The Proposal of use of Hybrid Systems in Situational Control of Jet Turbo-compressor Engines

[1]Rudolf Andoga, [2]Ladislav Madarász, [3]Miloš Karas

[1]Department of Cybernetics and Artifficial Intelligence TU Košice, andoga@neuron.tuke.sk

[2]Department of Cybernetics and Artifficial Intelligence,TU Košice ladislav.madarasz@tuke.sk

[3]Institute of Aeronautics TU Košice, karas@vlake.army.sk

Abstract: Aircrafts' turbo-compressor engines may be considered as very complex systems with many mutual and also positive feedbacks. Another characteristic of such systems is that they operate in a very large range of outer environment parameters which causes very different behaviour within their working conditions. Critical susceptibility to erroneous states where requirements for reliability are set to highest degree, it is necessary to secure control of such engines in their every state and secure their operation under every environmental or engine conditions. Situational control methods offer such tools to secure not just stabilization of an engine, but its control, using different control strategies for different working conditions.

Keywords: situational control, turbo-compressor engine,hybrid systems

1 Introduction

State of present technologies in all areas of technical, but also non-technical practice gives rise to growing complex systems. A complex system in general is a high dimensional high parametric system with complex dynamics. For effective and optimal function of such systems it is necessary to propose and implement newest knowledge from the areas of cybernetics and artificial intelligence. Present control systems are often limited to control a complex system only at some given conditions. However in real-world applications these systems find themselves in very different working conditions, what influences parameters of their operation and characteristics of behavior and may lead to errors and critical states.

It is necessary to handle all these conditions and situations in such way that the system would work economically and effectively, thus optimally. It is possible to secure this factor of optimal operation of the controlled system in all eventual states of the environment and its inner states, represented by its inner parameters with use of situational control medthodics. The terms, situational, situational control intuitively tell that they represent control of a chosen complex system in its different situational states. In an ideal case this will represent the control of a complex system in its all operational states. However such an ideal case represents existence of infinite number of operational states but we posses only a limited number of control strategies (algorithms). So we are coming to the main idea of situational control methodics. Due to limitation of number of control algorithms, it is necessary to limit the number of operational situations, so that control strategies would cover all operational situations. By declaration of this fact we are getting towards situational classification, which demands proposal of situational classes and algorithms to control a system which finds itself within states defined by these situational classes. Situational class represents then a set of similar operational states of a complex system. Usually one control strategy covers one situational class, but a case can occur where more situational classes are covered by one suitable robust control strategy.

Applications, where methodics of situational control may be applied cover a vast area of complex systems, as are for example electricity networks, electric energy production, control of robot technological complexes, control of jet engines, etc. This article will be aimed at the use of the methods of situational control in the field of control of the aircraft turbo-compressor engines.

2 Situational Control Methodics

Situational control was designed for the control of complex systems, where the traditional cybernetic models weren't sufficient. [1]. The model proposed in [1] wasn't sufficient to control systems characterized by features like unique, dynamics, incompleteness and indeterminacy of description, ambiguity and presence of a free will. For systems, where it is difficult to describe their specific structure and behavior and where the presence of a human factor has an unforeseeable character and also where the system is developing by itself in time, methods of situational control have been developed. [3] More general approach to situational control is formatter control of complexes [4] Formatter control of a complex means not only the control of its parameters, but also the control of the form of a complex.

Following scheme is showing the functional scheme of situational control of a complex system [5].

