RE-AIMING

An Automatic Recalibration System

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Abstract

Vehicle headlights have a significant impact on road safety during night-time driving. Incorrectly adjusted lighting systems are among the main causes of impaired visibility and hazardous glare. This whitepaper analyzes the limitations of current calibration methods and presents an innovative re-aiming system that enables continuous, software-assisted readjustment of headlight alignment during driving. It combines high-resolution pixel headlights, front cameras, and AI-based image processing into a closed control loop that detects markers within the light distribution, analyzes them, and specifically adjusts the light output. Through full system integration, highly precise and adaptive alignment is achieved, optimizing both visibility and glare avoidance. Thus, the re-aiming system contributes to the advancement of modern vehicle lighting technology and to enhanced traffic safety.

Table of Contents

1 Motivation

Vehicle headlights play a decisive role in road safety during night-time driving. They are therefore a central focus of current research, particularly in the front lighting domain, which concentrates on increasing range, brightness, and quality of vision (better detection and recognition). At the same time, headlights must not dazzle the driver or other road users. To maximize traffic safety, these two aspects must be balanced and brought into harmony. In this process, the correct alignment of the headlight plays a central role, since a misaligned headlight can significantly impair both objectives. Horizontal as well as vertical misalignments cause considerable issues:

Headlights aimed too low reduce the driver's effective visibility range, while headlights aimed too high cause excessive glare and endanger oncoming traffic. Similarly, an incorrect horizontal alignment can restrict visibility at the roadside, and a deviation to the left (from the driver's perspective) increases glare for oncoming traffic.

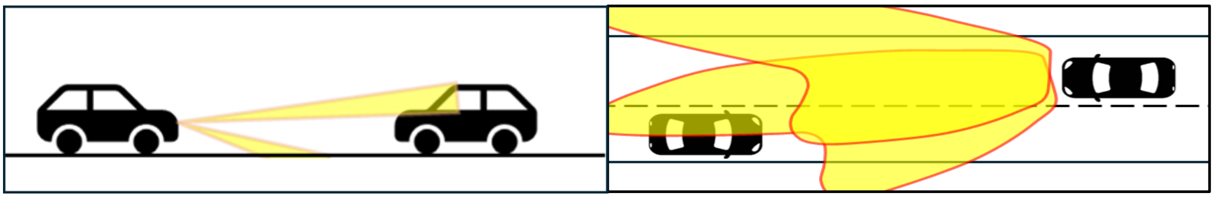

Figure 1: Exemplary representation of incorrect headlight alignments. Left – horizontal misalignment, Right – vertical misalignment

Relevance of the Problem

Despite technological progress, numerous studies at the Laboratory of Adaptive Lighting Systems and Visual Processing (ALSVV) at Technical University Darmstadt [4], as well as surveys conducted by organizations such as the FIA and ADAC, confirm that glare remains a major issue, perceived by many drivers as at least disturbing or even intolerable. While high beam is often cited as the main cause of glare, nearly half of the surveyed drivers also consider low beam to be excessively glaring. This indicates that even modern headlight systems can be problematic despite optimized low beam distribution and high beam assist systems. Since the participants' responses do not allow conclusions to be drawn regarding the type of glare (physiological/psychological glare, i.e., discomfort/disability glare) or any physically measurable parameters, it must be assumed that multiple causes are intermingled. However, several studies consistently show that no significant glare is perceived when headlights are properly adjusted. This is substantiated, among others, by the works of Totzauer [1], Locher et al. [2], Bullough et al. [3], Zydek [4], and Locher and Kaley [5].

This suggests that a large part of the glare issue is attributable to incorrect headlight alignment. Advanced systems such as glare-free high beam aim to reduce glare by dynamically adjusting the light distribution. However, the effectiveness of these systems also entirely depends on correct headlight alignment. Moreover, these technologies require safety buffers between the driver's own light and oncoming traffic, which results in visible dark gaps in illumination. The more precise the headlight alignment, the smaller these gaps can be—allowing more light on the road and thereby increasing overall safety. The need for precise alignment becomes even more crucial with future lighting technologies, which are evolving toward pixel-based headlight systems consisting of thousands of individually controllable segments (pixels). These systems allow for highly dynamic and adaptive light distributions by selectively dimming individual pixels. They function similarly to projectors and require precise synchronization between the vehicle camera and the headlight system to ensure that light is directed exactly where it is needed. A fundamental prerequisite for this technology is the highly accurate control of the headlight position to ensure that each pixel illuminates its intended target precisely.

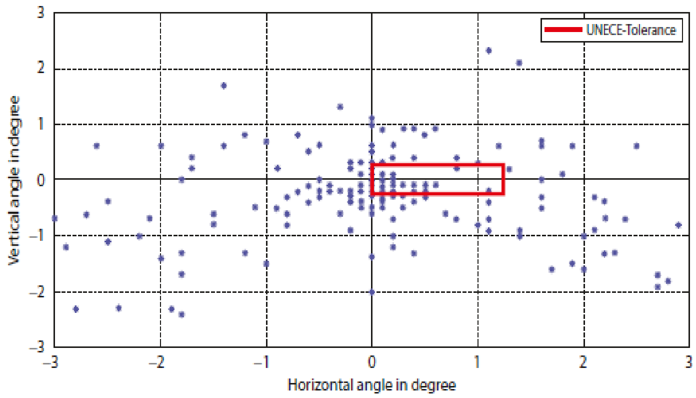

Figure 2: Horizontal and vertical deviations of vehicle headlights from a study by TU Darmstadt [6]. In red: the permissible UNECE tolerance range.

Empirical data on headlight alignment further underscore the urgency of this issue. A study conducted by Technical University Darmstadt revealed that 75% of the vehicles examined had incorrectly adjusted headlights [6]. Routine inspections, such as those conducted by the ADAC, consistently show high rates of misalignment, further emphasizing the need for improved headlight control and adjustment.

