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Auto-Leveling of HID Headlamp Using Preview Control

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A newly developed high intensity discharge (HID) automotive headlamp results in a high luminous gradient at the cutoff line, and proves the superior concept in safer and more comfortable nighttime driving. This new headlamp technology provides drivers expanded night vision by a significantly improved light pattern. However, the HID headlamp may dazzle other traffics during traversing a rough road or encountering an unexpected bump. To resolve this problem, an automatic headlamp leveling device is necessary. A preview control is presented for the design of the leveling system. The proposed control algorithm is capable of attenuating a dynamic glare which is one of the major detractors to a driving in dark roads. Computer simulations using ADAMS are carried out to confirm the effectiveness on the control system.

Key Words : High Intensity Discharge (HID), Vertical Cutoff, Auto-Leveling, Preview Control

1. Introduction

For decades automobile lighting designers have tried to develop brighter and more efficient automotive headlamps. A new electronic headlamp system, Litronic (light and electronic) or Xenon headlamp, has been available since 1991 (Huhn, 1995). The light from a high intensity discharge (HID) headlamp, which is closer to the hue of natural light and thus is thought to be better at illuminating a night road, comes from an electrode-ignited Xenon atmosphere. Providing good quality light patterns, the HID headlamp has intrinsic advantages-high luminous efficiency as well as low power consumption. Better visibility and visual guidance will essentially enhance driver's safety and comfort during nighttime driving.

According to Brussels-based Eureka project, a European program for the promotion of research and development, the HID headlamp system is expected to be a European standard within a few years (Sharke, 2001). However, it is noted that the dynamic glare occurs as vehicles change attitude during strong braking or when traversing rough roads. As lighting systems evolve, many complaints about the glare claim that the HID headlamp is too bright to those of opposing or preceding traffics. Vertical aim, along with beam pattern and light source, is found to be one of the most important factors in influencing the headlamp performance.

The European light pattern and its philosophy are well summarized by Sharke (2001). Imagine a line that runs straight out from a headlamp to a wall, and a point where the line hits the wall. Then, light patterns exhibit a sharp line at the point between the bright lower part of the beam and the dark upper part. The sharp line on the light pattern is called vertical cutoff. Conventional headlamps beam virtually no light above the vertical cutoff, so they are less capable of illuminating overhead signs. This downward aim with respect to the sharp vertical cutoff is partly due to a desire of minimizing the dynamic glare. While

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low-glare headlamps may solve the problem, they would shorten a driver's visibility on the night road. To blend the best of both conventional headlamps and HID lamps, lighting engineers introduced a new design concept in headlamp systems, that is, an auto-leveling. The automatic leveling system for headlamps prevents blinding a passing motorist. As European standards mandate the auto-leveling for HID headlamps, in most countries, it is expected that the self-leveling device will be a requirement for an advanced front lighting.

Among several control schemes, a preview control can be considered for the design of an auto-leveling system. The finite preview control can be realized practically in many applications, for example, with 'look-ahead' sensors in robotics or in active suspensions for automotives, etc. Yong (1997) applied the preview control to a contour-following of an industrial robot using a robot force control. To improve the ride comfort of automobiles, several studies using a preview control method are proposed. Bender (1968) found the optimal preview control by Wiener filter theory for a single degree of freedom vehicle model. Tomizuka (1976) applied continuous and discrete optimal preview control to a vehicle suspension system, while Foag (1988) proposed a preview control for an active suspension. Guo and Tomizuka (1997) proposed an optimization scheme for the hybrid feedforward controller in high-speed and high-precision digital motion control systems.

This study investigates an application of preview control to the automatic leveling of HID headlamps. Preview information about the road profile ahead of the vehicle is utilized to attenuate leveling disturbances against oncoming or preceding vehicles. In Section 2, we discuss HID headlamps and illuminating disturbances. Next, the design of the disturbance rejection controller based on the preview control algorithm is proposed in Section 3. In Section 4, assuming an optical preview sensor installed at the front bumper of a vehicle, computer simulations examine the preview control effects. The results are compared with a conventional headlamp without an auto-leveling, and the performance is verified. Finally, we conclude in Section 5.

