Hindawi
International Journal of Aerospace Engineering
Volume 2018, Article ID 8328792, 16 pages
https://doi.org/10.1155/2018/8328792

Research Article

Intelligent Situational Control of Small Turbojet Engines

Rudolf Andoga, Ladislav Főző, Jozef Judičák, Róbert Bréda, Stanislav Szabo, Róbert Rozenberg, and Milan Džunda

Faculty of Aeronautics, Technical University of Košice, Rampová 7, 041 21 Košice, Slovakia

Correspondence should be addressed to Rudolf Andoga; rudolf.andoga@tuke.sk

Received 8 December 2017; Revised 16 March 2018; Accepted 27 March 2018; Published 26 June 2018

Academic Editor: Konstantinos Kyprianidis

Improvements in reliability, safety, and operational efficiency of aeroengines can be brought in a cost-effective way using advanced control concepts, thus requiring only software updates of their digital control systems. The article presents a comprehensive approach in modular control system design suitable for small gas turbine engines. The control system is based on the methodology of situational control; this means control of the engine under all operational situations including atypical ones, also integrating a diagnostic system, which is usually a separate module. The resulting concept has been evaluated in real-world laboratory conditions using a unique design of small turbojet engine iSTC-21v as well as a state-of-the-art small turbojet engine TJ-100. Our results show that such advanced control system can bring operational quality of an engine with old turbocompressor core iSTC-21v on par with state-of-the-art engines.

Dedicated to the memory of Ladislav Madarász

1. Introduction

From the cybernetic point of view, aeroengines are nonlinear systems with complex dynamics operating in stochastic environment in a broad range of conditions as principally described in traditional handbooks [1, 2]. Energetic efficiency, ecologic efficiency, and safety are today the key factors in their development. Small gas turbine aeroengines are specifically characterized by compact dimensions weighing from 0.5 to 50 kilograms and relatively high static thrust outputs in the range up to 1500 N, producing very high power to weight ratios as defined in [3]. Such engines represent a great potential for commercial applications in different areas of aviation for propulsion of drones and small UAVs described in [4], as well as small airplanes or helicopters [5]. Because of compact dimensions as well as cost-effective operation and production, these engines can serve as experimental testbeds for research purposes as can be seen in the work of Benini and Giacometti [3], where a small turbojet engine with static thrust of 200 N has been designed. The idea of utilizing small turbojet engines for rapid prototyping of algorithms and construction has also been pursued by other authors, Pecinka and Jilek designing a cost-effective test cell for small turbojet engines [6], application of small turbojet engines in education described in the works [7, 8]. Small turbojet engines have also been used as testbeds in research of application alternative fuels for gas turbine engines using synthetic as well as biofuels in the works of Badami et al. [9, 10] or optimization of jet fuel combustion processes described in [11]. Small turbojet engines can be also used for aeroengines' component design and optimization as illustrated in optimization of turbine blades [12] or centrifugal compressors [13]. Small gas turbine engines have also been utilized in general gas path optimization described in sources [14, 15]. This research review shows that small gas turbine engines are a rapidly developing technology, which is usable not only for specific propulsion of different aerial vehicles but also for usable testbeds for rapid prototyping of components for normal-sized gas turbine engine.

In order to improve operational efficiency of gas turbine engines, constructional design changes can be done, like compressor redesign [13], combustion chamber material and design improvements, fuel nozzle redesign [11], or turbine blade redesign [12]. The other approach is to increase efficiency through design and implementation of progressive control algorithms utilizing digital control systems with a self-tuning control system as designed by Adibhatla and Lewis [16]. This allows improving operation of the controlled engine only through software algorithm updates, which may be a cost-effective solution especially in the area of unmanned systems, where certification is not as complicated as in general aviation legislation. Based on the previous state-of-the-art review, it can be concluded that utilizing small gas turbine engines for prototyping of new control methodologies and approaches is a new area, which has not been thoroughly explored and has a great potential even for applications in gas turbine engines used in civil general aviation.

Gas turbine engines currently used in general aviation are mainly controlled using digital engine control systems with full control authority—FADEC (full authority digital engine control), utilizing certified standard algorithms for handling the engine's operational states as well as managing its auxiliary systems and thrust as is systematically described in the textbooks [17, 18].

Algorithms, which are certified and commonly used in control of gas turbine engines, are based on the proven methodology of PID control [17] as well as scheduling strategies for higher level controllers like power management [18]. On top of that, special strategies like limiters and auxiliary systems are used to protect the engine from departing its operational envelope [19]. Transient states of the engine are handled by acceleration/deceleration min/max schedulers [19], typical architecture of the baseline digital engine control using engine protection logic being shown in the recent work of Connolly et al. in [20]. Diagnostics and health management are usually running as a separate process influencing operation and control of the engine using limiters [18, 19]. Life-extending measures like employment of the N_dot control methodology can be taken as progressive [21].

Utilization of digital control systems having the engine's control algorithms and laws running as software allows improvement of its efficiency only by modification of those algorithms or updating the control laws. This has been pursued by many authors in the recent decades bringing advances in the field of control theory and computational intelligence into control systems of gas turbine engines in order to increase their efficiency and reliability without the need of structural optimizations of the engine's components as comprehensively described in a survey of intelligent technologies for application in gas turbine engines [21, 22].

An approach, which is quite often used in advanced concepts of gas turbine engine control, is the use of the methodology of adaptive control [23, 24], using specialized model-based algorithms to change or compute coefficients of PID controllers according to environmental or model parameters as presented for example in [16]; adaptive control methodology can also utilize engine performance and health computational models to adapt controllers as shown in the conceptual designs described in [25] and, on theoretical level, analyzed in [26]. These works are providing a link between engine diagnostic and control systems, while also using methodologies of computational intelligence (ARMAX model) as for example applied by Mu et al. in [27]. Other approaches which have been taken in advanced control of gas turbine engines were robust, LQ, and optimal control. These methodologies have been already found to be beneficial in solution of complex control problems as illustrated for example in [28, 29]. They were successfully applied in the envisioned engine control systems, the robust control algorithm being described in [30], and LQ control algorithms applied in gas turbine engine control [31, 32]. Even more advanced methodologies like model predictive control [33] or hybrid fuzzy-genetic algorithms have been proposed in adaptation of gas turbine engine controllers as described in [34].

The works from the area of adaptive control link control algorithms to diagnostic algorithms or engine health evaluation algorithms as described in [25, 26]. Digital diagnostic systems are directly connected to safety and reliability of any control system operation but are however often investigated as separate systems utilizing progressive methodologies and algorithms like support vector machines and decision trees as designed in [35] or application of neural networks in engine fault detection as described in [36] connecting the diagnostic system to the engine's control system. Fuzzy inference rule-based diagnostic combined with neural networks system has been also proposed for application in fault detection system of gas turbine engines in [37].

These works illustrate that by application of progressive control methodologies, efficiency, reliability, and safety of operation of gas turbine engines can be improved. However, most of them base their results and conclusions solely on simulations like [19, 27, 30, 34] or present only conceptual designs like [21, 22, 25]. Application of methodologies from the field of computational intelligence can also be seen together with interconnection of diagnostic and control systems [21, 22, 27], which can further enhance the control system's reliability and efficiency.

The aim of the research presented in this paper is to design a highly integrated control and diagnostic system suitable for control of gas turbine engines, which is modular and able to combine different progressive as well as classical control methodologies in a unified architecture, thus increasing efficiency of the complete system. Emphasis in this design is put on strong integration of the control system with diagnostics and the ability to control the engine also during atypical operational states using the most efficient controller in the current situation. The designed system is presented as a framework architecture using the methodology of situational control modified specifically for digital control of gas turbine engines.

Contrary to most results presented in research papers, the aim is to prove the operability of the framework control system's design in real-world laboratory conditions utilizing a small turbojet engine iSTC-21v with static thrust of 500 N based on an old turbostarter TS-21. The resulting prototype architecture of the control system is aimed to bring the efficiency of this old turbocompressor engine design to modern standards by application of the designed situational control framework. This framework is aimed to be specifically applied on small turbojet engines; however, it is expected to be also applicable on normal sized gas turbine engines, using the small engine as a demonstrator of the approach.

2. Situational Control Methodology Framework Design

It is very difficult to design a single controller, which will be able to control a complex dynamic nonlinear system operating in a stochastic environment with high quality in all its operational states. Progressive methodologies like robust control [30], linear quadratic control [31, 32], and model predictive and fuzzy control [33, 34] are able to produce controllers robust enough to cover a large spectrum of states and uncertainties; they are however often computationally too complex as shown in the references. Another approach, which has already been often used in solution of control problems, is to design simpler specific controllers for specific operational states of the investigated dynamic system for example in an application using different controllers for gas turbine generator and power system of aeropropulsion system as described in [38].

In aviation, this approach is widely used in flight control systems with a broad spectrum of applicable algorithms [39] combined in modern avionic digital control systems [40] as well as engine control system switching control algorithms for optimal dynamic characteristics [41]. In flight control, the control laws are different for different flight phases like ground, take-off, flight, and landing [40]. A similar pattern can be found in aeroengine control algorithms—the oldest approach is the application of acceleration schedulers, which are specialized controllers to handle acceleration as a special control strategy as shown in the traditional engine control concept [21]. Setpoint/trim controllers are then used to keep the engine at a stable operating speed or thrust [17, 21].

It is a logical step in solution of control problems being able to design simpler and more specialized controllers for certain operational states as defined in [21] having different control loops for limiting, governing, and acceleration/deceleration. These control approaches are however not integrated; individual controllers are not interacting and are switched only by the use of minimum or maximum selection logic [21, 22] or using energy-based switching as shown in [41]. On the other hand, situational control represents an interconnected controllers' framework usable in control of complex dynamic systems under all operational states, emphasizing control in the atypical ones as defined by Madarász et al. in [42], not just using limiters in order to protect the engine's envelope but allow active control during atypical operational state, like high angle of attack flight, engine overheat conditions, and compressor stalls.

The basic foundation design of a situational control system suitable for general application on turbojet engines has been developed in [42] and expanded in [43]; the resulting basic control concept is shown in Figure 1. Analyzers process the measured data describing the operational state of the system and are defined as input (ANX), output (ANY), state (ANZ), and control (ANR).