Objective of this Whitepaper

In view of the critical role correct headlight alignment plays in road safety, this paper outlines an automated system that monitors and adjusts headlight alignment and positioning during driving operation. Additionally, it delves into the requirements and methods that can be used within such a system. Both continuous re-calibration and initial calibration before driving are to be made possible. Such a re-aiming system would ensure that the headlights are adjusted as intended and function as desired, allowing all lighting functions to be fully utilized in the best possible way. Such a system can thus help improve night-time visibility while minimizing glare.

By implementing this automated re-aiming technology, the effectiveness of modern lighting systems can be maximized while minimizing glare for other road users at the same time.

This whitepaper serves both as scientific and technical documentation and is intended as a reference for future developments in the field of dynamic headlight alignment.

2 Problem Statement

Despite the importance of precise headlight alignment, ensuring long-term accuracy under real driving conditions remains a major challenge. In principle, it is possible to achieve precise headlight alignment. Digital headlight aiming devices allow for accuracies of 0.2° to 0.1° [7]. This permits an initial aiming accuracy during factory setup in the range of ±0.2% (approx. ±0.1°) [8].

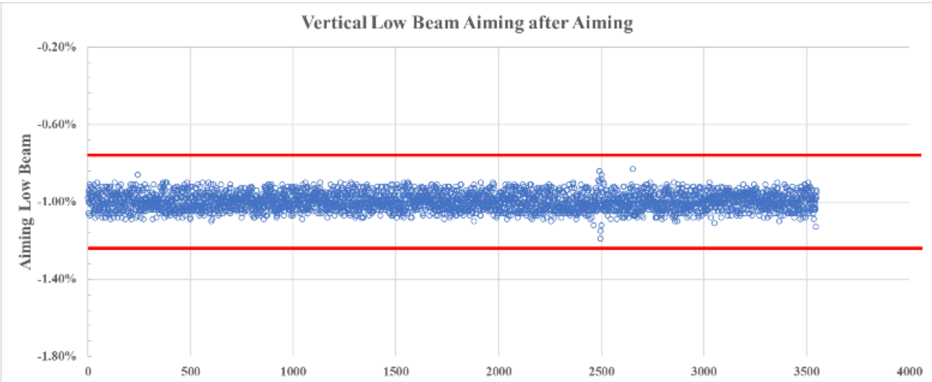

Figure 3: Vertical low beam alignment on the production line of an OEM [8].

However, this high-precision adjustment deteriorates over time due to various external influences, leading to a gradual loss of alignment accuracy [6][9][10]. In everyday operation, numerous mechanical and environmental factors affect the positioning of the headlights. Various external and internal influencing factors can be identified as main causes of headlight misalignment. These include mechanical stress during transport or driving, as well as wear-related changes such as to the mounting components [6][9][10]. In addition, there are further external and temporary influences such as fuel level, driver, passengers and cargo load, as well as temperature variations and tire pressure [9][11].

All these factors can alter the original headlight alignment and thus impair the precise light distribution. Current measures for headlight adjustment rely on manual calibration by the driver or automatic leveling. However, both methods only allow a statically defined, relative adjustment based on changes in vehicle inclination; they are unable to continuously monitor and correct the absolute position of the headlight in order to maintain absolute alignment. Furthermore, these systems only address vertical alignment changes, while horizontal misalignment—an equally critical factor for glare prevention and precise illumination—is neglected.

Another calibration option in the form of professional re-adjustment in workshops is unfortunately just as unreliable as manual adjustment by the driver, since calibrations, re-adjustments, and alignment checks are only carried out sporadically, inconsistently, and are highly dependent on the skill and precision of the personnel performing the adjustment. Studies show that even after professional re-adjustment in a workshop, a significant proportion of headlights remain incorrectly aligned [9]. Therefore, long-term precise alignment of headlights under real conditions remains a major challenge.

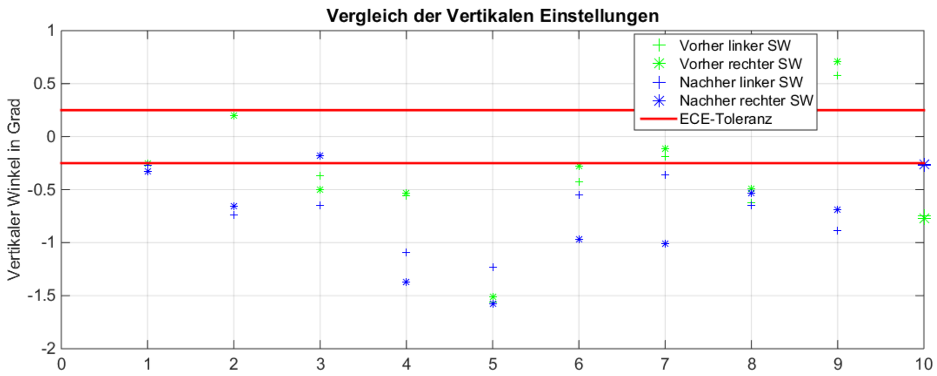

Figure 4: Vertical headlight alignment from [9]
In red: ECE tolerance range

In view of the increasing demand for high-precision lighting solutions that ensure optimal light quality and safety, conventional methods of headlight alignment prove insufficient. Their limitations make it clear that an automated system is required that continuously monitors and corrects headlight positioning. A system such as proposed in the re-aiming concept would not only improve night-time visibility and reduce glare but also maximize the effectiveness of modern lighting technologies and thus enhance traffic safety for all road users.