2.High Intensity Discharge Headlamps

(Huhn, 1995 ; Hege, et al., 1996 ; Sharke, 2001)

The HID headlamp uses the similar mechanical and electrical interfaces as does the standard all halogen equipped projector type headlamp. Reflector, shade, lens holder, and lens itself are forming a closed and rigid cage around the HID bulb. In general, the main light output is accomplished by a lens with a diameter of 60mm. Adding an outer ring, reflector will enlarge the illuminated area for a more conventional signal image of the headlamp. The detail structure of HID headlamp system can be found in Hege, et al. (1996).

The low beam headlamps only are equipped with the superior HID systems, as in standard traffic situations more than 90% of the driving takes place with dipped headlamps. The HID light is very distinct by its different color, and the driver's eyes accept the blueish-white as white in driving practice. This makes it attractive by an innovative appearance. It was reported that the tested HID systems had very wide illumination angles. This provided good visual guidance and good orientation to the driver in various traffic situations, such as nighttime driving, fog, snow, or rain condition. Limitation of maximum illumination values together with the later-on described automatic leveling system prevents glare to other traffics.

For the well known conventional headlamps, there exist environmental and lighting requirements. With the introduction of new HID headlamps, a complex high voltage driven system in the car's front end emerges. Therefore, some new requirements have to be added such as safety, electrical conditions, and system lifetime, etc. In this study, we consider only the requirement in safety aspects during driving situations, i.e., the vertical aiming in light pattern.

Eureka project defined requirements for advanced headlamp systems through industries. At least one existing regulation already calls for European regulations governing discharge lighting. Among the notable results of the project, lighting that reduced glare on wet or dark roads helped both the drivers of cars equipped with HID headlamps and the drivers of opposing vehicles. It was also found that the more intense a glare, the more it disturbed oncoming drivers; the size of the light source affected the level of discomfort. After sources were normalized to the same luminous intensity, the researchers discovered that small areas of the glare were more disturbing than large ones. As much as dynamic glare, momentary flashes also disturbed opposing drivers more as their duration increased. Light pulses lasting less than a half-second were generally tolerated. Those lasting longer than eight to ten seconds degraded visual performance, because it took longer time for eyes to readapt to lower light levels once the pulse ceased.

The efforts for reducing lighting discomfort can be realized by the auto-leveling system. The hardware may comprise: sensor on the front and/or rear axles, electronic control unit, stepper or DC motor inside of each headlamp. This system prevents the glare and short visibility distances, provided that the headlamp aiming is correct.

3. Auto-Leveling using Preview Control

In cars with very soft suspension, while driving a rough road or encountering a sudden bump, the oscillatory and higher vertical aiming may disturb oncoming and preceding traffics. Although a stiffer suspension will reduce such effects, the better solution for the problems is to employ an automatic headlamp leveling system. Furthermore, if we can apply a preview control algorithm, the controller may take into consideration the 'look-ahead' leveling disturbance source to the system. The preview control prescribes the inclusion of the modes of the disturbances from the preview sensor.

3.1 System description

Similar to Nagiri et al. (1992), Fig. 1 shows a vehicle model illustrating the concept of preview control. The control system is constructed of an ordinary feedback loop and a feedforward preview loop. The feedback loop consists of leveling sensors, a feedback controller, an actuator, etc. The leveling sensors can be implemented on the front/rear axle or suspension system. The vertical cutoff level of lighting will be controlled to attain the set value, i.e., the zero level. In general, the magnitude and phase of the disturbance input to a control system are not known in advance. If information about the disturbance is obtained a priori, it makes sense to use available knowledge of the disturbance signal for better disturbance rejection. To realize this, the previewed road profile signal is provided to the feedforward controller, which is led to better leveling capabilities. This will enhance the conventional leveling device so that the entire system achieves a better performance, e.g., good disturbance rejection properties in HID headlamp systems.

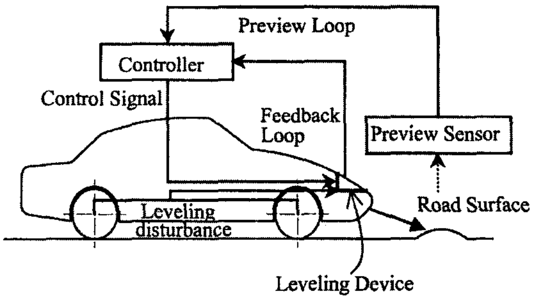

Fig. 1 Auto-Leveling using preview control

3.2 An optimal preview control algorithm

The basic idea of preview control, comparing with the LQ-optimal control principles (Lewis, 1986a), can be stated that the final time in the optimization problem is actually a moving time with a fixed time-to-go (a finite preview length). The preview control requires an artificial constraint for a constant solution of the associated Riccati equation, even for optimization problems over a finite time interval. Using the constraint on the choice of performance measure, the resulting control system can be decoupled into a feedback part and a feedforward component.

