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Matrix Headlight Control Loop for Undistorted Symbol Projection

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Abstract

Projecting symbols onto road surfaces using matrix headlights enhances communication between automated vehicles and their environment. However, when such symbols are projected onto uneven road surfaces, the resulting distortions can significantly impair the legibility and interpretability of the projected information. This contribution presents an advanced feedback control methodology that mitigates these distortions by dynamically adjusting the projection parameters based on real-time analysis of the symbol's appearance on an imaginary plane. Unlike previous methods that rely on global optimization, which can introduce instability in abrupt symbol movements, the proposed approach uses a cascaded feedback control architecture. This architecture separates the control of the symbol's position and shape, allowing smoother transitions and improved robustness. The effectiveness of the proposed method is evaluated using a virtual simulation environment modeled after the German city of Lippstadt.

Index Terms: Matrix Headlights, Symbol Projection, Control, Stabilization

1 Introduction

The field of automotive lighting has undergone significant advancements in recent years, particularly in matrix headlight technology. One of the most intriguing applications of this technology is the projection of symbols onto the road surface in front of a vehicle. This capability revolutionizes communication between automated vehicles and their surroundings, including pedestrians and other road users. However, the practical implementation of this technology faces several challenges, primarily due to the uneven nature of road surfaces.

The issue addressed in this research is the distortion and positional changes that occur when symbols are projected onto non-uniform surfaces [1,2]. As seen in Fig. 1, these distortions can impair the legibility and interpretability of the projected symbols, thereby diminishing their effectiveness as a communication tool. The importance of this problem cannot be overstated, as unambiguous communication is paramount in the context of automated driving systems.

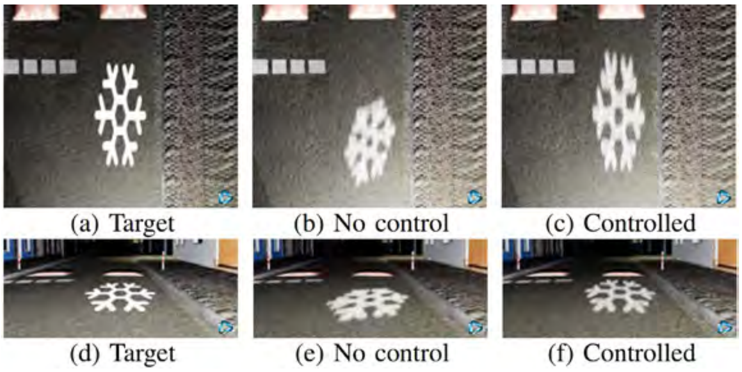

(a) Target (b) No control (c) Controlled
(d) Target (e) No control (f) Controlled

Fig. 1: Projection of a snowflake on an uneven road without and with feedback control [1].

This contribution's presented feedback control algorithm builds upon our previous work [1], which introduced a feedback control approach for projected symbols based on global optimization. The novelty of the initial approach lays in the ability to correct distortions without relying on measured or estimated surface elevations of the road [2]. Not requiring an environment model is a significant advantage, as it eliminates the need for complex and potentially unreliable road surface mapping systems, e.g., with structured light [3]. However, [1] used a gradient-free global optimization method to minimize the error between the target and the current projected symbol in this system. This led to abrupt changes and jumps in the projected symbol's appearance, which could distract observers. Such sudden movements could be distracting or confusing to other road users, potentially defeating the purpose of the communication system.

The current paper builds on this previous work by introducing a novel feedback control framework that operates in the domain of an imaginary appearance plane. This approach decouples the control of the symbol's position and shape, allowing for more intuitive and continuous adjustments. The improved controller uses no single gradient-free global optimization but four novel independent feedback controllers and projection errors. The cascaded control loop comprises an outer loop that regulates the symbol's position and orientation on the imaginary plane based on the novel errors and an inner loop that optimally utilizes the pixels of the matrix headlight to achieve the desired projection on this plane. This improved method enhances the smoothness of the symbol's appearance control on the road surface, as it avoids abrupt changes and jumps. The smooth behavior is a crucial improvement, as it enhances the readability and comprehensibility of the projected symbols, making them more effective as a communication tool.

In Section 2, the concept of the matrix headlight cascaded control loop will be described. Section 3 presents the novel definition of the control error, and Section 4 the evaluation, followed by the conclusion and outlook in Section 5.

