ENGINE CONTROL UNIT BASED ON THE NI COMPACTRIO PLATFORM

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SHRNUTÍ

Byla vyvinuta programovatelná řídicí jednotka na platformě CompactRIO s programem vytvořeným v prostředí LabVIEW. Jednotka byla vyvíjena jako univerzální a byla testována při řízení malého zážehového motoru YAMAHA YZF R6. Jednotka je dále použitelná pro zážehové motory různé koncepce, přepínané i nepřepínané. Požadavku na univerzálnost jednotky byl přizpůsoben řídicí program, který je uspořádán ve vzájemně komunikujících samostatných blocích. Zařízení je rozšiřitelné o další I/O moduly, což umožňuje použití dalších snímačů, aktuátorů nebo modulů pro komunikaci. Rozhraní pro zesílení výstupů napájejících zapalování a vstřikovače bylo vyvinuto pro řízení motoru YAMAHA YZF R6. Toto zařízení zároveň stabilizuje napájení snímačů motoru a filtruje jejich výstupní signály. Článek je shrnutím procesu vývoje řídicí jednotky motoru, obsahuje přehled použitých zařízení, seznamuje s řídicím programem a zkušenostmi z testování na motoru.

KLÍČOVÁ SLOVA: ŘÍDICÍ JEDNOTKA MOTORU, COMPACTRIO, LABVIEW

ABSTRACT

A programmable engine management system based on the NI CompactRIO platform and LabVIEW software was developed and used as an engine control unit (ECU) for a YAMAHA YZF R6. The unit was developed as a universal tool for engine control, and the unit has been tested on a test rig with a small gasoline engine, the Yamaha YZF R6. The unit is also applicable for gasoline engines, different concepts, supercharged and naturally aspirated. The universality of the unit is due to being adapted to a control program, which is arranged in separate mutually communicating blocks. The device is expandable with additional I / O modules, allowing the use of additional sensors, actuators, and communication modules. An interface for amplification of the CompactRIO outputs for ignition and injection has been developed for Yamaha YZF R6 engine control. This device also stabilizes voltage for sensors, and filters the output signals. The article is a summary of the development process for an engine control unit, and includes an overview of the equipment, introduces the control program and the experience of testing on the engine.

KEY WORDS: ENGINE CONTROL UNIT, COMPACTRIO, LABVIEW

1. MOTIVATION

Stock engines are widely used for research purposes as the base engines for further research and development of their components, optimization of their engine management and related experimental work. Experimental work on an IC engine usually requires changes in its engine control unit (ECU) data, particularly in cases where the engine management lacks any adaptive control. A standard used in automotive industry for ECU development is the ETAS INCA software [6]. This tool provides an integrated environment for measurement, ECU calibration and engine diagnostics. The cost of the software and the required hardware for ECU connection is beyond the budget of most institutions, such as universities and small research

centers. In some cases the ETAS system is more robust than is needed when the main objective is not the development of a completely new ECU for the automotive industry. On the other hand, there are many other programmable ECUs used mainly in motorsport, but these are not suited for research purposes because they have limited programming capabilities. The units usually have only editable tables, use predefined inputs and the options for choosing outputs are finite. Developing an ECU based on NI CompactRIO equipment was chosen as a solution which is cost effective. The new ECU provides the required flexibility, programming capabilities and independent control.

2. INTRODUCTION

The motorcycle engine YAMAHA YZF R6 was chosen for the developing and testing of a CompactRIO based ECU because this engine has simple electronics and engine control. The engine is also used in the CTU Formula Student car, and thus provides an opportunity to engage more students in the research work. However, the developed engine management system is usable for other engines as the system is graphically programmed using LabVIEW and the programming philosophy is user friendly. Figure 1 shows a schematic of YAMAHA YZF R6 engine management. The engine fuel system of the Yamaha YZF R6 engine comprises two groups of injectors, which are located in the intake manifold at different distances from the intake valve. The primary injectors (Fig. 1, link 1) operate across the entire engine speed range, while the secondary injectors deliver fuel

only at higher engine speeds. The secondary injectors are placed in the engine airbox. Such an arrangement is to ensure the delivery of a homogeneous mixture into the engine cylinder over the entire engine speed range, and fast engine response during transient operation. The volume of injected fuel is controlled by the time the injectors are opened. The injection duration and the injection timing are controlled by the ECU where default values of these variables are stored in the maps.

