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The Use of Lane-Centering to Assure the Visible Light Communication Connectivity for a Platoon of Autonomous Vehicles

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***Abstract*—**The new emerging Visible Light Communication (VLC) technology has been subjected to intensive investigation, evaluation, and lately, deployed in the context of convoy-based applications for Intelligent Transportations Systems (ITS). The technology limitations were defined and supported by different solutions proposals to enhance the crucial alignment and mobility limitations. In this paper, we propose the incorporation of VLC technology and Lane-Centering (LC) technique to assure the VLC-connectivity by keeping the autonomous vehicle aligned to the lane center using vision-based lane detection in a convoy-based formation. Such combination can ensure the optical communication connectivity with a lateral error less than 30 cm. As soon as the road lanes are detectable, the evaluated system showed stable behavior independently from the inter-vehicle distances and without the need for any exchanged information of the remote vehicles. The evaluation of the proposed system is verified using VLC prototype and an empirical result of LC running application over 60 km in Madrid M40 highway.

***Keywords*—**VLC, lane-centering, platoon, ITS, road safety applications.

I. INTRODUCTION

NOWADAYS, Intelligent Transportation Systems (ITS) promise to provide safer and more secure autonomous vehicular mobility by combining and utilizing vehicular sensors, control systems, different sort of vehicular communication methods, and even specific driving formations. Such information intended to provide the necessary remote and local data to perceive the vehicle's surrounding environment and increase the independent vehicles awareness. Moreover, the proper information exchange between vehicles in convoy-based applications by enabling the Cooperative ITS (C-ITS) mode can further improve road traffic safety and string stability, especially for fully autonomous applications [1], [2].

Due to the vast deployment of C-ITS services for vehicular applications, well-known wireless technologies such as the standardized Dedicated short-range (DSR) communications for ITS [3], [4]. These standardized vehicular communication technologies such as the widely deployed IEEE 802.11p are pushed toward an insatiable performance for wireless networks data access, with a remarkable increase in both latency and channel congestion levels. This instability introduced more usage constraints for hard-safety ITS applications, for instance, convoy-based applications [5], [2].

New communication solutions using both independent medium and channel, such as VLC was recently proved to be a suitable supportive solution for the radio-based communication in vehicular environments. In addition to the many advantages when optical-based communication solutions are deployed. VLC has the advantage of re-using the vehicular existed infrastructure by realizing both low-cost implementation and dual functionality [6], [7], [2]. Still, Ambient noise and the Field-of-View (FOV) limitations are two main crucial challenges may prevent using VLC for ITS application. Diverse solutions were proposed to overcome such constraints [8], [9]. Even though, the Field-of-View (FOV) limitation which is expressed as the maximum angular size of the Photo-diode (PD), remained as the primary mobility challenge when VLC-based platoon members face slight changes in driving course, or lane changing.

On the other hand, the lane detection technique was always considered as a crucial cost-efficient and reliable enabler for many driving-assistance autonomous systems [10]. The concept of Lane-Centering (LC) systems is simple and depends on performing real-time processing of the lane detection data and restoring the autonomous vehicle position by locating itself referring to the side lanes (no cooperation is required). Such technique can be beneficial in tunnels driving scenarios or when the alignment of convoy-based vehicles is essential.

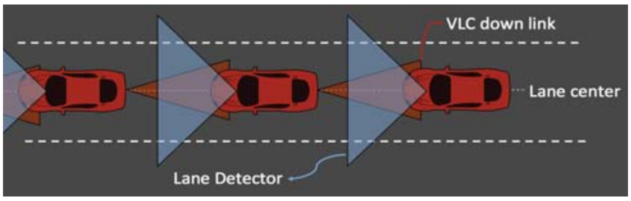

Fig. 1 Lane Detection and VLC down-link for platooning application

In this paper, we propose the use of LC technique to enhance the VLC inter-connectivity between the members of autonomous vehicles as depicted in Fig. 1. By combining both solutions (VLC and LC), the dependency to exchange

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vehicular status and GPS positions will not be essential to relocate platoon members and ensure direct Line-of-Sight (LoS). Therefore, the main focus of our proposal will be on preserving the alignment between platoon members with the minimum possible error and independently from any inter-vehicle exchanged information. Such deployment is expected to allow the autonomous platoon members to retreat to the aligned status even during the VLC disturbance, which is likely to occur. In this paper, we make the following contributions:

- Suggesting a new architecture intends to enhance the platoon performance by utilizing both LC and VLC.
- Define the limitations and performance of both technologies.
- Evaluating the overall system performance.