All operational states of the controlled complex system are then decomposed into n situational frames, which represent specific groups of operational states. In case of a gas turbine engine, these can be states like start-up, acceleration, and stable operation. The situational classifier is acting here as a decision-making element, selecting controllers in an intelligent manner to handle certain situational frames with the highest control efficiency. This high-level modular concept represents the design base for the situational control system, which can be further modified for application in gas turbine aeroengines with possible combination of any control algorithms nowadays used or proposed for gas turbine engines. The concept of situational control methodology designed by the authors also creates a platform for strong integration of the engine's diagnostic system into its control this integration being described in [43]. Development of the diagnostic system and its integration into the situational control system is further described in [44].

On the basis of these previous development iterations of the situational control system as presented in [45], a new complex general architecture has been developed, which is suitable for turbojet, turboshaft, and turboprop engines presented in Figure 2. The new core part of the system is the intelligent supervisory element, which largely expands functions of the situational classifier replacing the one designed in [45] and previous publications [42, 43]. The resulting design is original and based on practical experiments with the iSTC-21v engine in laboratory conditions. Intelligent supervisory element is integrating diagnostic module, selecting individual controllers, and computing command signals for individual situational controllers C_i. The diagnostic module generates disturbance indications, thus helping situational classification and validates the selected parameters of the engine and its environment; these data are then used by the individual controllers as well as the intelligent supervisory element. Description of the designed diagnostic module can be found in [44, 45].

The newly designed intelligent supervisory element has to solve the following tasks in the proposed expanded implementation shown in Figure 3:

(i) Power management—setting the optimal command values for speed, exhaust nozzle diameter, propeller pitch, or shaft load

(ii) Situational classifier—classification of the engine's operational state into a situational frame

(iii) Situational selector—an algorithm securing fluid switching between individual controllers and generating controller selection gating signals

(iv) Adaptive limiters—adaptive limits in order to keep the engine operating within changing operational envelope for increased safety

The main task of the power management is to calculate the optimal commands for the engine's main state parameters. These are commands for the controlled variables like the turbocompressor's setpoint defined as its shaft speed or the propeller's speed or defined by its angle of attack. The

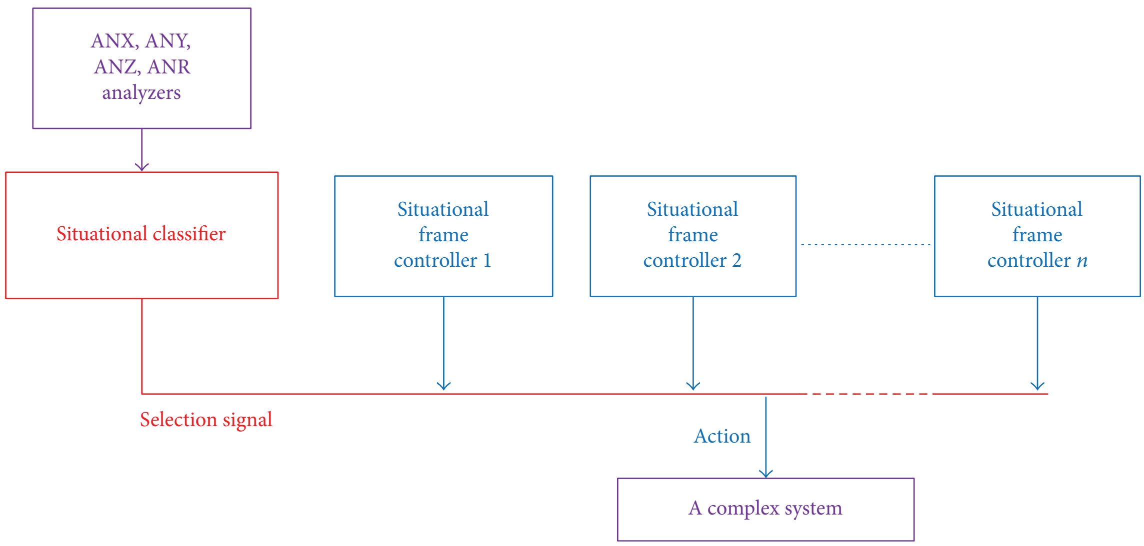

Figure 1: The basic concept of the situational control system [42, 43].

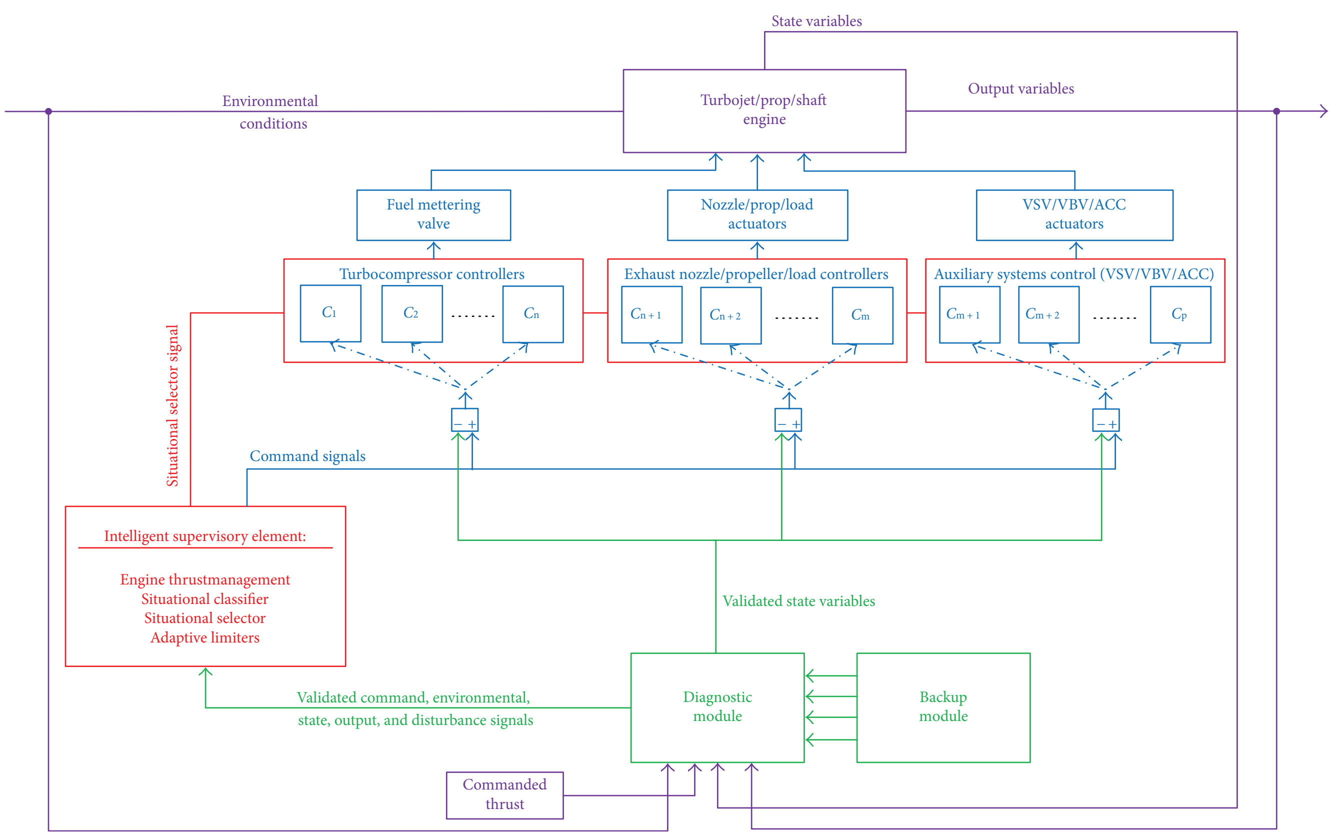

Figure 2: The designed situational control system for gas turbine aeroengines.

block also contains a situational classifier, which finds the situational frame (or mode) in which the engine currently operates. This indication is then sent to the situational selector, which secures fluent transitions between the switched controllers on the lower level and assigns the corresponding controller to the actual situational frame.

The composition of the system including the lower level controllers is shown in Figure 4.

Safety is maintained by operating the engine within its operational envelope using a set of adaptive limiters; the commanded parameter as computed by the lower level controllers is being compared to the output of the adaptive limiters, and a minimum or maximum is selected. Adaptivity of the limiters relies on the principle that the maximal shaft speed or exhaust gas temperature of the engine can be adjusted according to flight conditions or

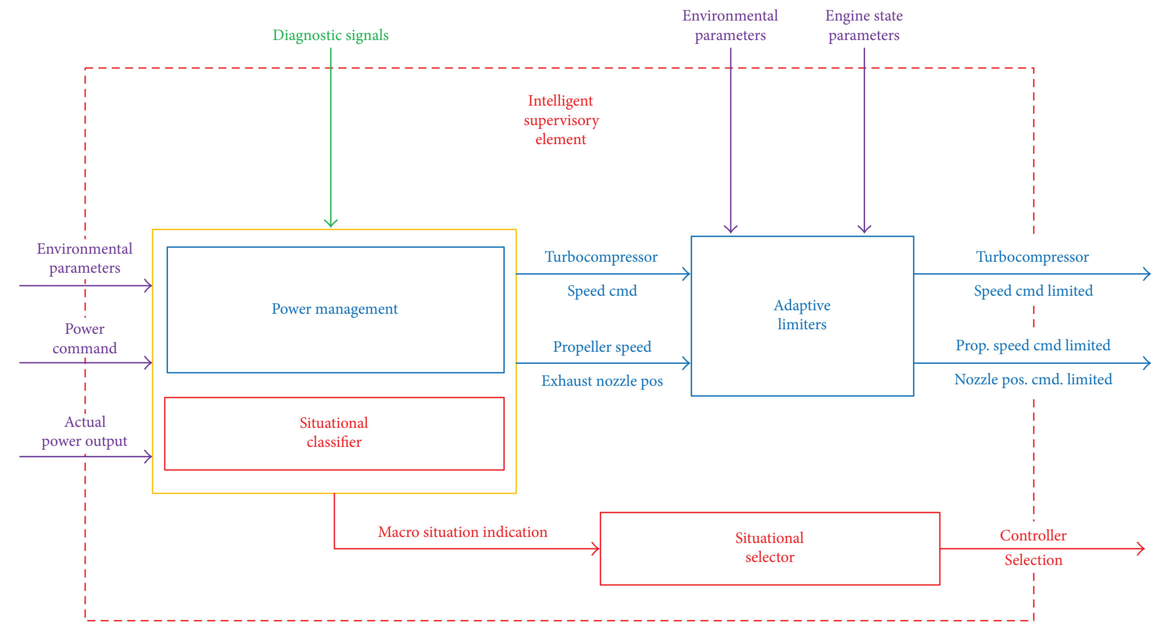

Figure 3: Intelligent supervisory element.

