Development Principles of Knowledge Database of Intelligent System for Estimation of Dynamical Interaction of Orbital Systems with Space Debris

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***Abstract*—In the paper, a principles underlying the construction of an intelligent information system estimated results of the dynamic interaction of orbital systems with space debris is presented. It describes the knowledge database model based on these principles which is the synthesis of theoretical and practical information in the field of estimating the high-speed interaction of objects.**

Keywords—intelligent information system; space garbage; knowledge database; fuzzy systems; damage risk assessment

Spacecrafts (S) are exposed to blows of particles of space garbage (SG). Therefore the solution of a problem of damage risk assessment and development of actions for its decrease and creation of protection systems of S against influence of superfast particles of SG is very urgent [12].

The main information about impact of SG on spacecrafts is given by ground bench tests with superfast blows application. Computer simulation is used as supplement.

The main method of development testing is experimental superfast blow and its purpose is examination how S or its components will be able to sustain collision in space with SG.

However there are certain borders of opportunities in this direction. There are difficulties with acceleration of large shells to typical speeds of collisions in low-orbital area of the near-Earth space environment. These restrictions reduce damage prediction accuracy from collision with average and small SG.

Computer modeling serves as the connecting link between results of inspection of the surfaces which were really affected by SG in space and researchers assumptions and checks and calibrates the last. Models also allow extrapolating the data obtained in laboratory in the limited range to a wide range of conditions which cannot be reproduced in laboratory [11].

According to OST 134-1031-2003 "The general requirements for protection of space means from mechanical influence of particles of a natural and technogenic origin" (item 5.6), an resistance indicator of S to mechanical influence of high-speed particles of a natural and technogenic origin is its undamage probability (UDP). It is probability that it doesn't happen any "dangerous" collision of a high-speed particle with a vulnerable surface of S (n = 0) during time τ. PUD is calculated on a formula:

$$\text{UDP} \equiv P_{n=0} = e^{-\overline{N}}$$

Given that it is convenient to use GNP for operational estimates of one element of a vulnerable surface, value is defined as:

$$\overline{N} = N_{ex} S_{el} \tau$$

where N_{ex} is value of medium-integrated flux of high-speed particles with a critical mass of m_{ex} - extreme minimum value of particle mass of SG at which the considered element of a surface of S, $m^{-2} \cdot year^{-1}$ is damaged (according to the accepted criterion);

S_{el} is the considered area of a vulnerable element of surface of S, m^2;

τ is residence time of S in SG environment - time of exploitation of S, year.

The value of N_{kp} depends on the critical mass of m_{ex} or, equivalently, the critical diameter of d_{ex}-particles of SG which cause damage to protection of S. It is expected that density of particles material of SG is known. The value of d_{ex} is defined with help of ballistic limit equations (BLE).

BLE represent ratios for determination of the minimum diameter (the minimum weight) of the flying particle at which wall damage occurs. The specified type of the equations is called the efficiency equations. When it determines UDP, damage function is built by means of BLE of efficiency. It shows dependence of d_{kp} on the speed of blow of V.

The known BLE for a single wall are considered in [1, 3, 7]. To improve veracity BLE were modified with use of experimental surveys results and measured data which carried

The research was done within the government task of the Ministry of Education and Science. The number for the publication is 2.1777.2017/4.6

ISSN (Print): 2204-0595
ISSN (Online): 2203-1731

out on the returned elements of S, space stations "Mir" and the ISS, the Hubble space telescope, the LDEF (LongDuratio-nExposureFacility) satellite, etc. [2, 5, 7-9] .

BLE are equated for multilayered protection (several walls at distance from each other with additional layers on surfaces and between them) allow to calculate thickness of a forward wall from blow, and the minimum thickness of a back wall without damage. It is accepted that a wall from blow of SG is called a bumper.

