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Improving the energy efficiency of a two-stroke engine with crankcase scavenging for UAVs by implementing an electronic fuel injection system

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The article considers the use of an electronic fuel injection system as a way to increase the energy efficiency of a two-stroke piston engine with crank-chamber purge for UAVs. An analysis of publications reveals the advantages of injection over carburetor power systems, particularly increased power, reduced fuel consumption, and lower emissions of harmful substances. An electronic fuel injection system, based on a microcontroller electronic control unit with sensors (MAP, TPS, ECT, IAT, CKP) and actuators, has been developed. EFI Studio software has been implemented for system calibration and monitoring. The control algorithm is based on the Alpha-N method taking into account dead time and injection phase shift. A hardware implementation is presented that provides dosing accuracy and flexible control of engine operating modes. The results confirm the practical significance of the technology for increasing the efficiency and environmental friendliness of small UAV engines.

Key words: *UAV engine, two-stroke engine, electronic fuel injection, electronic control unit, energy efficiency*

1. Introduction

Recently, unmanned aerial vehicle (UAV) technologies have been rapidly advancing alongside the swift development of microelectronics and communication technologies. Compared to manned aircraft, UAVs typically have significantly smaller dimensions, lower weight, and are less demanding in terms of runway characteristics. They are also characterized by relatively low production and operational costs. As a result, UAVs are widely used in the military, geographic services, satellite operations, navigation, medicine, and other fields [10].

A key component of any UAV is its powerplant, which provides propulsion and supplies energy to onboard systems. Reciprocating engines are the most common type of propulsion for UAVs. These engines have several types, among which the two-stroke engines are the most common ones [15].

Two-stroke piston engines with crankcase-scavenged loop charging and spark-ignition of the air-fuel mixture are characterized by high specific power output and mechanical simplicity. These features have contributed to their widespread adoption in small- and medium-sized unmanned aerial vehicles (UAVs) [13, 15]. Numerous companies – such as 3W, Gobler Hirth, and Limbach in Germany; Wilksch in the United Kingdom; Zanzottera in Italy; and XRDi and DeltaHawk in the United States, as well as DLA in China – currently specialize in the production of this class of engines [17].

Flight endurance has increasingly been regarded as one of the most important technical parameters in evaluating UAV performance. Given the limited onboard fuel capacity of UAVs, their endurance is directly influenced by the thermodynamic efficiency of the propulsion system, i.e., the fuel consumption of the aircraft engine.

Unlike conventional four-stroke engines, which are equipped with complex valvetrain mechanisms, gas exchange in two-stroke engines is typically achieved by the movement of the piston itself. While this simplified scavenging mechanism facilitates engine design and manufacturing, it also results in lower volumetric efficiency and a substantial loss of the fresh charge from the cylinder during the scavenging process [4, 9, 19, 20, 24].

Thus, optimizing the working cycle of these engines remains a relevant engineering challenge. Improving engine performance necessitates the implementation of advanced technologies that enable effective control of combustion processes and, as a result, the realization of the engine's full potential. The integration of modern electronic fuel injection systems offers a promising approach to enhancing the operational characteristics of two-stroke engines. The replacement of traditional carburetion systems with electronic fuel injection (EFI) has become a focus of research for both academic institutions and engineering firms. While carburetors offer certain advantages, detailed analyses of their performance have revealed several limitations. These include high sensitivity to ambient environmental conditions, a tendency to flood, dependence on the physical properties of gasoline, and the risk of carburetor icing. For example, 3W International offers engine models equipped with either carburetor or EFI systems, emphasizing the advantages of EFI [1]. These include reduced fuel consumption, improved air-fuel mixture formation, enhanced power output, and more stable performance across varying engine orientations and environmental conditions. Moreover, EFI systems significantly reduce the dependency on the physical and chemical properties of gasoline (such as volatility), sensitivity to ambient conditions, and the risk of fuel condensation or intake manifold icing. This marks a substantial improvement over carbureted systems, which are more susceptible to these limitations.

Fuel injection serves as an alternative to carburetion for preparing the air-fuel mixture suitable for proper functioning of spark-ignition (SI) engines. Injection systems operate based on physical principles distinct from those of carburetors, both in terms of fuel metering and atomization within the air mass. Specifically, these systems meter fuel in proportion to the engine's air intake flow, relying not on the intake vacuum generated by the engine but on increased fuel pressure provided by a pump. Moreover, whereas in a carburetor fuel atomization is driven by the higher velocity of the intake air stream that entrains and breaks the fuel into progressively finer droplets. In an injection system, fuel is delivered at high velocity through a nozzle, producing a fine spray via kinetic atomization.

2. Literature review

The efficiency of the engine combustion process can be enhanced, and the flight endurance of UAVs can be extended, through the implementation of optimal fuel delivery control technologies. Consequently, an increasing number of researchers and engineers have turned their attention to the development and refinement of fuel supply systems for UAV engines [3, 6, 7, 12, 21, 22].

There is a general trend toward the adoption of electronic fuel injection (EFI) systems in two-stroke spark-ignition engines [12, 22]. Although fuel injection into the intake manifold of two-stroke engines does not eliminate fuel–air mixture losses during scavenging, it can improve overall engine performance due to more precise control of the air–fuel ratio. In general, EFI systems allow the engine to operate with leaner mixtures compared to carbureted systems. Another notable advantage is that fuel injection can provide up to 20% higher output power relative to a carbureted version. Moreover, hydrocarbon (HC) emissions are significantly lower across the full throttle range when using injection systems. For instance, in [12], which investigates the application of such an injection system in a two-stroke engine, an increase in power from 3.6 kW to 4.2 kW was observed, accompanied by a reduction in HC emissions from 2310 ppm to 1200 ppm. In [22], additional studies were conducted to improve the efficiency of UAV powerplants by employing intake manifold fuel injection. A fuel delivery strategy based on controlling the excess air coefficient (λ) was proposed, and a control algorithm using a PID regulator was implemented to mitigate deviations in λ under all engine operating conditions. As a result, the thermal efficiency of the cycle was improved by 5–25%. Other reported benefits of such systems include improved cold start behavior and enhanced engine controllability [3].