The remainder of this paper is organized as follows. Section II discusses the previous literature review and related work. The over-all system proposal for platooning application enhancing the VLC connectivity using LC is further explained in Section III. We report the system performance and our findings in Section IV. Finally, conclusion and future work are given in Section V.

II. RELATED WORKS

The convoy-based autonomous vehicles formation concept has been widely investigated and proposed to improve traffic fluidity by increasing roads capacity, at the same time reducing fossil fuel consumption and CO_2 levels. The leading PATH project in California [11] and PRAXITELE project in France [12] were the pioneering projects demonstrating the platoon application. Other projects such as Auto21 CDS [13] are dedicated to advance the smooth merging/leaving for a platooning-enabled system. Also, the SARTRE project [14] has successfully demonstrated the fully autonomous platoon.

On the vehicular control level, the most straightforward requirement to form a platoon is usually the longitudinal control as described in [15], [16]. Simple approaches such as the Adaptive Cruise Control (ACC) with a constant time headway policy has been a universal solution to ensure a safe inter-distance between platoon members [16].

Both conceptual and experimental studies on the use-case of VLC for outdoor applications are conducted and presented for convoy-based ITS applications [6], [8], [17]-[19]. The studies and system evaluation have tackled the main technology limitations and use-cases showing that VLC can satisfy the stringent reachability requirements for Inter-Vehicle Communication (IVC) in dense vehicle traffic conditions [20]. We at INRIA [21] have also implemented our VLC prototype to evaluate and test the performance of VLC technology for platoon application in outdoor conditions [22].

Our previous conducted work [22] was dedicated to evaluating the deployment of Laser-Range-Finder (LRF) and VLC for the same exact platoon application. The evaluation and system implementation were intended to provide a reliable backup system to switching the autonomous driving modes between ACC and Cooperative-ACC (C-ACC) to even emergency stop when failure scenario is detected.

Moreover, laser detection use-cases and deployment to improve vehicle awareness using different approaches include the use of laser detection to implement obstacle detection applications remains [23] costly solution and requires a high computational process compared to the Camera-based vision detection.

By using vision-detection, Lane Detection approach can offer either alternative or supportive solution to the laser-based sensors systems compared with the previous proposal that uses Laser Range Finder (LRF) alongside the VLC in [22]. Further challenges to deploying vision-based lane detection for autonomous driving has also been discussed in DARPA project [24].

Further contributions such as Yue Wang in [10] have proposed the use of a B-Snake algorithm to improve lane detection models. Others, such as Hafner in [25] focused on the lane detection deployment limitations for ITS and provided interesting mathematical solutions to overcome some computational and decision barriers. J. W. Lee has also presented a unique lane centering and control algorithm based on future predictions for autonomous driving maneuvers [26].

III. PLATOON CONTROL USING BOTH VLC AND LANE CENTERING

In this section, we first present both vehicles classic kinematic longitudinal and lateral control model that governs the motion of an autonomous vehicle, and which was used to drive platoon in our previous studies [6], [22]. Afterwards, we present the proposed LC control mechanism to apply longitudinal-correction controller based on the vision-based lanes detection.

A. Communication-Based Platoon Control Model

Usually, to study the vehicle overall kinematics model, we approximate the Ackerman steering mechanism of the vehicle to be a bicycle model. The bicycle model is defined by three main parameters, δ, l and α_0, ϕ, which respectively represents the steering angle, wheelbase, the orientation, and relative orientation of the vehicle. Therefore, the kinematic model which governs the vehicle motion is given by:

$$\begin{cases} \alpha_0 = atan\left(\frac{\Delta y}{\Delta x}\right) \\ \Delta x = X_L - X_F \\ \Delta y = Y_L - Y_F \end{cases}, \tag{1}$$

where the steer angle δ is given by:

$$\delta = atan\left(\frac{2 \cdot l \cdot sin(\phi)}{\sqrt{\Delta x^2 + \Delta y^2}}\right). \tag{2}$$

Fig. 2 depicts the general horizontal plan overview of two vehicles forming a platoon. A longitudinal and lateral distances Δx and Δy represents the projection of the inter-distance d. To estimate d value, the controller obliged to be aware and updated about (Δx, Δy, δ, α) in real-time, which will, therefore, allow a proper longitudinal and lateral control corrections with some error margin. The GPS location, vehicle orientation, and vehicle relative speed are to be passed over one-hop to every proceeding member in platoon chain (from proceeding to follower vehicle).

