Design and Implementation of an Electronic Control Unit for a CFR Bi-Fuel Spark Ignition Engine

Carmelo Maniscalco(✉), Vincenzo Di Majo, Emiliano Pipitone, and G. Costantino Giaconia

Università degli Studi di Palermo, Viale Delle Scienze, 90128 Palermo, Italy
carmelo.maniscalco01@community.unipa.it, vincenzo.dimajo01@studenti.unipa.it, {emiliano.pipitone, costantino.giaconia}@unipa.it

Abstract. In this work an Electronic Control Unit for the management of a CFR engine will be described. The engine, which is used both for fuel octane rating (both in terms of RON and MON) and for research purpose, is equipped with a double injection system, with the aim to independently operate both with liquid and gaseous fuels. The developed ECU, hence, is able to control the injections of both kind of fuel, together with the spark ignition. Furthermore the system is also able to measure fuel's consumption, instantaneous engine speed of rotation and air-fuel ratio, showing all the running parameters both on a local LCD display and on a PC based graphical user interface.

Keywords: Engine control unit · Spark ignition · STM-Nucleo board · Embedded programming

Symbols and Acronyms

A/F	Air/fuel ratio
BDC	Bottom dead centre
BTDC	Before top dead centre
CAD	Crank angle degrees
ECU	Electronic control unit
IMEP	Indicated mean effective pressure
CFR	Cooperative fuel research
COV	Coefficient of variation (ratio between standard deviation and mean value)
MON	Motor octane number
RON	Research octane number
SA	Spark advance
TDC	Top dead centre
λ	Relative Air/Fuel ratio = actual A/F divided by stoichiometric A/F

A. De Gloria (ed.), *Applications in Electronics Pervading Industry, Environment and Society*, Lecture Notes in Electrical Engineering 429,
DOI 10.1007/978-3-319-55071-8_10

1 Introduction

The CFR (Cooperative Fuel Research) engine is a four-stroke two valve stationary single-cylinder spark-ignition engine currently prescribed by the ASTM standard D2700 [1] for fuel octane rating [2, 3]; it features a particular head arrangement that allows to accurately vary the volumetric compression ratio from 4.5 to 16: this characteristic allow to carry out a wide variety of experimental test, thus making the CFR a robust and versatile research engine [4–6]. The unit employed in this work, moreover, has been further equipped with an electronic ignition control module and a double injection system with the aim to perform the independent injection of both liquid and gaseous fuels, thus allowing to test almost liquid or gaseous fuel, as well as their mixtures [7], which is nowadays a fundamental part of internal combustion engine research and development for pollutant reduction and sustainable mobility purpose [8]. This setting allows the CFR engine to precisely determine the octane number of fuels mixture, such as natural gas-gasoline or propane-gasoline [9]. The main characteristics of the CFR engine used in this work (model F4) are detailed in the mentioned ASTM standard D2700 [1].

1.1 Engine Control Unit Specifications

In order to exploit the full potential of the CFR engine, a control unit is necessary for the precise control of both the spark generation inside the combustion chamber and the fuels injection in the intake duct, according to the user-defined settings and parameters.

The *input signals* for the desired ECU are hence:

- Two digital pulse trains generated by an optical encoder, mounted on the engine crankshaft, necessary for engine speed measurement (one pulse per revolution) and for crank position determination (360 pulses per revolution);
- One digital signal coming from the CFR native ignition system, used as phase reference signal;
- Some analog signals, such as the Coriolis type fuel mass flow meters and the Venturi air flow meter, used for fuel consumption and Air/Fuel ratio measurement.

In this work, the gasoline mass flow has been easily obtained on the basis of the fuel injection time and of the injector flow map previously determined by the gravimetric method, using a high precision laboratory grade scale. The designed system can enable or disable the fuel injection control in *closed loop* both for gasoline or gaseous fuel. The control in *closed loop for gasoline injection* is carried out using as set-point value the overall Air/Fuel ratio (A/F), while the *closed-loop for gas injection* is performed using as set-point value either the A/F or the gas mass fraction when a fuels mixture is adopted. Starting from these input parameter, the ECU is capable to output the following signals:

- The command pulse for ignition coil (engine ignition). In particular the pulse width was fixed (8 ms) and pre-calibrated, while a programmable starting point with respect to the engine phase signal was implemented in order to precisely set the spark advance with respect to engine Top Dead Centre (TDC);

- The command pulse for the gasoline injection, whose duration can be set by the user (in *open loop* mode) or heuristically calculated when the *closed loop* control on the injection is enabled;
- The command for gas injection, in *open* or *closed loop*.