According to the analysis of calculations results and experimental data is shown that reliability of the analysis of protection S against SG on UDP will be reached if BLE, which use at this case, are satisfied the following requirements [7]:

- BLE have to include all optimized variables;
- range of optimized variables change in BLE has to be rather wide.

Thus, it is possible to allocate the following main problems inherent in a problem of forecasting of results of interaction of S and SG:

- possibility of collecting a large number of data about interaction of S and SG and practical lack of their statistical stability that calls into question trust degree to the models constructed by methods of probability theory and classical mathematical statistics;
- insufficient reliability of representation of forecasting results in the form of the determined defeat functions because many influencing factors have the fuzzy nature and difficult formalizations for traditional modeling methods application.

Within the conducted researches there is a problem of creation of the knowledge base of an intellectual information system which considers results of forecasting of dynamic interaction of orbital systems and space debris and is effectively applied in the conditions of uncertainty. KB has to conform to requirements of adequacy, completeness and consistency, and also accuracy and an interpretation of the received results. Mechanisms of its construction have to provide a possibility of introduction of new data on subject domain and use these data for maintenance of KB in an urgent state, including its timely correction (training).

Existence of statistical data gives an opportunity to consider as effective tools of technology of the operational accounting of data (OLAP) and their intellectual analysis (Data Mining): genetic algorithms and neural networks.

Two aspects of information resource lie in the modern theory of the artificial intelligence (AI) at the heart of methods of the knowledge representation (KR) and representation of abilities:

- mathematical formalization or logical completeness of the considered information object;
  - cognitive approach or understanding (perception/interpretation) of process of awareness of knowledge by the person.

The greatest distribution at practical developments in the field of artificial intelligence was gained by productional, frame models and semantic networks, and also a specific place was held by hybrid model, thanks to object-oriented approach of representation of knowledge [15].

For creation of knowledge base, the hybrid model of representation of knowledge in the form of a neuro and indistinct network formalism is chosen. Constructed, on its basis the neuro and indistinct network, is isomorphic to matrixes of rules (knowledge) and reflects the interrelations revealed in experimental data and has important human (intellectual) properties: representation of knowledge in a natural language, an interpretation of the received results and learning ability in real time.

This approach application gives the chance to eliminate a number of the defects characteristic of traditional methods. First, fuzzy sets are convenient means of formalization of the sizes having the qualitative nature, and their application for formation of the fuzzy forecast is most acceptable in the conditions of uncertainty of parameters of forecasting. Secondly, efficiency of forecasting model and forecast reliability are great importance and they demand the choice of the corresponding methods for its construction. In this regard, genetic algorithms which realize the mechanism of random search and are characterized by the corresponding advantages (overcoming problems of a local optimum and "dimension damnations"), represent the effective instrument of design of indistinct knowledge bases by their extraction from experimental data.

I. Principles of Creation of the Knowledge Base of Intellectual System

The main idea of the evaluation is concluded in the following rule: "If collision happened, the damage caused to SG depends on the sizes and the relative speed of S and SG, composition of their material, a corner under which the SG hit in S and degree of vulnerability of the place (component) of S on which the blow fell".

From these positions it is possible to consider defeat of S as the problem of identification having the following properties [4]:

- it is necessary to establish dependence between input and output variables for evaluating results;
- input variables are associated with parameters of condition of an identification object and conditions of possible interaction. The quantity of particles of SG and their characteristic taking into account features of S is initial information for determination of the expected damage;
- the output variable is associated with a condition of S after interaction with SG. Vulnerability (defeat) of S in a flux of SG can be defined as a combination of probabilities of elements undamage, taking into account importance (criticality) of everyone components
- output and input variables can have quantitative and quality standards.

ISSN (Print): 2204-0595
ISSN (Online): 2203-1731

- the structure of interrelation between output and input variables is described by the rules IF <inputs>, THEN <output> which use quality standards of variables and representing fuzzy knowledge base.