One method of reducing fuel loss through the exhaust ports is the use of resonant exhaust systems, as presented in [18]. However, due to UAV design constraints, integrating specific exhaust system geometries is not always feasible. Therefore, one promising approach to reducing, or potentially eliminating fuel losses during scavenging and minimizing hydrocarbon emissions in the exhaust gases involves the use of direct fuel injection into the engine cylinders [4, 7, 11, 13]. Nonetheless, due to the unique operating characteristics of two-stroke engines, implementing such a system significantly complicates the lubrication system. Perhaps the most representative contributions reflecting the current state of the art are those presented in [11, 13]. These studies employed high-pressure fuel injection systems similar to those used in diesel engines. While peak engine power was found to be nearly unaffected by the application of direct injection, there was a notable reduction in brake-specific fuel consumption (BSFC), reaching 300 g/kWh, compared to 370 g/kWh for the carbureted version. A similar pattern was observed for emissions: hydrocarbon emissions were reduced by 53%, and carbon monoxide (CO) emissions by 40% when using injection systems as compared to carburetors [13]. The effectiveness of direct fuel injection was further confirmed in [11] with the use of compressed natural gas, where the maximum brake thermal efficiency was increased by 9.1%, while unburned HC emissions were reduced by 79.3% and CO emissions by 94.5% compared to the carbureted engine.

The aim of this study is to implement measures aimed at improving the energy efficiency of a two-stroke engine with crankcase scavenging through the integration of an electronic fuel injection system.

3. Principle of fuel quantity calculation

Spark-ignition engines operate by combusting a premixed fuel–air charge. Accordingly, the primary function of the fuel supply system is to meter the appropriate amount of fuel required to achieve an optimal air–fuel ratio (AFR) in accordance with the engine's operating conditions. In principle, the optimal AFR for spark-ignition engines depends to some extent on the specific operating conditions. That is, it is defined as the ratio that ensures the required output power with the lowest possible fuel consumption, while maintaining uninterrupted and reliable engine operation.

Combustion of the fuel–air mixture in the cylinder of an internal combustion engine with spark ignition occurs only within a certain range of AFR, typically from 8.0 to 25.5. The stoichiometric ratio is approximately 14.7. Lean mixtures generally improve fuel economy, whereas rich mixtures tend to increase engine torque output. Enrichment of the air–fuel mixture can also be employed as a strategy to reduce combustion temperatures and prevent thermal overload during high-load operating modes (see Fig. 1).

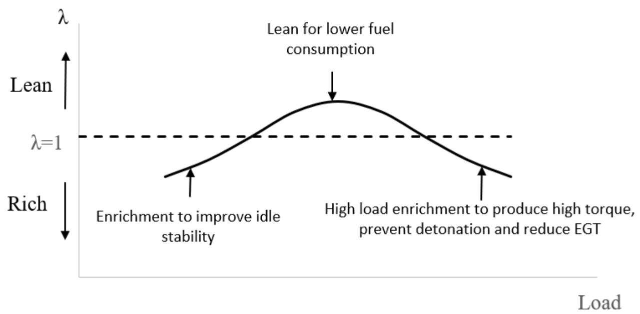

Fig. 1. Influence of the air–fuel mixture composition on engine operating modes

Therefore, depending on the specific operating conditions, it is necessary to find a compromise between competing requirements by selecting the value of the air–fuel equivalence ratio, λ, that yields the most favorable results. This implies that, for each point within the engine's operating range, it is possible to define, based on different performance requirements, the most appropriate value of λ, which the fuel supply system should aim to maintain.

Moreover, λ is defined as the ratio of the actual amount of air participating in the combustion process to the theoretical amount of air required for the complete combustion of the given quantity of fuel. It can be expressed as follows:

$$\lambda = \frac{m_{air}}{l_0 \cdot m_{fuel}} \tag{1}$$

where m_{air} is the mass of air that participates in the combustion of m_{fuel} kilograms of fuel.

The mass airflow rate in the intake manifold passing through the throttle valve is given by:

$$m_{air} = \frac{n \cdot V_h \cdot \rho_{air} \cdot \eta_v}{60} \tag{2}$$

where ρ_{air} is the air density in the intake manifold, n is the engine speed, V_h is the engine displacement volume, and η_v is the volumetric efficiency.

Since air density can be expressed as $\rho_{air} = P_{air}/(RT_{air})$, where P_{air} and T_{air} represent the pressure and temperature of the air in the intake manifold, and R is the specific gas constant, the equation can also be written as:

$$m_{air} = \frac{n \cdot V_h \cdot P_{air} \cdot \eta_v}{60 \cdot R \cdot T_{air}} \tag{3}$$

When the injector opens, fuel is delivered under high pressure, generating a fuel flow. The following equation can describe the fuel flow rate:

$$m_{fuel} = \mu S_{inj} \sqrt{2 \cdot g \cdot \rho_f (P_{fuel} - P_m) \cdot PW} \tag{4}$$

where $\dot{m}_{fuel}$ denotes the mass flow rate of fuel during a single injection event, μ is the injector discharge coefficient, S_{inj} represents the total area of the injector orifices, ρ_f is the fuel density, P_{fuel} is the fuel pressure, P_m is the intake manifold pressure, and PW is the fuel injection pulse width per engine cycle.

The following section considers the characteristics of well-known algorithms used to calculate the required amount of fuel based on input parameters received by the engine control unit (ECU).

