Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 07, July - 2025

Adaptive Windshield Wiper System Based on an Intelligent Control Algorithm

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***Abstract*—This paper presents a case study that resulted in the practical implementation of an automatic windshield wiper control system. The system operates based on an intelligent control algorithm that considers the amount of raindrops on the windshield surface and the speed of the vehicle, so that the time period between two successive actuations of the system, as well as the rotation speed and implicitly the duration of the arm travel, are dynamically adjusted. The proposed control scheme is based on information received from the rain sensor and the potentiometer that simulates the speed of the car. Due to the use of a DC motor with reversible direction, this approach represents an alternative to the classical windshield wiper systems, and it has certain advantages, including reduced weight and mechanical complexity (fewer components), silent operation and an improved level of assembly reliability.**

***Keywords*—windshield wiper; closed-loop control system; rain sensor, control unit, embedded system; real-time operating system; control systems; adaptive control.**

I. INTRODUCTION

The automotive industry is one of the most important branches of the global economy that has contributed massively to the development of human society. In recent decades, it has evolved at a rapid pace driven by advances in computer science, sensor technology and artificial intelligence.

Due to its potential to free the drivers from attention-distracting or tiring activities and to improve travel safety and traffic efficiency, vehicle automation technology is increasingly common both in the surrounding reality and in the debates of ideas, with the aim of solving a series of problems related to passenger safety and creating high-performance navigation systems.

Modern day vehicles are equipped with safety cameras and sensors behind the windshield, and it is the duty of the windshield wiper system to keep these components and the driver’s view unobstructed. This is mandatory for autonomous vehicles and Advanced Driver Assistance Systems (ADAS), such as pre-collision detection and adaptive cruise control, in order for them to work properly.

Classical windshield wiper systems are becoming unsuitable for modern vehicles, as they have a high level of complexity and take up a lot of space as the number of electronic modules present on cars is increasing. To address this issue, efforts are made to improve the design of these systems and to optimize the production costs.

This paper, based on the author work [1], focuses on the implementation of an automatic windshield wiper control system, which operates via an intelligent control algorithm. This approach is a viable alternative to classical approaches, with certain advantages, such as reduced weight and mechanical complexity, silent operation and improved reliability. The structure of the paper is as follows. Section II is dedicated to related works. In Section III, several aspects related to control systems for wiper systems are presented. Section IV presents an innovative structure of the implemented control system. In Section V, the adaptive windshield wiper control application is described, and Section VI is focused on the closed-loop block diagram. Section VII presents the physical structure of the experimental setup and Section VIII the experimental results. Finally, Section IX contains the conclusions and the future research directions.

II. RELATED WORKS

Over the years, the design of windshield wipers has undergone significant developments to optimize windshield cleaning. Automatic windshield wiper systems are a globally recognized technological advancement. They provide drivers with increased comfort and safety. An automatic windshield wiper detects rain and automatically activates the cleaning process, adjusting the speed and frequency of the wiping movement according to the intensity of the rain [2].

They are designed to work in all weather conditions and be compatible with every vehicle model. In some continents with varied weather conditions, such as North America, Europe and Asia, windshield wipers ensure perfect visibility during rainy or snowy seasons, when visibility is reduced. Automatic wipers are significantly advantageous for drivers in urban centers with heavy traffic, allowing them to focus more on the traffic on busy streets. In recent years, automatic wipers have become popular in modern cars, prioritizing safety and comfort. Many well-known car brands, such as Toyota, Honda, Ford, etc., already use this feature and now offer models with automatic wipers.

The issue of automatic windshield wiper control is a topical one, with multiple concerns in the specialized literature in this field.

S. Kato and T. Tashiro proposed a method for designing windshield wiper control that can reduce the oscillations of wiper arm vibrations. The system is designed based on the H-infinite control theory and is verified by a windshield wiper test bench, and the verification results demonstrated the effectiveness of the control by comparing it with the conventional control designed by an optimal controller [3].

R.M. Alti has developed, under laboratory conditions, an automatic windshield wiper system with an LCD display based on a microcontroller. The main components of this device are the raindrop sensor, Arduino Nano, LCD and servo motor. The device was able to detect the presence of rainwater, activate the wiper lever and operate with an intensity proportional to the rainfall, information displayed on the LCD device [4].

In order to improve the comfort of the driver and passengers, Y. Z. Chu et al. have proposed a solution to reduce the noise of the reverse rotation of windshield wipers by using an integrated system. According to these researchers, the noise generated by windshield wipers can be about 80 dB and is unpleasant for a driver in the case of a quiet car such as an electric vehicle. Therefore, sophisticated control of the wiper speed is required, and this control should be achieved by an integrated system for precise control of the motor speed using a PID algorithm, and the results indicate a noise reduction of 10 dB, which corresponds to a two-thirds reduction in the noise perceived by humans [5].

