

Intelligent Idle Speed Control for Modern Intelligent Automobiles

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Abstract— *The paper presents an application of a recently developed Fuzzy logic controller for time-delay systems to the idle speed control (ISC) problem in spark ignition (SI) internal combustion (IC) engines.*

Automobiles spark ignition engines spend a large percentage of their time operating in the idle speed region. The engine idle speed control system design is a difficult problem because are inherently nonlinear, incorporating variable time delays characteristics exists everywhere between the input and output of an engine. The output time delay which varies inversely with the engine speed makes the control process even harder. Furthermore, disturbances caused by different operating conditions may arise during engine idle speed running. All these reasons have increased difficulties to control the idle speed accurately.

Engines are inherently nonlinear, incorporating variable time delays and discontinuities which make modeling difficult, and for this reason their control is well suited to optimization using Fuzzy logic algorithms. This paper aims to apply Fuzzy logical controller to maintain a constant idle speed, in this experiment, a SAAB B202 engine was used to identify idle speed appearance. The developed model has a control-design oriented philosophy and is capable to significantly minimize the varying of idle speed within an engine speed.

Keywords— *idle speed control, spark ignition, inherently nonlinear, time delay, fuzzy logical control.*

I. INTRODUCTION

The problem of idle speed control is to maintain the engine speed at a prescribed set-point in the presence of various disturbances such as those due to air conditioning, transmission engagement or power steering accessory load torques [1]. The engine torque is normally adjusted by manipulating the intake air amount or the advance ignition timing according to the disturbance experienced by the engine [2,3]. According to Environmental Protection Administration, R.O.C. experimental statistics, a car stop and go every day, idle time of more than 30 minutes a year will waste 640 liters of gasoline, resulting in 3.4 kg of organic compounds, the release of 54.3 kg of carbon monoxide and 1.4 tons of carbon dioxide [4].

When the automotive release the accelerator, the engines speed slows. At a preset speed the engine idle circuit takes over and the engine runs at the lowest speed possible without stalling. An idle speed around 500 to 900 revolution per minute (RPM). The engine's idle speed also changes, based on outside conditions. A computer is adjusting the idle speed, based on complex calculations.

In the past, adjusting an engine's idle speed was easy. Manufactures have removed these adjustments on modern automotives. The engine control module (ECM) now determines the speed at which an engine idles, based on several input sensors manual adjustment of idle speed is not possible on modern automotive and diagnosis of problems is a bit complex.

When the engine has a carburetor, they always provide a means to adjust the idle speed. A simple turn of a screw corrected the problem if the engine's idle speed was too slow or too fast. With electronic fuel injection they eliminate the manual adjustment and the computer makes all corrections to the engine's idle speed.

They have eliminated the idle speed adjustment for many and involved reasons. Fuel injection carefully monitors the air flow, as it is directly relates to the fuel air mixture. Carburetors set fuel air mixture with jets. Air flowing through a venture, draws a fixed amount of fuel based on the size of the jet. More air entering through the carburetor means more fuel and an increase in engine speed. With this system, as we open the throttle the speed increases, because we draw in more fuel.

Early fuel injection normally uses an idle speed control (ISC) valve to control the speed of the engine's idle. They use several designs, but most work in a similar manner. On early automotive, often uses a stepper motor that turns a thread valve or spring-load plunger the ECM change duty-cycle to the magnetic coil. Rotation of the armature moves the air valve in and out, adjusting the idle speed of the engine.

With drive by wire, we no longer need the ISC system. The ECM directly controls an engine's idle speed by opening and closing the throttle valve. Each time we open the throttle valve, the ECM increases the fuel injector's pulse width to keep air fuel mixture correct. The air flow meter, air intake temperature sensor, engine temperature sensor, barometric pressure and other sensor provide data the ECM uses to calculate injector pulse width. Air fuel sensors also monitor the exhaust and make further corrections to the air fuel mixture as needed.

The idle speed will increase fuel consumption, causing unnecessary waste when it is too high, while the idle speed is too low to make obvious reinforcement effect of exhaust gas dilution of mixture in cylinder, if a slight change of load or resistance will cause instability or even shut down engine operation. Therefore, in order to meet the requirements of increasingly stringent emission regulations, as far as possible, we should reduce the idle speed and maintain the stability of idle speed appears especially important. But the engine idle speed control system is the most important in the electronic control system and it is also one of the most complicated part, researchers have a lot of research on the idle speed control around the world, however, its performance is still not satisfactory.

