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Diagnosis of Gasoline Injection Engine and Fault Tolerant Control

Marius Singureanu[1], Ion Copae[2]
[1, 2]Department of Military Vehicles and Transportation, Military Technical Academy "Ferdinand I", Bucharest, Romania

***Abstract:** The paper presents some considerations regarding the diagnosis and control of a gasoline injection engine for motor vehicles. The growing importance of diagnosis is highlighted in the conditions in which the practice has shown that there are always some faults, the fault being defined as a deviation of a parameter or a variable from its nominal value. Here are some solutions used in the gasoline injection engine, related to fault tolerant control. It is exemplified by treating the air pressure control system admitted in the engine cylinders of the Audi A6 car, targeting the pressure sensor in the intake manifold.*
***Keywords:** motor vehicle, diagnosis, fault tolerant control (FTC), PID controller, fuzzy logic, control reconfiguration*

I. INTRODUCTION

The high-performance solutions of current and future engines put the diagnosis at the forefront, and depending on the findings, the on-board computer will decide on the control. Thus, the engine control solution appeared in the presence of faults. According to this control strategy, the existence of faults is tolerated, which are inevitable anyway, and the on-board computer elaborates commands to the actuators in accordance with those found after the diagnosis. It can therefore be said that the FTC is a set of control techniques that ensure the ability of a system to meet the proposed objectives despite the occurrence of faults [1], [2], [4], [7]. Subsequently, the algorithm was refined, appearing the diagnostic solution by reconfiguring the control [8],[10].

In the sense of those presented, it is necessary to mention the definitions of some notions with which the diagnosis operates. Thus, the SAFEPROCESS technical committee named as fault an impermissible deviation of at least one characteristic property/variable of a system from the acceptable/usual/standard/nominal behavior. As can be seen from this definition, a fault means a deviation from the nominal value of a parameter or a functional variable.

Another notion, the error, is the quantitative measure of a fault and is a deviation of the system parameters from their nominal values, or a deviation of a variable from its usual value (corresponding to normal operation).

Finally, a failure means a fault that involves the permanent interruption of the system's ability to perform a required function under specified operating conditions.

As it can be seen from the presented, the fault appears in the physical plan, the error in the informational plan, and the failure in the user plan.

The goal of diagnosis is to generate a decision about the fault, based on observations and knowledge, and to decide whether or not it is a fault at some point, and also to be able to identify it. The diagnostic process is based on the operations called fault detection, isolation and identification. Fault detection means determining if there are faults in the system, as well as the detection time (time of occurrence). Fault isolation means determining its location, for example which is the fault component, as well as the type of fault. By identifying the fault is meant determining its size, so a quantitative assessment of the fault. Thus, the notion of detecting, isolating and identifying the fault appeared.

In the case of fault tolerant control, those presented are supplemented with fault accommodation, which means reconfiguring the system (through reconfiguration control) so that operation can be maintained within acceptable limits despite the existence of a fault. Thus, another notion emerged, called detection, isolation, identification and accommodation to faults.

II. CONTROL SYSTEMS IN THE PRESENCE OF FAULTS

These systems are of two main types: passive and active. Passive fault tolerance is achieved when the feedback loop remains functional without changing the controller. If the controller is changed when the fault is detected, for example by the parameters of the controller or even by its structure, the approach is called active. Regarding the two solutions, there is passive diagnosis and active diagnosis.

Passive systems are the classic ones, for example using PID controller and its variants [5], [9], using fuzzy logic (P - fuzzy controller in fig.1, PD controller - fuzzy in fig.2), using ANFIS algorithm (neural networks and logic fuzzy in fig.3; ANFIS - Adaptive Neuro Fuzzy Inference System).

