The combustion engine as a mechatronic object in mechanical technology undergraduate curriculum

El motor de combustión como objeto mecatrónico en el currículo de Tecnología Mecánica

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Abstract— **Internal combustion engines, ICE, have evolved to mechatronic systems. They consist of thermodynamic processes, electromechanic, hydraulic or pneumatic actuators, electronic sensors and one or more digital control units. This paper is aimed at presenting the modern combustion engines from a Mechatronics perspective to be taken into account in the course on Mechatronics in the "Mechanical Technology curriculum" at the Universidad Tecnológica de Pereira. The Laboratory of Mechatronics is under development and the course methodology seeks to use some machines, among which the internal combustion engine is listed. It is described the broad concept of mechatronics, the composition of modern ICE engines; two engine test benche sdeveloped as teaching tools for testing and control of ICE are presented.**

Key Word— **Mechatronics, curriculum, internal combustion engines**

Resumen— **Los motores de combustión interna MCI se han convertido en sistemas mecatrónicos. Ellos comprenden: procesos termodinámicos, sensores electrónicos, actuadores electromecánicos, hidráulicos y neumáticos, unidades de control y sistemas de comunicación. En este artículo se comenta la utilización del MCI para prácticas del curso de Mecatrónica ofrecido en el Programa de Tecnología Mecánica en la Universidad Tecnológica de Pereira. El Laboratorio de Mecatrónica se encuentra en desarrollo y la metodología de las clases busca emplear algunas máquinas representativas, entre las cuales figura el MCI, como objeto de mecatrónica. Se describe la mecatrónica en general, la composición de los motores modernos y se resumen algunos trabajos que se realizan en el laboratorio de motores relacionados con los temas de la asignatura Mecatrónica Dos bancos de pruebas de MCI desarrollados tienen utilidad en la enseñanza y se enfocan trabajos futuros de desarrollo, prueba y control de los MCI como sistemas mecatrónicos.**

Palabras Clave — **Mecatrónica, currículo, motores de combustión interna**

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I. INTRODUCCIÓN

The need for a broad based understanding and application of new technologies used in automation systems, characterized by the integration of components and assemblies performing some or all of the tasks of a control chain, has led the "Mechanical Technology" Department at the Universidad Tecnológica de Pereira to the design and offering of a course on Mechatronics intended to complement and update the curriculum and skills of undergraduate students.

While the laboratory of mechatronics is being implemented, the internal combustion engine laboratory has been seen as a place where the students can make the initial steps in mechatronics. The argument for this is that internal combustion engines are the paradigm of mechanical machines, they incorporate mechanisms, fluid and thermal systems, electrical systems, and electronics. Measuring, monitoring, and control elements have been part of the engine in minor or broad scale, since the first engines were run [1]. This article is aimed at presenting the works related to mechatronics conducted at the internal combustion engine laboratory. Sensors and actuators used in conjunction with electronic control units are characterized. The implementation of some sensors as well as the hardware control of the hydraulic dynamometer of the test bench is one of the projects that can be used in the course of mechatronics. The project is on its initial state. Future work will deal with the construction of the maps, the design and simulation of the models, and the development of an engine controller.

While most of the sensors used with internal combustion engines are used to monitor processes, only a few sensors of the industrial automation are implemented. To cover a broader range of sensors two other objects have been considered to be part of the object oriented laboratory. Such objects are an injection molding machine and a manufacturing cell, comprised by a machining and turning center, a conveyor and a robot. The instrumentation, design and implementation of a control for an injection molding machine will be a second object of the course on Mechatronics.

In the next sessions of the presentation, it will be outlined the mechatronics as a core course in “mechanical technology” curriculum. Then, some mechatronics aspects of the modern internal combustion engines will be described, followed by an illustration of the works carried out at the internal combustion engine laboratory.