The injection duration is in general determined from the maps according to signals from the throttle position sensor (Fig. 1, link 2) or intake air pressure sensor (Fig. 1, link 7) and engine speed. The engine speed is determined from the signal of a crankshaft position sensor (Fig. 1, link 6). The outputs of coolant temperature sensor (Fig. 1, link 3), an atmospheric pressure sensor (Fig. 1, link 4), an air temperature sensor (Fig. 1, link 8) and an O₂ sensor (Fig. 1, link 9) are used for corrections of basic injection duration. The corrections extend or reduce the time duration depending on the ambient conditions, engine temperature, throttle position, engine speed changes and mixture quality. The injection timing is determined based on signals from the crankshaft position sensor (Fig. 1, link 6) and camshaft position sensor (Fig. 1, link 5).

The engine management system of the YAMAHA YZF R6 engine is specific because the amount of inducted air is not measured directly. In this way the system is similar to the old Bosch D-Jetronic engine management where a control unit determines an amount of a fuel to be injected depending on the amount of inducted air. The amount of inducted air is determined indirectly from measured intake manifold pressure and intake air temperature, engine speed and other factors. The basic fuel volume corresponding to an injection time duration is obtained on the basis of the air amount. The time duration of injection is further corrected depending on the evaluated throttle position and velocity of its position changes. The throttle position sensor indicates the position of the throttle, and the velocity of the position change is simultaneously evaluated. A rapid position change during throttle opening indicates an acceleration requirement, and this as well as wide open or closed throttle results in further correction of injection time duration. The precise control of injection is crucial for this engine because fast engine response to throttle changes is required. The original management of the YAMAHA YZF R6 engine is equipped with closed-loop control of the A/F mixture using the lambda sensor in the exhaust manifold.

FIGURE 1: YAMAHA YZF R6 engine management scheme [1],[3],[4],[5].

OBRAZEK 1: Schéma řízení motoru YAMAHA YZF R6.

- 1. Primary injectors • 2. Throttle position sensor • 3. Coolant temperature sensor • 4. Atmospheric pressure sensor • 5. Camshaft position sensor • 6. Crankshaft position sensor • 7. Intake air pressure sensor • 8. Air temperature sensor • 9. O₂ sensor • 10. Injection control • 11. Ignition control • 12. Control bridge • 13. Interface • 14. Voltage of sensors • 15. EFI Euro 4 ECU • 16. CompactRIO system (a-FPGA chassis NI9104, b- NI9012 real-time controller, c- module of outputs, d- module of inputs NI9201) • 17. LabVIEW software • 18. Information panel

3. NI COMPACTRIO CONFIGURATION

The developed engine management system combines in-house developed hardware with the modular programmable automation controller CompactRIO made by National Instruments. The

CompactRIO device combines a real-time controller, I/O modules and an FPGA chassis. Our equipment consists of the real-time controller NI9012, which features an industrial 400 MHz real-time processor for deterministic and reliable real-time applications. It contains 64 MB of DRAM memory and a minimum of 128 MB of nonvolatile storage. The module of inputs NI 9201 contains 8 analog inputs and it was used for the connection of output signals from the engine's sensors. The module NI-9478 controls outputs for engine management. The module contains 16 outputs with the option of loading one channel up to 5A, or up to 1.2A if all channels are used. The real time controller and the I/O modules are swapped in the chassis NI 9104 with an embedded field-programmable gate array (FPGA).

4. INTERFACE

The sensors for measurement of coolant temperature (Fig. 1, link 3), throttle angle (Fig. 1, link 2), atmospheric pressure (Fig. 1, link 4), intake air pressure sensor (Fig. 1, link 7), air temperature (Fig. 1, link 8), crankshaft position sensor (Fig. 1, link 6) and camshaft position sensor (Fig. 1, link 5) are connected to the NI9201 module via an in-house developed interface, see the schematic in Figure 2. The interface (Fig. 1, link 13) stabilizes the 5V voltage, which is used in the sensors, filters the sensors' outputs via RC filters and amplifies the CompactRIO outputs.

FIGURE 2: Schematic diagram of the interface connecting CompactRIO and the engine [1].

OBRAZEK 2: Schéma rozhraní spojujícího CompactRIO a motor [1].

5. FUEL INJECTION AND IGNITION TIMING

The engine's crankshaft and camshaft position are the main parameters for the control of ignition and fuel injection timing. Their values are determined from the position sensors, and one can calculate the engine speed and the top dead center position of a given piston. The sensors are connected via analog module NI 9201. The camshaft sensor has an output at TTL level and the crankshaft sensor generates analog derivative pulses of approximately $\pm 20V$.