Some digital outputs are taken into consideration and sent to a host PC to be displayed at user convenience: rotation speed, air mass flow, fuels mass flow, spark ignition advance and measured A/F. Communication between ECU and the remote PC is implemented with a Bluetooth module and the whole unit is battery powered.

2 ECU Hardware Features

The adopted solution was designed around an STM32-NUCLEO development board (F401RE) [10]. It is based on STM32F4 microcontroller (ARM CortexM4 32bit 84 MHz, Flash 512 Mb, SDRAM 96 Kb), where the ECU management firmware was running. A custom designed expansion board was designed to host the *level shifter* CD4504 [11] necessary to move the logical levels of the optical encoder signals from 5 V TTL to 3.3 V CMOS; and some diodes (1N4148), for protection against spikes for the three digital inputs to the ECU. A keypad controller ADP5585 [12] was also helpful for fast menu management, some voltage dividers for analog conditioning and the drivers IRS4427 [13] for the IGBT, driving the ignition coil. Furthermore another board has been designed and realized in order to properly implement a MAX1758 [14] based battery charger controller.

Figure 1 shows the block diagram of custom designed expansion board, while in Fig. 2 the generic block diagram of the ECU firmware is represented.

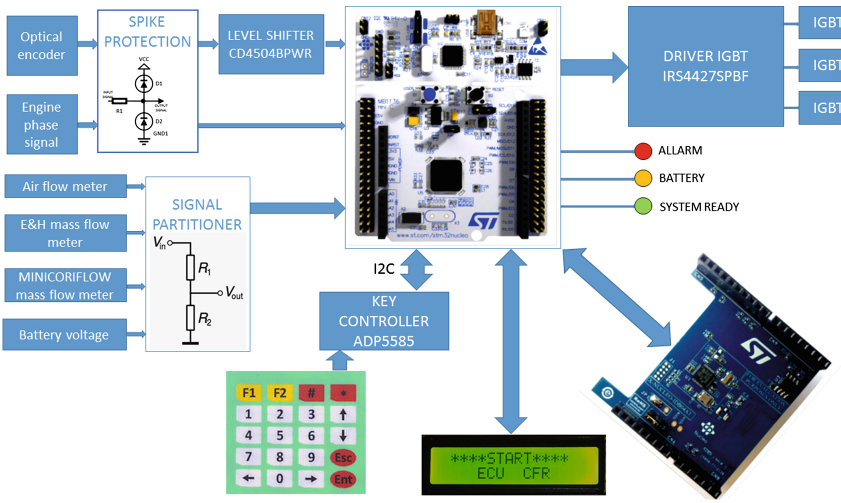


Fig. 1. Block diagram of the custom designed expansion board

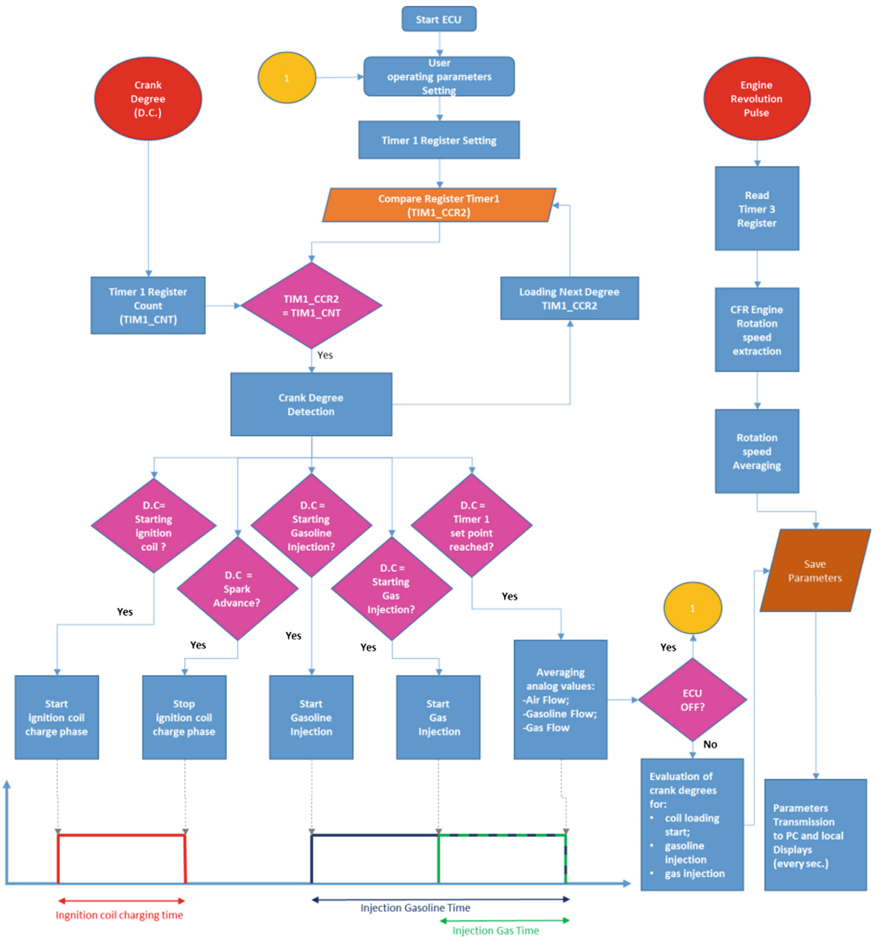


Fig. 2. Block diagram of the ECU Firmware

2.1 ECU User Interface

The user can set and display the ECU and engine operating parameters via a PC based software (running on Windows 10 OS and coded with Visual Studio 2015 IDE) connected via Bluetooth 4.0 provided through an X-NUCLEO [15] expansion board, or via a local keypad and a 16 × 2 local display (Fig. 3).

2.2 Engine Management

The engine management consists in the generation of the injection signals for both fuels and the ignition signal, all adequately phased with respect to the piston position and movement. As mentioned before, the ignition pulse has a duration of 8 ms, previously calibrated as the correct dwell time (primary coil charging time) [16]. The phase of this

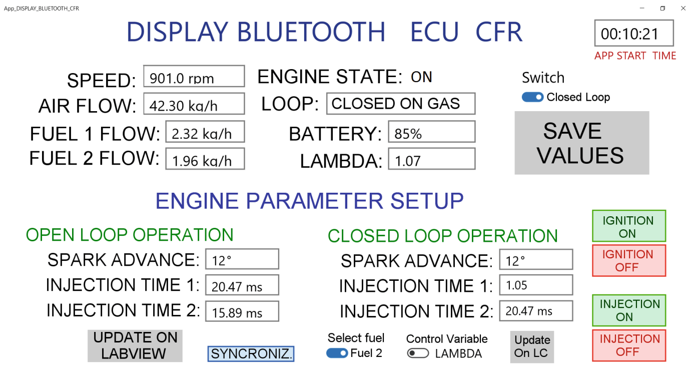


Fig. 3. PC GUI in the *upper part* the output parameters and saved values are shown, while in the *lower part* the setting parameters are reported