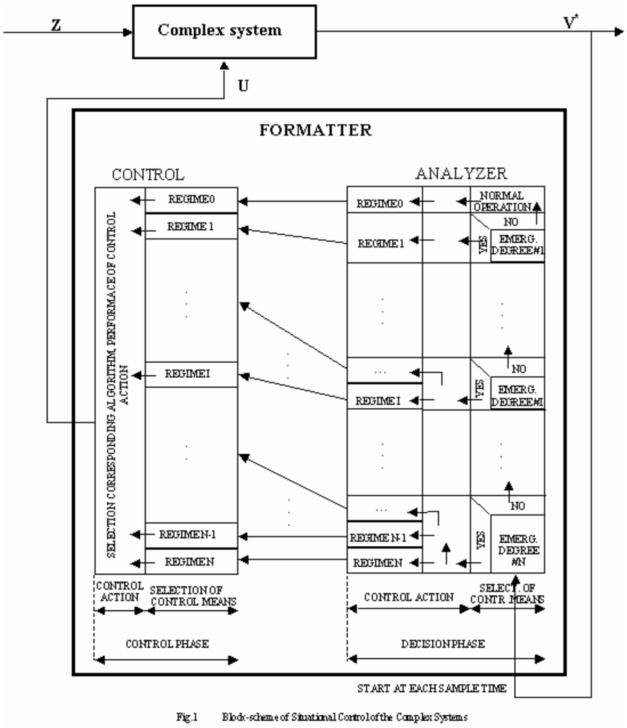

Figure 1
The functional scheme of a cycle in situational control

The control process itself is composed of two phases, decision and the control phase, where each of them is divided into a classification and an action phase. Processed situation is analyzed in the selection part of the decision phase. According to results of situational analysis a situation is then assigned to one of the “N” standard situations, which are designed to process according emergency situations. Every standard situation has a certain file of algorithms which are saved in memory to its disposition. During the action period of the decision-making phase, the most suitable file of algorithms is being activated to process the given situation.

During the selection interval of the control phase, these algorithms adapt themselves for solution of according situation (parameterization and other adaptation connected with activation). Realization of control activity occurs then in the action period of the control phase (Madarász, L., 1996).

For the design of a system respecting the requirements of control in anytime, the following algorithm is proposed [5]:

a) description of the structure and function of the controlled complex system,

b) global goal designation,

c) classification of erroneous operational states and their causes,

d) classification and description regimes functions of the control, that are assigned to individual erroneous states,

e) algorithmization of individual regimes of control,

f) implementation.

By algorithmization and design of regimes of control and also by the design of a classification mechanism, it is today necessary to consider use of robust intelligent methods for these tasks. In the past for situational classification methods of multi-criteria decision making [1], expert system [5], or catastrophe and chaos theory have been used. Nowadays however, as classification systems neural networks that are able to approximate any continuous function with the ability to learn. By proposal and algorithmization it is necessary to choose a very susceptive approach to selection of an optimal modern method to control the chosen complex. In the following chapters we will be aimed at hybrid approaches in this area.

3 Aircraft Turbo-compressor Engines

3.1 Object Description

Aircrafts' turbo-compressor engines represent one specific class of complex systems. They represent high dimensional objects of control with the existence of cross bindings between inputs and outputs which are created by the complex thermo-mechanical processes ongoing in the inner parts of an engine with dominating load. Except the poly-functional and crossing dependencies also other dependencies may arise by synthesis of the control elements, which can seriously influence the functionality and integrity of the whole mechatronic object (engine+aircraft). General aim of control of high dimension objects, objects with s_{ij} parameters is to obtain the optimal quality and stability of the whole control circuit. Techniques of solution of this task are represented by two basic approaches [6]:

1. Achievement of local extremes (minimum, or maximum) of every of the control variables. This approach is the most common one nowadays. The effective method by this approach is the comparison of desired parameters of an engine with the actual parameters, by a certain control system.

2. Achievement of a global (general) extreme by a general quality marker which is dependant upon all control variables. Such marker may be specific

fuel consumption by an aircraft turbo-compressor engine which is the resulting variable of a whole complex of parameters.

For evaluation of control quality, except these main approaches, other criteria are used, as susceptibility of a system to changes of object characteristics. Small susceptibility of a system to changes of object parameters has a great impact for function of the whole system. Also from this point of view, it is suitable to use methods of situational control and situational classes with according control algorithms. This means control of an engine, also in its critical states and thus to secure low susceptibility of the control system to erroneous state of the engine.

