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Zone-Based Matrix Headlight Feedback Control

M. Waldner[1*], N. Müller[1*], T. Bertram[1]

1: TU Dortmund University, Institute of Control Theory and Systems Engineering (RST), Dortmund, Germany
*: Equal contribution

1. Abstract

The contribution at hand introduces Zone-Based Lighting (ZBL), a novel feedback control approach for matrix headlights that dynamically adjusts illumination using real-time camera feedback. Unlike object-based systems relying on object detection, ZBL divides the vehicle's forward space into customizable 3D zones, each independently controlled by a PID controller to maintain optimal brightness levels. The system continuously measures and adjusts zone brightness to compensate for varying surface reflectivity and environmental conditions. Empirical evaluation demonstrates successful brightness control across different scenarios. ZBL offers cost-effectiveness by requiring only camera data without complex object detection systems, representing a paradigm shift toward dynamic zone-oriented illumination control that adapts to real-world conditions.

Keywords: Matrix Headlight Control, Adaptive Lighting

2. Introduction

Nighttime driving presents unique challenges in automotive safety, with visual perception significantly impaired compared to daytime conditions. Matrix headlight systems offer adaptive selective illumination by controlling individual light segments called pixellights. Controlling matrix headlights typically relies on predetermined illumination patterns based on dynamic object detection [1, 2], traffic object probabilities, driver gaze behavior [3], and environment classification, often failing to adequately address the complex dynamic interplay of varying road surfaces, weather conditions, and diverse traffic scenarios.

The contribution at hand introduces ZBL, a novel feedback control approach for matrix headlights that dynamically adjusts illumination based on real-time camera feedback. Unlike conventional open-loop systems that rely on object detection and topographical information,

ZBL divides the space in front of the vehicle into customizable 3D illumination zones, each independently controlled to maintain optimal brightness levels regardless of changing environmental variables. A zone can be a rectangle on the road or a cuboid flying over the sidewalk. The user defines the zones based on subjective preferences depending on the environment. Fig. 1 shows the zones as colored rectangles. The zones of the example are independent of the current road situation, some are located below the road in this example.

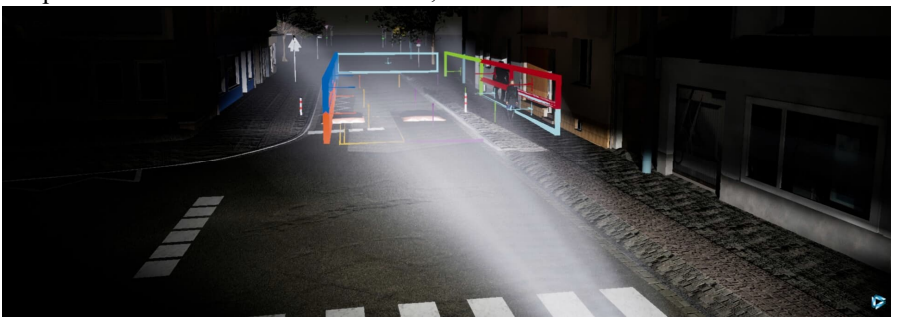

Figure 1: 3D illumination zones are shown as colored rectangles. A volumetric fog simulation illustrates the propagation of the headlamp beam.

The primary innovation of ZBL lies in its real-time camera-based feedback mechanism, which continuously measures and adjusts zone brightness to compensate for varying surface reflectivity and ambient lighting conditions. This approach represents a paradigm shift from traditional, precalculated, and static matrix headlamp illuminations to arbitrary, dynamic, and zone-oriented illumination control, offering more responsive and situation-aware illumination that adapts to real-world conditions rather than relying solely on pre-programmed patterns. One of the core motivations behind ZBL lies in its simplicity and adaptability. ZBL reduces sensor complexity and system costs by relying solely on camera-based image data. Additionally, the flexibility to define illumination zones according to subjective user requirements or specific traffic scenarios enables the creation of situation-tailored lighting.