MAF

According to this algorithm, the amount of injected fuel is calculated directly based on the input from the Mass Air Flow (MAF) sensor and the desired air-fuel ratio. Fuel injection systems employing this approach interpret the MAF sensor output as a direct representation of the engine's current air intake flow. This method enables a straightforward and intuitive calculation of the required fuel quantity and does not require specific calibration for each engine or its sensors. In this case, the engine load (volumetric efficiency) can be instantly determined as:

$$m_{air} = \frac{MAF}{V_h \cdot \rho_{air} \cdot n} \tag{5}$$

The required fuel mass flow rate can be determined using the following expression:

$$m_{fuel} = \frac{m_{air}}{AFR_{target}} \tag{6}$$

where AFR_{target} is the desired air-fuel ratio.

Speed Density

An alternative to direct measurement of the intake air flow is the estimation of air mass based on signals from other sensors, such as those measuring intake manifold pressure and air temperature. This fuel injection control strategy is referred to as the Speed-Density method [14] (Fig. 2). In this approach, the intake air flow rate is not measured directly. Instead, the mass of air entering the engine is calculated based on intake air temperature, manifold absolute pressure (MAP), and engine speed, using a reference volumetric efficiency (VE) table.

The volumetric efficiency of the engine is a parameter influenced by both operating conditions (such as crankshaft rotational speed and manifold pressure) and engine design characteristics (such as displacement volume, intake manifold geometry, and compression ratio). The primary VE table is typically defined as a two-dimensional function of manifold absolute pressure (MAP) and engine speed (RPM).

Based on the selected VE value, along with the measured MAP and intake air temperature, the engine control unit calculates the air mass entering the engine.

For a warmed-up engine, the air mass per cylinder per cycle ma is calculated using the following expression:

$$m_{air} = \eta_v(N) \cdot \rho_{air}(T, P) \cdot V_h = \frac{\eta_v \cdot V_h \cdot P_{air}}{R \cdot T_{air}} \tag{7}$$

After calculating the mass air flow entering the engine, the corresponding fuel mass flow rate can be determined. The primary limitation of this method lies in the necessity to develop or calibrate the VE table individually for each engine type. This requirement arises because the airflow velocity may exhibit similar values under different engine speeds and MAP sensor operating conditions. Therefore, it becomes essential to determine the steady-state values of the volumetric efficiency η_v across all regions of the VE table with sufficient accuracy.

Alpha-N

In the Alpha-N strategy, the air mass is calculated using an empirical map and is defined as follows:

$$m_{air} = VE(\alpha, N) \cdot V_h \cdot \rho_a(T, p) \tag{8}$$

In other words, the injector opening duration is calculated based on empirical correlations between the engine crankshaft speed and the throttle valve opening angle (Fig. 3). To improve accuracy, ambient air pressure and temperature are also taken into account.

For each of these primary algorithms, additional strategies for adjusting the injector opening duration may be implemented depending on the engine's operational model:

Percent Baro (Speed-Density + Atmospheric Pressure)

This strategy adjusts the volumetric efficiency based on an additional ambient atmospheric pressure sensor. Its application is particularly relevant for UAVs operating above 1000 meters, where air–fuel mixture correction becomes necessary.