As mentioned before ATCE (Aircraft Turbo-Compressor Engines) are characterized by some unique characteristics compared to other engine classes (rocket, scramjet, piston, atom). Also from the complexity point of view the individual types of ATCE differ greatly. ATCE can be generally divided upon the basis of technical design into the following classes [7]:

1 According to the number of shafts (single shaft, double shafts, ... , n-shafts).

2 According to the number of air streams (single stream, double streams, triple stream).

3 According to the compressor type (radial, axial).

The basic scheme of a double shaft, single stream ATCS is shown in the following figure:

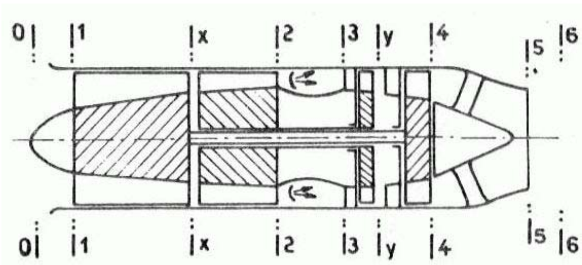

Figure 2
Scheme of a single stream, double shaft engine [8]

3.2 Mathematical Model of ATCE

First of the points of situational control system proposal is the creation of a mathematical model and structure description of the investigated system [5]. By completion of the mathematical model it is necessary to take in account the type of solved task and upon this basis to build an adequate mathematical model. For one type of ATCE, it is possible to build more non-equal models.

For the needs of proposal of regulation elements and demonstration of use of situational control methods we will consider a linear model of double shaft, single stream engine without afterburner. The structure of linear dynamic model can be expressed in the state space though a form of state growths in the following manner:

$$\Delta \dot{\mathbf{Y}} = \mathbf{A}\Delta\mathbf{X} + \mathbf{B}\Delta\mathbf{U}$$
$$\Delta \mathbf{Y} = \mathbf{C}\Delta\mathbf{X} + \mathbf{D}\Delta\mathbf{U} \quad (1)$$

While the individual vectors on the right side of (1) have the following dimensions:

$\Delta\mathbf{X} = [\Delta n_1; \Delta n_2; ...; \Delta n_r]$ - State coordinates of rotors of ATCE

$\Delta\mathbf{U} = [\Delta u_1; \Delta u_2; ...; \Delta u_m]$ - Vector of the control variables (2)

$\Delta\mathbf{Y} = [\Delta y_1; \Delta y_2; ...; \Delta y_s]$ - Vector of the observed variables of ATCE

r, m, s – number of compressor stages, control variables, observed variables.

Matrixes of the individual coefficients of the engine have the following dimensions:

$\mathbf{A}[rxr]; \mathbf{B}[rxm]; \mathbf{C}[sxr]; \mathbf{D}[sxm]$ - parameters to find. (3)

Calculation of parameters will be done upon the basis of measured offsets from a stable regime of the engine operation, for example on an engine brake. From the investigated double shaft aircraft turbo-compressor engine we will consider a model that isn't influenced by the outer environment conditions. Within the frame of this engine complex we will model the following attributes (3).

1 State parameters of ATCE:

- Δn_1; Δn_2 – growths of rotations upon the stages of rotors (compressors)

2 Control parameters of ATCE:

- G_{pal} – fuel supply (dependant upon the lever of engine control)

3 Observed parameters of ATCE:

- ΔT_{pr}^* – temperature beyond the combustion chamber
- ΔT_T^* – temperature at the turbine
- Δp_t^* – pressure increase at the turbine
- Δp_k^* – pressure increase on the compressor
- ΔT_k^* – temperature increase on the compressor
- ΔG_v^* – air flow increase through the shaft of the engine
- ΔP^* – increase of thrust of the engine

Structure of the model has the following form according to (2):

$$\Delta \dot{\mathbf{n}} = \mathbf{A}\Delta \mathbf{n} + \mathbf{B}\Delta \mathbf{u} \quad (4)$$

$$\Delta \mathbf{y} = \mathbf{C}\Delta \mathbf{n} + \mathbf{D}\Delta \mathbf{u}$$

while:

$$\Delta \mathbf{n} = [\Delta \mathbf{n}_1 ; \Delta \mathbf{n}_2]; \Delta \mathbf{U} = \Delta G_{pal}; \quad (5)$$

$$\Delta \mathbf{Y} = [\Delta T^*_{pr}; \Delta T^*_T; \Delta p^*_{pr}; \Delta p^*_T; \Delta T^*_K; \Delta G^*_V; \Delta P]$$

After completion of systems of equations resulting from (2) and (4) and induction of the known parameters of meassured values (2), we can build a linear model of our double shaft ATCE. Parameters count would become higher if we consider ed engine as an object acting in outer environment, but also by adding other control variables (control of angle of the compressor blades, control of the cross section of the engine outlet, afterburner). The resulting dynamic linear model of a double shaft engine is shown in picture 3.

