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Review

A review on control system architecture of a SI engine management system

B. Ashok*, S. Denis Ashok, C. Ramesh Kumar

School of Mechanical Engineering (SMEC), VIT University, Vellore 632014, India

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ABSTRACT

Engine management systems (EMS) has become an essential component of a spark ignition (SI) engine in order to achieve high performance; low fuel consumption and low exhaust emissions. An engine management system (EMS) is a mixed-signal embedded system interacting with the engine through number of sensors and actuators. In addition, it includes an engine control algorithm in the control unit. The control strategies in EMS are intended for air-to-fuel ratio control, ignition control, electronic throttle control, idle speed control, etc. Hence, the control system architecture of an EMS consists of many sub-control modules in its structural design to provide an effective output from the engine. Superior output from the engine is attained by the effective design and implementation of the control system in EMS. The design of an engine control system is a very challenging task because of the complexity of the functions involved. This paper consolidates an overview of the vital developments within the SI engine control system strategies and reviews about some of the basic control modules in the engine management system.

1. Introduction

Enhancements in fuel economy and emission reductions are two active areas of engine research. Advanced engine control techniques are engaged because of the strict emission regulations and demand for higher fuel economy. It is of great importance to design the power train components in order to improve the fuel efficiency and reduce emissions while fulfilling drivability and ride comfort issues. Control has always been a part of engine design and it is one of the most complex problems in the application (Stobart, Challen, & Bowyer, 2001). Automobile engines effectively encompass the spirit of mechatronic systems with their abundant application of electronics, sensors, actuators and microprocessor based control systems to provide improved performance, fuel economy and emission levels. The classical approach of engine-control tasks is accomplished by means of a mechanical approach, but now it is being replaced by electronic control systems. In such systems, engine performance such as power, torque, fuel-consumption and emission level, is significantly affected by the control strategies followed in the engine management system (EMS) (Lee, Park, & Sunwoo, 2004). The modern spark ignition engines are generally equipped with an EMS whose task is to provide the desired output from the engine and it plays an important role in the driver's control of the vehicle. It controls the operations such as ignition, air-to-fuel ratio, idle speed and complex variable valve timing, etc., in order to reduce the emissions and improve the average fuel economy (George & Michael, 2014). Compared with ordinary embedded systems, it requires more stringent demands on reliability, resource sharing and cost efficiency (Guojun, Wenqing, & Youtong, 2010).

Engine management system (EMS) usually consists of various sensors to monitor the real-time operating conditions of the engine and actuators to control injector, spark plug, throttle, etc. The control signal sent to different actuators is accomplished by means of the EMS control system, which is comprised of a large number of control modules (control loops) in its architecture. The schematic representation of the control system architecture of SI engine is shown in Fig. 1. Some of the basic modules within the EMS which are coordinated with the torque control module are, 1) air–fuel ratio (AFR) control; 2) electronic throttle control (ETC); 3) idle speed control; 4) ignition timing control; 5) knock control; 6) diagnostics control, etc. Besides these modules, cam shaft control, turbocharger, EGR, after treatment controls, etc. are also a part of the control modules in an actual production vehicle EMS (Andreas & Torsten, 2001; Guenther & Gerhardt, 2000; Guzzella & Onder, 2010; Hammel, Jessen, Andreas, & Harald, 2003; Hillion et al., 2008; Hong et al., 2013; Isermann, 2014; Jurgen, Honninger, & Bischof, 1998; Le Solliec, Berr, Colin, Corde, & Chamaillard, 2007; Le Solliec et al., 2007; Ribbens, 1998). All these modules are run in parallel to the torque control structure in order to produce the desired engine output as demanded by the driver. Other modules are

* Corresponding author. Tel.: +91 9865467729.
E-mail address: ashok.b@vit.ac.in, ashokmts@gmail.com (B. Ashok).

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coordinated with the torque control module in order to accomplish the engine output for the torque demand. The coordinated overall torque reference value is realized by the manipulation of variables like throttle position, ignition timing, injection timing, etc. by the respective actuators. Hence, the torque control module is the fundamental part of the entire engine control system architecture.

The control functions are managed by software control algorithms in the EMS. The design and implementation of control algorithms is a crucial element in the development of automotive engine-control systems because of different operating modes of engines such as: the start-up mode, idling mode, normal operation mode, high power output mode, etc. Once the engine is started, the EMS must make a judgment about the engine operating conditions according to the data collected by different sensors. Through this process the EMS calculates and adjusts the injection time, ignition advance, throttle angle, etc. by the respective actuators (Isermann & Michael, 2001; Kiencke & Nielsen, 2005; Wang, Yu, Gomm, Page, & Douglas, 2006). The engine management system (EMS) coordinates with other vehicle control systems (cruise control, ABS, ESP, etc.) for enhanced vehicle performance and handling.

The application layer of the software architecture in the EMS is the separation of the engine functions from the vehicle functions. The vehicle functions include all the concerns of powertrain management within the vehicle, that are not specific to the engine combustion like electrical supply system, thermal management system, vehicle speed governor, etc. Started as a standalone injection control system in SI engines, the modern EMS includes the other control algorithm such as torque coordination, ignition control, throttle control, knock control, diagnostic controls, turbocharger control, etc. All of these algorithms are in the application software architecture of an EMS (Hammel et al., 2003). Currently, engine control algorithms are mostly accomplished by a mathematical model-based design and non-linear feedforward control is implemented using engine maps, i.e., matrix-based lookup tables that have been derived through extensive engine test bench operations during calibration (Gonzalez, Florez, & Arab, 2008; Huan, Huang, Dai, & Hu, 2014; Krishnaswami, Luh, & Rizzoni, 1995; Markus, Johansson, & McKelvey, 2014). An engine management system has hundreds of functions with thousands of parameters; each of these functions needs to be properly calibrated and tested together with the other electronic control unit (ECU) software. These calibration processes are usually complicated and include a lot of test contents. The main contents are steady state calibration tests, transient operation, idle operation, covering a lot of parameters including fuel parameters like fuel injection timing, ignition parameters like ignition advance, etc. in the form of lookup tables. All of such lookup tables are part of the control algorithms which are stored in the memory of the controller. Also, the control system should be robust with respect to process parameter variations caused by production deviations, variations of external conditions (e.g. temperature), and aging. And finally, the control strategy should have a simple structure, convenient for implementation on a typical low-cost automotive microcontroller system (Eriksson & Nielsen, 2014; Lumpp, Tanimou, Bouillon, & Muenzenmay, 2014; Tomohiko & Hayakawa, 2011; Wong, Tam, & Ke, 2012). In recent years, many control theories have been successfully applied to engine control systems. For example, PID control, recurrent neural network, trainable fuzzy control, adaptive control, optimal control, H_∞ control, hybrid control and nonlinear control have been used to control the different control modules such as engine torque control (Gafvert, Arzen, Bernhardsson, & Pedersen, 2000, Gafvert, Arzen, Pedersen, & Bernhardsson, 2004; Heintz, Mews, Stier, Beaumont, & Noble, 2001; Jurgen et al., 1998; Le Solliec, Berr et al., 2007, Le Solliec et al., 2007; Petrovich, 2000), air–fuel ratio (Al-Himyari, Yasin, & Gitano, 2014; Alain, Vigild, & Hendricks, 2000; Alexander & Kolmanovsky, 2002; Anurak & Sooraksa, 2012; Behrouz et al., 2012; Bin, Shen, Kako, & Ouyang, 2008; Dickinson, 2009; Feng et al., 2006; Ferdinando & Lavorgna, 2006; Franceschi, Muske, Peyton Jones, & Makki, 2007; Franchek Matthew, Mohrfeld, & Osburn, 2006; Grizzle, Cook, & Milam, 1994; Guo, Baiyu, Yunfen, & Hong, 2013; Haiping & Qian, 2010; Hajime et al., 2002; Holzmann, Halfmann, & Isermann, 1997; Ivan, Marotta, Pianese, & Sorrentino, 2006; Kahveci Nazli & Jankovic, 2010; Kwiatkowski, Werner, Blath, Ali, & Schultalbers, 2009; Mayr Christian, Euler-Rolle, Kozek, Hametner, & Jakubek, 2014; Nicolo, Corti, & Moro, 2010; Per, Olsen, Poulsen, Vigild, & Hendricks, 1998; Rajagopalan et al., 2014; Roberto, Villante, & Sughayyer, 2005; Rui, Li, Dong, & Tang, 2009; Sardarmehni, Keighobadi, Menhaj, & Rahmani, 2013; Shuntaro, Kato, Kako, & Ohata, 2009; Sei-Bum, Won, & Hedrick, 1994; Seungbum, Yoon, & Sunwoo, 2003; Stroh David, Franchek, & Kerns, 2001; Tseng & Cheng, 1999; Winge, Andersen, Hendricks, & Struwe, 1999; Yildiray, 2009; Yildiray, Annaswamy, Yanakiev, & Kolmanovsky, 2010; Yildiray, Annaswamy, Yanakiev, & Kolmanovsky, 2008; Zhai & Yu, 2009; Zhai, Yu, Tafreshi, & Al-Hamidi, 2011), throttle control (Al-samarraie & Abbas, 2012; Alt et al., 2010; Andreas & Eriksson, 2009; Aono & Kowatari, 2006; Chen & Ran, 2009; Chen, Lin, & Wei, 2012; Chen, Tsai, & Lin, 2010; Chen, Tsai, & Lin, 2010; Chris & Watson, 2003; Danijel, Deur, Jansz, & Peric, 2006; Deur, Pavkovi, Peri, Jansz, & Hrovat, 2004; Devor & Sun, 1997; Di Bernardo, Montanaro, Santini, di Gaeta, & Giglio, 2009; Eiji, Ishiguro, Yasui, & Akazaki, 2003; Feru et al., 2012; Giulio, Corno, & Savaresi, 2013; Grepl & Lee, 2010; Griffiths, 2002; Jae & Byun, 1999; Lars & Nielsen, 2000; Mercorelli, 2009; Montanaro et al., 2014; Nakano et al., 2006; Shugang, Smith, & Kitchen, 2009; Takeru, Asada, Tsuyuguchi, Yamazaki, & Hotta, 2009; Thomasson & Eriksson, 2011; Thornhill & Sindano, 2000; Toshihiro & Kowatari, 2001; Umit, Hong, & Pan, 2001; Wang et al., 2010; Wang & Huang, 2013; Yang, 2004; Yurkovich & Li, 2005; Xiaofang & Wang, 2009; Yildiz, Annaswamy, Yanakiev, & Kolmanovsky, 2007; Yuan, Wang, & Wu, 2008; Zeng & Wan, 2011; Zhang, Yang, & Zhu, 2014), idle speed (Chamaillard et al., 2004; Danijel, Deur, & Kolmanovsky, 2009; di Gaeta, Montanaro, & Giglio, 2010; Feng-Chi, Chen, & Wu, 2007; Howell & Best, 2000; Jacek, 2010; Jingshun & Kurihara, 2003; Jiangyan, Shen, & Marino, 2010; Josko, Ivanovi, Pavkovi, & Jansz, 2004; Kong, Yuhua, Xiaoguang, & Xigeng, 2006; Luigi, Santini, & Serra, 1999; Manivannan, 2011; Nicolo et al., 2003; Scillieri, 2002; Singh, Vig, & Sharma, 2002; Stefan & Eriksson, 2006; Subramaniam, Dessert, Sharma, & Yasin, 2002; Yildiray, Annaswamy, Yanakiev, & Kolmanovsky, 2011 Yildiz et al., 2007), ignition timing (Arno, Layher, & Däschner, 2012; Baitao, Wang, & Prucka, 2013; Bhot & Quayle, 1982; Czarnigowski, Wendeker, Jakliński, Boulet, & Breaban, 2007; Desheng, Yunfeng, & Hong, 2014; Enrico et al., 2014; Eriksson & Nielsen, 1997; Go-Long, Wu, Chen, & Chuang, 2004; Herbert & Ploeger, 2007; Huang & Chen, 2006; Masatake et al., 2001; Raducanu, Arotaritei, & Dimitriu, 2001; Saravana Prabu & Naiju, 2009; Yankun & Liu, 2010; Zhengmao, 2001; Zhang et al., 1999; Zhihu & Run, 2008), etc. in the engine management system (EMS). As there are different types control approaches and complexity are involved in the engine control system, this review paper aims to summarize the some of the basic engine control modules, in a collective approach.

Existing research activities were focused on describing the particular control module and its development rather than a holistic approach of engine control system development. This review paper will serve as a fundamental guide for future studies to improve the performance aspects of the EMS control system architecture of a SI engine. In this paper, an attempt is made to review some of the basic and essential control modules in an engine management system (EMS) of an SI engine. This review paper will not enforce any new results, rather than it will gives a combined approach of the various research activities on the engine control system and discuss the future prospects of SI engine controls. The paper is organized

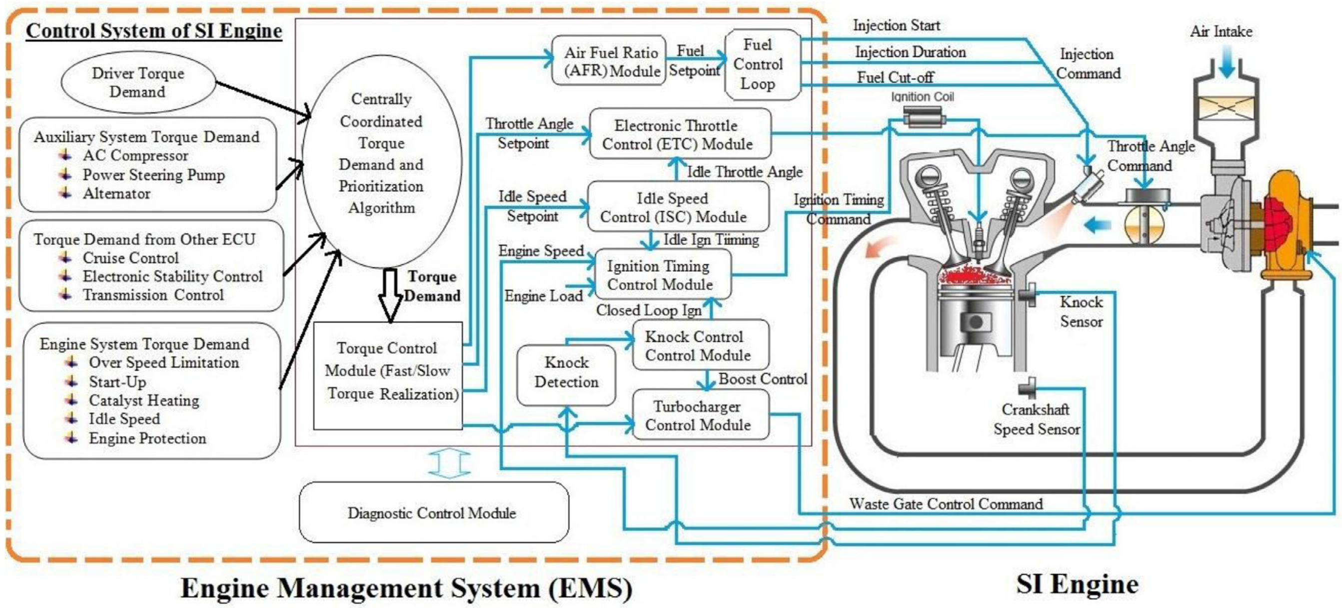

Fig. 1. Schematic representation of the EMS control system in a SI engine.

in multiple sections, Section 2 deals with the torque based engine module, followed by Section 3 which deals with the air fuel ratio control module, Section 4 with electronic throttle control, Section 5 discuss idle speed control, and Section 6 with ignition control module. Where Section 7 deals with knock detection and control module and Section 8 describes the diagnostic system in the EMS.