2 Symbol Projection Feedback Control Loop

The presented feedback control algorithm extends the already published control concept [1] further by introducing a more sophisticated control mechanism to smooth the adjustment of the projected symbol. The key innovation of this new approach is the introduction of an imaginary appearance plane. The appearance plane is defined as an imaginary surface on which the symbol appears to lie, distinct from the actual physical surface onto which the symbol is projected. A computer vision algorithm estimates the imaginary appearance plane from the taken vehicle camera image. The projection plane is a target plane by the headlamp pixel utilization controller, as the controller assumes the real surface to calculate the optimal pixel utilizations. Fig. 2 shows the real road surface, the imaginary appearance, and the projection plane.

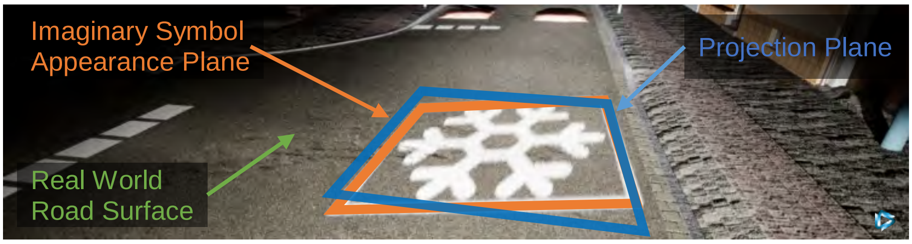


Fig. 2: Visualization of the differences of the imaginary symbol appearance plane and the projection

The control system proposed in this research minimizes the difference between the ideal appearance plane and the current appearance plane of the projected symbol in the camera image. The plane differences manifest as errors in both the position and shape of the symbol plane. A cascaded two-step control system minimizes the absolute number of errors. The cascaded control system consists of two primary components [1]: an outer controller of the appearance plane and an inner controller of the pixel utilizations. The outer controller is responsible for managing the position and rotation of the appearance plane. It calculates an optimal projection plane based on the discrepancies between the ideal and current appearance planes. This projection plane serves as a target for the inner controller. Our feedforward headlight pixel controller [4] determines the optimal pixel utilization for the projection plane calculated by the outer controller. This controller translates the abstract projection plane into concrete instructions for the matrix headlight system, specifying which pixels should be activated and at what intensity to achieve the desired projection. Fig. 3 shows the complete control loop.

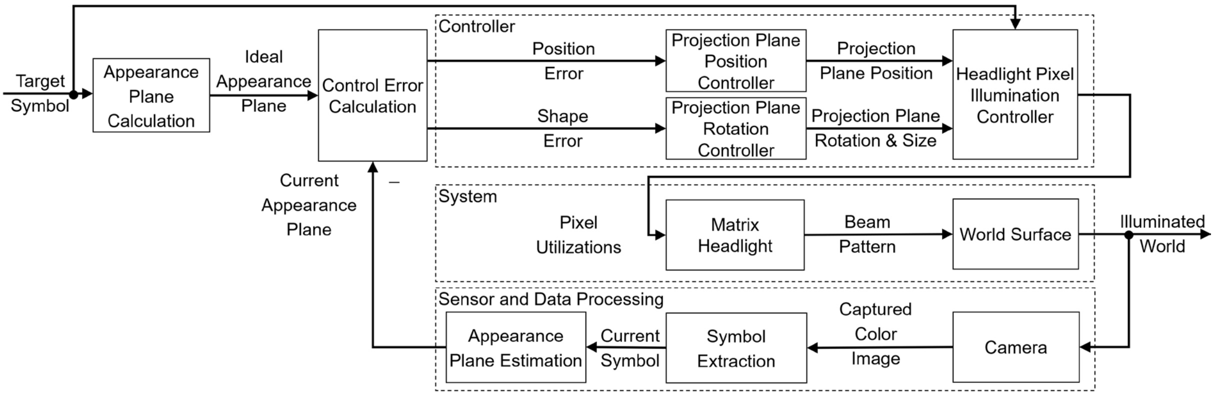


Fig. 3: Symbol projection feedback control loop. The imaginary appearance is controlled by the outer feedback controller and the matrix headlight pixels by the inner feedforward controller.

A critical component of this control loop is the feedback mechanism. The vehicle's onboard camera system captures the projected symbol. The current appearance plane must be estimated from this captured image, which machine learning techniques or point correspondence algorithms can do.

Machine learning methods could potentially provide robust and real-time estimation of the appearance plane. Such an approach would involve training a neural network on a large dataset of projected symbols under various road conditions. The network would learn to infer the parameters of the appearance plane from the distorted image captured by the camera. The advantage of this approach is its potential for high-speed operation and its ability to generalize to unseen road conditions. However, substantial training in data and computational resources is required.