3.3 Simulations of the Linear Model of ATCE in Connection with Methodics of Situational Control

ATCE is a system in general that able to stabilize itself. Such a self stabilizing system has however too long responses to changes of the control variables, furthermore non controlled influence of fuel supply and the random processes from outer environment would cause a danger to the engine's operation. To show, how a situational control system would be able to handle such system we will use a clean non-regulated self stabilizing model. From the proposal of situational control methods point of view it is necessary to describe the situational frames (classes) and to design the control strategies for them, together with composition of these into the global model of situational control. Behavior of such system upon a linear model shows picture 4.

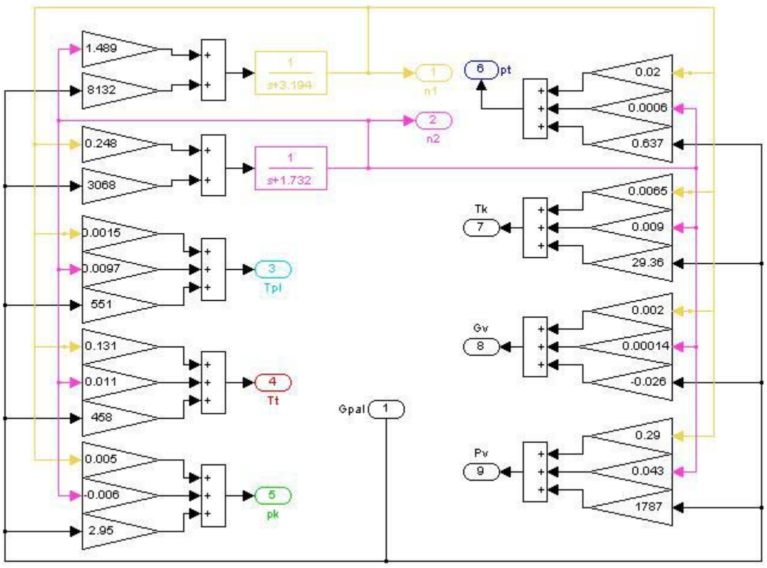

Figure 3
Model scheme of the double shaft ATCE

Colors of individual variables correspond with the colors shown in figure 3 and their interpretations in (3).

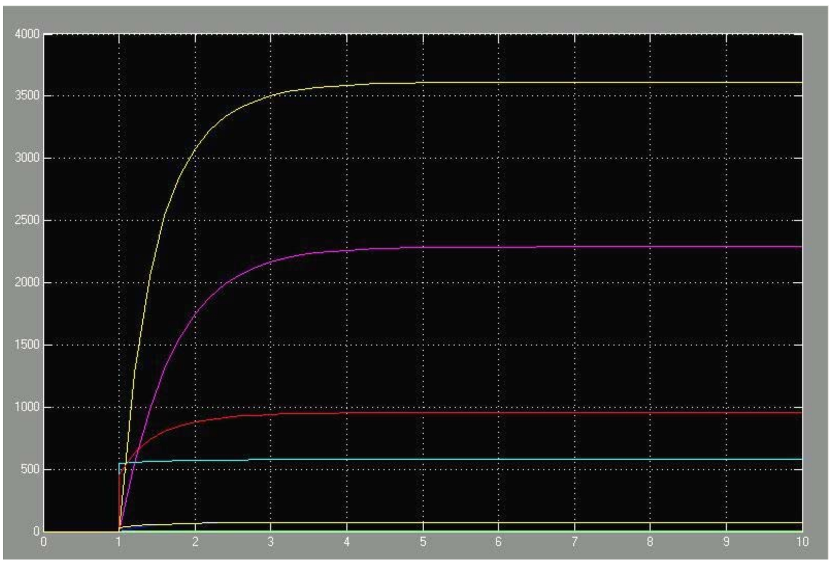

Figure 4
Response of ATCE to a single step change of fuel supply

As for operation of jet engines is the situation in figure 4, which actually represents the start of an engine. This point would become one of the situational frames (**frame 0)**, as in this situation it is necessary to observe and control functions of all observed variables and to make only small or none regulation hits and in case of any possible emergency to shut the engine down. This frame represents startup diagnostics of the engine.