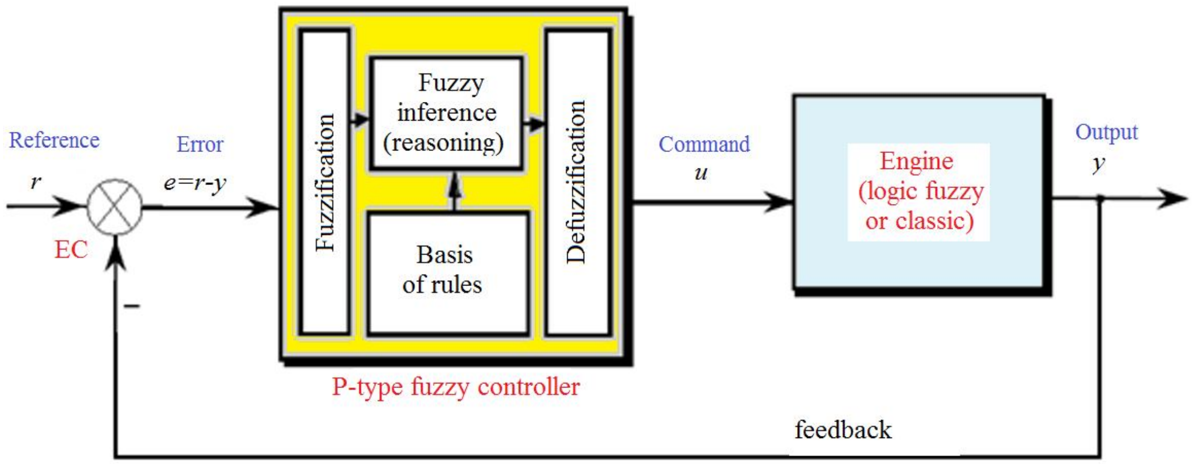

Fig. 1 P - type fuzzy controller

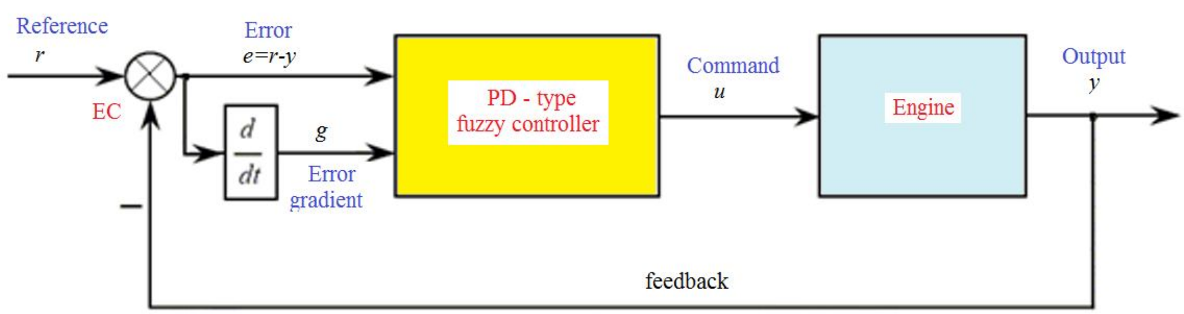

Fig. 2 PD - type fuzzy controller

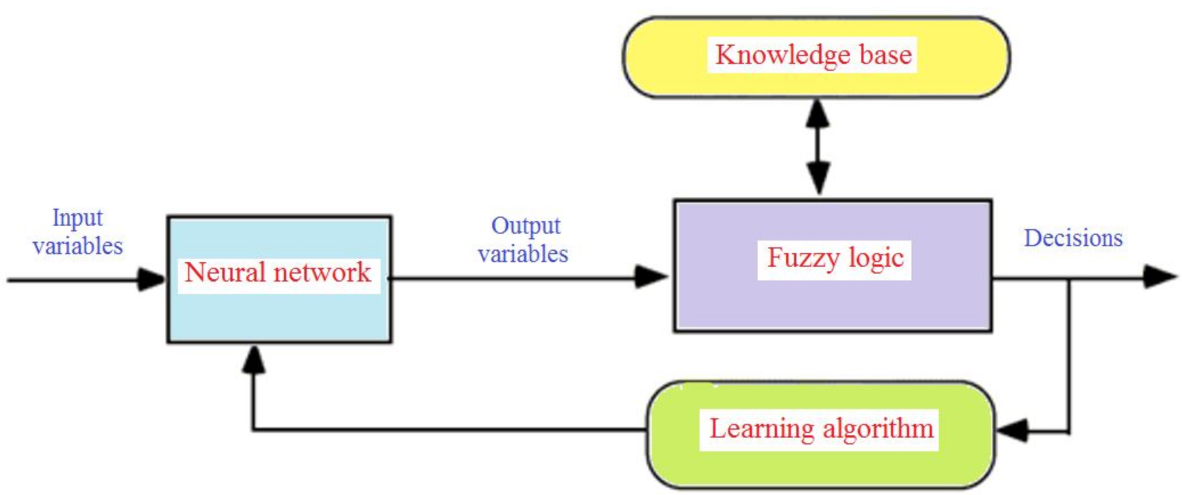

Fig. 3 Schematic diagram of the ANFIS algorithm

Fuzzy control is increasingly used today, individually or in combination with neural networks (neuro-fuzzy control) and genetic algorithms. All these forms are part of the broader category of intelligent control, so named because it uses concepts and algorithms specific to the biological field. The general scheme of the fuzzy control motor is presented in fig.1. The controller is based on fuzzy logic, and the mathematical model of the engine can also appeal to fuzzy sets or can be described by classical mathematical models. As it can be seen from fig.1, the controller has as input quantity the error *e*, and as output quantity the command *u*; consequently, it is a fuzzy type P (proportional) controller.

Instead, the diagram in fig. 2 contains a fuzzy controller that has two input quantities: error *e* and its derivative (gradient *g*). As a result, there is a fuzzy PD (proportional-derivative) controller.
In the two control schemes in fig. 1 and fig. 2, where there is a unit negative feedback loop, the error *e* represents the difference between the reference quantity *r* and the output quantity *y*:

$$e(t) = r(t) - y(t) \quad (1)$$

The derivative of the error (its gradient) from fig.2 is:

$$g(t) = \frac{\mathrm{d}e(t)}{\mathrm{d}t} = e'(t) \quad (2)$$

The role of fuzzy control is to establish the control variable *u*, through a mechanism shown in fig.1: fuzzification, establishing the basis of rules and defuzzification.
Fig. 3 shows an example in which the fuzzy logic is combined with the neural networks, thus obtaining the neuro-fuzzy control, respectively the ANFIS algorithm (Adaptive NeuroFuzzy Inference System). As it turns out, the ANFIS algorithm applies neuro-adaptive learning techniques, which provide the data needed for modeling using fuzzy sets. Using the input and output data, a system is built whose fuzzy sets adjust the coefficients of the mathematical model through an algorithm specific to neural networks. For this purpose, the number of activation functions from neural networks must be equal to that of fuzzy rules, and the algorithm is based on the fuzzy neuron.
Practice has shown that usually any technical system (including the vehicle engine) does not work at the nominal parameters imposed by the design. For this reason, it is considered that the dynamics of systems is always characterized by the presence of faults, in the unanimously accepted sense of their definition. If it is not operated during operation, these faults may develop until the components failure. These are the reasons for the emergence of a new way of diagnosing systems in the presence of faults.
This mode is known as ***active diagnostics***, as opposed to passive diagnostics, which only detects the fault, without then intervening during operation. The intervention in active diagnosis is done by reconfiguring the control, and the solution is defined as fault tolerant control (FTC). Obviously, in order to detect the fault, the information from the built-in sensors and actuators is used and therefore it is necessary to know the deviations from the nominal operating regime. The control is then reconfigured according to the size of the fault found. Reconfiguring the control involves finding a new feedback control law, called a reconfigured controller after a system fault occurs. Thus, the reconfigured controller must recover as well as possible the closed-loop control objectives, such as stability and dynamic performance. Therefore, reconfiguration of control is a set of techniques that define the ability of systems to maintain the required objectives despite the occurrence of faults. For this purpose there are several reconfiguration procedures, most using algorithms such as adaptive control, supervision, compensation, and so on.
Fig. 4 and fig. 5 show an active diagnostic scheme [3], [6], [8], with control of operation in the presence of faults, in the case of a gasoline injection engine.