Since the feedback loop concentrates on the system stability and robustness, determining the feedback component rather than the feedforward loop is firstly motivated. Ideally, the feedback component should contain the mapping from the disturbance signals to the corresponding control input, such that no system error occurs by applying this control input to the process. However, as long as this mapping is not perfect, system errors occur and the feedforward controller is necessary to enhance the disturbance rejection capabilities. Accordingly, the feedforward controller will be designed based on the determined feedback gains. Theoretically, the feedforward preview control has no effect on the system stability, because it is placed outside of the basic feedback loop. However, the feedforward structure also incorporates a contribution to the feedback loop, caused by the fact that any error signal will be based on measurements of a process output. This means that the feedforward control with inaccurate preview information may cause stability problems and/or saturation of actuators.

3.3 Controller design

For designing the control system, it is required to obtain the angular positioning dynamics of the leveling device. Since the leveling system should compensate the leveling error caused by a pitching motion of an automobile, it is desirable that the dynamics of the leveling device is close to the pitching mode of the vehicle. Therefore, we analyzed the dynamics according to Inman (1994), and the resulting model in the discrete domain can be represented by

$$G(z)=\frac{0.1464z^{-1}+0.1211z^{-2}}{1-1.3019z^{-1}+0.5694z^{-2}}\left[\frac{\text{deg}}{\text{deg}}\right] \qquad (1)$$

where z indicates a Z-transform variable.

The preview control algorithm requires a parametric model of the plant. The model of the leveling system (1) can be transformed to the discrete state-space representation such as

$$\begin{aligned} \mathbf{x}(k+1) &= \Phi\mathbf{x}(k)+\Gamma u(k) \\ y(k) &= \mathbf{H}\mathbf{x}(k) \end{aligned} \qquad (2)$$

where $\mathbf{x}(k)$ is a state vector, $u(k)$ is a control input, $y(k)$ is a system output, Φ is a system matrix, Γ is an input vector, and $\mathbf{H}$ is an output vector.

Using a preview sensor, we anticipate the disturbance signals from a road profile such that

$$\mathbf{p}(k)=[p(k+1)\ \ p(k+2)\ \ \cdots\ \ p(k+N_p)]^T \qquad (3)$$

where $[\cdot]^T$ denotes the transpose of $[\cdot]$, and N_p indicates a finite preview length. This preview information will be incorporated into the preview servo model. The controller processing interval time will determine the duration of a preview step. A performance index is also necessary to design the preview controller. A typical performance index can be defined by

$$J(i)=\frac{1}{2}\sum_{k=i}^{\infty}[e^2(k)Q+u^2(k)R] \qquad (4)$$

where $e(k)$ represents a leveling error, R and Q are positive scalar weighting factors. Q in the cost function penalizes the error quantity and R penalizes large values of the control input. With the given performance index, the optimal feedback controller, $\mathbf{K}$, and the feedforward preview controller, $\mathbf{K}_{pr}$, will be designed after some mathematical manipulation presented in Yong (1997). Then, the control input, $u(k)$, for the leveling system yields

$$u(k)=-\mathbf{K}\mathbf{x}(k)-\mathbf{K}_{pr}\mathbf{p}(k). \qquad (5)$$

The optimal feedback component assures a good system dynamic performance as well as a closed-loop system stability. To determine the feedback gains, a proper choice of the weighting factor ratio, $\rho_c=Q/R$, in the defined performance index provides a good transient performance. The higher weighting factor ratio, the lower damping ratio - it yields higher percent overshoot, and the system presents unstable behavior. Decreasing the weighting factor ratio stabilizes the control system, but implies some loss of performance as well. We applied $\rho_c=6000$ for the most reasonable performance in simulations, and the corresponding feedback gains and 5-step preview gains are

$$\begin{aligned} \mathbf{K} &= [8.3646\ \ 6.5494] \\ \mathbf{K} &= [-6.0482\ \ -0.6761\ \ 0.5075 \\ &\quad -0.2983\ \ 0.0875]. \end{aligned} \qquad (6)$$

The preview component is equipped to acquire and utilize the knowledge of the road profile disturbance signal, which is not taken into account (quantitatively) in the feedback design, so that the system performance is optimized during control. In order to determine appropriate preview steps, it is necessary to repeat the design process iteratively. In this investigation, 5-steps of preview is found to cancel the disturbance effectively. This agrees with simulations performed in the next section.