There are embedded transistors for amplifying the current supply for injectors and ignition coils in the interface.

COP type induction coils and shower-type injectors consume a current of approximately 5A and 2A in the steady state. Such currents can also be switched by the output module CompactRIO units. The problem, however, is the derivative pulse which is generated by the coil when this is disconnected. The induced voltage value is over 100V. Appropriate energy must be converted into heat, which is achieved by strengthening the CompactRIO outputs using unipolar transistors and backward diodes. Adequate cooling is required for the transistors switching on the inductive coils, because when disconnecting the coils, the transistors are heated by the energy of the coils. Transistors for the injectors can be used without additional cooling. The transistors are covered with TO220 housings.

A 5V reference voltage is used by the analog pressure, temperature, camshaft and throttle position sensors. This voltage is stabilized by stabilizer 7805 covered with a TO220 case. The signals from the coolant temperature, pressure and throttle position sensors are filtered by 100 μF capacitors, which are connected in parallel with them. All wires are connected via screw terminals for easy installation. The board was designed with regard to the placement of coolers on the transistors. Coolers are placed on the transistors T1, T2, T7 and T8.

The crankshaft sensor is an inductive sensor which reads the position of the crankshaft gear consisting of 20 teeth and one extended length tooth via 4 teeth (24-4 configuration), see Figure 3. The TDC of the first and fourth cylinder indicates the rising edge of the seventh tooth after passing of the extended tooth through the inductive sensor. The TDC of the second and third cylinder indicates the rising edge of the nineteenth tooth after passing of the extended tooth through the inductive sensor. The camshaft sensor determines the firing TDC position of the second cylinder and the gas exchange TDC of the third cylinder, see Figure 3. The firing TDC of the second cylinder is used for

the determination of fuel injection and ignition timing because it sets a logical value of a RS circuit. The RS circuit takes values of LOG 1 or LOG 0 and it controls the application of injection or ignition via Table 1. The timing of injection and ignition is calculated as a delay from the TDC of a given cylinder.

Rising edge detection of the extended tooth takes place as follows: if the time between actual teeth is 2 times longer than the average time of the last 4 teeth, then an elongated tooth has passed. Averaging the time of the last 4 teeth also eliminates false detection of the extended tooth during engine acceleration.

FIGURE 3: The fuel injection and ignition timing scheme of the YAMAHA YZF R6 engine [1].

OBRAZĚK 3: Schéma časování zapalování a vstřikování paliva motoru YAMAHA YZF R6 [1].

Actuator	Tooth of crankshaft gear	RS circuit value
Injector 1	7	LOG 0
Injector 2	19	LOG 1
Injector 3	19	LOG 0
Injector 4	7	LOG 1
Ignition 1	19	LOG 0
Ignition 2	7	LOG 0
Ignition 3	7	LOG 1
Ignition 4	19	LOG 1

TABLE 1: Table of RS circuit values for timing of injection and ignition.

TABULKA 1: Tabulka hodnot RS obvodu pro časování vstřikování a zapalování.

6. NI LABVIEW BASED ECU SOFTWARE

Software for the ECU based on the CompactRIO was created in the graphical programming language NI LabVIEW. NI LabVIEW programming language is suitable for programming measuring equipment in laboratories, but the software can be programmed for any other applications and the developed code can be compiled into an executable file. The measuring device communicates over many types of interface. The network interface protocol TCP/IP was chosen for communication between the CompactRIO and the computer for which the software has been developed. The base software was developed as part of

a bachelor degree project [2]. Software for CompactRIO consists of two separated and mutually communicating programs. The first one is for the real-time controller NI9012, see its simplified schematic in Figure 5. The second one is for the FPGA, which is part of chassis NI9104, see its simplified schematic in Figure 5. The FPGA program must run synchronously with the running engine. This program applies values that are calculated in the controller. There are three main loops in the sample program, see Figure 4, which represent three main tasks of the FPGA. The first loop determines crankshaft and camshaft position from digital sensors for subsequent usage. The second loop senses data from analog sensors of throttle position, temperature and pressure, and sends them to the controller. The most important function is exact timing of injection and ignition, which is performed by the third loop. The timing is controlled on the basis of signals from camshaft and crankshaft sensors, because from these two signals it is possible to very accurately determine the position of the engine, see Figure 3.