Nevertheless, ZBL is not without challenges. The system's effectiveness is influenced by the accuracy with which illumination zones are defined for the current environment, as mismatched or improperly shaped zones may diminish performance. Fig. 1 illustrates a zone mismatch on the road, where some zones are positioned below the road. Shadows and rapidly changing surface reflections represent additional disturbances that impact system reliability. However, all object-, environment-, and material-based adaptive illuminations generally have these drawbacks.

3. Zone-Based Feedback Controlled Lighting

Object-Based Lighting (OBL) functions [1, 2] depend on the detected traffic objects by the ego vehicle. Examples are marker lights, which highlight potentially dangerous objects, and the projection of warning symbols on the road. ZBL does not rely on detected objects and requires only regions of interest in the camera image. However, additional data, such as map information or detected objects, can be used to refine the zones more precisely.

As Fig. 1 and 2 show, the area in front of the ego vehicle is divided by the lighting engineer into arbitrary 3D zones for ZBL implementation. A possible setup involves using a rectangular zone for the driving lane, a separate zone for the oncoming lane, and additional zones for the sidewalks. Moreover, zones can be positioned sequentially to divide the road into different distance segments. Fig. 2 illustrates a zone configuration from the perspective of the ego vehicle's camera.

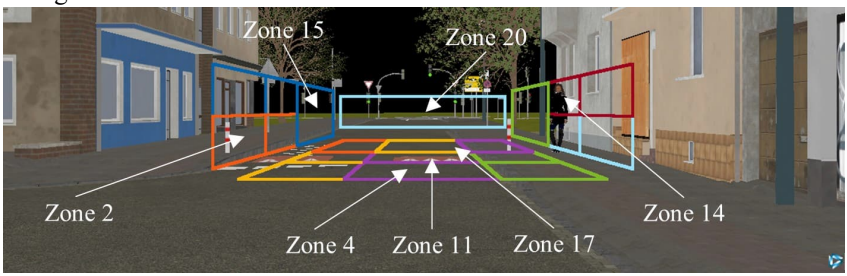

Figure 2: Illumination control zones as an overlay on the camera image.

Each zone has a lighting setpoint $w_k \in \mathbb{R}_{\geq 0}$ derived from an assessment function, where k is the zone index. The matrix headlight controller adapts the emitted light of the pixellights to fulfill these setpoints by analyzing the captured camera image $\boldsymbol{I} \in \mathbb{R}_{\geq 0}^{n_\mathrm{r} \times n_\mathrm{c}}$ from the ego vehicle. The camera image is assumed to be grayscale and has n_r rows and n_c columns of image pixels. The assessment of $\boldsymbol{I}$ results in a zone actual value $r_k \in \mathbb{R}_{\geq 0}$ and in the zone control error $e_k = w_k - r_k \in \mathbb{R}$.

When using a feedback controller like a PID and no optimizer or search algorithm, the lighting assessment function of $\boldsymbol{I}$ must be monotonic to the headlamp emitted luminous intensity. This ensures that the sign of e_k correctly indicates whether the zone target brightness should be increased or decreased. The zone brightness is defined by the zone headlamp relative luminous intensity setpoint $I_{\mathrm{v},k} \in \mathbb{R}_{\geq 0, \leq 1}$, which is uniform over the entire zone for homogeneous lighting. $I_{\mathrm{v},k}$ is the relative amount of the current headlamp's maximal luminous intensity $I_{\mathrm{v,max}}$.

As the zone assessment must be a monotonic function of $I_{\mathrm{v},k}$, the Weber contrast, which is the ratio of foreground to background brightness, can't be used. The reasons are camera pixel saturation, the limited sensor dynamic range, and blooming effects, which allow increasing headlamp lighting to enhance and later decrease object contrast. For example,

when the camera image pixels of the foreground object are in saturation, increasing the headlamp illumination will only brighten the background in $\boldsymbol{I}$, so the Weber contrast decreases.

