

A Hybrid Diagnostic System for a Small Turbojet Engine

Hibridan dijagnostički sustav za male turbomlazne strojeve

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Summary

A diagnostic system is one of the key components securing the safety of operation of a turbojet engine. There are many different engineering approaches how to design engine diagnostic systems applied in real-world conditions. We propose a novel approach for a diagnostic system design to be applied on the object of a small turbojet engine using thermal diagnostics combined with a more traditional model based approach. The combination of these two approaches together with application of methods from the area of computational intelligence create a hybrid diagnostic system, which can be integrated with a control system of the engine. The article also deals with experimental validation of the designed diagnostic system on the object of a small turbojet engine iSTC-21v in laboratory conditions.

KEY WORDS

turbojet engines
diagnostics
computational intelligence
hybrid systems

Sažetak

Dijagnostički sustav je jedan od ključnih komponenata priskrbljivanja sigurnosti rada turbomlaznog stroja. Postoje mnogi različiti strojarski pristupi o tome kako stvoriti dijagnostičke sustave koji se primjenjuju u uvjetima pravog svijeta. Predlažemo jedan novi pristup dizajnu dijagnostičkog sustava koji se ima primijeniti na objekt mali turbomlazni stroj, korištenjem termalne dijagnostike koja je kombinirana s pristupom koji je tradicionalniji. Kombinacija ova dva pristupa skupa s primjenom metoda iz područja računalne inteligencije, stvaraju hibridan dijagnostički sustav koji se može integrirati u sustav kontrole stroja. Članak također obrađuje eksperimentalno vrednovanje dizajniranog dijagnostičkog sustava na objektu mali turbomlazni stroj iSTC-21v u laboratorijskim uvjetima.

KLJUČNE RIJEČI

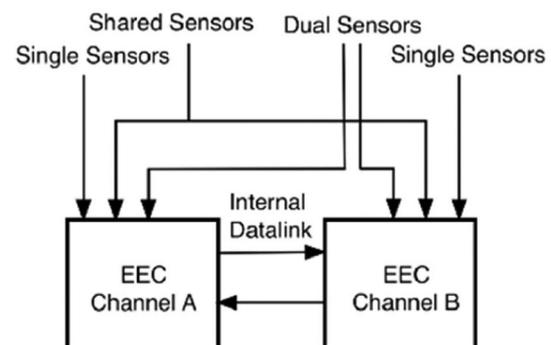
turbomlazni strojevi
dijagnostika
računalna inteligencija
hibridni sustavi

1. INTRODUCTION

Turbojet engines can generally be considered as complex systems operating in a broad environmental external parameters' range as well as under extreme internal thermodynamic conditions. Safety of operation of aircraft and their engines are directly interconnected. The approach to increase the level of safety has always lied in increased redundancy of its systems. Current trend in control of aircraft engines lays in the use of full authority digital engine control systems (FADEC). The use of digital processors and elements in a control system allows its miniaturization, but also puts higher demands on reliability due to new possible elements, like electro-magnetic disturbances, which can cause failures. Increased reliability is achieved mainly through redundancy in such control systems. The electronic engine control system usually consists of two control units (channels); certification requirements may however demand as much as three redundant channels. Increased safety in engine control systems is usually achieved by the following means [1]:

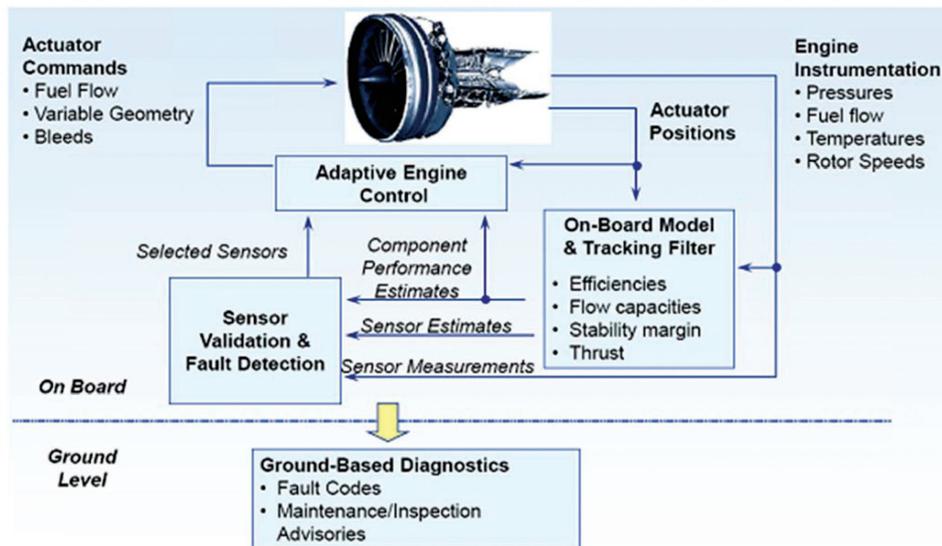
- Sensors backup/redundancy (dual sensors, single ended sensors, shared sensors).

- Main engine control algorithm redundancy (FADEC channels A and B).
- Health management/diagnostics.



Source: [1]

Figure 1 Dual channel architecture with redundant sensors



Source: [3]

Figure 2 Advanced engine control using sensor validation and fault detection

The presented article will specifically deal with the area of small turbojet/turbo-shaft/turbo-prop engines [2] with a conceptual design of a highly redundant control system with increased redundancy of sensors by application of virtual channels and increased redundancy of its main control algorithm channels by utilization of intelligent selectors. The designed control system and redundant elements/backup will be tested on a laboratory object represented by a small turbojet engine iSTC-21v derived from the turbo-starter TS-20. The presently used dual channel architecture with redundant sensors is shown in the figure 1.

2. INCREASED ENGINE SYSTEMS' REDUNDANCY – THE GENERAL CONCEPT

To improve safety of the two channel architecture two measures are proposed to be taken:

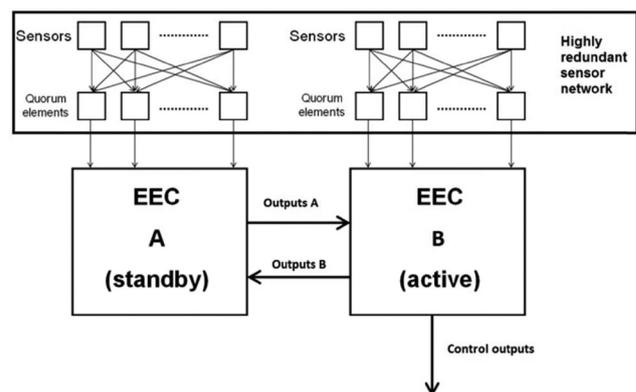
- Increase redundancy of sensors through virtualization of selected channels
- Solve the problem of diagnostics and intelligent selection of the active EEC channel

Solution of both these problems is connected with diagnostics or fault detection in sensors or electronic engine control unit. Diagnostics of sensors is done usually through a system that validates outputs of individual sensors and selects sensors channels entering the control system as shown in the figure 2 [3].

The proposed approach in sensors validation and fault detection expands the concept by application of a quorum element method, which will act as a diagnostic system for sensors and back-up system at the same time, creating a highly redundant sensor network. The concept will be described in the following chapters and is illustrated in figure 3.

The second problem, which lies in selection of the active channel of EEC, which is directly interfaced with fuel flow supply to the engine, can be solved by application of intelligent selectors creating integrated control/diagnostics architectures. By intelligent selector a decision making

element based on neural networks is proposed. The resulting architecture is presented in figure 4.