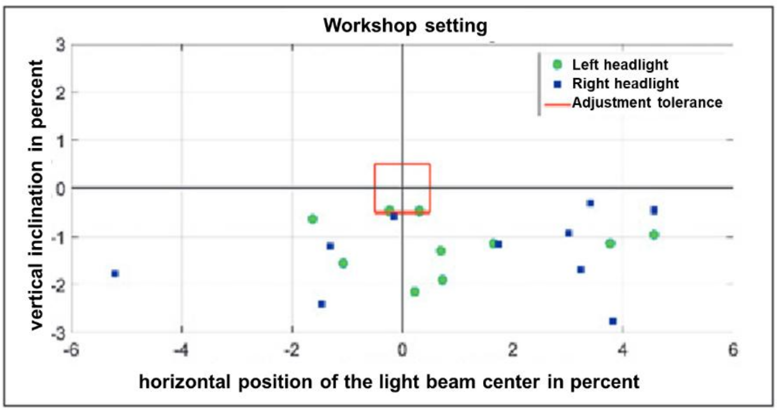

Figure 5: Horizontal and vertical headlight alignment from [9]
In red: ECE tolerance range

3 System Description

The previously described problem analysis clearly shows that existing solutions for headlight adjustment are not capable of maintaining the necessary precision under real and dynamically changing operating conditions over the long term. This necessitates a system that continuously monitors the headlights even during driving operation and automatically corrects them when required, since even initially correctly adjusted systems lose their correct alignment during use. This development affects not only conventional headlight systems but especially high-resolution, adaptive lighting systems, whose performance critically depends on exact calibration. Accordingly, both the demands on light quality and on system safety increase – a circumstance that current solutions have so far been unable to meet.

Numerous current research projects show that individual aspects of automated calibration are already technically addressable. For example, Söhner [12] and Schäfer [13] demonstrate that automatic calibration of headlights is fundamentally feasible – although so far mostly only under stationary conditions, such as in front of a calibration wall, and without dynamic adaptation during driving. The use of distinct features within the light distribution, such as the cut-off line or other sharp-edged light-shadow transitions, is proposed in several studies as a suitable basis for the detection and correction of misalignment [12][13].

In particular, neural networks show potential in this regard: Thom et al. [14] demonstrated that AI-supported image processing can reliably detect and evaluate light distributions even during driving operation. Furthermore, Totzauer [1] and Schneider [15] confirm that actively projected markers – i.e., deliberately generated light patterns – are especially advantageous for detection. They offer high contrast, clear geometry, and are more robust to disruptive environmental conditions than passive light distributions. These markers can include both classical geometric shapes and coded patterns. Their generation and detection – especially the tracking of vehicle movement using such markers, for example by means of laser modules – was successfully tested by Totzauer [1], among others.

Despite these advances, a comprehensive, integrated system concept that combines all these technologies and fully automates both static initial alignment and dynamic recalibration under real driving conditions is still lacking. This is precisely where the re-aiming system presented here comes in.

The goal of the re-aiming system presented here is therefore the development of an automated, software-based overall concept that enables continuous and precise monitoring and correction of headlight alignment. By integrating modern sensors, intelligent image processing, and dynamic light control, the system should be capable of autonomously identifying and compensating for any kind of misalignment – whether mechanical, temperature-related, or usage-induced. This not only optimizes visibility range and quality but also minimizes the risk of disturbing or hazardous glare

In contrast to previous systems that allow only static or manually initiated calibration, the approach presented here pursues an adaptive calibration concept integrated into vehicle operation. It independently recognizes suitable situations for recalibration, continuously analyzes the projected light distribution, and, if necessary, applies software-based corrections – without the need for mechanical adjustment or external intervention. As a result, the light distribution remains consistently within specified tolerances and matches the precision of professional factory adjustment.

The system pursues several key objectives:

- an automatic initial and recalibration process without human intervention
- elimination of manual sources of error in headlight alignment
- continuous real-time monitoring of the light distribution
- dynamic, adaptive adjustment to external influences such as vehicle load, movement, and road conditions
- precision on the level of professional factory alignment (<= 0.1°)
- the use of already existing vehicle components to increase efficiency
- and full integration into existing systems without introducing additional risks such as glare, distraction, or disturbance for the driver or other road users

These objectives require interaction between high-resolution, controllable light sources, imaging sensors, and intelligent processing. The re-aiming system makes use of modern front cameras, high-resolution pixel LED headlights, and AI-supported image processing to realize a closed-loop control system: the light distribution is generated, captured, analyzed, and, if necessary, adjusted in real time – all by the system itself, without mechanical wear parts or external intervention. Control is performed software-based via targeted activation of individual light pixels, eliminating the need for mechanical re-adjustment.

The following presents this overall concept in a structured manner. First, the calibration approach on which the system development is based will be outlined. Then, the main system components will be described in detail: the light-emitting unit, the sensing unit, and the processing system. Finally, the overall process will be consolidated in an exemplary process scenario to illustrate the practical implementation and interaction of the components.

To achieve this objective, interaction between several technical subsystems is required, which must communicate within a closed-loop control system. The technical implementation is divided into three main components:

- a light-emitting unit for active projection of analyzable light patterns
- a sensing unit for optical and sensor-based acquisition of the light distribution
- a processing system that compiles, analyzes, and, if necessary, intervenes based on all measurement data

The following chapters describe these three core components of the re-aiming system in detail and explain their respective areas of responsibility, technical requirements, and contributions to overall system performance.

3.1 Component Description

The technical implementation of the re-aiming system is based on three main components that must be precisely coordinated:

1. Light-emitting unit (headlights)
2. Sensing unit (camera and supporting sensors)
3. Processing system (control and image analysis)

The synchronization of these units forms the foundation for the continuous detection and correction of misalignment. An initial calibration ensures that the coordinate systems of the headlights, the sensing units, and the road surface as a projection plane are correctly aligned with one another and can be transferred into a shared world coordinate system. This is essential in order to detect and track shifts and rotational errors of the headlights with precision. Calibration can take place after final vehicle assembly, for example during the process of initializing the driver assistance systems at the manufacturer's plant.

