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Comparative review of advanced seatbelt detection: Infrared sensors vs. image-based systems

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Abstract. The seatbelt, often heralded as the first line of defense in vehicular safety, plays an indispensable role in mitigating the risks associated with traffic incidents. Consequently, the push towards enhancing transportation safety has led to the emergence of sophisticated seatbelt detection systems. In this study, we undertake a comprehensive examination of four cutting-edge detection methodologies: RF (Radio Frequency), Infrared Marker Vision, Convolutional Neural Networks (CNN), and the You Only Look Once (YOLO) approach. Each method is dissected to understand its efficacy in determining if a passenger has properly donned their seatbelt. Beyond just immediate detection, this paper also casts a vision towards the horizon of seatbelt detection advancements. We explore how such detection systems might seamlessly integrate with advanced vehicle safety infrastructures, and postulate on their pivotal role in the burgeoning domain of autonomous vehicles. As self-driving cars become an imminent reality, the importance of reliable seatbelt detection mechanisms will only magnify. Thus, through this paper, we not only shed light on current methodologies but also endeavor to chart the trajectory of future innovations in the realm of seatbelt safety detection.

Keywords: Seatbelt detection system, RF, Infrared technology, Convolutional Neural Networks, You Only Look Once.

1. Introduction

As we all know, the wearing of seat belts can greatly protect the safety of drivers and passengers. According to experimental data, even if the speed is only 20km/h, without the wearing of a seat belt, there will be fatal danger. When the car is only traveling at a speed of 40 kilometers per hour when the collision occurs, the force of the body forward will be equivalent to dropping a bag of 50 kilograms of cement from four stories upstairs, so its momentum can be imagined.

Nowadays, the seat belt alarm device has almost become standard in cars for driving safety. If the driver or passenger is not wearing a seat belt, the icon on the upper left will be lit up on the dashboard and accompanied by an alarm tone. However, this way of seat belt monitoring is too simple. It's a threat to people's safety.

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The results of these thesis can better ensure that drivers and passengers wear seat belts. By monitoring and reminding the wearing of seat belts, they can better ensure the safety of drivers and passengers in the event of an emergency environment.

2. Infrared Sensors Module-Based Seatbelt Detection

2.1. Introduction to RFID Technology

RFID is an electronic identification system composed of three parts: reader, tag and database. The first is the reader, which consists of a power supply, a clock, a read-write module, an RF module and an antenna. The user can read or delete the information stored by the label through it, and can send and receive signals through the antenna. The second is the label, which allows the user to control the information stored in their memory through the control module. Finally, the information stored in the label is processed and applied through the database.

2.2. Introduction to Infrared Sensors Technology

The infrared scanning and positioning system mainly consists of infrared transmitting array, infrared receiving array, scanning control single chip computer and host computer. Infrared emission array, infrared receiving array and scanning control microcontroller scan the infrared reflective material attached to a specific part to detect the movement of objects, and then input the required signal to the switchboard through the host computer. Finally, the host will calculate the time or distance of the infrared reflective part, so as to achieve the purpose of the experiment.

2.3. Implementation by the Indian Research Team

In this thesis, the Indian team chose to install an RF transmitter with a range of 200m on the side of the road and will install a receiver in the car to check the speed. And then there's the seatbelt part. The team uses pressure sensors attached to the underside of the seat to detect whether there are passengers above it. The passenger and driver are then confirmed to be wearing the seat belt by detecting the white stripes smeared on the seat belt by an IR (infrared sensor) pre-installed in one of the four components of the seat belt — Retractor. There are warnings for both drivers and passengers who are not wearing seat belts, such as turning off the engine if the driver is not wearing a seat belt, and turning on the lights if the co-driver is not wearing a seat belt. The system can comprehensively analyze the infrared signal and button opening and closing to monitor whether the passenger is wearing the seat belt in real time.

