Non-Contact Sensing Technologies for Intelligent Tire Condition Monitoring Using Laser Distance and IR Temperature Sensors

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ABSTRACT

Tyre degradation caused by tread wear and abnormal temperature rise directly affects vehicle safety, braking efficiency, and handling stability. Conventional tyre monitoring techniques primarily rely on manual inspection or pressure-based systems, which fail to provide continuous health assessment. This paper presents a real-time, non-contact Smart Tyre Health Monitoring System that simultaneously measures tyre tread depth and surface temperature. A VL53L0X Time-of-Flight laser distance sensor is used for accurate tread wear measurement, while an MLX90614 infrared sensor monitors tyre surface temperature without physical contact. Sensor data are processed using an Arduino microcontroller and continuously compared with predefined safety thresholds. Experimental evaluation demonstrates tread depth measurement accuracy within ±1 mm and reliable temperature monitoring up to 75 °C under dynamic conditions. Visual and audible alerts are generated when unsafe conditions are detected. The proposed system offers a low-cost, non-invasive, and scalable solution suitable for preventive maintenance and enhanced vehicle safety.

Keywords— Real-time monitoring, Non-contact sensing, Tyre tread wear, Infrared temperature sensing, Laser distance sensor, Vehicle safety.

INTRODUCTION

The only parts of a car that are in constant contact with the road surface are tyres, and thus they have a very important role in the safety of the vehicle, braking, and handling stability, as well as the comfort of the ride. Tyre condition has direct influence on traction and steering response especially during poor road and weather conditions [7], [8]. The wear of treads and abnormal increase of temperatures are progressive because of friction, loading conditions, and characteristics of the roads and driving behaviour. When not identified, the factors contribute a lot to the risk of skidding, hydroplaning, prolonged braking distance, and even sudden tyre failure [9]. The traditional methods of tyre care are majorly based on the periodic hand check techniques like the visual inspection, the tread depth gauges or even the coin-based tests [22].

These approaches are subjective, discontinuous and rely on driver awareness even though these methods are simple and cheap. Consequently, the gradual wearing of treads or abrupt anomalous situations between inspections are frequent and usually go undetected [3]. The modern cars are usually using tyre pressure monitoring systems but these systems only give information about the inflation pressure and not about the tread wear patterns or surface temperature behaviour [1], [5]. The process of wear of tires is a complicated mechanical phenomenon that is achieved due to the constant contact between the rubber treads and the road surface.

Poor inflation, misalignment of wheels, unequal load distribution, rough driving styles etc., are factors that lead to irregular wear patterns, such as shoulders wear, centre wear and cupping [4]. Studies have shown that even bad inflation can lead to a rise in tyre wear with over 30 percent, whereas excessive operating temperature upgrades the degradation of the treads and shortens the life of the tyres [5], [20]. High

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temperatures can also cause the structural damage and tyre blowouts, especially when driving at a high speed or using the brakes, especially in the long run [21]. Recent studies have looked at sensor-based and vision-based tyre monitoring methods, but most of the existingsolutions are either contact based sensors, sophisticated imaging, or expensive to install, thereby restricting its use at large scale [6], [10]. Moreover, the use of single combined platform to monitor in real time and non-contact tread depth and surface temperature is comparatively unexplored [13], [15].

Research Gap and Objectives

Notwithstanding the recent developments in the area of tyre pressure monitoring and vehicle diagnostics, the operation of constant real-time monitoring of the tread wear and surface temperature of tyres by means of non-contact methods is still insufficient. The solutions available are either manual, or are based on contact sensing, or are limited to measuring only one parameter of tyre health, which is not as effective as a system that considers all aspects of tyre health [12], [18]. In order to overcome such limitations, the proposed research will develop and deploy a low-cost, real-time, non-contact Smart Tyre Health Monitoring System that is able to measure the tyre tread depth in real-time using a laser-based Time-of-Flight sensor, and determine the tyre surface temperature using an infrared sensor.

An embedded microcontroller constantly takes sensor data and compares the results to predetermined safety limits to provide timely visual and audible feedback. The proposed system allows preventing maintenance in the early stages, improves the safety of vehicles, and helps to increase the duration of a tyre life and the general driving reliability [14], [21].