There are some well-known control problem, one of the most important of which is the time delay between the intake stroke and combustion stroke of the engine. This time delay limits the achievable performance in the electronic throttle control loop. The second problem is that the controller performance must be robust to changes in the idle-speed set-point.

II. IDLE SPEED CONTROL

Engine idling is one of the most commonly encountered operating conditions of urban idling control of the quality of almost every aspect of Automotive performance, such as fuel economy, emissions, drivability, etc. ISC issues have been extensively studied and a comprehensive overview of the topic can be found in [5].

The main purpose of idle control is to keep the engine speed at the desired set point in the presence of various load disturbances. Automotive engine idle speed means the complete release of throttle without external power out-put, while at the same time maintaining minimum steady speed, to allow conservation of engine stability. To ensure engine idle speed, air mass is record with the air flow meter (or manifold pressure sensor), together with speed and other fuel correction signals. Measurement is recorded during the closing of throttle; air enters through the throttle gap and idle control port from by-pass air valve into the engine. Idle speed control system is governed by the ECM, as a result of the constant change in resistance force within the automotive engine. In case of increase engine load, such as starting the engine, auto-deceleration, parking, the engine should stay in stable idle speed.

Excess idle speed can result in increase fuel consumption and additional fuel cost, especially under long term urban driving circumstances, which consists of constant deceleration, parking, and starting of the vehicle. On the other hand, inefficient idle speed, adjustment of duty or resistance can lead to idle speed instability, air pollution and engine stall. Due to the common use of air conditioning system, automatic transmission, cooling system, power steering system and other electronics; idle speed instability can be a result of this extended power load. Reduction of idle speed produces greater emission, environmentally, it is important to monitor the accuracy and control of idle speed since both HC and CO are the main vehicle exhaust emission produced by idle speed.

III. ENGINE MODELS FOR ISC

The engine model, which contains the most important characteristics and dynamics of the engine idling operation, is given in Figure 1. It uses the model structure in development and is made up of actuator characteristics. Manifold dynamics Engine pumping characteristics intake to dynamic Stroke delay, Torque characteristics and Engine Rotational Dynamics [6]. The standard plant model [7] for an Idle Speed Control is explained in this section. The control input is taken as throttle angle in degrees and the output is taken as engine speed in revolution per minute (rpm). The modeling requirements are discussed as below:

3.1 Throttle Mass Flow:

The air mass flow through the throttle valve opening during idling can be modeled using choked flow equation:

$$W_{th} = A_{th} \frac{P_a}{\sqrt{2RT}} \quad (1)$$

Where W_{th} is the air mass flow rate passing through throttle opening, A_{th} is the effective area of throttle, P_a is the ambient

pressure, T is the ambient temperature, R is the universal gas constant. The throttle area is a non-linear function of throttle position but given that during idling the throttle movement is very small, hence a linear relationship will be assumed between the throttle position and throttle effective flow area.

3.2 Intake Manifold:

Based on the isothermal conditions, the pressure dynamics can be modeled as:

$$\frac{dP_m}{dx} = \frac{RT_m}{V_m} (wW_{th} - W_{eng}) \quad (2)$$

Where P_m , T_m , V_m are manifold pressure, temperature and volume respectively and W_{eng} is the air mass flow rate exiting the intake manifold and entering the engine.

3.3 Engine Air mass Flow:

The mean value of fuel-air mixture flow rate entering the engine cylinders can be approximated using the following equation:

$$W_{mix} = \eta_v \frac{P_m v_d N}{RT_m 4\pi} \quad (3)$$

Where η_v is the volumetric efficiency, v_d is the displacement volume and N is the engine speed in radians per second. Air mass flow rate entering the cylinders can be found using the formula

$$W_{eng} = \frac{W_{mix}}{[1 + \Phi(\frac{F}{A})_s]} \quad (4)$$

Where $(F/A)_s$ and Φ represent the stoichiometric fuel-to-air ratio and fuel-to-air ratio normalized by the stoichiometric fuel to air ratio, respectively. Φ is referred as equivalence ratio.