Principles of creation of the knowledge base of intellectual system for estimate of results of S and SG dynamic interaction include:

1. The principle of the linguistic description of the used variables on an input and an output.

According to this principle, inputs of an object and its output are considered as linguistic variables which are estimated by qualitative terms (a term - from English term - to call).

The undamage probability of S (UDP) depends on the following factors which influence on vulnerability of S is most essential and for which it exists real possibility of collecting experimental data.

The influencing factors and the UDP output parameter with ranges of values and used for the description term-sets are shown in table 1.

2. The principle of use of one-dimensional and multidimensional membership functions of linguistic terms for the description of input and output variables.

In compliance with this principle fuzzy variables with functions of accessory of one or several arguments can be used as terms during a fuzzy logical conclusion.

It is connected with initial division of space of input variables into classes.

Generally it is considered independent variables on an input which form set of not crossed classes. Each input variable has own input sets, it allows to use simple and evident representation of membership function (for example, triangular or trapezoid), and also to apply simple computing procedures when carrying out all stages of fuzzy conclusion. As applied to solvable problems of assessment of interaction between SC and SG, such variables are the linguistic variables connected with parameters of particles of SG, parameters of a wall of SC and a protective bumper.

TABLE I. CHARACTERISTICS OF FORMED TERM-SETS

Name (linguistic variable)	**Sym bol**	**Variable range (universal set) and its dimension**	**Term-sets of linguistic variable value**
High-speed collision parameters			
Interaction speed SG and S in encounter point, v_n, $km \cdot s^{-1}$	X1	0…20 $km \cdot s^{-1}$	Low (L), Under average (UA), Average (A), Above average (AA), High (H)
A corner between a particle speed vector and a normal to a surface, θ	X2	0…±180°	Small (S), Average (A), Normal (N), Big (B), Huge (H)
Parameters of a SG			
Particle diameter, d_p	X3	0.1…1000 cm	Small (S), Average (A), Big (B)
Particle speed, v_p	X4	3…8 $km \cdot s^{-1}$	Low (L), Average (A), High (H)
Density of the particle material, ρ_p	X5	2.5-5 g/cm3	Aluminum alloy (Aap), Titanium alloy (Tap), Stainless steel (Ssp)
Particle mass, m_p	X6	$10^{-5}…10^{3}$ t	Small (S), Average (A), Big (B)
S wall parameters			
Wall thickness, l_w	X7	0.13-0.4 cm	Small (S), Average (A), Big (B)
Density of the wall material, ρ_w	X8	2.5-7 g/cm3	Aluminum alloy (Aa), Titanium alloy (Ta), Stainless steel (Ss)
Hardness of the wall material by Brinell, HB	X9	60-150 MPa	Small (S), Average (A), Big (B)
Bumper parameters			
Bumper thickness, l_w	X10	0.33-0.55 cm	Small (S), Average (A), Big (B)
Hardness of the bumper material, ρb	X11	0.01-2.5 g/cm3	Small (S), Average (A), Big (B)
A gap between a bumper and a back wall of S	X12	0…6 cm	Small (S), Average (A), Big (B)
Value of material yielding stress of back wall, σ_w	X13	130-540 MPa (N/mm2)	Low (L), Average (A), High (H)
Speed of S, v_s	X14	3…8 $km \cdot s^{-1}$	Low (L), Average (A), High (H)
Undamage wall probability, UDPs	P	0.5…0.999	Low (L), Average (A), High (H)

However linguistic variables can have rather difficult physical nature demanding to use several connected sizes. For hierarchical systems of fuzzy conclusion, it spring up a certain degree of blurring that can lead to loss of the importance of result. One of solutions of this problem is use of terms of linguistic variables with functions of accessory of several arguments.

Methods of fuzzy clustering can be used when multidimensional membership function is being formed [14].