Effact of Tyre Wear on Safety and Performance

The effect of tyre wear is directly proportional and measurable to vehicle safety and overall the performance. With less tread depth the water-pushing ability of the tyre out of the contact patch is greatly compromised, and the unit is likely to hydroplane and lose control in wet road conditions [7]. It has been shown that worn tyres have lower friction coefficients which directly determine the braking efficiency and increase the stopping distance, especially in the emergency manoeuvre [8], [9]. The conditions are even worsened with high-speed driving conditions and poor weather conditions.

The asymmetries in tread wear patterns (shoulder wear, centre wear, and cupping) also present further safety issues by creating vibration, steering imbalance and uneven contact between tyres and the road [4]. These types of irregular wear not only reduce the level of ride comfort, but also have an adverse effect on the level of steering accuracy and handling stability, thus making drivers more fatigued and susceptible to accidents [8]. In extreme situations, wear may have become excessive or asymmetric causing structural weakness of the tyre, and thereby creating high chances of separation of the treads, or even blowouts when being used [21].

Besides the safety aspects, the wear of tyres also significantly affects the vehicle performance and efficiency. Tyres that are ripped off or underinflated raise the rolling resistance hence high fuel consumption, and low energy efficiency [5], [9]. It has been demonstrated that keeping the tyres within recommended limits of wear and pressure can enhance fuel efficiency by up to 10 percent as well as increase the service life of the tyres by about 20 percent [9]. These are a major performance loss mostly on commercial and fleet automobiles, and tyre-related losses to performance add up to higher operational expenses.

Tyre temperature is an important factor in promoting wear performance and performance characteristics. Overheating due to excessive braking, overloading or underinflation of the tires causes the tread compound to become soft and thus accelerates abrasion and decreases grip [20]. Constant high operating temperature also leads to the probability of thermo-mechanical failure and temperature monitoring is a necessity in the health assessment of tyres [21]. Continuous monitoring of tyre temperature is usually not an issue in the traditional maintenance methods, due to its significance.

Thus, precise and instant measurement of tyre tread life and surface temperature is needed not only to guarantee vehicle safety but also to enhance fuel economy, ride comfort, and vehicle stability in general. A

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preventive strategy in tyre maintenance that can be applied using sensing technologies that will be able to monitor all these parameters will help to detect the unsafe conditions at an earlier stage and allow a proactive approach to be used instead of the reactive approaches used in the past [12], [14].

Role of Smart Tyre Health Monitoring System

The growing need of vehicle safety, reliability, and smart diagnostics resulted in the invention of smart sensing systems that are able to monitor the critical components of a vehicle in a constant manner. In that regard, a Smart Tyre Health Monitoring System has an essential role to play by offering real-time data regarding the state of a tyre conditions that is otherwise challenging to estimate when a vehicle is in motion [12]. Such systems can be used to fill the divide between the current periodic inspection and the requirements of constant safety premium by regularly checking tread wear and surface temperature.

The proposed Smart Tyre Health Monitoring System will make use of laser tread depth and infrared temperature sensors to completely assess the health of tyres. Non-contact sensors are used to ensure that the sensor can be constantly monitored without mechanical interference, wear, and tear and therefore the system can be used in long-term automotive applications [15], [17]. In a way the proposed solution to the problem of conventional tyre pressure monitoring devices that only measure inflation pressure, the proposed solution measures two important signs of tyre degradation, including tread wear and thermal behaviour, which provides a more comprehensive measure of tyre condition [1], [3].

Trend wear monitoring Real time monitoring of tread wear can be used to promptly discover progressive wear and abnormal wear trends due to misalignment, improper inflation or unequal load distribution [4]. Early fault identification makes corrective measures taken in time to avoid abrupt failures and improve vehicle maneuverability and braking effect like replacing tyres or engaging the steering wheels [8], [9]. In a similar fashion, the temperature measurement of surfaces allows monitoring of overheating situations due to excessive friction and use of braking or underinflation, both of which are known antecedents of tyre explosion and rapid tread wear [20], [21].