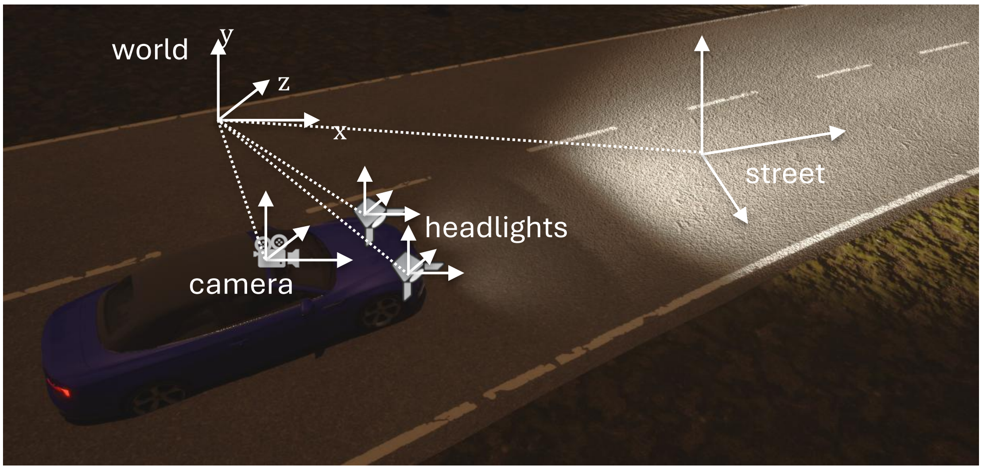

Figure 6: Representation of the coordinate systems involved in the re-aiming system. The vehicle systems ("headlights", "camera"), the global system ("world"), and the road plane ("street"). Transformations between these systems form the basis for headlight alignment.

This basic calibration can be performed once and/or continuously optimized by self-learning algorithms. For position determination, classical geometric methods (e.g., homography, triangulation) or AI-supported pattern recognition can be used.

Each system component is embedded in its own specific coordinate system. The overall system performance of the re-aiming system therefore depends significantly on the detection and evaluation of calibration-relevant states and changes. In addition to the components themselves, the coordinate systems of the entire vehicle and the road must also be considered, since both are subject to a wide range of dynamic influences.

The road coordinate system changes, for example, due to curves, crests, dips, varying road gradients, weather effects, or changes in surface condition. The processing system must therefore include environmental monitoring that accounts for the road coordinate system, including vehicle position, trajectory, topology, as well as surface characteristics, brightness, and contrast capability depending on the color and texture of asphalt, concrete, etc.

The vehicle coordinate system is also not static. Influences acting on the overall coordinate system of the vehicle include variations in load, number of passengers, vehicle body dynamics, and other parameters as previously described. These influences may already be stored as baseline data from the initial calibration at the factory and can be compared with current values or supplied by the vehicle's own sensor systems. Within the vehicle coordinate system, both headlights and camera possess their own local coordinate systems with specific tolerances.

For the headlight coordinate system, mechanical/optical settings and tolerances of the components within the headlight assembly process are particularly relevant. The lighting unit itself consists of subcomponents such as light generation, optical imaging, and mechanical installation in the headlight housing. These tolerances could already be recorded during vehicle calibration, documented, and continuously monitored during operation.

The sensing unit, e.g., a camera, is also integrated into the vehicle coordinate system with its own tolerances and is subject to internal and external mechanical deviations, such as mounting tolerances or suspension. These aspects must be taken into account and, if necessary, corrected during operation.

The overall system must therefore be capable of continuously monitoring all relevant coordinate systems and dynamically referencing them. Additionally, during initial factory calibration, further data could be collected, such as the reaction of the vehicle coordinate system to loading, driver/passenger weight, or fuel level curves. This could improve and accelerate future corrections through pre-determined starting parameters. All mentioned influences and factors are incorporated into a decision logic by which the system automatically detects whether and when recalibration is necessary. This evaluation is performed continuously and forms the basis for precise, robust, and adaptive re-aiming under real-world driving conditions.

3.1.1 Light-emitting Unit

The light-emitting unit is responsible for generating visible reference points (markers) within the light distribution. These can correspond to significant points of the light pattern, such as the cut-off line or the HV-point, or be actively generated by the system.

Actively generated markers offer the advantage of higher precision and can be realized either through shadow projection or light markings. It must be ensured that their shape, characteristics, contrast, size, and distance allow detection by the vehicle camera using appropriate algorithms. For better detection, the patterns should go beyond individual points. Suitable examples include simple geometric shapes such as circles, squares, rectangles, triangles, or lines; more complex patterns such as grid structures, barcodes, or checkerboard-like layouts; and even highly complex patterns such as QR codes, ArUco markers, freeform patterns, dynamic light signatures, or combinations of the aforementioned types

It must be ensured that actively created markers neither disturb nor distract the driver or other road users. This can be achieved through suitable measures such as projection outside the driver's direct field of view, use of patterns or arrangements that are only visible from the camera's perspective, or the use of very short, high-frequency light pulses (e.g., <16 ms), which are imperceptible to the human observer but detectable by the coupled camera.

Systems with individually controllable pixel segments are suitable for implementation – similar to projectors or displays. Ideal are high-resolution, high-contrast systems based on LED or laser technology, such as matrix or pixel LED systems, µ-LED systems, DMD systems, laser systems, multilens arrays (MLA), or comparable technologies.

3.1.2 Sensing Unit

The sensing unit collects all relevant information for the analysis and calculation of the light distribution. Its central component is at least one vehicle camera. Depending on the system architecture, the sensing unit can be extended with additional cameras or sensors to increase detection robustness or to ensure higher accuracy. Possible supporting sensors include lidar and radar for depth sensing; gyroscopes, tilt and inertial sensors for detecting dynamic vehicle movements (e.g., pitch and roll); or GPS-based positioning for supporting global calibration with georeferenced data. Other extensions with similar sensors are also conceivable. The sensing unit thus forms the interface between the physical world and digital processing by forwarding the collected data to the subsequent processing system.

3.1.3 Processing System

The processing system forms the central control unit of the re-aiming system and is responsible for the entire recalibration process. It analyzes the sensor data from the sensing unit, detects deviations in headlight alignment, and calculates the necessary corrections for the light-emitting unit.

Its areas of responsibility include:

- monitoring the environment
- monitoring and analyzing misalignments
- correction of misalignment

Through the close integration of environmental analysis, misalignment detection, image processing, and dynamic light control, the processing system ensures a continuously optimal headlight alignment. It thus represents the core of the automated re-aiming technology by enabling a precise, reliable, and adaptively controlled light distribution.

