Quality Assessment of Unmanned Aerial Systems Using Bayesian Trust Networks Processing of Testing Data

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Abstract. Unmanned aerial systems (UAS) recently have been rapidly developing both conceptually and technically. The reason for this is that they have become an effective alternative to traditional means and technical systems in a number of applications. The tasks, which are solved with the help of UAS, traditionally include air surveillance, intelligence and communication support both at daytime or at night and in different meteorological conditions. At the same time, the suitability of the UAS for the performance of certain tasks is determined by their qualitative metrics, which must first be evaluated during the tests. As a rule, this is done according to the technical diagnostics because its results are reflected in the quality metrics. But in this case there is a problem of the determination the required duration and content of testing to ensure the economy of resources and time. With proper planning and execution of expertise, it is possible to avoid situations where further testing becomes ineffective. The article describes an express method for assessing the qualitative metrics of UAS by data of technical diagnostics based on use of Bayesian trust networks (BNT). The proposed method allows not only quickly determine the duration of test program, but also a list of the most important characteristics that affect the quality of UAS. In addition, the use of BNT allows to evaluate these characteristics and to correct test plan in real time that increasing the reliability and efficiency of the conformity assessment.

Keywords: Unmanned Aerial Systems, Testing, Quality Metrics, Technical Diagnosis, Bayesian Networks of Trust.

1 Introduction

Unmanned aerial systems recently have been rapidly developing [1] both conceptually and technically. The reason for this is they quite unexpectedly found as effective alternative to traditional means and technical systems in a number of areas of use. The tasks that are solved with the help of UAS traditionally include air surveillance, reconnaissance and communication support both in daytime and at night, and under different meteorological conditions. Recently, the task of using UAS for delivery to the required place cargo, both civil and military, is becoming more and more important. For these reasons becomes understandable constant attention of scientists and industry to the issues of further improvement of UAS, increasing their quality and efficiency.

As in most modern technical systems, energy, material and information flows interact in the UAS by complicated way, which greatly complicates the realization the tasks of all phases of the life cycle (Fig. 1).

The examinations perform a special role in the lifecycle of the UAS. Their purpose is to determine experimentally the actual (achieved) properties' characteristics of the sample tested and determine the degree of its compliance with the technical task or technical specifications received from the developer. Thus the task of rational organization of examinations is relevant.

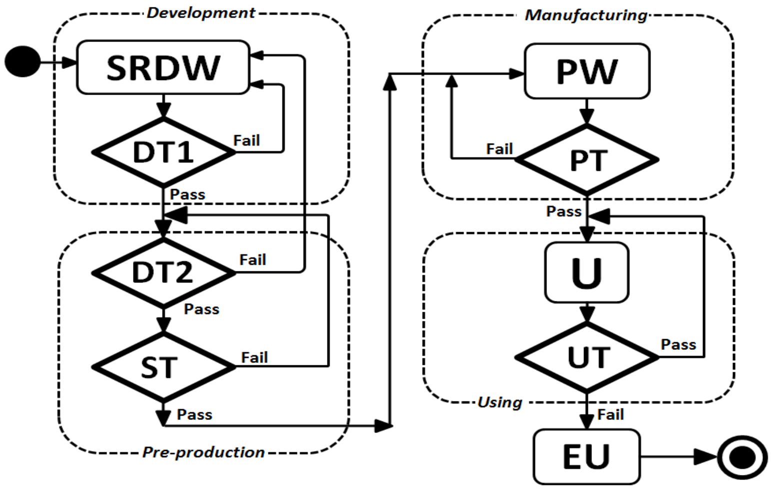

Fig. 1. The place of tests (examinations) in the UAS lifecycle. SRDW – scientific researches and design works; DT1 – developer's testing; DT2 – defining departmental tests; ST – state tests; PW – UAS production; PT – test by the manufacturer; U – use (exploitation); UT – periodical tests during exploitation; EU – end utilization.