2. Torque based engine control module

Due to the increasing complexity of engine control systems and the integration of vehicle control systems, torque-based engine control strategies come into usage (Chamaillard et al., 2004; Ml, Minghui, & Anthony, 2008). The torque-based system can easily interact with external torque interfaces (transmission, traction control, etc.). The torque based EMS control module converts the various inputs into the engine torque variable, which is used as the major interface between the engine control unit and other functionalities inside the vehicle control system. The coordination between engine control, transmission control and brake control, etc. is also accomplished through this torque variable. Hence, based on the physical value of torque, all demands can be coordinated before the optimal conversion to the respective engine control values takes place. As the torque demands are originating from the driver and also form the engine management functions (i.e. engine start, idle speed control, catalyst heating), external subsystems like the transmission control unit, the cruise control system, traction control system, etc. (Guenther & Gerhardt, 2000; Heintz et al., 2001). Engine torque control provides coordination of engine actuators (throttle position, spark advance, cam phase positions and others) to achieve torque requested by driver or a vehicle subsystem. Some of the research works carried on the torque based control module are listed in Table 1. The torque- based engine control system was initially presented by Bosch and applied in Bosch ME7 version engine management system (EMS). Nowadays this kind of coordinated powertrain control system has become a standard in the automotive industry. All powertrain control suppliers develop solutions to provide coordinated powertrain torque control.

From the research work listed above it is evident that, initially a non coordinated torque control was applicable for the engine control functions. Because of the several torque or efficiency demands arises simultaneously from different subsystems there is a necessity of the central coordination. Such coordination for the subsystems is accomplished by means of the centrally coordinated torque control module in the EMS. As the driver requests a torque from the engine via accelerator pedal input, this torque is converted to a torque setpoint, through the driver interpreter which is the interface between the driver and the ECU. Its mission is to interpret the driver demand generated by an accelerator pedal through a potentiometer sensor and this electrical signal is equivalent to the driver torque requests from the vehicle (Andreas & Torsten, 2001). The driver torque demand is given by a pedal map as shown in Fig. 2. From that map, depending on the accelerator pedal position and engine speed sensor signal, the values are transformed into a desired torque demand by considering the demand from other systems as shown in Fig. 3. As the torque demand is the only interface between the accelerator pedal position and the engine control strategies, the response of the vehicle corresponding to the pedal position can be easily influenced by changing the pedal map (Heintz et al., 2001; Isermann, 2014).

Engine torque control consists of feedforward and feedback subsystems providing transient and steady state engine performance controls. Feedforward engine torque control provides us with calculation of desired actuator positions to produce requested torque value. Whereas the feedback system corrects feed-forward subsystem based on estimated torque. One of key elements of the engine torque control is engine torque estimation. Engine torque control algorithm contains two main subsystems: engine torque estimation and engine torque control. The engine torque estimation is used because engine torque sensors are not available in production intended vehicle. Engine torque estimate is calibrated by engine torque calibration engineers, and accuracy is within the engine torque error specification. Based on the major input variables such as relative cylinder charge, lambda and ignition timing an internal torque is generated by combustion. Taking internal losses caused by the gas exchange and friction into account as well as losses caused by accessories the engine torque output can be calculated. Engine torque estimate is then used as achieved torque, and used to calculate torque errors in reference to desired torque commands (Bernhard, Jessen, Kaiser, & Gerhardt, 2001; Ml et al., 2008).

Table 1
Different control approaches for the torque based engine control module.

S. no.	Authors	Year	Outcomes
1	(Jurgen et al., 1998)	1998	This paper describes the new engine management system (EMS) ME7. Torque and A/F demands for modern EMS result from both, internal functions and external systems. With ME7 these demands are processed to the optimized actions of the actuators by a centrally coordinated torque and A/F management.
2	(Petrovich, 2000)	2000	Torque based approach with rapid control prototyping, to verify the feasibility of DISI control system was presented.
3	(Gafvert et al., 2000, 2004)	2000	The controller consists of a combination of sub-controllers, where torque feedback is a central part. The sub-controllers are with a few exceptions designed using simple linear feedback and feedforward control design methods. Special mode switch strategies are used to minimize the torque bumps during combustion mode changes.
4	(Guenther & Gerhardt, 2000)	2000	MOTRONIC (ME7) Bosch introduced torque based functional architecture. This includes the optimization of engine performance and compliance with legal standards on emission, fuel consumption and diagnosis. Bosch CARTRONIC, an ordering concept which integrates the engine control into vehicle control system.
5	(Bernhard et al., 2001)	2001	This paper defines the inter-face between vehicle coordination and a CARTRONIC compatible engine management system. Additionally, smart torque conversion strategies are introduced.
6	(Andreas & Torsten, 2001)	2001	The software design of this new engine control unit is based on a unique and homogenous torque structure. All input signals are converted into torque equivalents and a torque coordinator determines their influence on the final torque delivered to the powertrain. The basic torque structure is independent on the type.
7	(Heintz et al.,)	2001	A torque-based engine control architecture which uses a central torque demand variable to control the regulating qualities. This torque demand variable is the result of the coordination of all torque requests throughout the vehicle. Therefore, the system manages the whole process of prioritizing the torque demands of the different subsystems.
8	(Julie & Frashure, 2007)	2002	Describes an in-vehicle torque sensing system that was created to supplement the engine dynamometer development and validation of an ECM torque model.
9	(Manjunath, 2003)	2003	GDI engine management system motronic (MED-7) with their unique and advanced torque guided functional architecture was discussed.
10	(Triwiyatno et al., 2011)	2004	A mean-value powertrain model for Engine Torque Control and it describes model validation and calibration process. This model may be used in different Engine Torque Control design phases such as control structure design, robustness and stability analysis, and DFMEA.
11	(Corsetti, O'Connell, & Watkins, 2002)	2005	A simple but effective method to estimate the engine torque based on an extended Kalman filter used in combination with a polynomial engine model and a simple friction model.
12	(Abid & Blath, 2006)	2006	Three techniques to the torque control of a SI direct injection engine. The first scheme applies feedback. The second approach, nonlinear model predictive control, optimizes the control law over finite time horizon taking the input and state constraints. The third is gain-scheduled LQ-optimal control scheme based on the state-space of system.
13	(Livshiz, Kao, & Will, 2004)	2007	An integrated powertrain control system to improve large vehicle system reliability, development, and development efficiency. This system composed of 4 parts: generation part, mediating part, modification part and distribution part.
14	(Le Solliec, Berr et al., 2007, Le Solliec et al., 2007)	2007	A model based engine control development of a downsized spark ignition engine, from torque-based structure scheme tested in simulation to integration and calibration.
15	(Ml et al., 2008)	2008	It gives an overview of Engine Torque Control architecture with main elements, and discusses control system requirements. An Engine Torque Control transient response in terms of classical control theory metrics such as overshoot, steady state error, and response time.
16	(Shinya et al.,)	2008	This paper describes torque-based engine control technologies for SI engine to improve torque control accuracy using a feedback control algorithm and an airflow sensor. The proposed combined feedforward-feedback control with learning map has a feedback loop of intake air by an airflow sensor.
17	(Liang, Tsai, Peng, & Wu, 2013)	2008	Based on the physical principle and experimental data's, an engine and powertrain model for torque based control strategy is described. A mean-value engine model, it incorporates throttle inlet, intake manifold intake, cylinder inlet, engine rotation dynamics and vehicle dynamics with mean-value type of fidelity.
18	(Junxi, Mao, Zhu, Song, & Zhuo, 2009)	2011	A new design method of fuzzy robust control proposed build an integrated-control that can anticipate a system that works on a wide operating point and have different characters for each operating point
19	(Grünbacher, Kefer, & del Re, 2005)	2013	A torque-based EMS for a range extender engine which is a 125 cc four-stroke semi-direct injection engine and fueled by liquefied petroleum gas (LPG).
20	(Kuwahara, Kubonoya, Mizuno, Kaigawa, & Kono, 2007)	2014	Model-based Calibration (MBC) technology is applied to develop the torque control system of gasoline engines, which consists of the desired map calibration and tracking control. The desired calibration map contains spark advance angle map, air fuel ratio (AFR) map, torque explanation map.

Then the for the torque demand the torque control module block converts the desired torque into working torque, i.e. with friction, pumping losses, and accessory loads, etc. are subtracted (Gafvert et al., 2000, 2004; Petrovich, 2000). Mechanical friction is compensated by a torque loss component, imported from a friction look-up table depending on engine temperature and engine speed. Pumping losses are considered in a table depending on engine speed and engine charge. As a second step, the resulting torque demand is converted into the available torque-influencing control values by the respective control modules. These are the throttle angle (in case of a drive-by-wire system with an electronic throttle control—ETC), the injection time, the "pattern" of the injector deactivation (for torque reduction, the fuel is not injected into all cylinders), the ignition timing, as well as waste-gate control for turbocharged engines (if equipped).

2.1. Actuator control in a torque control module

A typical torque management system for the driver torque setpoint along with the other demands, to the engine actuator control is shown in Fig. 4. For the torque setpoint the engine controller sub-system modules (AFR, ignition, etc.) which have their own algorithms respectively to calculate optimum spark advance, fuel mass and air charge in order to obtain that desired torque. Then the corresponding signals are provided to the actuator control block (driver circuit) and a driver circuit provides the activation signals to the actuators which must actuate the necessary actuators namely fuel injectors, spark plug and air throttle, etc. (Luigi, Vasca, & Rossi, 2000). The engine torque management controls all torque influencing actuators in the engine, based on the desired torque. It is used both in torque control and in speed control operation modes. In speed control mode, the torque control system provides signals for actuator controls to achieve requested engine speed under coast down and steady state idle conditions (Ml et al., 2008). Taking the real cylinder charge into consideration, the two torque conversion paths (cylinder charge path and crank synchronous path) are linked, so that no other coordination of the two paths is necessary (Bernhard et al., 2001; Guenther & Gerhardt, 2000; Manjunath, 2003; Matthias, Moser, & Philipp, 1999). Hence in order to satisfy the required torque demand the

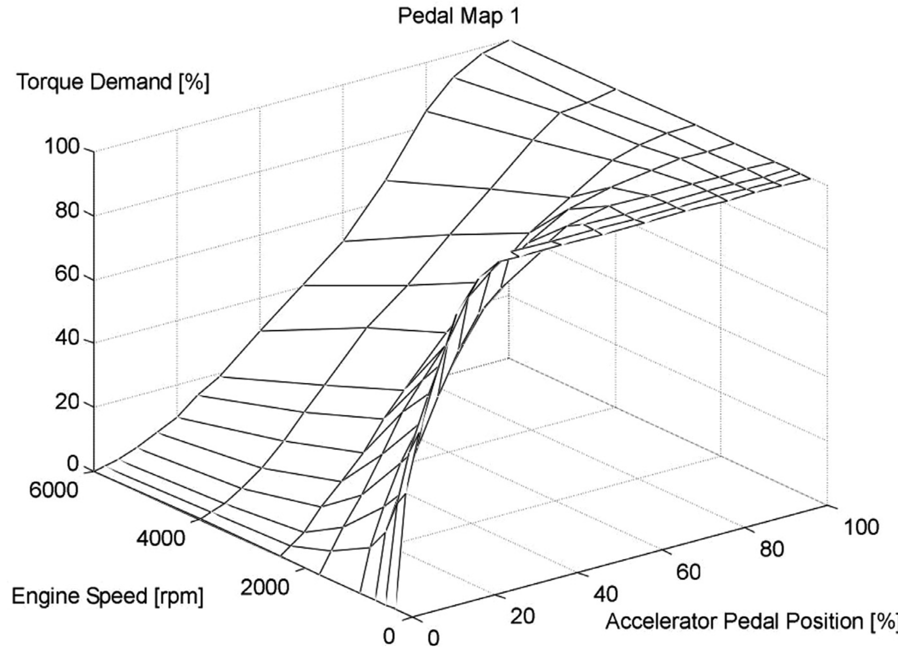

Fig. 2. Driver torque demand pedal map (Chamaillard et al., 2004).

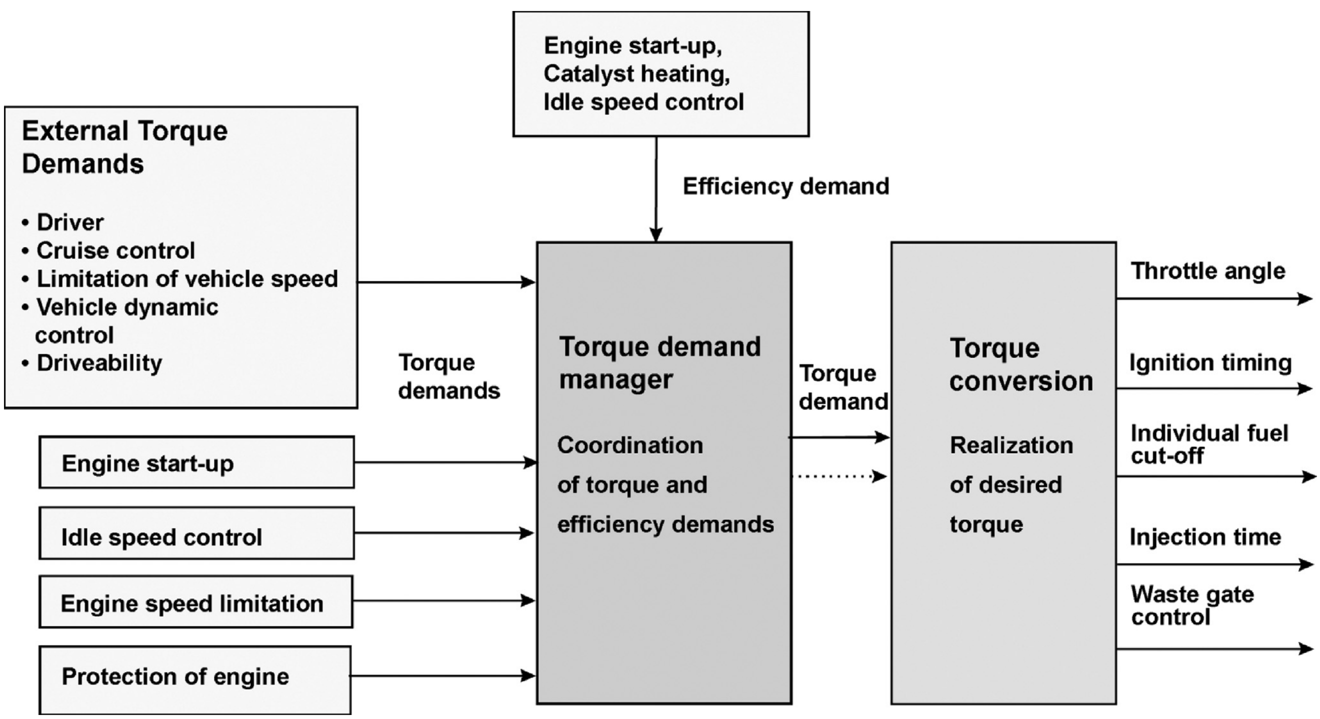

Fig. 3. Centrally coordinated torque based control structure (Jurgen et al., 1998; Bernhard et al., 2001; Manjunath, 2003).

corresponding actuators (throttle, injector, spark plug, etc.) has to be controlled by the respective control modules.