2.4. Advantages of RF Module-Based Detection

This thesis supplies a new way to confirm the wearing of seat belt, and there are two advantages. This design is powered by the vehicle, so there is no need to worry about the power supply. The whole system is integrated, and if the driver's seat belt is not on, then he cannot start the engine which means that he won’t be hurt on the road. The cost of accessories is low and the implementation is easy.

2.5. Limitations of RF Module-Based Detection

The author of India believes that this design has the following three limitations. This system (Transmitter) can be employed in highly populated area. This system (Transmitter) can be incorporated at Accident prone areas. This system can also be used for other vehicles like Travellers, SUVs, Heavy Vehicles etc [1]. What’s more, there is still one problem which the Indian authors haven’t notice. The installation of this system (Transmitter). Users need to install enough Transmitter to make it become useful which may take a huge amount of manpower and material resources.

2.6. Limitations of Infrared Sensors Module-Based Detection

There are still three problems with this way of checking whether the seat belt is worn by IR. The experiment to determine whether the seat belt is being worn is too simple. The system does not take into account that people's body types and habits lead to different positions. These differences can lead to

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misjudgments in system detection. The detection system is reflected by infrared light. If the reflected white stripes are contaminated or worn, it could lead to miscalculation.

The authors set the system to turn off the engine 10 seconds later if the driver unbuckles the seat belt while driving. Obviously, the author did not consider the situation of the driver on the highway. If the engine is turned off at high speed, it will cause the car to stall, resulting in a huge car crash. It's not safe.

3. Image-Based Seatbelt Detection

3.1. Infrared Marker Vision

In response to the prevailing issue of inadequate seat belt assembly, an integrated detection approach for assessing seatbelt compliance was introduced. This approach utilized a three-point safety belt equipped with a surface coating containing infrared-sensitive markers. Augmented reality technology was employed for the swift identification and localization of seatbelt markers. Thereafter, a series of algorithms, including the quantity threshold algorithm, the fuzzy clustering threshold algorithm, the curve-fitting tolerance algorithm, and the shoulder outline intersection positioning algorithm, were individually designed for the assessment of four distinct criteria: whether the seatbelt was worn, the manner in which it was worn, its tightness, and its positioning [2]. This approach enabled the determination of whether the seatbelt was correctly and safely worn. Experimental results demonstrated recognition accuracies of 95.4%, 93.1%, 79.5%, and 85.3% for the four aforementioned assessments, even under various imaging conditions and image background interferences [3]. The overall recognition accuracy for seatbelt compliance reached 89.5%, thus confirming the precision, effectiveness, and adaptability of the algorithm [4].

3.2. Convolutional Neural Networks and Support Vector Machine (SVM)

Most existing methods primarily rely on edge detection and the Hough Transform for seatbelt detection [5]. However, due to the diverse array of vehicle types and varying background environments, these methods often yield a multitude of potential edges, leading to a frequent occurrence of false positives. Consequently, a seatbelt detection algorithm tailored for intricate road backgrounds was introduced, based on the extraction of multi-scale features through deep learning techniques.

Initially, multi-scale features were extracted from designated regions encompassing the labeled vehicle, windshield, and seatbelt to facilitate the training of detection models using convolutional neural networks [6]. Subsequently, the algorithm identified coarse candidates for the vehicle, windshield, and seatbelt within test images [7]. To refine the detection outcomes, a post-processing step was introduced, leveraging detection scores and the relative positions of these vehicle components. A classification model was established through the application of a support vector machine. Subsequently, a meticulous mapping and identification process was conducted in the seatbelt region using this classification model [8]. This approach demonstrated exceptional performance when applied to an image database sourced from road surveillance cameras. The algorithm is characterized by its intuitive, precise, and robust nature, yielding a substantial reduction in false positive and undetected rates.

3.3. You Only Look Once

In the field of seat belt detection, You Only Look Once has emerged as a groundbreaking approach. YOLO, renowned for its real-time object detection capabilities, offers considerable promise for enhancing seat belt assembly assessment. This innovative system departs from traditional methods, allowing for simultaneous object identification and localization within a single image or video frame, all in a single pass, differentiating it from all other methods [9].