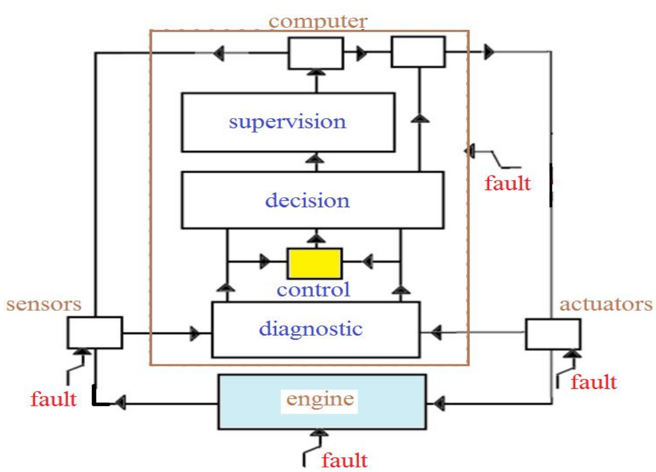

Fig. 4 Active diagnostic scheme

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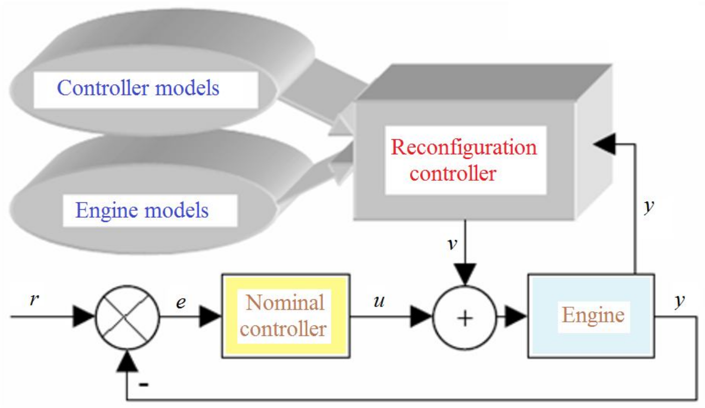

Fig. 5 Diagnostic scheme with reconfiguration control

As can be seen from fig. 4, during the operation of the engine, first the diagnosis is made and only then the control according to the findings on the faults (the scheme includes the software, not only the hardware belonging to the sensors, actuators and engine components).

The diagram in fig.5 highlights the nominal controller, ie the one related to the fault-free operation. In addition, the reconfiguration controller appears, which uses various mathematical models of the engine and the nominal controller related to faults of different amplitudes. In this way there is the *u* command for the nominal controller, as well as the *v* command as a result of reconfiguring the control to compensate for the negative effects of faults.

The PID controller (Proportional-Integrator-Derivative), widely used, with various variants, emits the command variable:

$$u(t) = \underbrace{k_p e(t)}_{P} + \underbrace{k_i \int_0^t e(t)\mathrm{d}t}_{I} + \underbrace{k_d \frac{\mathrm{d}e(t)}{\mathrm{d}t}}_{D} \tag{3}$$

hence the transfer function:

$$C(s) = \frac{u(s)}{e(s)} = \underbrace{k_p}_{P} + \underbrace{\frac{k_i}{s}}_{I} + \underbrace{k_d s}_{D} = \frac{k_d s^2 + k_p s + k_i}{s} \tag{4}$$

In these expressions: k_p – static transfer coefficient for the proportional element *P*; k_i – static transfer coefficient for the integrating element *I*; k_d – static transfer coefficient for the derivative element *D*.

Adaptive control, whose principle diagram is shown in fig. 6, benefits from a real-time identification and as a result the synthesis of the controller has the same character.

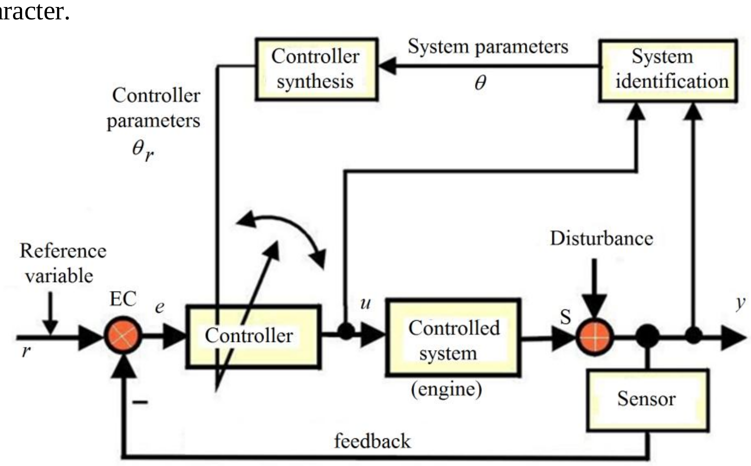

Fig. 6 Schematic diagram of adaptive control

As can be seen in fig. 6, these systems benefit from the procedures for identifying the model parameters □ and constantly adapts to their variation, and the controller benefits from a permanent synthesis through its parameters□□$_r$. Therefore, if the feedback loop diminishes the effects of system disturbances and uncertainties (including those related to faults), the adaptive control changes accordingly.

The adaptive control algorithm uses the mathematical description, for example for a second order system, in the general form:

$$\begin{cases} x_1' = x_2 + \theta \cdot f_1(x_1, x_2) \\ x_2' = \theta \cdot f_2(x_1, x_2) + u \end{cases} \tag{5}$$

in which: u – command, $\mathbf{x} = [x_1 \quad x_2]$ state vector, and f_1 and f_2 there are two nonlinear functions.

III. AIR PRESSURE CONTROL IN THE INTAKE MANIFOLD

In this case, the air pressure sensor is targeted p_a from the intake manifold. As a result, the static characteristic of this sensor is used $p_{ast}(n,$ □), established on the basis of experimental data, shown in fig.7 including by the analytical expression (1) in the graph, where n is the engine speed and □ the position of the throttle (hence the engine load).