3. Air fuel ratio (AFR) control module

Air fuel ratio (AFR) is one of the important control modules in the EMS since the ratio has been varied according to the torque demand requirement originated from the torque structure by considering the engine demands (catalyst heating, AC, etc.) and vehicle demand (cruise control, transmission control, etc.) as well. The three way catalytic converter (TWC) achieves its best efficiency only if the engine is operated within a narrow band around the stoichiometric air/fuel ratio. Due to the TWC's ability to store oxygen and carbon monoxide on its surface, short excursions of the air/fuel ratio can be tolerated as long as they do not exceed the remaining storage capacity and the mean deviation. So, the AFR module needs to maintain the air–fuel ratio in a stoichiometric condition in order to ensure the maximum conversion efficiency of the TWC (Hongming, 1999; Rolf & Norbert, 2003; Sardarmehnia, Keighobada, Menhaj, & Rahmani, 2013). The main problems faced by the researchers in this area are, concern with the variety of engine operating regimes, nonlinear dynamics, complexity of

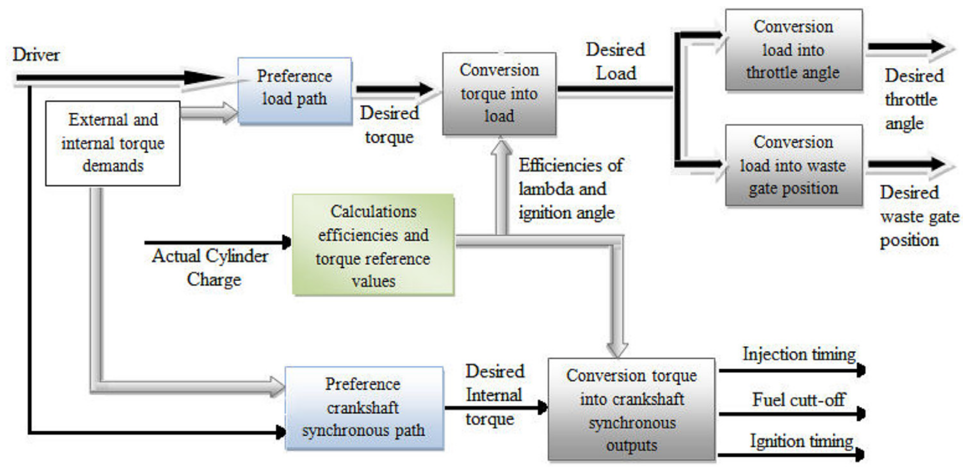

Fig. 4. Actuator control of the torque control module (Bernhard et al., 2001).

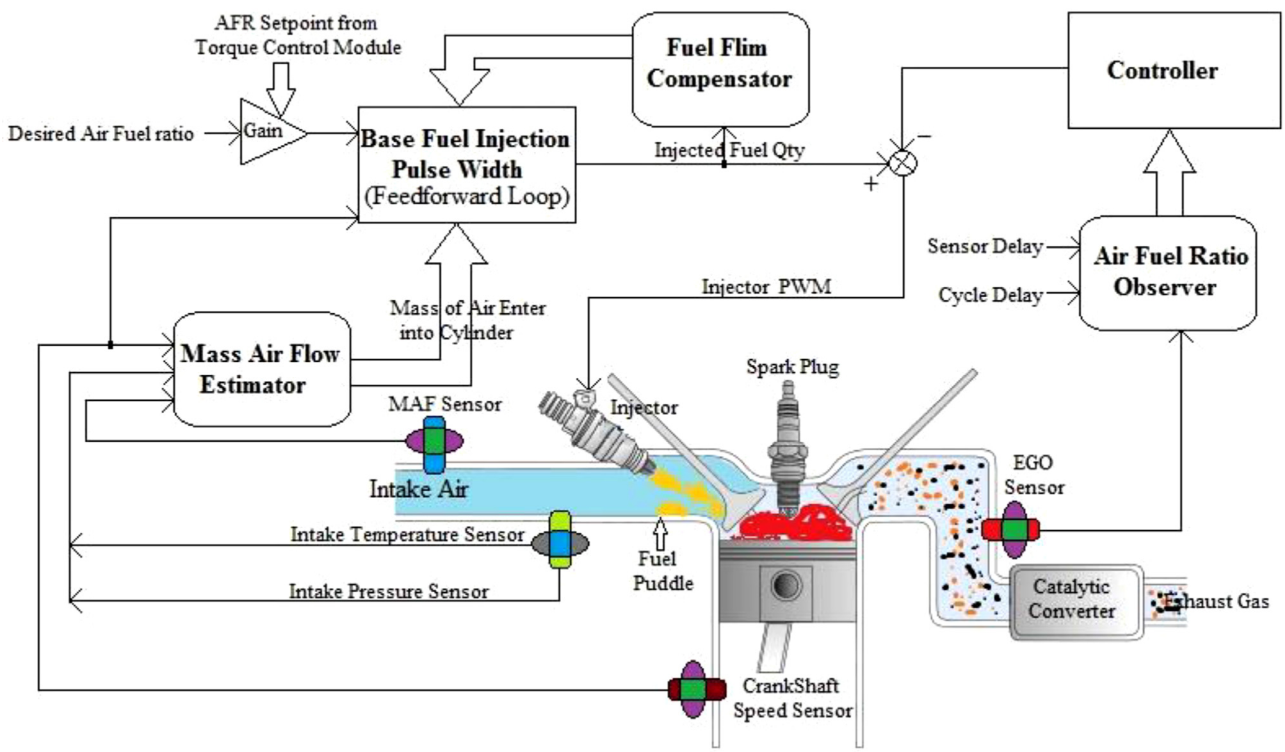

Fig. 5. Air fuel ratio control module of a SI engine.

physical & chemical processes in the engine, uncertainties, noise, disturbances, number of un-measurable variables which directly affect AFR and demanded torque (Gerasimov, Javaherian, & Nikiforov, 2011). The major elements of the AFR control module shown in Fig. 5, are mass air flow estimator, fuel film compensator, A/F ratio observer and the controller which makes use of all the information provided by the elements to produce the appropriate injector pulse width (Tseng & Cheng, 1999).

3.1. Mass air flow estimator

To meter the correct amount of fuel, it is necessary to know the air mass inducted into the cylinder. The base fuel mass required to maintain stoichiometric combustion based on the air flow and manifold air pressure is calculated by the engine control unit (Franceschi et al., 2007). In general two techniques are followed to estimate the air flow into the cylinder of an SI engine. A conventional technique which uses a manifold absolute pressure (MAP) sensor and other widely used technique is Mass Air Flow (MAF) sensor based, which measures the air mass directly (Alexander & Kolmanovsky, 2002; Haiping & Qian, 2010). Both of these techniques have their own advantages and disadvantages. The MAP sensor technique uses speed density equation relating the manifold pressure and the intake air temperature with the known volumetric efficiency (lookup table) characteristics of the engine, in order to calculate the airflow into the cylinder and thus makes it possible to calculate fueling requirements. In this method, density of the air is measured by the temperature of the inlet air and manifold pressure (MAP). With the density of intake air as a known value, the AFR control module then calculates, how much air is expects to be moving at a specific engine speed and manifold pressure

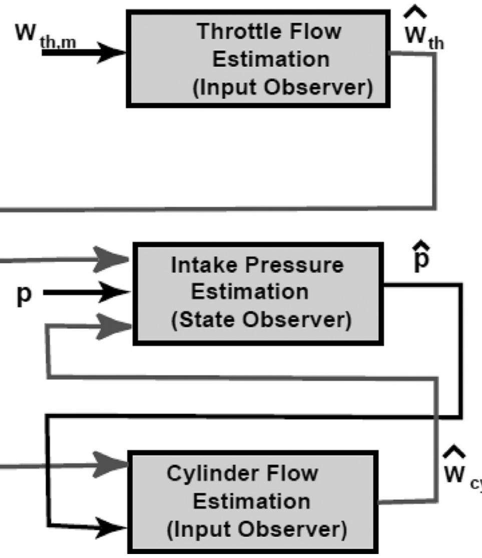

Fig. 6. Overall engine cylinder flow estimation scheme (Alexander & Kolmanovsky, 2002).

(Alexander & Kolmanovsky, 2002).

$$W_{cyl} = \eta_v \frac{\eta_e}{2} V_d \frac{p}{RT} \quad (1)$$

Where W_{cyl} is the mean value of the flow into the engine cylinders, V_d is the engine displacement and η_e is the engine speed; T is the intake manifold temperature, p is the mean value of the intake manifold pressure and η_v is the volumetric efficiency of the engine. This is done in the volumetric efficiency table or VE table and needs to be mapped in the control unit during calibration. Traditionally the VE table is in 2D format, it has two axes, where one is engine speed (RPM) and other is the manifold pressure. However variations in the volumetric efficiency due to some factors such as engine aging and wear, combustion chamber deposit buildup etc., can introduce errors in the air flow estimation.

In the MAF sensor type, air mass flow is directly measured in the intake. Air flow measurement by means of a MAF sensor (which is generally a hot wire anemometer) accurately estimates the flow in the cylinder only in steady state, while in transient state the intake manifold filling/empting dynamics play a significant role (Ferdinando & Lavorgna, 2006). Hence in MAF type air flow measurement an input estimator can be used to correct the air flow into the cylinder during both in transient and in steady state operation. In general there are lots of approaches followed for the estimator algorithm and in the following section we will discuss one such approach developed by Stotsky and Kolmanovsky. Input estimators are an important class of observer algorithms aimed at estimating unmeasured inputs to dynamic systems from state and output measurements. Practical issues such as the need to deal with MAF sensor time constant and filter out periodic noise at the engine firing frequency dictate that this input observer be combined with additional filters into a larger estimation scheme (Alain et al., 2000; Grizzle et al., 1994). The resulting, overall estimation scheme shown in Fig. 6, consists of three interconnected observers and the approach uses the signals from the intake manifold pressure sensor (in some system called as Boost Pressure Sensor-BPS) and throttle mass flow. The first observer estimates the flow through the throttle based on the signal from the MAF sensor thereby compensating for the MAF sensor time constant. The second observer estimates the intake manifold pressure using the ideal gas law and the signal from the intake manifold pressure sensor. This second observer is introduced to filter out the noise and periodic oscillations at the engine firing frequency contained in the intake manifold pressure and throttle mass flow signals. This second observer is of a state estimation type as opposed to input estimation type. The third observer is at the core of the estimation scheme, and it is the one that provides an on-line correction to the cylinder flow estimation (Alexander & Kolmanovsky, 2002).

3.2. Fuel film compensator

In the port fuel injection system, some of the fuel which is injected at the intake port does not enter the cylinder immediately, in fact, the fuel will impinge on the port walls, on the valve stem, and on the backside of the intake valve forming a fuel-film, causing a difference between the injected mass of fuel and that which is inducted within the cylinder. A fraction of the injected fuel mass remains vaporized and is mixed with the air before it is sucked into the combustion chamber. When this 'fuel lag' is not compensated, there are significant spikes in the A/F ratio response. A compensation action is therefore necessary to balance this fuel film mass and it is accomplished by a model based approach. A model describing the fuel mass flow into the cylinders is necessary, since not all of the injected fuel mass is in gaseous form when the intake valves opens. One of the most popular models describing the behavior of the fuel-film is the Aquino model; which is a simple first-order model and macroscopically tracks the liquid puddle dynamics inside the engine intake manifold. It has been widely used to develop fuel-metering strategies, which compensate for the fuel transport lag. The fueling model estimates the fuel puddle mass balance as a function of the injected fuel mass rate as the input to the model and the liquid fuel flow into the cylinder as output of the model (Franchek Matthew et al., 2006; Roberto et al., 2005). This fuel film compensator which is the part of AFR control module modifies the quantity of injected fuel quantity in order to balance the amount of fuel stored in and released by the film (Alain et al., 2000). The fuel film compensator model may not be required for the direct injection engine because of the fuel is injected directly inside the combustion chamber.

3.3. A/F ratio observer

The information required from the observer of a control loop concerns the air–fuel ratio in the individual cylinders. Most of the AFR observer approaches are based on the development of a simplified model for exhaust transport delay, mixing phenomena, and sensor dynamics. The transport delay mainly consists of two parts: the cycle delay due to the four strokes of the engine and the exhaust gas transport delay caused by the exhaust gas flowing from the exhaust valve to the tailpipe exhaust gas oxygen (EGO) sensor. A predetermined model or a time-delay look-up table (2D map) is used by the controller while computing the required time delay compensation. In addition, the time delay is largely dependent on the engine operating condition defined by the engine speed and the air mass flow. A 2D map yields the specific time-delay for any given combination of engine speed and load. Throughout the engine operating envelope, the time delay can change significantly (Feng, Grigoriadis, Franchek, & Makki, 2006). In practice, the estimated time delay does not exactly match the actual total engine delay (Rajagopalan et al., 2014; Yildiray, 2009; Yildiray et al., 2008). For engine transients, signal compensation is needed because of the sensors finite time response, time delay and mixing behavior between the exhaust gases from the different cylinders (Hajime et al., 2002; Tseng & Cheng, 1999). An observer is then applied to the model, in order to perform real-time state estimation of air–fuel ratio, and many approaches have been followed, such as Linear Quadratic Gaussian, sliding mode control, Kalman filter, static steady-state observer, nonlinear observer, etc. (Bin et al., 2008).

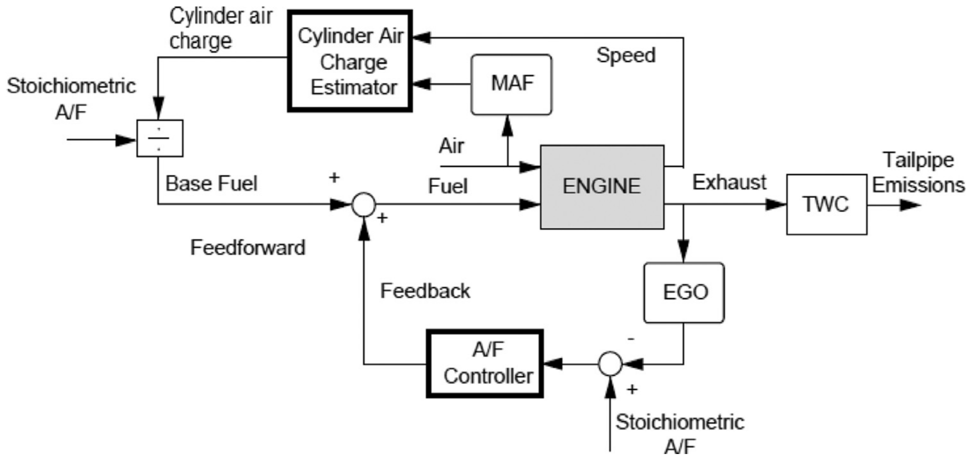

Fig. 7. Controller with feedforward and feedback elements of the air fuel ratio module in SI engine.

In order to construct an observer for the lambda control loop, it is first necessary to model the dynamics of the injection to exhaust dynamics (Per et al., 1998). In the AFR observer the information sought is the fuel air equivalence ratio of the individual cylinders. For this purpose the basic measurement is provided by the EGO sensor signal which is linear and the necessary compensation action will be carried out for the time delay, mixing phenomena and sensor characteristics by a proper model. The exhaust oxygen sensor provides the information for close loop A/F ratio feedback control. This information is then converted into an injection time correction that is identical for all the engine cylinders, on a cycle-by-cycle basis (Al-Himyari et al., 2014; Nicolo et al., 2010).

3.4. A/F ratio controller

Most of the current production AFR controllers are based on the gain-scheduling approach to design feedforward and feedback control system by constructing lookup tables. The AFR module consists of estimation of the air and fuel path dynamics combined with appropriate compensations. The controller calculates the injector pulse width (IPW) based on air flow estimation, either by a manifold absolute pressure (MAP) or mass air flow (MAF) sensors approach with respect to the driver demand and engine speed. This predicted air mass is used to estimate the mass of fuel that must enter into the cylinder to achieve the air/fuel ratio specified in advance as per the driver torque demand. To deliver this mass of fuel, a fueling path model based on injector characteristics, fuel puddling dynamics, fuel vaporization, and fuel entrainment dynamics is used to estimate the needed injector pulse width command (Franchek Matthew et al., 2006; Winge et al., 1999). If the air-path model and fuel-path model are accurate, the application of the feedforward fueling strategy will result in a stoichiometric air–fuel ratio during constant throttle operation (Stroh David et al., 2001). A conventional air-to-fuel ratio control module as shown in Fig. 7 includes two nested control loop, a feedforward and feedback control. The feedforward controller is tuned by means of experimental study during the calibration phase of the engine development and obtained fuel injection map (lookup table) values are stored in the memory of the controller. Generally, the procedure of constructing the fuel injection map in the feedforward loop means the tuning of the feedforward controller for various operating conditions in order to obtain a final injection map. The look-up tables is generated empirically for different engine operating conditions and mappings are done for a large number of speeds and loads during calibration phase (Seungbum et al., 2003; Dickinson, 2009; Rajagopalan, Stephen Yurkovich, Dudek, Guezennec, & Meyer, 2014; Tianyu, Haiqiao, & Zhao, 2011). In vehicle applications, the driver prescribes a torque demand to the control system through the accelerator pedal. This information is directly transformed into AFR control module as desired air-mass set point, using a manifold model or a 2D look-up table.