The testing of the UAS is a complex operation. For their implementation the considerable material, time and organizational resources are spent, so the practice put forward the following objectives in relation to the examinations:

- to reduce the examination duration and cost, if possible to eliminate non-rational time expenditures;
- to increase the conclusions validity of the examinations, reduce the influence of subjectivity.

In the process of examination, the decision making person (DMP) constantly receives technical diagnostic data. These data affect qualitative metrics (QM) assessment of which is the purpose of the expertise. The use of BNT allows DMP to assess which test factors affect quality metrics most strongly. By proper planning and performing the test program it allows to avoiding situations where further testing becomes inefficient.

The purpose of the article is to describe the method of assessing the UAS quality of by the technical diagnostics data and BNT to increase the validity of decisions on their compliance with the system requirements.

2 Actual Scientific Researches and Issues Analysis

In accordance with [2], under the test of industrial products (engineering samples), one understood an experimental determination of the quantitative or qualitative characteristics of the test object that arises from:

- result of the impact on it;
- it's functioning;
- process of modeling an object or affecting it.

In [3] the traditional method of UAS examination is described. Here it is offered to design the systems and technologies to UAS self-control for predict them technical condition. The proposed self-diagnostic approach is capable to facilitate and speed up the testing process. But it not decides the problem of express analysis of quality metrics and correction the test plan in real time.

The article formulates the proposals, how it is possible on the basis of modeling:

- to automate the process of identifying complex failures;
- to analyze impacts and generate recommendations;
- to use this information to assist in assessing the diagnostic capabilities and to make the right choice of sensor types and models.

At the same time, more and more researchers' attention is attracted [4] to the methodology of using BNT to solve a variety of technical problems, especially those related to uncertainty and the need to combine expert estimates with numerical data accumulated in various databases.

BNT now deservedly occupies [5] the place of one of the most productive mathematical approaches that allows flexible and adequate description of decision making by qualified experts in the diagnosis of complex systems under uncertainty. Models built on these principles show themselves well in the tasks associated with incomplete and inaccurate information. With the help of BNT significant advances have been made in such areas as medicine (diagnosis of lymph nodes, refinement of diagnoses), automatic speech recognition systems, image processing, classification of data of various natures, and others.

The author rightly points out that the probabilistic approach to the solution of complex technical problems based on the mathematical apparatus of BNT has the following main advantages:

- the simulation results obtained by experts' knowledge and presented as the structure of the trust graph and as the form of probabilistic tables in nodes of the trust network are more reliable;
- here is the ability to save time and resources;
- there is more possibility of a quick understanding of situations and visual representation of the elements (variables) interactions when technical system is modeled in the form of BNT;
- there is the possibility to adjust the models used and their parameters, taking into account the receipt of new information about the behavior of the object being studied.

Despite the fact that Bayesian networks are given a lot of attention in the world scientific literature, the principles of their construction and use are not yet sufficiently covered in domestic publications, which greatly impedes their understanding and application.

3 Definition Methodology for UAS Quality Indicators with Use the Data of Technical Diagnosis

UAS QM is semantically defined as a tuple

$$QM = \langle \boldsymbol{Y}, M \rangle, \tag{1}$$

where $\boldsymbol{Y}=\{Y_i\}$ is a set of functions (properties) of a technical sample that are relevant to Q and which are tested during its examination;

M – the numerical representation of the QM which serves to quantify it. In most cases, according to [6, 7], M_Q are calculated as relative values:

$$M_Q = \frac{|\boldsymbol{X}|}{|\boldsymbol{Y}|} \text{ or } M_Q = \frac{|\boldsymbol{Z}|}{|\boldsymbol{Y}|}, \tag{2}$$

where $|\boldsymbol{A}|$ means the power (number of elements) of the set $\boldsymbol{A}$.

In the formula (2):

$\boldsymbol{X}=\{Xj\}$, $\boldsymbol{X} \subseteq \boldsymbol{Y}$ is the set of functions (properties) of the technical sample that are performed according to the Q during the examination;

$\boldsymbol{Z} = \boldsymbol{Y} \backslash \boldsymbol{X}$ is the set of functions (properties) of the technical sample that are not performed according to the Q during the examination.