3.4 Torque Generation:

In general, generation of torque is a non-linear function of engine speed, mass flow rate into the engine cylinder, equivalence ratio and spark advance:

$$T_q = f(N, W_{mix}, \Phi, S_a) \quad (5)$$

Where, S_a represents the spark advance. Note that the induction to power delay enters into system dynamics through above equation as torque depends on the delayed value of the mass flow rate into the engine cylinders.

3.5 Engine Rotational Dynamics:

The equation of engine rotational dynamics is as follows:

$$\frac{dN}{dt} = \frac{1}{j} (T_q - T_e) \quad (6)$$

Where, j is the inertia of engine in neutral state and T_e is the load torque on the engine including internal engine friction

IV. IDLE SPEED CONTROL MODEL

For ISC model, a nonlinear behavior engine model based on the above set of models was linearized at a nominal speed of 900 rpm to obtain a linear plant model [8]. Considering deviation in throttle position in degrees as input and deviation in engine speed in rpm as the output for this model.

The transfer function for this model is:

$$G(s) = 29.8 \frac{s^2 + 50s + 833}{s^3 + 21.2s^2 + 51.3s + 189.5} e^{-0.15s} \quad (7)$$

The Induction to Power delay at a nominal speed of 900 rpm is 125 ms assuming this delay as the result of 360° of crank rotation or 1 revolution of crankshaft. However we are taking this revolution only as an approximation because we don't receive maximum torque calculation at top dead center of crankshaft rotation. Hence we receive an overall delay of 150ms by the combination of actuator delay and computational delay

V. THE NONLINEAR HYSTERETIC ELECTRONIC THROTTLE

The electronic throttle in modern automobiles is usually a brushless DC motor with 12V/5A rating. It is also a strong nonlinear device with hysteretic phenomenon, friction, and return spring nonlinearities, as shown in the following Figure 1.

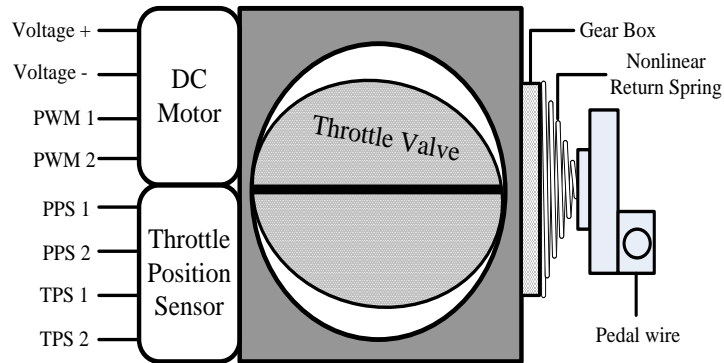


FIGURE 1. THE NONLINEAR ELECTRONIC THROTTLE

The dotted block in Figure 2 shows the schematic diagram for electronic throttle body. The H-bridge is the power amplifier to boost the power of the control output from the electronic controller.

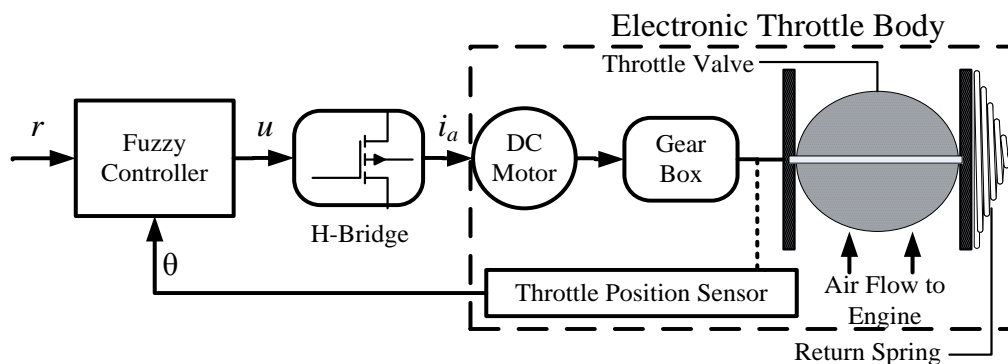


FIGURE 2. THE ELECTRONIC THROTTLE WITH CONTROLLER.