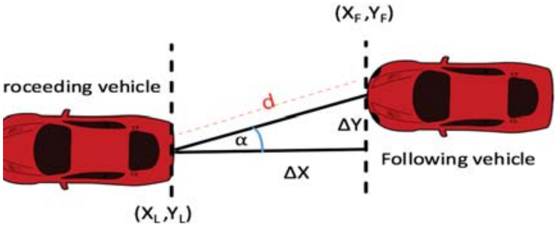

Fig. 2 Plan view of two vehicles platoon (Leader and Follower) which have the longitudinal (Δx) and lateral (Δy), inter-vehicle distance (d)

Such requirements make it essential to have continuous and reliable communication between platoon members, where any disconnection can result in hazardous situations and hazardous driving consequences.

B. Lane Centering Model

The LC concept can be expressed as a longitudinal control adjustment forcing the autonomous vehicle to center its position by continuously referring to the side lanes, and without the need for any further cooperative information.

Such lateral correction can be highly useful for convoy-based applications. For platooning convoy formation, ensuring members centering can even remarkably improve the over-all system string stability [27]. Furthermore, it becomes even more interesting when an optical-based communication system (VLC) is used to exchange information between platoon members. This approach allows every individual vehicle in convoy formation to locally change its behavior (orientation) to ensure a fixed position all along the driving path even when communication is interrupted.

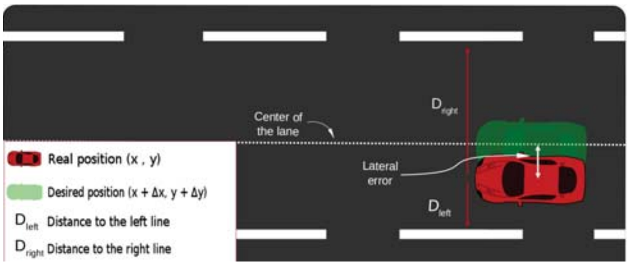

Fig. 3 System overview for Lane-Centering mechanism depicting the lateral error left and right values (D_{left}, D_{right}) obtained by the artificial vision system

Fig. 3 describes the LC over-all detection mechanism and the applied lateral correction to compensate the misalignment and locate the desired vehicle (red vehicle) onto its desired location (lane center). The location error of the red vehicle represents the current position in UTM (Universal Transverse Mercator) coordinates x and y; where both D_{left} and D_{right} are representing the distance from the vehicle center point to the road far edges (sidelines) respectively.

By estimating D_{left} and D_{right} values, and compare them with the local vehicle position, the vehicle will have an initial awareness of the lateral error ε and execute corrections based on further orientation calculations to reach the desired position.

Estimating the lateral error (ε) as defined by (3) is the first step to execute correction, where $C_{position}$, represents the reference point (lane-center) obtained directly from the artificial vision sensor (MOBIL-EYE Camera [28]).

$$\varepsilon = \begin{cases} \mathrm{D_{right}} - \mathrm{C_{position}}, & if \quad \mathrm{C_{position}} \leq 0 \\ \mathrm{D_{left}} - \mathrm{C_{position}}, & otherwise \end{cases} \tag{3}$$

To ensure proper autonomous driving orientation to locate the vehicle on the lane-center. We use (4) to calculate the exact displacement projection using the vehicle local GPS coordinations (x, y), where δx and δy represents the error in both x and the y coordinates respectively.

$$\begin{aligned} \delta x &= \cos(\theta) * \varepsilon * \sigma_{north} \\ \delta y &= \sin(\theta) * \varepsilon * \sigma_{east} \end{aligned} \tag{4}$$

where the calculation of θ is depending on (ε) direction and the azimuth angle ($\dot{\alpha}$) as following:

For ($\varepsilon < 0$):

$$\theta = \begin{cases} \dot{\alpha}, & 0^\circ \leq \dot{\alpha} < 90^\circ \\ \dot{\alpha} - 90, & 90^\circ \leq \dot{\alpha} < 180^\circ \\ \dot{\alpha} - 180, & 180^\circ \leq \dot{\alpha} < 270^\circ \\ \dot{\alpha} - 270, & otherwise \end{cases} \tag{5}$$