The entire processing level can be operated in two ways. First, in real time, if the algorithms and methods used, as well as the hardware, allow it. Otherwise, processing can be carried out on temporarily stored data. The following subsections will now explain the individual areas in more detail.

Environmental Monitoring

Environmental monitoring ensures that recalibration is carried out only under stable and suitable conditions. For this purpose, the collected environmental data is continuously analyzed to assess the calibratability and susceptibility to interference of the current driving situation. Scenarios in which the light projection can be clearly detected are identified, and situations in which incorrect measurements or disruptive influences could lead to inaccurate calibration are excluded. Of particular interest are factors such as road surface and geometry, vehicle movements, the vehicle's position in relation to the road, weather conditions, light influences, and traffic.

Figure 7: Examples of scenario selection.
Left and center: Re-aiming can be performed due to favorable environmental conditions.
Right: Execution is not possible due to dense traffic.

Based on the camera images, classical image processing techniques such as edge detection, line extraction, and Hough transformation are used to analyze the road geometry. In addition, texture and structural features (e.g., Gabor filters, Local Binary Patterns) and feature-based methods such as SIFT and SURF allow for assessment of the surface condition. This information helps evaluate whether the road is suitable for calibration – for instance, with regard to vibrations or low contrast. To detect dynamic changes and movements, the calculation of optical flow can be used to identify motion patterns in the image, such as pitch or roll movements of the vehicle. This analysis is supplemented by evaluating color histograms or global image features, which provide information on environmental influences such as fog, glare, or highly variable lighting.

Particularly powerful are AI-based methods such as convolutional neural networks (CNNs), which can extract complex scene characteristics. Semantic segmentation methods additionally allow pixel-precise classification of image content into categories such as roadway, markings, vegetation, or other vehicles. This enables a differentiated assessment of the suitability for calibration. In addition to single-frame analysis, temporal evaluation of image sequences is also relevant. Recurrent networks (e.g., LSTM) can be used here to detect changes in lighting conditions or weather. Anomaly detection methods such as autoencoders or GANs help identify and exclude unusual scenarios. Transformer-based approaches can deliver global image analyses and thus recognize complex image contexts.

As previously described, image processing can also be supplemented by non-optical sensors. These must be seamlessly integrated into the monitoring and decision-making process.

For decision-making itself, both rule-based systems and data-driven models can be used. Rule sets offer a simple and transparent way to define hard thresholds, such as requiring that calibration only be performed under clear visibility, stable vehicle dynamics, and recognizable markings. Alternatively or in addition, fuzzy logic systems enable a more flexible evaluation based on imprecise conditions, particularly in borderline cases such as light rain or early dusk. Combining multiple methods in so-called ensemble approaches appears reasonable. Likewise, a trained AI agent could take over decision-making.

All of these procedures and technologies serve the goal of allowing recalibration only when the conditions are stable, unambiguous, and interference-free within defined tolerances. This not only improves the accuracy and repeatability of calibration but also minimizes the risk of incorrect adjustments.

Misalignment Detection

The goal of misalignment detection is the precise determination of the current orientation of the headlights and whether a relevant deviation exists that makes recalibration necessary. The starting point is the detection of the markers generated by the headlights in the camera images. A wide range of specific methods from image processing, geometry, artificial intelligence, and statistical signal processing are used for this purpose. The markers must have been designed in such a way that they are clearly identifiable and evaluable – both in terms of shape, position, and contrast.

Detection begins with image preprocessing steps that improve the image and support detection. Markers are isolated, image noise is reduced, and relevant contours or features are extracted. Subsequently, the exact position, orientation, and, if applicable, deformation of the markers in the image is determined. Techniques such as histogram equalization, adaptive contrast enhancement, Gaussian or median filtering, and similar methods are suitable for this.

For the detection of points, lines, or rectangles, classical feature extraction methods such as edge detection (e.g., Canny or Sobel filters), gradient histograms, Hough transformation, or template matching can be used. For more complex, encoded patterns such as ArUco markers, QR codes, or checkerboard patterns, detection typically occurs using AI-supported detectors or specialized CNN-based models that determine both marker position and identity. A combination of various methods can also be useful here.

Since headlight misalignment can be divided into horizontal and vertical deviations, different algorithms and methods may be required. Correcting a vertical deviation requires greater accuracy in evaluating the horizontal projection share. Multipixel projections with a focus on precisely determining the vertical position on the road can be used for this purpose. The goal of misalignment detection is to determine the projection's vertical position with an accuracy better than 0.1°.

To calculate the actual misalignment, displacement vectors and rotations are primarily considered. Additionally, perspective distortion, depth information, and angle changes can also be taken into account. Using the camera parameters and calibration data (e.g., a previously calculated homography), the actual position and orientation of the headlight in the world coordinate system can be determined. Classical methods for these transformations include the Perspective-n-Point (PnP) method, direct homography calculations, scaled or adjusted homographies, or triangulation. Beyond these classical methods, direct regression methods using neural networks are also possible, where the model is trained to estimate a displacement and rotation directly from the image or marker segment – either as a vector or as a full transformation matrix. These methods show advantages especially under challenging lighting conditions or partially occluded markers, as they enable more robust estimations.

For precise detection, it is usually not sufficient to analyze a single image. Therefore, evaluation must be performed across multiple image data points. Sliding averages, weighted averaging, or (Kalman) filters can be used for this purpose. An additional plausibility check verifies the physical feasibility of the calculated transformation, for example through maximum angle deviations or known mechanical limits. Robustness can be further increased by methods such as RANSAC, which detect and exclude erroneous single detections.

In combination, these methods enable highly precise, purely software-based monitoring and evaluation of headlight alignment. They form the bridge between real-world projection and digital control and are thus one of the key components for a robust and maintenance-free re-aiming system. Misalignment detection provides the direct link between optical capture and active light control and enables highly accurate headlight alignment.