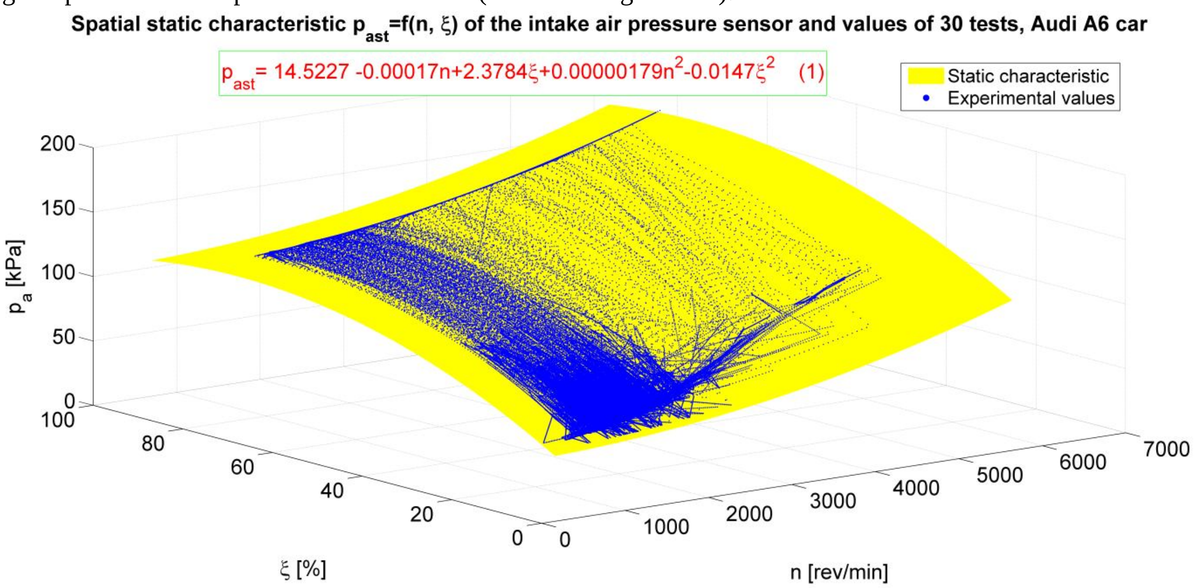

Fig.7 Spatial static characteristic p_a=f(n, □) and values of 30 experimental tests, Audi A6 car engine

Fig. 7 shows the analytical expression of the static characteristic:

$$p_{ast} = 14.5227 - 0.00017n + 2.3784\xi + 0.00000179n^2 - 0.0147\xi^2 \tag{6}$$

It is still considered a 40% fault of the intake air pressure sensor, which means that it has a measurement error of 40%. As a result, if this fault occurs in the experimental test D2, at time t = 270 s (in point C), then the results from fig.8 are obtained. The graph shows the curves related to the fault-free operation (nominal curve), the 40% malfunction and the difference between them. The graph shows the transfer function of the faulty sensor:

$$W_d(s) = \frac{k_d}{T_d s + 1} = \frac{0.5913}{0.0033s + 1} \tag{7}$$

which corresponds to the differential equation:

$$0.0033 p_a'(t) + p_a(t) = 0.5913 p_{st}(n, \xi) \tag{8}$$

Fig. 8 also shows that by damaging the sensor by 40%, in the time period t = 270-600 s, the average value of the pressure decreases with 11.5%, and its norm 2 with 13.8%.

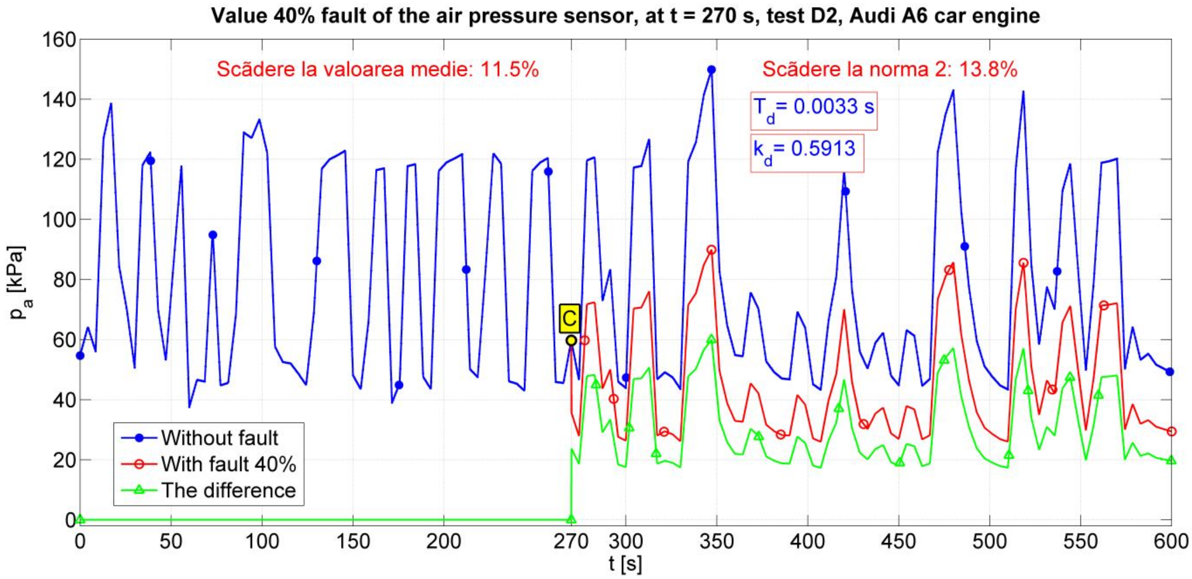

Fig. 8 Value 40% fault of the air pressure sensor, Audi A6 car engine

For the reconfiguration control, which has the role of restoring the air pressure to the values of the sensor without fault, a PI (proportional-integrator) type controller is used, as seen in fig. 9 in part 3 of the Simulink diagram in Matlab.