Merging of the backward characteristic of electronic throttle [9], the complete hysteresis loop can be shown in the following Figure 3. One of the major factors of the hysteresis of electronic throttle is the return spring. The other reason is due to the copper coils inside the BLDC.

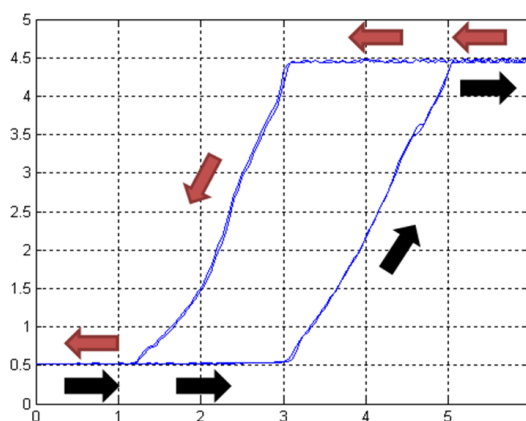


FIGURE 3. THE HYSTERESIS LOOP OF ELECTRONIC THROTTLE

VI. ISC CONTROLLER DESIGN

The choice of required engine set-speed and spark retard is a complex design tradeoff process and is beyond the scope of this paper. The control problem addressed here is the speed tracking problem which can be formally stated as etc. For a given desired engine set idle speed, a controller is designed that generates commands for the throttle valve based on the measured engine speed to vary the engine speed from the set idle in the presence of load disturbances minimize. Control system schematic diagram shown in Figure 4.

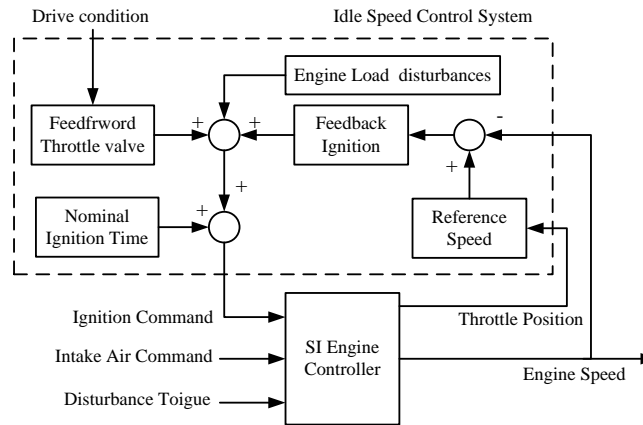


FIGURE 4. ISC CONTROL SYSTEM

The mathematical model described in Section 3 can be used to design the control strategy for fuzzy logic. A feedforward general ISC system is shown in the block diagram of Figure 5.

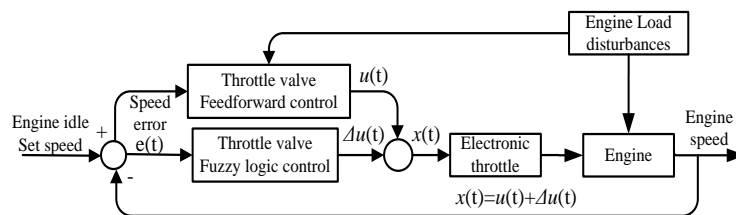


FIGURE 5. ISC SYSTEM WITH FEEDFORWARD CONTROL

Feedforward control is considered to be an effective mechanism to suppress load disturbances. Especially small engines. When a disturbance is measured, control signals can be generated in an attempt to counteract its effect. A typical ISC strategy has feedforward only for the throttle valve control, and the feedforward is designed based on static engine mapping data. For example, if an air conditioning switch sensor is installed an extra amount of air will be scheduled to prevent engine speed droop when the AC compressor is engaged. The amount of feedforward control can be determined as equation (5), the available engine torque to balance the load torque is related to the mass air flow and engine speed through.

By estimating the load torque presented to the engine by the measured disturbance can calculate for fixed air fuel ratio the amount of air that is needed to maintain the engine speed at the fixed set speed. The feedforward control can be applied either as a multiplier or an added to the control signal.