The confidence of a neural network, e.g. YOLO, in its object detection is also a non-monotonic function of the headlamp brightness [4]. It can, therefore, also not be used as a control function.

A monotonic function of $I_{\mathrm{v},k}$ is the average brightness of the zone in the captured camera image. For the grayscale image $\boldsymbol{I}$ the average brightness $r_{\mathrm{a}} \in \mathbb{R}_{\geq 0}$ is

$$r_a = \frac{1}{n_{\mathrm{r}} n_c} \sum_{i=1}^{n_c} \sum_{j=1}^{n_{\mathrm{r}}} I(j,i)\,, \tag{1}$$

which monotonically increases when the headlamp increases the illumination of the objects in the image. An alternative function is the number of pixels over a brightness threshold. This function is not used in the contribution because it is not that sensitive to illumination changes and has more plateaus than the average brightness. Therefore e_k is defined as the difference in the average zone brightness in the camera image.

Each zone has an individual e_k and controller, which is a PID controller. The PID controller adjusts the zone $I_{\mathrm{v},k}$ to minimize $|e_k|$. The following Super Sampling Control (SSC) step calculates the utilization of the matrix headlight pixellights in real-time from the 3D definitions of the zones, namely position, size, and orientation, and all $I_{\mathrm{v},k}$ [5]. SSC takes the zones as target illumination objects and adjusts the pixellights to best reproduce the target illumination objects with the headlamp beam pattern. Using SSC allows zones to have arbitrary shapes, e.g., cuboids, and be positioned anywhere in front of the ego vehicle.

The matrix headlamp emits light into the environment, which is reflected by object surfaces and captured by the ego vehicle's camera. The camera sensor measures this reflected light as the system output, which is fed back to the controllers via image processing to close the control loop.

The image processing first segments $\boldsymbol{I}$ in the zones and assigns the pixel values to the zones. This processing creates for every zone an image pixel value tuple $\boldsymbol{i}_k \in \mathbb{R}_{\geq 0}^{n_k}$, containing the current grayscale values of all n_k pixels inside the convex hull of the zone object in $\boldsymbol{I}$. Therefore, all vertices of the zones, which are 3D corner points, are perspective transformed into the image coordinate system. Then, a monotone chain algorithm calculates the convex zone hull around the transformed points [6]. Fig. 3 shows a zone hull example of three cuboid zones and the resulting convex hulls. The indices of all pixels inside the hull are estimated and used to fill $\boldsymbol{i}_k$ with the current pixel values. The indices only have to be recalculated when the zone 3D definitions change. Using convex hulls has the advantage that the zones can have arbitrary shapes and are not limited to rectangles.

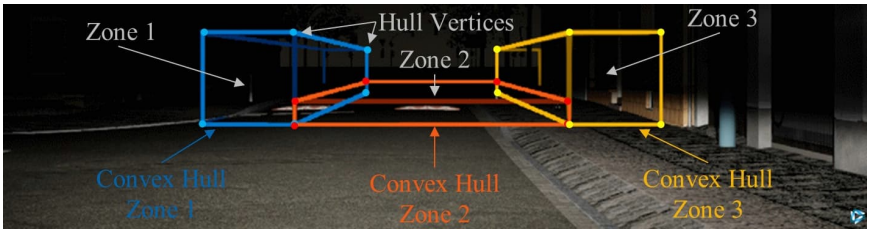

Figure 3: Convex zone hulls (light color) of cuboid zones (dark color).

The following zone assessment applies the assessment function to every $\boldsymbol{i}_k$ to calculate r_k. With the average brightness from (1), the assessment is

$$r_k = \frac{1}{n_k} \sum_{j=1}^{n_k} i_k(j), \tag{2}$$

with $i_k(j)$ as the access function to the j-th element of $\boldsymbol{i}_k$. Then $e_k = w_k - r_k$ is calculated, which closes the control loop. Fig. 4 shows the complete loop for an arbitrary number of n_z zones by showing the loop for the first and the k-th zone.