Properties $\boldsymbol{Y}$ get defined during the technical samples testing through the implementation of diagnostic procedures which are components of technical diagnostics (TD).

The semantics of technical diagnostics is determined on the logical model, which, in turn, corresponds to the system of sets

$$TD = \langle T, M \rangle \tag{3}$$

where $\boldsymbol{T} = \{T_i \mid i \in (1 \ldots m), X_i \leftrightarrow T_i\}$ is a set of tests that are performed (or symptoms observed) when technical sample is examining;

$\boldsymbol{M} = \{M_j \mid j \in (1 \dots k)\}$ – is the set of *QM*, which are calculated from the results of tests $\boldsymbol{T}$ by the formulas (2).

The logical connection between T and M can be illustrated by the incidence matrix *TM*:

$$TM = \begin{array}{|c|c|c|c|c|l} \multicolumn{1}{c}{T_1} & \multicolumn{1}{c}{T_2} & \multicolumn{1}{c}{T_3} & \multicolumn{1}{c}{\dots} & \multicolumn{1}{c}{T_m} & \\ \hline 1 & 0 & 0 & \dots & 1 & M_1 \\ \hline 0 & 1 & 0 & \dots & & M_2 \\ \hline 1 & 0 & 1 & \dots & 1 & M_3 \\ \hline \dots & \dots & \dots & \dots & \dots & \dots \\ \hline 0 & 1 & 0 & \dots & 0 & M_k \\ \hline \end{array} \tag{4}$$

In the matrix (4) $TM_{ij} = 1$ if the metric M_j is to be calculated for the test T_i, which, in turn, can be either “Pass” or “Fail” in the simplest case.

Further, the failures $\boldsymbol{R} = \{R_t| \; t \in (1 \dots n)\}$ affect to results of tests (observations) $\boldsymbol{T}$. The relationship between sets $\boldsymbol{T}$ and $\boldsymbol{R}$ can be explained by the *RT* incidence matrix:

$$RT = \begin{array}{|c|c|c|c|c|l} \multicolumn{1}{c}{R_1} & \multicolumn{1}{c}{R_2} & \multicolumn{1}{c}{R_3} & \multicolumn{1}{c}{\dots} & \multicolumn{1}{c}{R_n} & \\ \hline 0 & 1 & 0 & \dots & 1 & T_1 \\ \hline 1 & 1 & 0 & \dots & & T_2 \\ \hline 1 & 0 & 0 & \dots & 1 & T_3 \\ \hline \dots & \dots & \dots & \dots & \dots & \dots \\ \hline 0 & 1 & 1 & \dots & 0 & T_m \\ \hline \end{array} \tag{5}$$

In the matrix (5) $RT_{ij} = 1$ if the failure R_i is one of the reasons which affects to the result of test T_j.

The analysis of the TD process and the logical connections found in it allow us to construct a diagram of causes and consequences in determining of UAS QM(Fig. 2).

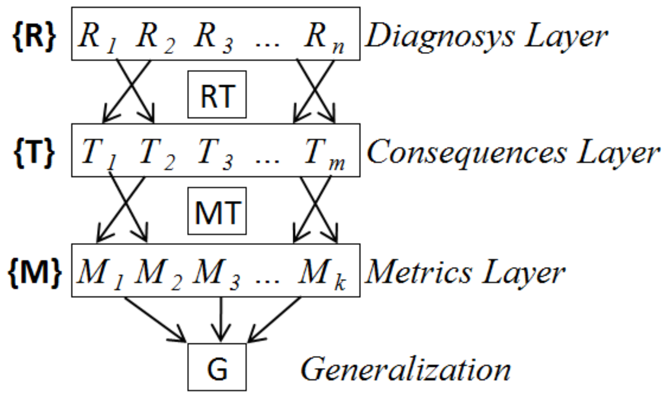

Fig. 2. Causes and consequences diagram of the TD procedure.