Usually the full system state, $\mathbf{x}(k)$, is not directly accessible, thus a state estimator is required in the feedback loop. Considering noise effects on the system, an optimal estimator can be found by defining the following linear time-invariant discrete-time estimator model,

$$\begin{aligned} \mathbf{x}(k+1) &= \Phi\mathbf{x}(k) + \Gamma\mathbf{u}(k) + \Gamma_w w(k) \\ y(k) &= \mathbf{H}\mathbf{x}(k) + v(k) \end{aligned} \tag{7}$$

where $v(k)$ represents an actual measurement noise, and $w(k)$ is a pseudo process noise whose assumed intensity is used in filter tuning. Suppose that $w(k)$ and $v(k)$ are random white noise sequences with zero mean, i.e., $E[w(k)]=E[v(k)]=0$. Here, $E[\cdot]$ denotes an expected value or mean value of $[\cdot]$. Also assume that $w(k)$ and $v(k)$ are uncorrelated with each other and normal, and have covariances defined by

$$E[w^2(k)]=R_w,\ E[v^2(k)]=R_v. \tag{8}$$

Then, an optimal estimator gain will be determined corresponding to R_w and R_v. If we feed back the error signal, $e(k)$, we can obtain the estimated state vector $\hat{\mathbf{x}}(k)$ such as

$$\hat{\mathbf{x}}(k)=\bar{\mathbf{x}}(k)+\mathbf{L}\{e(k)-\mathbf{H}\bar{\mathbf{x}}(k)\} \tag{9}$$

where $\mathbf{L}$ is the constant estimator gain obtained by error covariance propagation (Lewis, 1986b), and $\bar{\mathbf{x}}(k)$ is the time updated state from

$$\bar{\mathbf{x}}(k+1)=\Phi\hat{\mathbf{x}}(k)+\Gamma u(k). \tag{10}$$

Note that the noise covariance ratio, $\rho_e=R_w/R_v$, plays a major role to design the optimal estimator. Since actual process noise variance is not available, the gain should be determined so that the filter removes the undesired oscillation without introducing too much lag and slowing the response. In this analysis, we found $\rho_e=5000$ is the appropriate ratio, which results in

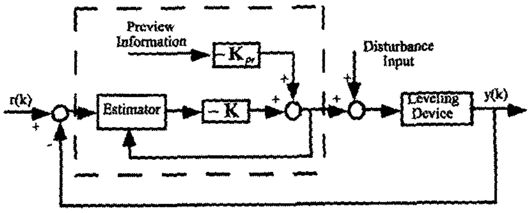

Fig. 2 Block diagram of auto-leveling system

$$\mathbf{L}=[0.9919\ \ 0.7105]^T. \tag{11}$$

Figure 2 shows an entire control system with the preview control method including the optimal estimator, where $r(k)$ indicates the desired vertical level (zero leveling), and $y(k)$ represents the actual vertical aiming. The dashed lines indicate the injection and observation of the road profile through the preview controller.

From Fig. 2, it becomes clear how the feedforward component is incorporated with a feedback loop. The controller for leveling disturbance rejection herein is implemented in a 'plug-in' fashion, meaning the feedforward compensator using the preview control scheme is used to augment the conventional servo. If the preview control is excluded, the control system results in a pure optimal feedback control or an LQG-controller. In this case, the auto-leveling system will only take account of instant leveling error signal relative offset of the front axle with respect to the rear axle. When a vehicle experiences fast acceleration or strong braking, the auto-leveler is supposed to be activated solely by the feedback compensator, since no preview information is available.