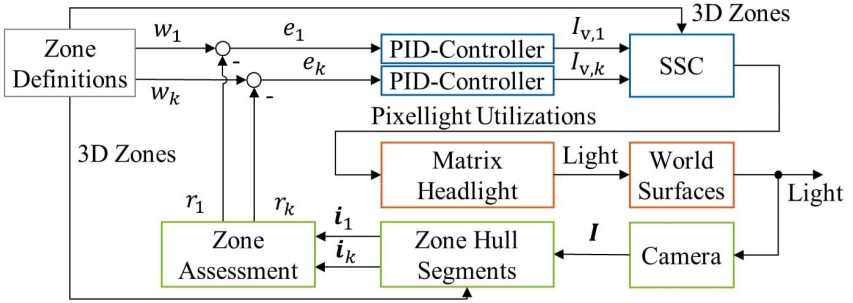

Figure 4: Zone-based headlight control loop consisting of controller (blue), system (orange) and sensor (green) components for an arbitrary zone count k.

4. Challenges in the Application

The application of the ZBL control concept presents two major challenges: properly defining the zones and effectively parametrizing the PID controllers. The definition of the zones includes choosing w_k and determining their 3D appearance, which both depend on the environmental situation. Since a zone defines a target illumination plane, discrepancies arise between current and expected lighting when the plane and zone do not correspond to the actual surface geometry.

Fig. 5 illustrates an extreme mismatch scenario, where a zone is defined in front of the sky, indicating that there is no real-world surface for the zone to reflect light. Therefore, the controller cannot influence the brightness of the zone because the emitted light from the

headlamp is not visible due to the lack of reflection. In this scenario, the controller will set the pixellights, which would illuminate the zone to maximal brightness because the zone hull in $\boldsymbol{I}$ will always be too dark. Another example in Fig. 5 is a zone defined on road height for a raised inner-city sidewalk. This results in a zone below the sidewalk so that the headlamps do not illuminate the entire sidewalk. Fig. 5 shows additional zone mismatch examples, and Fig. 3 displays the convex hulls of the same zones overlaid on a camera image.

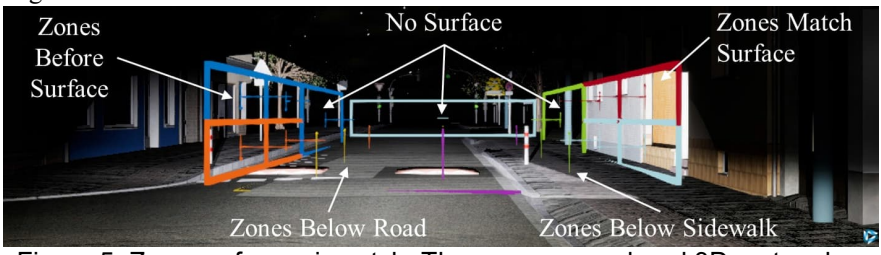

Figure 5: Zone surface mismatch. The zones are colored 3D rectangles, and arrows indicate their center points. Surfaces mask non-visible zones.

To minimize the zone surface mismatch, the zones must be adapted to the current environment. However, changing the 3D appearance of a zone results in a recalculation of the convex hull in $\boldsymbol{I}$. One way to achieve zone adaptation is to define a set of zones optimized for different environmental classifications, such as urban, suburban, rural roads, or wet road conditions.