II. MECHATRONICS AS A CORE COURSE IN “MECHANICAL TECHNOLOGY”CURRICULUM

Mechatronics is defined as a synergic combination of mechanical and electrical engineering, electronics, computer systems, and control methods and systems used in built-in intelligent functional units or assemblies, applied along the entire design process, modeling, simulation, and manufacturing.

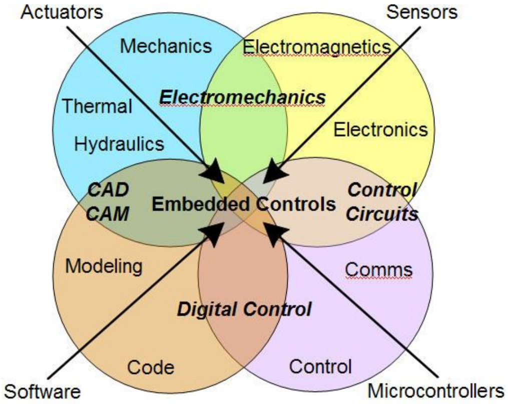

Figure 1. Schematic of the mechatronic systems concept

There is a consensus on the need for a course in which the students could have contact with the new technology that comes together with the classical mechanical devices and is being implemented in industrial world. This relates to transducers, electronics, and controllers. This belief has been fundamental to the establishment of a course on mechatronics.

Undergraduate students from “Mechanical Technology” will deal in the industrial world with ever modernizing industrial processes, in which while the core process remain unchanged and traditional, the introduction of new control technology is the main feature. As an example, in a steam power plant the basics of the power generation have not changed, but the control technology has become more sophisticated and relies on electronics and information technology. Actuator valves incorporate the electronics and may incorporate sensors as functional or mechatronic units. Competitiveness and innovation skills of our professionals are not possible without a good understanding of the elements involved in modern control and automation of industrial processes that is without a good understanding of mechatronics.

Mechatronics and Automation of processes call for extensive use of sensors, actuators and related electronics interfacing with the controllers [2]. A basic course on mechatronics should cover the broad variety of sensors and actuators available for different applications, classifying them by principle of operation, construction, application or performance parameters. Among others, the course should also cover fundamentals of control theory, sampling and signals treatment, architecture of controllers, programmable logic controllers (PLC), communication protocols, and analogous device/interface technology.

In a typical mechatronics system design process, software tools must be available to aid the designer in creating and debugging the mathematical system models. Some tools that are particularly useful to allow the designer to represent the system by creating a system block diagram from simple building blocks such as integrators, gain stages, summing junctions, and nonlinear switches. One of those programs is LabVIEW®. With these programs, the designer can create a plant model, and then validate it against real world measurements. Once the plant model has been validated, the designer can then design the control system and optimize it until the satisfactory response is achieved. These simulation tools also allow the designer to interface to actual sensors and actuators. The hardware in the loop simulation testing provides the designer reassurance that any assumptions made on the plant model were correct. If any assumptions were incorrect, however, the designer does have the opportunity to optimize the design before committing to the real target hardware platform.

Until now, though novel product engineering has resulted, many of the products developed in the country have been the result of reverse engineering processes [1]. It is expected that the course of Mechatronics will enable undergraduate students, become professionals, impact and improve the product development competence in our country. The contents and methodology of the course should be upgraded and improved continuously.

III. OUTLINE OF THE INTERNAL COMBUSTION ENGINE AS AN OBJECT OF MECHATRONICS

Internal combustion engines are machines that generate power by converting chemical energy bound in the fuel into heat, and this in turn into mechanical work. Chemical energy is converted into heat through combustion. The subsequent conversion of this thermal energy into mechanical work is performed by allowing the heat energy to increase the pressure of the combustion products within the cylinder, forcing a piston to perform work as gases expand [5].