Giving it an embedded microcontroller allows performing sensor data processing in real-time and comparing it to predetermined safety limits. In case of unsafe conditions, the system will provide visual and audible alerts to draw the driver attention and make him/her aware of any such case even in those cases when a visual check-up cannot be performed [14]. This is an active warning system that assists in the preventative maintenance measures as opposed to responding to the damage in the tyres once the damage has taken place [12].

Altogether, the Smart Tyre Health Monitoring System can be treated as a smart safety device that improves the driver awareness level, enhances the level of vehicle reliability, and helps to decrease the maintenance costs. The system is a viable step towards smarter and safer vehicle operation by integrating non-contact sensing, real-time data processing, and automated alerts to the modern connected and intelligent transportation systems and especially [13], [21].

Tire Monitoring System

The proposed Smart Tyre Health Monitoring System is based upon the tyre monitoring system as its main functional unit. It is to be capable of obtaining real time information regarding wear on tyre treads and surface temperature via non-contact sensing. The optical and thermal sensors used in the system combined with an internal processing unit will provide constant condition monitoring with no mechanical intervention hence the system is applicable in dynamic automotive conditions [12], [14].

Sensor and Architecture

The suggested system will utilize two non-contact sensors such as a laser distance sensor used to measure the tread depth and infrared temperature sensor used to monitor the surface temperature. The sensors are both attached in the wheel arch part facing the tyre surface to successfully capture the data on a continuous basis when the vehicle is in motion. The general system architecture is composed of sensing, Arduino microcontroller to process the data, and output devices to generate the alerts as shown in Fig. 1.

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The sensor data is sent to the microcontroller over the Inter-Integrated Circuit (I2C) communication protocol; this allows synchronous data transfer at the minimal complexity of wiring. The embedded controller then compares the sensor values with the preset safety conditions and provides visual and auditory notification of abnormal conditions as they occur. The architecture can be used to provide real-time and quick driver notification as well as promoting vehicle safety by using the architecture [14], [19].

Laser Distance Sensor

The tread depth measurement is performed with the VL53L0X laser distance sensor designed by STMicroelectronics that works with the Time-of-Flight (ToF) technology [15]. The sensor sends an infrared laser pulse to the tyre tread surface and the distance is calculated by measuring the time it takes the reflected signal to get back. The technique can be used to accurately estimate the distance regardless of the surface colour, texture, or ambient light.

The VL53L0X offers a better measurement accuracy and response time as compared to conventional ultrasonic sensors, and that is summarized in Table I, and therefore has limitations in terms of reliability in the automotive world. By contrast, the laser-based ToF sensor is able to reach millimetre level accuracy and operates consistently even when there is a change in operating conditions [15], [16]. The sensor is non-contact, which removes the mechanical wear and mechanical alignment problems, therefore, it can be used during extended use in a vehicle setting.

TABLE I. Laser Distance Sensor Comparition with Conventional Sensor

Parameters	**Ultrasonic sensors**	**Laser Distance Sensor**
Measurement Accuracy	Limited accuracy and affected by surface orientation and vibration	High precision with millimetre-level accuracy using Time-of-Flight measurement
Contact Requirement	Requires physical contact or proximity, leading to wear and alignment issues	Non-contact measurement, eliminating mechanical wear and ensuring consistent readings
Response & Reliability	Slower response and susceptible to noise from road and environmental conditions	Fast response with stable performance under varying operating conditions

Infrared Tempering sensor

MLX90614 infrared temperature sensor monitors real time tyre surface temperature. The sensor works toward identifying infrared radiations cast off by the surface of tyres and transforms it into a certain temperature message with no physical contact [17]. This feature also renders it especially appropriate to rotating tyres, where contact-based temperature sensors are unfeasible and subject to failure.

The MLX90614 has a broad range of measurements between [?]70 degC and +380 degC and gives fast response that can be applied to a real-time application. Normal driving temperatures of tyre surfaces do not go beyond 60 degC under normal operation conditions and sustained temperatures over 75 degC are signs of abnormal operation conditions, such as excessive friction, underinflation, or extended braking [20]. Table II provides the comparison between the traditional contact-based temperature sensors and the infrared temperature sensor and points out to the benefits of non-contact measurements in terms of reliability, response time, and durability [17], [18].