4. Simulation Results and Discussions

Computer simulations using ADAMS, the commercial multibody dynamic analysis program, are carried out when a vehicle encounters bumps at the vehicle traveling speed of 20 Km/h. Considering a simple two degree-of-freedom model of the passenger vehicle, we analyzed the motion in the plane of symmetry of the automobile (Inman, 1994). Although the motion of the vehicle includes both bouncing and pitching, we concerned only the pitching behavior in this investigation. The profile of bumps in a paved road is described

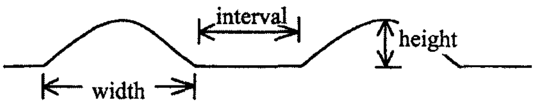

Fig. 3 Bump profile in a road

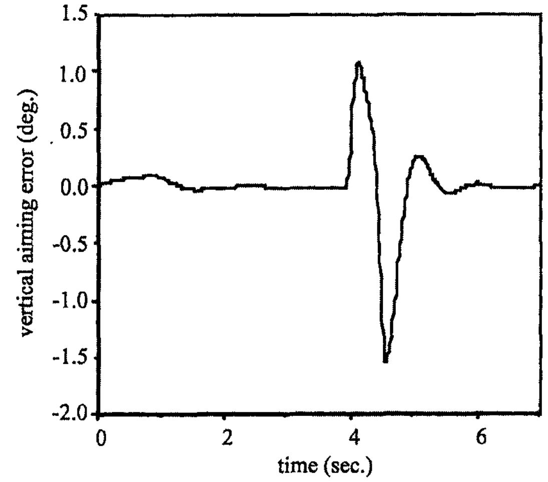

Fig. 4 Encountering a bump without auto-leveler

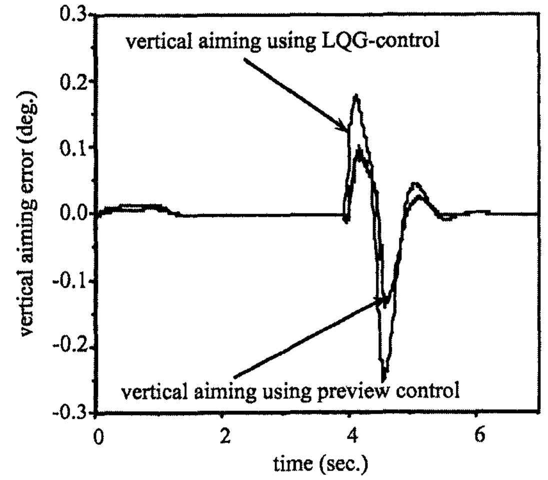

Fig. 5 Encountering a bump with auto-leveler

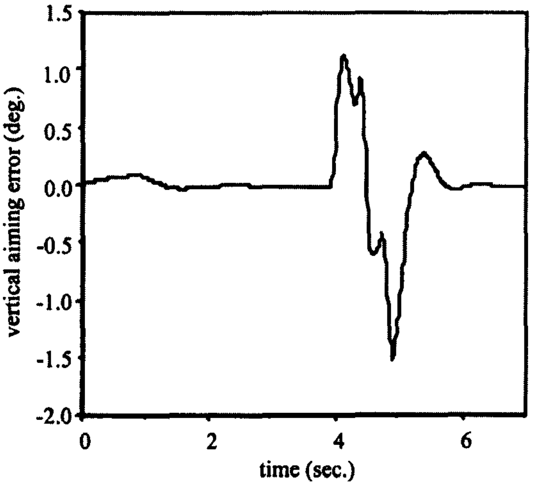

Fig. 6 Traversing sequential bumps (interval: 1.0 m) without auto-leveler

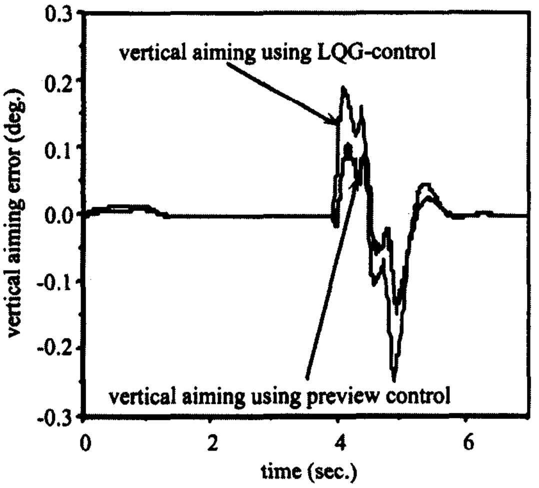

Fig. 7 Traversing sequential bumps (interval : 1.0 m) with auto-leveler

in Fig. 3, where the width and the height of bumps are 1.0 m and 0.08 m, respectively.