T. Haijima et al., studying the reduction of overtravel by optimizing the motion trajectory, have designed a motion trajectory of wipers, whereby the position of the peak speed and the speed reduction ratio around the motion reversal position can be explicitly adjusted, so as to reduce overtravel, which can cause significant damage and generate noise, especially by colliding with a pole or the vehicle body. If a wiper system is damaged in a collision, serious accidents can occur due to limited visibility in rainy conditions [6].

A.M.P. Ramos et al. have developed a prototype based on a rain sensor module that approximates the number of raindrops on the windshield, connected to a microcontroller, which uses the data to determine when to activate the wiper. Using a potentiometer interfaced through the microcontroller, the user can adjust the approximate amount of moisture required on the windshield to activate the wiper [7].

Other research has developed a rain-sensing windshield wiper system using a Raspberry Pico microcontroller and weather sensors, thereby helping to improve driver safety and comfort by automating its operation based on real-time rain and weather data. When rain is detected, the system activates a servo motor to control the movement of the wipers, ensuring clear visibility for the driver. In addition, the system provides up-to-date weather information via an LCD display and alerts the driver with audible signals via a buzzer, demonstrating the potential of IoT technology to improve driving experience, making them safer and more intuitive. As technology continues to advance, such systems promise to redefine the standards of safety and comfort of vehicles [8].

V. Gaikwad et al. claim that smart and automated cars are the future of the automotive industry due to the advantages they present, namely accuracy and precision in operation. They have designed a system that integrates a wide range of mechanisms, designed by merging hardware and software elements, and embodied in an automatic windshield wiper mechanism, a parking alarm mechanism, a lane detection mechanism and a weather parameter detection mechanism. All of these mechanisms contribute to reducing the stress on the driver while driving the car. The automatic windshield wiper system detects precipitation and automatically activates the rain wipers. The peculiarity of this system lies in the incorporation of the Internet into the vehicle. The use of the Internet has made all devices connected to each other through an intense exchange of data and constant communication, and the vehicle has thus become a smart car [9].

In conclusion, smart cars offer a variety of advantages, with the fundamental intention of increasing passenger safety and reducing accidents caused by driver inattention. These increased safety features have attracted the attention of many manufacturers, so much so that they have begun to replace traditional cars with smart cars. In a short time, due to the variety of advantages, smart cars are and will be a very promising industry in the future.

III. CONTROL OF WINDSHIELD WIPER SYSTEMS

The windshield of a vehicle is the main element that can affect the visibility of drivers, therefore, for their safety it is imperative that it is constantly clean, in any weather conditions. In this sense, the windshield wiper has the role of cleaning raindrops, dust, snow or other deposits caused by unfavorable traffic conditions in order to maintain the driver's field of vision. It is very important that, while the vehicle is moving, the windshield surface is always kept clean and transparent for active safety and visual efficiency. The transparency of the windshield, i.e. the visual distance, decreases due to raindrops and disappears completely with the increase in the intensity of heavy rain. Nowadays, the windshield wiper plays an important role in protecting the vision not only of the driver, but also of the surveillance cameras in the vehicle. The wiper cleans the windshield surface with a rubber blade attached to a movable arm. This principle has not changed for many years. However, new technologies regarding the operation, mechanism and control of wiper systems have been researched and introduced into vehicles.

Studies show that driver inattention can cause devastating accidents, with 26% of all car accidents being caused by talking on a mobile phone, eating while driving and other similar concerns that distract the driver from the road. Even manually adjusting the wipers and windshield washer spray can distract the driver, which can be another direct cause of an accident. Thus, driver distraction can be reduced by eliminating the need for them to constantly adjust the wiper speed. The traditional wiper system requires constant attention to adjust the wiper speed using a manual switch [10]. In this context, windshield wiper systems are one of the important safety-related automotive components, to remove rain, dust or snow from a vehicle's windshield, thus contributing to the safety, flexibility, comfort and reliability of drivers and passengers.

Currently, the windshield wiper motors of vehicles are controlled in two different ways. In the first case, the actuation of the wiper motor is carried out using time relays. Here, the activation of the windshield wipers and the waiting time for two successive wipes are regulated using predetermined constant steps of the time relay. The driver usually determines the value of these steps with a mechanical lever located to the right of the steering wheel. However, as the variation of the rain concentration on the windshield is taken into account, the driver must adjust the time steps of the windshield wipers during the movement of the vehicle.

