Multi-actuators vehicle collision avoidance system - Experimental validation

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Abstract. The Insurance Institute for Highway Safety (IIHS) of the United States of America in their reports has mentioned that a significant amount of the road mishaps would be preventable if more automated active safety applications are adopted into the vehicle. This includes the incorporation of collision avoidance system. The autonomous intervention by the active steering and braking systems in the hazardous scenario can aid the driver in mitigating the collisions. In this work, a real-time platform of a multi-actuators vehicle collision avoidance system is developed. It is a continuous research scheme to develop a fully autonomous vehicle in Malaysia. The vehicle is a modular platform which can be utilized for different research purposes and is denominated as Intelligent Drive Project (iDrive). The vehicle collision avoidance proposed design is validated in a controlled environment, where the coupled longitudinal and lateral motion control system is expected to provide desired braking and steering actuation in the occurrence of a frontal static obstacle. Results indicate the ability of the platform to yield multi-actuators collision avoidance navigation in the hazardous scenario, thus avoiding the obstacle. The findings of this work are beneficial for the development of a more complex and nonlinear real-time collision avoidance work in the future.

1. Introduction
Road fatalities remain one of the major death factors in South East Asian region [1]. It is estimated that the hazardous occurrences killed more than 300,000 people annually, i.e. 25% of the road fatalities total globally [2]. In a report by the Institute of Highway Safety of the United States (IIHS), the automation of the vehicle safety feature is reported to have the ability to reduce the casualties figure [3]. This has catalyzed the development of autonomous vehicle globally. The automated driving field is expected to transform the automotive sectors due to its disruptive innovation nature [4]. The advent of autonomous vehicles is mentioned in many future automotive roadmaps, and the technology is expected to be marketed to the general audience as early as in the year 2025 [5 - 6]. In addition to the aforementioned progress, many major scientific bodies such as the Fédération Internationale des Sociétés d'Ingénieurs des Techniques de l'Automobile (FISITA), Institute of Electrical and Electronics Engineers (IEEE) and
Society of Automotive Engineers (SAE) are organizing academic and industrial conferences which are focusing on the autonomous vehicle development [7-9]. However, to the best of the authors’ knowledge, the autonomous vehicle field is yet to be widely discussed in Malaysia, despite the rapid progress done globally [10-11]. Thus, this work is a part of a continuous research in Malaysia by Universiti Teknologi Malaysia, with the support from PROTON Holdings Berhad to reduce road fatalities and developing a fully autonomous vehicle technology. Most of the preliminary works by the authors involve simulation works as well as hardware implementations of other Advanced driver-assistance systems (ADAS), which include the Blind Spot Monitoring System, Side Collision Avoidance, Lane Change and Lane Departure Assistance Systems [12-16]. Despite this, prior to this work, the development of a multi-actuators platform on a real vehicle for frontal collision avoidance system has not yet been done by the authors. Since frontal collision avoidance is an important feature of an autonomous vehicle, consequently, this work focuses on the development and experimental validation of a vehicle collision avoidance system. A vehicle of modular nature which can be upgraded for various research purposes is used as the research platform. It is important to be noted that since the focus of this work is to develop a collision avoidance (CA) system for the autonomous vehicle, the paper’s discussion will be limited to the said topic. The paper is organized as follows. Section 2 briefly describes the platform architecture and design. Section 3 discusses the development of the collision avoidance system, where it consists of modular longitudinal and lateral tracking strategies. In section 4, the experimental designs are discussed, followed by its results. In the final section, the conclusions of this work are jotted down as well as the future research suggestions.