Alternatively, point correspondence algorithms from computer vision could be employed. These methods work by identifying specific points in the projected symbol and matching them to corresponding points in the ideal symbol. By analyzing the transformations required to map these points, the algorithm can infer the parameters of the appearance plane. This approach may be more interpretable and requires less training data, but it could be less robust to severe distortions, environment lighting, or partial occlusions of the symbol. The corresponding points must be robust and detectable in the projected symbol.

3 Definition of the Control Errors

The novel method of this contribution redefines the single control error from [1] into two separate position and shape components. This decomposition of the error signal provides more nuanced information about the nature of the distortion, allowing for more precise corrective actions. Specifically, the sign and magnitude of these error components directly indicate the amount and direction of the required adjustments.

To get the current projected symbol by the matrix headlights for the controller, the symbol is extracted from the camera image as a scalar (grayscale) symbol image $\boldsymbol{I} \in \mathbb{R}_{\geq 0}^{n_\mathrm{r} \times n_\mathrm{c}}$ with n_r rows and n_c columns via background subtraction [1]. $\boldsymbol{I}$ consist ideally only of the current symbol in white on uniform black after extracting it from the current camera image by subtracting an image without a symbol. Therefore, the presented control approach's stability and robustness depend on the symbol extraction quality via background subtraction.

Raw image moments [1,5] estimate the imaginary appearance image plane in this contribution. The function $I(y, x)$ returns a single image element at image position x, y, so a raw image moment $m_{i,j}$ of $\boldsymbol{I}$ is

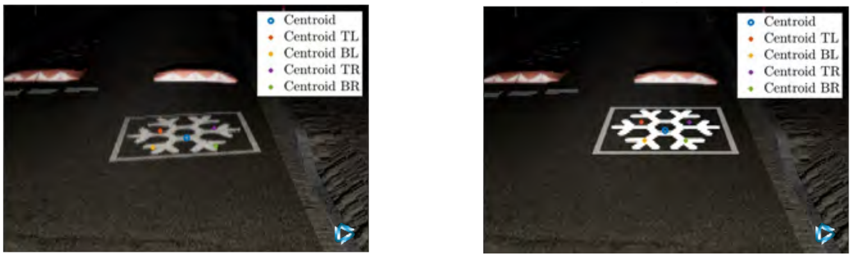
$$m_{i,j} = \sum_{x=0}^{n_\mathrm{c}-1} \sum_{y=0}^{n_\mathrm{r}-1} x^i \, y^j \, I(y, x), \tag{1}$$

and with them the position $\boldsymbol{p_c} \in \mathbb{R}^2$ of the image centroid is

$$\boldsymbol{p}_\mathrm{c} = \begin{bmatrix} \frac{m_{1,0}}{m_{0,0}} & \frac{m_{0,1}}{m_{0,0}} \end{bmatrix}^\mathrm{T} = [p_\mathrm{c}(1) \quad p_\mathrm{c}(2)]^\mathrm{T}, \tag{2}$$

with the function $p_\mathrm{c}(i)$ to get the i-th element/coordinate of $\boldsymbol{p}_\mathrm{c}$. With (1) and (2), the position error of the appearance plane is similar to [1] the difference in the position of the centroid of the current symbol image and the target one. The error in the image x-direction is $e_\mathrm{x} = p_\mathrm{c}(1) - p_\mathrm{c,t}(1)$ and in y-direction $e_\mathrm{y} = p_\mathrm{c}(2) - p_\mathrm{c,t}(2)$ with $\boldsymbol{p}_\mathrm{c,t}$ as the target centroid.

The novelty of this paper is the definition of the rotation error, which is based on comparing four centroids to estimate the rotation of the appearance plane. Centroids have the property that their position calculation in (1) and (2) is robust against symmetric image distortions and symmetric equally distributed additive noise around their ideal position, which makes them good features for interference-resistant image processing. To calculate the new four centroids $\boldsymbol{I}$ is divided at $\boldsymbol{p_c}$ into four sub-images, and for every image, an individual centroid $\boldsymbol{p}_{\boldsymbol{c},\mathrm{tl}} \in \mathbb{R}^2$ of the Top-Left (tl) image, $\boldsymbol{p}_{\boldsymbol{c},\mathrm{tr}} \in \mathbb{R}^2$ of Top-Right (tr) $\boldsymbol{p}_{\boldsymbol{c},\mathrm{bl}} \in \mathbb{R}^2$ of Bottom-Left (bl) and $\boldsymbol{p}_{\boldsymbol{c},\mathrm{br}} \in \mathbb{R}^2$ of Bottom-Right (br) is calculated. Fig. 4 shows the centroids for a snowflake symbol and that the position of the four outer centroids is not at the same spot as the current distorted symbol, an ideal target one. The relative difference is caused by the division of $\boldsymbol{I}$ into four sub-images so that an overall symmetric distortion is not symmetric for the sub-images.



