Integrated Control Systems in Modern Automobiles

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Abstract- This work presents an overview of an automotive control, which is the means by which different systems and subsystems in an automobile is controlled to achieve a coordinated operation of the vehicle. Special emphasis was made on electronic control in automotive, which is carried out by an Electronic Control Unit (ECU). There are many types of ECUs in a modern automobile, these ECUs control different systems while still interact with each other. ECUs are made up different basic functional parts, these parts include; sensors, actuators, analogue-digital converters, microcontrollers, communication links to other ECUs, a firmware etc. These parts come together to make the control of automobile efficient electronically.

Indexed Terms- ECU (Electronic Control Unit), ECM (Engine Control Module), ABS (Anti-Lock Brake System), RTOS (Real-Time Operating System)

I. AUTOMOTIVE CONTROL

Automotive which also stands for automobile is a complex machine or vehicle that is used primarily to transport passengers over a distance on land usually on four wheels and it is powered most times by an internal combustion engine [1]. Automobiles are complex machines that a divided into smaller or simpler subsystems that work together to achieve the main aim of transporting passengers over a distance.

Automobile different subsystems are put together into one general system to fulfill the main aim; this is possible by the help of the automotive control system [2]. Automotive control is the mechanism or process of systematically making the different parts of an automobile function as one unit according to design range [2]. Apart from just moving passengers from one point to the other, modern automobiles are expected to meet to up to some certain standards, example automobiles are expected to meet up to a strict emission level and to do this stringent controls are embedded in the engines of these auto mobiles which are controlled by the Engine control module (ECM) [3].

The control of automobiles was initially done mechanically. With the development of human society, control of automobiles has been gradually replaced with modern automotive electronics technology and better vehicle integration. This replacement is been caused by higher requirements concerning environmental performance of vehicles, unresolved issues concerning vehicle functions, and needs [4]. The use of electronics in various aspects of automobile control does not only improve the vehicles comfort, driving stability, economy, power and security, it has also made the development of the automobile industry better.

From the mid-1990s to 2010, there was significant development in engineering technology, particularly in the field of automotive electronics. The industry now provides highly advanced, very functional, and stable power supplies, sensors, large-capacity memory, and microprocessors. These advancements have allowed for a more coordinated approach to the overall design of automotive mechatronic systems. Focus has shifted toward enhancing automotive electronic control technology to address the automation of vehicle components. The widespread use of computer networks and information technology has furthered the automation and intelligence of vehicles, integrating automotive technology more closely with societal needs and addressing issues related to transportation [5].

II. ELECTRONIC CONTROL UNIT (ECU)

An Electronic control unit is an embedded computer in an automobile that controls different mechanical and electrical subsystems in a vehicle [3]. For an ECU to function properly it makes use of signals from sensors as input to know the current condition of the vehicle and sends out the appropriate signal to actuators to control different operation of the vehicle [6]. ECUs are made up of parts such as microcontroller, static random access memory (SRAM), Electrically Erasable programmable read only memory (EEPROM), input for power supply, signal input from sensors and a communication link to other ECUs and the mother ECU. Typical structure of an ECU and its functional parts are shown in figure 1, the functional parts will be discussed later. A mother ECU (MECU) can be likened to the central control ECU in an automobile. It is a special kind of ECU, which has more computational power, more memory, and more bus size than other ECUs in the vehicle. Every ECU in an automotive has a specific function it coordinates, but all ECUs communicate with each other in an organized manner in order to ensure that their general operations are properly coordinated. For other ECUs to communicate with each other they make use of the communication link provided by the Mother ECU [7]. The MECU play more of a supervisory role in automobile control, other ECUs are under its control making it possible for it to deactivate another ECU at any given time [8]. Applications which must be available during the operation of the automobile are integrated into the MECU, therefore the MECU is more reliable than traditional ECUs [6].

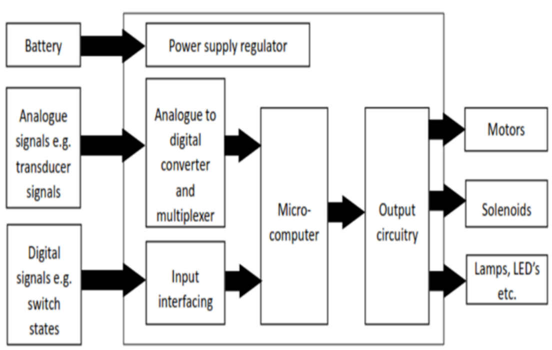

Figure 1: Functional parts of a typical automotive control system.