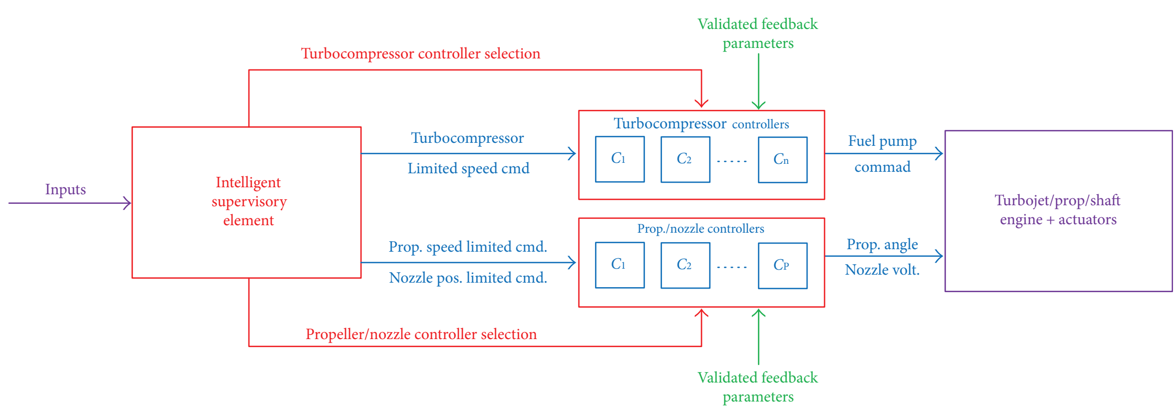

Figure 4: Connection of the intelligent supervisory element with lower level controllers.

environmental conditions. The expanded situational control system developed in Figures 2, 3, and 4, as framework architecture, is the foundation of an intelligent FADEC or i-FADEC to be implemented and tested on a small turbojet engine. In order to design similar situational control frameworks and to define its elements, the following design steps are proposed:

(i) Selection of operational parameters for individual data analyzers

(ii) Decomposition of all operational states of the system into situational frames

(iii) Selection of the methodologies used in the subsystems of the intelligent supervisory element

(iv) Selection of the methodologies for the diagnostic and backup system

These steps will be taken in order to use this framework for design of a situational control system for a small turbojet engine iSTC-21v.

3. A Small Turbojet Engine: An Experimental Object

Small turbojet engines present an ideal platform for development and testing of advanced control algorithms for gas turbine engines as mentioned in the introduction chapter. An experimental small turbojet engine iSTC-21v has been developed from the turbostarter TS-21 used in turboshaft configuration for start-up of normal-sized aircraft engines, used in legacy aircraft utilizing engines Lyulka AL-21F and Tumansky R-29, characteristics of it being described in [46]. It is a single spool, single stream engine with a radial compressor and a single-stage noncooled turbine of old design in a standard configuration of a small gas turbine engine as described for example in [2, 3]. It has been modified by the authors having implemented a digital control system with a direct control of fuel flow supply utilizing a BLDC oil/fuel pump as an actuator in a similar arrangement to the most modern small turbine engines like the TJ-100 engine together with digital data acquisition system [5, 46]. Moreover, the engine was expanded and redesigned with a digitally controlled variable exhaust nozzle, which is a unique design in this class of turbojet engines [46]. The engine on a test bench as used in laboratory conditions is shown in Figure 5. It has to be noted that its turbocompressor core components have unknown history as it was salvaged from a flight unworthy aircraft. Using auxiliary power units or turbostarters from flight unworthy aircraft is a cost-effective solution for testing and design of progressive algorithms for this class of engines.

The following basic engine parameters are measured at the basic sampling frequency of $f_s = 10$ Hz using a National Instruments Compact DAQ system and are used in control of the engine in individual data analyzers, the measurement system being described in [45, 46]:

(i) Outside air temperature T_0 (°C) and atmospheric pressure P_0 (Atm)

(ii) Total air temperature at the inlet of the radial compressor T_{1C} (°C)

(iii) Total air temperature at the outlet from the diffuser of the radial compressor T_{2C} (°C)

(iv) Total gas temperature at the inlet of the gas turbine T_{3C} (°C)

(v) Total gas temperature at the outlet of the gas turbine T_{4C} (°C)

(vi) Total pressure of air at the outlet of the compressor P_{2c} (Atm)

(vii) Total pressure of gases at the inlet of the gas turbine P_{3c} (Atm)

(viii) Fuel flow supply FF (l/min)

(ix) Thrust T_h (kg)

(x) Shaft speed of the turbine/compressor, n_1 (rpm)

(xi) Exhaust nozzle diameter A_5 (mm)

The temperatures and pressures points of the engine measured are the standard measurement points [1, 2] and are specifically for a small turbojet engine in Figure 6.

One run of the engine in laboratory conditions is shown in Figure 7. The graph shows operation of the engine with a stable command of fuel flow supply set at $\mathrm{FF}_{\mathrm{cmd}} = \{0.9\,\mathrm{l/min}\}$ without the situational control system using a traditional closed loop PI controller to meter the fuel flow at the desired level utilizing the electromechanical servo valve LUN 6743 [46]. This is basically showing a state of the engine with only one available setpoint preselected before starting the engine without situational control or other complex control algorithm. The results are illustrative showing the operational parameters of the engine running at a shaft speed setpoint $n_{\mathrm{cmd}} = \{40{,}000\,\mathrm{rpm}\}$.

Fluctuations and disturbances in shaft speed, temperatures, and pressures, as well as other dynamic parameters, can be seen because of the old construction and the technical state of the engine's core components. The aim of the proposed situational control system is to considerably improve the engine's operational qualitative characteristics by application of the situational control methodology.

4. Situational Control System for a Small Turbojet Engine

4.1. Situational Control System Architecture. In order to design a situational control system with an integrated backup diagnostic module, the general framework as shown and designed in Figure 2 has been applied. The whole operation of the engine is systematically decomposed into the following macrosituational frames as envisioned in [44, 45]:

(1) Prestart control

(2) Start-up control

(3) Operational control

(4) Shutdown

Macrosituational frames are the frames, which incorporate several situational frames. The scheme in Figure 8 shows a set of eleven controllers specifically designed to control iSTC-21v engine in the same number of situational frames expanding and reevaluating the situational frames designed in [44]. The resulting architecture of the control system depicted in Figure 8 is highly modular although specifically designed for a small turbojet engine. Modularity of the control system is one of its key design points, and controller elements and other algorithms can be easily added without disrupting the functionality of other subsystems. This design will be further expanded by implementation of the exhaust nozzle controller and implementation of thrust management algorithms.

4.2. Control Strategies and Situational Decomposition. In design of the control system for a small turbojet engine with fixed exhaust, only the turbocompressor controllers block (see Figure 2 and Figure 8) will be defined. The performed situational decomposition consists of situational frames designated as S_i ($i = 1,\ldots,n$; n is the number of situational frames) with the corresponding controllers designated as C_j ($j = 1,\ldots,n$; n is the number of situational frames). If each situational frame has a controller directly assigned to it, then $i = j$ and the controller can be designated as C_i. The situational frames are organized in a horizontal decomposition and cover the following situations in control of the small turbojet engine iSTC-21v.

The situations S_7, S_8, S_9, and S_{10} represent atypical operational conditions with specialized control strategies to handle them and are shown in grey in Figure 8 as well as the

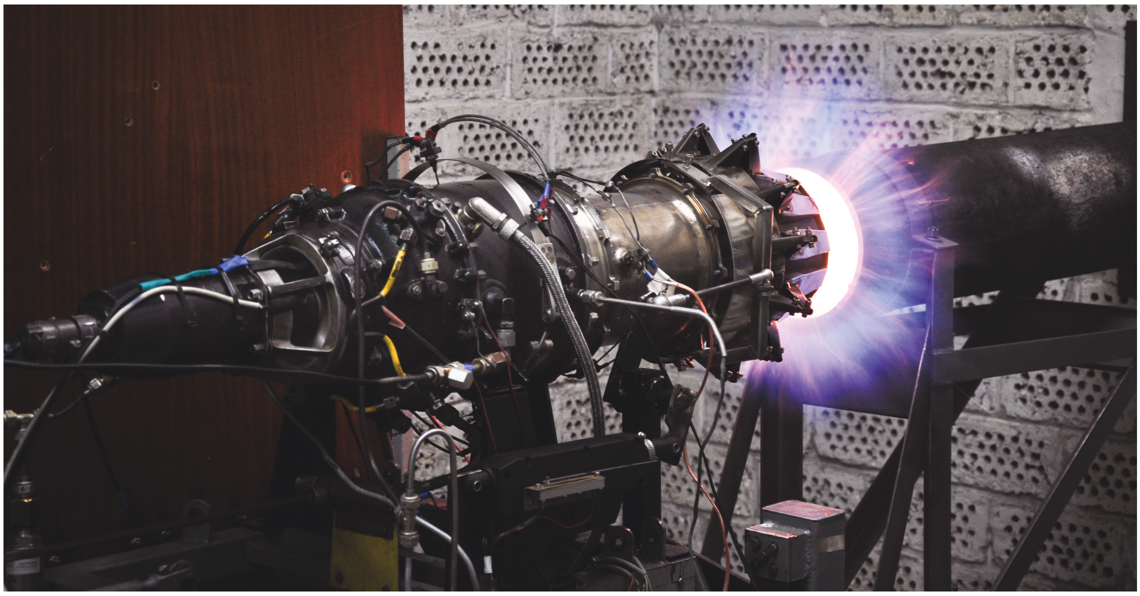

Figure 5: iSTC-21v during operation in laboratory conditions.