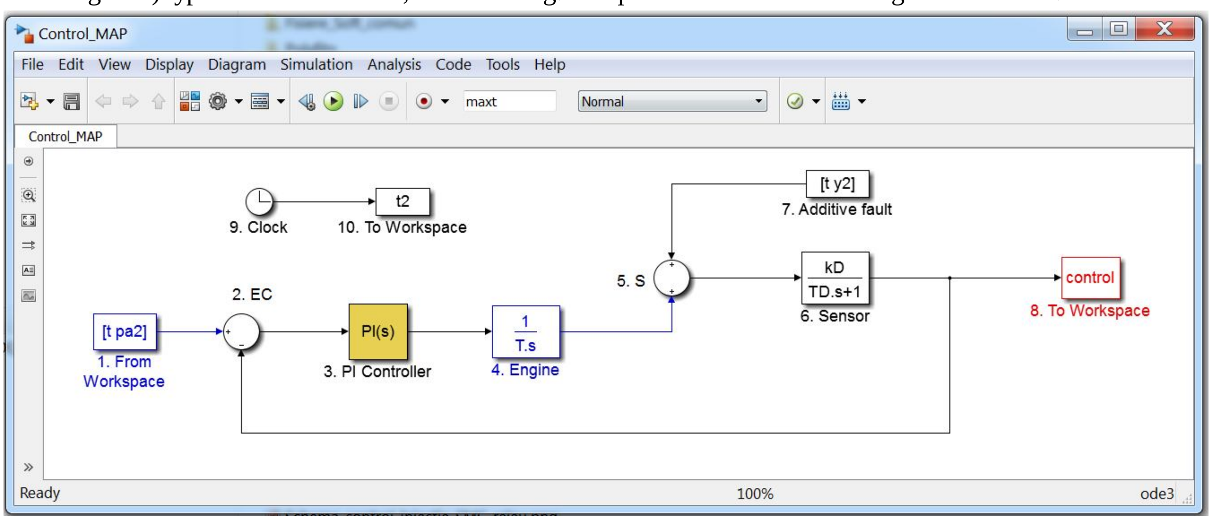

Fig. 9 Simulink / Matlab diagram with reconfiguration control

In the diagram, the values of the time constant T_d of the sensor (TD in the diagram) and its static transfer coefficient k_d (kD in the diagram) are those in relation (7). In addition, the diagram also shows the transfer function of the engine, in the form of an integrating element:

$$W_m(s) = \frac{1}{Ts} \quad (9)$$

where T is the time constant of the engine, and s is the argument of the Laplace transform. To determine the time constant T we start from the differential equation of engine operation in dynamic mode:

$$J\frac{\mathrm{d}\omega(t)}{\mathrm{d}t} = M_e(t) - M_r(t) \quad (10)$$

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where J represents the reduced moment of inertia at the crankshaft, ω the angular velocity of the crankshaft (determined experimentally based on the engine speed n), M_e the engine torque (experimentally set), and M_r the moment required to overcome the reduced forward resistances on the axis crankshaft. The angular velocity of the crankshaft is determined by the expression:

$$\omega = \frac{\pi n}{30} \tag{11}$$

and as a result the relation (10) becomes:

$$\frac{\pi J}{30}\frac{\mathrm{d}n(t)}{\mathrm{d}t} = M_e(t) - M_r(t) \tag{12}$$

Noting:

$$T = \frac{\pi J}{30} \tag{13}$$

from expression (12) results:

$$T\frac{\mathrm{d}n(t)}{\mathrm{d}t} = M_e(t) - M_r(t) \tag{14}$$

where the desired transfer function is obtained (9).
The moment of inertia J is the sum of the moment of inertia of the engine J_m and the moment of inertia of the vehicle J_a reduced to the axis of the crankshaft:

$$J = J_m + J_a \tag{15}$$

in which:

$$J_a = \beta m_a \left(\frac{r_r}{i_t}\right)^2 \tag{16}$$

where m_a is the mass of the vehicle, the coefficient β = 1.03-1.3 (small values in small m_a), r_r wheel running radius, i_t the total transmission ratio, and J_m = 0.6-0.8.

For the Audi A6 car, where the gears in the gearbox have been established experimentally (fig.10a), so the ratios i_t are known, knowing the mass m_a as well as the running radius r_r, it results that the values of the moment of inertia J can be established, as it appears from fig.10b.

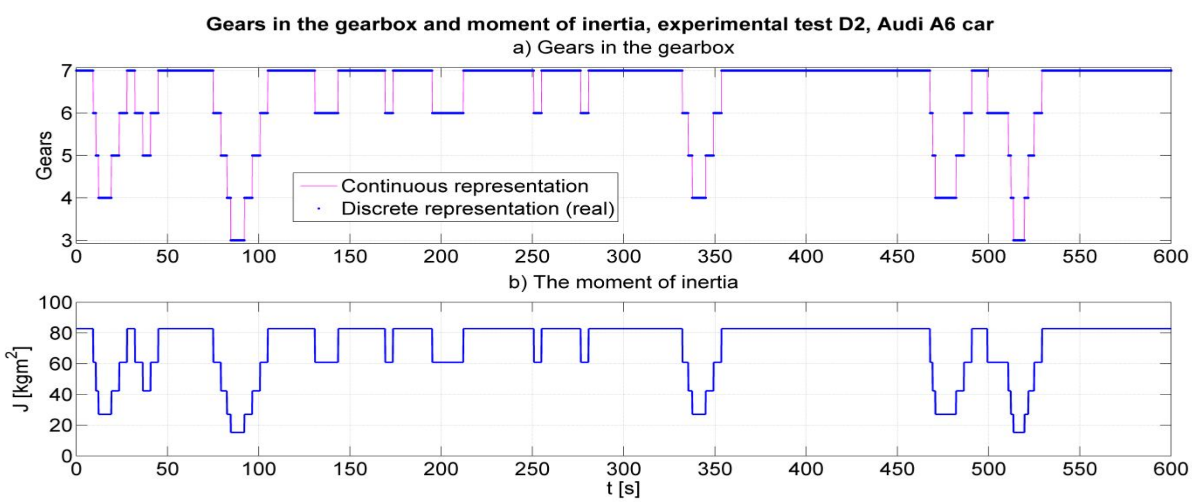

Fig. 10 Gears in the gearbox and moment of inertia, Audi A6 car

From fig.10b it results that the parameter *T* from the relation (13) varies in time due to the variation of the total transmission ratio, implicitly also to the variation of the moment of inertia. In addition, in expression (12), the engine torque M_e is known on the basis of experiments. Also the moment necessary to overcome the reduced forward resistances to the crankshaft axis M_r can be established using the relation:

