural redundancy for the range of values defined as the objective function of behaviour by the temperature level as a whole can be solved for a discrete time interval according to formula 1 or in generalized form according to the formula 6:

$$e^2 = \sum_{i=1}^{n} g_i^2 - \frac{4m^2}{n}.$$  \hspace{1cm} (6)

where n – amount of nodes gi – degree of i-th node, m – amount of edges of the graph.

As it has already been mentioned at the beginning of the article, this indicator features the underutilization of the structure's capabilities in achieving maximum connectivity and allows to identify the system from the point of holistic representation of its structure, determining the excessive or insufficient number of connections between its nodes and chains.

In programmatic form, this search for this solution can be expressed through a call to the StructuralRedundancy function, which determines the structural redundancy of fuzzied data.

```java
public void structuralRedundancy(int n, int countE, int[,] A, out double R, out double e2)
{
    R = 0;
    for (int i = 0; i < n; i++)
    for (int j = 0; j < n; j++)
    R += A[i, j];
    R = R * 0.5 / (double)(n - 1) - 1;
    e2 = 0;
}  
```
for (int i = 0; i < n; i++)
{
    int degreeV = 0;
    for (int j = 0; j < n; j++)
        degreeV += A[i, j];
    e2 += degreeV * degreeV;
}
e2 -= 4 * countE * countE / (double)n;

In the analysis, strongly correlated variables are combined into one functionally normal group, as a result of which the variance of the probabilities of certain events is redistributed between the components and a matrix structure that is convenient for processing and subsequent analysis within the framework of fuzzification is obtained. During aggregation, there is a certain correlation of components: within each factor processed by developing a fuzzy rule, there will be higher value comparing to their correlation with the components of other factors.

This procedure also allows to isolate hidden variables, which is especially important when analyzing perceptions and values. However, it is necessary to work out this categorical unit as a criterion for identification of new properties for the research object. This is important, because, for example, while analysing estimates obtained on several scales, the researcher notices that they are similar to each other and have a high correlation coefficient, it can be assumed that there is a hidden variable that can explain the observed similarity of expert estimates of systems and humans [8,9].

8. Conclusion

For the first time, the possibility of implementation of an operational control and identification system for a temperature control system for an industrial building has been investigated and demonstrated through the implementation of a software and hardware product that implements:

- decomposition of functionally similar parameters of the technological process (for example, the separation of groups of temperature values);
- linearisation of feature descriptions in the form of a linear system of equations;
- fuzzification;
- implementation and formalization of the rules for the formation of fuzzy rules for the implementation of operational control of the process by break points (groups T1-T3).

Ultimately, that made it possible to implement a check for structural redundancy of the technological process control system through the analysis of antecedent data as a new method of predictive analytics: allowing to develop control actions and modify temperature control systems, based on the calculated values of structural and topological redundancy for a finite sample of values in the interested time interval [10].

The developed complex method makes it possible to simplify the existing paradigm of organization of operational control for a system with functional homogeneity and structural uncertainty (it is not clear whether the existing connections and elements are enough) and identification of connections through the calculation of parameters from group theory and systems theory [11,12].

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