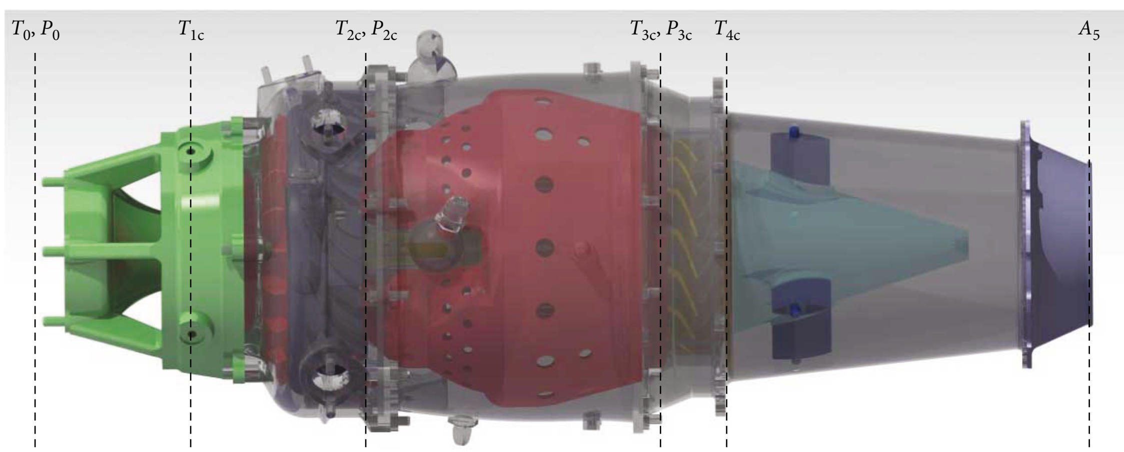

Figure 6: Measurement points on a small turbojet engine.

Table 1. All feedback and command signals are transferred through the diagnostic block, which validates them and in case of any sensor's failure is able to replace its value with a computed synthetic value also being able to trigger atypical situations for the situational selector block [44, 45].

The following standard operational situational frames and the corresponding control strategies have been implemented and tested so far in order to demonstrate the functionality of the envisioned design:

(i) Prestart control strategy C_1: the control system performs a check of all aggregates and powers up all corresponding subsystem needed to be powered for launch [44, 45]

(ii) Launch control C_2: preignition control—spinning the electric starter up to 12,000 rpm, open the fuel valve, and energize spark plugs [44, 45]

(iii) Postignition control C_3: control of startup, during postignition—a feedback adaptive fuzzy controller is used to meter the fuel in combustion chamber in order to minimize EGT peak during startup [43]

(iv) Restricted acceleration/deceleration C_4: a PID controller is used to handle the fastest possible acceleration of the engine without exceeding its operational envelope

(v) Stable operation of the engine C_5: a specialized PID controller is used for handling of the constant speed operations of the engine

(vi) Idle control C_6: precise fuel metering near idle speeds of the engine where flameout might happen

(vii) Engine shutdown C_{11}: disabling fuel flow supply and closing of electromagnetic fuel and oil valves [45]

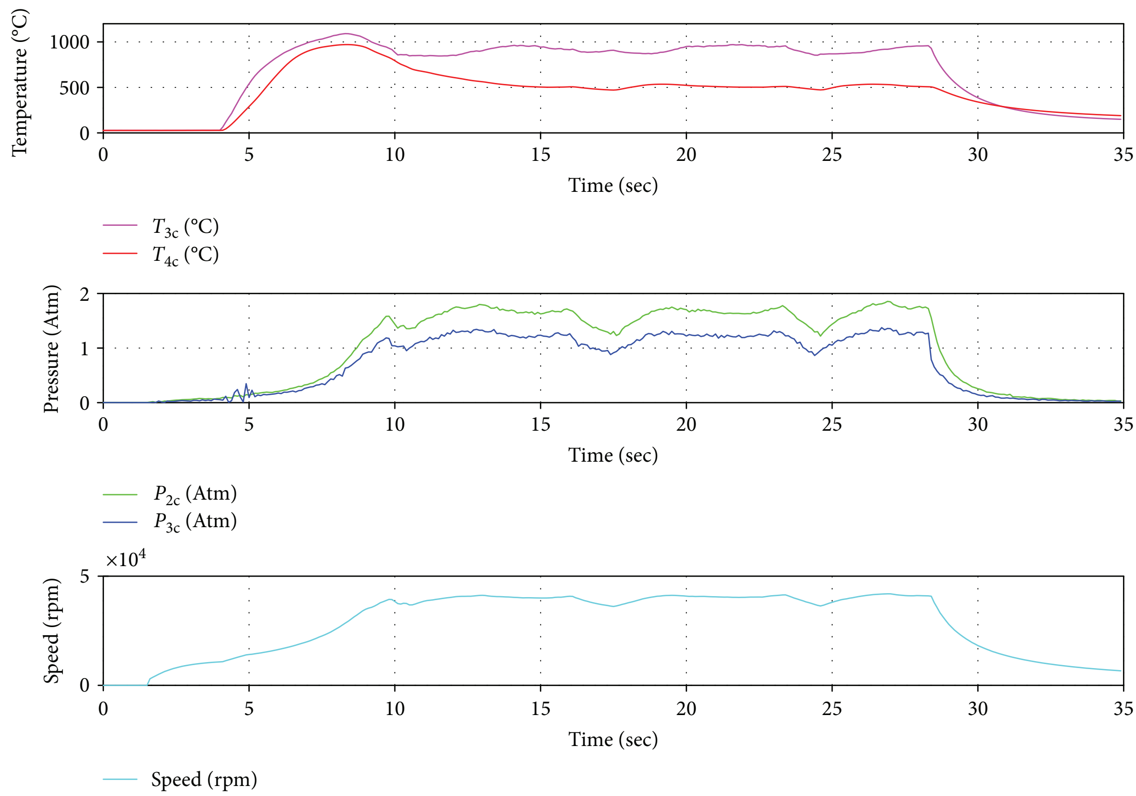

FIGURE 7: Dynamic engine data using the nonsituational PI control system.

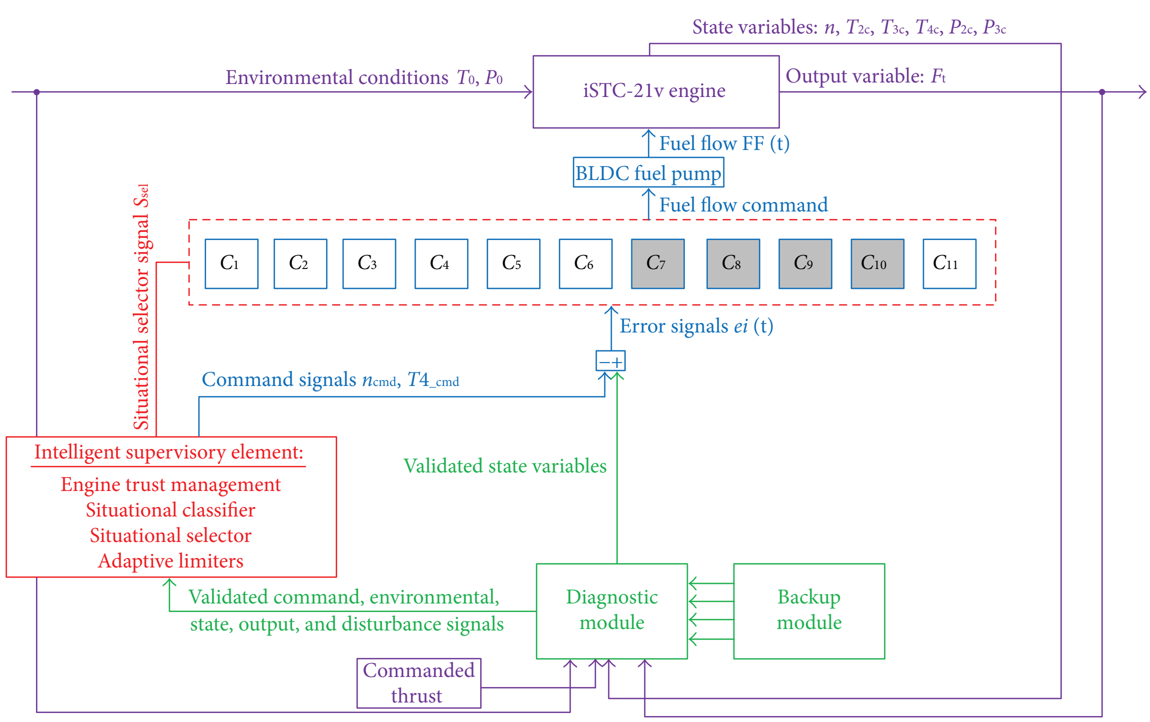

FIGURE 8: The situational control system of the iSTC-21v engine.

Table 1: Definition of situational frames and the corresponding controllers.

Situation	Strategy	Controller
S_1	Prestart control	C_1
S_2	Launch control	C_2
S_3	Ignition control	C_3
S_4	Acceleration/deceleration	C_4
S_5	Stable operation of the engine	C_5
S_6	Idle control	C_6
S_7	Compressor stall	C_7
S_8	Turbocompressor over speed	C_8
S_9	Turbine overheat	C_9
S_{10}	Unspecific degraded mode of operation	C_{10}
S_{11}	Engine shutdown	C_{11}

4.3. Intelligent Supervisory Element. This subsystem is the core element of the complex situational control system; it is acting as a supervisory control system as well as a decision-making element. It is designed to solve the following tasks:

(i) Compute commands for the engine's speed and exhaust nozzle diameter in case of optimal thrust control.

(ii) Evaluate the current state of the engine using all observed and measured parameters and perform situational classification.

(iii) Create switching signals for fluent transitions between controllers and assign controllers to corresponding situational frames—performed by the situational selector.

(iv) Limiting of computed commands and actions for certain control strategies is performed by the block of adaptive limiters.