Figures 4~5 present leveling responses encountering a single bump. Here, the slight error profile at the earlier part of the responses reflects the aiming error caused by the vehicle acceleration. The results announce that the dynamic glare without a leveling device will affect other traffics significantly. On the other hand, the vertical aiming error is noticeably reduced by the auto-leveling system, especially controlled by the preview control. The preview controller attenuates the peak amplitude by a factor of 10~12, while the LQG-controller reduces it about a factor of 5~6.

Figures 6~7 examine the vertical aiming while a vehicle traverses sequential bumps, which have an interval of 1.0m. In Fig. 7, the performance of the auto-leveling system is also apparent in reducing the leveling error for this type of disturbance. Comparing with the LQG-control, the

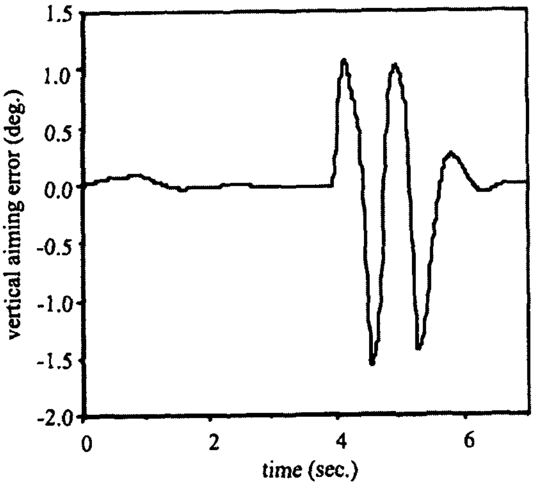

Fig. 8 Traversing sequential bumps (interval: 3.0 m) without auto-leveler

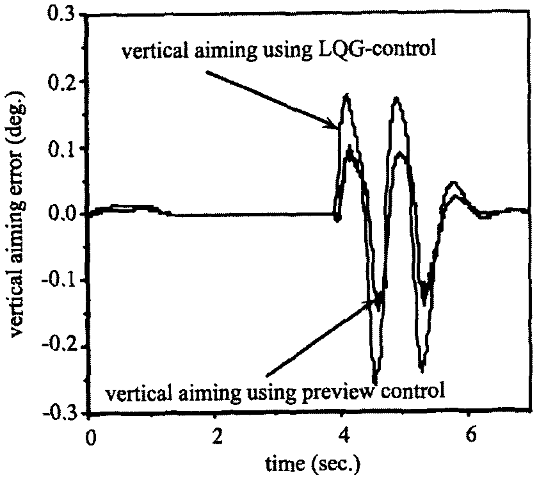

Fig. 9 Traversing sequential bumps (interval: 3.0 m) with auto-leveler

preview control decreased the magnitude of aiming error more effectively. The results also show that the peak amplitude of leveling error by the preview control is about half of that controlled by the conventional nonpreview control.

Trends of cutoff level responding to a series of bumps are also illustrated in Figs. 8~9, where the interval of bumps is 3.0 m. The disturbance is rejected well by the auto-leveling under acceptable aiming error range. Similar to the previous simulations, Fig. 9 shows that the auto-leveler using the preview control achieves more stable cutoff level along with less peak aiming error, even compared with the leveling system controlled by the LQG-control. Meanwhile, the headlamp without a leveling device suffers an extensive aiming error and oscillations. This observation justifies the use of automatic leveling system.

5. Conclusions

This study has investigated the usefulness of an automatic headlamp leveling in automotives. The aim of auto-leveling is to reduce vertical aiming error in light pattern. To achieve more efficient regulation against external leveling disturbances, the preview scheme is used to control a leveling device. Computer simulations are carried out to evaluate the performance of the automatic leveling systems. Two types of auto-leveler are examined: one employs the preview control, and the other uses a nonpreview control method such as the LQG-control.

Simulation results present the preview control in auto-leveling improves the vertical aiming performance drastically. It is shown that this type of auto-leveler reduced peak leveling error in angular position by a factor of 10~12 compared with the headlamp system without an auto-leveling. It is also noted that the effectiveness of the preview control is about twice higher than that of the LQG-control considering the same performance measurement. This investigation demonstrates that the preview control is well suited for controlling the HID headlamp leveling system.

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