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http://www.ijert.org
International Journal of Engineering Research & Technology (IJERT)
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Fig. 1. Selection lever set to automatic windshield wiper control mode

If the driver does not make the adjustment in time, visibility will decrease or eventually disappear due to excessive water concentration. If the rain concentration is too low, the windshield wiper works in vain. On the other hand, while adjusting the windshield wiper steps, the driver may lose focus on the road. Another method of controlling the windshield wiper motor is the automatic method (Fig. 1) which is based on information received from the rain sensor. In this method, the data is analyzed by the control unit, and the motor speed is set either based on multiple threshold values, or proportionally to the sensor saturation value. Thus, the greater the amount of precipitation on the windshield, the higher the speed of the windshield wiper.

Rain sensors are of several types [11]:

- Optical sensors - this type of sensor measures the variation in the refraction of infrared light when raindrops contact the glass surface of the sensor.
- Conductive sensors - these contain two interleaved printed circuits that are separated by an insulator. The sensor measures the electrical conductivity between the two circuits when raindrops touch the sensor surface.
- Piezoelectric sensors – these sensors contain a crystal that detects the sound vibration produced by raindrops at a specific frequency.

Rain-sensing windshield wiper systems periodically measure the amount of precipitation to determine how wet the windshield is. This information is used to operate the wipers accordingly, without the need for driver intervention.

IV. PROPOSED SYSTEM ARCHITECTURE

For the implementation of the adaptive windshield wipers system based on intelligent control algorithm, the hardware and software architecture described below were developed [1].

A. Hardware architecture

The role of hardware architecture is to establish the necessary components and plan how they will interact within the system that is to be created. Fig. 2 shows the proposed hardware architecture for the development of the adaptive windshield wiper system.