In order for the concept of the situational control system to work, situational classification and interconnection of control strategies to situational frames are the key factors; therefore, these will be addressed further. The whole operational space of the engine can be described by the vector of parameters defined as $O_s = [E, S, O, I, C]$, which are the inputs of the situational classifier and represent the following parameters:

(i) E is the set of environmental parameters: T_0 and P_0

(ii) S is the set of state parameters: T_{1C}, T_{2C}, T_{3C}, T_{4C}; P_{2C}; P_{3C}; n_1

(iii) O is the set of output parameters: T_{h}, EPR

(iv) I is the set of input control parameters FF, A_5

(v) C is the set of command parameters: n_{1_cmd};$T_{\mathrm{h\_cmd}}$

The purpose of the situational classifier is to transform this multidimensional vector of parameters into a signal which will indicate a situational frame as its output. An ith situational frame S_i either occurs or not, using Boolean logic this means $S_i = \{0\,;1\}$. Fuzzy logic can however also be used, where indication of the ith situational frame would be represented by a closed interval, where $S_i = <0\,;1>$. The resulting output of the situational classifier can be formalized as a vector of indicated situational frames: $S_{cl} = [S_1, S_2, S_3, \ldots, S_i, \ldots, S_n]$, $i = 1, \ldots, n$, where n is the number of situational frames. The situational classifier is then a function which transforms the multidimensional vector of the engine's parameters into the output classifier signal at any given time:

$$S_{\mathrm{classifier}}(t)\colon O_s(t) \rightarrow S_{\mathrm{cl}}(t). \tag{1}$$

Any decision-making algorithm can be used in the role of the situational classifier, be it a rule-based system or a neural network. In the case of situational control of a small turbojet engine, a suitable and computational less intensive approach was taken in the form of combination of a rule-based expert system for indication of start-up and shutdown situations S_1, S_2, S_3, and S_{11} and a fuzzy inference system for indication of the remaining operational situations $S_4, \ldots, S_{10}$.

This combination is necessary in order to secure fluent transitions between the controllers during operational feedback control of the engine, where Boolean indication is enough for start-up and shutdown operational states, where direct feedback control signals are not used. Start-up and shutdown situational frames with the corresponding control strategies are described in [44, 45]. To further enhance the quality of switching of individual controllers, the output of the situational classifier is transformed through time-based first-order differential equations, by the situational selector, output of which is designated as $S_{\mathrm{sel}}(i)$. The selector then transforms the indication-gating signals for the ith situational frame according to the following differential equation in time t:

$$T\,\frac{\mathrm{dS}(i,t)}{\mathrm{dt}} + S(i,t) = S_{\mathrm{sel}}(i,t), \tag{2}$$

where T is an arbitrary time constant.

The time constant defines the speed of situational frame switch; for a fast system like a small turbojet, values from the interval $T = <0.1, 0.7>$ are suitable.

The resulting architecture of the situational classifier and selector systems suitable for small turbojet engines is shown in Figure 9. The situational frames correspond to the designed situational frames for the small turbojet engine iSTC-21v as described in the previous chapter.

The output of the situational selector is used to gate the individual situational controllers, thus fluently switching them on or off. An output from the ith controller can be expressed by its transfer function expressed after Laplace transformation:

$$\mathrm{FF}_i(s) = C_i(s)\left(S_{\mathrm{sel}}(i)e_i(s)\right), \tag{3}$$

where in (3), $\mathrm{FF}_i(s)$ is the fuel flow supply calculated by the ith situational controller, $C_i(s)$ is the transfer function of the ith controller, and $e_i(s)$ is the control error expressed as a difference between the commanded and actual value of

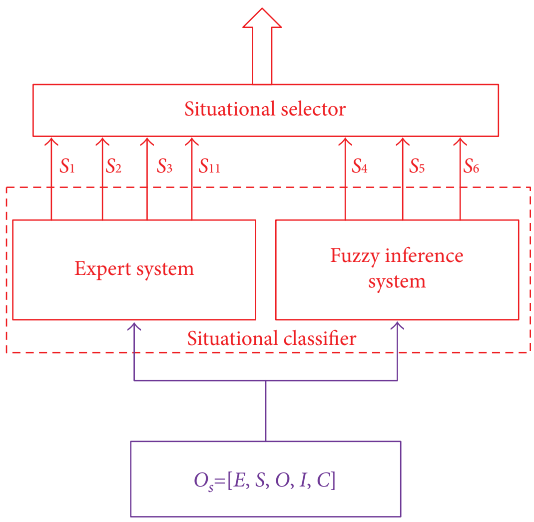

Figure 9: The situational classifier and the situational selector for the iSTC-21v engine.

the controlled parameter. The final commanded fuel $\mathrm{FF}_{\mathrm{cmd}}$ flow for the digitally controlled fuel pump of the engine is then a sum of all fuel flows computed by the individual situational controllers expressed as

$$\mathrm{FF}_{\mathrm{cmd}}(s) = \sum_{i=1}^{n} S_{\mathrm{sel}}(i)\mathrm{FF}_i(s). \tag{4}$$

It needs to be noted here that both the input and the output of the controllers are multiplied by a signal from the situational selector in order to stop individual integrators at their inputs and to reset them at their outputs.

4.4. Design of Individual Controllers. For operational control after ignition and startup of the small turbojet engine, the controllers, C_4—acceleration control, C_5—constant shaft speed control, and C_6—idle control, have been designed and tested. In order to compute parameters of these regulators, linearized dynamic models of the iSTC-21v engine have been used as well as nonlinear dynamic models used for testing and tuning as described in [47]. The simplest controller of these is the idle regime controller designated as C_6. The control law of this controller is defined according to (5), which represents a feedback PI controller operating in a fuel flow feedback loop, maintaining fuel flow at the lowest preset possible value for the iSTC-21v engine:

$$\mathrm{FF}_6(s) = (\mathrm{FF}_{\mathrm{idle}}(s) - \mathrm{FF}_{\mathrm{act}}(s))\left(K + T_i\frac{1}{s}\right), \tag{5}$$

where $\mathrm{FF}_{\mathrm{act}}(s)$ is the actual value of the current fuel flow, K and T_i are the coefficients of the PI controller. The idle fuel flow is set to $\mathrm{FF}_{\mathrm{idle}} = 0.75$ l/min for zero speed and zero altitude conditions. The resulting designed controller has been computed by the Naslin method [48] using a dynamic transfer function model of the fuel supply system. The Naslin method provided the best control quality during tests of the fuel flow control feedback loop. The resulting controller has the following control law:

$$\mathrm{FF}_6(s) = (0.75 - \mathrm{FF}_{\mathrm{act}}(s))\left(0.1 + 0.3\frac{1}{s}\right). \tag{6}$$

In operational control, the acceleration and constant speed controllers are the most important ones, as they are responsible for tracking of command signals [1, 2, 20]. Both controllers can be also designed as a single robust feedback controller [30, 31] or fuel flow scheduler [19, 20]; however, the situational control approach allows to design them as two specialized feedback controllers aimed to improve the resulting control quality. The situational control system with intelligent switching can fluently switch between those controllers and even have them operate in cooperative mode to further enhance control quality in order to remove any transients, which could appear during a switch between the acceleration and constant speed controllers. The acceleration/deceleration controller C_4 is defined as a feedback PID controller with the control law defined as follows:

$$\mathrm{FF}_4(s) = (n_{\mathrm{cmd}}(s) - n_{\mathrm{act}}(s))\left(K + T_i\frac{1}{s} + T_d s\right), \tag{7}$$

where $n_{\mathrm{cmd}}(s)$ represents the commanded shaft speed of the engine by the operator or the higher level engine thrust management algorithm and $n_{\mathrm{act}}(s)$ represents the actual shaft speed. K, T_i, and T_d are the coefficients of the PID controller. The controller is limited in computation of fuel flow constrained in the interval $\mathrm{FF}_4(s) = <0.75, 1.6>$ l/min. Anti-windup algorithm is also implemented for the integrator of the controller. In order to tune the controller, Ziegler-Nichols algorithm has been used [49], as the engine is a nonlinear system with complex dynamics and hysteresis. Individual C_i controllers have been afterwards validated using a simulation nonlinear model based on transfer functions obtained by means of experimental identification [47], with follow-up experimental tuning of the computed PID coefficient during operation of the engine in the region of ±5% from the computed design point.

The resulting acceleration controller has the following transfer function:

$$\mathrm{FF}_4(s) = (n_{\mathrm{cmd}}(s) - n_{\mathrm{act}}(s)) \left(0.000042 + 0.00006\frac{1}{s} + 0.000015s\right). \tag{8}$$

The constant speed controller C_5 has been also designed by means of the Ziegler-Nichols tuning rule resulting in a different tuning of the PID controller corresponding to the different control strategy of constant speed hold, where the resulting fuel flow supply command is a sum of a direct setpoint of the fuel flow supply and the action hit of a less aggressive PID controller with its derivative gain equal to zero:

$$\mathrm{FF}_5(s) = \mathrm{FF}_{\mathrm{setpoint}}(s) + \mathrm{FF}_{\mathrm{PID}}(s), \tag{9}$$

$$\mathrm{FF}_{\mathrm{setpoint}}(s) = a_2 n^2(s) + a_1 n(s) + a_0, \tag{10}$$

$$\mathrm{FF}_{\mathrm{PID}}(s) = (n_{\mathrm{cmd}}(s) - n_{\mathrm{act}}(s))\left(K + T_i\frac{1}{s} + T_d s\right), \tag{11}$$

$$\mathrm{FF}_{\mathrm{PI}}(s) = < -0.15, 0.15 > l/\mathrm{min}. \tag{12}$$

The setpoint fuel flow $\mathrm{FF}_{\mathrm{setpoint}}$ is a direct linear inverse model of the engine and the PI controller is tuned for limited response in the interval $\mathrm{FF}_{\mathrm{PI}} = < -0.15{,}015 >$ l/min with antiwindup protection. The resulting controller's output with computed coefficients is defined as follows:

$$\begin{aligned}\mathrm{FF}_5(s) &= \left(3.6e^{-09}n^2(s) - 0.000282n(s) + 6.37\right) \\ &\quad + \left(n_{\mathrm{cmd}}(s) - n_{\mathrm{act}}(s)\right)\left(0.00005 + 0.000015\frac{1}{s}\right).\end{aligned} \tag{13}$$

5. Experimental Evaluation of the Designed Control System

The proposed framework has been tested in laboratory experiments in a pilot testing program, to verify that the situational control system with situational frame switching is working as designed. In these experiments, a small turbojet engine iSTC-21v has been employed with exhaust nozzle fixed [46]. These tests have been executed as a proof concept of the designed control system and compared to experimental results measured with the TJ-100 engine in our laboratory, which represents a current modern production small turbojet engine with fixed exhaust nozzle and a state-of-the-art FADEC control system [5]. The functionality of the situational control system is demonstrated in Figures 10 and 11 with the iSTC-21v operating from start-up to shutdown with all situational controllers employed. The figures show efficient control of the engine's shaft speed and exhaust gas temperature.