Thus, feedforward loop generates a reference AFR value based on the torque demand from the torque control module and by means of the controller the feedback loop maintains the air fuel ratio as close as possible to the desired AFR using the feedback output measured by the EGO sensor signal. The correction factor for the feedforward controller is accomplished by the feedback controller using the signal from EGO sensor. But in actual operation of engine, the transient condition tends to give an error in the feedforward controller due to modeling deficiencies, arising from say environmental factors, variation in fuel composition, manufacturing tolerances or mechanical wear. Thus the air/fuel ratio feedback control system compensates the unavoidable errors in the feedforward loop. Because the base fuel calculation has a tendency to drift off from the intended stoichiometric operating point and an active closed loop lambda control is necessary to adjust the base fuel calculation (Ohyama, 2001; Per et al., 1998). Feedforward control is fast which may not be accurate and also handles the transients, but the feedback control- loop is slow, due to the feed gas oxygen delay, but it ensures the required higher steady-state accuracy. For the feedforward control loop the time-varying delay is the key parameter in the AFR control that imposes a limitation on the bandwidth of the AFR feedback loop by decreasing the phase margin (Ivan et al., 2006). In order to stabilize the unstable internal dynamics of the system and reduce the effect of unmatched disturbances on the steady-state tracking error, various controllers are used. Lot of approaches dealing with AFR prediction and control methods has been proposed which are listed in Table 2.

However, most of the controllers in production vehicle fuel-injection systems consist of an open-loop feed-forward control which employs a look-up table and closed loop feedback control with PID, which works on the basis of a gain-scheduling approach. Due to their reliability and ease in implementation, PID controllers are far most dominant control design approach for the AFR control applications in the vehicles. This is due to its simple structure and robust performance over a wide range of operating conditions. In addition the major advantage of the PID controller over the other approaches is the familiarity of the algorithm and the relatively few tuning parameters and also there is no need of system model. These results in a significant reduction on the tuning and calibration effort required to implement the controller.

Table 2
Different controllers used in the air fuel ratio (AFR) module.

S. no.	Controller used for AFR module	Authors	Year	Outcomes
1	PID	(Franceschi et al., 2007)	2007	Discrete, time-based, delay-compensated, adaptive PID control algorithm for AFR control is employed.
		(Kwiatkowski et al., 2009)	2009	Using a hybrid evolutionary-algebraic synthesis approach that combines LMI techniques based on K-S iteration with evolutionary search, a scheduled PID controller is designed.
		(Behrouz et al., 2012)	2012	A new synthesis method for AFR control by the time-varying delay in the system dynamics is first approximated by Pade approximation with time-varying parameters. The associated error is then utilized to construct a filtered PID controller combined with a parameter-varying dynamic compensator.
		(Guo et al., 2013)	2013	PID controller is aimed to track the given value of fuel injection quantity. Tuning controller parameters are chosen by randomized algorithm according to the criteria of performance.
		(Mayr Christian et al., 2014)	2014	New approach for automated calibration of nonlinear PID controllers and feedforward maps is introduced. A dynamic local model network is used for actual physical process.
2	Adaptive control	(Tseng & Cheng, 1999)	1999	Adaptive AFR control scheme based on a one- parameter port fuel dynamics model with the parameter being identified online.
		(Stroh David et al., 2001)	2001	The steady-state adaptive fueling controller presented in this paper incorporates a modular model structure which eliminates static maps and enables a plug and play feature for changes to the sensor set.
		(Yildiray et al., 2008)	2008	Two controllers for AFR, an Adaptive Feed-Forward Controller (AFFC) and an Adaptive Posicast Controller (APC), have been developed and implemented in a vehicle.
		(Rui et al., 2009)	2009	Nonlinear control approaches for multi-input multi-output (MIMO) engine models is developed, by developing adaptive control and learning control methods.
		(Yildiray et al., 2010)	2010	Two adaptive controller designs are considered. The designed AFR controller must reject disturbances due to canister vapor purge and inaccuracies in air charge estimation and wall-wetting compensation.
		(Kahveci Nazli & Jankovic, 2010)	2010	An adaptive control structure which consists of an adaptive PI controller and an adaptive Smith predictor for time-delay systems with unknown plant parameters
3	Neural network	(Seungbum et al., 2003)	2003	The control is based on the feedback error learning. The controller consists of Neural Network (NN) with linear feedback. The NN are radial basis function network that are trained by using the feedback error.
		(Wang et al., 2005)	2005	Model predictive control (MPC) based on neural network model for air–fuel ratio, in which the model is adapted on-line to cope with nonlinear dynamics and parameter uncertainties.
		(Ivan et al., 2006)	2006	Recurrent Neural Networks for modeling and controlling AFR. The developed forward model used to generate a reference AFR signal to train another RNN model aimed at simulating the inverse AFR dynamics by evaluating the fuel injection time as function of AFR, manifold pressure and engine speed.
		(Zhai & Yu, 2009)	2009	MPC strategy is applied to air/fuel ratio control using neural network. The neural network uses information from multivariable and considers dynamics to do multi-step ahead prediction.
		(Zhai et al., 2011)	2011	MPC based on adaptive NN model attempted for AFR control. A Radial basis function (RBF) network employed and recursive least squares (RLS) algorithm used for weight updating.
		(Sardarmehni et al., 2013)	2013	MPC system is designed for robust control of lambda. Based on the simulation data, two neural networks models of the engine are generated. The identified Multi- Layer Perceptron (MLP) NN model yields small verification error compared with that of the adaptive Radial Base Function (RBF).
4	Fuzzy logic	(Anurak & Sooraksa, 2012)	2012	Improvement of mean value model (MVEM) and effective nonlinear control for the AFR regulator. The regulator is designed by a discrete fuzzy PI algorithm, which provides easy tuning, robustness.
		(Farzin, Mansoorzadeh, Zare, Shahryarzadeh, & Akbari, 2013)	2013	Approach for fuel control combines the design technique from variable structure controller is based on Lyapunov& fuzzy estimator to estimate the nonlinearity of undefined dynamic in backstepping controller
5	Model based methods for non-linear control	(Roberto et al., 2005)	2005	Model-based AFR control technique is proposed: this is based on a dynamical model of the air dynamics inside inlet manifolds and on the online identification of the fuel-film parameters.
		(Bin et al., 2008)	2008	From multirate sampling method, control-oriented model, combining fuel delivery and exhaust gas dynamics, is established. From estimated AFR, a decoupled PI compensator is designed.
		(Shuntaro et al., 2009)	2009	The control consists of a feedforward control using a fuel behavior model, a feedback control using an UEGO sensor and a feedback control HEGO sensor.
6	Sliding mode control (SMC)	(Sei-Bum et al., 1994)	1994	An observer-based control algorithm based on sliding mode control technique is suggested for fast response and small amplitude chattering of the air to- fuel ratio.
		(Hajime et al., 2002)	2002	SMC-based AFR feedback section with the oxygen storage mass predicting and controlling section with a self tuning strategy.
7	Other controls in the AFR module	(Holzmann et al., 1997)	1997	Neuro-fuzzy approach is discussed. For replacing 3D maps a modeling of engine characteristics for vehicle control and simulation by multi-layer Perceptron and radial-basis function networks is developed.
		(Winge et al., 1999)	1999	A new lambda (normalized AFR) control methodology ($H\infty$-control) which has a somewhat larger bandwidth and guarantee robustness with respect to selected engine variable and parameter variations.
		(Alain et al., 2000)	2000	AFR control method with feedforward, feedback methods with the injector puddling models.
		(Ferdinando & Lavorgna, 2006)	2006	Soft computing mass air flow estimator which is able to estimate, by using the combustion pressure signal, the incoming mass air flow both in steady states and in transient conditions

(*continued on next page*)

Table 2 (*continued*)

S. no.	Controller used for AFR module	Authors	Year	Outcomes
		(Franchek Matthew et al., 2006)	2006	The feedforward fueling control is separated into steady state and transient phenomena. Nonlinear behavior associated with fueling is captured with nonlinear steady state models.
		(Feng et al., 2006)	2006	An approach to combine an input shaping method together with a linear parameter varying (LPV) feedback controller is proposed to solve the transient air–fuel ratio tracking problem.
		(Dickinson, 2009)	2009	Systematic calibration of fuelling and speed controller. Non-linear black-box parameter directly produces a dynamic inverse multivariable NARMA feedforward controller and linearizing feedback compensator.
		(Nicolo et al., 2010)	2010	A real time application of an original closed-loop individual cylinder AFR control system, based on a spectral analysis of the lambda sensor signal is proposed.
		(Gerasimov et al., 2011)	2011	Torque tracking and air-to-fuel ratio (AFR) stabilization at the stoichiometric level are addressed. A data driven approach based on the design of direct and inverse models is proposed
		(Rajagopalan et al., 2014)	2014	Control architecture for AFR control of designed to work with switching and/or wide range EGO sensors, for minimizing calibration effort while meeting performance requirements.
		(Efimov, Nikiforov, & Javaherian, 2014)	2014	The first control law is based on an a priori off-line identified engine model, while the second control law is adaptive; it provides on-line adaptive adjustment to closed loop system. The supervisor realizes a switching rule between these control laws providing better performance of regulation.

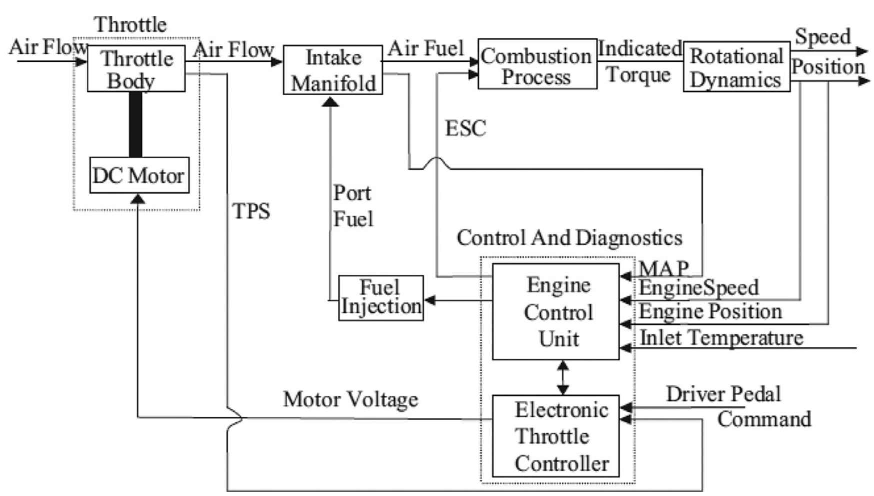

Fig. 8. Schematic of electronic throttle in SI engine (Conatser et al., 2004).

4. Electronic throttle control (ETC) module

In the electronic fuel injection system of a SI engine, the throttle valve in the intake system controls the air flow into the engine and thereby the cylinder charge, which determines the engine power and torque output. In conventional mechanical throttle actuation technology (throttle body with stepper motor as an 'idle speed actuator'), the throttle valve assumed as a mechanical butterfly valve, is directly linked to the accelerator pedal. The air flow through the throttle valve is therefore set by the driver and therefore operates the control device according to the need for power and torque. In this case, the control of the idle air control (IAC) bypass valve which is typically very small using a stepper motor or a solenoid is accomplished by the EMS.

The mechanical throttle system described above has been replaced by an electronic throttle control (ETC) as shown in Fig. 8 which is also known as drive by wire (DBW) for a multitude of technical benefits. Thus in such systems accelerator pedal is not mechanically linked to the throttle device. It only facilitates the driver torque request from the engine through an accelerator pedal sensor to the EMS. The principle of using a butterfly valve remains the same; however a servo motor operates it. The throttle opening angle is controlled by the engine management system, based on the torque control module for the torque demand by the driver through signals from the accelerator pedal sensor and other system requirements. In addition, a throttle position sensor is integrated into the throttle device to give the actual position of the throttle valve. Based on this signal the closed loop control is maintained by the ETC control module to accomplish the throttle angle requirement from the torque control module (Christopher, 2012; Daniel, Nichols, & Schreurs, 2000; Liang, Saikalis, McCune, De Ridder, & Lin, 200; Piero, Moro, Ponti, & Rizzoni, 1998; Stewart, 1998; Sood, Michael, & Michael, 2011; Suresh, Ganesan, Mallikarjuna, & Govindarajan, 2013; Wengert, Dierk, & Ronny, 2007). Also, the electronic throttle body control offers the method to integrate 'idle air control valve (IAC)' and throttle plate regulation into a single unit to control the angle of butterfly valve. But in case of the vehicles using mechanical throttle body (non ETC type) an idle speed actuator (stepper motor) which activates the air bypass valve circuit, provides an airflow pathway around the closed throttle plate to maintain the engine speed at idle (Conatser, Wagner, Ganta, & Walker, 2004; Chris & Watson, 2003; Devor & Sun, 1997; Yildiz et al., 2007).

As per the torque demand from the driver and other external systems (cruise control, traction control, etc.) the desired torque value is made as a setpoint for the engine by the torque control module. In order to obtain the torque demand the required cylinder charge has to be calculated initially and the resulting value represents the target cylinder charge which is necessary to realize the demanded torque (Jurgen et al., 1998).

For the indicated torque set point, trapped air mass and recirculated exhaust gas mass (if equipped) has to be considered.

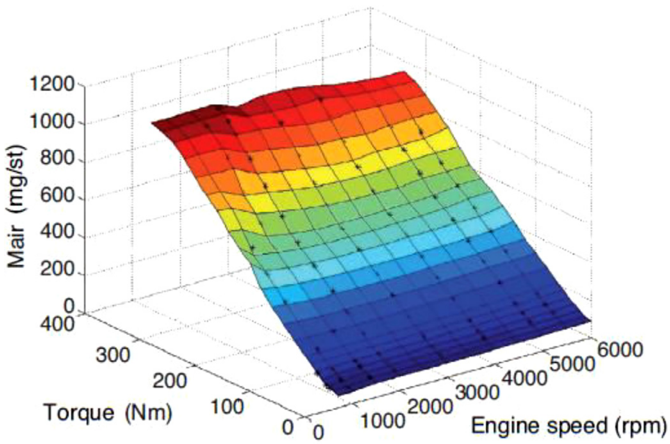

Fig. 9. Air mass set point function of engine speed and torque set point (Le Solliec, Berr et al., 2007; Le Solliec et al., 2007).

Thus the air path control is split as the air mass control (throttle valve and waste gate) and the re-circulated exhaust gas mass control. Based on the engine speed and torque demand setpoint, the desired amount of air flow is calculated by a predetermined look-up table as shown in Fig. 9 of 1.8 l Renault F5R engine which is experimentally determined on a test bench, and that information is used to calculate the target throttle position in order to achieve the cylinder charge. For the required mass of air the target throttle position can be determined based on a separate physical model of intake manifold functions. In this case, an accurate model that can describe the nonlinearity of the process is needed (Ingram Grant, Franchek, & Balakrishnan, 2003; Shinya et al., 2008). Then the information is transferred to the corresponding throttle actuator to open the throttle valve angle independent from the position of the accelerator by the electronic throttle control (ETC) module. For the required air mass set point, the control commands are given to the throttle actuator and waste gate actuator opening (if turbocharger is equipped) (Abid & Blath, 2006; Le Solliec, Berr et al., 2007; Le Solliec et al., 2007; Paul, Zavala, & Fleming, 2005).However, it is difficult to control the electronic throttle valve as there exists some non- smooth nonlinearities, i.e., stick-slip friction, gear backlash, and a nonlinear spring for the limphome position (Umit et al., 2001).