The second challenge is to parametrize the PID controllers to achieve smooth and fast illumination control without introducing disturbing flickering effects. Fig. 6 shows the step responses of the zone brightness, allowing for a comparison of the different material reflection properties. The controlled systems are the world surfaces that behave like simple proportional transfer functions without memory, as they reflect light to the camera. Due to the light beam spread characteristics governed by the inverse-square law, the camera-captured light intensity depends on both the distance from the headlamp to the surface and the distance from the surface to the camera. Therefore, the proportional gain of the controlled system $K_{\mathrm{s,p}} \in \mathbb{R}_{\geq 0}$ depends on the distance. This can be seen in the different heights of the step response in Fig. 6 for road zones 4 and 17 for identical $I_{\mathrm{v},k}$ stimulus.

Moreover, $K_{\mathrm{s,p}}$ depends on the surface properties and reflection characteristics, like the wetness of asphalt or the color of painted house walls. Additional aspects are potential zone mismatches or shadows on surfaces, which may reduce the reflected light. The camera sensor's behavior may introduce nonlinearities and disturbances to the image's appearance. Because of these effects, $K_{\mathrm{s,p}}$ of a zone typically changes when the ego vehicle moves. These changes can be rapid and discontinuous, particularly when environmental conditions shift abruptly, such as transitioning from a white building wall to green vegetation. In Fig. 6, the step responses of zone 2 (solid orange line), a sidewalk and wall with shadows, and zone 4

(solid purple line), the road, show the influence of shadows on $K_{s,p}$. Shadows remain dark independent of the headlamp-emitted light, which is a possible explanation for the similar r_k of ~0.3 before the $I_{v,k}$ jump and the different values of $r_2 = 0.47$ and $r_4 = 0.39$ after.

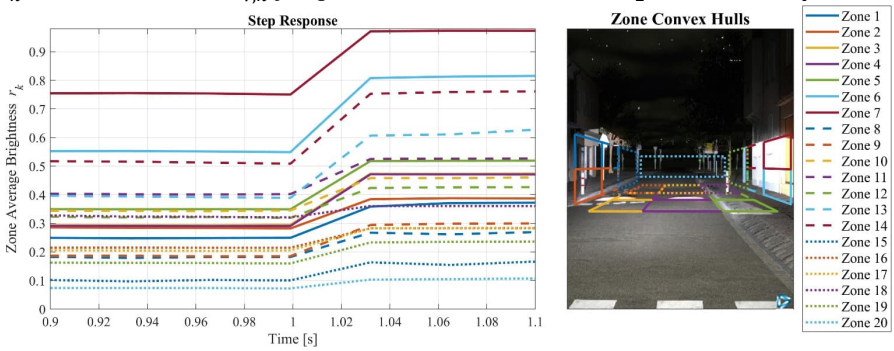

Figure 6: Step response of zone r_k. $I_{v,k}$ jumps for all zones at 1 s from 10 % to 40 % of $I_{v,max}$. The sample time is 33 ms and the zone hulls are shown on the right.

The uncertainties in the system's behavior limit the practical and robust application of the ZBL feedback-control approach. Therefore, this contribution proposes different application scenarios for ZBL featuring either fast or slow responses to environmental changes. Fast response application scenarios involve lighting adaptions to moving pedestrians, inhomogeneous street lighting, and speed bumps, with maximal adaptation times of under one second, which should be typically much faster. Slow response scenarios encompass lighting adaptation to lateral slow environmental class transitions, such as from residential areas to forest boundaries or from new to weathered road surfaces, with adaptation times exceeding three seconds.

In its current state, it is not advisable to use ZBL for fast-response applications because abrupt changes in system parameters can result in unstable fast-responding controllers, causing very disturbing lighting flicker. The empirical evaluation in the next section will demonstrate that the zone controller can adjust the lighting stably and slowly to match the environment. However, due to the complexity of dynamic system behavior, formal stability proof cannot be provided in this contribution. For rapid adjustments, combining zone feedback controllers with open-loop, fast, dynamic object-based lighting control strategies is recommended.