VII. USING FUZZY LOGIC CONTROLLER FOR ELECTRONIC THROTTLE

This closed loop control can be described by the Fig. 5. Then the controller sends the consistent duty signal, which is PWM to the H-bridge circuit and drives the throttle to operate in the correct position.

As described above, the phenomenon of idle speed in the spark ignition engine can be easily identified as problems of nonlinear and time-delay control dilemma. Fuzzy logical models are known to solve problems of nonlinear models with its flexible mathematical structures [10].

The fuzzy sets in the rules serve as an interface amongst qualitative variables in the model, and the input and output numerical variables. The fuzzy modeling approach has several advantages when compared to other nonlinear modeling

techniques; in general, fuzzy models can provide a more transparent representation of the system under study, maintaining a high degree of accuracy.

The structure of control is a Mamdani-type [11] fuzzy logic controller with a typical 'If-Then' rule and logical connectives to establish relations between the variables defined for the model of the system structure [12].

For the past two decades, the FLC has been widely and successfully utilized and implemented in numerous industrial applications [13], [14]. A general FLC consists of four modules: fuzzification module, fuzzy rule-base, fuzzy inference engine and de-fuzzification module [15], as shown in the dotted area in Figure 6.

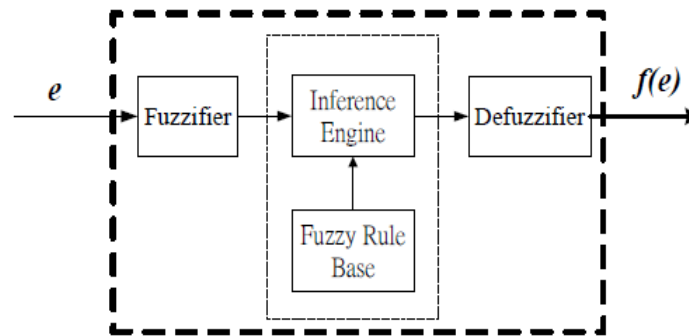


FIGURE 6. THE FUZZY LOGIC CONTROLLER.

Engine speed idling control of the target, first set the basic electronic throttle control u , making the electronic throttle can have a basic opening.

When the engine has a target after the launch speed rpm^* , the speed error e and Δe to modify the throttle opening, a non-linear car engine after a reaction time T to produce a new engine speed rpm , this time using the back control to achieve engine speed stability. The response time T will be different according to the different engine and vehicle conditions, if the time is less than T to read the speed signal will make the phenomenon of speed shocks; and time is greater than T to read the speed signal will make the system more sensitive response. In this paper, the experimental vehicle used for SAAB 9000 (B202 engine) reaction time T has been experimentally measured about 0.8 seconds.

The nonlinear idle speed control using fuzzy logic shown in Figure 3 has two input fuzzy linguistic variables: Error (e) is difference between output engine speed and set idle speed and delta error (Δe) is difference between error now and previous error. Fuzzy output is duty cycle of PWM signal which is used to control DC motor microcontroller's built in timer, this leads to an output variable as the throttle valve motor (x) which indicates the increased airflow percentage from the intake pipe in to combustion chamber.

A controller compares the engine idle speed ($N_i(t)$) with the setting idle speed ($N_s(t)$) and produces the control signal to minimize the error. The equations for $e(k)$, $\Delta e(k)$ are:

$$e(k) = N_i(k) - N_s(k)$$

$$\Delta e(k) = e(k) - e(k-1)$$

Where, k is the sampling instant of the process. The variables $e(k)$, $\Delta e(k)$ are the conditions monitored by the fuzzy logic control. These conditions are expressed in terms of linguistic variables as negative large (NL), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), positive large (PL). The five membership functions {NL, NM, ZE, PM, PL} of e and Δe . The seven membership functions {NL, NM, NS, ZE, PS, PM, PL} of Output Δu .