A comprehensive ETC control module strategy usually consists of a controller and nonlinear compensators that handle nonlinear effects such as friction, and limp-home mode effects (Chen et al., 2010; Shugang et al., 2009).Thus, based on the throttle position setpoint and the current throttle valve position measurement through the position sensor along with the necessary compensations, the throttle control module determines the needed motor-control voltage with corresponding PWM signal. The electronic throttle consists of an H-bridge that receives PWM signals from the controller. Based on the PWM signal duty cycle and direction information from the controller, brushed DC motor and the gear train arrangements produce the required torque to move the throttle plate for the setpoint angle. For fail-safe reasons, the throttle mechanism contains two springs to positioning at a certain angle position to prevent the plate form completely. Such mechanical default throttle angle allows the engine to provide enough power for the vehicle to "limp home mode (LH)" in the case of power supply failure (Xiaofang & Wang, 2009; Di Bernardo et al., 2009; Toshihiro & Kowatari, 2001; Griffiths, 2002).

However, the electronic throttle control module performance is significantly deteriorated in the small- signal operating mode due to the servo motor drive train system friction and the dual return spring nonlinearity in the LH position. The slow response is a consequence of the stiction influences between the gear modules. This friction occurs in the gearbox as well as in the throttle valve and motor shaft bearings. Similarly, a significant response delay (a standstill interval) appears while the throttle passes through the nonlinear LH region.

In order to improve the control system performance in the small-signal region operating mode, the controller is extended with necessary friction and LH compensators as shown in Fig. 10 (Yang, 2004; Danijel et al., 2006). Thus the friction compensator consists of a friction estimator which compensates for the static and dynamic friction in the mathematical model [(Giulio et al., 2013; Lars & Nielsen, 2000), and (Takeru et al., 2009)]. Similarly the spring nonlinearity at LH position is also compensated by means of a perfect spring model. Hence for the precise control of throttle opening by the ETC module, several control strategies have been proposed as shown in Table 3.

From the table it is evident that among all of those methods, adaptive control using PID controller is widely used in the production vehicle engine management system. This controlling method enables high robustness and precise control performance. As the friction and LH are the two nonlinearities affecting the stability of the system was addressed with various approaches. Also the electronic throttle body is an electromechanical device which deteriorates in its performance due to wear and aging factors. In order to address such factors a superior control system is needed.

5. Idle speed control (ISC) module

The objective of the idle speed control module is to keep the engine speed close to the set point (selected target idle speed)

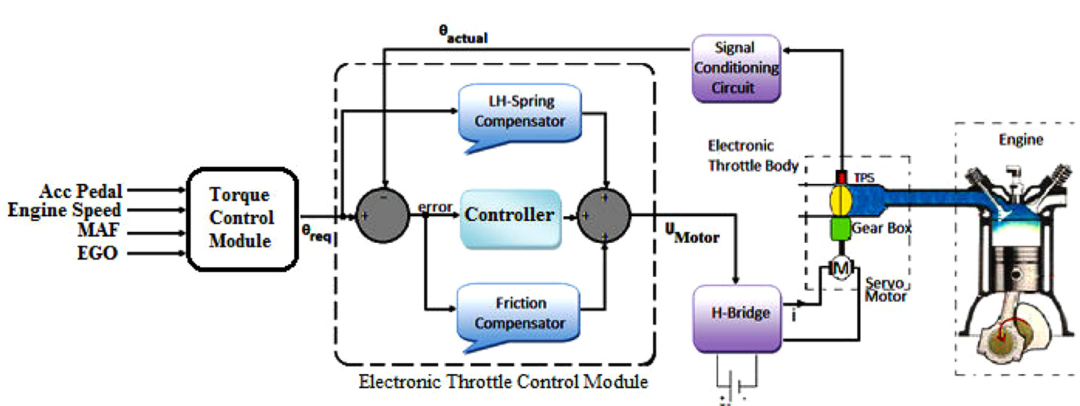

Fig. 10. Electronic throttle control system of a SI engine in an EMS.

Table 3
Different controllers used in the electronic throttle module.

S. no.	Controller used for ETC module	Authors	Year	Outcomes
1	PID controller	(Jae & Byun, 1999)	1999	Throttle actuator for traction control system with a PID control to reduce the error is proposed.
		(Yang, 2004)	2004	PID controller with friction shaker to cancel the friction leads to minimize the nonlinearity is designed.
		(Danijel et al., 2006;Deur et al., 2004)	2006	Throttle control consisting of a PID controller with nonlinear friction and limp-home compensators. Also the adaptive strategy consists of auto-tuning and self-tuning algorithms in the throttle control.
		(Shugang et al., 2009)	2009	Two-Degree-of-Freedom PID controller with Iterative Feedback Tuning (IFT) method is employed for gain optimization.
		(Andreas & Eriksson, 2009)	2009	Static compensators to counter nonlinearities with a PID controller. IMC design is applied to design the PD controller and a gain scheduled I-part is added for robustness against errors.
		(Grepl & Lee, 2010)	2009	PID controller with nonlinear compensators for limphome and four different approaches for the friction nonlinearity is proposed.
		(Mercorelli, 2009)	2010	State observer for the Sensorless operation is developed. A real-time self-tuning of an approximated proportional derivative (PD) regulator compensates tracking error caused by inexact feedback.
		(Chen et al., 2010)	2010	Two degree-of-freedom control system was designed, for nonlinear preload spring and disturbance rejection against friction. The nonlinear behavior is verified using a simple PID control loop.
		(Alt et al., 2010)	2010	Controller includes I-PD controller and a nonlinear control helps to compensate nonlinearities. Control parameters are tuned automatically using an adaptive model based approach.
		(Zeng & Wan, 2011)	2011	A nonlinear PID controller is proposed, it constantly adjusts the controller parameters proportional gain -P, integral gain -I and differential gain -D with the system error changing.
		(Thomasson & Eriksson, 2011)	2011	Simultaneously active, static compensators to counter the nonlinearities. A PID controller is designed for the linearized system, where pole placement is applied to design the PD controller and a gain scheduled I-part is added for robustness against model errors.
		(Al-samarraie & Abbas, 2012)	2012	Proposed control law replaces the integral of the conventional PID controller by an integral term that uses the arc tan function for the error instead of the linear error function.
2	Adaptive control	(Eiji et al., 2003)	2003	To attain robustness, an adaptive control system has been constructed using sliding mode control and includes an identifier for sequential calculations in the throttle control.
		(Di Bernardo et al., 2009)	2009	Model reference adaptive algorithm, LQ-MCS: Linear Quadratic-Minimal Control Synthesis. The feature of this controller is that minimal synthesis is needed to implement the strategy.
		(Giulio et al., 2013)	2012	Friction phenomena are expected to be time-varying; an adaptive extension of the controller is proposed and validated for motorcycle.
3	Fuzzy logic	(Chen & Ran, 2009)	2009	A fuzzy immune adaptive PID control based on immune feedback is proposed for electronic throttle.
		(Wang et al., 2010)	2010	Fuzzy-PID was modeled for controller; simulation was accomplished during the transient condition.
		(Chen et al., 2012)	2012	Adaptive fuzzy logic based sliding mode controller to enhance the control strategy robustness with respect to parameter variations and external disturbances for electronic throttle.
		(Wang & Huang, 2013)	2013	Nonlinear hysteretic adopted for electronic throttle. A new closed-loop back-propagation tuning is proposed for tuning of fuzzy output membership functions to yield better tracking.
5	Model based methods	(Lars & Nielsen, 2000)	2000	The model-based controller is designed to compensate for the friction present in the system as well as the varying torque that comes from the air flow past the throttle plate.
		(Montanaro et al., 2014)	2007	Model predictive control (MPC) strategy is derived for the electronic throttle with the procedure is proposed to model friction in a discrete-time piecewise affine (PWA).
		(Yuan and Wang, 2009)	2009	Approximate model-based robust nonlinear control (AMRNC) for uncertainty compensation is proposed
		(Nakano et al., 2006)	2014	Model reference adaptive control (MRAC) method is designed and tested on 2-L engine to provide the robust handling of nonlinear torques acting on the plant due to limphome.
6	Sliding mode control	(Umit et al., 2001)	2001	The discrete-time sliding mode controller together with the sliding mode observer is designed to realize the robust tracking control.
		(Aono & Kowatari, 2006)	2006	Observer-based sliding-mode controller with prescribed transient response is designed for the system.
7	Other controls	(Paul et al., 2005)	2004	A pole placement controller by the multiobjective optimization technique with the objective of reducing or eliminating the oscillatory response is designed.
		(Yuan et al., 2008)	2006	Throttle-control algorithm for improving engine response is proposed. This algorithm compensates the two delays based on the delay in the throttle response and manifold filling.
		(Feru et al., 2012)	2008	Support vector machine (SVM)-based approximate model control for the electronic throttle. The nonlinear control derived based on Taylor expansion, which avoids not only complex control development and intensive computation but also online learning or adjustment.
		(Feru et al., 2012)	2012	Lyapunov-based control using for throttle and cam timing to reduce exhaust emissions is proposed.
		(Thornhill & Sindano, 2000)	2014	Mixed constrained $H_2/H\infty$ LPV controller was designed for the LPV throttle control system using the linear matrix inequality convex optimization approach.
		(Yurkovich & Li, 2005)	2014	Discrete-time gain-scheduling H_2 controller is designed for an electronic throttle system based upon the LMI (linear matrix equality) convex optimization scheme.

and at the same time prevent engine stalling when disturbance loads are applied or removed. The torque disturbances are mainly due to the intermittent use of devices powered by the engine, for example headlamp, air conditioning compressors, power steering pumps, electric windows and battery charging and other electrical accessories that affect the engine speed at idle mode (Howell & Best, 2000). The idle speed system with its physical inputs and outputs are represented in Fig. 11, which shows that the controller only has control over the fuel, air, re-circulated exhaust gas and spark timing. The other factors affecting the idle engine speed are either part of the engine design or function of atmospheric conditions (Yurkovich & Li, 2005).

Smooth transitions from higher engine speeds to idle speed are also required to increase drivability. Factors that most affect the

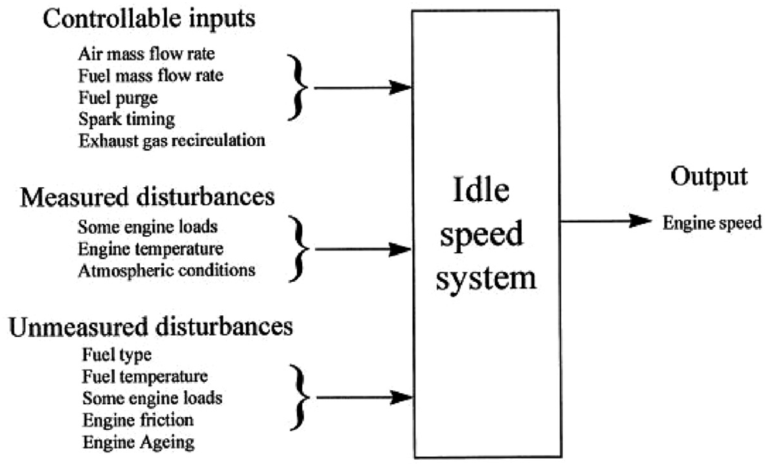

Fig. 11. Inputs, outputs and disturbances to the idle speed system (Yurkovich & Li, 2005).

idle speed are the intake-airflow and the ignition timing (Christian, Bohme, Staate, & Manemann, 2006). The spark advance and the throttle which controls the mixture mass (cylinder filling factor) are used to control the engine speed. Idle speed regulation is made with these two main actions. One is control by the intake air flow (throttle angle) and other is the control of spark advance for fast torque response in some cases (Luigi et al., 1999; Manivannan, 2011; Scillieri, 2002; Stefan & Eriksson, 2006). One of the aspects to be taken into account is that, the control action using the spark advance path is faster than using the air-channel. Hence the typical idle speed module utilizes two control paths for the controller action. It first uses the spark advance as the main control input and afterward, as soon as the engine speed is taken care of by the air input, the spark advance should go back to its nominal value. In other words, the spark advance should exert its fast action mainly during the first part of the transient phase (Jacek, 2010). In most cases, both of them are used in parallel. The two control signals should be aware of each other and the relative spark advance has to converge to a desired setpoint value. Thus for the changes in additional loads, idle speed control is accomplished by the mixture mass to reach the cylinder that is being adjusted. If the changes are smaller and quick response is required, control is executed by adjusting spark advance (Stefan & Eriksson, 2006).

The idle speed setpoint depends on the various torque disturbances to the engine during idling mode. But the load torque is not actually measurable, only predictable through the feedforward lookup tables of the various disturbances, since the ECU knows the accessories are switched on (Jingshun & Kurihara, 2003). There is a feedforward controller consist of multiple lookup tables which might, predict the loads due to accessories for different operating conditions. By estimating the load torque presented to the engine by the measured disturbance one can calculate, for fixed A/F ratio and spark, the amount of air that is needed to maintain the engine speed at the fixed setpoint. A closed loop controller determines the compensation with throttle and ignition actuators for the engine speed tracking error and is typically gain-scheduled on operating conditions where nonlinear maps are used to determine the gains (di Gaeta et al., 2010; Yildiz et al., 2007).

While designing the idle speed control module the main complexity that needs to be handled is the control process of induction-to-torque delay in the engine (Christian et al., 2006). This dead time in the process of intake air control is one of the reasons that cause the worse response and poor stability of idle speed control. Thus the response and stability is to be improved because of combustion delay, passage delay, speed detection delay, torque disturbance, electricity load and other related problems in an intake air control system (Luigi et al., 1999). Hence, the idle speed control loop should compensate for these kinds of time delays in the process and other related effects, either by an appropriate compensated model or by feedforward methods (Jacek, 2010). This problem is typically addressed by combining some form of a feedforward control with a closed-loop compensation based on the engine speed error. If the speed error goes beyond the threshold range, ECU regulate idle valve through the stepper motor position in case of mechanical throttle system, (whereas in electronic throttle control the servo motor adjust the butterfly valve) to adjust intake mass flow to maintain the desired crankshaft speed (Le Solliec, Berr, et al., 2007; Chamaillard et al., 2004; Jingshun & Kurihara, 2003). Hence, the typical idle peed control module shown in Fig. 12 consists of time delay compensators, load estimators for the idle speed setpoint based on the load torque and a controller to maintain the idle speed setpoint.

The controller provides the reference throttle angle (θreq) to the throttle control module based on the idle speed setpoint (ωIdle Speed) by considering the different load torque requirements. Similarly the spark control loop provides the spark angle based on the idle setpoint (Jacek, 2010; Yildiray et al., 2011).If the error derivative exceeds pre-defined thresholds, control is activated on both throttle angle and spark advance values; otherwise the control is enabled only on spark advance values. Such choice is mainly due to two reasons: the large amount of engine torque variation contained in the range of spark advance angle and manifold pressure shows the better torque difference. If both the controls are activated, the first new throttle angle value is held constant for a certain time interval, while the error (residual or due to an unknown load) is compensated by new spark angle values. A so-called synchronization function of the controller verifies if the spark angle values fall within an interval centered on the nominal angle value. If this condition is not matched for a certain number of computing steps, the ISC actuates the throttle, by varying their positions of pre-defined increments. Spark advance is then restored to its nominal value (Singh et al., 2002; Subramaniam et al., 2002). Several possible controllers are employed for the idle speed control modules are listed in Table 4.