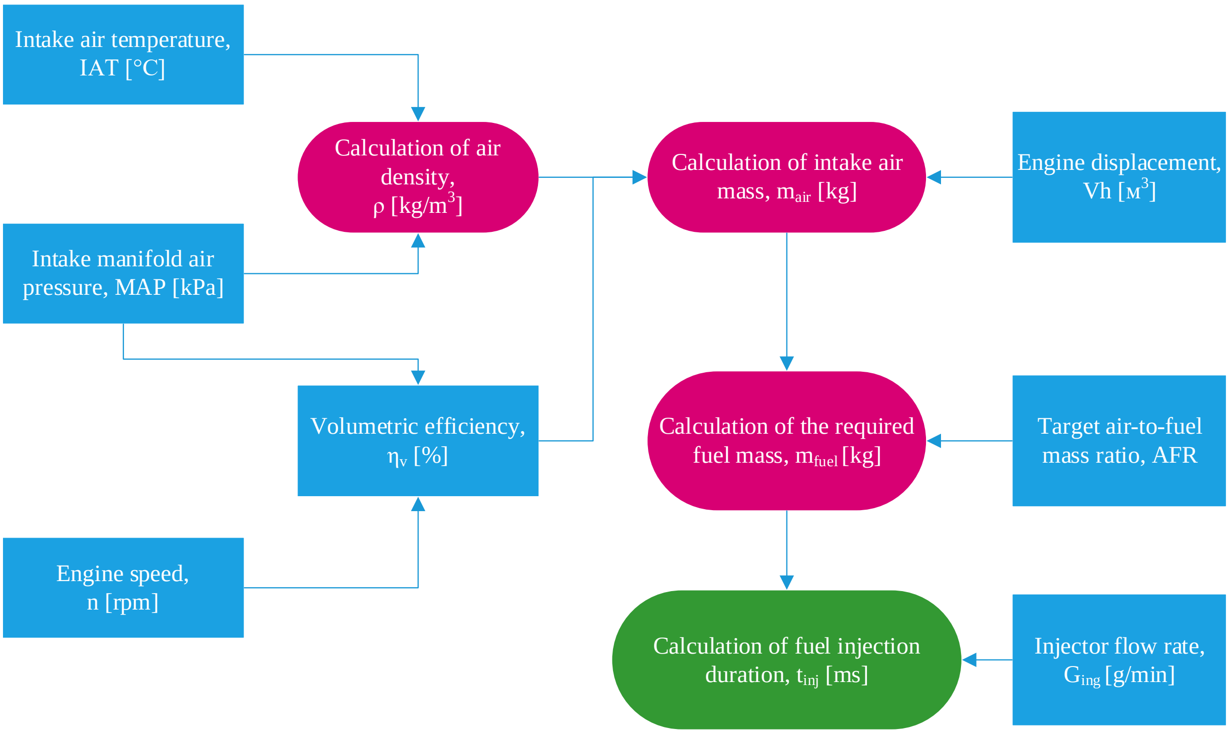

Fig. 2. Speed Density algorithm for calculating the required fuel quantity

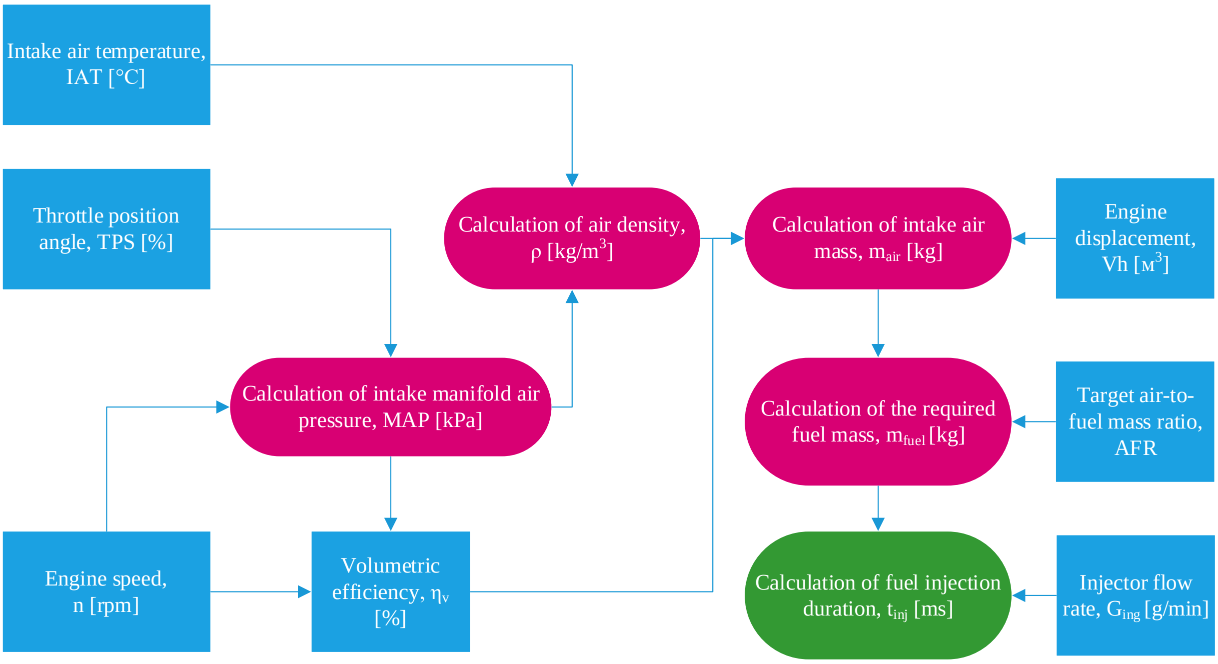

Fig. 3. Alpha-N algorithm for calculating the required fuel quantity

Lambda Feedback (Closed-Loop Control)

This method monitors the composition of the exhaust gases to fine-tune fuel injection in real time, ensuring the air–fuel ratio (AFR) remains close to the target value.

Transient Fuel Compensation

This adjustment controls fuel delivery during rapid throttle changes. It includes fuel enrichment during acceleration and fuel cut-off during deceleration.

Cold Start Enrichment

This strategy compensates for poor fuel vaporization at low temperatures by enriching the mixture during cold engine starts.

4. Implementation of the fuel injection system for a two-stroke UAV engine with crankcase scavenging

The fuel injection system must be capable of detecting changes in parameters that influence the optimal air–fuel ratio required by the engine and transmitting this information to the Electronic Control Unit (ECU). The ECU integrates the individual signals received from sensors and calculates the required amount of fuel m_{fuel} to be injected for a given engine operating mode.

Thus, in the fuel injection system, the primary control parameters that must be continuously monitored for accurate dosing are:

– Intake air flow rate, which serves as the fundamental input for calculating the mass of fuel to be injected
– Ambient air temperature and pressure, which influence air density and mixture formation
– Crankshaft rotational speed, which determines the injection frequency and the amount of fuel required per cycle
– Pressure differential Δp is maintained across the injector nozzle, which affects fuel atomization and delivery
– Throttle valve position, representing the engine load index which, in conjunction with crankshaft speed, allows the ECU to identify the appropriate value on predefined maps stored in memory
– Engine temperature is used for fuel delivery correction. During cold starts, increased injection duration is required. During engine warm-up, a temporary enrichment of the mixture is applied, depending on the engine temperature.

The developed electronic fuel injection unit is a microcontroller-based system that reads sensor data from the engine and generates an actuation signal for the injector, which is installed in the engine's intake manifold. The required pulse width for injector opening duration is computed based on lookup tables and constants stored in the microcontroller's memory.

A block diagram of the fuel injection control unit is shown in Fig. 4. Functionally, the system consists of a fuel injection control unit, a set of sensors (including the throttle position sensor (TPS), engine temperature sensor (CHT), manifold absolute pressure (MAP) sensor, intake air temperature (IAT) sensor, and crankshaft position sensor), and actuators (a fuel pump with a pressure regulator and injectors).

Figure 5 presents the schematic diagram of the fuel injection control unit. The control unit comprises the following components: an 8-bit microcontroller (ATmega328P) with digital input/output ports and a 10-bit analog-to-digital converter (ADC); an interface IC for actuator control (MC33812); a CAN bus module for bidirectional data exchange; and signal conditioning and input protection circuitry for the microcontroller.