Source: [5]

Figure 3 A highly redundant sensors network with quorum elements connected to an EEC

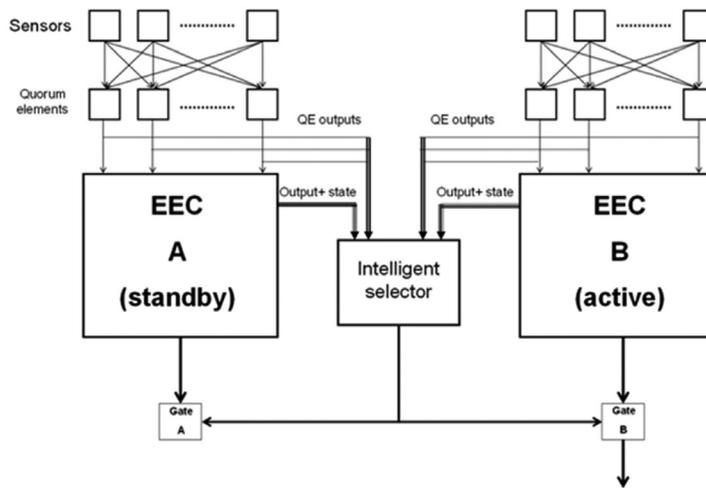
The main advantage of using such arrangement is increased reliability and resulting safety without needing to implement a third monitor channel, because the intelligent selector is able to select the correctly operating EEC channel based on outputs from the sensor network as well as output and state parameters computed by both EECs [4].

3. INTELLIGENT SUPERVISORY CONTROL SYSTEM

The intelligent supervisory system for small turbojet engine can be decomposed into four basic parts.

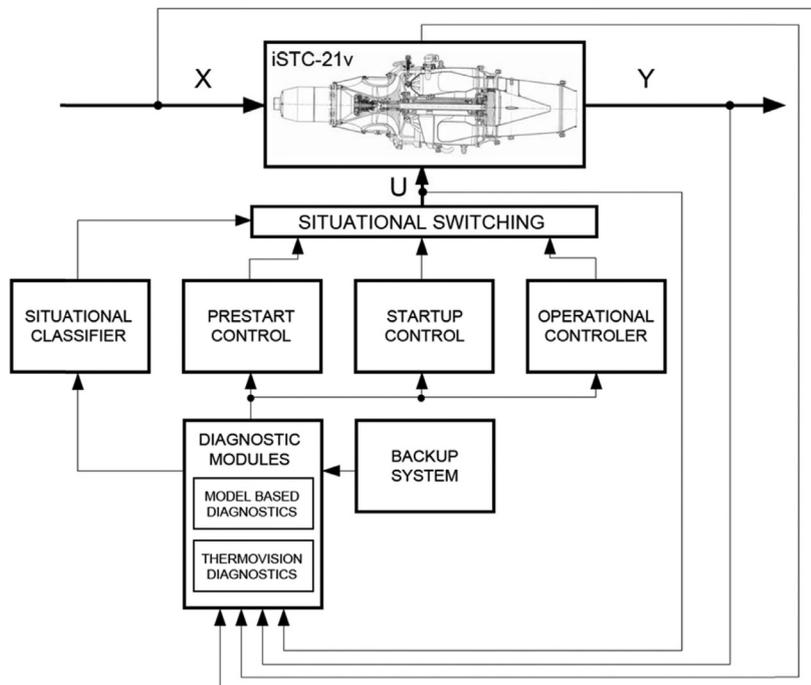
- Pre-start diagnostic system.
- Online diagnostic system.
- Backup system.
- Start-up control system.

All the systems operate with mathematical models of the engine as described in the previous chapters. The following figure illustrates how the intelligent supervisory system is designed on the highest level of situational control for the small turbojet engine.



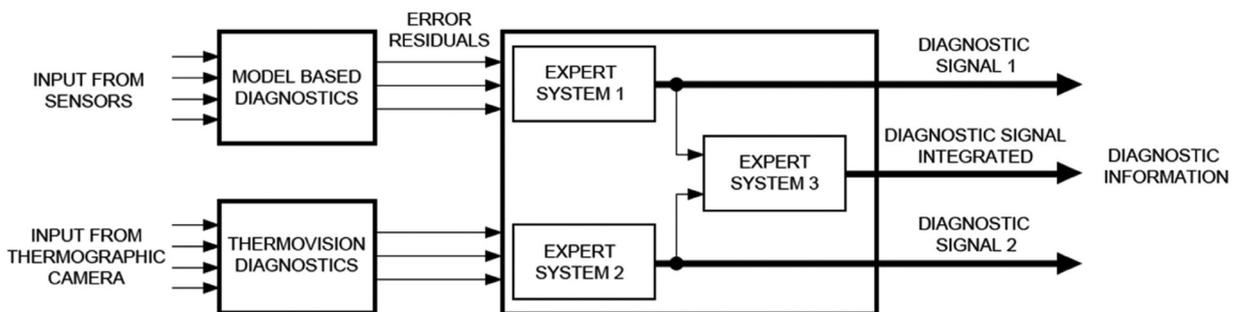
Source: [5]