In This Paper, The Triangular Membership Functions Are Adopted As The Mfs For All Fuzzy Variables. We Define The Triangular Membership Function As $E(x,a,b,c)$ Where $A \leq B \leq C$, As Shown In The Following (8) And Figure 7.

$$e(x, a, b, c) = \begin{cases} \frac{x-a}{b-a} & \text{for } a \leq x \leq b \\ \frac{c-x}{c-b} & \text{for } b \leq x \leq c \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

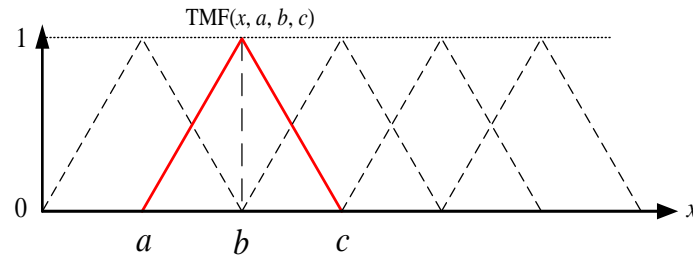


FIGURE 7. TRIANGULAR MEMBERSHIP FUNCTION E(X, A, B, C).

For example, the triangular MFs of speed error (e) are listed as follows:

$$e_{NL}(x, -300, -200, -100) = \begin{cases} \frac{x+300}{100}, & -300 \leq x \leq -200 \\ \frac{-100-x}{100}, & -200 \leq x \leq -100 \\ 0, & \text{otrerwise} \end{cases} \tag{9}$$

$$e_{NM}(x, -200, -100, 0) = \begin{cases} \frac{x+200}{100}, & -200 \leq x \leq -100 \\ \frac{-100-x}{100}, & -100 \leq x \leq 0 \\ 0, & \text{otrerwise} \end{cases} \tag{10}$$

$$e_{ZE}(x, -100, 0, 100) = \begin{cases} \frac{x+100}{100}, & -100 \leq x \leq 0 \\ \frac{100-x}{100}, & 0 \leq x \leq 100 \\ 0, & \text{otrerwise} \end{cases} \tag{11}$$

$$e_{PS}(x, 0, 100, 200) = \begin{cases} \frac{x-0}{100}, & 0 \leq x \leq 100 \\ \frac{200-x}{100}, & 100 \leq x \leq 200 \\ 0, & \text{otrerwise} \end{cases} \tag{12}$$

$$e_{PL}(x, 100, 200, 300) = \begin{cases} \frac{x-100}{100}, & 100 \leq x \leq 200 \\ \frac{300-x}{100}, & 200 \leq x \leq 300 \\ 0, & \text{otrerwise} \end{cases} \tag{13}$$

The idle speed error (e) in an automobile is between set point speed±300 rpm and we allow the deviation of 100 rpm in the five MFs of e, as shown in the following Figure 8. Therefore we also set the delta error (Δe) as error (e)

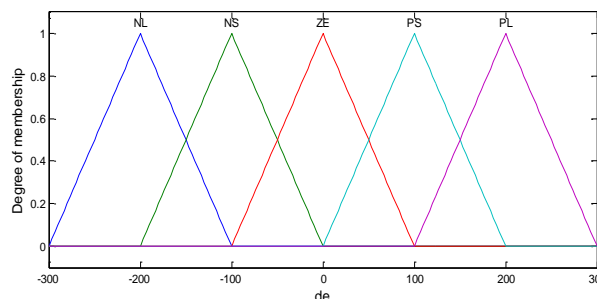


FIGURE 8. THE FIVE MFs (NL, NS, ZE,PS,PL) FOR E AND ΔE

Finally, the output is the throttle drive motor (Δu). According to our expert experience, we let $-6 \leq \Delta u \leq 6$ and define seven MFs for NL, NM, NS, ZE, PS, PM, PL, as shown in the following Figure 9. In terms of TMF shown in (8), they are:

$$u_{NL}(x) = TMF(x, a, b, c) = TMF(x, -6, -3.6, -2.4)$$

$$u_{NM}(x) = TMF(x, a, b, c) = TMF(x, -3.6, -2.4, -1.2)$$

$$\begin{aligned}
 u_{ns}(x) &= TMF(x, a, b, c) = TMF(x, -2.4, -1.2, 0) \\
 u_{ze}(x) &= TMF(x, a, b, c) = TMF(x, -1.2, 0, 1.2) \\
 u_{ps}(x) &= TMF(x, a, b, c) = TMF(x, 0, 1.2, 2.4) \\
 u_{pm}(x) &= TMF(x, a, b, c) = TMF(x, 1.2, 2.4, 3.6) \\
 u_{pl}(x) &= TMF(x, a, b, c) = TMF(x, 2.4, 3.6, 6)
 \end{aligned}$$