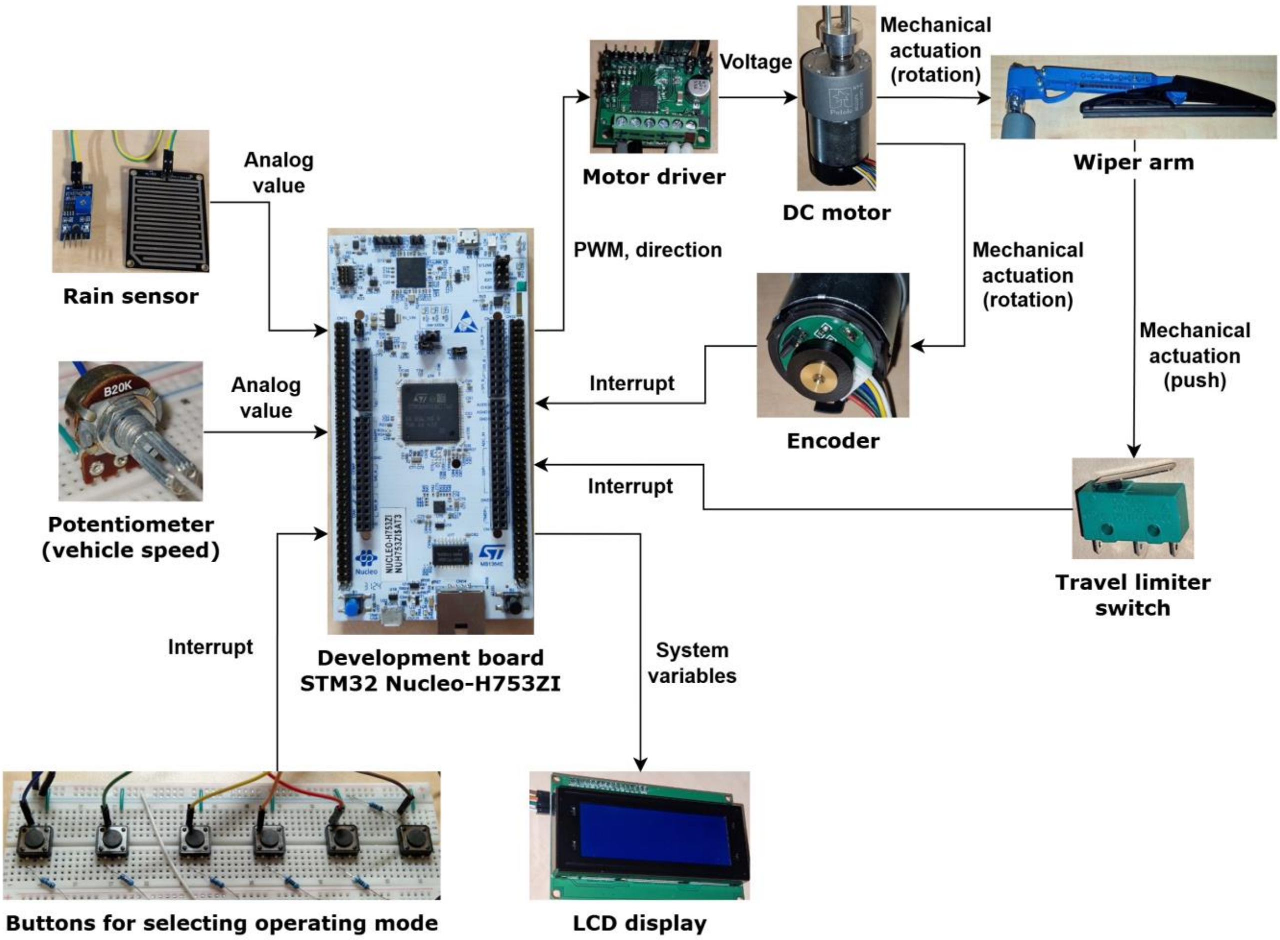

Fig. 2. Proposed hardware architecture

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 07, July - 2025

The control unit of the system is represented by the STM32 Nucleo-H753ZI development board, which has as inputs the values coming from the raindrop sensor, the potentiometer simulating the vehicle speed, but also the interrupt signals transmitted by the operating mode selector, the travel limiter and the position encoder of the DC motor. The system outputs are connected to the driver that controls the DC motor, which rotates both the windshield wiper arm and the position encoder attached to the opposite end of the shaft, and to the LCD display that shows system variables and uses the I2C communication protocol. The travel limiter switch is mechanically actuated by the wiper arm when it reaches the bottom of the windshield for the initial calibration of the starting position. The components used are the following:

- STM32 Nucleo-H753ZI development board – it integrates the STM32H753ZI microcontroller, which runs at a frequency of 480 MHz and uses 3.3 V logic.
- 12 V DC motor with magnetic encoder and gearbox – the standalone motor has a maximum speed of 1600 RPM and a current consumption of 720 mA in load, the maximum resolution of the encoder is 64 counts per revolution, the gearbox ratio is 150:1 and the maximum output speed of the assembly is 58 RPM.
- Toshiba TB67H420FTG DC motor driver – dual channel H-bridge driver with a working voltage of 10-47 V and a maximum current of 1.7 A per channel in continuous load. It drives the motor using PWM signal.
- 3D printed mechanical wiper arm with flexible joint and adjustable spring to press the rubber blade against the windshield.
- Travel limit switch – this is used for initial calibration of the bottom start position of the wiper arm.
- Conductive rains sensor – this sensor is used to determine the amount of water droplets from the windshield surface.
- Potentiometer – this is used to simulate the vehicle speed and to test the system in various scenarios.
- Buttons – for selecting the operating mode of the windshield wiper.
- LCD display – for displaying system variables.
- Plexiglass windshield.
- 12 V power supply to power the system.

B. Software architecture

The role of a software architecture is to provide a basic structure for a robust, functional, and sustainable system, guiding the development process while defining how its components interact and organize to achieve the system's goals. It establishes the foundation on which application software is built, influencing its quality, maintainability, scalability, and performance. It also allows for flexibility, by seamlessly adapting to changes or incorporating new features, reducing development time and costs.

Fig. 3 shows the software architecture that has been designed for a scalable system. It implements the principles of the FreeRTOS real-time operating system and is divided into several tasks that are executed periodically and interrupt handling routines with event-based execution.