ignition pulse is instead determined on the basis of user input, thus accomplishing the desired Spark Advance (SA), expressed as Crank Angle Degrees (CAD) Before Top Dead Centre (BTDC).

The duration of each injection pulses is attained either in *Open Loop* or in *Closed Loop*, thanks to the measured fuels and air mass flows. The phase of both injection pulses, instead, has been previously determined and fixed with respect to the trigger pulse, aiming to ensure that the conclusion of each fuel injection happens to be not later than 90 crank angle degrees before the start of intake stroke [17].

Firmware is organized with some actions routinely done as main assignment while the most delicate engine management functions are arranged in a prioritized interrupts fashion in order to reach the required low latency performances. In particular four interrupt routines are used, with decreasing priority and implemented by using internal MCU timers.

ROUTINE 1: it has the highest priority, generates the injection and the ignition signals and computes the necessary moving averages parameters values starting from the measured analog inputs. It is started as a result of an interrupt request which provides to count the crank angle degrees.

At $start_{inj1}$ and $start_{inj2}$ crank positions, gasoline and gaseous fuel injector are respectively started, and the timer counts for the two injection durations $Tinj1$ and $Tinj2$.

The primary coil charging time (set to 8 ms in this work) can be varied by acting on the *start_bob* and *stop_bob* values (in crank degrees) via local od PC interface as long as some suitable limits are respected. The computation of moving average values of each necessary parameter runs once every engine cycle. The number of cycles to employ for each average can be set by the user from 1 to 500.

ROUTINE 2: it is started by the single pulse per revolution of the optical encoder and measures the time interval between two consecutive pulses in order to determine the engine speed of rotation.

ROUTINE 3: it is invoked by the transition from the high to low logic level of the CFR original ignition signal, and its task is to generate the phase reference signal used for injection and ignition control.

ROUTINE 4: it is called up for the acquisition of analog input signals, with a frequency that can be set by the user from 1 to 5 kHz. In the acquisition, the ADC has been set up in DMA mode (Direct Memory Access) with maximum resolution (12 bit) and with an averaging time interval of 15 engine cycles.