In order to further experimentally evaluate efficiency of the situational control system, the following experimental pilot testing set-up has been designed:

(i) The operational controllers are tested at the commanded speeds defining three operational points $n_{\mathrm{cmd}} = \{40{,}000\ \mathrm{rpm}\,;45{,}000\ \mathrm{rpm}\,;50{,}000\ \mathrm{rpm}\}$.

(ii) Each operational point is held by a command for time $T = 15$ sec.

(iii) The resulting acceleration, rise and settling times between the situationally controlled iSTC-21v and FADEC controlled TJ-100, is compared.

(iv) The resulting constant speed deviations between the situationally controlled iSTC-21v and FADEC controlled TJ-100 are compared.

Experimental results as measured in laboratory conditions are shown in Figures 12–14. The figures illustrate that control systems of both engines have acceptable control quality, as there are no undamped oscillations or large overshoots. Figure 12 is showing acceleration of the engine from the stable operating $n_{\mathrm{cmd}} = \{40{,}000\ \mathrm{rpm}\}$ to the operating point $n_{\mathrm{cmd}} = \{45{,}000\ \mathrm{rpm}\}$; the time plot depicts dynamic characteristics of the situationally controlled iSTC-21v engine and the TJ-100 engine. The TJ-100 is slightly slower in acceleration and has a small overshoot and undershoot, while it is very good in maintaining the steady shaft speed. In comparison, the situational controller of the iSTC-21v engine is quite fluent in accelerations and decelerations with a bit quicker rise and settling times.

The second comparison shown in Figure 13 depicts accelerations from the operating point $n_{\mathrm{cmd}} = \{40{,}000\ \mathrm{rpm}\}$ to the operating point $n_{\mathrm{cmd}} = \{50{,}000\ \mathrm{rpm}\}$, which is the operating point near the maximum speed of the iSTC-21v engine. The situational control system employed on the iSTC-21v has very good acceleration characteristics here; its acceleration is considerably faster than the TJ-100, and both control systems are fluent; however, the settling characteristics of the iSTC-21v are qualitatively better here, as the controller does not have any overshoots.

In order to quantify the differences between control systems of both engines, mean absolute errors and standard deviations [50] of both engines have been compared during the steady state of their operation with results depicted in Figure 14. The steady state is defined as a state where the actual shaft speed is in the interval $n_{\mathrm{act}} = < -200, 200\ \mathrm{rpm} >$.

As can be seen in Figure 14, the iSTC-21v engine performs slightly worse at the stable operating points $n_{\mathrm{cmd}} = \{40{,}000\ \mathrm{rpm}\}$ and $n_{\mathrm{cmd}} = \{45{,}000\ \mathrm{rpm}\}$ as it has larger deviation from the commanded setpoint speed. However, it performs better at the operating point $n_{\mathrm{cmd}} = \{50{,}000\ \mathrm{rpm}\}$ where it has lower average deviation from the setpoint speed. Standard deviations at these setpoints are nearly equal; this means that the controlled shaft speeds oscillate in a similar way. It can be concluded that both control systems are comparable in maintaining the steady operational point.

In order to compare and evaluate acceleration times, rise and settling times of both engines in accelerations to the previously defined operating points $n_{\mathrm{cmd}} = \{45{,}000\ \mathrm{rpm}, 50{,}000\ \mathrm{rpm}\}$ have been measured. The rise time is defined as the time it takes for the response to rise from 10% to 90% of the steady-state response. The settling time is defined as the time it takes for the shaft speed error to fall to into the interval $n_{\mathrm{act}} = < -200, 200 >$ rpm. The results of the average measured acceleration times during three performed accelerations as shown in Figures 12 and 13 are presented in Table 2.

The table shows that the situational control system of the iSTC-21v engine is dynamically better than the acceleration control of the TJ-100 engine. This can be also attributed to the fact that the control system of the TJ-100 engine has to be more robust as it is also tuned during flight conditions. In overall evaluation, it can be stated that both control systems are comparable in quality, but a fact is that iSTC-21v engine is using a turbocompressor core, which is of old construction and a worse technical state than the TJ-100 engine, which uses state-of-the-art technical and design solutions in its construction; moreover, it is an engine with only 2 hours of runtime in laboratory conditions; thus, its technical state is flawless. In this regard, the results obtained with the intelligent situational control system employed on iSTC-21v engine can be considered as very positive. The control system of the iSTC-21v has to exert much more effort just to keep a stable operational

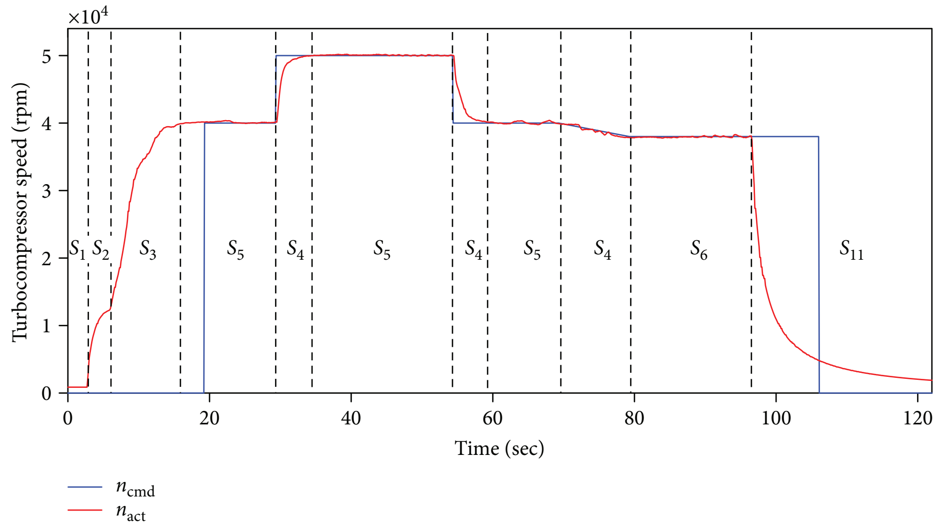

FIGURE 10: A single run of the iSTC-21v engine with the situational control system.

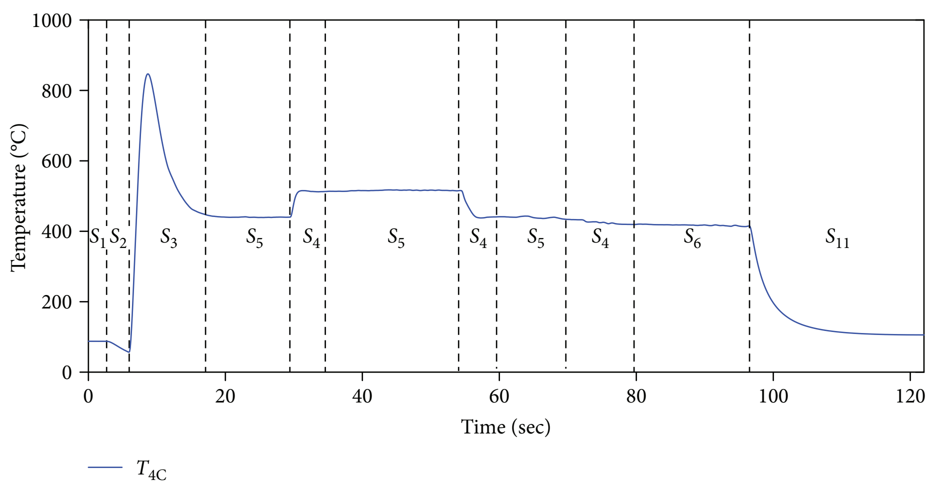

FIGURE 11: Exhaust gas temperature during operation of the situational control system.

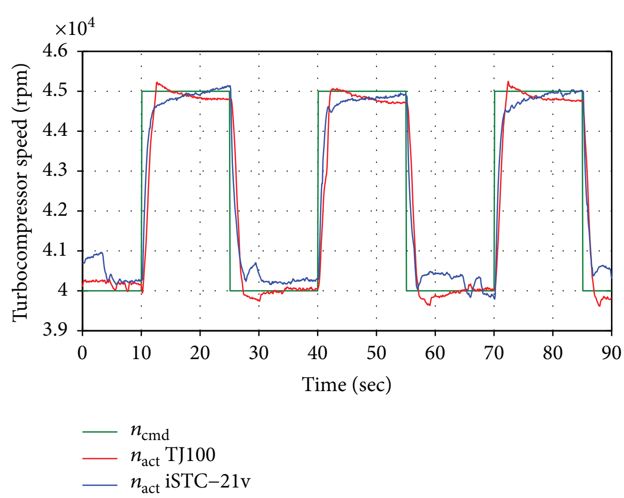

FIGURE 12: Acceleration from 40,000 rpm to 45,000 rpm.

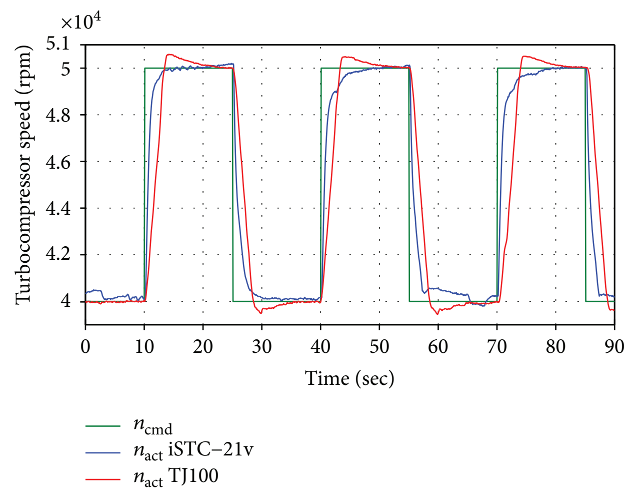

Figure 13: Acceleration from 40,000 rpm to 50,000 rpm.