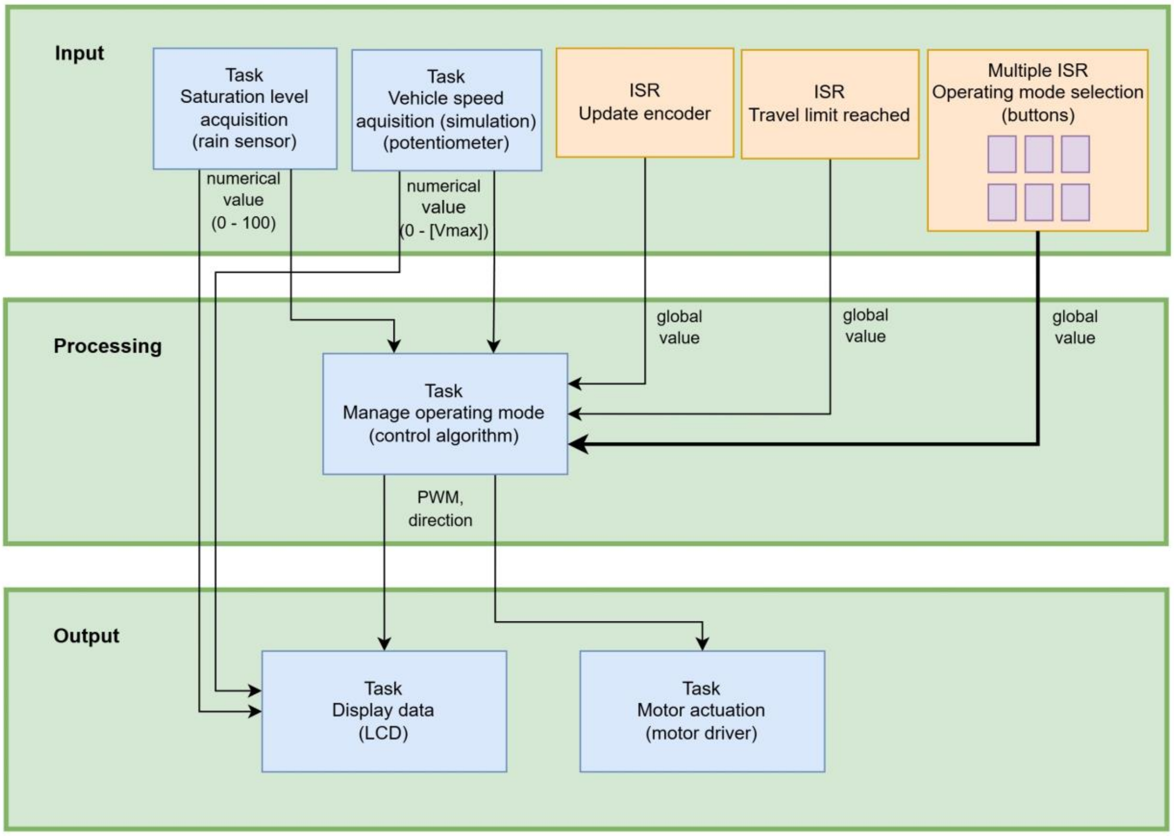

Fig. 3. Proposed software architecture

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 07, July - 2025

This architecture has the advantage of being modular, being divided into several levels, thus, the production of information is decoupled from its consumption, which allows the tasks that extract the information and distribute it (sampling tasks) to operate at a different frequency than those that consume the information (processing tasks). Also, the frequency of tasks that perform less important tasks can be reduced, thus freeing up their load on the microcontroller, a resource that can be assigned to tasks with higher priority.

The tasks communicate with each other, and the information crosses the levels in order (input - processing - output). The input level involves the acquisition of data from sensors, this is performed periodically through tasks for the rain sensor and potentiometer and event-based for the encoder, travel limiter and operating mode selection buttons. The processing level is responsible for the automatic control algorithm. The output level sends the optimal command to the DC motor driver and displays the values of the system variables on an LCD screen.

FreeRTOS is an open source, real-time operating system, distributed as a collection of C libraries consisting of a real-time kernel and a set of modular libraries that implement complementary functionality. It is ideal for embedded real-time applications using microcontrollers that include a combination of both hard and soft real-time requirements. Soft real-time requirements are those that set a time limit, but exceeding this time limit would not render the system useless. On the opposite spectrum there are hard real-time requirements that set a time limit, and exceeding this time limit could cause an outright system failure [12].

V. ADAPTIVE WINDSHIELD WIPER CONTROL APPLICATION

The hardware architecture in Fig. 2 is translated to the virtual level through the software architecture in Fig. 3. The close connection between hardware and software in the context of this project led to the development of the automatic control algorithm of the windshield wiper system.

The software application has the role of controlling the hardware components presented in the previous subchapters and is implemented in C++ using the principles of the FreeRTOS real-time operating system to create a flexible, efficient solution that responds promptly and reliably to environmental changes and user requirements. The application includes several tasks divided into input, processing, and output levels and has the following functionalities and characteristics:

- The input level includes:
  - The task for acquiring the saturation level of the rain sensor:
    - This reads the ADC0 input of the microcontroller and obtains a numerical value in the range 0 - 1023 corresponding to the analog voltage level provided by the rain sensor depending on the amount of raindrops on it. The numerical value is translated into the percentage range 0 – 100 and the average value is computed for the time interval of the last 1000 ms, then it is further transmitted to the processing task on the next level via a queue.
    - It has a period of 10 ms.
  - The task for acquiring (simulating) the vehicle speed:
    - This task simulates the vehicle speed via the analog voltage level provided by a rotary potentiometer. The task reads the ADC1 input of the microcontroller and obtains a numerical value in the range 0 - 1023 which translates into the range 0 - [maximum vehicle speed] and transmits it to the processing task on the next level via a queue.
    - It has a period of 10 ms.
  - Several interrupt service routines for the buttons that make up the operating mode selector:
    - each event of pressing one of the buttons triggers an interrupt that leads to the execution of a routine in which the value of a global variable changes depending on the selected operating mode: OFF, MANUAL (Slow, Medium, Fast), AUTOMATIC.
    - It is triggered based on event.
  - Interrupt service routine for incrementing / decrementing the counter associated with the position encoder:
    - The position of the motor shaft is determined using the position encoder, and the interrupts generated by its two rectangular signals are handled by a routine in which the counter value is updated.
    - It is triggered based on event.
  - Interrupt service routine for signaling that the travel limit was reached:
    - When it is pressed by the arm, the travel limiter generates an interrupt, and the routine associated with it resets the value of the counter associated with the position encoder, because the encoder starts counting from the position where it starts. This mechanism helps the system to calibrate itself and start each time from the end position.
    - It is triggered based on event.
- The processing level involves:
  - The task for managing the operating mode:
    - This is the main task of the application that controls the system and performs the following:
    - Receives information from the tasks located on the input level.
    - Processes the data and implements the PID controller based on a variable sinusoidal signal for the arm movement.
    - Automatically calibrates the system if it does not start from the correct position.
    - Manages the operating mode of the system through a finite state machine, where each state represents an operating mode that uses certain parameters related to the period and speed of the motor drive. The AUTOMATIC mode is the one