(a) Current symbol. (b) Target symbol.

Fig. 4: Centroid of whole symbol and of the four sub-images for a snowflake symbol.

With the four centroids $\boldsymbol{p}_{\mathbf{c},\mathrm{tl,t}} \in \mathbb{R}^2$, $\boldsymbol{p}_{\mathbf{c},\mathrm{tr,t}} \in \mathbb{R}^2$, $\boldsymbol{p}_{\mathbf{c},\mathrm{bl,t}} \in \mathbb{R}^2$ and $\boldsymbol{p}_{\mathbf{c},\mathrm{dr,t}} \in \mathbb{R}^2$of the target symbol, the appearance plane roll error e_r around the plane longitudinal axis is

$$e_\mathrm{r} = \frac{\left(p_{\mathrm{c,tr}}(2) - p_{\mathrm{c,tl}}(2) + p_{\mathrm{c,br}}(2) - p_{\mathrm{c,bl}}(2)\right)}{2} - \frac{\left(p_{\mathrm{c,tr,t}}(2) - p_{\mathrm{c,tl,t}}(2) + p_{\mathrm{c,br,t}}(2) - p_{\mathrm{c,bl,t}}(2)\right)}{2}, \tag{3}$$

and the appearance plane pitch error e_p around the transverse axis is

$$e_\mathrm{p} = \frac{\left(p_{\mathrm{c,tr}}(2) + p_{\mathrm{c,tl}}(2)\right)}{2} - \frac{\left(p_{\mathrm{c,br}}(2) + p_{\mathrm{c,bl}}(2)\right)}{2} - \frac{\left(p_{\mathrm{c,tr,t}}(2) + p_{\mathrm{c,tl,t}}(2)\right)}{2} + \frac{\left(p_{\mathrm{c,br,t}}(2) + p_{\mathrm{c,bl,t}}(2)\right)}{2}. \tag{4}$$

This reformulation of the symbol projection control with the four errors $e_\mathrm{x}, e_\mathrm{y}, e_\mathrm{r}$ and e_p enables the use of four proportional-integral-derivative (PID) controllers as the outer controller in the cascaded system. The PID controllers attempt to minimize the absolute error of this error over time by adjusting a control variable, which, in this case, would be the parameters of the projection plane. The projection plane has in general, nine degrees of freedom, three positions, three rotations, and three sizes, but after previous experiments of [1], only four degrees are used because some are over light propagation connected like plane size and rotation and lead to similar looking results [1]. The PID controllers control the world x-, y-position of the plane, which are distance and horizontal alignment to the ego-vehicle. The plane z-position is set fixed to the estimated road height. They also control the right-handed roll and pitch angle of the plane, and the yaw is set to fixed 0°. The size of the projection plane is fixed to the target symbol size in world space and not adjusted.