TABLE II. INFRARED TEMPERATURE SENSOR Comparison with Other Conventional Sensors

Parameters	**Thermistor / RTD / Thermocouple**	**Infrared Temperature Sensor**
Measurement Method	Requires direct contact with the tyre surface, leading to wear and installation complexity	Non-contact infrared sensing allows temperature measurement without physical contact

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Response Time & Safety	Slower response and vulnerable to damage due to friction, rotation, and harsh tyre conditions	Fast response with safe operation, unaffected by tyre rotation or surface wea
Reliability & Durability	Accuracy degrades due to dirt, vibration, and repeated mechanical stress	High reliability with stable performance under harsh automotive environment

Sensor Integration and Data Communication.

The VL53L0X laser distance sensor and the MLX90614 infrared temperature sensor are both connected to the Arduino microcontroller via the I2C communication protocol, and it is possible to have them running in parallel to retrieve the necessary data simultaneously provided by several sensors. The microcontroller does a simplified signal conditioning such as averaging and filtering to reduce the impacts of vibration, dust, and other environmental interference that is usually encountered during automotive applications [19].

Continuous comparison of the processed sensor data with predefined threshold values is done and the system output sent to the display and alert modules. The combined sensing strategy allows to monitor mechanical wear and thermal behaviour simultaneously, which offers a global evaluation of tyre health. The design of the system is modular, thus can be easily scaled and adapted to various types of vehicles, including passenger car, commercial, and electric vehicles [13], [21].

METHODOLOGY

The approach used in the proposed Smart Tyre Health Monitoring System is based on accurate and real time measurements of tyre tread wear and surface temperature through sensors that are non-contact. The system works based on the principles of calendar sensing, concurrent data recording, signal processing, threshold-based assessment, and the creation of alerts. The systematic methodology will guarantee sound tyre condition measurements during normal automotive working conditions [12], [14].

Tread Measuring System

The tread depth measurement subsystem is anchored on the VL53L0X Time-of-Flight laser distance sensor that measures the distance between the sensor and the tyre tread surface in seconds based on the time duration it takes an emitted infrared laser pulse to reflect upon hitting the surface [15]. Before deployment, known reference distances are used to calibrate the sensor to minimize offset and systematic measurement errors. Calibration makes measurements consistent and repeatable when the system is in operation.

The tread depth of a new tyre in normal passenger vehicle tyres is normally between 7 mm and 9 mm, with the lowest legal tyre tread being 1.6 mm deep [15]. In order to support the early alarm and proactive maintenance, the suggested system is going to use a threshold of 2.0 mm as the warning threshold. In case the tread depth is lower than this value, the system detects excessive wear and sends an alert to the driver [14].

The VL53L0X sensor has a distance resolution of about 20 mm to 1200 mm with a precision of +-1 mm hence it can be used in measuring slow tread wears [15], [16]. Sampling rate of about 10 Hz is used to record more than one reading per second even at low to medium vehicle speeds. In order to reduce the effects of vibration and other passing disturbances, averaging of successive measurements is carried out, and then an evaluation is done. It has been experimentally proven that the system can give consistent and reliable tread depth measurements under controlled conditions [16].

Temperature Monitoring

The temperature monitoring subsystem uses MLX90614 infrared temperature sensor to measure the temperature of the rotating tyre in real time. The sensor works on Ray of infrared radiation sent on the surface of the tyre and changes it into a temperature reading, without requiring physical touch [17]. The non-contact operation also removes mechanical wear and the operation is very reliable in harsh automotive conditions.

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In normal driving, the surface temperatures of the tyres are usually in a range of 40 deg C to 60 deg C. Prolonged temperatures that are above 75 degC point to anomalous operating conditions that include excessive friction, extended braking, underinflation or overloading, all contributing to accelerated tread wear and chances of tyre failure [20], [21]. In this respect, the suggested system uses 75 degC as the critical temperature point from which an alert is to be generated.

MLX90614 sensor has a large range of operation between [?]70 degC and +380 degC and has a quick response time of about 100 ms, which allows it to sense changes in temperature rapidly [17].