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 07, July - 2025

that implements an intelligent control of the wiper arm that dynamically adjusts the parameters of the sinusoidal signal used as input for the PID controller. Depending on the saturation level of the rain sensor, the time period at which the wiper rises to make a travel is dynamically adjusted, and the car speed value adjusts the duration of travel. Thus, a higher saturation of the rain sensor determines a shorter period between two actuations (and vice versa), and a higher vehicle speed implies a shorter travel duration (and vice versa).

- After processing, it sends the PWM command value and the direction of rotation to the tasks on the output level for controlling the motor and displaying data.
- It has a period of 20 ms.

- The output level consists of:
  - The task of controlling the motor via the driver:
    - It receives from the task for managing the operating mode, via a queue, the numerical value for the PWM command and interacts with the driver to control the motor supply voltage.
    - It has a period of 20 ms.
  - The task for displaying data:
    - This task informs the user about the values of the system variables, such as operating mode, rain sensor saturation, vehicle speed, sine wave signal, command values. The information is received via queues from the tasks on the input and processing levels. The information is displayed via an LCD screen connected via I2C communication and can also be sent to a laptop / PC connected via USB serial communication.
    - It has a period of 20 ms.

VI. CLOSED-LOOP BLOCK DIAGRAM OF THE SYSTEM

The closed-loop block diagram of the developed control system is shown in Fig. 4.

The variable sine wave block has as inputs the rain sensor saturation and the vehicle speed. The output of this block can be seen in the in the Fig. 5 with the red line and the associated equation is (1) which is detailed with the help of (2).

$$reference = (-1)*[(A/2) + (A/2)*\sin(2*\pi*f*t + \phi)] \quad (1)$$

where the amplitude is

$$A = [Travel\_degrees]/360*[Encoder\_CPR]*[Gear\_ratio] \quad (2)$$

In this case, the travel has 95 degrees, the encoder is set to 16 counts per revolution, and the gear ratio is 150:1.