Initially internal combustion engines were defined as machines composed basically of two mechanisms, crankshaft mechanism and camshaft mechanism, and five systems: fuel and air feeding system, ignition system, exhaust system, cooling system, and lubrication system. Systems and mechanisms were assembled in an engine block, a crankcase and a cylinder head [6][7]. Today the core design of internal combustion engines has not changed, but it has been complemented by sophisticated sub-systems and real – time controllers. Originally, these were designed to use various tables of properties, driven by engine speed and load. Today, in the most advanced control implementations, the controller relies on embedded system models (i. e. model – based control) to make projections and decisions [8].

At the end of the 1970s, the first engine control units came onto the market primarily to replace conventional magnetic ignition systems. The resulting need for test equipment was initially met by simple stimulators which provided the power supply and some essential sensor signals like the engine speed. Later on, the pressure in the intake manifold and other sensor values were measured [9]. More sophisticated test systems which directly calculate the sensor values by means of a model that takes into account the actual outputs of the engine control unit were developed. During the 1980s, engine control units became more complex with regard to their functional features, but also because onboard diagnostics became mandatory for all vehicles mostly in the United States in 1988 [10]. This regulation required continuous monitoring of all exhaust-relevant electronics in engine control unit software.

Regulation regarding exhaust emissions became more and more stringent with the OBD II and Euro standards. The new developments meant that engine control units had to check the plausibility and consistency of sensor signals, for example, that a certain engine speed corresponds to a certain air mass flow. As a result, simple stimulators were no longer suitable for testing. From this time on, automatic closed-loop tests became the standard test procedure for all advanced engine control functions, as well as for complex OBD II functionality.

Today, engineers at original equipment manufacturers and Tier 1 suppliers working on the development and optimization of engine management systems utilize hardware-in-the-loop (HIL) technology extensively for regression tests, acceptance tests, functional tests, and integration tests. HIL interfaces needed to set up closed-loop test systems are the main objective of technological research processes in vehicle power train development, interfaces for precise crank-based ignition and injection measurement, crank and cam signal generation, knock or ionization signal synthesis, or linear lambda probe simulation; both hardware and software aspects are developed simultaneously [11].

During the development processes, simulation models are crucial for proper HIL operation. Thus, real-time combustion engine simulation, starting with the standard mean value engine models are validated, engine models providing in-cylinder pressure and temperature are also introduced. These more sophisticated models, running at higher sample rates, are needed for upcoming engine control units which utilize in-cylinder pressure sensors. Last HIL applications deal with test systems for single engine control units (component testers) and with test systems for networked engine control units, e.g., for the complete powertrain of a car. These types of virtual laboratory vehicles are growing in importance, especially with the introduction of power management and hybrid electrical systems [11].

General Engine Control Unit Functionality

For both gasoline and Diesel engines, the main task is to provide a certain torque at the crankshaft according to the operator’s demand. This task and other sub-controls tasks, like start-up, idle and overspeed, or soot emissions control, have to be implemented to meet the exhaust emissions legislation. Gasoline engine control units perform this task basically in two steps: first, by controlling the air-filling of the cylinder by a throttle in the intake manifold [13]. This control is normally based on a hot-wire or hot-film air-mass sensor. Second, the engine control unit controls the injection valves to provide a corresponding amount of fuel to get a stoichiometric air-fuel ratio in the combustion chamber. This mixture is then ignited by the spark plug. Injection and ignition have to be controlled precisely with respect to the crank angle position, which is calculated from the crank/cam sensor information by a time processing unit [3][4].

In Diesel engines the torque output and emissions are controlled by precise, high-pressure, direct fuel injection. The exact fuel metering and the precise crankangle-related injection "timing" determine the engines' behavior. Today’s Diesel engine control units use pre-, main, post-injection, and even more pulses to obtain optimal performance. Additionally, Diesel engines are equipped with waste gate or variable turbine geometry, electronically controlled turbochargers to enhance power. For testing these highly functional engine control units, the real combustion engine with its sensors and actuators is replaced by a mathematical simulation model running on a real time processor. An input/output interface is used to connect the virtual engine, engine model-processor, to the engine control unit. Such a setup, called a hardware-in-the-loop simulator, is a means for the efficient development of engine control units [11].