$$M_r = \frac{f m_a g r_r}{i_t \eta_t} + \frac{k S r_r^3}{i_t^3 \eta_t} \omega^2 \tag{17}$$

in which the movement on a horizontal track was considered, as the experiments were carried out.

In the right term of the expression (17) all the variables are known from experiments, where: *f* - rolling resistance coefficient, *k* - aerodynamic coefficient, *S* - cross-sectional area, η_t - transmission efficiency. Thus, the values of the moment M_r shown in fig.11 are obtained together with other variables mentioned in the graph.

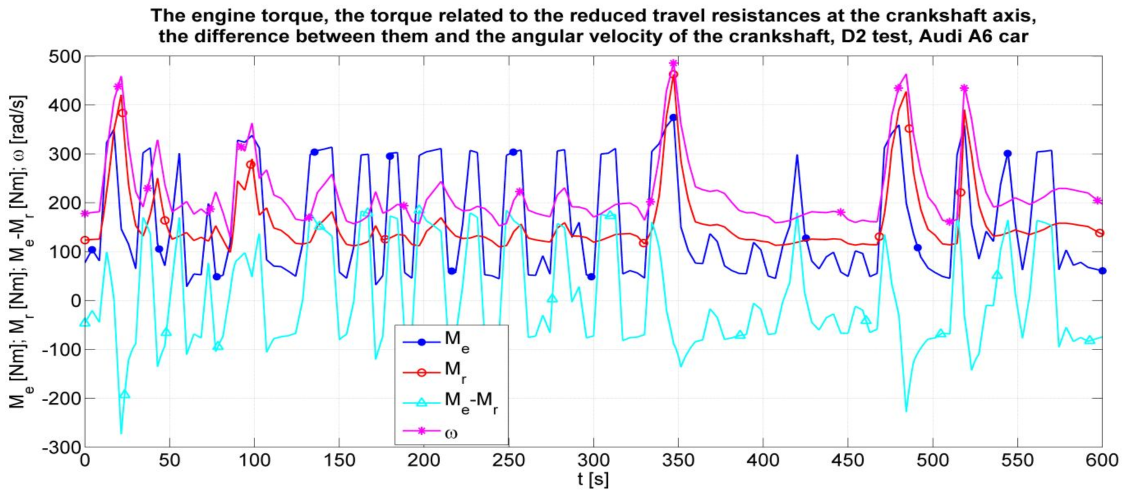

Fig. 11 Moments and angular speed of the crankshaft, the Audi A6 car

Consequently, all variables being known, using the reconfiguration control in fig. 9, the values of the allowable air pressure shown in fig. 12 are obtained.

As can be seen from the graph, the two average values are very close (76.2 kPa and 76.3 kPa).

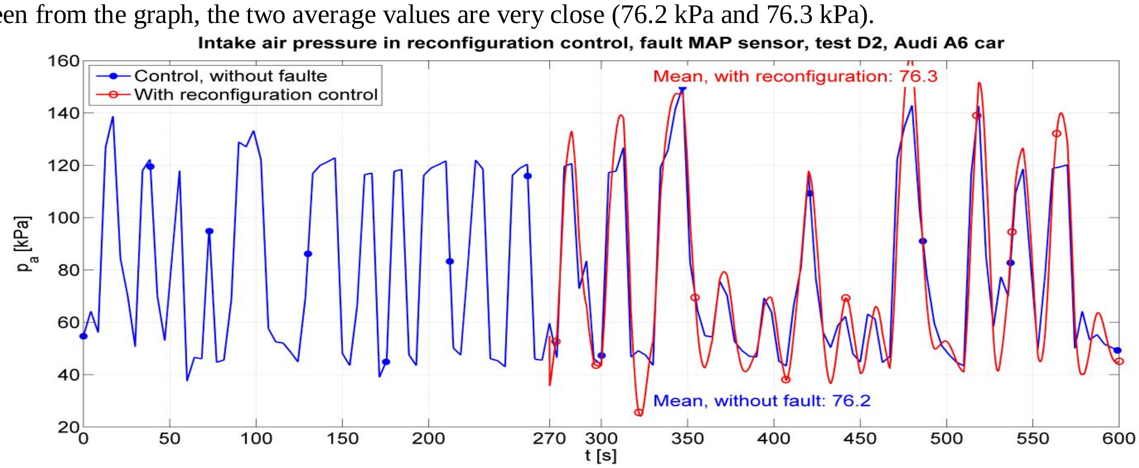

Fig. 12 Intake air pressure from the reconfiguration control, the engine of the Audi A6 car

Other variables can also be obtained from the reconfiguration control, such as the position of the throttle □ in fig. 13, which is the load on the engine.

The graph shows that the average value of the engine load in case of lack of fault is 35%, and through the reconfiguration control an average value of 37.1% is obtained.