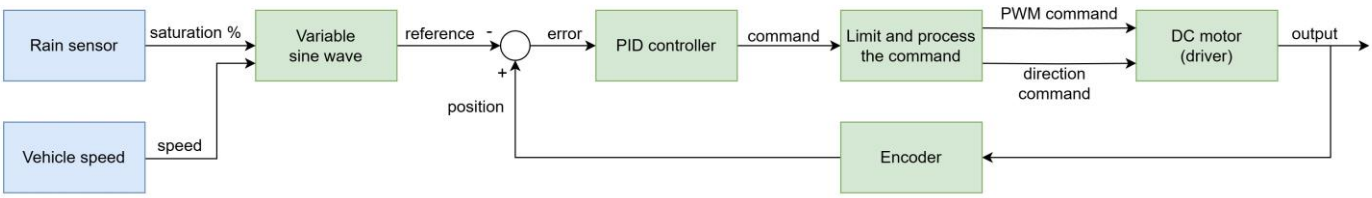

Fig. 4. Closed-loop block diagram of the developed control system

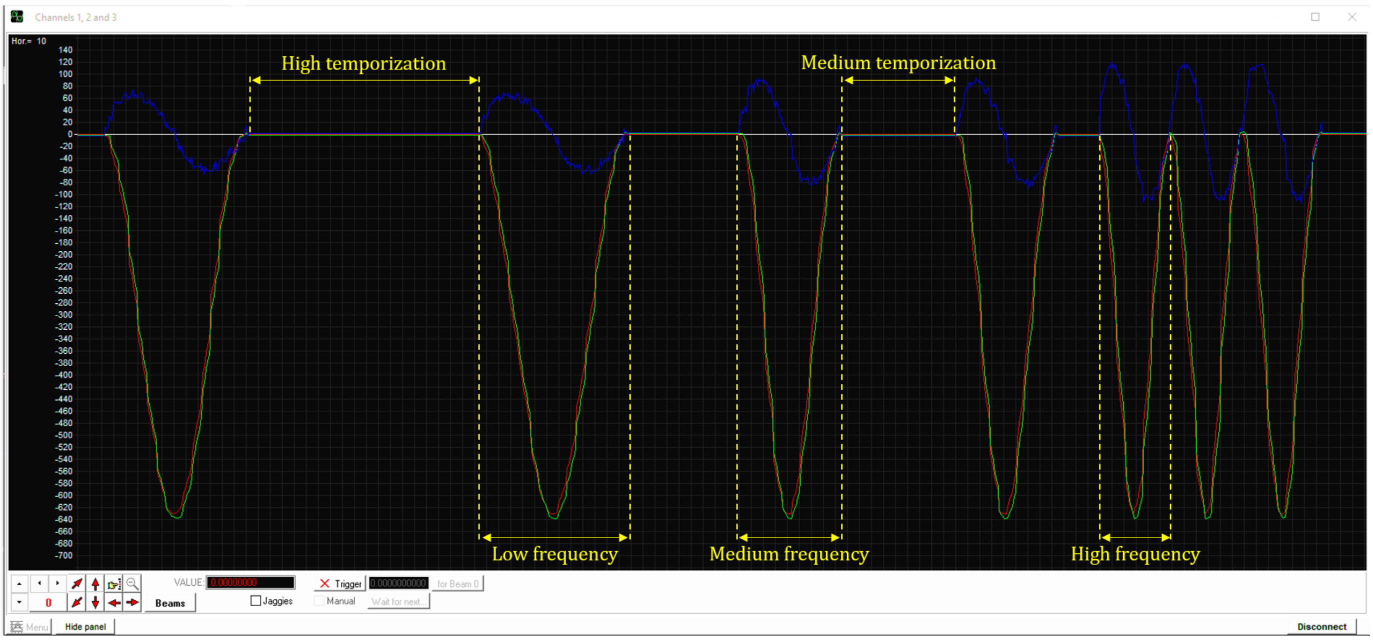

Fig. 5. System response graph (setpoint – red line, PID command – blue line, encoder position – green line)

The PID controller is implemented with (3) which is explained with the help of (4) and (5).

$$command = K_P*error + K_I*error_{integrator} + K_D*(\Delta error/\Delta t) \quad (3)$$

where,

$$error = position - reference \quad (4)$$

$$error_{integrator,\,k} = error_{integrator,\,k-1} + error * \Delta t \quad (5)$$

The value of error integrator is limited to prevent the phenomenon of integrator windup. PID parameters were adjusted by experimental methods as follows: KP=2.5, KI=1.1, KD=0.1. The output of the PID controller is shown in the Fig. 5 with the blue line and with the green line is shown the current encoder position.

VII. PROJECT ASSEMBLY

For the physical realization of the assembly, a 50 cm x 50 cm plexiglass plate was used to simulate the car windshield. This is attached vertically to a wooden board with metal joints with screws. On the surface of the plexiglass plate, facing outward, are attached the wiper motor-arm-blade assembly, the travel limiter switch and the rain sensor (Fig. 6). On the other side, facing inward, are the Nucleo development board, the operating mode selector, the potentiometer for simulating the speed of travel and the LCD screen with an informative role for the user (Fig. 7).

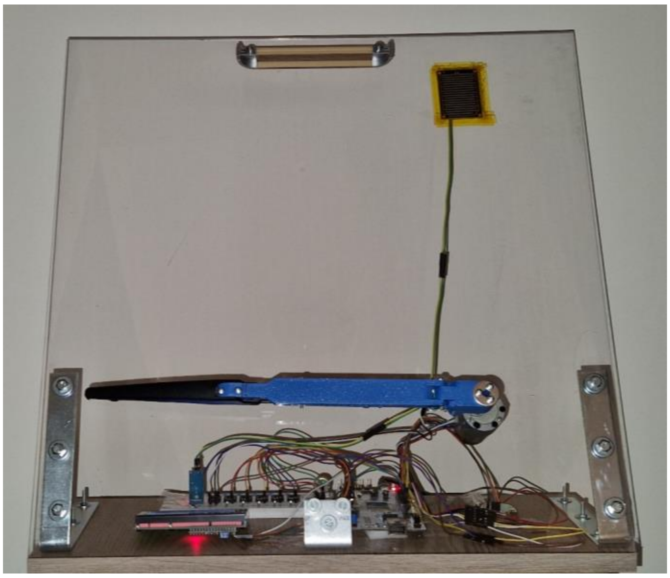

Fig. 6. Front view of the project assembly (wiper arm)