Correction of Misalignment

The actual correction of the light distribution can be implemented in two ways. When using high-resolution headlight systems, it is realized through dynamic software compensation. In this case, individual pixels of the light-emitting unit are selectively controlled to adjust brightness and modify the light distribution precisely. Control can be performed either locally, by selectively adjusting individual light segments, globally, through an overall recalculation of the complete light distribution, or through a combination of both. This combination ensures an accurate and at the same time smooth correction without abrupt changes in lighting.

If mechanical actuators are used for headlight adjustment, the determined misalignment can be passed on to them in order to physically re-align the headlights. A key factor for the processing system's overall strategy is the decision of when a calibration is to be carried out. Not every detected deviation requires immediate adjustment – in many cases, a stable calibration remains sufficient. However, if significant misalignment is identified, the system performs a gradual adaptation of the light distribution. Care is taken to avoid abrupt changes, ensuring smooth and unobtrusive adjustment.

3.2 Exemplary Procedures

The following scenarios illustrate exemplary procedures of the re-aiming process and show the interaction of the system components and methods described above. These examples serve as a reference for possible implementations and clarify the functionality of the system under real operating conditions. The principle of re-aiming is explicitly not limited to the method combinations presented here but can be implemented in different configurations of components or subcomponents, as long as the fundamental principles and considerations are fulfilled.

Activation and Trigger Conditions

The re-aiming system can be activated in various ways, e.g., automatically when the headlights are switched on, at regular time intervals, or situationally based on defined triggers. Possible activation mechanisms include:

- permanent activation during driving operation
- time- or mileage-based intervals
- GPS-controlled activation zones
- manual activation by the driver

Since not every driving situation is suitable for reliable calibration, predefined or AI-recognized route profiles with favorable conditions – such as straight-ahead driving at constant speed and clear visibility – can be used as suitable trigger conditions.

Pattern Projection and Sensing

The light-emitting unit projects a defined light pattern onto the road surface. This pattern can be emitted at high frequency and with extremely short display durations so that it is imperceptible to the human observer but can still be reliably detected by the coupled camera. Alternatively, the pattern can be projected for a longer duration or continuously. If the pattern exhibits little to no temporal variation, it may, with some habituation, be perceived as an intentional inhomogeneity and not be considered distracting by the driver. This, however, must be verified through further studies.

Figure 8: Simulated examples of markers on the road.
Left (blue vehicle) – view from the human driver's perspective
Center and right (red vehicle) – example markers as they might be perceived by the camera

If multiple patterns are used for vertical and horizontal correction, a smooth transition between them can enable continuous analysis without distracting the driver. The projection must be performed in such a way that the pattern remains clearly identifiable from the camera perspective – despite real-world imaging distortions such as blurry or asymmetric light pixels.

Adaptive Process Design

Depending on the type of misalignment occurring, the correction intervals can be varied. Slowly changing influences such as thermal or mechanical drift within the headlight coordinate system can be checked at longer intervals. In contrast, dynamic changes to the vehicle or road coordinate system require shorter response times in the millisecond range.

Another option for performing the re-aiming process under optimal conditions of the involved coordinate systems is retrospective evaluation of previously driven states. An image buffer allows subsequent analysis of already passed scenes, provided they are later classified as suitable for calibration. Depending on storage capacity, this can include several seconds, minutes, or entire trips. This facilitates post hoc verification of the coordinate systems as retrospectively suitable. The vehicle system can then calculate the parameters and tolerances and initiate the correction of the misalignment. Using AI-supported algorithms, suitable situations can also be calculated predictively, and the correction can be carried out within those periods. Storage can include entire driving segments or only individual calibration-suitable images.

Process Types and System Integration

Various process variants with differing levels of complexity and objectives can be considered for executing re-aiming. For example, a basic process under reference conditions (e.g., one driver, constant weight, straight road) could be defined. This can optionally be extended with additional optimization for occurring tolerances (temperature, aging, settling behavior, etc.). Simplified variations are also conceivable, such as processes limited to correcting vertical misalignment, primarily to minimize glare along the cut-off line.

In addition, process-driven procedures could be initiated following workshop visits, repairs, or regular inspections, in which individual basic re-aiming routines are executed to restore and verify the respective default settings of the vehicle.

Beyond these basic variants, a qualitatively and technically more elaborate process could be implemented, in which the vehicle coordinate system itself is continuously monitored and corrected. This would require integration of in-vehicle sensors to capture load conditions, fuel level, pitch or roll movement. To further increase system accuracy and robustness, direct integration of additional sensor technology within the individual system components is also conceivable. For example, tilt sensors within the headlights or the camera unit – comparable to MEMS accelerometers in mobile devices – could be used to monitor internal coordinate systems. This would allow position changes or mechanical tolerances to be detected immediately and independently of external context.

If, in addition to the headlight and vehicle coordinate systems, the road coordinate system is actively taken into account, a quasi-permanent correct alignment could be achieved. This would require the integration of external data sources such as GPS, digital maps, route information, as well as AI-controlled algorithms for scene analysis with determination of the current vehicle position and trajectory.

Suitable Calibration Conditions

For precise calibration, suitable calibration conditions must be identified or created. For example, identifying quasi-static coordinate systems for base or default corrections can be of great importance. Driving straight on country roads or highways at constant speed and with a road profile low in variation is particularly advantageous for such corrections. If the system detects such a situation over a sufficiently long period of time – live or retrospectively – it can serve as a basis for performing re-aiming.

In the case of dynamic corrections, the system must be capable of reacting quickly enough to the driven speed, the dynamics of the vehicle, and the road topology – likely in the millisecond range or faster. At a constant speed of 80 km/h, the vehicle covers 22.22 meters per second. The respective acceptable tolerances of the coordinate systems must be compared, and the system's sensing and reaction speed must be adapted to this dynamic. The target is a correction accuracy of ±0.1°, which places high demands on spatial and temporal resolution.

In addition to identifying suitable scenarios, conditions must be created – in the form of the projected markers and patterns – that allow for reliable detection and subsequent calculation of misalignment. Headlight control must ensure that the pattern is projected in such a way that it is clearly identifiable in the camera recording. It is particularly important to consider how individual pixels of the headlight are actually imaged onto the road.