2. Experimental Platform Design and Architecture

![Development of iDrive Research Platform.](image)

An experimental platform, which is denominated as Intelligent Drive project (iDrive) is utilized for the development of a comprehensive multi-actuators collision avoidance system in this work. It is originated from Proton Exora. Since the work is the continuation of the previous studies done by the authors, for brevity, the detailed design of iDrive will not be written and can be found in [12], [13] and [14]. iDrive is designed with several modules, which include the IMU Module, Perception Module, Monitoring Module as well as the Collision Avoidance System Module. IMU Module aids the vehicle to obtain its current motion states using xSense IMU unit. For the environmental and obstacle detection, iDrive perceives its surrounding using Smartmicro UMRR-0A Radar for frontal obstacle detection, and a couple of Continental SRR-208 for rear blind spot monitoring. The authors discuss the Collision Avoidance system module in the next section. The modules are connected to each other by several means of protocols, which include User Datagram Protocol (UDP), Universal Serial Bus (USB) and Controller...
Area Network Bus (CAN). MATLAB and dSPACE MicroAutobox are integrated into the platform to allow rapid online computation of the systems. More details on iDrive’s parameters are available in [12-14].

3. Vehicle Collision Avoidance System Architecture

![Figure 2. iDrive Collision Avoidance Systems Top-level Module View.](image)

In this section, the vehicle collision avoidance system architecture is discussed, where it is incorporated with a Guidance and Navigation Control System, which is designed from the scenario-based behaviour of the human driver in unwanted events [17]. The architecture is modelled using hierarchically layered architectures and consists of a high-level planning to the low-level control workflow. The high level is depicted in Figure 2, where it consists of the perception and path replanning modules. To allow feasible CA navigation during risky scenarios, the vehicle is assigned with multi-actuators interventions, i.e. active front steering (AFS) and active braking torques. A brushless DC motor with a rotary encoder is adapted for the AFS installation. For the braking actuator, Firgelli Auto linear sensor’s installation allows for the active braking intervention. As shown in Figure 2, the perception module is responsible for the environmental sensing of the host vehicle. It includes the obstacle detection. The findings of the module will be sent to the path replanning block. If the threat assessment threshold is violated by the host vehicle, the replanned path will be tracked by the motion guidance. The required steering angle and braking torques for the CA navigation are then fed to the iDrive. The details on the path replanning and motion guidance blocks are written in the next subsections.

3.1. Lateral Motion Controller (Active Steering Intervention)

Both AFS and Active Braking intervention is activated in relation to the threshold of Potential Field Strategy Threat Assessment. The formulation of the Potential Field is formulated based on the work of [16], [18] and [19]. The decision-making formulation for the CA maneuver is written below, where the vehicle distance to the frontal obstacle is measured by the front radar. Once the vehicle violated the threat assessment and safe-distance threshold, its current x coordinate, \( x_{\text{cur}} \) will be equivalent to \( x_{\text{start}} \), which indicates the point where the steering and braking interventions begin. \( x_{\text{start}} \) is formulated in accordance with the safe distance of the host vehicle to the expected collision point, which subsequently allows the research platform to maintain the safe time metrics during the avoidance [15].

![Figure 3. Active Steering Intervention Formulation.](image)
\[\delta_F = \begin{cases} \delta_F & \text{if } x_{\text{cur}} \geq x_{\text{start}} \\ \delta_{CA} & \text{if } x_{\text{cur}} \leq x_{\text{start}} \end{cases} \] (1)

With the violation, the current steering angle of iDrive, \(\delta_F\) is replaced with an emergency collision avoidance actuation, \(\delta_{CA}\). The formulation of the reference steering angle is formulated with a sinusoidal path lane change strategy [20]. The strategy formulated the \(\delta_{CA}\) by initially calculating the desired avoidance lateral acceleration as follows:

\[a_{lat} = \begin{cases} \frac{2\pi d}{t_{LC}} \sin \left( \frac{2\pi}{t_{LC}} (t - t_{lat}) \right), & \text{if } t \subset [t_{lat}, t_{LC} + t_{lat}] \\ 0, & \text{otherwise} \end{cases} \] (2)

where \(a_{lat}\) refers to the desired lateral acceleration during the maneuver, \(t_{LC}\) depicts the total time taken to complete the lane change and \(t\) is the time for the whole formulation to be computed and \(d\) is the lateral distance to the road centerline. Deriving from Equation 2, the \(\delta_{CA}\) is derived as written below:

\[\delta_{CA} = \frac{2\pi d_y}{t_{CA}^2} \sin \left( \frac{2\pi}{t_{CA}} (t - t_{init}) \right), \text{if } t \subset [t_{init}, t_{CA} + t_{init}] \] (3)