The stability of temperature under steady-state conditions proved to be between +-0.5 degC after repeated measurements, which proves the appropriateness of the sensor in the application of the sensor in real-time tyre monitoring [18].

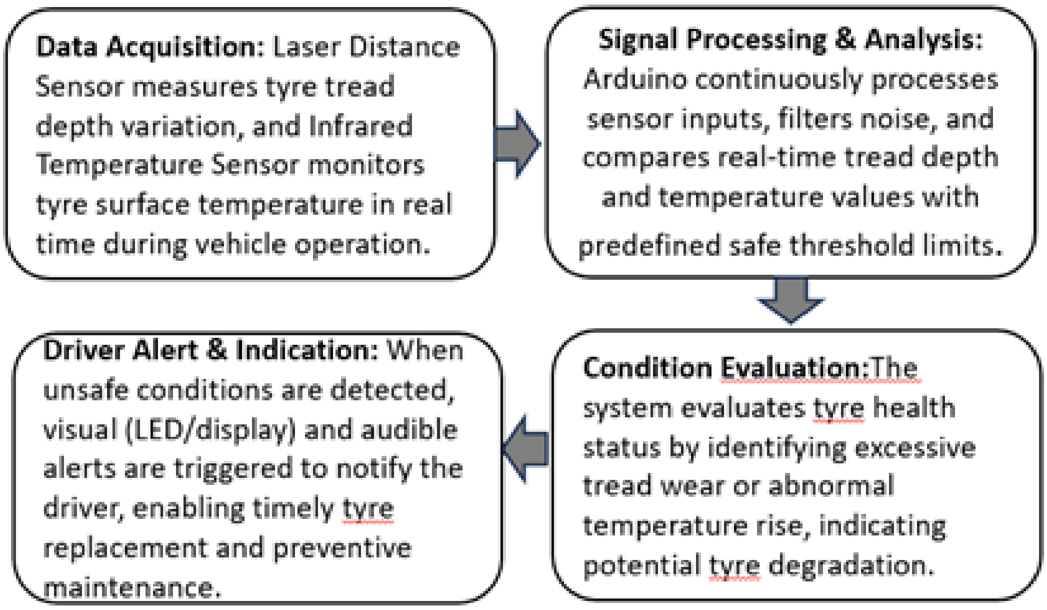

Fig. 1. Tyre Condition Monitoring System Architecture

Alert Mechanism

The alert system is set up to give a clear and timely feedback to the driver according to the analysed tyre condition. Arduino microcontroller sensor data are also constantly matched against an established tread depth and temperature limit. Once the tread depth is less than 2.0 mm or, the surface temperature is greater than 75 degC and maintained over an extended period of time, the system indicates the possibility of a safety risk and switches on the alert mechanism [14], [19].

Display unit also provides visual alerts to notify the current tread depth and temperature values and thus enables the driver to monitor the tyre condition information in real-time. Moreover, there is an audible buzzer that is activated in case of emergency situations in order to attract immediate attention.

The logical alert uses time to validate prior to the issuance of warnings to minimise false alarms due to brief fluctuations. The multi-level alert approach guarantees the drivers early warning on preventive measures to take, and it is reliable in conditions of dynamic driving [12], [21].

System Integration

The stage of system integration is dedicated to the actual application of the proposed Smart Tyre Health Monitoring System into a car setting. The accurate real-time monitoring and driver awareness when operating under dynamic conditions can be achieved only with proper sensors positioning, robust data processing, and efficient delivery of alerts [14], [21].

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System Placement and Functionality

The VL53L0X laser distance sensor is attached to the inside of the wheel arch in such a manner that the optical axis is facing the tyre tread surface. Such positioning enables the sensor to keep on estimating tread progressively by choosing the change in the distance between the sensor and the tyre surface with wear [3], [15]. Placing the sensor within the wheel arch reduces outer disturbance, and ensures the geometry of measurements is consistent in various operating conditions.

The MLX90614 infrared temperature sensor is placed next to the laser sensor and it is facing the sidewall of the tyre to check the temperature distribution on the surface when the tyre rotates. This design allows the device to measure the temperature in a non-contact manner, which means that it will not only hold good when the tyres are on motion, but it also resists environmental conditions [17], [18]. Both the sensors are connected to the Arduino microcontroller, which takes the obtained data in real time.