Figure 4 A highly redundant sensors network connected with redundant EEC gated by an intelligent selector



Source: authors

Figure 5 The intelligent supervisory engine control system – a general scheme

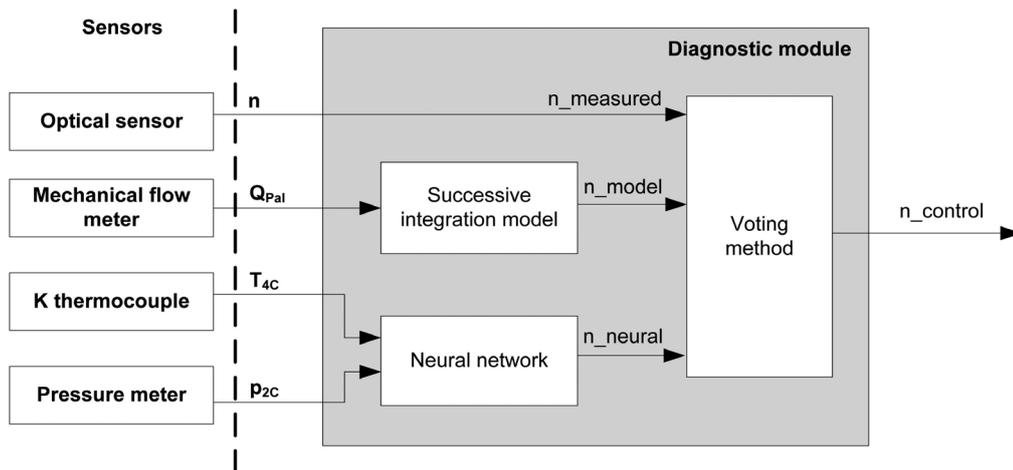


Source: authors

Figure 6 Diagnostic Modules and Expert Systems

The diagnostic module is composed of two basic modules that utilize different inputs from the engine's sensors (figure 6). The first one is the model based diagnostics using computational models of the selected parameters in order to compute error residuals and the second one is based on thermoVision diagnostics

using a thermal image of the engine and a neural network. Both systems are described in more detail in the following chapters. The error residuals are further processed by expert systems which are rule based systems producing diagnostic signals, which can be further utilized by the control system.



Source: [6]

Figure 7 The structure of the diagnostic module

4. SMALL TURBOJET ENGINE DIAGNOSTIC/BACKUP SYSTEM

The small turbojet engine iSTC-21v also serves us for testing purposes of redundant backup/diagnostic systems. The designed architecture of such system has been tested for a single engine parameter the speed of the engine. This parameter is crucial as it defines thrust and power output of the engine and is the primary controlled parameter. The main way to measure the speed of the engine is the optical sensor, while the other ways are synthetic model values:

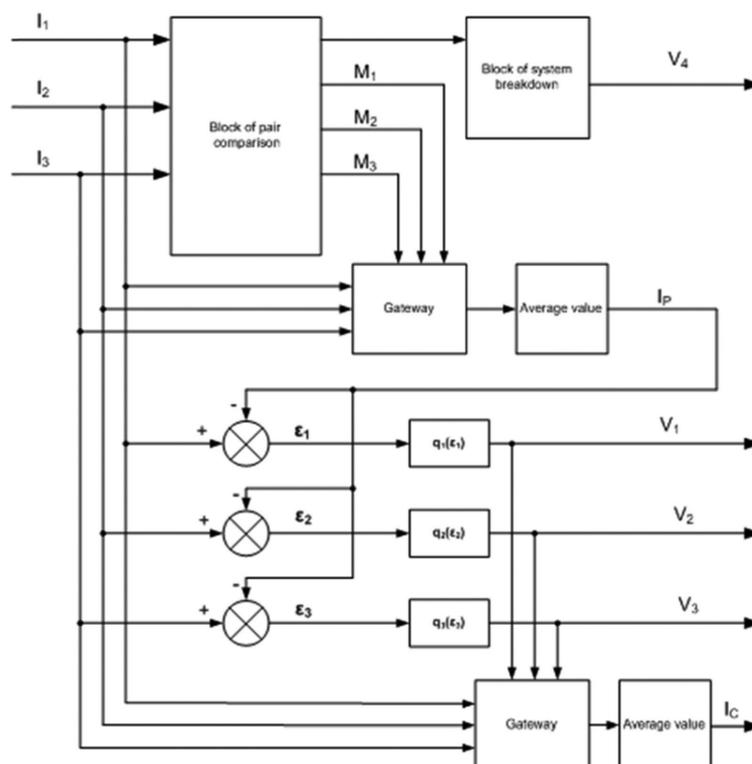
- successive integration dynamic model,
- a neural network.

The basic designed architecture of a simple single parameter diagnostic system is shown in the figure 7. Reliability of the model is secured through independence of input parameters while utilizing virtual engine models to

compute the speed. There are two basic errors that can occur with the optical sensor:

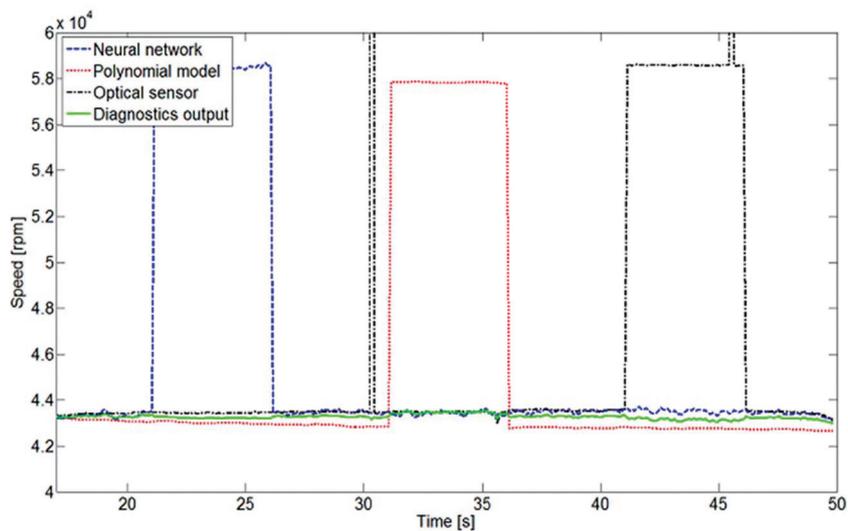
- A random value – caused by electro-magnetic environment disturbance,
- Sensor failure – it can be caused by a loss of power, loss of communication channel, loss of reflex area on the compressor blade.

The designed backup/diagnostic system is utilizing adaptive voting majority methods and its principal implementation is shown in the figure 8. The system can exclude faulty speed computation/measurement from its output and can also indicate its own total failure utilizing precise dynamic engine models. The resulting speed of the engine is represented by the average value of all means of speed computation/measurement I_c .



Source: [6]

Figure 8 The structure of the diagnostic module



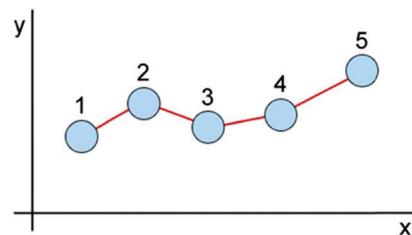
Source: [6]

Figure 9 Diagnostic/backup system test results

The designed diagnostic/backup system has been experimentally tested with the iSTC-21v engine during its operation within running on speed of 43500 RPM. During the test all input had simulated errors that are shown in the figure 9.

During the test even real error of the optical sensor occurred at time of 30 seconds. The output of the diagnostic/backup system however was not influenced and has operated as desired. Further expansion of the system will lead into a highly redundant diagnostic/backup system utilizing the presented concept, where all important engine parameters (temperatures, pressures, fuel flow, thrust) will be mutually backed up, thus creating a highly redundant backup system.