Over the years different closed loop idle speed control system designs have been adapted in the literature. However there is a scope for providing a superior performance in the idle speed control module by tackling the time delay factor, changes in operating conditions and aging of the components by providing an adaptive algorithm. Also in order to meet the emission targets, by adapting the start stop system in the engine during idling mode can also be improved by the robust control system design.

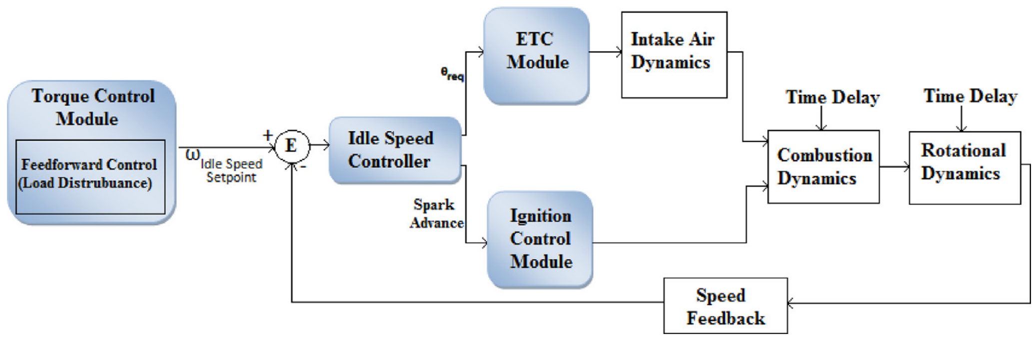

Fig. 12. Idle speed control module of a SI engine.

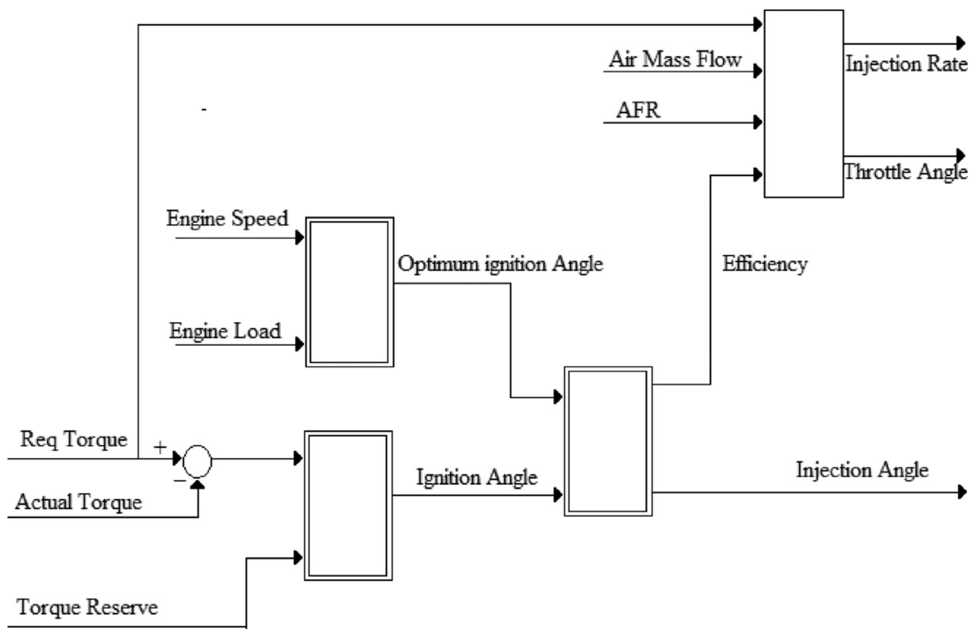

Fig. 13. Ignition angle and other relevant outputs in the torque structure (Andreas & Torsten, 2001).

6. Ignition control module

In the torque control structure of an SI engine, for the demanded torque, control signals are fed into the actuating paths such as throttle control, injection timing and ignition timing as shown in Fig. 13. The superior ignition timing determines the significant quality and efficiency output from the engine. The ignition timing is evaluated based on the set value of the torque and other parameters like engine speed and actual engine air flow (Gafvert et al., 2004).

The ignition control module varies its operation for different operating modes such as idling, cranking, overrun and normal conditions. During idling, the ECU controls the ignition advance according to engine idle speed setpoint and coolant temperature. When cranking the engine, the ignition signal is produced by the crankshaft position signal for a pre-set value of ignition advance and similarly during the over speed the ignition angle advance for a pre-set value, in order to limit the engine speed. These pre-set values are obtained during the calibration for cranking and over speed protection separately, and stored in the controller. During the normal condition, the ignition advance is controlled in open-loop or closed-loop mode (Zhengmao, 2001).

Thus, in the transient operating conditions open-loop control is adopted for fast response and in the steady or higher load conditions closed loop control is followed, based on the knock feedback signal the ignition advanced angle is corrected. Some of the research works carried on the Ignition control module are listed in Table 5.

The two ways by which ignition timing is controlled in an EMS, are open-loop control and closed-loop control. The open-loop scheme for the ignition timing control relies on pre-determined look-up tables. The base ignition timing is stored in the memory of the controller which acts as a feedforward controller. Open-loop control is a scheduled program control where a table-based ignition strategy is used, which generates the optimized spark angle based on the current engine working point. A first optimization takes place during the calibration phase (experiments on engine or chassis dynamometers) of the engine development process to obtain the values of the best ignition advance angle of various working conditions. These values have been stored in the ECU as a table, which are called the basic ignition advanced angle map. In order to determine the required values of ignition timing for achieving a certain torque demand by the ignition control loop, the mass air flow, engine temperature, speed and other related signals from the engine has to be known. During the operation of the engine, for the corresponding engine speed and load, the ignition advanced angle is determined from the map (lookup table) as shown in Fig. 14, from the EMS. Thus, by means of the feedforward controller the nominal ignition angles (realizing maximum brake torque while avoiding knock and excessive engine-out pollution levels) depending on the engine speed and load (as measured by manifold pressure or other related signals) is obtained. This

Table 4
Different controllers used in the idle speed control (ISC) module.

S. no.	Controller used for ETC module	Authors	Year	Outcomes
1	PID controller	(Howell & Best, 2000)	2000	Tuning process of PID is automated through the use of continuous action reinforcement learning automata. These are used to simultaneously tune the parameters of a three term controller on-line.
		(Chamaillard et al., 2004)	2001	A PID controller is used for idle speed control for a torque based engine control. The controller output delivers the required torque demand component to keep the engine speed on the setpoint.
		(Jacek, 2010)	2004	Analytical design method of tuning PI and PID idle speed controllers is proposed. The method based on damping optimum criterion. Design of advanced, polynomial speed controller is also presented.
		(Luigi et al., 1999)	2006	A model-based control method for idle speed of spark-ignition (SI) engines. It is based on mid-ranging, a multivariable control strategy that is more commonly used in process control. The basic building blocks of the control structure are two PI controllers.
		(Jingshun & Kurihara, 2003)	2010	Idle speed control for GDI engines have been tackled and solved via a gain scheduling PID strategy in conjunction with an AFR dynamics compensator.
		(Scillieri, 2002)	2011	The simple idle speed model developed in this work was found to be effective in determining a set of PID control parameters that are similar to the best values obtained using experiments.
2	Adaptive control	(Josko et al., 2004)	2006	A Map-based injection, oxygen feedback and adaptive PID controller are combined to form a quick and low-cost air–fuel ratio control system, by which a low steady Idle-speed is realized on SI engine.
		(Yildiz et al., 2007;di Gaeta et al., 2010)	2007	Adaptive Posicast Controller for time-delay systems to the idle speed control (ISC) problem in IC engines. It regulates the engine speed at a prescribed set-point in the presence of accessory load torque.
		(Kong et al., 2006)	2007	An adaptive multi-input single-output (MISO) controller based on self-tuning regulator. The Recursive Least Square technique is employed to identify the engine as a first-order MISO linear model. Pole placement technique is then used to design the adaptive MISO controller.
		(Yildiray & Anuradha, 2011)	2009	Torque estimator based on an adaptive Kalman filter. The estimator is used to establish a fast load torque compensation path within a PI controller-based idle speed control system.
3	Neural network	(Stefan & Eriksson, 2006)	2010	Algorithm of idle speed stabilization in the SI engine by means of spark advance control. The algorithm is based on a well-known approach of a model-based adaptive control and uses artificial neural networks model observer of the additional effective torque.
4	Fuzzy logic	(Feng-Chi et al., 2007)	2002	Analytically developed fuzzy control law can be used in practical application such as the idle speed control problem provided that certain modifications and assumptions are taken into consideration in the derivation and the application of the control law.
		(Danijel et al., 2009)	2002	Two control variables one controlling the air by-pass valve and other the timing of the spark that differ sensibly in both their quantitative and temporal effectiveness are addressed SI engine model.
5	Model based methods	(Chris & Watson, 2003)	–	Proposed ISC consisting of decoupled manifold pressure and spark retard control loops. Controller incorporates a model predictive element in the selection of the bypass valve duty cycle, which is used to set the intake manifold pressure.
		(Subramaniam et al., 2002)	2003	A model-based approach to idle speed control design has been presented. Further developments concern a smoother transition from ISC to other model-based strategies (torque-based engine control, for example), and also the analysis of engine management strategies for the cranking phase
		(Singh et al., 2002)	2010	Model-based control scheme to the cold-start speed control in SI engine. The multi-variable control algorithm is developed with the purpose of improving the transient performance of the starting speed.
6	Other controls	(Jacek, 2010)	1999	Idle-speed control designed through optimal LQ technique taking into account during the design phase the presence of finite time delay between variations of manifold pressure and the produced torque.
		(Luigi et al., 1999)	2003	Dead time compensation for intake air control is by adopting a Smith predictor combining with disturbance compensator to improve the idle speed control system's response to the disturbance.
		(Nicolo et al., 2003)	2003	A directly identified non-linear inverse-NARMA compensation methodology for stable systems has applied to the dynamics of SI engine for the idle-speed regulation robust control problem.
		(Christian et al., 2006)	2005	Sliding mode Control method was applied to the IC engine idle speed control, not for stabilization (because the engine is stable itself during idling) but for compensation with the effects of the delay.
		(Manivannan, 2011)	2006	Nonlinear engine model for idle speed controllers is described. The suitability of model has been shown through a straightforward MIMO H∞ design using the torque reserve as an additional output
		(Jiangyan et al., 2010)	2007	A new concept for idle speed control is designed. This control is based on a two degree-Of-freedom sliding mode algorithm. It controls engine speed by altering both the valve lift and the ignition timing.

correlation is static and is only optimal for that engine from which the ignition data was obtained during the calibration of the ECU (Arno et al., 2012; Baitao et al., 2013; Bhot & Quayle, 1982; Enrico et al., 2014; Eriksson & Nielsen, 1997; Guzzella & Onder, 2010; Huang & Chen, 2006; Kosuke, Yasui, & Sato, 2007; Masatake et al., 2001; Molina, Barros, Baeta, & Fabricio, 2004; Petridis & Shenton, 2003; Pacheco et al., 2004; Saravana Prabu & Naiju, 2009).

Ignition timing that arrives from the feedforward controller has to be finalized based on considering the some of the correction factors. One of such correction is based on the temperature of the engine coolant to arrive at the final ignition advanced angle and is shown in Fig. 15. Thus by using the ignition control loop for the measured engine speed and the relative load, a nominal spark advance angle is selected (block "map1" in Fig. 14). A simplified

Table 5
Control approaches followed in the ignition control module.

S. no.	Authors	Year	Outcomes
1	(Baitao et al., 2013)	1997	A feedback scheme based on ionization current interpretation for spark advance control to optimize engine performance.
2	(Zhengmao, 2001)	1999	Design of adaptive ignition control system to adjust the timing automatically according to knock signal.
3	(Desheng et al., 2014)	2001	This paper presents a new control strategy based on fuzzy logic for the ignition advances and for the fuel injected per cycle for an engine.
4	(Eriksson & Nielsen, 1997)	2001	The electronic controlled ignition system has been developed in accordance with various working conditions of the engine, the system adjusted corresponding control parameters; air fuel ratio and ignition timing.
5	(Yankun & Liu, 2010)	2004	This paper presents the application of rapid prototyping electronic control unit (ECU) to fuel injection and ignition control of electronic fuel injection motorcycle engine by using Model-Based environment
6	(Bhot & Quayle, 1982)	2006	Ignition control based on curving surface-fitting algorithm is accomplished, following two stage development guideline, separating" establishment of ignition control model" from" real time ignition control", making system renovation easily, system control high precise, and real-timing.
7	(Zhihu & Run, 2008)	2007	The paper presents an algorithm of idle speed control of the spark ignition automotive engine by means of spark advance control. The control algorithm is based on a neural network model of the effective torque.
8	(Czarnigowski et al., 2007)	2007	Closed-loop control architecture for spark timing is proposed. Using in-cylinder ionization signals both borderline knock and retard spark limits are regulated using closed-loop stochastic limit controls. MBT timing is also controlled closed-loop using an MBT criterion derived from in-cylinder ionization signals.
9	(Raducanu et al., 2001)	2008	An electronic control ignition system is designed, based on parameters including engine velocity, load and the reference ignition signal of engine. Control system adopts the proper strategy in accordance with the operating mode.
10	(Enrico et al., 2014)	2010	Design and simulation of control strategy for ignition advanced angle in various conditions. The analysis of closed-loop control of ignition advanced angle based on knock signal and control strategy of idle condition are emphasized.
11	(Herbert & Ploeger, 2007)	2011	A combined neural network and fuzzy logic-based control scheme is designed for spark advance control to get MBT timing. The controller works in conjunction with RNN model for cylinder pressure identification.
12	(Saravana Prabu & Naiju, 2009)	2013	A model based ignition control algorithm with an aim to reduce advanced engine calibration time. A semi-physical approach has been investigated which utilizes an artificial NN to convert a well-proven discrete time domain quasi-dimensional turbulent flame propagation model into a mean value combustion duration model.
13	(Huang & Chen, 2006)	2014	The paper describes a methodology aimed at calibration of Spark Advance. Operations are carried out on test bench in dynamic conditions, during engine speed sweeps at constant load.

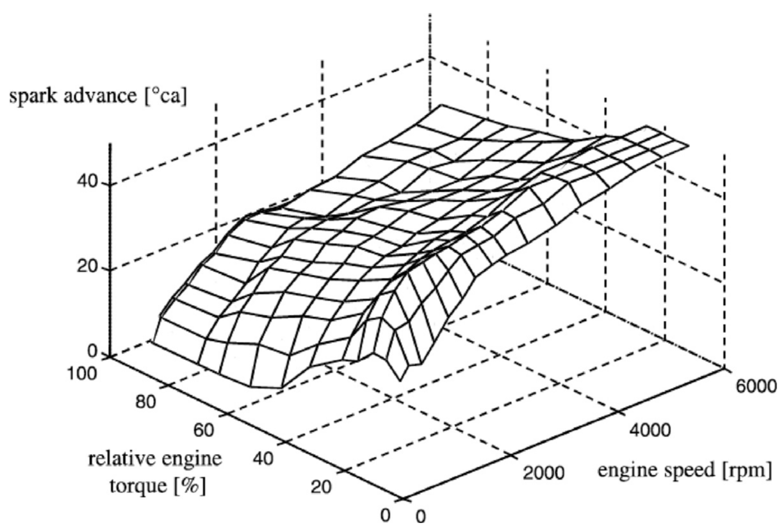

Fig. 14. Example of a "Spark advance angle map" stored in an ECU (Guzzella & Onder, 2010).