Situational frame 1 - represents control of engine during normal conditions and circumstances where changes of the inner variables vary only within acceptable regions.

Situational frame (frame 2) - error of the high pressure compressor:

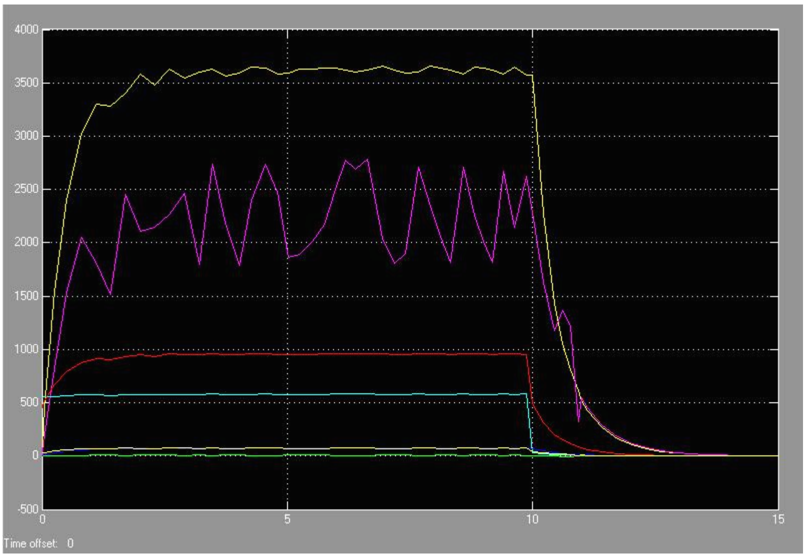

Figure 5
Error of the high pressure compressor

The engine is less susceptible to errors of HP compressor, therefore it is not necessary to shut down the whole system if an error occurs. It is however important to observe and evaluate progress of this error by the prediction module (fig. 11), limit maximum output and rotations per minute with the aim to get the engine into a stabile state. If the system exceeds maximum values shut down of the whole engine, or only the damaged stage of compressor.

Situational frame 3 – represents an error of the low pressure compressor, shown in figure 9.

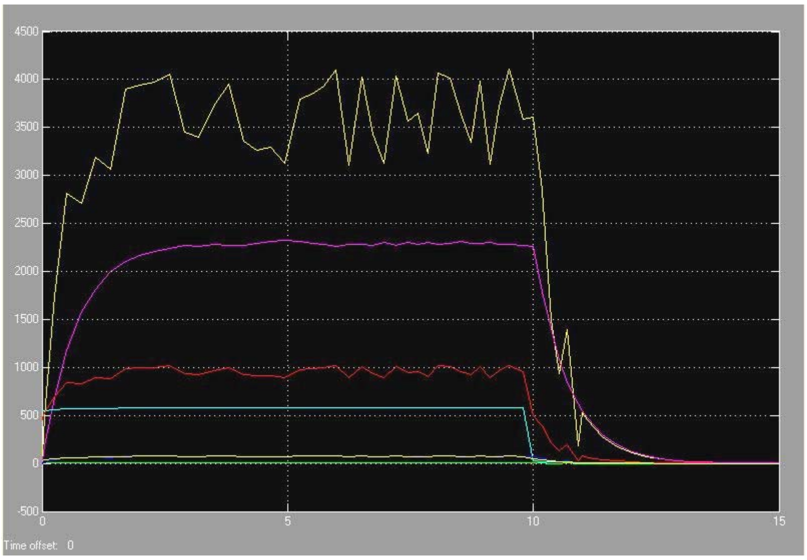

Figure 6
Error of the low pressure compressor

Error of the low pressure compressor is much more cardinal problem for operation of the whole engine complex. The low pressure compressor represents the input system for the double shaft engine and thus influences all parameters of the engine and has a big impact upon the turbine temperatures, where exceeding of maximum values may lead to destruction of the system. Error indicated in the figure 9 may also represent turbulence. To handle this situation strategy is to lower the rotations of the input compressor so it wouldn't exceed the temperature limits upon the turbine.