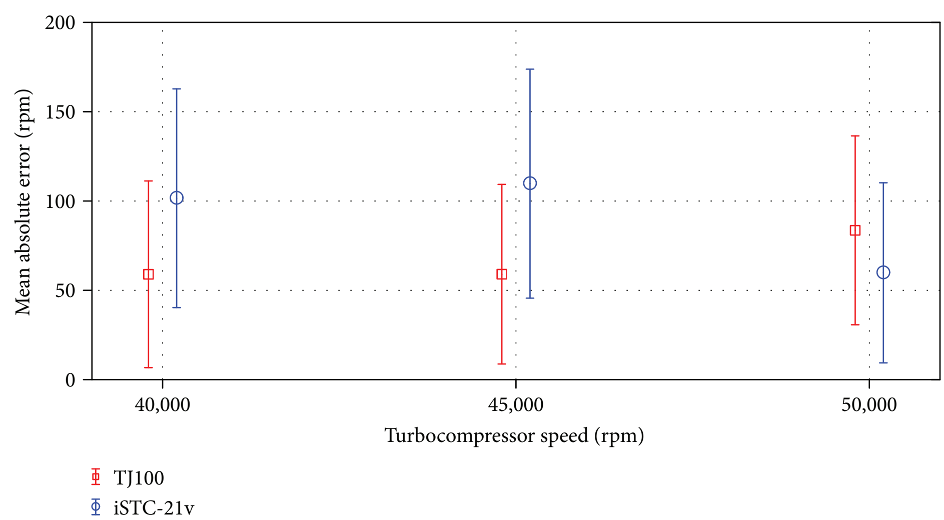

Figure 14: The comparison of mean absolute error and standard deviations of the error during the steady state.

Table 2: Comparison of rise and settling times.

Rise/settling times	$n_{cmd} = 45{,}000$ rpm	$n_{cmd} = 50{,}000$ rpm
Rise time: iSTC-21v	1.7 sec	2.1 sec
Rise time: TJ-100	1.8 sec	3.1 sec
Settling time: iSTC-21v	4.5 sec	6 sec
Settling time: TJ-100	5 sec	8.5 sec

point in order to compensate for its old constructional and material faults. In order to illustrate this point, the situational control system is compared with the classical nonsituational control system in Figure 15 with the engine accelerating to the shaft speed $n_{cmd} = \{40{,}000 \text{ rpm}\}$.

As can be seen in the figure, the engine iSTC-21v with the situational control system has much better characteristics during its startup with a lower exhaust gas temperature T_{4c} by 200°C, speeds and pressures without oscillations, which makes its running a lot smoother.

6. Conclusions

The paper presents a comprehensive description of an approach, which can be taken in design of a complex intelligent control system suitable for small turbojet engines. The system can be considered as an evolution of FADEC systems, and it can be designated as an intelligent i-FADEC. Its main asset is its modularity, as each module can be further improved by utilizing better or more advanced algorithms, be it algorithms of the situational classifier or improved individual controller modules. The main aim of the paper was to present the framework architecture as a working solution, and operability and efficiency of which has been demonstrated in real-world laboratory conditions with a small turbojet engine, not just as a simulation example. This aim has been fulfilled; moreover, the obtained control quality equals or even surpasses the control quality of a modern turbojet engine TJ-100 lowering the acceleration times of the engine up to 30%.

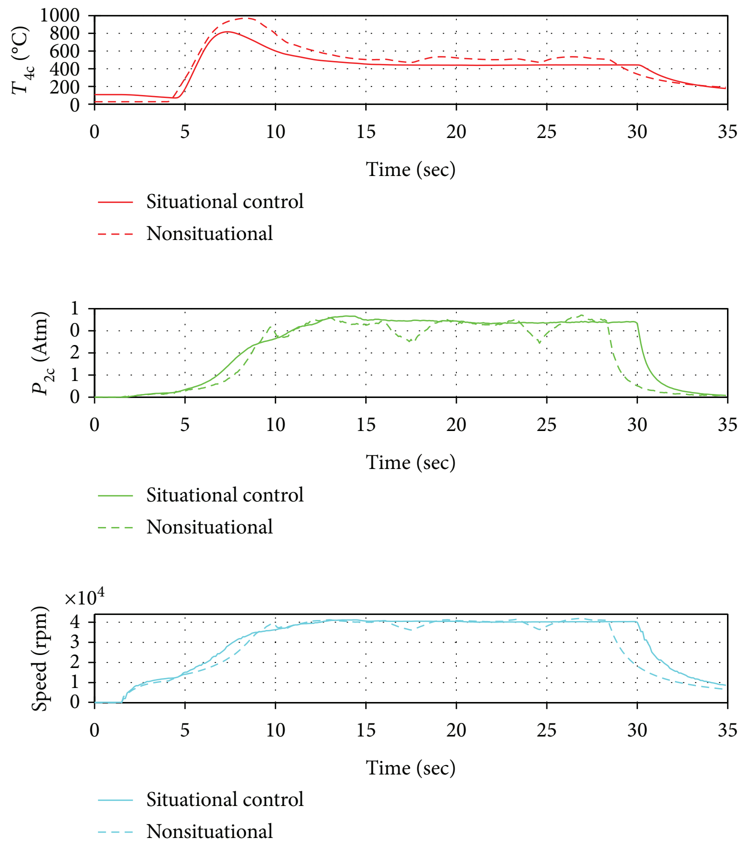

Figure 15: Comparison of the situational control system on the iSTC-21v with the nonsituational PI control system.

The designed control system needs to be taken as a proof of concept, and it is expected that a similar or even higher increase in control quality can be achieved using a state-of-the-art engine like TJ-100, this being one of the next research aims. The efficiency of the control system can be further enhanced by follow-up design of different control strategies for individual situational states, utilization of methodologies from the areas of robust or LQ control, focusing on control strategies during atypical modes of operation as well as cooperative control strategies with intelligent controller switching, where several cooperating controllers can be used to handle a certain situation.

In conclusion, the proposed situational control system has to cope with an engine core from the TS-21 engine, which is a very old design from the last century; it is hard to control being in a flawed technical condition, the engine not being previously designed as a multiregime engine. It can be concluded that the designed intelligent FADEC situational control system was able to bring its dynamic characteristics comparable to modern standards, which can be considered as a substantial engineering and design success. The core control system is a real-time software implementation, and our results show that by application of progressive control methodologies, the efficiency and reliability of an old turbojet engine can be considerably improved and the methodology of situational control can be applied and operated successfully in real-world conditions.

Nomenclature

A_5:	Exhaust nozzle diameter, mm
BLDC:	Brushless DC motor
C_i:	Transfer function of the ith controller
EGT:	Exhaust gas temperature
EPR:	Engine pressure ratio
FADEC:	Full authority digital engine control
FF:	Fuel flow, l/min
i-FADEC:	Intelligent full authority digital engine control
iSTC-21v:	Intelligent small turbocompressor engine-21 with variable exhaust nozzle
n_1:	Turbocompressor shaft speed, rpm
N_dot:	Derivative of shaft speed stabilization algorithm
PID:	Proportional integral derivative controller
P_0:	Atmospheric pressure, Atm
P_2:	Compressor outlet pressure, Atm
P_3:	Turbine inlet pressure, Atm
P_4:	Turbine outlet pressure, Atm
S_{cl}:	A vector of indicated situational frames
S_i:	ith situational frame
S_{sel}:	Output of the situational selector
T_0:	Outside air temperature, °C
T_{2C}:	Air temperature at the outlet from the diffuser of the radial compressor, °C
T_{3C}:	Gas temperatures in front of the gas turbine, °C
T_{4C}:	Total gas temperature aft of the gas turbine, °C
T_h:	Thrust, kg

TJ-100: Turbojet 100
TS-21: Turbostarter-21.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The work was supported by the project ESPOSA—Efficient Systems and Propulsion for Small Aircraft, funded by the European Commission in the Seventh Framework Programme under Grant Agreement no. ACP1-GA-2011-284859-ESPOSA and Slovak Research and Development Agency APVV under Grant Agreement no. DO7RP-0023-11.

References

[1] M. Boyce, *Gas Turbine Engineering Handbook*, Elsevier, Oxford, UK, Third edition, 2006.

[2] Rolls-Royce, *The Jet Engine*, Wiley-Blackwell, London, UK, 5th edition, 2015.

[3] E. Benini and S. Giacometti, "Design, manufacturing and operation of a small turbojet-engine for research purposes," *Applied Energy*, vol. 84, no. 11, pp. 1102–1116, 2007.

[4] B. C. Min, C. H. Cho, K. M. Choi, and D. H. Kim, "Development of a micro quad-rotor UAV for monitoring an indoor environment: advances in robotics," in *Advances in Robotics. FIRA 2009*, J. H. Kim, S. S. Ge, P. Vadakkepat, N. Jesse, A. Manum, K. Sadasivan Puthusserypady, U. Rückert, J. Sitte, U. Witkowski, R. Nakatsu, T. Braunl, J. Baltes, J. Anderson, C.-C. Wong, I. Verner, and D. Ahlgren, Eds., vol. 5744 of Lecture Notes in Computer Science, pp. 262–271, Springer, Berlin, Heidelberg, 2009.

[5] PBS Velká Bíteš Aircraft Engines websitehttp://www.pbsvb.com/customer-industries/aerospace/aircraft-engines.

[6] J. Pecinka and A. Jilek, "Preliminary design of a low-cost mobile test cell for small gas turbine engines," in *Proceedings of ASME Turbo Expo 2012: Turbine Technical Conference and Exposition*, pp. 471–478, Copenhagen, Denmark, 2012.

[7] A. J. B. Jackson, P. Laskaridis, and P. Pilidis, "A test bed for small aero gas turbines for education and for university: industry collaboration," in *Proceedings of ASME Turbo Expo 2004: Power for Land, Sea, and Air*, pp. 901–909, Vienna, Austria, 2004.