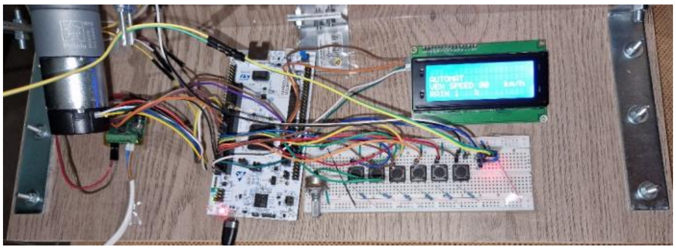

Fig. 7. Back-view of the project assembly (electronic components)

Fig. 8. Information shown on the LCD display

The system is powered by a 12 V adapter, which simulates the vehicle battery voltage. In Fig. 8 is shown the real-time information available on the LCD display.
This includes the current operating mode, rain percentage, vehicle speed, wiper actuation timer, wiper arm travel frequency, PWM value for motor and wiper arm travel direction.

VIII. EXPERIMENTAL RESULTS

The system is configured to initialize in OFF mode for safety reasons, then the user can select one of the other operating modes from the buttons. In MANUAL mode, the wiper arm travels to the upper end of the glass surface, after which it returns to the horizontal position. The wiping intensity is set by the user via the button selector with predefined values.
In AUTOMATIC mode, unlike manual mode, the parameters are dynamically adjusted according to the values recorded by the two sensors (rain and speed). Thus, by testing this operating mode, the following experimental results were obtained:

- At a simulated speed of 50 km/h:
  - By lightly sprinkling the sensor on the windshield with water droplets, it registers a saturation value in the range of 30-40%. In this case, the wiping intensity of the system is low to moderate.
  - By sprinkling more abundantly the sensor on the windshield with water droplets, it registers a saturation value in the range of 70-80%. In this case, the wiping speed of the system is considerably higher.
- At a simulated speed of 120 km/h:
  - By lightly sprinkling the sensor on the windshield with water droplets, it registers a saturation value in the range of 30-40%. In this case, the wiping intensity of the system is moderate, the arm rotation speed is noticeably higher than at lower vehicle speed.
  - By spraying the sensor on the windshield more abundantly with water droplets, it registers a saturation value in the range of 75-85%. In this case, the wiping intensity is high to very high, the system acting rapidly.

The rain sensor is cleaned after each wiper travel by the rubber blade that slides onto its surface, as can be seen in Fig. 9. The system is efficient and manages to keep the windshield clean, thus the driver's view and the car's sensors are unobstructed.

Fig. 9. Rubber blade cleaning the windshield and the rain sensor

IX. CONCLUSIONS

Currently, in order to increase the level of vehicle safety, and also the efficiency with which transport activities are carried out, the technology through which the process of driving a vehicle is automated represents one of the main areas of research. In order to develop methods and tools for vehicle automation, the academic environment together with various research institutes and production companies in the field are collaborating more and more intensively for this purpose.

In today's automotive industry, the integration of intelligent technologies has revolutionized the driving experience, prioritizing safety and comfort. Today, most automobile manufacturing companies automate many of the mechanisms of their vehicles to offer best-in-class features and ensure an effortless driving experience for customers. Also, as automation is introduced in these newly manufactured vehicles, it has also improved driver safety.

The development of this case study started from the premise that the windshield is the main element that can affect the visibility of drivers, with serious consequences for their safety and comfort, when it is not clean. Also, an obstructed windshield can affect the operation of the cameras and sensors that modern vehicles are equipped with and that are mounted behind it.

Based on the developed software and hardware architecture, the project demonstrates the ability to adjust itself dynamically. The implemented system is designed around the STM32 Nucleo-H753ZI development board. It receives input signals from the operating mode selector, the rain sensor, the potentiometer that simulates the vehicle speed, the wiper arm travel limiter and the encoder attached to the motor shaft. The signals are processed into digital data and used within the intelligent control algorithm to send an optimal command to the driver of the DC motor that rotates the wiper arm on the glass surface to remove raindrops.

The system has three operating modes: OFF, MANUAL and AUTOMATIC, the latter operating based on the intelligent control algorithm. The operating mode selection is made by the driver through a button-based selector, which has a contemporary and minimalist design.

This design aims to keep the windshield clean in diverse whether conditions, thus the vehicle's integrated sensors for driver assistance systems can be maintained unobstructed and in optimal parameters.

For the future, due to its modular architecture, the project can be expanded by adding new functionalities that allow the automatic triggering of the windshield washer, by operating the liquid pump, simultaneously with the wipers starting, depending on the degree of impurities on the glass surface.

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