\(t_{CA}\) in Equation 3 refers to the total time for the complete avoidance navigation taken by the steering, \(t\) is the elapsed time for the maneuver while \(d\) is the lateral distance. \(t_{init}\) refers to the time for the whole formulation to be computed. This replanning module can be considered as an offline path planning, where the path is already predefined. In the event of obstacle’s existence, the replanned steering angle will be tracked by the actuators.

3.2. Longitudinal Motion Controller (Active Braking Intervention)

As for the active braking intervention, which tracks the vehicle desired speed in the occurrence of obstacles’ risk, the algorithms formulation is:

![Figure 4. Active Braking Intervention Formulation.](image)

\[F_B = \begin{cases} k \cdot F_B & \text{if } x_{\text{cur}} \leq x_{\text{start}} \\ 0 & \text{if } x_{\text{cur}} \geq x_{\text{start}} \end{cases} \] (4)

where \(F_B\) stands for the full braking actuation, while \(k\) is the braking ratio. The value of \(k\) is obtained heuristically. In the case when fully braking intervention is desirable, \(k\) is set to 1. Similar to the AFS, the Active Braking intervention is formulated in relation to the Potential Field Threat Assessment strategy.
3.3. Motion Guidance Modules Validation

Prior to the collision avoidance performance experimental validation, simple scenario preliminary evaluations are done to verify the performance of the sensors and low-level controllers (actuators). The preliminary tests are done in Universiti Teknologi Malaysia, Kuala Lumpur campus area. Two scenarios are done, where each of the tests requires the vehicle to mitigate the collision with single AFS and single Active Braking intervention, respectively. Due to the safety issues and limited size of the testing area, the vehicle speed is set at low speed (below 10 km/h). This is to allow sufficient time for the host vehicle to mitigate the collisions [15]. The safe-distance threshold is set to a value of 15 m. Once the threshold is violated, the CA intervention begin. Both scenarios serve to verify iDrive’s ability to act as formulated in Equations 1-4. The experiment is considered successful once the vehicle managed to outputs needed steering or braking actions to steer and avoid the frontal obstacle.

![Diagram of host vehicle and frontal static obstacle](image)

**Figure 5.** Active Front Steering Collision Avoidance Evaluation.

For AFS, the steering controller is shown to successfully tracked the desired steering angle in Figure 5 by yielding $\delta_{CA}$ when the vehicle reaches $x_{start}$ (Equations 1-3). The safe distance for the active braking intervention evaluation is set to be 5 m. In Figure 6, it is shown that iDrive is able to actuate the active braking in the occurrence of the obstacle. As can be seen, the host vehicle fully stops after the braking, thus mitigating the collisions. iDrive successfully yield 100% braking actuation to allow the vehicle for a full deceleration once the 5 m threshold distance is violated. Both of the pseudo-obstacle avoidance scenarios validation in Figures 5-6 show that the vehicle hardware features are able to steer and brake in a timely manner in relation to the obstacle detection by the sensors. Thus, iDrive is expected to perform well as a multi-actuators CA platform for the CA experiment, which will be discussed in the next section.
4. Controlled Environment Collision Avoidance Setup (Experimental Design)
The collision avoidance experiment was done to validate the iDrive’s ability as a multi-actuators CA platform. The test is done in a standard football field-sized open space in Universiti Teknologi Malaysia, Johor Bahru campus. The host vehicle initially navigates with the maximum speed of 50 km/h. A dummy obstacle is created using Polyvinyl chloride-based (PVC) pipes. The obstacle dimension is the same as a Honda Jazz dimension. Its size in relation to the iDrive is depicted in Figure 7. Its initial position is located 80 m in front of the host vehicle initial whereabouts. The avoidance’s idea is similar to Figure 5’s scenario, but with a higher speed and required multi-actuators intervention during the CA navigation. The host vehicle needs to provide multi-actuation interventions (braking and steering), relative to the Risk Measurement by the Potential Field strategy. Once the threshold is violated, the host vehicle will initially decelerate, before tracking the reference steering angle. The reference trajectories are as formulated in Equations 1-4. Due to the limited length of the work, the results only discuss the ability of the iDrive as the multi-actuators CA platform to avoid the collision with the obstacle.