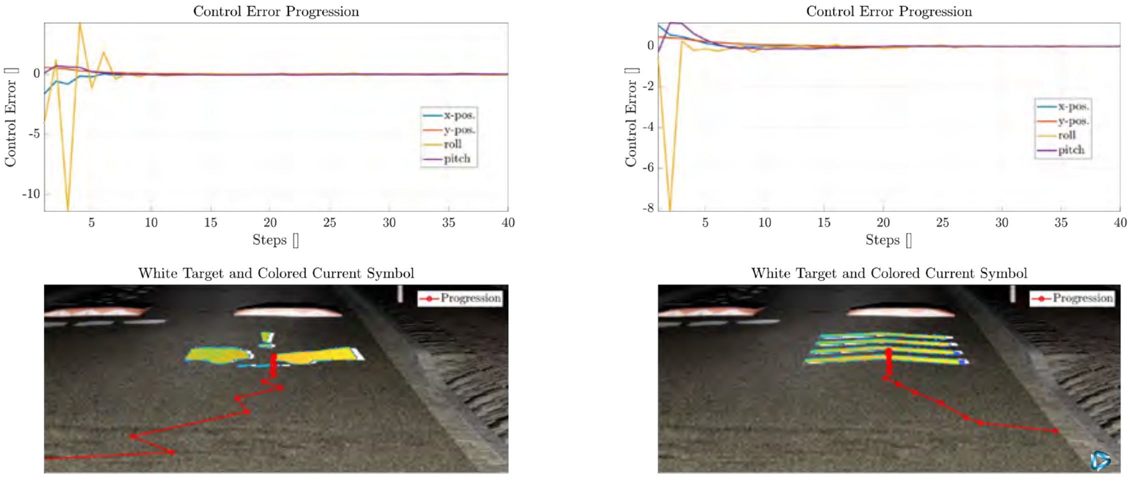
4 Evaluation

The theoretical thoughts for the general evaluation of the feedback symbol control can be found in [1], so in this contribution only additional remarks for the PID approach are discussed. As the system is an illuminated world, there are no relevant past values, time dependences, and delays. However, there are location dependencies. For example, suppose a symbol is moved smoothly over a curb without adjusting the height of the projection surface. In that case, the change of its centroid position is abrupt and, therefore, depends on the current surface. Additionally, the correct calculation of the centroids depends of the quality and robustness of the symbol extraction from the camera image under all environmental light conditions, which can change fast, e.g. by other headlights. Therefore, it is challenging to make theoretical statements about the stability range and robustness of the controller for all surface profiles, environment lightings, and headlight types. Limiting the controller's possible values, especially the rotation angles, is advised to ensure that all five centroids can be calculated, which is mandatory for the errors. The controller obviously becomes unstable if no symbol can be extracted from the camera image because it is not visible or not all five centroids can be calculated.

The experimental evaluation of the improved symbol projection control algorithm is done virtually in Unreal Engine 5.2 [1] with our matrix headlight simulation [4,6]. The feedback controller works on the actual SSL|HD headlight by the Forvia-Hella GmbH, which can be due to a Non-Disclosure-Agreement (NDA) not shown, so this contribution uses an idealized matrix headlight with 1024 rows and 332 columns. The horizontal beam angle area is $\pm 10^\circ$ and vertical -1.5° top to 3.5° down. The symbol is only projected by the left headlight and should be 17 m directly in front of the ego-vehicle with a width of 2 m, height of 4 m and no rotation. The parameters of the PID controllers were adjusted empirically with suggestive approximation and the controllers are implemented in MATLAB. The example scenario is similar to [1] and is the uneven Bastionstraße 4 in a virtual 3D environment of the real German city Lippstadt, which Fig. 5 shows. The 3D environment was created by the 3D Mapping Solutions GmbH based on environment scans.

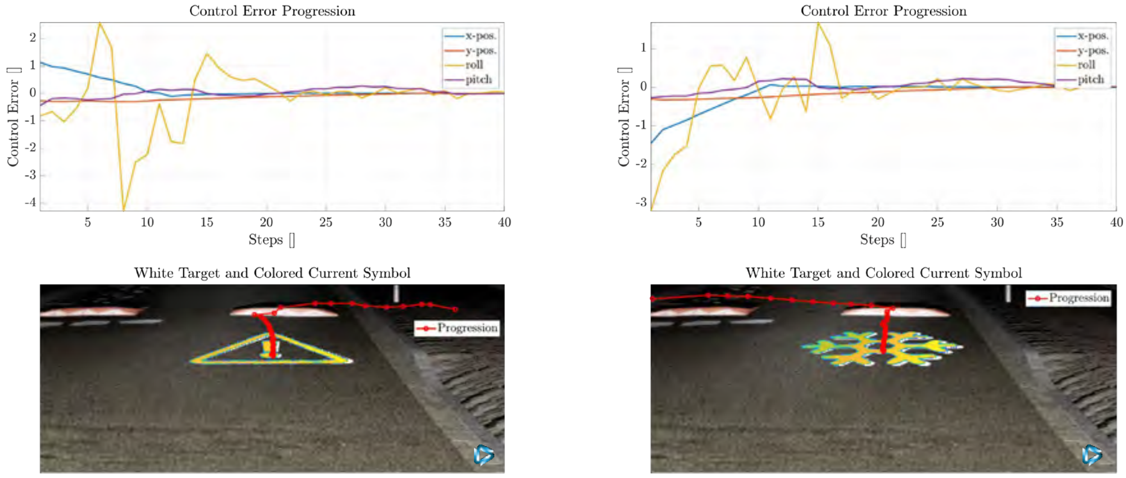
Fig. 5: Evaluation scenario with displayed mesh to visualize the unevenness of the road and the non-rotated projection plane in blue. The ego-vehicle is placed at the bottom right.