The processed information is shown to the driver in the form of a visual display and audible alert system. In the case of tread depth which is lower than the safety limit set or in case the surface temperature is higher than the critical temperature, the system will alert the driver and corrective measures can be done in time with the decrease of speed or tyre examination or maintaining schedule [1], [14]. The small and portable form of the system enables easy implementation which does not necessitate a major alteration at the vehicle framework, and thus it is applicable as an aftermarket product [21].

Contrast With Traditional Approaches

Older types of tyre wear testing are mostly manual and incorporate visual inspection, tread depth gauges, and coin-based tests [22]. Although these methods are easy and cheap, they are discontinuous in their nature and therefore require the awareness of the drivers and the rate of their inspection. As a result, the progressive tread wear or the abrupt unpredictable wear that takes place between inspection is usually not noticed and this puts people at risk of accident involving tyres [3].

On the same note, traditional tyre care measures seldom include constant temperature checks, although there is a high correlation between the excessive heat production and the increased tyre consumption or malfunction [20]. Such contact-based temperature sensors as thermistors and thermocouples must have physical contact with the surface of tyre, and so they cannot be used to monitor rotating tyres and are subject to mechanical wear, friction and complicated installation [17].

The Smart Tyre Health Monitoring System that is proposed will eliminate these weaknesses by using infrared and non-contact laser sensors that monitor the health conditions in real time. The Time-of-Flight sensor is based on a laser, meaning that it is more accurate in measurements and has higher response time than the traditional ultrasonic sensors that can be easily affected by vibrations and noise in the environment [15], [16]. Similarly, Table II compares the infrared temperature sensing advantages with the contact-based sensors such as response time, robustness, and reliability in severe automotive environments [17], [18].

The proposed system allows continuous, automated, and objective tyre health monitoring by combining both tread wear and temperature monitoring into one embedded system. The system provides real-time alerts to the driver unlike the traditional methods, and thus it provides early intervention and preventative maintenance. The combined methodology will improve the safety features of the vehicle, save costs related to maintenance, and the overall vehicle performance and reliability [12], [21]

Restrictions and Practical problems

Even though the proposed Smart Tyre Health Monitoring System has several benefits, there are some limitations and practical challenges that need to be looked into as far as real-life implementation is concerned. Surface contamination is one of the major problems. When mud, dust, water or debris are on the tyre tread, the reflectivity of the laser beam may change and cause slight inaccuracy in measuring the tread depth [22].

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Equally, dust or other contaminants can be accumulated and in a small amount affect the infrared radiation detection hence temperature measurements in extreme environmental conditions are affected [17].

Another aspect that determines system performance is vehicle speed. When the rotational speed increases, especially beyond the moderate driving conditions, the high rate of movement of the tyre can result in fewer sensor readings effectively being taken per unit time. This is capable of creating small differences in tread depth estimation because of motion blur and lack of sampling opportunities [6]. Nevertheless, the system is mostly suggested to operate at low to medium speed like in city driving, inspection before the drive, and diagnostic operations, in which the reliability of measurements is high.

The sensor readings may also be varied by the ambient environmental conditions. Acute alterations in the ambient temperature or direct exposure to sunlight may also affect infrared temperature measurements, particularly when an instrument is operated over a long period in the open air [20]. Calibration, signal filtering and compensation algorithms that are incorporated in the microcontroller can reduce these effects [18].

The other weakness is the fact that the current prototype lacks wireless communication. Processing sensor data is done on board, and only onboard indicators (visual and audible) can be used to issue alerts. Though this method maintains the simplicity and low cost, it limits the possibilities of remote monitoring and analyzing the data in the long term [12]. Also, the system fails to take into consideration tyre pressure variations that can also determine wear and temperature behaviour.

Though these drawbacks do not play a major role in the undermining of the effectiveness of the proposed system, they pinpoint the aspects on which the suggested system can be improved. Improvements on sensor protection, adaptive sampling mechanisms, and efficient data processing methods can also be used to handle these challenges in order to achieve better accuracy and strength of the system in various operating environments [11], [21].