The design of the printed circuit board (Fig. 6) is based on the use of the MC33812 integrated circuit [16], which was specifically developed by NXP for control units in 2-stroke and 4-stroke engine applications. This chip integrates a voltage regulator and actuator drivers, and includes diagnostic functionality to detect faults such as open or short circuits in the actuators.

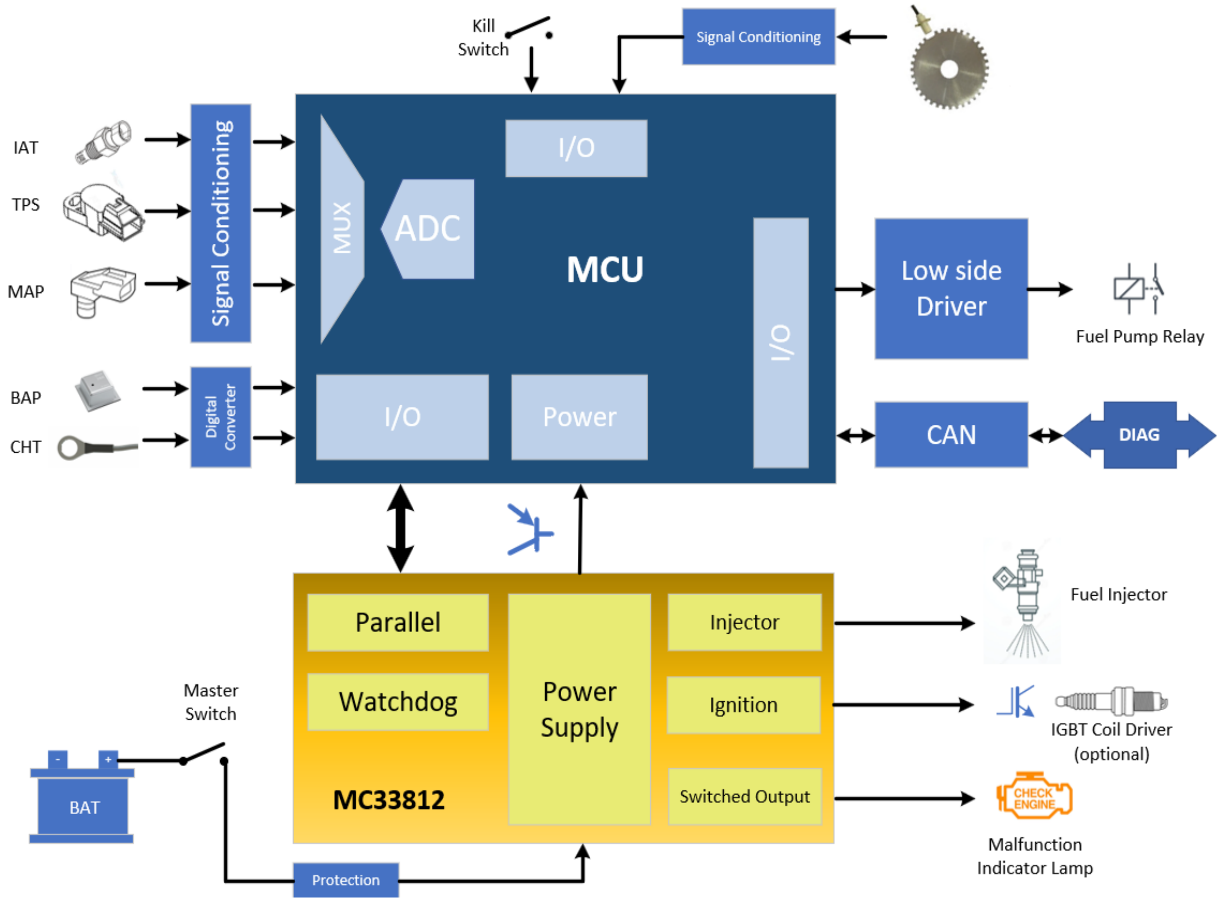

Fig. 4. Block diagram of the electronic fuel injection control system

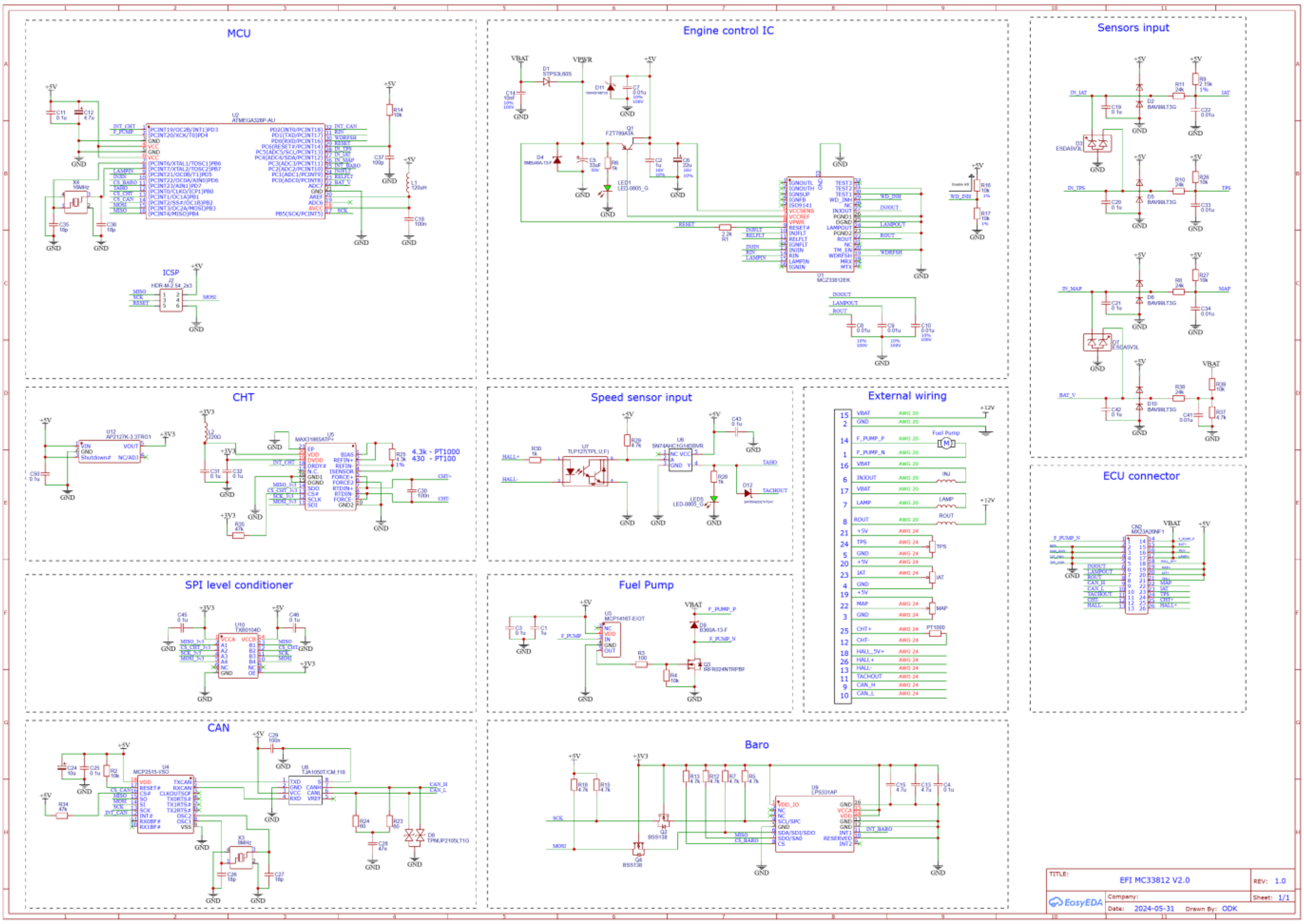

Fig. 5. Schematic diagram of the electronic fuel injection control unit

A platinum PT100 sensor is used as the engine cylinder temperature sensor (CHT). Its characteristics enable high-accuracy temperature measurements across a wide operating range from –50°C to +400°C. The MAX31865 [2] resistance-to-digital converter is employed for signal conditioning. In addition to high-precision resistance measurements, this chip supports diagnostics for sensor disconnection and short circuits. It includes a DRDY (Data Ready) output to indicate the completion of conversion and readiness of data for reading.

The fuel injection control unit is equipped with a barometric pressure sensor for altitude-based correction of fuel delivery. This sensor is implemented using the LPS331AP integrated circuit. It interfaces with the main microcontroller via SPI and includes a dedicated INT1 interrupt output to signal data readiness.

Since the ATmega328P microcontroller does not include a built-in CAN interface, this functionality is provided by two external components: the MCP2515 CAN controller and the TJA1050T transceiver. By utilizing the SPI interface and structuring data as 1–4 byte packets per variable (including floating-point types), high data transfer speeds are achieved, minimizing delays in the main program during data transmission or reception.

The microcontroller's crankshaft position sensor (CKP) input is galvanically isolated via an optocoupler and further equipped with a Schmitt-trigger buffer to suppress electromagnetic interference.

Fig. 6. External view of the developed printed circuit board design for the fuel injection control unit

To configure the parameters of the fuel injection control unit, the EFI Studio software was developed within the LabVIEW environment. The software interface is shown in Fig. 7. This software enables diagnostics of the control unit, sensor calibration, real-time monitoring of parameters, and, most importantly, modification of the settings of tables and constants necessary for calculating the fuel injection duration, including:

- Engine displacement, cm³
- Injector flow rate, g/min
- VE table (n, TPS) – volumetric efficiency coefficient depending on engine speed and throttle position
- AFR table (n, TPS) – required air-fuel ratio depending on engine speed and throttle opening angle
- Correction coefficient tables: cor_IAT(IAT), cor_CHT(CHT), cor_Baro(Baro) – correction factors for intake air temperature, cylinder head temperature, and barometric pressure, respectively
- mult_start table (N_cycle) – enrichment coefficient during cold start
- DT = f(V_bat) table – injection duration correction map accounting for power supply voltage drop.

The algorithm for calculating the engine crankshaft speed utilizes the microcontroller's hardware features. For this purpose, the 16-bit timer/counter is configured in input capture mode. The filtered signal is fed to the microcontroller's ICP1 (Input Capture Pin). When a rising edge is detected, the current timer value is latched and copied into the ICR1 register, triggering an interrupt. During the first interrupt call, the ICR1 register value is stored; during the second call, the difference between the current and previous timer values is calculated. Since the timer continues running and is not reset, an overflow interrupt is used to count the number of full timer cycles. This overflow count is taken into account in the RPM calculation.

The primary advantage of this method is its high measurement accuracy, as signal capture occurs immediately upon detection, independent of the main program's execution.

The required fuel amount is calculated using the Alpha-N method described above. This method was selected based on the operating characteristics of the UAV engine, which runs mostly at throttle openings close to maximum during flight. Therefore, the Alpha-N strategy offers an advantage due to its simple implementation and good response to acceleration and deceleration.

Upon powering the EFI control unit, the fuel pump is briefly activated to pressurize the fuel rail. When the first crankshaft position sensor (CKP) pulse is received, a priming fuel injection occurs. The amount of fuel injected is determined from a table based on the engine cylinder temperature.

To generate the injector control signal, two timers are used. One timer controls the injection duration, while the other manages the injection phase shift relative to the CKP signal.