The way of a task of multidimensional functions of accessory of terms of linguistic variables includes the following stages:

- selection of linguistic variables and comparison of modeling subject characteristics to it;
- collecting statistical data on activity of a modeling subject;
- fuzzy clustering of statistical data for each linguistic variable;

  ISSN (Print): 2204-0595
ISSN (Online): 2203-1731

- linguistic variable terms formation by giving to the received clusters of names;
- formalization of functions of accessory of terms. [6].

As an example it is considered the linguistic variable "speed of interaction be-tween SG and S in a meeting point", including, "a corner between a vector of particle speed and a normal to a surface of S", "particle speed" and "speed of S".

Linguistic variables terms are formed by assignment names to the received clus-ters. For each term it is set in tabular form multidimensional membership function in the form of the matrix including arguments values matrix of X_i and a column of function values which is the appropriate for term line of a matrix of membership functions M_i.

3. The principle of formation of structure of dependence "input output" in the form of a matrix of rules

Matrixes of fuzzy conclusion rules are formed on the basis of empirical knowledge or experts knowledge in problem area, and they are presented in the form of fuzzy production of a standard look.

Each matrix of rules of a look IF <inputs>, THEN <output> characterizes the revealed interrelations in the allocated set of experimental data on each element of a design of S.

By consideration of a problem of interaction between S and SG it exists large number experimental and settlement data of the different nature and different in physical sense. In this regard it is quite difficult to find the expert who could create all necessary set of the fuzzy logical rules which are the basis for the fuzzy knowledge base as kernels of intellectual system.

In such situation there is a need of the solution of a problem of extraction of set of fuzzy logical rules which will display in the best way regularities of communications "inputs outputs" on a set of the available experimental data, without participation of the expert. The solution of this task is possible by carrying out the data mining based on genetic algorithms of optimization [4, 10].

Set of rules IF-THEN can be considered as a set of points in space <inputs outputs>. Use of the device of a fuzzy logical conclusion allows to restore a multidimensional surface which connects values of an exit at various combinations of values of input variables on these points.

4. Principle of hierarchy of the knowledge base

Interpretation and control of the received results it is connected with intellectual opportunities of the person on the limited volume of its random access memory.

In this regard it is expedient to carry out classification of input variables and to construct on its basis so-called tree of a conclusion which will represent system of hierarchically connected contours of mini-bases of smaller dimension.

Derivation tree for the entered input variables it is shown in fig. 1.

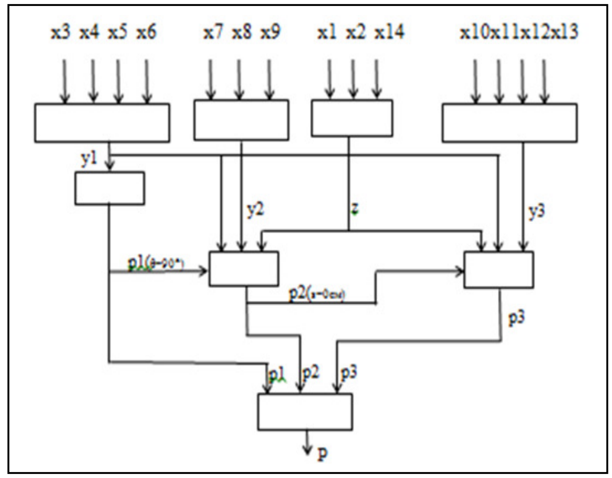

Fig. 1. Derivation tree.

Functional dependence P=P (x1, x2, x3,…, x14) which connected x1…x14 inputs and P output, are replaced with the sequence of substitutions:

$$P = P\left(p1,\ p2,\ p3\right),\ y1 = y1\left(x3,\ x4,\ x5,\ x6\right),$$
$$z = z\left(x1,\ x2,\ x14\right),\ y2 = y2\left(x7, x8,\ x9\right),$$

where y1, y2, y3, z, p1, p2 and p3-the intermediate outputs considered as linguistic variables.

Due to the principle of hierarchy it is possible to consider almost unlimited number of the input variables influencing assessment of an output variable. At creation of a derivation tree it is necessary to aspire to that the number of arguments (en-trance arrows) in each knot of a tree satisfied to the rule 7±2.