I/O Interface of Engine Control Units

The control algorithms of the ECU interact with the control plant by means of sensors and actuators connected to their inputs and outputs. Although there are different types of engines and engine control units, e.g., gasoline multi-point injection, gasoline direct injection, and Diesel engines, there are many sensors and actuators used in common by all of these different systems. The injectors’ main task is to meter the correct amount of fuel at the desired time in each combustion cycle. In Diesel engines, the injection angle is very important since it determines the start of combustion. Several types of injectors are used, depending on the engine type. In standard manifold gasoline engines, the injectors are controlled by applying the battery voltage continuously throughout the activation time. Due to the inductance of the solenoid, the current behaves according to a first order delay system [11].

There are several developers of electronic control systems for engine manufacturers, and among them, Bosch is one of the more representative in engine control research. A brief explanation of the Bosch MED9.6.1 Engine Management Systems reproduced in the following, to illustrate the composition of an actual modern engine control system. The Bosch Motronic Engine Management System, one of the most widely used engine control systems is based on a Motronic Electronic Control Unit, designated MED9.6.1 (Motronic, Electronic throttle control, Direct injection). This controller uses a printed circuit board design with a Motorola Silver Oak 66MHz 32 bit microprocessor with 2megabytes external flash memory, 32 kilobytes internal RAM, 32 kilobytes external RAM and a 1 kilobyte EEPROM. It is intended for off-engine mounting and has154 pins in 2 connectors. One connector is focused on engine connections and the other on vehicle connections. It is a state of the art controller designed for the latest emissions and OBD II requirements and incorporates General Motor's Local Area Network for intra-vehicle communication with over 20different networked control modules distributed strategically around the vehicle. These include the transmission control module, ABS, traction control and body control modules. The Bosch MED9.6.1 Engine Management System (EMS) is a torque-based system that controls the throttle and the positions of the intake and exhaust camshafts based on inputs from various sensors and the pedal demand of the driver. Air fuel ratio is controlled utilizing the signals from the mass airflow sensor and switching type oxygen sensors positioned in front of and behind the close coupled three way catalytic converters. The EMS controls injection duration, injection timing, number of injections per combustion, fuel pump, fuel rail pressure and ignition timing. Knock sensors are positioned on each side of the block and are utilized to minimize knock. Engine speed and crankshaft rotational angle are determined using a (60-2) target wheel and digital crankshaft position sensor. Camshaft phase angles are sensed with 4X quick start target wheels and digital sensors mounted on the front of each camshaft. Ignition is provided by multiple high energy coil on plug units, one per cylinder. The EMS also controls other functions such as evaporative emission canister purge control, diagnostics, component protection, cruise control, etc [3].

Modern engine experimental research demands a broad arrangement of numerical and experimental tools, as it is illustrated in figure 2.

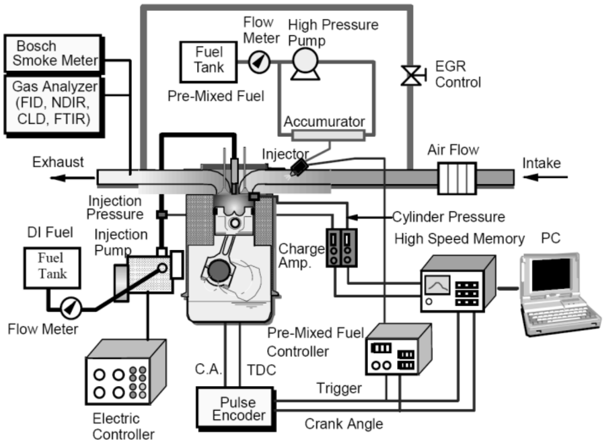

Figure 2. Experimental set-up of engine research [4].