III. APPLICATION OF AUTOMOTIVE ELECTRONIC CONTROL

Modern automobiles employ the use of electronic control units to regulate how different systems and subsystems operate. These control systems make use of accurate reading of signals sent by sensors to the specific ECUs before they are processed and sent out to the corresponding actuators. Electronic controls in automobiles are commonly applied in these systems in an automobile.

- Anti-lock brake control:

The all-important automotive safety device anti-lock brake system (ABS) prevents the wheels from locking when brake of a car is depressed hard, thus effectively avoiding accidents. This system optimizes the grip between the tire and the road, significantly enhancing the vehicle's braking capabilities to prevent risks like skidding and drifting. It improves directional stability and maneuverability, effectively reducing the braking distance and substantially boosting overall braking performance [4]. The system operates by measuring wheel speed and sending pulses to activate and deactivate the main brake system.

- The automatic electronically controlled transmission:

The electronic control system of the automatic transmission utilizes sensors to measure the degree of throttle opening and the vehicle's speed. These measurements are converted into electrical signals and transmitted to the Electronic Control Unit (ECU). Based on these inputs, the ECU adjusts the solenoid valves according to a pre-determined shift schedule, thereby controlling the hydraulic circuit. This precise control of the hydraulic system enables accurate adjustments of the vehicle's transmission ratio, optimizing both the timing and quality of gear shifts for peak performance. This makes the vehicle have low fuel consumption, high precision, better power transfer efficiency, extended service life and improve shifting comfort.

- Suspension system control:

The suspension system control function dynamically adjusts the damping and elastic stiffness of the suspension based on varying road conditions and how the vehicle is being operated. This automatic adjustment enhances vehicle handling, stability, and both the comfort and smoothness of the ride. The applications of this technology are divided into two categories: active suspension and semi-active suspension.

- Engine control module (ECM):

Engine control module in most literatures is also called engine control unit (ECU). ECM is an embedded system that adjusts and controls how an internal combustion engine operates. The ECM controls the engine operation by determining the right air-fuel injection ratio, the idle speed of the engine, and the various valve timing in the engine. The operation and control of an internal combustion engine is represented in figure 2, which shows the engine functional parts connected to the ECM [9]. Input signals for the ECM come from different sensors as shown in figure 2.

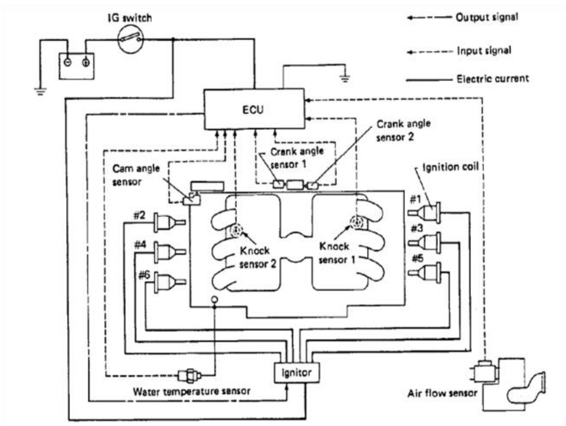

Figure 2: Subaru SVX Engine Circuit Diagram

Engine control module cover the electronic ignition advance control, the electronic fuel injection system, exhaust gas recirculation control, idle speed control, knocking control, the self-diagnostic and back-up systems. Electronic engine control module; maximizes the power of the engine, improves the engine running economy, minimizes emission of harmful substances by the vehicle.

a) The ignition timing control: This takes control of when the air fuel mixture is ignited in the engine cylinder and it is very essential to prolong the life of the engine, improve economy, reduce vibration, and increase power. To properly know then to induce the spark that ignites the air fuel mixture, the speed of engine rotation is used to determine the right time to send signal for the spark plug to ignite. The ignition timing control varies according to the engine rotation per minute (RPM) and the engine load. The firing time can be retarded or advanced depending on the driving condition and pattern. Earlier vehicles control ignition timing using distributors, but modern vehicles do so according to timing map on the ECM.

b) The fuel injection control: For an internal combustion engine to operate efficiently, the right amount of fuel must be supplied at the right time. The massive air flow sensor measures the amount of air that flows into the engine, the appropriate fuel ratio is determined and is supplied into the combustion chamber through the injectors. Injectors are operated by electric signals from the ECM that come in form of pulses, the width of the pulse determines the quantity of fuel to be supplied.

c) The idle speed control: Presently in the control of gasoline engine idle speed, centralized control of the idle speed control system is widely used. The main component that controls the idle speed of the engine in conjunction with the ECU signals is the idle air control valve (IACV). This valve maintains constant engine idle speed despite load by regulating the amount of air that flows through according to the signals from the ECM. This control prevents engine stalling when different loads are added to the vehicle.