Expediency of stepwise representation of expert knowledge is caused not only by natural hierarchy of objects of identification, but also need of the accounting of new variables in process of object knowledge accumulation.

5. Principle of two-stage setting up of fuzzy knowledge bases.

According to this principle, creation of model of the knowledge base is carried out step by step (fig. 2) which by analogy with classical methods can be considered stages structural and parametrical identification. The configured settings are the weight of fuzzy rules IF-THEN and a membership functions form.

At the first stage creation of a matrix of rules is carried out according to available information. In the chosen subject area there is no possibility of involvement of the expert who would simulate this or that object (process) that is connected with its complexity and a certain novelty and as a result that is connected its insufficient development.

ISSN (Print): 2204-0595
ISSN (Online): 2203-1731

In this regard process of creation of fuzzy knowledge bases is organized on the basis of the available experimental data obtained as a result of a research. For extraction rules it is used of the known mechanism of data mining realized in genetic algorithms of optimization.

As a result of creation of set of rules matrixes is formed the initial knowledge base. For ensuring reliability of the received estimates the second stage is provided at which training of a neural and fuzzy network formalism in examples, formed of experimental data.

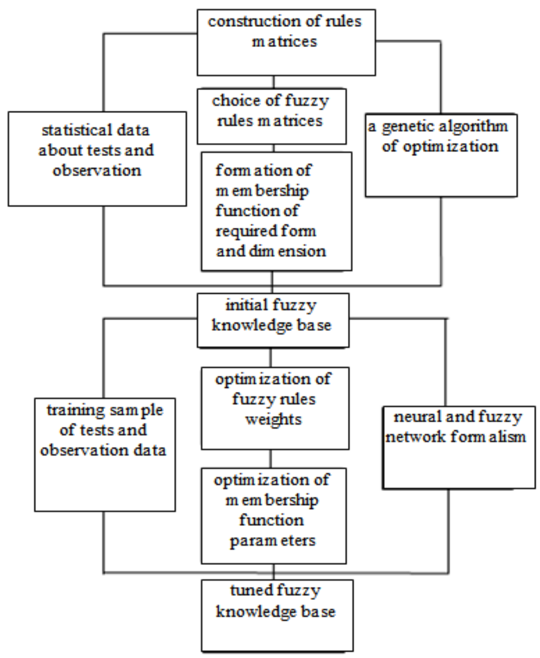

Fig. 2. Stages of setting up the fuzzy knowledge base.

The essence of KB fine tuning stage consists in selection of such weights of fuzzy rules IF-THEN and such parameters of membership functions which minimize distinction between desirable (experimental) and model (theoretical) behavior of an object.

The stage of the KB fine tuning is formulated as a problem of nonlinear optimiza-tion which can be solved by various methods among which the most universal method is method of steepest descent.

However, at a large number of input varia-bles and fuzzy terms in the knowledge base application of a method of steepest descent demands search of a minimum from the different initial points that significantly increases machine timetable. In work it is offered fine tuning of the fuzzy knowledge base with application of a method of neural networks training known as backpropagation [14].

6. The principle of multiloop setting up the fuzzy knowledge base for the objects having hierarchical structure.

It is necessary to allocate the contours solving independent problems of assessment during modeling the difficult systems having hierarchical structure.

Each contour has to learn independently. For this, it is necessary to form the training selections purposefully on each subtask.