Engine modelling

Numerous modelling approaches to handling the complexity of combustion and heat transfer in engines are possible and have been used. Before the advent of CFD codes, a common modelling approach was to do an overall heat and mass balance on the system. This is often referred to as zero-dimensional modelling because it does not give any spatial resolution. This type of zero-dimensional modelling can include detailed analysis of the chemical reactions and is often referred to as a stirred reactor or stirred vessel [8]. This type of modelling was made easier with the advent of electronic spreadsheets. Zero-dimensional models give a reasonable approximation of the overall performance of the engine, though it gives very little information on the detailed performance, such as local temperatures in the combustion chamber. Despite the disadvantages, solutions can be obtained very quickly. This is important for designing embedded system models.

The next level of complexity involves one-dimensional modelling. This is where only one spatial dimension is considered, and is often used to examine the detailed chemistry in a combustion process. One of the advantages is that faster results are possible, compared to multidimensional modelling. One-dimensional models greatly simplify the task of radiation modelling, which can become very complicated in multidimensional geometries [12].

The highest level of geometrical complexity involves multidimensional modelling, both two- and three-dimensional geometries. Wherever possible, three-dimensional problems are simulated by two-dimensional models or by axisymmetric geometries, which are three-dimensional problems that can be solved in two spatial variables. It may not always be possible to model the entire combustion system, so an approach that has often been taken is to separately simulate the flame region where small-scale effects are important and the combustor where large-scale effects are predominant. The results of the flame simulation can then be used as inputs to the large-scale modelling of the combustor itself. The obvious advantage of multidimensional modelling is that much higher spatial *resolution is possible. This can provide important insight into* the problem that is not possible with simpler geometrical models. However, there are some obvious disadvantages to multidimensional modelling, including longer computational times, difficulties in visualizing and interpreting the results, and more difficulty in separating the effects of individual parameters [12].

IV. INTERNAL COMBUSTION ENGINE TEST BENCH. STATUS OF THE PROJECTS

At ICE UTP Laboratory a hydraulic dynamometer has been designed and manufactured to be attached to a commercial Mazda 2.0 *l*, four in line engine. At the same time a Go–Power hydraulic dynamometer has been attached to a Robin 5,5 kW single cylinder four stroke air–cooled spark ignition engine. So we have been arranging two engine test benches to accomplish two main purposes: working with the Mazda engine we are trying to measure all parameters under different loads to build the maps and, in a future stage, to design a control unit that will enable the shift of the original carburetor type engine to an electronically fueled engine. It is sought to use the second Robin bench to study the changes in performance characteristics of the engine fed with different types of fuels under different operation loads. Mazda engine has been instrumented with sensors available for commercial electronic fuel injection system engines. We have installed manifold atmosphere pressure, air temperature, coolant temperature, throttle position, and oxygen sensors, all of them from Chevrolet Corsa. To measure the mass air flow a hot wire sensor from Mazda Matsuri has been chosen. To measure the knock phenomena a piezoresistor type knock sensor for a Chevrolet Cherokee engine has been placed. A proprietary type of coil pick-up has been designed to measure the high voltage signals in the secondary circuit of the ignition system. To register the indicator diagram a piezoelectric Kistler pressure sensor and a charge amplifier have been acquired. K type Thermocouples have been attached to the exhaust pipe to observe the changes in exhaust gases. It is planned to install J type thermocouples along with washers at the interfaces of the spark plugs and the cylinder head. Exhaust emissions of CO, unburned HC, CO_2, NO_x, and O_2 are being measured by a portable ECM analyzer. Figure 3 shows a snapshot of the engine-dynamometer setup. The Robin test bench has been equipped with combustion pressure sensor, rpm sensor, and a load cell to measure the torque. Currently it is planned to modify inlet and exhaust systems to place oxygen, temperature and pressure sensors in order to register the changes of emissions, and observe pressure and temperature waves along the track of the inlet and exhaust pipes. It is planned to install control valves along both intake and exhaust systems to simulate disturbances. Figure 2 shows the test bench with the Robin engine. Figure 3 shows a layout of the pressure monitoring system. For the Mazda and Robin engines the fuel consumption will be measured using a volumetric turbine type flow meter and a linear link amplifier provided by Flow Technology, Inc.