- colour conversion
- matrix transformation,
- preprocessing,
- normalization.



Source: authors

Figure 10 Topological structure of the Kohonen map with five neurons

5. APPLICATION OF NEURAL NETWORK IN CLASSIFICATION OF THERMAL IMAGES

In order to use neural networks for classification of pixels in a thermal image, it was necessary to prepare a training set for the network in order to create an applicable classifier. Five training images were selected for this reason in individual phases of the engine's operation and were deemed satisfactory. This number of images was sufficient to demonstrate pixel's classification into the individual levels, which may be critical in terms of safety for the operation of the engine and which pose no threat.

As a part of the research three types of graphic images were chosen to find, which type of an image will be the most appropriate for the application of neural network: binary, grayscale, RGB.

Because the thermal images captured also a part of exhaust gasses from the engine iSTC-21v, images were cropped from its original size 320x240 pixels into the size of 284x240 pixels. It was done to achieve more accurate results by application of a neural network on the pixels of the exhaust nozzle only, otherwise neurons would also cover an area, which is not important in classification of the thermal image.

The individual steps of application of a neural network were realized and programmed in Matlab. The steps included the following ones:

- image read,
- digitalization,

Kohonen self-organizing map (SOM) neural network was selected to classify individual image pixels after all previously described steps were applied to every thermal image [7, 8]. A topological grid size of 1x5 neurons was found in pilot experiments and topological structure of the network was a chain with Euclidian distance between neurons. The chosen type of grid can classify each image pixel into one of five clusters. In this way, we can obtain five different categories, which can be further labeled. The weights of the network were found during adaptation of training images and the corresponding five clusters indicate the criticality of the classified pixel. After transformation into a visible image, it means that the network will classify colours and areas on the thermal image, where its brightest parts include critical areas because of high temperature and darkest parts are the least critical areas.

Three neural networks have been created as classifiers for an individual type of training image with the following input layer.

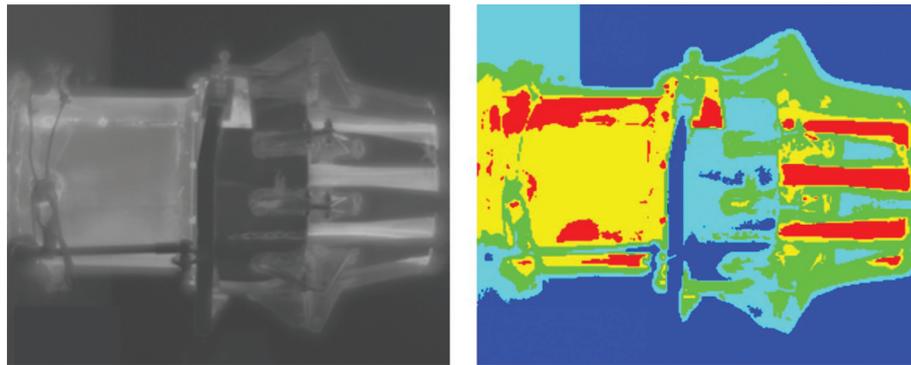
1. Black and white training image, SOM with two inputs (x, y position of a white dot)
2. Grayscale image, SOM with three inputs (x, y, grey)
3. RGB image, SOM with five inputs (x, y, R, G, B)

Because of the distribution of individual weight vectors (neurons), it was not possible identify which pixel points on