5. Results and Discussions
Figure 8 shows the still frame images of the experiment’s video recording. The host vehicle was navigating in a straight line when a frontal static obstacle was detected. The CA navigations are yielded
in the second and third sequence of Figure 8, and as can be seen, the human driver is not holding the steering wheel during the maneuver.

![Obstacle's detected](image1)
![CA navigation's activated](image2)
![Collision's avoided](image3)

**Figure 8.** Still frame images from the experiment’s video recording.

The results in Figure 9 shows that the Potential Field successfully provide risk measurement in relation to the relative distance between the host vehicle and obstacle, provided by the frontal sensor. The highest collision risk with the frontal obstacle is at $16 \, s$ of the experiment elapsed time. The host vehicle subsequently yielded the desired braking torques to allow for its deceleration at $12.5 \, \text{–} \, 13.8 \, \text{seconds of elapsed experimental time in Figure 10. The steering also provided an emergency actuation based on the sinusoidal reference trajectory, allowing the host vehicle to avoid the frontal obstacle to the left side when the risk fields threshold is violated (Figure 11).}
Figure 9. Potential Field Risk Assessment for Collision Avoidance Experiment.

Figure 10. Active Braking Intervention for Collision Avoidance Experiment.

Figure 11. Active Front Steering Actuation for Collision Avoidance Experiment.
However, several issues are identified in this experiment (Figures 9-11), which include:

1. In Figure 9, around 11.8 seconds, the signal of the radar is interrupted for a while due to the detection of another obstacle. Hence, it portrays a noise in the distance to the obstacle measurement reading. Thus, for safety reason, for a more complex scenario, more isolated areas are required for validation.

2. The braking torques are also shown to be providing unstable intervention after the maneuver (Figure 10, after 16 s). This is due to the absence of a reliable reference generator for the motion replanning.

3. Potential Field only considers the risk of obstacle, but it does not include the consideration of environmental risk (which include lane departure risk). Thus, after the maneuver, in Figure 11 (at 19 – 22 s), iDrive's steering is constantly showing evasive maneuver actuations though there are no obstacle, allowing lane departure.

4. The lane departure mentioned in number (4) above is also caused by the high velocity of the host vehicle (50 km/h), which demands a nonlinear tracking controller to accommodate the vehicle dynamics.

5. There are needs to design a more reliable system as the scenario only considers static obstacle.

Relying on these findings, the development of a more reliable collision avoidance will be considered in the future work of this research.

6. Conclusions
As detailed discussions on the results have been jotted in the previous section, a brief conclusion of this work is written in this section. In this work, a multi-actuators collision avoidance system research platform for the autonomous vehicle is developed (iDrive). The platform acts by providing multi-actuation collision avoidance maneuver (steering and braking interventions) during the emergence of an obstacle. To validate the performance, a real-time experiment is done where iDrive produced the desired emergency navigation, thus allowing for the collision to be avoided. This work is important since the results can be further implemented in the Malaysian-marketed cars in the future, as well as allowing more research works on the topics of the autonomous vehicle. Future works include the study on the optimal path during the avoidance as well as mimicking the human behavior. This is to ensure that the platform will abide the New Car Assessment Program for Southeast Asian Countries (ASEAN NCAP) before being marketed to the general audiences.

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