3 Experimental Results

The developed ECU was put to a test-bed with a CFR engine fuelled with commercial LPG, comparing its ignition and injection control performance with the performance obtained by a previously developed system, described in detail in [2, 3], based on the use of a DAQCard 6062E, a multifunction data acquisition board from National Instruments (NI). The DAQCard was connected, through the proper BNC2120 Connector Block, to the engine sensors and actuators, thus performing the injection control of both fuels, the ignition control and the data acquisition. A Kistler piezoelectric pressure sensor, flush mounted in the engine combustion chamber, was also employed for the in-cylinder pressure sampling thus allowing to perform combustion instability analysis. When using the developed ECU for the engine management, the NI DAQCard was employed only for data acquisition purpose.

The performance of the ECU injection control was evaluated in two different tests: the first aimed to verify the capability of the system to maintain the desired Air/Fuel ratio constant during the steady state operation, while the second was dedicated to evaluate the rapidity of the control system to bring the A/F inside the allowed interval (i.e. objective A/F $\pm$ 2%) [16, 17]. For the steady state operation, the comparison parameter is the Standard Deviation of the measured A/F within 100 consecutive engine cycles, while, for the second kind of test, the parameter taken into consideration for the comparison is the time interval employed by the control system to definitively enter the allowed interval values of the A/F, starting from a 10% higher value.

Figure 4 shows the results of this first series of test, normalized with respect to the values measured with the reference DAQCard based system: as clear, the developed ECU revealed a higher precision (i.e. lower dispersion) in maintaining the desired A/F objective value, and approximately the same rapidity in reaching the control window.

As concern the ignition control, the comparison tests aimed to verify both the reliability of the system to ignite the air-fuel mixture and the instability of the combustions produced. For the first comparison, the observed parameter is the number of misfires detected within 200 consecutive engine cycles [18], while for the second comparison two different parameters have been taken into consideration: the Coefficient of Variation (COV) of the Indicated Mean Effective Pressure (IMEP, a fundamental parameter for the characterization of internal combustion engine performances, [19]) and the maximum value of the standard deviation of the in-cylinder pressure measured during the combustion process: both parameters, evaluated over 200 consecutive engine cycles, increase with the combustion instability.

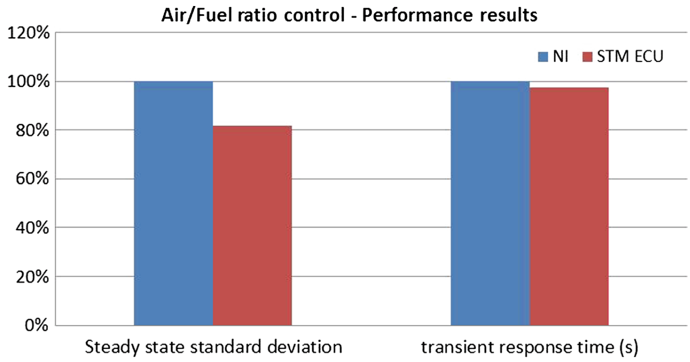
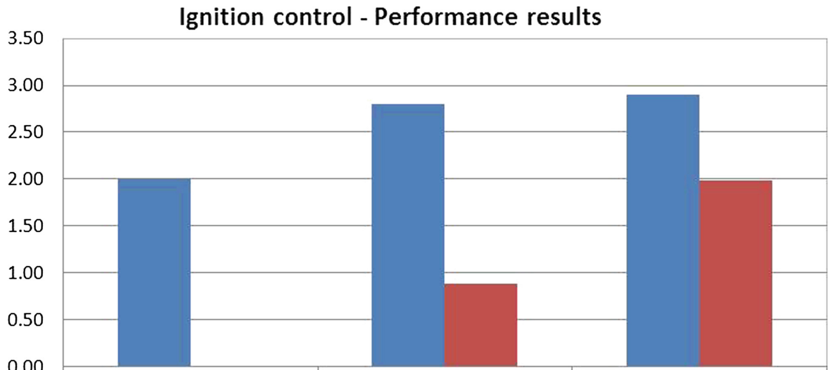


Fig. 4. Results of the Air/Fuel ratio control comparison test



	Misfire cycles (%)	Combustion instability - COV IMEP (%)	Combustion instability - pressure st. dev. (bar)
NI	2.00	2.80	2.90
STM ECU	0.00	0.88	1.99

Fig. 5. Results of the ignition control comparison test

As reported in Fig. 5, the developed ECU exhibited a very good reliability, with no misfires detected in the tests. Moreover, the ignition control performed by the ECU revealed also a remarkable lower instability, as resumed by the measured comparison parameters.