[8] C. R. Davison and A. M. Birk, "Set up and operational experience with a micro-turbine engine for research and education," in *Proceedings of ASME Turbo Expo 2004: Power for Land, Sea, and Air*, pp. 849–858, Vienna, Austria, 2004.

[9] M. Badami, P. Nuccio, and A. Signoretto, "Experimental and numerical analysis of a small-scale turbojet engine," *Energy Conversion and Management*, vol. 76, pp. 225–233, 2013.

[10] M. Badami, P. Nuccio, D. Pastrone, and A. Signoretto, "Performance of a small-scale turbojet engine fed with traditional and alternative fuels," *Energy Conversion and Management*, vol. 82, pp. 219–228, 2014.

[11] M. Makida, Y. Kurosawa, H. Yamada et al., "Emission characteristics through rich–lean combustor development process for small aircraft engine," *Journal of Propulsion and Power*, vol. 32, no. 6, pp. 1315–1324, 2016.

[12] J. Michalek and P. Straka, "A comparison of experimental and numerical studies performed on a low-pressure turbine blade cascade at high-speed conditions, low reynolds numbers and various turbulence intensities," *Journal of Thermal Science*, vol. 22, no. 5, pp. 413–423, 2013.

[13] S. Guo, F. Duan, H. Tang, S. C. Lim, and M. S. Yip, "Multi-objective optimization for centrifugal compressor of mini turbojet engine," *Aerospace Science and Technology*, vol. 39, pp. 414–425, 2014.

[14] A. O. Pugachev, A. V. Sheremetyev, V. V. Tykhomirov, and O. I. Shpilenko, "Structural dynamics optimization of rotor systems for a small-size turboprop engine," *Journal of Propulsion and Power*, vol. 31, no. 4, pp. 1083–1093, 2015.

[15] F. K. Lu and E. M. Braun, "Rotating detonation wave propulsion: experimental challenges, modeling, and engine concepts," *Journal of Propulsion and Power*, vol. 30, no. 5, pp. 1125–1142, 2014.

[16] S. Adibhatla and T. Lewis, "Model-based intelligent digital engine control (MoBIDEC)," in *33rd Joint Propulsion Conference and Exhibit*, pp. 1–10, Seattle, WA, U.S.A, 1997.

[17] L. C. Jaw and J. D. Mattingly, *Aircraft Engine Controls – Design, System Analysis, and Health Monitoring*, American Institute of Aeronautics and Astronautics, Reston, VA, USA, 2009.

[18] A. L. Diesinger, *Systems of Commercial Turbofan Engines*, Springer, Berlin, Heidelberg, 2008.

[19] J. Csank, R. May, J. Litt, and T.-H. Guo, *Control Design for a Generic Commercial Aircraft Engine*, NASA, Glenn Research Center, Cleveland, OH, USA, 2010.

[20] J. W. Connolly, J. Csank, A. Chicatelli, and K. Franco, "Propulsion controls modeling for a small turbofan engine," in *AIAA Propulsion and Energy Forum - 53rd AIAA/SAE/ASEE Joint Propulsion Conference*, pp. 1–15, Atlanta, GA, USA, 2017.

[21] J. S. Litt, D. L. Simon, S. Garg et al., "A survey of intelligent control and health management technologies for aircraft propulsion systems," *Journal of Aerospace Computing, Information, and Communication*, vol. 1, no. 12, pp. 543–563, 2004.

[22] J. S. Litt, J. Turso, N. Shah, T. Sowers, and A. Owen, "A demonstration of a retrofit architecture for intelligent control and diagnostics of a turbofan engine," in *Infotech@Aerospace Conferences*, pp. 1–18, Arlington, Virginia, 2005.

[23] I. D. Landau, R. Lozano, M. M'Saad, and A. Karimi, *Adaptive Control - Algorithms, Analysis and Applications*, Springer, London, UK, 2nd edition, 2011.

[24] R. C. Roman, M. B. Radac, R. E. Precup, and E. M. Petriu, "Data-driven model-free adaptive control tuned by virtual reference feedback tuning," *Acta Polytechnica Hungarica*, vol. 13, no. 1, pp. 83–96, 2016.

[25] S. Garg, "Controls and health management technologies for intelligent aerospace propulsion systems," in *NASA, Glenn Research Center*, Cleveland, OH, USA, 2004.

[26] Y. Diao and K. M. Passino, "Stable fault-tolerant adaptive fuzzy/neural control for a turbine engine," *IEEE Transactions on Control Systems Technology*, vol. 9, no. 3, pp. 494–509, 2001.

[27] J. Mu, D. Rees, and G. P. Liu, "Advanced controller design for aircraft gas turbine engines," *Control Engineering Practice*, vol. 13, no. 8, pp. 1001–1015, 2005.

[28] T. A. Várkonyi, J. Tar, and I. Rudas, "Improved stabilization for robust fixed point transformations-based controllers," *Journal of Advanced Computational Intelligence and Intelligent Informatics*, vol. 17, no. 3, pp. 418–424, 2013.

[29] J. K. Tar, J. F. Bitó, and I. J. Rudas, "Contradiction resolution in the adaptive control of underactuated mechanical systems evading the framework of optimal controllers," *Acta Polytechnica Hungarica*, vol. 13, no. 1, pp. 97–121, 2016.

[30] D. K. Frederick, S. Garg, and S. Adibhatla, "Turbofan engine control design using robust multivariable control technologies," *IEEE Transactions on Control Systems Technology*, vol. 8, no. 6, pp. 961–970, 2000.

[31] Z. Knoll and G. Tao, "Multivariable adaptive LQ control of jet engines," in *2015 American Control Conference (ACC)*, pp. 1193–1198, Chicago, IL, USA, 2015.

[32] I. Kisszolgyemi, K. Beneda, and Z. Faltin, "Linear quadratic integral (LQI) control for a small scale turbojet engine with variable exhaust nozzle," in *2017 International Conference on Military Technologies (ICMT)*, pp. 507–513, Brno, Czech Republic, 2017.

[33] B. J. Brunell, R. R. Bitmead, and A. J. Connolly, "Nonlinear model predictive control of an aircraft gas turbine engine," in *Proceedings of the 41st IEEE Conference on Decision and Control, 2002*, pp. 4649–4651, Las Vegas, NV, USA, 2002.

[34] M. Montazeri-Gh and A. Safari, "Tuning of fuzzy fuel controller for aero-engine thrust regulation and safety considerations using genetic algorithm," *Aerospace Science and Technology*, vol. 15, no. 3, pp. 183–192, 2011.

[35] W. Yan, C. J. Li, and K. F. Goebel, "A multiple classifier system for aircraft engine fault diagnosis," in *Proceedings of the 60th Meeting of the Society For Machinery Failure Prevention Technology (MFPT)*, pp. 271–279, Virginia Beach, Virginia, 2006.

[36] J. B. Armstrong and D. L. Simon, *Implementation of an Integrated OnBoard Aircraft Diagnostic System*, NASA, Glenn Research Center, Cleveland, OH, USA, 2012.

[37] A. Kyriazis and K. Mathioudakis, "Gas turbine fault diagnosis using fuzzy-based decision fusion," *Journal of Propulsion and Power*, vol. 25, no. 2, pp. 335–343, 2009.

[38] J. Seok, I. Kolmanovsky, and A. Girard, "Coordinated model predictive control of aircraft gas turbine engine and power system," *Journal of Guidance, Control, and Dynamics*, vol. 40, no. 10, pp. 2538–2555, 2017.

[39] J. Hu and H. Gu, "Survey on flight control technology for large-scale helicopter," *International Journal of Aerospace Engineering*, vol. 2017, Article ID 5309403, 14 pages, 2017.

[40] I. Moir, A. Seabridge, and M. Jukes, *Civil Avionics Systems*, AIAA Education Series, Reston, VA, USA, Second edition, 2013.

[41] X. Wang, J. Zhao, and X. Sun, "Overshoot-free acceleration of aero-engines: an energy-based switching control method," *Control Engineering Practice*, vol. 47, pp. 28–36, 2016.

[42] L. Madarász, R. Andoga, L. Fozo, and T. Lazar, "Situational control, modeling and diagnostics of large scale systems," in *Towards Intelligent Engineering and Information Technology*, I. J. Rudas, J. Fodor, and J. Kacprzyk, Eds., vol. 243 of Studies in Computational Intelligence, pp. 153–164, Springer, Berlin, Heidelberg, 2009.

[43] L. Madarász, R. Andoga, and L. Főző, "Intelligent technologies in modeling and control of turbojet engines," in *New Trends in Technologies: Control, Management, Computational Intelligence and Network Systems*, M. J. Er, Ed., pp. 17–38, Sciyo, Rijeka, Croatia, 2010.

[44] R. Andoga, L. Főző, L. Madarász, and T. Karo, "A digital diagnostic system for a small turbojet engine," *Acta Polytechnica Hungarica*, vol. 10, no. 4, pp. 45–58, 2013.

[45] R. Andoga, L. Madarász, L. Főző, T. Lazar, and V. Gašpar, "Innovative approaches in modeling, control and diagnostics of small turbojet engines," *Acta Polytechnica Hungarica*, vol. 10, no. 5, pp. 81–99, 2013.

[46] L. Főző, R. Andoga, L. Madarász, J. Kolesár, and J. Judičák, "Description of an intelligent small turbo-compressor engine with variable exhaust nozzle," in *2015 IEEE 13th International Symposium on Applied Machine Intelligence and Informatics (SAMI)*, pp. 22–24, Herl'any, Slovakia, 2015.

[47] L. Főző, R. Andoga, K. Beneda, and J. Kolesár, "Effect of operating point selection on non-linear experimental identification of iSTC–21v and TKT–1 small turbojet engines," *Periodica Polytechnica Transportation Engineering*, vol. 45, no. 3, pp. 141–147, 2017.

[48] P. Naslin, *Essentials of Optimal Control*, Boston Technical Publishers, Boston, MA, USA, 1969.

[49] J. Graf, *PID Control: Ziegler-Nichols Tuning*, CreateSpace Independent Publishing Platform, Cambridge, MA, USA, 2013.

[50] R. R. Wilcox, *Basic Statistics: Understanding Conventional Methods and Modern Insights*, Oxford University Press, Hannover, Germany, 1st edition, 2009.