Thus, objects that participate in the UAS examining can be grouped logically into the diagnostic layer $\{\boldsymbol{R}\}$, the effects layer $\{\boldsymbol{T}\}$, and the layer of QM $\{\boldsymbol{M}\}$, as shown in Fig. 2. The matrixes (4), (5) are acting as interfaces between these layers.

In Fig. 2 also there is the node of generalization of quality metrics *G* which is not mandatory in terms of normative documents. It looks useful technically for ensuring the possibility of final result obtaining and it can be interpreted simply in process of results analysis. Traditionally, it is calculated as a weighted sum of metrics M_i:

$$G = \sum_{i=1}^{k} \alpha_i M_{i.}, \tag{6}$$

where α_i is a weight of metric M_i:

The sequence of determination of UAS quality indices according to the TD data corresponds to the following algorithm.

1. The ***R, T*** and ***M*** sets must be determined based on the UAS technical documentation and the existing regulations. Their elements determine the course and results of the UAS assessment.
2. The matrices *RT* and *TM* are to be filled up. They determine the structure of causative relationships in the test procedure.
3. A test is conducted, during which:
   a) TD is performed and by this way the results of measurements and failures observation ***R*** become actualized;
   b) the results of the ***T*** test are determined, from which the ***X***-sets for each metric of the set ***M*** become actualized;
4. If necessary, the generalized index *G* is calculated according to the customer's test method.
5. To use the model in Fig. 2 as BNT, further it is necessary to define a priori probabilities for each of its objects. These a priori probabilities are determined either on the basis of the statistics of previous examinations, and/or on the basis of expert information.

The given algorithm has the following disadvantages:

1. The dimensions of *RT* and *TM* matrices can be quite large:

$|RT| = |\boldsymbol{R}|\times|\boldsymbol{T}|$ and $|TM| = |\boldsymbol{T}|\times|\boldsymbol{M}|$. Their filling is a labor-intensive work, therefore its simplification is urgent.

2. The wording of p.3b above defines a slow consecutive procedure based on the *RT* and *TM* matrices obtained in p.2. Such an approach does not pay attention to the possibility of a logical problem decomposition, taking into account the mutual different tests independence in the UAS structure, which belongs to different subsystems of it. The method described below shows how using BNT gets a solution to this problem.

3. Execution of p.5 of the above algorithm is a daunting task, since for each object it is necessary to determine a priori probabilities for the full range of common distribution of the probability of parent nodes. The situation may be much easier when:

- it is possible to determine the independence some objects from others in the model;
- when the objects of the model have a discrete distribution of values.

4 Construction the BNT for the UAS Examination

The diagram in Fig. 2 corresponds to the deterministic process of determining UAS QM, while the purpose of this study is to improve the mentioned process with the use of existing causal relationships between layers of test objects (Fig. 2), which opens up the possibility to use a powerful apparatus [4] estimation of conditional probabilities (degrees of confidence) between them. This math is based on the notion of trust networks, whose interconnection of elements is based on the well-known Bayesian theorem.

BNT is a graphical, high-quality illustration of the interactions between the plurality of variables it simulates. The structure of the "casual" oriented graph can simulate the cause-and-effect structure of the simulated subject area, although this is not necessary. When BNT is casual, it provides useful, structured information about the interactions between variables and allows predicting the effects of external manipulations.

The distribution of common probabilities presented in the BNT is based on the so-called "subjectivist" definition of probability. Given new observations (test results), the subjective distribution of common probabilities at the vertices of the graph is updated using the well-known Bayes formula:

$$P(A|B) = \frac{P(B|A) \cdot P(A)}{P(B)} \tag{7}$$

where *P(A|B)* is probability of event A provided that event *B* occurred;

P(B|A) – the likelihood of event B provided that event *A* occurred;

P(A) – a priori probability of event *A*;

P(B) – complete (marginal) probability of event *B*.

The calculation *P(B)* is related to fairly voluminous computations by the general formula

$$p(B) = \int_{range\ \boldsymbol{A}} p(B|A) \cdot p(A) \cdot d\boldsymbol{A}, \tag{8}$$

or, in the case when the set A consists of a discrete set of values – by the formula

$$p(B) = \sum_{i=1}^{n} p(B|A_i) \cdot p(A_i).. \tag{9}$$

Let's apply the above-mentioned method of constructing BNT for its creating in the case of analysis of the conditional examining procedure of UAS.