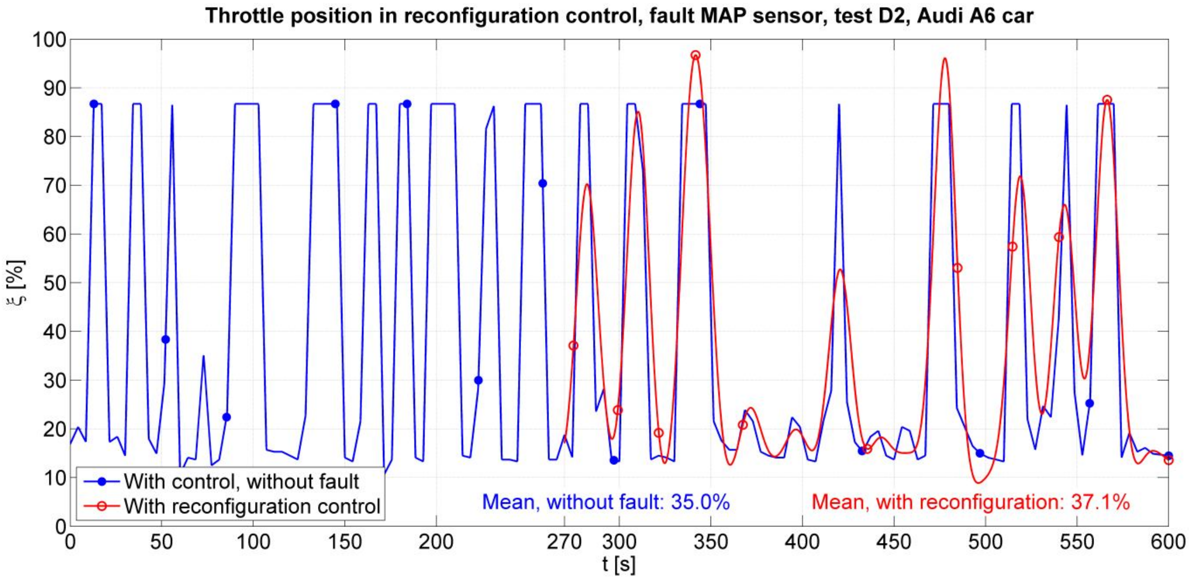

Fig. 13 Throttle position in reconfiguration control, Audi A6 car engine

Similarly, fig. 14 shows the value of the engine torque M_e. As can be seen from the graph, the average value in the absence of the fault is 147.8 Nm, and through the reconfiguration control an average value of 165.2 Nm is obtained. Therefore, the reconfiguration of the control results in an increase in the average value of 11.8%, so a positive effect.

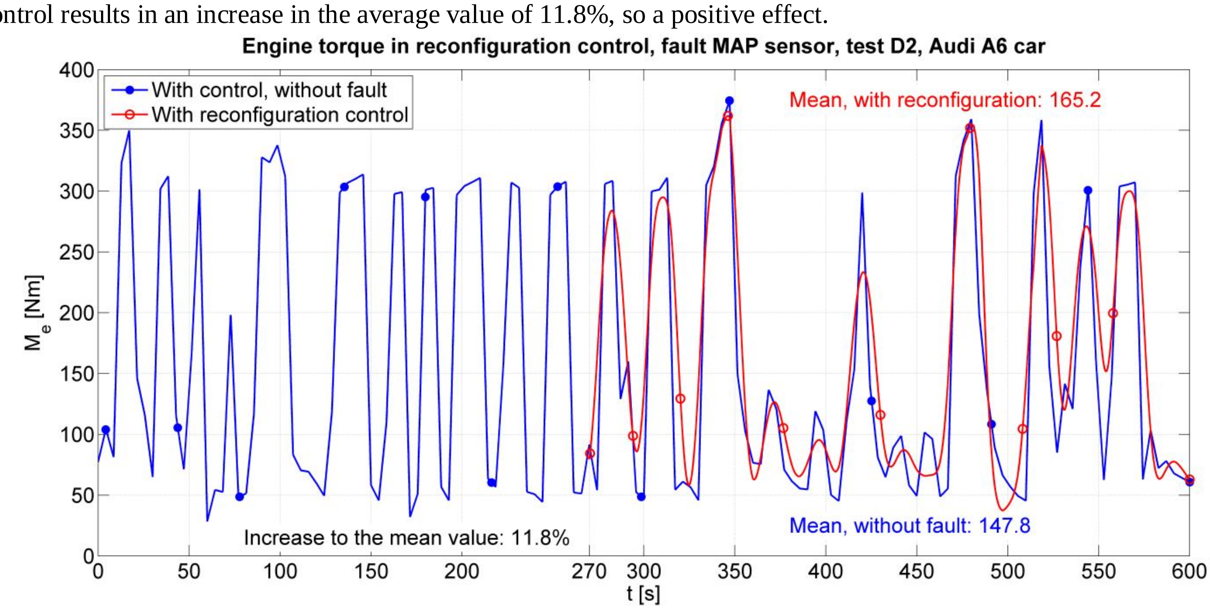

Fig. 14 The engine torque in the reconfiguration control, the engine of the Audi A6 car

Fig. 15 shows another functional variable, namely the cyclic flow of fuel c_c, established with the relation, valid for a 4-stroke engine with z cylinders:

$$c_c = \frac{100C_h}{3nz} \tag{18}$$

which also involves the engine speed n and hourly fuel consumption C_h.