For ($\varepsilon \geq 0$):

$$\theta = \begin{cases} 90 - \dot{\alpha}, & 0^\circ \leq \dot{\alpha} < 90^\circ \\ 180 - \dot{\alpha}, & 90^\circ \leq \dot{\alpha} < 180^\circ \\ 270 - \dot{\alpha}, & 180^\circ \leq \dot{\alpha} < 270^\circ \\ 360 - \dot{\alpha}, & otherwise \end{cases} \tag{6}$$

As orientation adjustments are required to apply the right correction (front vehicle direction), both azimuth angle ($\dot{\alpha}$) and correction direction (σ) are to be calculated as the following:

$$\sigma_{north} = \begin{cases} -1, & if \quad 270 > \dot{\alpha} \geq 90 \\ +1, & otherwise \end{cases} \tag{7}$$

$$\sigma_{east} = \begin{cases} -1, & if \quad \dot{\alpha} \leq 180 \\ +1, & otherwise \end{cases} \tag{8}$$

The azimuth angle ($\dot{\alpha}$) is a crucial element to calculate all necessary lateral control corrections. The more accurate estimation of $\dot{\alpha}$ can dramatically improve overall system performance. Therefore, a higher resolution (4-points method) described in Fig. 4 is applied to stabilize the estimated values further and avoid any GPS errors compared to the conventional 2-points method.

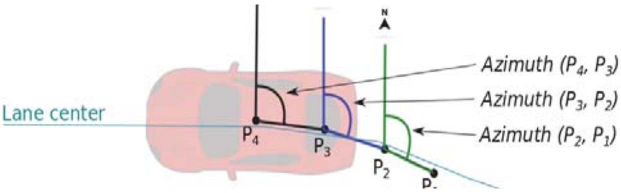

Fig. 4 The 4-points Azimuth angle calculation

Instead of using only 2 points, we use 4 points to successfully calculate 3 full consecutive azimuth angle updates and applying a mean to the result giving more weight to the last estimated values as in the following formula.

$$\dot{\alpha}_{final} = \sum_{i=1}^{3} \frac{\dot{\alpha}_i * W_i}{3} \quad | \quad W_i = [0.5;\ 0.3;\ 0.2] \tag{9}$$

TABLE I
LANE CENTERING CAMERA (MONIEYE) PARAMETERS

Artificial Vision Camera Parameter	Value
Model	Mobileye 5 Series
Transmission data Rate	10 Hz
Focus range	4m to infinity
Angle of view	35
Pixel size	6.0μm x 6.0μm

The platooning lane detection evaluations have used Mobileye [28] with the detailed parameters in Table I. The Mobileye refresh rate was tuned to limit vision to (~4m). Further sample image of the real-time detection is depicted in Fig. 5.

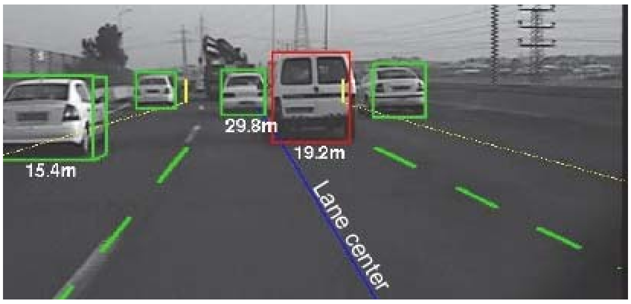

Fig. 5 A sample of the real-time artificial vision camera with detected objects for autonomous driving using mobieye

C. Visible Light Communication Model

The definition of the VLC channel characteristics strongly affected by few physical parameters such as the LED Lambertian emission pattern and both transmitter and receiver orientation as depicted in Fig. 6 [29], and the channel path-loss can be presented as:

$$P_{loss} = \begin{cases} \frac{(m+1)A_{ph}}{2\pi d^n} cos^m(\varphi) cos(\psi), & 0 < \psi, \varphi < \theta_c \\ 0 & elsewhere \end{cases}, \tag{10}$$

where θ_c is the maximum incidence and irradiance angles $max(\psi, \varphi)$. A_{ph} is the physical area of the PD and $m = -\frac{\ln 2}{\ln(cos\hat{\phi})}$ is the Lambertian emission order, which is a key parameter specifying the directivity of the transmitter.