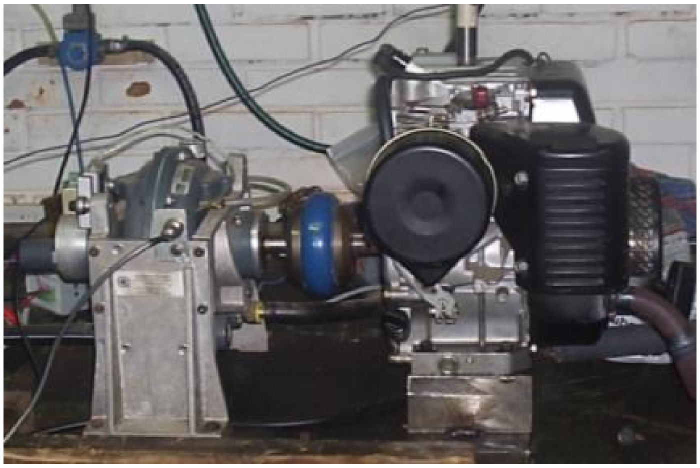
Figure 3. Experimental setup

Signals in engines are broadly divided into high speed and low speed signals. Low speed signals refer to those that do not change appreciably when an engine is steady at an operating regime. The sampling rate of such signals must be from 1 to 10 Hz. High speed data acquisition refers to data that change with crank angle and thus require very high sampling rates.

To acquire data provided by the sensors a National Instruments AT MIO 16 E 10 board, has been chosen with 16 analog inputs, and 12 bit resolution A/D conversion, and a sampling rate of up to 100 kHz. A computer program to collect data and to build the maps of the engine has been developed. To control the dynamometers electronic valves, provided by Danfoss, as well as a V/I converters have been installed. TDC and crank angle references come from an optical encoder with a resolution of one crank angle degree. To test the Mazda engine we have designed and attached a hydraulic 100 kW power absorption dynamometer. The main characteristics of this dynamometer were presented in other paper [1]. For testing the Robin engine a commercial Go–Power 100 T was acquired. The main drawback faced in our project is the lack of complete technical information of the installed sensors and actuators. This is due to the fact that car makers provide only the required literature to perform service and repair. Because of this, the work done up to now comprises the study of the sensors, their characteristics and responses, as well as the treatment needs, e.g. filtering, amplifying and sample rates, for every signal. Another project developed at the ICE laboratory is the 8051 Microcontroller based fuel injection system. A schematic of the system is presented in figure 4.

Other projects are being developed with the aim of producing inexpensive automated and fully instrumented dynamometers as teaching tools. The list has been generated from numerous brainstorming sessions with students and based on initial feasibility assessments focused on three points of view. The concepts developed for the dynamometer design stem from fluid braking systems, drum and disk mechanical braking systems, and electrical braking systems.