The challenge in designing such patterns lies in the fact that real pixels deviate significantly from idealized representations. Instead of perfect, sharply defined square pixels, real-world projections often produce blurry, irregular light spots – frequently round, oval, or asymmetric (see Figure 9). Their concrete appearance depends on the optics and the projection module used, as well as on whether the pixels are located in the center or at the edge of the distribution.

i) ii) iii)

a) b) c)

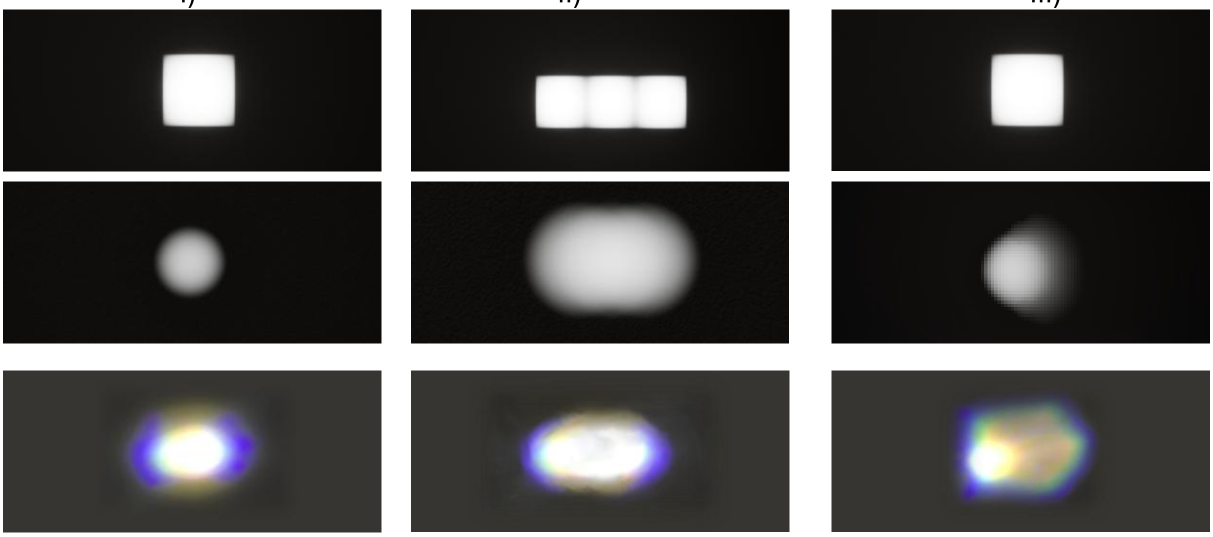

Figure 9: *Projection of headlight pixels*
Row a): perfect pixels, Row b): more realistic simulated pixels, Row c): real pixels
Column i): individual pixel centered, Column ii): row of pixels, Column iii): individual pixel at the edge of the light distribution

The division into correction of horizontal and vertical misalignment enables prioritization. Glare is presumably most often caused by vertical misalignments, i.e., movements of the primarily horizontal cut-off line. Therefore, patterns that enable correction of vertical misalignment should be prioritized – for example, lines, point lines, or combinations with differing vertical and horizontal extension on the road.

Correcting misalignment perpendicular to the cut-off line, such as in matrix segments or the low beam wedge area, may require different patterns. These could be designed and evaluated to form, when projected onto the road, representations of lines, point lines, or combinations with varying spread but vertical preference (i.e., in the direction of travel).

The non-ideal shape of the projected pixels requires special care in pattern design. Only through appropriate arrangement and evaluation of the actual light distributions can reliable conclusions about misalignment or adjustment deviation be drawn from the camera images. Ideally, the movement of the road surface within the camera images generates a baseline variation that blurs dirt spots or surface defects and leads to an averaged road representation with a situationally "mean" luminance and contrast evaluation capability. This should also be considered as a decision parameter. Preset empirical values and AI-based comparisons can be used for this purpose.

Image Analysis and Decision-Making

The camera continuously captures image data of the scene. Only those frames are processed further in which the projected patterns should be visible. If, for example, the markers are always projected at the same position within the light distribution, a geometric constraint may be beneficial for fast evaluation and response.

Appropriate visual computing algorithms, such as a neural network, check whether the current scene is suitable for reliable calibration. This can be done, for instance, with reference to the various coordinate systems. If a scene is identified as suitable – such as straight-ahead driving on a clear country road or highway with good visibility – misalignment detection is initiated. In this step, the detection of the markers and the precise determination of their positions is carried out. If the marker is detected in the stored image with high probability and its position determined, both are saved for the next step. For more robust evaluation, not just single images but sequences or entire sets of individual frames can be used. If, for example, a defined number of images (<10, 10, 20, 50, >50) with consistently detected markers is available, the resulting overall misalignment is calculated.

Correction and Regulation

The deviation determined by the image analysis serves as the basis for the subsequent correction. In systems with high-resolution pixel headlights, the light distribution can be dynamically adjusted by selectively controlling individual segments. In this way, the target projection can be achieved entirely via software. Alternatively, vertical correction can be performed using a stepper motor, as employed in dynamic headlight leveling systems. A combination of both or similar systems is also possible, for example, mechanical control of larger misalignments combined with software-based fine adjustment.

Through this cyclical evaluation – consisting of capture, evaluation, aggregation, analysis, and correction – continuous, software-supported recalibration of the light distributions is achieved. The entire process is designed to run unnoticed by the driver and enables high-precision operation over the entire vehicle service life.

4 Impact on regulations and Technical Vehicle Inspections

The system described above will also supplement existing legal regulations. In particular, ECE R48, which describes the installation of lighting equipment on vehicles and headlight adjustments, may be supplemented in the future.