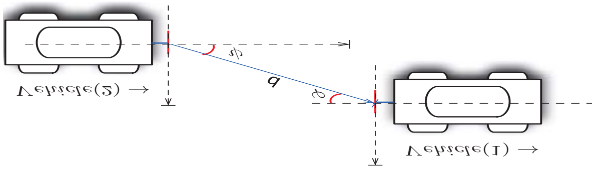

Fig. 6 Two vehicles VLC-based platoon, with an inter-vehicle distance d showing the incidence and irradiance angles (ψ, φ) used to calculate the path-loss

As mentioned earlier, we have conducted experimental system evaluation using a VLC prototype for platoon application in [18]. The evaluation confirmed the inverse square proportional relationship between inter-vehicle distance d and the received power for link range up to 30 meters in outdoor conditions.

The path-loss exponent n found to be 2 for various weather situations and also sensitive to any misalignment which is the exact reason to deploy assisting control application such as the LC in this work. For more excitement configuration details on both physical and packet level (see Table II).

TABLE II
VLC CONNECTIVITY AND RANGE EXPERIMENTAL PARAMETERS

VLC Platform Parameter	Value
Transmission data Rate	9.5 kbps
Link maximum range	30 meter
LED wavelength	635 nm (RED)
Line coding & Modulation	Manchester, OOK
LED power dissipation	3 Watt
Number of LED array	6
LED lens viewing angle	35°
PD active area	100 mm^2
Transmitter & Receiver heights	85 cm

IV. SYSTEM EVALUATION

The performance of the proposed platoon system deploying both VLC and LC is evaluated by independently defining the following:

- The 90% of the received power defining the lateral area at receiver side over different inter-vehicle distances, which represents the reliable performance of the VLC link with better immunity against ambient noise.
- The control lateral error before and after using the LC application, and how accurately the system can locate the platoon members on the lane center.

To validate and test the proposed LC system limitations, two vehicles (Mitsubishi IMIEV) where equipped with an LC (using mobieye camera). For initial positioning, one vehicle was positioned at the far left edge of the lane, while the seconds was located on the far right side of the same lane as depicted Fig. 6.

The experimentally acquired and processed data are of two vehicles driven in a platoon mode. Fig. 7 represents sample results of the second vehicle deviation variation from lane-center. The deviation variation over the interval (0 to 400 seconds) represents the case when LC system is inactive; this can explain the remarkable misalignment which can reach up to 1-meter lateral error over 10 meters of inter-vehicle distance, which is outside the VLC lateral coverage limitations for reliable connection as depicted in Fig. 8.

On the other hand, for the time interval (400 to 100 seconds), the deviation is reduced down to less than 20 cm on average just after the LC is activated.

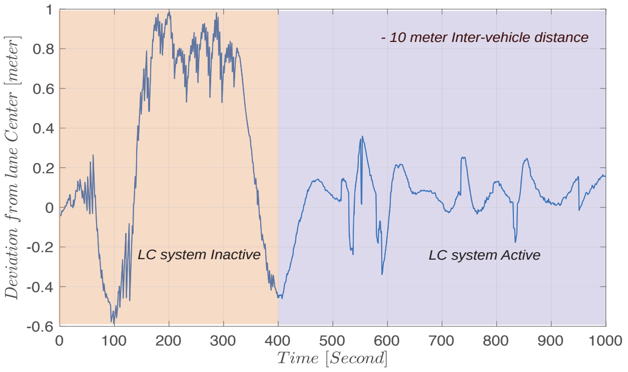

Fig. 7 Data Sample of a platoon member deviation from lane-center before and after the activating LC application

To further understand how the activation of LC system can assure the VLC connectivity, we provide empirical results of the VLC link range tests using an actual VLC prototype. Fig. 8 mapping the VLC link optical beam spot (spot diameter represent the lateral covering area) over different inter-vehicle distances. In Fig. 8, and for vehicle distance of 10 meters, the misalignment is limited to 90 cm from lane center to guarantee a detectable signal level with an adequately received signal over noise ratio (SNR).