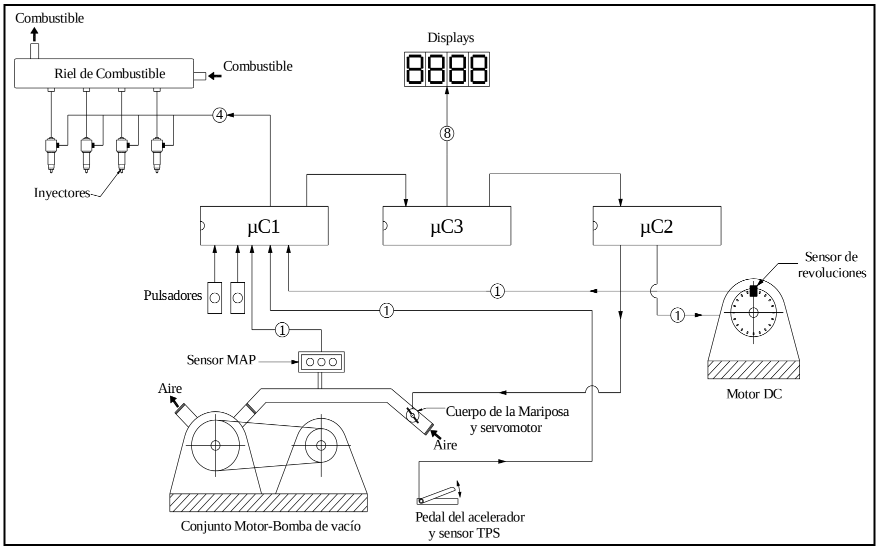

Figure 4. Layout of the fuel injection system developed at the ICE laboratory

V. CONCLUSIONS

It has been considered the introduction of a course on Mechatronics in a “Mechanical Technology” curriculum.
To study the characteristics of most of the sensors used in industrial processes, internal combustion engine can be used as an object, since its modern technology involves sensors, actuators, electronic control and information technology. Works on instrumentation and DAQ system development for two internal combustion engines have been presented.

Further work will involve the analysis of engine performance and the development of engine control modules, necessary for the shift of ignition and feeding systems to electronic controlled systems

Besides the look at the engine as an object of Mechatronics, the project could have various future uses: *Engine development* – in the calibration of engine control systems and the design of engine components; *Engine testing* – in combination with a programmable ECU the system could control an engine and record combustion data, i.e. spark timing sweeps measuring IMEP; *Engine control* – to research closed-loop control strategies using cylinder pressure or knock control; *Teaching tool* – tosupport thermodynamic and IC engine courses to demonstrate cylinder pressure data acquisition and the derived parameters.

REFERENCES

[1] C.A. Romero, “*Adecuación de un sistema de adquisición de datos para realizar el mapeo de un motor de combustión interna*”. Pereira. U. T. P., 2001.

[2] K. Daneshvar, “*Sensors, Actuators, and Applications*”. *V International Seminar on Advanced Manufacturing Systems*. Pereira. U. T. P., 2000.

[3] S. Mcneil, P. Adamovicz and F. Lieder. *Bosch Motronic MED9.6.1 EMS Applied on a 3.6L DOHC 4V V6 Direct Injection Engine*. *SAE paper* 2008-01-0133.

[4] C. Stan, G. Cipolla, “*Common Platforms for the Future Spark-Ignition and Compression-Ignition Engines*”. *SAE paper* 2006-01-3003.

[5] V. Ganesan, *Internal Combustion Engines*. McGraw-Hill, 2004.

[6] J. B. Heywood, *Internal Combustión Engine Fundamentals*. McGraw-Hill, Inc., 1988.

[7] M. S. Jóvaj, G. S. Máslov, *Motores de Automóvil*. Editorial Pueblo y Educación. La Habana. 1973.

[8] J. L. Lumley, *Engines: An Introduction*. Cambridge University Press, 1999.

[9] W. Pulkrabek, *Engineering Fundamentals of the Internal Combustion Engines*. Pearson Prentice-Hall. USA. 2004.

[10] W. B. Ribbens, *Understanding Automotive Electronics*. SAMS. North College, 1992.

[11] H. Hanselmann, “*DSP-based Automotive SensorSignal Generation for Hardware-in-the-LoopSimulation*”. *SAE paper* 94-01-85.

[12] L. Guzzella, C. Onder, “*Introduction to Modeling and Control of Internal Combustion Engine Systems*”. Springer Verlag, Berlin Heidelberg, 2004.

[13] D. Sundar, S. VenuMadhav, et al. “*Electronic Control of Air-Fuel Ratios in a Carburator for Two-Wheeler Application*”. *SAE paper* 2009-01-1429.