In the knowledge base constructed for area of high-speed impact of SC and SG it is possible to allocate three contours:

- the first contour allowing to estimate materials resistance of a design of SC to influence of SG. Data for rules extraction and matrixes creation can include all volume of results of the carried-out bench, polygon tests, at the same time the firing angle of targets is chosen 90 °. Input data are characteristics of a particle of SG (drummer): the weight, density, the size and speed of a particle, and also property of wall material of S: thickness, density and hardness of material ac-cording to Brinell. Output contour parameter is the received UDP value for wall material of S at interaction from SG on corners θ close to 90 ° (Normal). Such approach considers limited opportunities of the test bench on impact speeds (to 5 m/s), but allows to use these results for carrying out training of the second contour;
- the second contour of interaction results assessment of SG with a single-layer wall of S. Data for extraction of rules include the known data on a picture of real collisions in space, results of ground bench tests and the analysis of defeat function graphs for single-layer constructive materials S. Input data are characteristics of a particle of SG (drummer) - the weight, density, the size and speed of a particle, interaction condition between S and SG: a corner between a particle speed vector and a normal to a surface of S and the interaction speed between SG and S in a meeting point, and also characteristics of a wall of S: thickness, density and hardness of material according to Brinell. Output contour parameter is UDP value assessment for a single-layer wall of SC which can be interpreted as result for a two-layer wall (protection with a bumper) provided that S distance between a wall and a bumper is close to 0 cm (Small). Such approach allows to use the received results for training of the third contour;
- the third contour of interaction results assessment between SG and a two-layer wall of S. Data for rules extraction include the same data as in the second contour, but in relation to a wall with a protective bumper. Input data are characteristics of a particle of SG (drummer) - the weight, density, the size and speed of a particle, interaction condition between SC and SG: a corner between a vector of speed of a particle and a normal to a surface of S and the interaction speed between SG and S in a point of a meeting, the characteristic of

ISSN (Print): 2204-0595
ISSN (Online): 2203-1731

a wall of S: thickness, density and hardness of material according to Brinell, and also characteristics and features of placement of a bumper of protection: thickness and density of a bumper, tension of fluidity of material of a back wall and distance between a bumper and a back wall. Output parameter of a contour is UDP value assessment for a two-layer wall (protection with a bumper).

7. The principle of control (training) of KB in selections of experimental data which contain both accurate, and fuzzy (indistinct) values of input and output variables.

Fuzzy model control consists in finding of such parameters which minimize deviations between desirable and valid behavior of model. At the same time it is sup-posed that the desirable model behavior is set by the fuzzy training selection.

The illegibility in experimental data is not an obstacle for the KB exact control. In conditions when available experimental data are set by fuzzy numbers the problem of fuzzy KB control is carried out on the training selection with an accurate input and a fuzzy output. In this case modeling accuracy increases for fuzzy and accurate selection of data.

When experimental data for creation of rules matrix in the "inputs-an output" for-mat are formed on the expert judgments basis, the training selection can include fuzzy values of input and output variables. For ensuring accuracy of the KB tuning fuzzy selection has to be 3-4 times more, than accurate selection [9].

In a solvable task training selections are formed during tuning fuzzy knowledge database.

The results of materials stability assessment of S structure for influence of SG is used for tuning of the second contour.

The examples were created by results of interaction between SG and a single-layer wall of S is used for tuning of the third contour.

So the training selection will include both accurate and fuzzy (indistinct) values of input and output variables.

II. CONCLUSIONS

The problem of forecasting outcomes of dynamic interaction between S and SG is difficult from a position of accurate solutions.

Convenience of approach for assessment of high-speed interaction between S and SG is defined by simplicity and demonstrativeness which are inherent in the mechanism of fuzzy logical conclusion.

The formulated principles of building a fuzzy knowledge base summarize and they are development of the known provisions which define the solution of identification problems of a difficult objects condition by means of expert and experimental information.

Realization of the specified principles within the projected intellectual information system will allow to solve a problem of detection in real time the SG particles posing a threat of S, to predict results of possible interaction for making timely and informed decisions on operational protection, development and design of active and passive protection measures of SC in orbital flight.

The further direction of researches is development of the procedure of training of multicircuit neuro fuzzy network on the basis of realization of "generative competitive neural networks" mechanisms.

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ISSN (Print): 2204-0595
ISSN (Online): 2203-1731