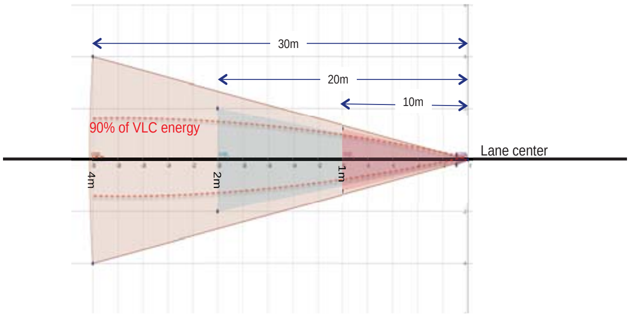

Fig. 8 The three main zones where the VLC receiver was placed to evaluate the received signal level. The experiment was conducted with respect to the variation of direct distances changes and out-door conditions

Other scenarios were experimentally validated as depicted in Fig. 9 which represents the same second platoon members deviation data but for an autonomous driving path of 60 km as depicted in Fig. 10. The second driving path was meant to evaluate the LC system introducing different detection confusion situations, where lanes-marks could be deficient, disconnected, or covered by on-road materials.

The depicted results in Fig. 9 record the spikes 0 and 1, which represent a confusion when the camera detects

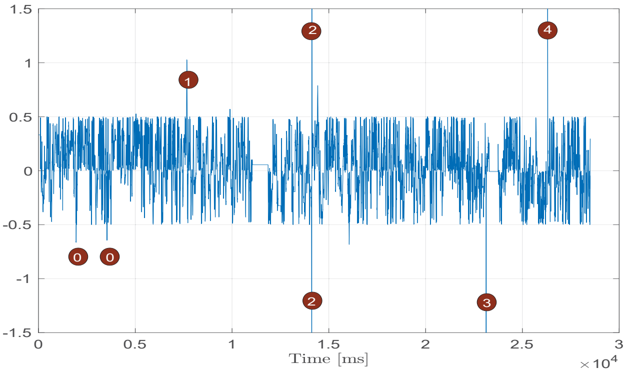

Fig. 9 Real-time lateral error sample data obtained during the 60km tour on M40 highwa- Madrid. The data demonstrating the undetectable lane marks on the road, cases 2,3, and 4

an adjacent multi-lane scenario due to the relatively long inter-vehicle distance. Spikes 0 and 1 are still tolerable to achieve a reliable VLC communication over 10 meters of inter-vehicle distance (see Fig. 8). Other spikes (2,3,4) can exceed the sustainable VLC lateral error (1 meter) which was a direct result of a temporary lane-marks deficiency along the driving path.

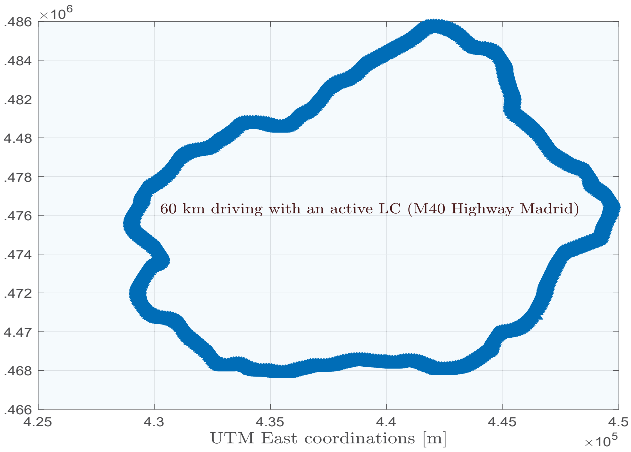

Fig. 10 60 km of Lane centering (LC) driving route in M40 highway Madrid

V. Conclusion and Future Work

In this paper, we studied and evaluated the deployment of the LC application to enhance the (VLC) optical-based communication connectivity for a platoon of autonomous vehicles. The obtained results confirm the enhancement of the misalignment between platoon members an assured the VLC link stability independently from any cooperation requirements as soon as the road lanes are detectable. Other detection confusion or temporary lane-marks deficiency scenarios can be tolerated and might introduce a temporary VLC interruption. Compared to communication-based platoon and LRF-VLC systems, we believe that the presented approach to applying the correction locally by using LC, make the system more resilient and reliable to rapidly recover any communication interruptions. However, the conducted work in this paper is an experimental-based investigation meant to validate the concept; we conclude that the study needs to further extend the investigation cases by including different trajectory scenarios, weather conditions, and more accurate platoon controllers.

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