Every other control unit or module in an automobile has the same basic functional makeup as the engine control module. The major differences between each module according to their function are computational capacity of the microcontroller, the size of memory, program, input sensors and actuators.

- Sensor

Sensors are devices that can pick different types of energy signatures and convert them to the appropriate electrical signals that can be measured by the ECM in automobiles. Sensors are very important in automotive control; sensor readings are the first step in automotive control. The present state of automobiles is obtained through sensor readings, it's these readings that the ECM knows how much compensation is required in any area before the desirable state is reached. Sensors pick up different energy signals and convert them to the appropriate electrical signal for the ECM to work with. The decision-making component of the ECU is a microcontroller, while most sensors give signals that are in analogue form. For the sensor to communicate properly with the microcontroller, an analogue-digital converter is needed. This converter, as the name goes converts the analogue signals from sensor to digital signals that can be fed into the microcontroller.

- Actuators

These are devices that respond to electrical signals from the electronic control unit to vary any operational parameter of the vehicle in order to achieve a desired state. Actuators mostly come in the form of motors, solenoid, switches and light. For actuators to be able carry out the task as sent by the ECU, a digital-analogue converter is employed. The digital analogue converts the digital signal from the microcontroller to analogue signals that can be understood by the actuators. Typical examples include radiator fan relay, injectors, idle air control valve, variable valve timing solenoid, airbag relays etc.

- Microcontroller

A microcontroller is a compact chip designed for embedded systems. Typically, microcontrollers operate at varying clock rate frequencies and process data in four-bit expressions. Common components of these devices include an 8-bit or 16-bit microprocessor, flash memory, and programmable read-only memory (PROM). They also feature a range of both serial and parallel input/output options, signal generators, timers, as well as analog-to-digital and digital-to-analog converters. These parts of a microcontroller enable it to be able to receive signals, process it according to program stored in it and send out the appropriate result.

The use of microcontrollers in the operation of automobiles has increased significantly due to the onset of increasingly complex electrical systems, applications, and processing needs of the modern-day automobile. Devices ranging from large equipment to smaller equipment, such as computers, air conditioning units, airplanes, ships, automobiles and even small cell phones employ the use of microcontrollers.

Microcontrollers are crucial components in modern automobiles, significantly influencing the functionality and sophistication of the vehicle. In a typical Ford vehicle, for example, there are between 25 to 35 electronic control units (ECUs), whereas luxury cars like the BMW seven series may have between 60 to 65 ECUs.

These microcontrollers oversee various ECU functions including:

- Seat adjustments
- Power windows
- Braking systems
- Steering mechanisms
- Taillights and headlights

The role of microcontrollers in automotive electronics is expanding, as evidenced by the diversity of units such as the AVR, 8051, and PIC microcontrollers. These devices typically contain a CPU, RAM (random-access memory), program memory, and programmable inputs/outputs, supporting a range from 8-bit to 32-bit Harvard architecture. This allows for low-cost yet high-performance CPU options and efficient data storage.

Furthermore, microcontrollers in automobiles can communicate with each other through multiplexing, enabling them to manage related systems independently. They use a BUS to communicate with other networks for specific functions. The integration of these systems forms networks like the CAN (controller area network), which supports complex interactions such as:

- Sensory systems monitoring
- Speed regulation
- Environmental adjustments like air conditioning based on outdoor conditions and in-car temperature
- Multimedia systems management
- Braking mechanisms

This networked approach enhances vehicle performance and user experience by allowing for coordinated control across various systems.

- ECU Firmware

ECUs are embedded systems that function according to the sequence coded into them. ECU firmware are those set of programs etched into the microcontroller of the electronic control unit, they are programmed to give instructions on how each unit controls a system or subsystem while communicating with other ECUs in an automobile. Despite the large the size of codes for ECU programming, the need to ensure the safety and optimal operation of automobiles has ensured that ECU programming is up to speed with the latest embedded system programing. Modern automobiles have up to 40,000,000 lines of codes, when all the units are put together [11]. Different programming ways of programming an ECU are thus.

- Sequential Programming: In sequential programming, the operations within an embedded system are predetermined to occur in a specific sequence, typically managed through timing or resource constraints that delay execution until certain conditions are met. These systems usually begin with an initialization phase, followed by a main loop where tasks are performed in sequence as their prerequisites are fulfilled. This approach, common in older electronic control units (ECUs), suits simpler systems that do not require dynamic resource allocation. Each function monopolizes the processor until its task is complete, preventing any subsequent task from starting until it finishes.