Future Scope and Innovation

The Smart Tyre Health Monitoring System suggested is a good basis of further developments in the intelligent safety of vehicles and predictive maintenance. Although the system under analysis is aimed at real time monitoring of tyre tread depth and surface temperature, some improvements can be implemented to make it more functional, upscaleable, and effective over the long-term without a dramatic increase in its complexity and prices [12], [21].

A possible extension of the system is that the technology can be applied to various types of vehicles in the market such as commercial automobiles, buses, trucks, and automobiles that are operated by fleets. Failure of tyres in such vehicles is a big burden to the cost of operation and safety. Constant tyre health measurements can also enable the fleet operators to manage maintenance to the benefit of optimizing schedules, lessening the downtime surprises, and enhancing the overall reliability of the vehicle [18]. The system can also be extended to motorsport and high-performance cars where the real-time tyre condition information can be exploited to control the thermal behaviour and optimize the tyre use in the harsh operating conditions [20].

Predictive maintenance by means of data analytics is another area of future development. Through the monitoring of tread wear and temperature change and operating conditions in the past, the trends of tyre degradation can also be estimated and the pattern of possible failures can also be predicted before they happen. By combining machine learning with sensor data, adaptive thresholding and condition-based maintenance can be implemented, which will not be dependent on the set limits and will get more accurate in the long term [6], [14]. Drivers and maintenance personnel can be improved in decision-making using such data-based approaches.

Wireless communication and Internet of Things (IoT) can also be added to the system. Sending tyre health information to cloud solutions would enable remote monitoring, long term storage and central analysis. This is especially useful in application of fleet management where several vehicles can be tracked at the same time to enhance safety and maintenance efficiency [11], [19]. Nonetheless, such integration should take into account the data security, reliability, and cost-effectiveness to make the deployment realistic.

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Moreover, active collaboration with the innovative driver-assistance systems (ADAS) and connected vehicle technologies provides the potential to improve the safety of the entire vehicle. Onboard control systems can use real-time tyre health information to change driving parameters, e.g. speed, braking or load distribution, in response to a degrading tyre condition [13]. There are also avenues that could be examined like vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication to allow shared knowledge of the critical tyre conditions to enhance road safety on a wider range of scales [12].

On the whole, these futuristic improvements are based on the current system structure and rely on the development of embedded systems, data analytics, and connectivity. The Smart Tyre Health Monitoring System will be able to become an all-encompassing part of intelligent transportation systems without losing its initial purpose of enhancing the safety and reliability of tyres.

CONCLUSION

This paper described a real time, noncontact Smart Tyre Health Monitoring system which was developed to improve vehicle safety by constant monitoring of the tyre wear and surface temperature of the tyre treads. The system combines a VL53L0X Time-of-Flight laser distance sensor and an MLX90614 infrared temperature sensor with an Arduino-based embedded control system to allow measurement of important tyre health parameters in an accurate and reliable way with no mechanical touch [15], [17]. In contrast to the traditional system of inspection and pressure-only monitoring, the suggested solution offers a continuous and automated analysis of the tyre condition, eliminating human checks and personal decisions [1], [22].

It was proven that the system was able to notice excessive wear of the treads and abnormal temperature increase in real time through the comparison of sensor readings and the preset safety limits. Both visual and audible warnings make sure that the driver is alerted in time, and the preventive control is taken before the tyre conditions can be dangerous [14], [19]. The non-contact sensing solution enhances robustness and stability during the dynamic automotive conditions and the low-cost and modular structure enables feasible implementation in both current and future automotive platforms [12], [21].

Despite some of the restrictions associated with contamination of surfaces, vehicle velocity, and environmental factors, they can be overcome by means of better sensor protection, adaptive calibration, and better data processing algorithms. The suggested system will be an excellent basis in future extensions in the predictive maintenance, connection with IoT, and links to sophisticated vehicle safety systems [6], [11], [13].

On the whole, the Smart Tyre Health Monitoring System forms a viable and efficient product that can be employed to measure the condition of the tyre in real-time. The system can help to provide better road safety, lower maintenance expenses, and increase the life of the tyres which makes it a valuable addition to the latest intelligent transportation systems [21], [23]

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