The program for the controller reads data from the engine's sensors via analog module NI9201 and the FPGA program, see a sample of this program in Figure 5. The program acquires four main values – throttle position, temperature, engine speed and intake pressure. Calculation of the injection duration and ignition timing is based on linear interpolation from the maps, see Figure 5. Figure 5 shows maps of injection duration, spark advance and correction. Values in the maps depend on the throttle position or intake pressure and engine speed. Values looked up and interpolated from the maps are multiplied by correction factors ensuring compensation of engine temperature. Two main values result from this process – duration of fuel injection and spark advance. These values are sent to the FPGA, where they are exactly applied to the engine. The main algorithms of the controller program were described on the basis of the program sample, because Figure 5 showing the sample is clearer than it would be if it depicted the full program.

Nevertheless, the full program contains a map of injection position and a few loops for ensuring optimal A/F ratio of the mixture during various conditions, for example starting correction, air pressure and temperature correction, acceleration enrichment and engine speed limiter.

The controller program includes a front panel, see Figure 6. The front panel displays values of the engine sensors (throttle position, engine speed, intake air pressure and temperature, and engine temperature) and calculated values for the engine control (duration of injection, timing of injection and ignition).

FIGURE 6: Front panel of the controller program [1].

OBRÁZEK 6: Informační panel programu pro kontroler [1].

7. VERIFICATION OF THE CONTROL UNIT FUNCTIONS

The YAMAHA YZF R6 engine was placed on the test stand during verification of the CompactRIO based ECU. The engine was managed by programmable ECU EFI EURO 4. The fuel maps and the spark advance map in the ECU EFI Euro 4 were set up on the basis of torque measurement on the engine test stand. The lambda sensor was used for optimizing of the A/F ratio for each cylinder separately during this measurement.

The test stand was equipped with toggle switches that enable selection of which ECU controls the engine. The engine can be fully controlled by the functional configuration of the ECU EFI EURO 4, or the ECU based on the CompactRIO can take over engine control. 8 switches are used – 4 for injectors and 4 for ignition on the test stand for switching the ECUs, see Figure 1. Thus it is possible to control each cycle of each cylinder separately. Verification was done step by step, the engine was not loaded. Only one injector was driven at the beginning. When no difference in engine running was recognized, the control loop was applied for all injectors and the CompactRIO started to manage all the injectors.

The developed CompactRIO ECU handles control of the injectors very well, the unloaded engine was keep running at idle even at speeds around 10 000 rpm. The engine also ran properly for an extended period without overheating of the transistors in the interface. No unusual phenomena in the software were identified during entire engine running. The values of injection duration, its timing and spark advance were checked on the front panel, see Figure 6, during the test. These values were the same as in the case where the engine was controlled by the EFI ECU. This affirms correct calculation of the controller program. Correct application of the ECU's data on the engine has not yet been tested. The correct injection and ignition timing will be checked in forthcoming studies. The control of ignition coils has been tested in the same way. However, the control of ignition is somewhat complex, because there are much higher demands on controlling of ignition energy and spark timing. Ignition energy and spark timing depend on switching

on and off of the ignition coil. The main task is precise determination of switch-on time and dwell period for required engine speed. The engine has been running trouble free during testing at higher engine speed, but additional experimental work will be performed on setting up of the ignition control for low engine speed.

8. CONCLUSION

An engine control unit based on the NI CompactRIO was developed and tested on the running engine YAMAHA YZF R6. A suitable configuration of the NI CompactRIO has been designed consisting of the real-time controller, the analog input module for reading data from sensors, and the digital output module for engine control actuators (injectors, ignition coil).

The interface between the engine and the CompactRIO unit was built and successfully tested with the running engine. The power transistors need to be better cooled, or switching on by a steeper pulse has to be improved.

The test stand at the Josef Bozek Research Center of Engine and Automotive Engineering has been modified for engine management by two ECUs. Using switches, it is possible to select any combination of control of injectors and ignition coils for various of the engine's cylinders from the two different ECUs. The fuel injection system has been tested successfully and the tested engine has run at different engine speeds, although only without load. The CompactRIO is able to control engine ignition in general, but more work has to be done on setting up of the right switch-on time of the ignition coils.

LIST OF ABBREVIATIONS

ECU	engine control unit
TDC	top dead center
TTL	transistor – transistor logic
NI	National Instruments
FPGA	field-programmable gate array
INJ	injector
IC	ignition coil
COP	coil on plug
RS	reset-set

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