The system features re-aiming, a self-diagnosis feature that is performed at different intervals depending on the model, as the aim is to improve the headlight alignment during vehicle operation. Re-aiming can also be performed during the periodic vehicle inspection by technical services (PTI) to confirm the correct headlight alignment (horizontal/vertical). For this purpose, the data stored during factory calibration (load behavior, fuel tank, driver weight, suspension, chassis, etc.) could be used. This allows the existing adjustment regulations for vehicles in ECE R.48 §6.1ff to be revised and supplemented. The adjustment, tolerances, and measurement methods can likely be modified and documented with smaller deviations. E.g. in particular, the large tolerances for vertical inclination (currently between 0.5% and 3.5%, depending on the mounting height) can be reduced with more precise adjustment capabilities. The existing legal requirements will be retained for vehicles without re-aiming, and vehicles with a re-aiming process can be included through an amendment.

Functional safety elements can also be tested, e.g., the settings of other lighting functions such as matrix segments, image and hazard projections, lane projections, etc.

The selected markings, dots, lines, crosses, etc., must be described during vehicle homologation, and their photometric properties must be documented and verified. This can be verified during type approval using appropriate test requirements for photometry, shape, sharpness, and position of the respective markings. Existing laboratory conditions with calibrated measuring equipment, goniometers, etc., are suitable for this purpose. For the first time, identical technical properties are present in a headlight light distribution system in the laboratory, in production, in series production testing, in periodic technical inspections, and in operation on the road.

The test requirements for photometry, the various calibration conditions, and the corrections in real road traffic do not yet exist. With the presentation of the first prototypes of the re-aiming system, the specifications can be started to put into practice based on such concrete examples. The specific final requirements must be discussed in further working groups e.g. by GTB experts and Testhouses.

5 Conclusion and Future Perspectives

The re-aiming system described in this paper enables continuous, software-supported recalibration of vehicle headlights under real-world operating conditions. This approach overcomes the limitations of conventional calibration methods and ensures a precise, dynamic, and long-term stable alignment of the light distribution. By integrating modern imaging and lighting technologies with intelligent processing algorithms, the system achieves high accuracy, robustness, and adaptability.

The implementation of such a system can significantly increase the safety and performance of modern lighting systems by ensuring optimal visibility and minimizing glare. In particular, the combination of software-based control and real-time environmental analysis allows for precise and situation-dependent headlight alignment with the potential to operate without manual intervention and mechanical wear.

Looking ahead, further development steps are conceivable in which the re-aiming system is linked with other vehicle functions. For example, integration into assistance systems, vehicle dynamics control, or V2X communication could enable even more comprehensive adaptation of the light distribution to the specific driving situation. In addition, future vehicle architectures with centrally controlled sensor and lighting systems offer promising possibilities for even deeper integration of the re-aiming concept.

Overall, the re-aiming system offers a sustainable and forward-looking solution to meet the increasing demands on safety, comfort, and performance in automotive lighting technology.

6 Sources

[1] Totzauer, A.: Kalibrierung und Wahrnehmung von blendfreiem LED-Fernlicht. Herbert Utz Verlag (2013)

[2] Locher, J., Aldiek, L., Stroop, P.: Influence of Luminance and Illuminance on Headlamp Glare. In: Proceedings ISAL Tagung 2015, S. 679–686, Darmstadt

[3] Bullough, J.D., Van Derlofske, J., Dee, P., Chen, J., Akashi, Y.: An Investigation of Headlamp Glare: Intensity, Spectrum and Size. Technical Report HS-809 672, (2004)

[4] Zydek, B.: Blendungsbewertung von Kraftfahrzeugscheinwerfern unter dynamischen Bedingungen. Dissertation, Universitäts- und Landesbibliothek Darmstadt (2014)

[5] Locher, J., Kaley, F.: Disability and Discomfort Glare of Headlamps. In: Light & Engineering, Vol. 18, No. 2 (2010)

[6] Khanh, T.Q., Kobbert, J., Singer, T.: Sichtverbesserungssysteme und Signaleinrichtungen. In: Handbuch Assistiertes und Automatisiertes Fahren. Wiesbaden: Springer Fachmedien Wiesbaden, S. 761–792 (2024)

[7] Hinterwälder, C., Hamm, M.: Analysis of Human Intra- and Interpersonal Aiming Accuracy of Cutoff Lines. SAE Technical Paper 2021-01-0849 (2021). doi:10.4271/2021-01-0849

[8] The Aiming of Headlamps and Resulting Influences on Benchmarks and Road Users Christian Hinterwälder, Michael Hamm, Jonas Kobbert, AUDI AG, Germany ISAL 2022, ISBN 978-3-8316-4953-2

[8] Hinterwälder, C., Hamm, M., Kobbert, J.: The Aiming of Headlamps and Resulting Influences on Benchmarks and Road Users. In: ISAL 2022. ISBN 978-3-8316-4953-2

[9] Kosmas, K., Kobbert, J., Khanh, T.Q.: Anforderungen an die dynamische Leuchtweitenregelung zur Vermeidung der Blendung entgegenkommender Verkehrsteilnehmer. Berichte der Bundesanstalt für Straßenwesen, Fahrzeugtechnik, Heft F 129 (2019)

[10] Hamm, M., Hinterwaelder, C.: Investigations on Headlamp and Car Body Tolerances in Real Life. SAE Technical Paper (2020)

[11] Hamm, M.: Influence Parameters on Headlamp Performance in Rating Systems and Reality. SAE Technical Paper 2017-01-1359 (2017). doi:10.4271/2017-01-135

[12] Söhner, S.: Entwicklung einer automatisierten Scheinwerfereinstellung mittels aktiver Triangulation. Cuvillier Verlag (2015)

[13] Schäfer, S.: ASSIST – Die erste Generation selbstjustierender Scheinwerfer. Tagungsband Lux Junior (2015)

[14] Thom, M., Ulken, M., Krüger, L., Ritter, W.: Headlight Range Calibration During Driving Operation. In: Proc. Int. Symposium on Automotive Lighting (2011)

[15] Schneider, C.: Entwicklung eines tiefenwahrnehmenden Scheinwerfer-Kamera-Systems. Cuvillier Verlag (2019)