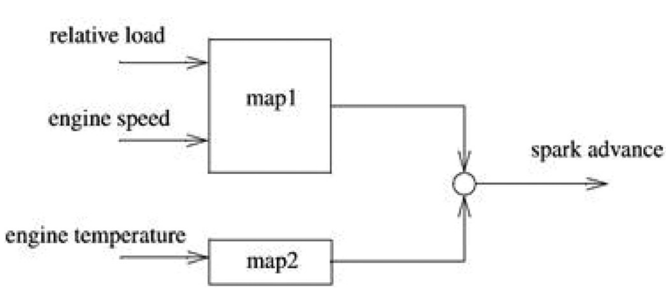

Fig. 15. Example of a simple correction map structure (Guzzella & Onder, 2010).

case in which correction of spark advance for the engine temperature only is considered as shown in Fig. 15 (block "map2"). Like this other parameters and efficiency also need to be considered while obtaining the final spark advance angle. In a real ignition control system, additional corrections would be applied such as for varying the battery voltages, to avoid engine overheating and knock, air/fuel ratio, fuel characteristics, EGR, etc. In addition, the idle-speed control system also influences the ignition control loop (Guzzella & Onder, 2010). Thus, the final spark angle for better efficiency and considering related correction factors, a time-processing unit (TPU) in the ECU triggers the ignition event at the correct crank angle values based on the crank angle and cam shaft sensor pulses from the engine (Yankun & Liu, 2010; Zhang et al., 1999).

In a closed-loop control of ignition timing, the feedback control is added on the base feedforward open-loop control module, which utilizes the output of the knock detection system to adapt the ignition angle for a safe and fuel efficient value despite variations in environmental conditions, fuel quality, etc. Considering the

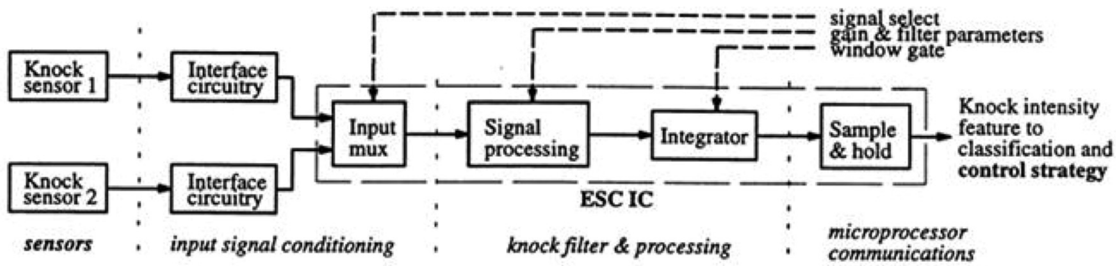

Fig. 16. Knock detection system based on band-pass filter (Haoyun et al., 2013).

control cost and accuracy, open-loop control combined with closed-loop control are adopted in the control system in order to achieve faster response and better control accuracy (Guzzella & Onder, 2010; Enrico et al., 2014). In the closed-loop control, the knock sensor signal is selected as the feedback signal to keep the ignition advanced angle around the critical knocking point (Cui, 2008). In the next section we will discuss knock detection and control strategy.

7. Knock detection and control module

Advancing the ignition timing by the ignition control module in the torque structure is one of the important factors for maximizing the output torque and the fuel economy of an engine. Unfortunately, the optimum spark timing is often accompanied by the occurrence of knock in the combustion, and even leads to damage to the engine in extreme conditions. Therefore, a trade-off is necessary in engine control between; maximizing the spark advance and avoiding the occurrence of engine knock (Go-Long et al., 2004). Most commonly, knock is defined to occur when it is audible. Knock sensing plays an important role in knock control. Hence the knock control module consists of knock detection and controller for controlling the knock phenomena. The majority of control algorithms therefore detect the resulting knock in the combustion chamber by means of different techniques. Many approaches have been applied to detect the knock, and each has its own merits. Commonly techniques applied to knock detection include either in-cylinder pressure transducers, engine block mounted accelerometers or ionization signal form the combustion. Knock detection based on in-cylinder pressure transducers is very effective but these sensors are expensive for the production engines (Herbert & Ploeger, 2007). Hence the dedicated knock sensors, basically a piezoelectric acceleration sensor attached to the engine block is used in production vehicles. Typically, one or two sensors are used depending on the application (e.g., one sensor per bank on a 'V' block engine; one sensor for an 'in-line' block). The fundamental role of the knock sensor is to extract a feature characteristic of knock that allows discrimination between normal engine noises and knock (Haoyun, Yang, Shen, & Peyton Jones, 2013).

7.1. Knock detection

A knock control module consists of a separate signal detection unit to spot the knock from the accelerometer sensor signal as shown in Fig. 16, which is composed of three main elements: knock sensors, knock detector and control strategy executing on the controller. The traditional approach for knock detection system uses a band-pass filter, and recognizes the frequency band of the knocking from the normal noises of combustion and friction. Hence, the output of the accelerometer sensor passes through a band-pass filter which selects the most representative resonant frequency components of the knock signal. The resonance frequency depends on the dimensions of the combustion chamber and on sound velocity of the cylinder charge. The resulting output signal is then integrated and compared over the crank-angle window where knock is expected to occur, in order to obtain knock intensity (Flolka, 2006; John, Keane, Koseluk, & Whitlock, 1998; Kaneyasu, Kurihara, Katogi, & Tabuchi, 1995; Peyton Jones, Spelina, & Frey, 2013; Samir, Agarwal, & Chand, 2011; Stefan, Rychetsky, Glesner, & Groppo, 1997). For every cycle of any cylinder, the maximum amplitude of the band pass-filtered signal is calculated and passed to the knock controller. Knocking cycles are identified by the peak value of the band-pass filtered sensor signal. The threshold for defining a cycle as knocking is set as a preset value during the calibration. The peak amplitude of the band pass filtered signal is used as individual cycle knock intensity (KI) (Timo, Schuerg, & Kempf, 2012; Zhu Guoming, Haskara, & Winkelman, 2005).

7.2. Knock control system

To limit the knock when it is detected, commonly used control approaches are retarding the spark timing or by reducing the load, i.e., closing of the intake throttle or by controlling the waste gate in the case of turbocharged engines(if equipped). Load reduction is used only if knock cannot be suppressed by delaying the ignition angle. Thus, knock control mostly is accomplished by changing the ignition timing in the consecutive cycle itself. This is accomplished by changing the ignition timing in the next power stroke cycle itself, which leads to reduce the knock (Piernikarski, Hunicz, & Komsta, 2013).Thus a knock control module consists of a feedforward open loop in order to determine the base spark timing based on the engine operation conditions and, a feedback control system which has knock detection and a control unit.

A knock control module of a SI engine consists of feedforward lookup table of the ignition timing and a closed-loop control strategy for ignition timing correction based on feedback from the knock sensor signal as shown in Fig. 17. The closed loop correction of ignition timing controls the knock by adjusting the spark timing in order to optimize the engine operation and prevent damage. The knock controller determines the corrected spark timing which is the sum of the base spark timing obtained from the map. The knock controller uses the knock intensity (KI) as an input signal to control the ignition timing so that a certain knock rate will not exceed the threshold limit. When the cycle knock intensity exceeds the threshold value, the ignition timing for the considered cylinder is retarded by a certain angle. Afterward, the ignition angle is advanced again at the rate of 10 CA per second as long as the knock amplitude remains lower than the threshold. Thus, the ignition correction is subtracted from the nominal ignition angle given by the feedforward ignition controller. Hence, the knock control loop results in the operation of ignition angles closer to the knock limit and hence higher compression ratios can be implemented to increase the thermodynamic efficiency of the engine (Lonari, 2011; Siano & Bozza, 2013). Waste gate control is also employed in case of the turbocharged engine which is another possibility of reducing

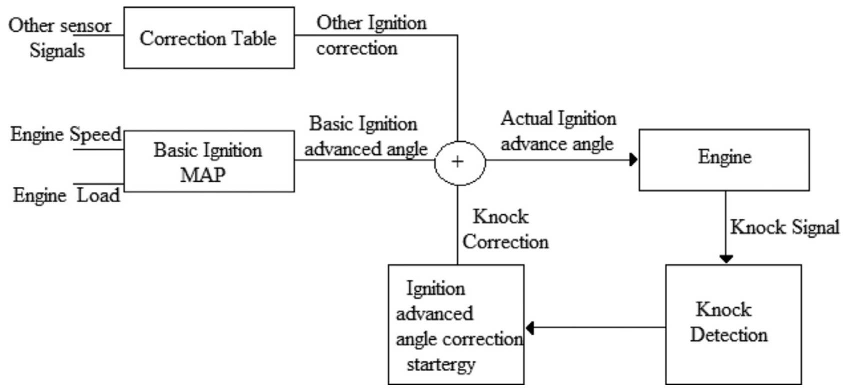

Fig. 17. Knock control strategy based on ignition control (Enrico et al., 2014).

the engine's susceptibility to knock by cooling the cylinder charge. This can be achieved by either cooling the aspirated air (in turbocharged systems, often an intercooler is applied after the compressor anyway) or by fuel enrichment, i.e., driving at air-to-fuel ratios lower than stoichiometric (Guzzella & Onder, 2010).

The various controllers used for knock control are listed in Table 6. All these controllers have common control objectives, the strategy by which the objectives are achieved can be varied significantly. Most production knock control modules use a standard knock control strategy where control movements are executed for each step. The magnitudes of these control moves are also fixed, advancing the spark by a small amount, whenever knock does not occur, or retarding by a much larger amount, if in fact knock does occur.

8. Diagnostics module

In order to regulate a superior engine system performance, more and more feedback control loops with embedded sensors, actuators and controllers are integrated in the engine management systems. Hence an increase in the complexity of engine systems and increased dependence on electronic engine controls leads to embedded fault detection and diagnosis as an indispensable module in the engine management systems. (Kjellqvist, 2005; Spelina Jill, Jones, & Frey, 2014).The diagnostic module in the EMS is to alert the driver if a system behavior diverges from the expected behavior, by means of a malfunction indicator lamp (MIL) in the instrument cluster. The need for failure diagnostics in automobiles originates from two perspectives: a maintenance-oriented perspective and a safety-oriented perspective. The diagnostic subsystem of an embedded control unit is commonly structured as a collection of diagnostic functions which check the state or operation of all relevant components and control functions in order to provide information about current operation and any faults. This information is required to decide whether a changeover to backup functionality or limp home action needs to take place (Weinhold, Ding, Jeinsch, & Schultalbers, 2005). The detection of faults in the engine is necessary to maintain the correct operation according to legislative requirements. Depending on the type of system unit or sensor to be monitored different strategies are employed. Some examples of diagnostic control strategies employed are given below,

- *Model based*—A model is used to find any deviations between a theoretical model and the physical process which is used to determine fault conditions in the control system.
- *Knowledge based*—Prior knowledge of the physical process is used to ascertain when a fault condition has occurred.
- *Signal based*—The signals of a sensor or other strategy is analyzed or filtered to yield further information regarding the detection of faults.
- *Data based*—A neural network can be used to train a 'black box' process model, without having a detailed understanding of the physical processes involved, and then this is used to compare against the actual physical process to determine an out of tolerance condition (Jianhui, Krishna, Qiao, & Chigusa, 2007).

Various control approaches of the diagnostic module are listed in Table 7. One of the most widely used strategies for fault diagnosis is based on the model based diagnostics approach in which the control system to be diagnosed is modeled based on the physics of the system, and this model of the system is executed at runtime along with the actual system (Amr, Soliman, & Rizzoni, 2003; Filippo et al., 2009; Frank, Schwarte, & Isermann, 2005; Isermann, 2005; Kwang, Simpson, Bell, & Majkowski, 2000; McDowell, McCullough, Wang, Kruger, & Irwin, 2007; Mischker, Hillner, & Schiemann, 1998; Nicolo, Corti, Sgatti, Guidotti, & Cavanna, 2008; Olof & Prytz, 2014; Wha & Rizzoni, 1998).

8.1. Model based diagnostic control system

In a model-based fault detection approach different methods can be applied, such as parameter estimation, parity equations, state variable estimation, etc. (Olof & Prytz, 2014). The approaches of the model-based fault detection involve, mathematically describing the process and the model is employed to check for discrepancies between different sensors. From these it is possible to calculate internal process quantities, for example, residuals, parameters or state estimates, which are called features. From these process quantities, faults can be detected. Then, from the analysis of the differences or residuals, symptoms can be generated and subsequently used in fault diagnosis. When using residuals, the output is usually referenced to a known threshold value. Exceeding this threshold value generates an indication about the fault. An example of such generalized model-based diagnostic module is shown in Fig. 18 (Jianhui et al., 2007). All systems or sub-systems have to be monitored to ensure correct operation for the life of the engine. Thus, the diagnostic system monitors the entire engine related systems such as air path, fuel path, emission related, etc.

The process of the diagnostic system consists of the detection of faults in sensors, actuators, and faults in the mechanical, electromechanical, or hydraulic plant, by using the dependencies between different measurable signals. In order to detect the minor differences between the normal operation of a system and its faulty operation, a reasonably sophisticated model is required. The ultimate accuracy of diagnostic algorithms is dependent on the accuracy of the model employed to predict the behavior of

Table 6
Different controllers used in the knock control module.

S. no.	Controller used for ETC module	Authors	Year	Outcomes
1	Likelihood-based controllers	(Go-Long et al., 2004)	2013	Likelihood-based knock controller is implemented and tested in SI engine. The binomial probability theory maximum likelihood estimation and the control law which adjusts the spark advance according to the likelihood of the observed knock events relative to the target knock probability are presented.
		(Go-Long et al., 2004)	2013	Presented likelihood based stochastic knock controller achieves a significantly improved regulatory response relative to conventional strategies, while also maintaining a rapid transient response.
2	Stochastic knock controls	(Lezius, Schultalbers, Drewelow, & Lampe, 2007)	2004	A stochastic closed loop retard limit management system includes a retard limit feedback computation method derived from in-cylinder ionization signals and multi loop closed loop control method.
		(Flolka, 2006)	2005	This paper proposes a stochastic limit control strategy for borderline knock control. It also develops a simple stochastic model for evaluating the proposed stochastic controller.
		(Christel, Lindstrom, Angstrom, Grandin, & Kalghatgi, 2003)	2009	Unlike previous 'stochastic' knock controllers, the new algorithm does not average or low pass filter the knock intensity signal and the transient response of the controller is consequently much faster.
		(Ibrahim, Zhu, & Winkelman, 2004, Peyton, Muske, Frey, & Scholl, 2009)	2011	Stochastic Knock Detection method using a model based design approach. The SKD set consists of a Knock Signal Simulator as the plant model for the engine and a Knock Detection Module (KDM).
		(Lonari, 2011)	2014	Knock control based stochastic knock detection (SKD). The real-time stochastic knock control (SKC) is developed in Simulink, and the SKC software is integrated with production engine control strategy.
3	Knock detection	(Samir et al., 2011)	1995	Detection accuracy by detecting the knock resonance frequencies. The developed knock detection module makes knock control possible throughout the entire engine speed for each engine cylinder.
		(John et al., 1998)	1997	An advanced approach solving the knock detection task. It is based on a two level feature extraction solution followed by a neural detection step trained in a constructive supervised way.
		(Lonari, 2011)	1998	Knock-detection method using cylinder pressure, block vibration and sound pressure signals from a SI engine. As a first step, knock window and knock frequencies were determined.
		(Timo et al., 2012)	2003	An empirically based knock model was integrated in a one-dimensional simulation tool. The empirical knock model was optimized and validated against engine tests for a variety of speeds and air fuel ratio.
		(Wei, Chen, Naber, & Glugla, 2014)	2004	A transient knock prediction technique by coupling a zero-dimensional knocking simulation with chemical kinetics and a one-dimensional gas exchange engine model to study the occurrence of knock.
		(Lee, Hwang, Lim, Jeon, & Cho, 1998)	2005	Implement a real-time control system of the knock using soft-computing techniques to have a more accurate prediction of knock intensity.
		(Kaneyasu et al., 1995)	2006	Knock detection method called Wavelet Based Knock Detection which is based on joint time-frequency analysis of the pressure signal is proposed.
		(Lezius et al., 2007)	2007	Controller uses cylinder-pressure signals to estimate distance to knock limit and control ignition angle.
		(Noda, Hasegawa, Kubo, & Itoh, 2004)	2013	Using optical signal from the combustion chamber the spectral properties of the combustion flame is investigated with special regard to the detection and estimation of intensity of knocking combustion.
		(Taglialatela, Moselli, & Lavorgna, 2005)	2013	Based on the use of statistical analysis by applying an auto regressive moving average technique, a parametric model is applied to the instantaneous in-cylinder pressure measurements, is highly sensitive to knock occurrence and is able to identify soft or heavy knock presence is used.