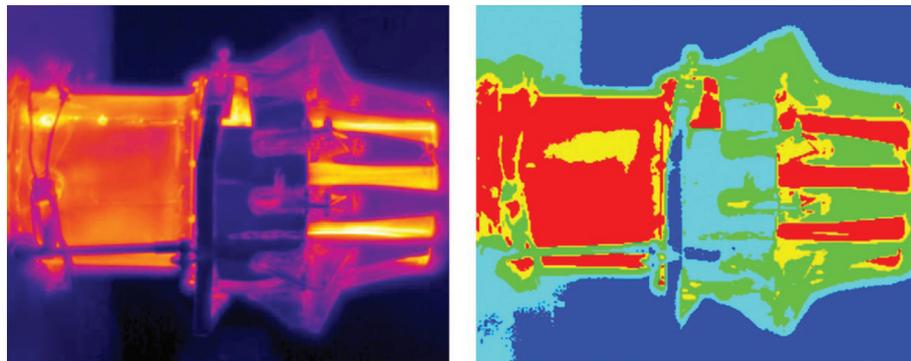
Source: authors

Figure 11 Classified binary image



Source: authors

Figure 12 Classified grayscale images



Source: authors

Figure 13 Classified RGB image

the image belong to the individual levels (weights), so each weight was assigned a color. Red colour represents the most critical area, blue color the least critical area.

The following part of the article presents results of the application of the Kohonen neural network with previously described structure on the individual types of graphic images.

Classification of pixels on the binary type of image (figure 11), it is possible to observe that the activity of neurons gradually goes through each segmented areas of the exhaust nozzle, which do not mean classification areas on the nozzle according of criticality level, network takes into reasoning only their spatial distribution. Size of the areas depends on the thresholding algorithm parameters and thus the resulting diagnostic information will be defined only by the size of the area classified by a particular neuron.

The results of classification on a grayscale image (figure

12) show that the image is classified according to the level of grey and spatial disposition. The colour image shows red areas, which are critically heated, while blue colour represents areas, which are colder and not critical. These areas can be considered as safe in terms of nozzle activity.

The third classifier was trained on a RGB image set and the results of classification of individual areas by activating different neurons can be seen in the figure 13. The RGB image shows that the critical area of the exhaust nozzle is larger. We consider the RGB classifier as the most perspective and precise as it has larger input information in classification.

6. CONCLUSION

The article presents a novel method in turbojet engines' diagnostics using thermal vision and a model based approach, integrating them both in a single diagnostic system. Further

integration is done by interconnecting this system to the engine's control system allowing the concept of engine control in all its operational states including control during failure states. This has a potential to increase the safety of operation of turbojet engines and this is paramount to flight safety. As the design is modular any number of diagnostic approaches, like vibro diagnostics, can be integrated in the presented way, further increasing redundancy and safety as a result.

REFERENCES

- [1] Linke-Diesinger, A.: *Systems of Commercial Turbofan Engines: An Introduction to Systems Functions*. Hamburg, 2008. 239 pp. ISBN 078-3-540-73619-6.
- [2] Design of measurement chain to measure r.p.m. of an aviation turbo jet engine / Róbert Bréda, Tomáš Patz - 2013. In: *Przeglad Elektrotechniczny*. Vol. 89, no. 3a (2013), p. 141-144. - ISSN 0033-2097
- [3] Sanjay, G.: *Aircraft Turbine Engine Control Research at NASA Glenn Research Center*, NASA/TM—2013-217821, USA, 2013
- [4] Jaw, C. L., Mattingly, D. J.: *Aircraft Engine Controls Design, System Analysis, And Health Monitoring*, American Institute of Aeronautics and Astronautics, 2009, pp. 361, ISBN 978-1-60086-705
- [5] Andoga, R., Fözö, L., Považan, J., Judičák, J., Madarász, L.: *Intelligent redundant systems for small turbo-compressor engines*. 2014. In: *MSC 2014: The 2014 IEEE Multi-Conference on Systems and Control*: Antibes, France, 8th - 10th October 2014. - [Piscataway] : IEEE, 2014 P. 1901-1905. - ISBN 978-1-4799-7405-4.
- [6] Andoga, R., Madarász, L., Fözö, L., Lazar, T., Gašpar, V.: *Innovative approaches in modeling, control and diagnostics of small turbojet engines*. 2013. In: *Acta Polytechnica Hungarica*. Vol. 10, no. 5 (2013), p. 81-99. - ISSN 1785-8860.
- [7] Haykin S.: *Neural Networks - A Comprehensive Foundation*. India: Pearson Education, 1999. 823 p. ISBN 81-7808-300-0.
- [8] Kasabov N. K.: *Foundation of Neural Networks, Fuzzy Systems, and Knowledge Engineering*. England: The MIT Press, 1998. 568 p. ISBN 0-262-11212-4.