Basically, YOLO employs a grid-based approach, dividing the input image into cells responsible for predicting bounding boxes and associated class probabilities. This grid-based structure not only enhances efficiency but also eliminates the need for multiple passes and intricate object localization techniques [10]. YOLO excels in generating bounding boxes around objects, assigning class probabilities to these boxes, and providing confidence scores for each predicted object [11]. Post-

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processing through non-maximum suppression (NMS) then ensures the retention of the most accurate and relevant object detections by eliminating redundancy and overlapping predictions [12]. In the realm of seat belt detection, YOLO's real-time capabilities, high computational efficiency, and simultaneous object detection and classification represent a significant advancement, promising to address the challenges posed by diverse vehicle types and varying environmental conditions. Furthermore, the false positive rates and missed chances are dramatically reduced using YOLO.

4. Comparative Analysis of Techniques

4.1. Evaluation Metrics and Criteria

In this subsection, the evaluation metrics and criteria are utilized to assess the performance of advanced seatbelt detection techniques, which include parameters employed to measure the effectiveness and accuracy of the introduced methodologies. Key aspects include precision, recall, F1-score, and computational efficiency, etc.

4.2. Comparative Performance of RF Module-Based, Image-Based, and YOLO-Based Techniques

RF-based systems, known for their cost-effectiveness and straightforward deployment, typically use electrical conductivity to detect seatbelt presence. However, these systems often struggle to accurately assess seatbelt position and tightness. Furthermore, they can easily produce false positives when metallic objects are nearby, making them less ideal for multi-class detection in intricate situations. In contrast, infrared marker vision offers improved accuracy over RF-based systems. This approach allows for precise determination of seatbelt positioning and tension, making it apt for multi-class detection that includes correctly worn, incorrectly worn, and non-worn seatbelts. Yet, its efficiency is compromised under poor lighting conditions, and variations in image clarity can hinder its detection accuracy. For some systems, real-time processing may pose challenges.

Another noteworthy technique merges the deep learning capabilities of CNN with the meticulousness of SVM, offering a hybrid solution. This synergy facilitates high accuracy in intricate scenarios and enables nuanced detection. But the method requires significant computational power and extensive datasets, and its implementation can be complex, especially in real-time contexts. Among these, the YOLO system distinguishes itself with its real-time proficiency. It seamlessly integrates object detection and classification in one go, making it ideal for dynamic settings. Its accuracy in seatbelt detection, including multi-class categorization and localization, is commendable. Yet, due to its computational demands, YOLO necessitates powerful hardware. And, in certain challenging environmental conditions, it can produce both false positives and negatives, thus requiring meticulous calibration for peak performance. To conclude, when choosing a seatbelt detection system, one must consider the unique requirements of the application, balancing the trade-offs between accuracy and real-time responsiveness.

4.3. Practical Considerations and Real-World Applicability

In real-world applicability, RF-based systems, due to their cost-effectiveness, may find utility in budget-constrained scenarios but are limited by their inability to assess seatbelt positioning and tightness. Infrared-based systems offer versatility yet are influenced by lighting conditions and image quality. The hybrid CNN and SVM approach, although accurate, presents hardware and implementation complexities. YOLO-based detection, with its real-time capabilities, holds promise but demands robust hardware and fine-tuning for reliable performance. Real-world deployment hinges on factors such as budget constraints, environmental conditions, and hardware readiness, shaping the practical feasibility of each technique for seatbelt compliance assessment.

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5. Future Directions in Seatbelt Detection

5.1. Emerging Technologies and Research Trends

Computer vision: Using computer vision techniques, such as object detection and image recognition to develop a seatbelt detection system. These systems use cameras to analyze images or videos and detect whether the seatbelt is being fastened correctly. Machine learning: people are now developing machine learning algorithms to improve the accuracy and stability of the seatbelt detection system. These algorithms will analyze various data and start learning to judge whether a seatbelt is correctly worn. In-car sensing Technologies: For example, pressure sensors or weight sensors embedded in the seat, these sensors will detect the existence of passengers; tension sensors embedded in the seatbelt, these sensors will detect if the seatbelt is pulled out. Combining these sensors together can determine whether a seatbelt is being fastened. Overall, emerging technologies and research trends in seatbelt detection aim to improve the effectiveness and accuracy of the seatbelt detection system, finally improve the safety of passenger in vehicles.