5. Evaluation

The empirical evaluation of the proposed ZBL controller utilizes Unreal Engine 5, along with our SOL matrix headlight simulation and a virtual model of the German city of Lippstadt created by 3D Mapping Solutions GmbHand based on high-resolution

environment scans. The scenario shown in Fig. 1 utilizes the left matrix headlight, which has a resolution of 1024 × 400 = 409,600 pixels, a horizontal beam angle of ±20 ° and a vertical beam angle of ±5 °. In all evaluations, the ego vehicle remains stationary. The PID controllers have a cycle time of 33 ms and should maintain a target average image brightness of 50 % on the road and 35 % on the sides. The PIDs for the road have the parameters in mathematical description $K_\mathrm{p} = 30$ and $K_\mathrm{I} = K_\mathrm{D} = 20$. The side PIDs have $K_\mathrm{P} = K_\mathrm{I} = K_\mathrm{D} = 1$. The parameters are manually tuned empirically through successive approximation to create a compromise between control speed and flicker avoidance. Since the side zones are expected to exhibit higher variation in surface properties, the PIDs have a slower response than the road controllers to prevent flickering. The PID setup is designed to provide a slow response to environmental changes. Fig. 7 shows the progression of e_k for the road zones and Fig. 8 shows the e_k progression for the side zones. Fig. 9 illustrates the system's behavior when a person wearing black clothing acts as a disturbance.

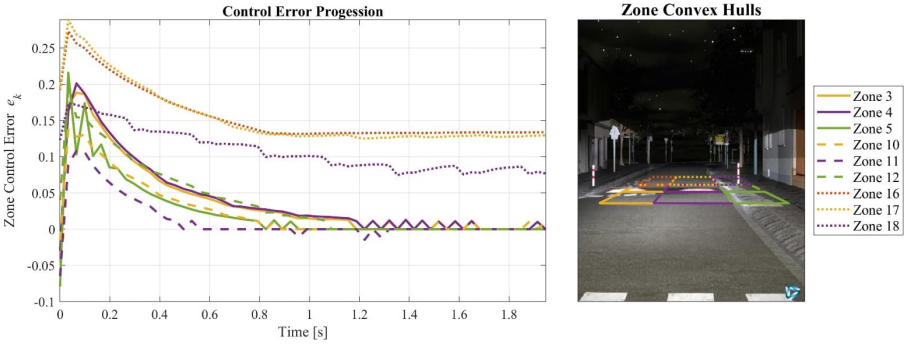

Figure 7: Zone control error e_k progression for road zones.

For the near road zones 3-5 (solid lines) and 10-12 (dashed lines) in Fig. 7, the controller can reduce $|e_k|$ to zero. For zone 11 the controller reduces $I_{\mathrm{v},11}$ to compensate for the stronger reflection of the speed bumper compared to the road surface. This increases the contrast and visibility of the bumper. The average brightness of zone 4 and 11 is similar. For the far zones 16-18, achieving $|e_k| = 0$ is not possible because the target surface is too far away, and the matrix headlight cannot emit sufficient light. The controller sets $I_{\mathrm{v},k}$ to $I_{\mathrm{v,max}}$ and the zones remain too dark in $\boldsymbol{I}$.

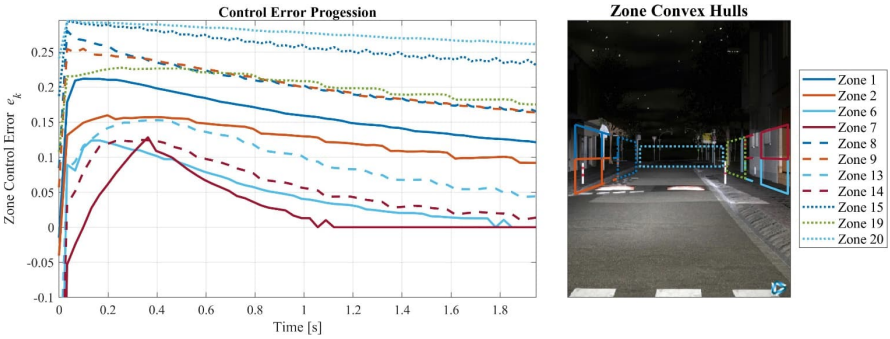

Figure 8: Zone control error e_k progression for side zones.