The core of the control program is a state machine, which coordinates and manages the operating modes of the electronic control unit. Its main task is to ensure a consistent transition between modes such as "normal operation", "startup mode," and "programming/debugging mode".

Figure 8 shows an oscilloscope trace of current and voltage at the injector terminals. From this waveform, it can be concluded that when controlling fuel injectors, it is necessary to consider the so-called dead time – the delay between the application of the electrical pulse and the actual start of fuel injection. This delay depends on supply voltage and the physical characteristics of the injector, and it significantly affects fuel metering accuracy. Neglecting this delay can lead to enrichment or enleanment of the air-fuel mixture, especially in operating modes with short injection durations. Since the dead time is independent of the injection duration and is a function of the injector's electrical characteristics (under constant fuel pressure), it should be treated as an additive constant, which is added on top of the other multiplicative factors [23].

5. Conclusions

1. The use of two-stroke engines as the powerplant for UAVs is considered the most promising due to their simple design and high specific power characteristics.

2. The efficiency of the engine combustion process can be improved, and the UAV flight duration extended, through the use of electronic fuel injection (EFI) systems.

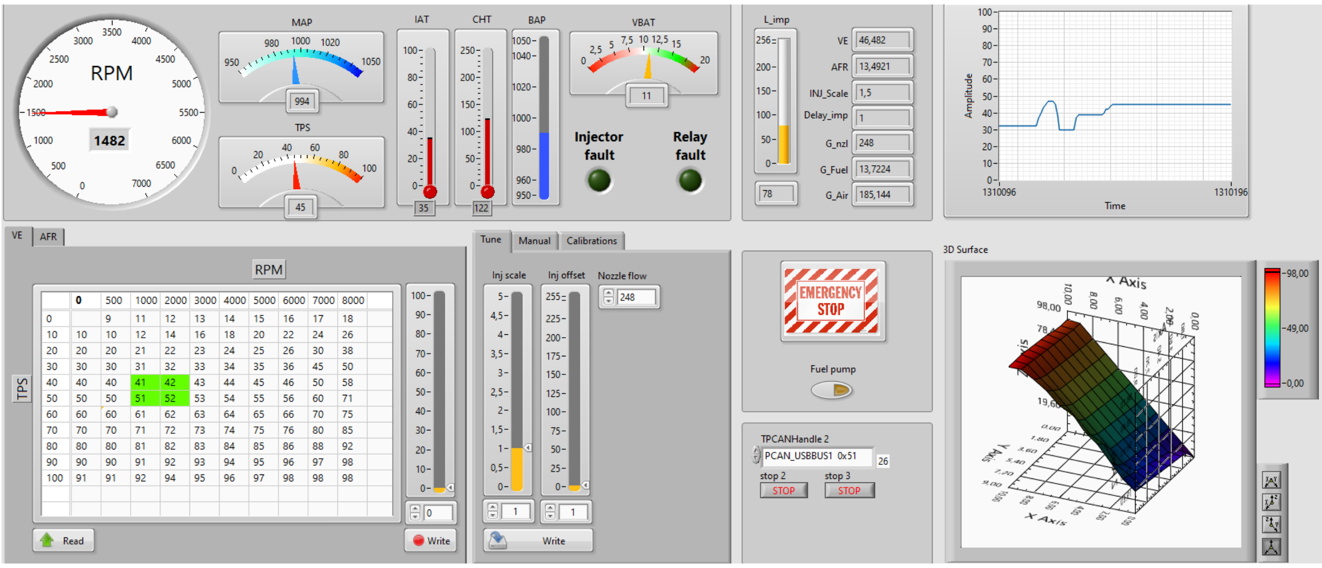

Fig. 7. Interface of the developed EFI Studio software

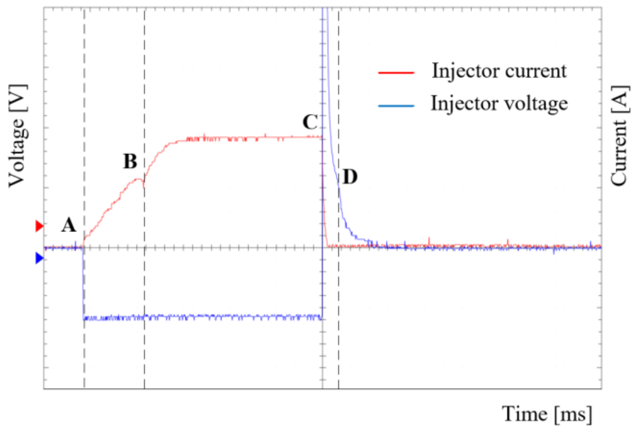

Fig. 8. Oscillogram of the injector control signal; AB – injector opening, BC – fully open nozzle, CD – injector closing, AC – EFI control pulse

3. One of the most effective methods for reducing or even eliminating fuel losses through the exhaust port during scavenging, as well as for decreasing hydrocarbon emissions in two-stroke engines, is the implementation of direct fuel injection into the cylinders. However, given the operating specifics of a two-stroke engine, such an approach significantly complicates the lubrication system.

4. Within the framework of this study, an electronic fuel injection control unit was developed for a two-stroke engine with crankcase scavenging. The unit includes an 8-bit ATmega328P microcontroller, an MC33812 interface IC for actuator control, a CAN bus module for bidirectional data exchange, signal conditioning circuits, and input protection for the microcontroller.

5. Since the UAV engine operates mostly at wide open throttle during flight, the Alpha-N algorithm was selected for fuel quantity calculation.

6. Dedicated software called EFI Studio was developed in the LabView environment to configure the parameters of the EFI control unit.

7. A current and voltage oscilloscope trace at the injector terminals was obtained for one of the operating modes, confirming the functionality of the developed electronic control unit.