5.2. Integration with Advanced Vehicle Safety Systems

One of the future trends of seatbelt detection is the integration with advanced vehicle safety systems. As vehicles are being more and more advanced, they also equipped a vary of safety functions. The seatbelt detection system can work with these safety functions to improve the passenger's safety.

For example, seatbelt detection system can be integrated with airbag deployment system. When detecting the seatbelt is not fastened, the airbag system can be adjusted to deploy in different ways, in order to provide protection to passengers who do not fasten the seatbelt especially. Additionally, seatbelt detection system can also be integrated with collision avoidance systems. If the seatbelt detection system detect that a passenger dose not wear a seatbelt correctly, it will send signals to the collision avoidance system to adjust the response accordingly. This includes adjusting the braking or steering system of the vehicles, so that to decrease the influence of potential collisions. The integration of seatbelt detection system and advance vehicle safety system can help to build a more comprehensive and coordinated network. By combining the functions of different safety system, the overall effectiveness of protecting passengers can be sharply improved. One thing should be noted is that the integration of seatbelt detection system with advanced vehicle safety system should consider the privacy and agreement of the vehicle occupants. Every data collected by these systems should be handled in accordance with the privacy policy and only be used for safety purposes.

5.3. The Role of Seatbelt Detection in Autonomous Vehicles

Seatbelt detection plays an important role in ensuring passenger's safety in autonomous vehicles. As autonomous vehicles become more and more general, it is significant to ensure that passengers are properly restrained to decrease the risk of injury in a collision and a sudden braking.

Here are some key points of seatbelt detection in autonomous vehicles: Passenger protection: Seatbelts are important in preventing occupants from being thrown around or ejected from the vehicles in events like collision or sudden barking. Seatbelt detection system of autonomous vehicles will ensure that passengers are restrained properly to offer extra protection. Integration with Autonomous system: Seatbelt detection system can be integrated with Autonomous systems to improve safety. For example, if a passenger is detected to be unbelted, the autonomous system will change the driving ways, give priority to smoother braking and acceleration, for minimizing the risk of injury. Data Collection and Analysis: Seatbelt detection system of autonomous vehicles can collect data about seatbelt using patterns and analyze them to derive trends and domain should be improved. These data can be used to enhance safety protocols, formulate targeted interventions and improve occupant safety.

In general, seatbelt detection system of autonomous vehicles is essential for obeying traffic rules and ensuring passenger safety. By integrating seatbelt detection system with autonomous system, promotes the use of seatbelt and creates a safer experience of autonomous driving.

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6. Conclusion

In summary, the role of seatbelt detection systems is paramount in ensuring passenger safety and adherence to traffic regulations. This study delves into two principal techniques for seatbelt detection: the RF module-based approach and the image-based method. A comparative examination of these methods illuminates their respective strengths, limitations, and real-world applicability. The RF module-based approach offers simplicity, reliability, and cost-effectiveness. However, it falls short in terms of accuracy and is sensitive to environmental variables. Conversely, the image-based method, capitalizing on computational advancements, tends to be more accurate and resilient. Furthermore, integrating seatbelt detection systems with advanced vehicular safety protocols and autonomous driving technologies can significantly reduce the likelihood of accidents and subsequent injuries, thereby bolstering passenger safety. In essence, seatbelt detection systems are indispensable in fortifying passenger safety and bolstering vehicular security. As research and development in this arena persistently evolve, we anticipate the emergence of even more sophisticated and precise seatbelt detection technologies, paving the way for an enhanced and safer transportation landscape.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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