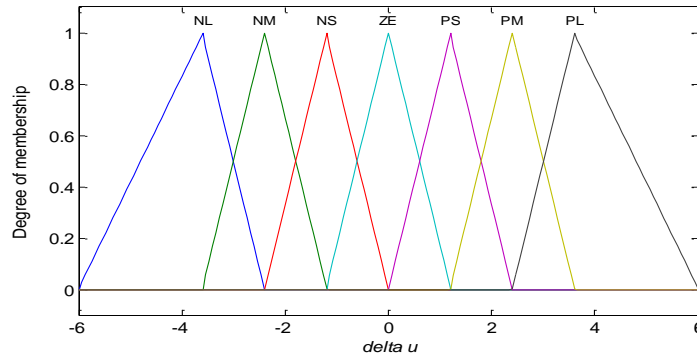
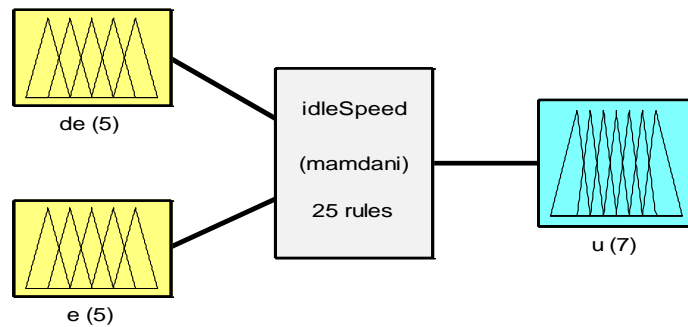


FIGURE 9. THE FIVE MFs (NL, NM, NS ZE, PS, PM, PL) FOR Δu

Figure 10 summarizes the total picture of our fuzzy logic system for finding the Δu of idle speed control.



System idleSpeed: 2 inputs, 1 outputs, 25 rules

FIGURE 10. FUZZY LOGIC SYSTEM

We adopt the Center-Of-Area (COA) for defuzzification, as shown in the following (9):

$$Z_{COA} = \frac{\sum_{j=1}^n u_c(Z_j)Z_j}{\sum_{j=1}^n u_c(Z_j)} \tag{14}$$

Here we have the following Table 5-2 to show the fuzzy rule-base to complete the above FLS.

TABLE 1
THE FUZZY RULE BASE FOR OUTPUT PWM SIGNAL (Δu)

Δe / e	NL	NS	ZE	PS	PL
NL	PL	PM	PS	ZE	ZE
NS	PM	PS	ZE	ZE	NS
ZE	PS	PS	ZE	NS	NS
PS	PS	ZE	ZE	NS	NM
PL	ZE	ZE	NS	NM	NL

Therefore the following Algorithm shows the steps in realizing the Intelligent Idle Speed Controller in Figure 3: Algorithm: The Intelligent idle speed Controller

1. Initialization. Set $x=0$. Find the throttle position for idle according to the current setting idle speed. This can be done from the following Look-Up-Table [16]:

TABLE2
THROTTLE ANGLE POSITION

<i>Throttle Angle</i> (Degree)	<i>TPS</i> (Voltage = Integer)
84° (idle position)	0.4 v = 20
72°	1.03 v = 53
60°	1.62 v = 83
48°	2.19 v = 112
36°	2.85 v = 145
24°	3.4 v = 173
12°	4 v = 204

2. For a given current throttle position, if the current TPS is not close to its TPS for idle position, then GO TO Step 4. There is no need to adjust in Figure 3, set $x=0$. GO TO 2.
3. Perform the tracking of 100% of the current idle speed using the control configuration shown in Fig. 3 with its associated FLC. Set initial u . The Δu will be determined by the FLC to track the desired idle speed.
4. If the above tracking is finished, GO TO Step 1.
5. END

In order to reduce the system in the operational difficulty, and speed up the processing speed. We convert the original fuzzy controller into a table. Table 3 provides a quick calculation of the pre-computed control signal Δu by querying the positions of $e(k)$ and $\Delta e(k)$.