The adopted hardware configuration proved a good precision in the acquisition of the analog and digital signals tanks to the microcontroller's computing power; the battery, adequately charged via MAX1758chip, provided up to 8 h of operation thus allowing to work without connecting to the electricity grid and hence without the related electrical interferences; the communication with the PC was ensured by the Low Energy Bluetooth, while the interface with the user revealed very simple and intuitive, allowing to adequately set all the necessary operating parameters of the ECU and of the engine.

4 Conclusions

This work concerns the design and implementation of an electronic control unit for a CFR Bi-Fuel spark ignition engine, based on an ST-Nucleo development board. The designed ECU allows the user to precisely set up the ECU and engine operating parameters, through two different user interfaces:

- Interface with local display and keypad.
- Interface based on the Bluetooth communication protocol between the ECU and an host PC.
- a dedicated application has been created in order to implement the input parameters control view and a live visualization of the engine status from the host PC.

ECU was built with some tailored PCB boards that host all needed components for controlling proper engine operations and the correct acquisition of the analog and digital signals.

It was also developed the firmware for the acquisition of analog and digital signals for the generation of control pulses for the fuel injections and for loading of the ignition coil.

The total cost for the construction of the system is very low compared to other systems that offer the same characteristics.

References

1. Standard test method for motor octane number of spark-ignition engine fuel. ASTM International D2700
2. Douaud, A., Eyzat, P.: Four-octane-number method for predicting the anti-knock behavior of fuels and engines. SAE Technical Paper 780080, 1978. doi:10.4271/780080
3. Pipitone, E., Genchi, G.: Experimental determination of liquefied petroleum gas-gasoline mixtures knock resistance. J. Eng. Gas Turbines Power **136**(12), 121502/01–121502/07. doi:10.1115/1.4027831
4. Morganti, K., Foong, T., Brear, M., Da Silva, G., et al.: Design and analysis of a modified CFR engine for the octane rating of liquefied petroleum gases (LPG). SAE Int. J. Fuels Lubr. **7**(1), 283–300 (2014). doi:10.4271/2014-01-1474
5. Zamboni, G., Marelli, S., Marmorato, G., Capobianco, M.: An experimental apparatus for testing biodiesels based on a CFR engine—Setup and validation with different methyl ester blends. Int. J. Green Energy **13**(5), 481–488 (2016)
6. Kubesh, J., King, S., Liss, W.: Effect of gas composition on octane number of natural gas fuels. SAE Technical Paper 922359 (1992). doi:10.4271/922359
7. Pipitone, E., Beccari, S.: Calibration of a knock prediction model for the combustion of gasoline-natural gas mixtures. In: ASME Internal Combustion Engine Conference (ICEF 2009), pp. 191–197, September 2009, Lucerne, Switzerland. doi:10.1115/ICEF2009-14057
8. Iodice, P., Senatore, A.: Influence of ethanol-gasoline blended fuels on cold start emissions of a four-stroke motorcycle. Methodology and results. SAE Technical Paper 2013-24-0117 (2013). doi:10.4271/2013-24-0117

9. Genchi, G., Pipitone, E., Beccari, S., Piacentino, A.: Knock resistance increase through the addition of natural gas or LPG to gasoline: an experimental study. SAE Technical Paper 2013-24-0100 (2013). doi:10.4271/2013-24-0100
10. ST-Microelectronics. RM0368-Reference Manual STM32F401
11. Texas Instruments, CD4505B Types, Datasheet
12. Analog Devices, ADP5585, Datasheet
13. International-Rectifier, Datatsheet IRS4427
14. Maxim integrated, MAX1758, Datasheet
15. ST Microelectronics, AN4559-Developer's guide to creating Bluetooth® low energy applications using STM32 Nucleo and BlueNRG
16. Robert Bosch GmbH: Gasoline-Engine Management. Wiley (2006). ISBN 0470057572
17. Lenz, H.P.: Mixture Formation in Spark-Ignition Engines. Springer, Wien. ISBN 978-3-211-82331-6
18. Beccari, A., Beccari, S., Pipitone, E.: An analytical approach for the evaluation of the optimal combustion phase in spark ignition engines. J. Eng. Gas Turbines Power **132**(3) (2010). doi:10.1115/1.3155395
19. Heywood, J.B.: Internal Combustion Engines Fundamentals. McGraw-Hill Automotive Technology Series (1988). ISBN 0-07-100499-8