The examination procedure can be formally-logical imagined as a tuple

$$E = \langle \boldsymbol{R}, \boldsymbol{T}, \boldsymbol{M}, G \rangle \tag{10}$$

in which:

- set R – different kinds of failure, inconsistency and malfunction in UAS;

- set T – the consequences to which R leads. This may be:

1. the results of tests that are specifically performed by the testers during the examination;
2. symptoms that are directly observed;

- the set of M is the metric of UAS QM (formula (2));
- a generalized UAS quality index G .

These elements can be grouped according to the layers, as shown in Fig. 3.

5 Determination of the Relative Impact of UAS Examining's Factors for Improving the Examination Procedure

As noted in [8], the notion of conditional probability is not limited to the recalculation of the occurrence quantities some events, but means the mathematical dependence some random variables from others. That is why BNT in Fig. 4 can be considered as "a black box". Let its inputs to be consistent with the actualization of objects from the diagnostic layer *{R}*, and with the variable *G* that is target function as well. The transfer function of the "black box" is formed by the set *J* of common probability distributions in BNT.

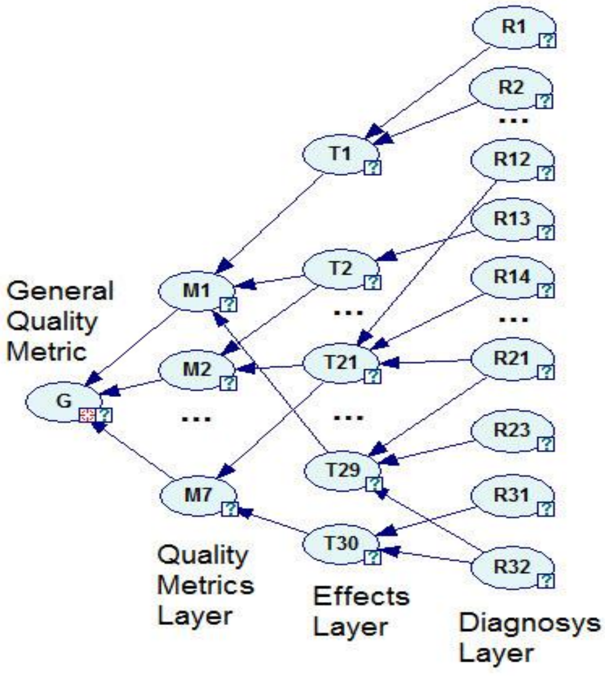

Fig. 3. Oriented graph F of the BNT for examining procedure E.

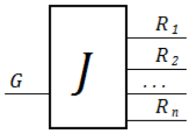

Fig. 4. BNT as "a black box".

Mathematically it's possible to show this as

$$G = G(\boldsymbol{J}, R_1, R_2, \dots, R_n). \tag{11}$$

The relative influence of the inputs $\{\boldsymbol{R}\}$ to the formation of the value of the target function G can be estimated [10] by the values of partial derivatives

$$f_i = \frac{\partial G}{\partial R_i} \mid i \in (1 \dots n), \tag{12}$$

which in [10] have been called levels of influence (LI), or impact factors.

The calculation values f_i requires a numerical differentiation (11), which, as noted above, involves performing calculations of common probabilities. In the worst case these calculations have the computational complexity level of *O(NP)* [8]. To solve the problems the BNT BayesFusion GeNIe Modeler 2.3 [10] modeling application was used. The model which had been constructed in this application is shown in Fig. 3.

Further, according to the above goal of the study, we will define as the target node GQM (Fig.5).

After this application can estimate the degree of influence of other nodes, after which the graph of the model takes the view on Fig. 5.

A detailed level influence (LI) analysis was carried out using numerical estimates exported from the simulation environment. According to these data a diagram (Fig. 6) was constructed.