4 Model of Situational Control of ATCE

In the basic aprroach we are coming from a structure of a formatter control system and the functional scheme shown in the figure 1. We expect use of the formatter control of the complex, that means that the controller is able to change the form of a complex (for example angle of blades of compressors in an engine, outlet die diameter, some circuits disconnection, etc.)

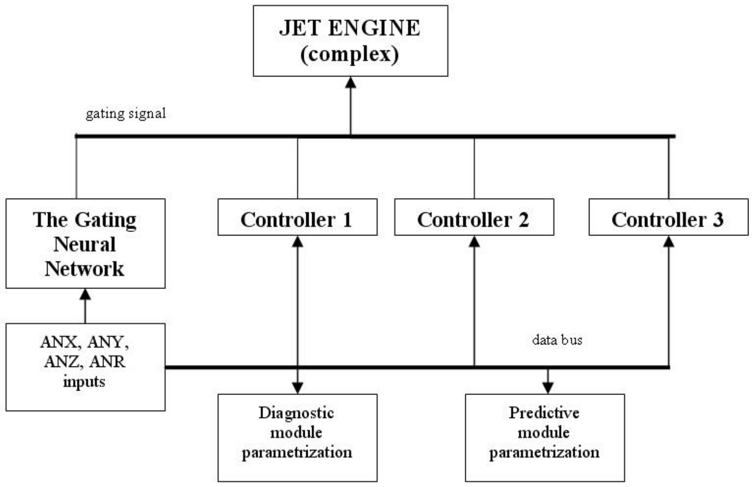

Figure 7
Model of Situational Control of Aircraft Turbo-Compressor engine

- Executive module – the actual set of control systems, that execute the final action hit to the complex.
- Predictive module – makes decisions prior to actual situations, that are based upon the conditions given by ANX, ANR, ANZ variables. This module influences actual parameters of controllers of the executive module. For example it may change characteristics of the control to prevent an emergency situation.
- Diagnostic module – observes variables of the actual object (a jet engine) and evaluates if an emergency situation has occurred and according to such situation makes a direct hit (e.g. shutdown, or influencing the executive module through controller parameters).

This is a general approach to control of a complex system like a jet engine. In the following part we will try to propose the architecture of a model of the executive module of situational control. There are many possible ways how to realize the actual classification of actual situations into situations frames. We selected a connectionist neural network to do the actual classification. Here many approaches may be selected to obtain the best results. As a perspective approach we consider the ART networks and use concretely PointMAP network [25]. This network will work as a gating network, which will set gates for the individual controllers used in the system.

Three regulators and a diagnostic module represent four situation classes. First one, the startup of an engine would be handled only by the diagnostics module, which would observe all variables of the engine and in case of emergency shut the engine immediately down. Other three controllers represent three possible situational classes, as described in chapter 5.

- **Controller 1** – regulation under normal conditions of the engine's operation. It can be realized by a traditional PID system, which is in present state often implemented in the form of a mechanical subsystem of an engine.
- **Controller 2** – use of a fuzzy regulator for regulation of an engine by non-stable function of rotations of the high pressure compressor. Diagnostic module indicates error of this subsystem an may directly parameterize the regulator if needed to minimize the error with the cooperation of the predictive module.
- **Controller 3** – use of a fuzzy regulator for regulation of rotations of the low pressure compressor. Again with cooperation of the diagnostics module indication of errors occurs and upon this basis parameterization of the regulator may occur.

Conclusions

Situational control of complex system is based upon the situational classification, situational estimation and situational recognition of an actual situation into premeditatedly prepared situational frames (classes). A corresponding control strategy (regime) is then associated with these frames, which has to secure a function of the complex and according to circumstances also its return into a normal, or desired state. Together with the mentioned problem areas, questions of proposal of a general control architecture come into foresight and also incorporation of principles and methods of artificial intelligence allowing adaptation not just in offline, but also in online mode of operation. The proposed system is one of the possible realizations of situational control of an aircraft turbo-compressor engine with hybrid neuro-fuzzy architecture. A system using methods of situational control will bring more optimal and safer operation of these engines.

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