For side zones 6 (solid cyan line) and 7 (solid purple line) in front of a house wall in Fig. 8, the controller can reduce $|e_k|$ to zero. For the other zones, the effectiveness of the control depends, as described in Sec. 4, on the amount of shadowing, like in zones 1 (solid blue line) and 2 (solid orange line), and clear skies behind zones, such as in zones 15 (dotted blue line) and 20 (dotted cyan line). For zone 20, the controller increases $I_{\mathrm{v},k}$ from 1 % to 17 % of $I_{\mathrm{v,max}}$ in 1.95 s, which does not strongly reduce e_{20}. The $I_{\mathrm{v},k}$ increase for zone 1 is 1 % to 10 % at the same time, which has a greater impact on e_k. Due to shadows and the absence of world surfaces, it is difficult for the controller to fulfill the control objectives. However, all conceivable matrix headlight control strategies generally have problems in these scenarios because they cannot directly influence shaded areas, as the headlight origin is fixed.

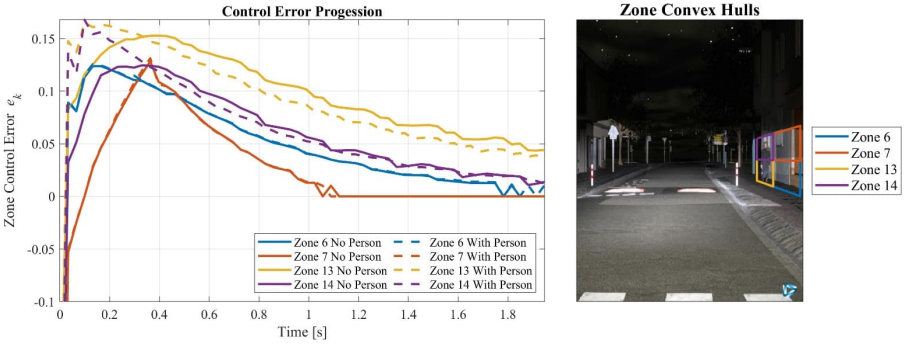

Figure 9: Changes in zone control error e_k progression from potential pedestrians in front of the wall in zones 13 and 14.

Fig. 9 illustrates the changes in the control error progression when a black-clothed woman appears in front of a world surface, specifically when it is a white-painted house wall on the right. The woman affects only the zones in which she appears. After the first significant

differences, the error progression gets similar. However, for zone 14 (solid purple line), the controller uses a ~7 % higher $I_{v,14}$ to compensate for the woman's dark clothing.

This black-clothed woman on the sidewalk is used to evaluate the influence of ZBL on neural network-based object detection. With a low beam, the default YOLOv8 [7] neural network without any special training does not detect this person due to the low environmental light. High beam enables detection, and ZBL with the described setup increases YOLO's confidence by 51 % relative to high beam. This first experiment shows the potential of ZBL to improve automated driving and object detection.

6. Conclusion & Outlook

This contribution presents a novel zone-based matrix headlight feedback control concept that dynamically adapts illumination to arbitrary environmental conditions. The controller requires only camera imagery without detected objects or map data, making this approach both cost-effective and computationally efficient compared to object-based systems. Empirical results demonstrate the applicability of the concept across diverse environmental conditions. ZBL represents a promising approach for achieving enhanced adaptive lighting performance.

Future research should aim to improve the ZBL response time and stability, enabling faster reactions to environmental changes. One promising direction is to utilize fast OBL for rapid open-loop responses to detected traffic objects while employing ZBL for general lighting adaptation. This hybrid approach combines the strengths of both methodologies to advance next-generation dynamic adaptive front lighting systems.

7. References

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