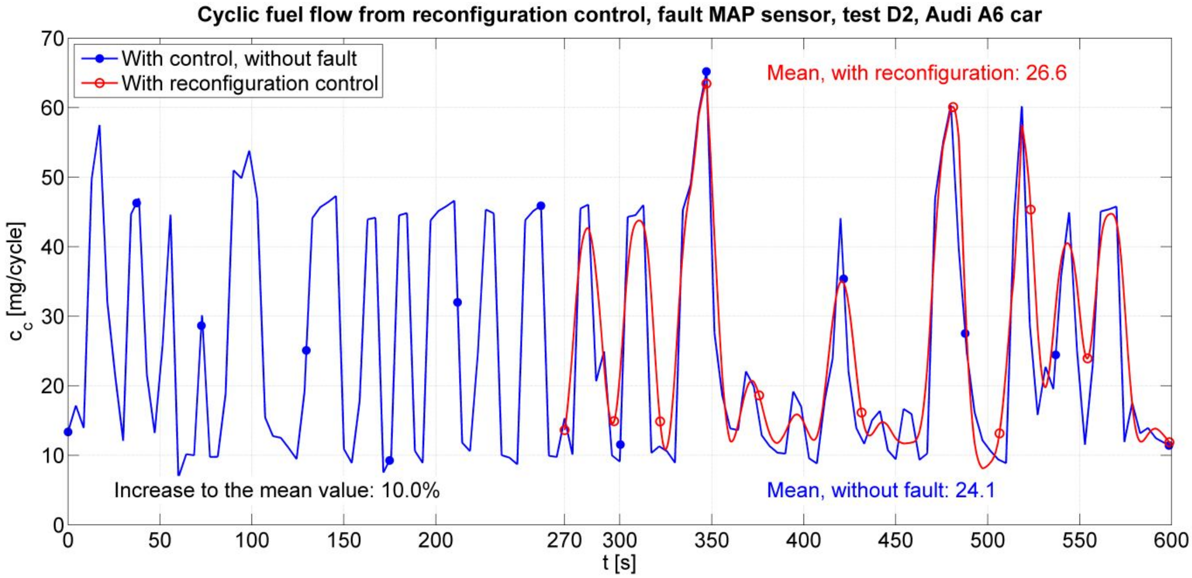

Fig. 15 Cyclic fuel flow from reconfiguration control, Audi A6 car engine

As it can be seen from fig.15, the average value in the absence of the fault is 24.1 mg/cycle, and through the reconfiguration control an average value of 26.6 mg/cycle is obtained. Therefore, the reconfiguration of the control results in an increase of the average value by 10%, with a positive effect on engine power.

IV. CONCLUSIONS

The practice of using vehicles has shown that there are always deviations of the functional variables from their imposed nominal values. In the sense of defining them, it follows that there are always faults of greater or lesser magnitude. For this reason, the role of vehicle engine diagnostics has increased, providing real-time information on faults. This information is received by the on-board computer, which establishes the control law in order to restore the nominal values of the functional variables.

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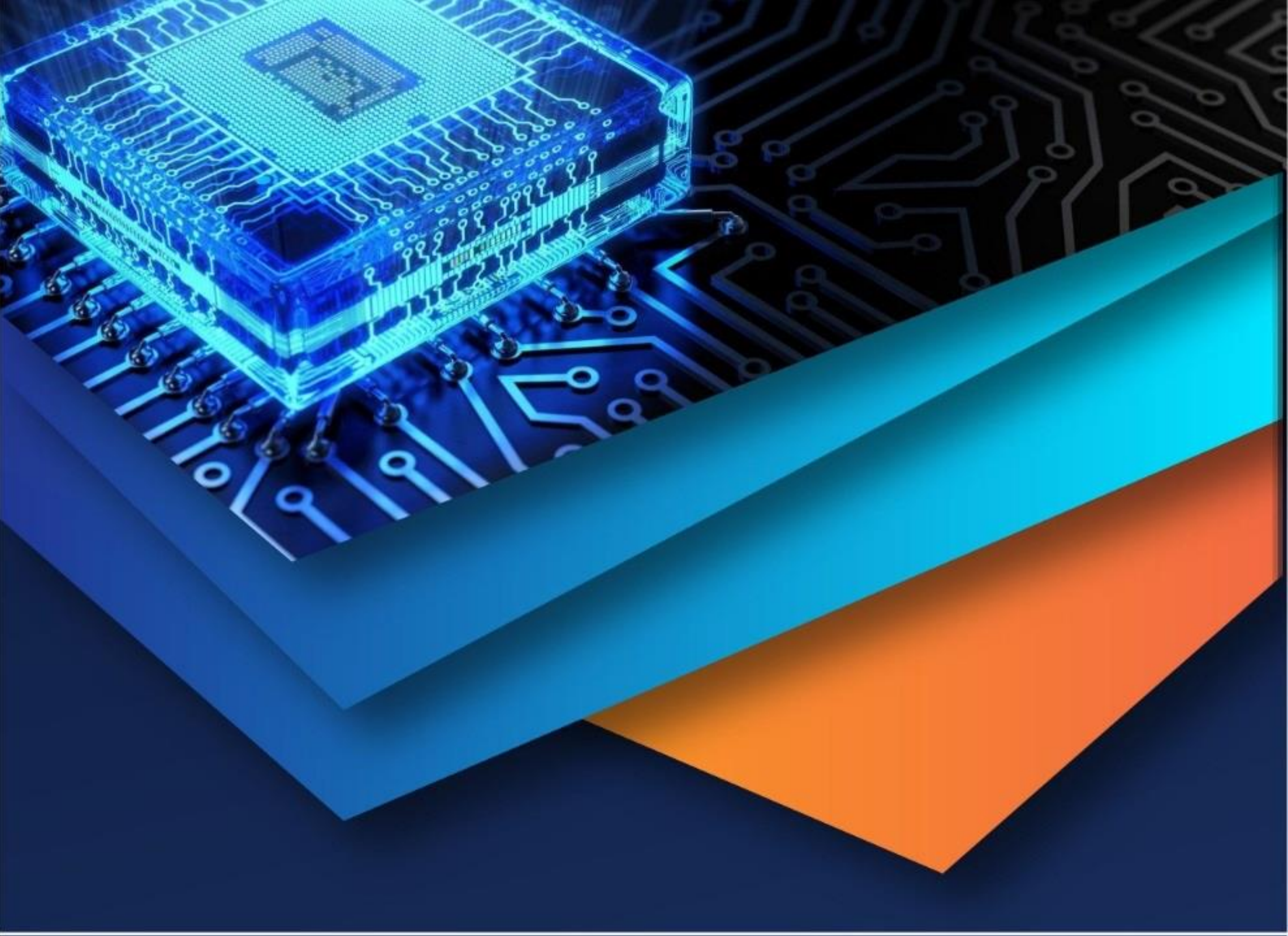

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