TABLE 3
TABLE LOOK-UP TABLE

$e / \Delta e$	-225	-150	-75	0	75	150	225
-225	4.021	3.462	2.053	1.200	0.347	-0.000	0.000
-150	3.462	2.859	1.426	0.600	0.411	-0.600	-0.600
-75	2.053	1.800	0.853	0.000	-0.347	-0.600	-1.200
0	1.200	1.200	0.853	0.000	-0.853	-1.200	-1.200
75	1.200	0.600	0.000	-0.853	-0.853	-1.800	-2.053
150	0.600	0.600	-0.411	-1.200	-1.800	-2.859	-3.462
225	0.0	-0.000	-0.347	-1.200	-2.053	-3.462	-4.021

Figure11. Shows our electronic throttle and control circuits, which are set up on our experiment car.

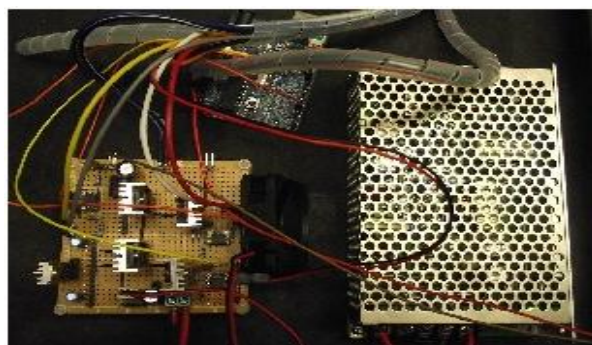


FIGURE11 REAL TIME ETC IN SAAB 9000

The real time testing is performed in this experiment plant idle speed point to the real actions of automobile drivers figure 12 shows under the condition of engine with no load, its working temperature is above 80°C and set ignition on 10° before top dead center. When set-point idle speed was prescribed at 900 ± 20 rpm running in total of 600 seconds, most of the engine speed reading fall with a tolerance less than set deviation point.

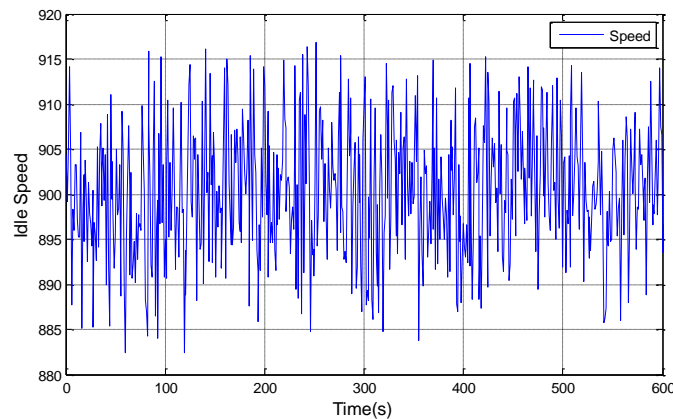


FIGURE 12. REAL-TIME IDLE SPEED RESPONSE

**TABLE 3
DATA STATISTIC**

Min	882.4
Max	916.9
Medan	900.4
Standard deviation	7.24

VIII. CONCLUSION

Idle speed control is one of the highest confrontations for automobile industry and researchers as they were addressing many issues in relation to engine stalling at rest position and fuel saving economy. An engine model plays a major role in defining the correct parameters for control system. So, we defined the engine model based on certain aspects and analyzed it properly to fit in the system.

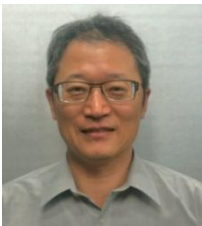
Idle speed control problem is effectively eliminated by the use of intelligent fuzzy logic to control the electronic throttle. In comparison to previously published experiments, less deviation range, and more steady testing period were observed. The experimental result shows that a stable fuzzy logic control can be realized to control the nonlinear hysteretic electronic throttle motor. Results were carried over to the real time implementation of fuzzy logic control to control an actual electronic throttle in Saab 9000. Testing vehicle idle performance additionally increased in stability, and engine vacuum deviation was also escalated.

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