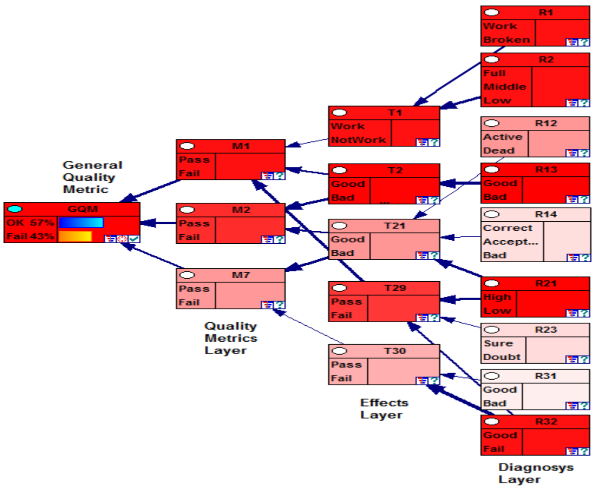

Fig.5. The analysis of model's nodes impact factors to the target node.

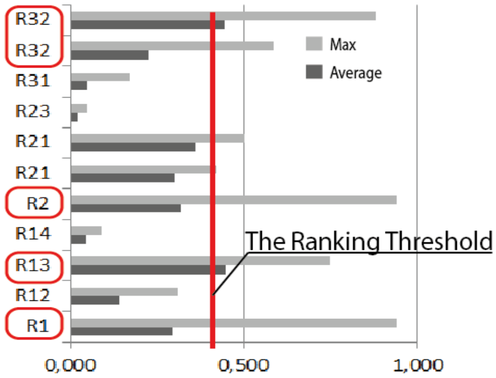

Fig. 6. LI comparison and ranking for nodes.

Based on the diagrams given in Fig. 6, the ranking threshold T_R was selected. The nodes ranking of the primary layer of diagnosis as meaningful $\boldsymbol{R}_m \subseteq \boldsymbol{R}$ and insignificant is performed by the condition:

$$\forall R \in \boldsymbol{R}_{\mathrm{m}}: \mathrm{LI}_R > T_{R.} \tag{13}$$

In our case $\boldsymbol{R}_{\mathrm{m}} = \{R_1, R_2, R_{13}, R_{32}\}$ was defined as meaningful.

After performing the described actions the model of Fig.8 can determine how the initial conditional probability *p(GQM=OK)* = 57% changes in cases when each of the nodes $R \in \boldsymbol{R}_{\mathrm{m}}$ will alternately obtain the worst of the values specified in it. The simulation results are as follows.

$p(GQM{=}OK|R_1{=}Broken)$=23%,

$p(GQM{=}OK|R_2{=}Low)$=23%,

$p(GQM{=}OK|R_{13}{=}Bad)$=20%,

$p(GQM{=}OK|R_{32}{=}Fail)$=26%.

The obtained results can be evaluated as inappropriate in terms of the success of the entire expertise. This allows you to build an testing strategy that performs the most critical tests. In the example above the number of needed tests may be reduced from 11 to 5 (45% of common number). Receiving negative results either on one of test, or on their combination, will mean stopping the redundant work of performing other inspections.

6 Conclusions

1. The proposed method for assessment UAS QM that use BNT in combination with technical diagnostic data had allowed to obtain information about the efficiency of the complex test in the early stages of its implementation. In real conditions this will allow to organize efficiently the examination process, reduce the time needed for its execution and reduce material spending.
2. Developed algorithms that use the BNT to determine UAS QM provide the definition which tests are expected to be implemented during the expertise up to the final

result. This opens the opportunity to determine the most efficient test which includes the only significant checks that give a reliable and fast result.

3. Bayesian trust network allows to quickly finding the most probable causes of test failures in the process of examining, localize their causes and quickly eliminate them, which is an important factor in accelerating the testing.
4. This study may be further developed in the direction of creating semi-automatic planning and testing systems using BNT for purpose of the determination the most effective strategy for UAS expertise.

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