- Real-Time Operating System (RTOS): In more recent, though not the latest, ECUs, the structure resembles the main loops of sequential programming but is executed over multiple cores with intricate scheduling. An RTOS is essential for timing, managing, and distributing tasks across CPU cores, ensuring timely execution. This setup supports concurrent operation of critical functions like sensor readings, system health checks, and fuel injection, enhancing speed, responsiveness, safety, and overall performance.

- Contemporary Systems: Modern ECUs leverage a finite state machine (FSM) model to streamline engine functionality and enhance performance, ensuring all inputs are processed and preventing undefined behaviors. An FSM represents different states reflecting the current parameters of the system. Although it may operate on an RTOS, it restricts each ECU's functionality strictly within the defined states. State transitions are meticulously managed by the RTOS, bolstering the consistency and safety of each embedded component.

- Simulation

Automotive control is a very complex and vast system that is made up of different subsystems that are controlled by different means. For this simulation, the relationship between engine speed, load and throttle position is carried out on MATLAB/Simulink in figure 3 below.

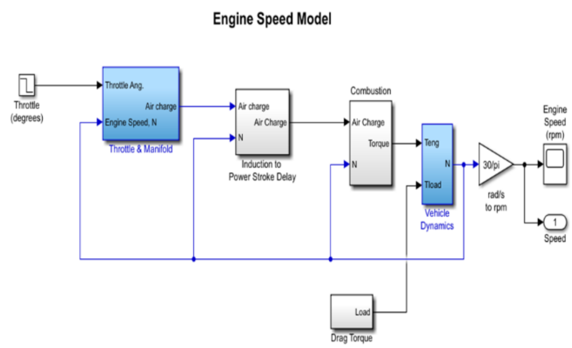

Figure 3: Engine speed control model.

The simulated as carried out in figure 3 above shows the various functional blocks of an internal combustion engine that have to do with air inlet, engine power, engine speed dynamics, torque and load. In this simulation the main controlling measure is the throttle position, which when varied changes the engine speed which is also dependent on load. The throttle opening degree when varied affected the amount of air that flows into the engine. Engine speed is directly proportional to the opening of the throttle valve and inversely proportional to the engine load. The result in Table 1 shows the change in engine speed as the throttle opening degree is increased. From the result, it is observed that when load is kept constant, and the throttle degree is increased the engine speed increases. When the load is increased the engine speed reduces. To prevent engine stalling when load is added the throttle valve opening has to be increased.

Throttle Degree	Engine Speed (RPM)
10	1797
20	2946
30	3334
40	3447
50	3487

60	3505
70	3516
80	3520
90	3523

Table 1: engine speed readings as throttle degree is changed.

A more advanced system is the implementation of an engine idle speed feedback control system. In this system the engine speed is automatically maintained at a set point. This is achieved by the use of the ECU, which constantly measures the engine speed, compares it with the set idle speed and when there is a difference it adjusts the throttle position according to the difference from the set idle speed.

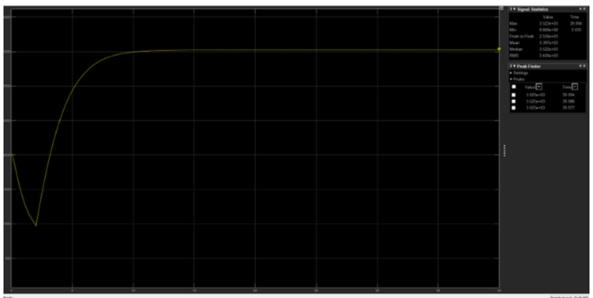

Figure 4: Output result from Throttle Engine Speed

CONCLUSION

The control of Automobiles electronically involves the control of a physical system or subsystem by systematically altering certain input values of the physical system. For a system to be controlled the output must be measured, it must also have a physical value that can be altered to give a desired change on the output of the system and finally the need for a mechanism that determines the amount of alteration that is needed from the present state of the system. This is shown in figure 4; where the acquisition is performed by different sensors, computing and decision making is carried by the microcontroller, while the act of varying the physical parameters is done by actuators while controlled system can either be the engine, automatic transmission system or other subsystems in an automotive. Electronic control of automobile is popular because it is; less cumbersome, more efficient, less power consumption, it is easy to replicate and can be easily tuned to change the parameters and lastly it involves parts that that cause less effect on the dynamics of the automobile.

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