8. The next stage of research will focus on testing the developed injection system directly on a two-stroke internal combustion engine, with an assessment of the efficiency and environmental characteristics of the fuel-injected engine in comparison to the carbureted version.

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Nomenclature

AFR	air-fuel ratio
BSFC	brake-specific fuel consumption
CKP	crankshaft position
CO	carbon monoxide
ECU	engine control unit
EFI	electronic fuel injection
HC	hydrocarbon
IAT	intake air temperature
MAF	mass Air Flow
MAP	manifold absolute pressure
SI	spark ignition
TPS	throttle position sensor
UAV	unmanned aerial vehicles
VE	volumetric efficiency

Bibliography

[1] 3W-International’s performance partner sky power releases new injection and ignition system. UAS Weekly; 2018 Apr 6. https://uasweekly.com/2018/04/06/3w-internationals-performance-partner-sky-power-release-new-injection-and-ignition-system/ (accessed on 2025.09.24)

[2] Analog Devices. MAX31865 RTD-to-digital converter. Data sheet. https://www.analog.com/media/en/technical-documentation/data-sheets/max31865.pdf

[3] Archer M, Bell G. Advanced electronic fuel injection systems – an emissions solution for both 2- and 4-stroke small vehicle engines. SAE Technical Paper 2001-26-0010. 2001. https://doi.org/10.4271/2001-26-0010

[4] Blair G. Design and simulation of two-stroke engines. SAE International 1996:623.

[5] Blyenburg & Co. UAS Yearbook: Unmanned aircraft systems – the global perspective 2010/2011. Paris 2010:214. http://www.dcabr.org.br/download/cursos-eventos/eventos/eventos-realizados/2010/seminario-vant-27-10-2010/cd-uvs-yearbook/

[6] Darwin RB, Purwoko AT, Sopiyan. Design and experiment of a prototype electronic control unit direct injection fuel system arduino-based for 2-stroke spark ignition engine. Automotive Experiences. 2022;5(1):49-56. https://doi.org/10.31603/ae.5472

[7] Darzi M, Johnson D, Ulishney C, Clark N. Low pressure direct injection strategies effect on a small SI natural gas two-stroke engine’s energy distribution and emissions. Appl Energy. 2018;230:1585-1602. https://doi.org/10.1016/j.apenergy.2018.09.091

[8] Hassanalian M, Rice D, Abdelkef A. Evolution of space drones for planetary exploration: a review. Prog Aerosp Sci. 2017;97:61-105. https://doi.org/10.1016/j.paerosci.2018.01.003

[9] Heywood JB. Internal combustion engine fundamentals. New York: McGraw-Hill 1988.

[10] Kolisnyk K, Kartashov V, Tomashevskyi R, Kolisnyk V, Koval S, Zamiatin P. The use of drones to improve the efficiency of using telemedicine systems in emergencies. 2022 IEEE 3rd KhPI Week on Advanced Technology (KhPIWeek); 2022 Kharkiv. https://doi.org/10.1109/KhPIWeek57572.2022.9916362

[11] Kumarappa S, Prabhukumar GP. Improving the performance of two stroke spark ignition engine by direct electronic CNG

injection. Jordan Journal of Mechanical and Industrial Engineering. 2008;2:169-174.

[12] Loganathan M, Manivannan PV, Ramesh A. Investigations on performance and emissions of a two-stroke SI engine fitted with a manifold injection system. Indian Journal of Engineering & Materials Sciences. 2006;13:95-102.

[13] Marouf M, Mursaleen M, Saad P. Investigations on two stroke cycle spark ignition engine using gasoline direct injection. Energy and Power. 2012;2(7):116-122.

[14] Meng L, Luo J, Yang X, Zeng C. Intake air mass observer design based on extended Kalman filter for air-fuel ratio control on SI engine. Energies. 2019; 12(18):3444. https://doi.org/10.3390/en12183444

[15] Newcome LR. Unmanned aviation: a brief history of unmanned aerial vehicles. Reston (VA): AIAA 2004.

[16] NXP Semiconductors. Multifunctional ignition and injector driver 33812. Data sheet. https://www.nxp.com/docs/en/data-sheet/MC33812.pdf

[17] Obodets DK. Modern trends in the development of unmanned aerial vehicle engines. Aviation and Space Technology. 2024;5(199):27-38.

[18] Obodeh O, Otunuya AD. Improving the performance of two-stroke motorcycle with tuned adjustable exhaust pipe. Research Journal of Applied Sciences. Engineering and Technology. 2009;1(2):59-65.

[19] Sapate KD, Tikekar AN. Pollution aspects of emissions from small two-stroke automobile engines. Nat Env Poll Tech. 2008;7(1):33-38.

[20] Volckens J, Olson DA, Hays MD. Carbonaceous species emitted from handheld two-stroke engines. Atmos Environ. 2008;42(6);1239-1248.

[21] Wang Y, Shi Y, Cai M, Xu W, Zhang J, Zhong W. Optimization of fuel injection control system of two-stroke aeroengine of UAV. Complexity. 2020;8921320. https://doi.org/10.1155/2020/8921320

[22] Wang Y, Shi Y, Cai M, Xu W, Yu Q. Efficiency optimized fuel supply strategy of aircraft engine based on air-fuel ratio control. Chinese Journal of Aeronautics. 2019;32(2):489-498. https://doi.org/10.1016/j.cja.2018.10.002

[23] Więcławski K, Mączak J, Szczurowski K. Electric current characteristics of the injector generating fuel doses. Diagnostyka. 2018;19(4):59-64. https://doi.org/10.29354/diag/97225

[24] Wróblewski P, Bratkowski P, Borcuch D, Kiszkowiak Ł. Prototype station dedicated to aircraft engine propeller profiles and advanced materials testing. Combustion Engines. 2025;201(2):165-175. https://doi.org/10.19206/CE-204319

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