Four different start positions and symbols are evaluated to evaluate the stability of the controller and usability for different symbols. The positions are four outer positions at the edges of the illumination area of the used headlight, and the initial roll of the projection plane is set to $-5°$ and the pitch to $-2°$. Fig. 1 and Fig. 5 show the appearing of a not controlled symbol projection to give an impression of the expected distortions at the evaluation target point. Fig. 6 shows the results of the controller for the four initial positions and four different symbols. Fig. 6a uses the distance warning, Fig. 6b chevron arrows, Fig. 6c an exclamation mark inside a triangle as a warning sign, and Fig. 6d a snowflake symbol. The feedback controller can guide the symbol to its desired location and undistort it. As the road is not uniformly uneven, a slight difference between the target and the current symbol remains, which cannot be compensated. The red progression line shows the path of the symbol to the target position.



(a) Start bottom-left with collision waring symbol.

(b) Start bottom-right with chevron arrow symbol.

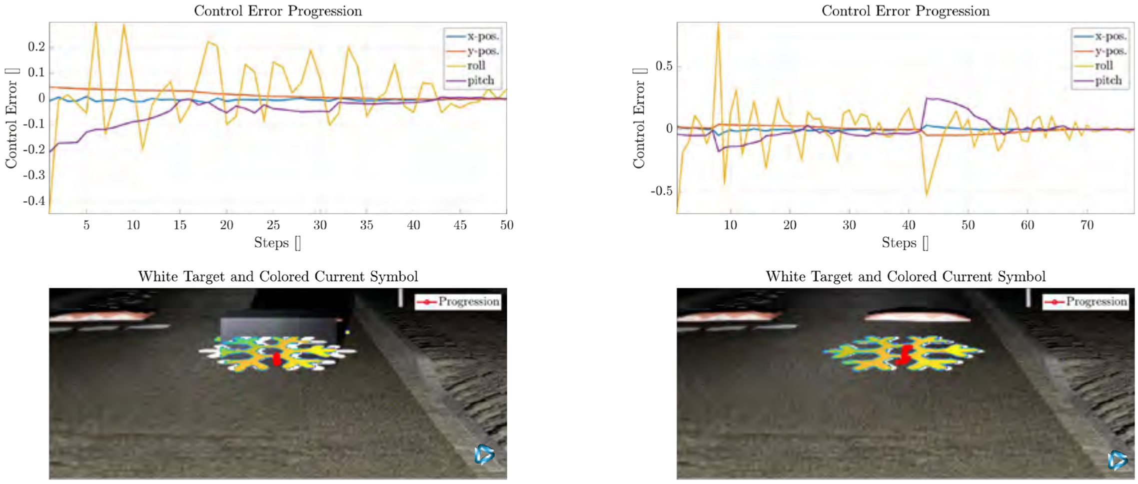


(c) Start top-right with warning sign symbol.

(d) Start top-left with snowflake symbol.

Fig. 6: Symbol projection control from four start positions and four symbol types on an uneven road. The course of the control errors is shown at the top in the subfigure for the control steps and the current symbol of the final control step is shown at the bottom as an overlay in false colors with parula colormap on the target image. The course of the symbol is marked with a red line.

The next evaluation task is to compensate for structural disturbances, e.g. the appearance or disappearance of objects. In this contribution, a black box appears and then disappears at the target area of the symbol. Fig. 7 shows the results for a block at target position in Fig. 7a and in Fig. 7b an at control step 7 appearing and at 42 disappearing box. The controller tries to compensate for the disturbance of the box by adjusting mainly the pitch angle of the projection plane.



(a) Black box is at the target position

(b) Box appears at control step 7 and disappears at step 42.

Fig. 7: Behavior of the controller towards objects in the target region.

5 Conclusion & Outlook

This contribution presented a novel feedback controller of the projected symbol by matrix headlights with four PID controllers. The controller can handle different types of matrix headlights, symbols, initial settings, structural interferences, and uneven roads and realize the symbol's smooth and continuous transition to its desired state. There is no need to estimate like [2] the road profile in front of the vehicle.

Further research will focus on finding rules for adjusting the PID control parameters and calculating the controller's stability range. Therefore, the system will be analytically modeled via ray tracing to make mathematically proven statements about the time behavior of the control errors and to prove stability.

6 Acknowledgment

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