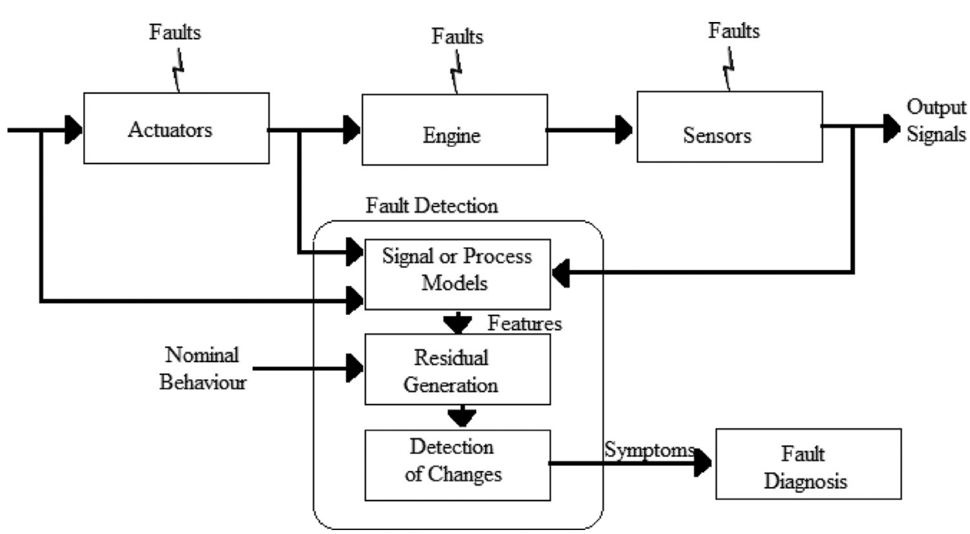

Fig. 18. Generalized model-based diagnostic system in EMS (Jianhui et al., 2007; Olof & Prytz, 2014; Wha & Rizzoni, 1998).

Table 7
Various control approaches the diagnostic module algorithms.

S. no.	Controller used for ETC module	Authors	Year	Outcomes
1	Model based diagnostic	(Krishnaswami et al., 1995)	1995	A nonlinear parity equation residual generation scheme that uses forward and inverse dynamic models of nonlinear systems, to problem of diagnosing sensor and actuator faults in IC engine is employed.
		(McDowell et al., 2007)	1998	The integrated control and diagnostics approach is based on using estimates of faulty inputs and outputs to either replace faulty measurements, or to partially correct for actuator faults.
		(Ding, Weinhold, Ding, Jeinsch, & Schultalbers,)	1999	A systematic and general method based on structure of hypothesis tests, possible to diagnose different faults. The method is applied to the diagnosis of sensor-faults and leakage in air-intake system.
		(Isermann, 2005)	2000	A coolant temperature model of an IC engine has been formulated to meet OBD II. A diagnostic scheme to detect and isolate various types of cooling system failures using engine soak time information available from a low power timer in the ECM.
		(Frank et al., 2005)	2003	Detection and isolation of component faults for which the local approaches simplifies and reduce the complicated FDI problem to mean value of Gaussian vector with a constant covariance matrix is used.
		(Kjellqvist, 2005)	2005	An embedded Fault Detection and Isolation (FDI)-system for the air intake system of an SI-engine has been presented.
		(Olof & Prytz, 2014)	2005	Semi physical dynamic process models, identification with special neural networks, signal models and parity equations residuals are generated for intake, injection system together with combustion process.
		(Nicolo et al., 2008)	2005	Scheme for detecting and isolating faults in the feedback control loops. The core design FDI functional units by making use of available tracking control structure and to integrate them into the control loops.
		(Spelina Jill et al., 2014)	2007	Model-based diagnostic employs a graph-based dependency model and mathematical models for online/offline diagnosis are developed.
		(Amr et al., 2003)	2008	Three different leak detection methods have been analyzed and developed by using a model-based approach: depressurization, air and fuel vapor compression, and natural vacuum pressure evolution.
		(Kwang et al., 2000)	2009	Model based approach to complete gas supply line diagnostic strategy may lead in a first step to the definition of several “blackbox” algorithms and a second time toward the inversion of whole model.
		(Eriksson, 2005)	2012	Observer using extended MVEMs for fault residue generation and state estimation using Extended Kalman Filter. This observer structure is expected to be able to detect faults across the engine system.
		(Mischker et al., 1998)	2014	Approach to fault detection and isolation that is based on off-board 1D simulation tools such as GT-power or AVL Boost. Algorithm is evaluated based on measurements from the air path system.
		(Nyberg, 1999)	2014	The sliding mode to design estimator is used. The estimation error from sliding mode observer is then used to detect abnormal behavior of turbocharged engine due to a leakage fault in the air-charge path.
2	Neural network	(Jonathan, Deb, Mukhopadhyay, & Pattada, 2012)	1998	Uses a NN based engine performance, fuel efficiency and emissions prediction system has been developed for SI engine. Through limited training of NN able to predict accurately real-time output.
		(Salehi, Alasty, & Vossoughi, 2014, Chris, Atkinson, Long, & Hanzevack, 1998)	2002	Describes hybrid solution, based on Artificial Neural Networks and production rule adopted in the realization of Instrument Fault Detection, Isolation, and Accommodation for automotive applications.
		(Capriglione)	2003	An on-line diagnostic system to detect the deterioration in a critical state of an IC engine has been developed by means of a multiplayer perceptron neural network and independent component analysis.
		(Capriglione, Liguori, Pianese, & Pietrosanto, 2003)	2008	An expert system for fault diagnosis in internal combustion engines using adaptive order tracking technique and artificial neural networks is presented.
		(Barnard & Aldrich, 2003)	2010	System consisted of manifold pressure signal feature extraction using discrete wavelet transform (DWT) and fault recognition using the neural network technique is proposed. To verify the both the radial basis function network (RBFN) and generalized regression neural network (GRNN) are used.
		(Wu, Chiang, Chang, & Shiao, 2008)	2011	Engine fault diagnosis system based on intake manifold pressure signal and artificial neural network with the Wigner–Ville distribution technique was followed.
3	Other diagnostic methods	(Weinhold et al., 2005)	1998	DSM which introduces improved object-oriented software architecture to meet OBD. DSM module consists of Fault Code Memory, an Inhibit Handler, Validator and Function Scheduler is employed.
		(Wu, Huang, Chang, & Shiao, 2010)	2013	Vehicle level optimized fault management strategy is proposed, a centralized Gateway Module has a global view of all the local faults monitored by individual ECUs in the vehicle network architecture, is responsible for fault management of the complete vehicle.

the system. At run time, the actual outputs of the any control system (AFR, ETC, etc.) are compared with the outputs predicted by the diagnostic model. Residual values are calculated as the differences between the actual and predicted outputs. Threshold values of the various residuals or of combinations of residuals are correlated at design time with various anticipated faults from the fault model. During run time, whenever such residual values exceed the predefined thresholds, the corresponding fault is considered to have occurred (Wu & Huang, 2011).

For instance, the diagnostic module has to detect a malfunctioning sensor if the sensor's output goes above or below certain specified limits, or fails to change for long periods of time. Thus, the diagnostic module detects the loss of a primary control sensor or actuator; it may choose to operate in a different mode until the problem is repaired. The operator is notified of such failure by a blinking MIL or some other indicator on the instrument panel. The controller will perform its basic system operations by means of a backup control (Limp Home) even after the fault has occurred and the specific fault code or Diagnostic Trouble Code (DTC) is stored in the memory for the detected failures. The DTC is required to indicate the likely area of the malfunction or identify which component or system was malfunctioning. These trouble codes are nothing more than a five digit alphanumeric descriptor that goes with a short text description. The fault will remain in memory for an extended period of time, for example 50 engine start/run cycles, unless the fault was determined to be no longer present or a service technician has erased the fault code in memory (Dibyendu, 2013; Gilberto, 2006; Paul, 2004). Such diagnosis is known as on-board diagnoses (OBD), and different versions are followed. Powertrain OBD systems are required to monitor all the components and functions of the emission control system and to indicate any fault or deterioration which might cause emissions to exceed certain limits. The current OBD methodology is based on various approaches to monitor the 'health' of the sensors or system units (Jianhui et al., 2007; Mischker et al., 1998; Weinhold et al., 2005).

9. Conclusions and future perspective

This paper presented a comprehensive review on the basic control modules in the SI engine management system (EMS) in terms of its function, and control strategies. The studies reviewed in this paper have been largely performed in simulation and experimental work and appears to confirm the general approach of the control system architecture in an SI engine management system (EMS). This review will serve as a basic understanding of the SI engine control system architecture for the future developing of an effective control system of EMS, with a high degree of engine performance, superior drivability and fewer emissions. From the studies, it is found that the control algorithm development is a promising area of research in the engine management system and the future perspectives in the control system development of a SI engine management system is highlighted below:

(1) Currently, the intellectual property (IP) rights from the supplier of engine management system (EMS) propose limitations for the modification in the control algorithms and also to implement it for different categories of engines in order to improve the performance. Adapting such proprietary EMS control algorithm for various engines by modification is a complex task due to the difficulty in software accessibility, customized hardware and calibration process. Hence, there is a need for development of an "Open architecture" based EMS in which control algorithms can be added, replaced or modified with plug and play features.

(2) Since the torque control system is the central part of the engine control, performance of the torque control system has a direct influence on the fuel economy, drivability and vehicle response. The estimated torque from control system output can be more efficiently compared with the actual torque output of the engine by a low cost torque sensor or with help of torque estimator mathematical model. A real time based low cost torque sensor is needed to address the effective control of the engine torque for better drivability and fuel economy requirements.

(3) Because of the fuel scarcity and stringent emission norm requirements, hybrid vehicles are going to dominate the future mobility. The control strategy and power train parameter significantly affects the dynamic performance and fuel economy. Since the hybrid vehicle operates in different operating modes (engine and electric mode), torque bumps during switchover (from engine to electric or vice versa) may affect the driver comfort. For such categories of vehicles the torque control system with a smooth mode-switching between different operating modes is needed. Hence, by means of the efficient control system logic for the different operating conditions the degree of hybridization can be extended.

(4) Present production EMS architecture uses PID controller along with a number of parameter maps, parameter values and time delays, various gains, correction factors in the form of lookup tables. In order to signify the real time nonlinear behavior and the dynamic effects of the engine, there are lots of feedforward lookup tables in the control system. It leads to time consuming calibration effort during the development phase and it requires more storage memory in the controller hardware. These strategies can be overcome by means of adapting the physical models and model-based control for the lookup tables in the architecture.

(5) Similarly there are numerous look-up tables in the engine control strategies for calculating various parameters during the real time operation of the engine. Such kinds of tables are obtained from the number of static dynamometer operating points for various loads and speed of the engine. In order to save the time in the calibration process, a simple way of calibration approach is needed in future. Such kind of design can reduce software development and calibration time while maintaining or improving the performance.

(6) The engine control system of SI engine consists of various sensors in the engine to provide an efficient control output to the actuators. There is a wide scope of replacing some of the sensors with soft sensing techniques and observers using accurate models. Also this can be accomplished by means of the sensor fusion techniques where data from different sensors can be aggregated to obtain a lower detection error probability and a higher reliability. This provides the motivation to undertake the research in the area of new control and estimation techniques for the possible sensor replacement.

(7) As there arises lot of complexities in the diagnostics of an engine control system due to the presence of many electronic and software components there is a need of trained technician to handle many issues related to the fault diagnostics. The next generation of diagnostic system will be in the form of integrated, intelligent approach through cloud computing. The real time running data's of the engine control can be acquired and distributed by means of wireless networks to the cloud computing server. In such technology, the remote diagnosis of the EMS system is possible through the monitoring the state of the system, health of the system, etc. in the EMS and online preventive actions can be provided based on the various analyses.

(8) As the engine control system is a nonlinear phenomenon because of the operating conditions, road conditions, etc., which are continuously changing, controlling the engine on real time aspect is a challenging task. However enabling a smart control system technology for EMS by adapting the driver behavior, road conditions, atmospheric conditions, products aging, etc. on a real time basis will provide an efficient and superior performance of the system.

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B. Ashok received his B.E. degree in Mechatronic Engineering from Anna University in the year of 2009. His M.Tech. degree is from Automotive Engineering from VIT University in the collaboration with ARAI (Automotive Research Association of India) in the year of 2011. He has worked as specialist engineer in the Force Motors Limited, India for couple of years in the projects related to the electronic control units development for engines, braking and instrument cluster systems. During the tenure in Force Motors, he played a core role in the development of antilock braking system for the SUV. He is currently working as an assistant professor at the Department of Automotive Engineering, VIT University, Vellore. His research activity is mainly focused on design of automotive control systems, automotive engineering related aspects and alternate fuels for IC engines. He has published over 15 research papers in the field of IC engines, automotive engineering and control system areas. Also he has successfully completed the project in the development of data acquisition system for Formula SAE vehicles.

S. Denis Ashok obtained his Bachelor's degree in Mechanical Engineering in the year 1998 from Kamaraj University. He worked as a Production Engineer in Donghee Vision Industrial Company Limited, which is an ancillary unit of Hyundai Motor India Limited during the year 1998–2000. He holds Master's degree in Production Engineering in the year 2003 from Thiagarajar College of Engineering, affiliated to Kamaraj University. He received his doctoral degree from Indian Institute of Technology, Madras in the year 2011. Currently, he is working as a professor in the Department of Design and Automation, School of Mechanical Engineering at VIT University, Vellore, India. He received the research funding for the "Development of machine vision based spindle error measurement system" from Department of Science of Technology, Delhi under the fast track young scientist scheme in the year 2012. He received the Innovative leadership award for his contributions in the indigenous development of automated egg vending machine, from Central Poultry Development Organization, India in the year 2013. Also he has received the sponsored research fund for the "development of a human powered hybrid vehicle" from Science for Equity, Empowerment and Development (SEED) Division, Department of Science of Technology, India in the year 2015. Recently, he has successfully completed the consultancy project on "Mobile controlled electrical appliances" for the TATA Power Company Limited, India. His research interests include automotive control system; steer by wire, machine vision and soft computing techniques. He has published more than 20 research papers in the reputed journals and conferences.

C. Ramesh Kumar graduated in Mechanical Engineering in the year 1999, from Barathidhasan University. He worked as service engineer in Cummins India Limited for 2 years. He obtained his Master's degree in Thermal Engineering from Annamalai University in the year 2002. He started his teaching career as lecturer in the year 2003. He obtained his Doctorate in Mechanical Engineering from College of Engineering, Anna University in the year 2012. He joined VIT University in the year 2005 as senior lecturer and now he is working as an associate professor. He is presently heading Automotive Engineering Department in School of Mechanical Engineering, VIT University, Vellore. His research interest includes Internal Combustion Engines, Alternate Fuels, Automotive Electronics and Heat transfer. He has published more than twenty research papers in the reputed international journals. He is the active member of Institute of Engineers, India. He has authored a text book in Alternate Fuels. Also he has completed six consultancy projects from various automotive industries.