Optical Design of Intelligent Projection

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Abstract - Intelligent projection headlamp includes critical technologies such as optical design and controller. It enables individual lighting for a small section of illumination surface. The light source is a multi-channel LED which is used as warning by combing on/off segments. If higher pixel light source is equipped, it can be used as interactive interface of autonomous car to provide visual aid functions such as warning, important tip and to become a direct and fast communication method between vehicle and driver.

In addition to intelligent display and illumination functions, if the headlight in this study is combined with long-range nighttime vehicle recognition and adaptive driving beam (ADB) algorithm to achieve real time detection, judgment partially turned off and partially lighting which can be used as ADB system. It can detect preceding and opposing vehicles in long distance and adjust illumination area automatically to prevent driver’s glare from headlight and improve safety of driving at night [1]. The functional design refers to relevant standard deviation and specification of SAE J3069: Adaptive Driving Beam which requires avoiding glaring for preceding and opposing vehicles at 30 – 155m and brightness upper limit of standard should not be exceeded.

In term of optical illumination performance for this study, there are total 12 segments of two illumination modules which include 49,600 – 52,300cd for each on/off section. Compensation design are used to deal with projection image blurred from bending of the focal plane of single lens and this design increase edge sharpness of the bright and dark areas. It can reduce halation between bright and dark areas and create clear information projection.

I. INTRODUCTION

The development trend of automotive system focuses on safety, performance and automatic driving assistant. Intelligent headlight will be one of communication means for advanced driver assistance systems (ADAS). In addition to electronic communications between systems, intelligent headlight can provide additional visual aid functions such as warning, important tip and to become a direct, fast communication method between vehicle and driver.

Intelligent headlight consists of image recognition module and optical projection module. The road condition is obtained through image recognition module which works with vehicle and path status to determine information to be projected to optical module. Different icon is displayed according to various information and be displayed on the road.

When vehicle with intelligent headlight system is driving at night and detects there is pedestrian or vehicle approaching in front, system can warn road user that there is autonomous car approaching with spot-light, or use optical pattern projection to project driving information of autonomous car such as start off, stop, left-turning and right-turning on road to help road user comprehend preceding driving status and increase warning capability.

If there are pedestrians on the left and right, spot-light will be projected to remind them to speed up or stop passing the intersection without affects other road users, as shown in figure 1. In addition to intelligent display function, it is able to work with preceding vehicle position identification for avoiding glaring to oncoming vehicles or vehicles ahead to improve driving safety of overall environment [2]. Compare to traditional headlight, 14~18m reaction distance is increased. Under 80km/hr speed, 0.6 ~ 0.8 sec. reaction time is increased. ADB is able to deal with 98% of road environment and it is expected to reduce accidents by 57% ~ 74% [3].

For design of projection lamp, the optical design is different from traditional vehicle lamps in response to the function change from “illumination” to “display”. The light source of this design is multi-channel LED which includes multiple luminescence dies that produce various brightness sections. The overall area of this type of LED is larger than general LED and the design is no longer based on overall light-emitting surface but on the individual one. With the exception of brightness and lighting pattern consideration, there are also requirements of sharpness.

II. TECHNICAL BACKGROUND

Use array light source as display warning purpose. Optical design is carried out according to array light-emitting characteristics to realize warning effect by combining multiple small area illumination unit and control illumination section brightness [4]. In terms of optical design, the sharpness is more important because of larger light-emitting area and avoiding glaring function, therefore, design is more difficult compare to existing lamping system. If a general lens is used to assemble several optical systems with small segment apertures, several auxiliary light-gathering lenses and projection lenses are required. There are also primary optical elements such as light guide bars to limit the light-emitting surface of each light-emitting area. Then use a projection lens to enlarge the projection to the front illumination surface. The light utilization rate is lower due to the use of multiple optical components. Consideration of stray light effect of each illumination area should be taken in optical design. Unexpected additional illumination for another area caused by light emitted with large angle which affects imaging should be avoided during design. Simulation software is used to construct light source, reflecting surface and lens optical unit in lamp design. Ray tracing is used to optimize design according to performance requirements of design target such as lighting pattern, luminous intensity, sharpness etc. In the future, the pixel of multi-channel LED will be getting higher with smaller unit and the requirement of sharpness will be increased to avoid mutual interference.

2.1 Array illumination module

This system includes multiple illumination module array which uses control illumination module to achieve avoiding glaring function and several section can be formed. In design, the distribution of luminous design of traditional lamps is reduced to the corresponding area, and light sources with different brightness are set according to the luminous intensity requirements of different areas. In design, due to the need for multiple illumination modules, the area of the lamp may be slightly larger than the general ones.

2.2 Multi-channel LED light source

Using multi-channel LED as light source of lamp which uses control
illumination module to achieve avoiding glaring function. Multiple avoiding glaring sections can be formed and the size is relatively compact. In terms of optical design, multi-channel LED light source which the parameter setting to complete distribution of luminous design and magnification. Compare to existing lamp design, the design is more difficult because configuration and arrangement of control LED position should take magnification of lamps into account, highest lighting efficiency for light source, optical design has larger area of light-emitting and better sharpness due to avoiding glaring function. If a general lens is used to assemble several optical systems with small segment apertures, several auxiliary light-gathering lenses and projection lenses are required [5].

Use cutoff mask and light-gathering lens to stack multiple segments and project light with projection lens which can be developed as multiple light pattern illumination system [6]. An optical unit, such as light guide bar, is used to divide each LED into blocks and projection lens is used to enlarge and guide the projection on road in front to achieve avoiding glaring which can be controlled independently in block.

Except for light guide bar, separation mask is also used to enhance cutoff of each segment. Projection lens set with 2 elements in 1 group is used to improve optical aberration and quality of light source image.

In theory, the more segments are the better system effect and higher cost. When considering uniformity of light distribution, especially system turns off some of the illumination modules to avoid glare to other drivers and the overall illumination visibility [8]

### III. DESIGN OBJECTIVE AND REGULATION REQUIREMENTS.

The objective of this study is to meet ECE-R112 high beam and SAE J3069 standard and regulation specifications.

#### 3.1 ECE-R112 distribution of luminous requirements of high beam

The requirement of distribution of luminous of high beam generated on screen is that luminosity at HV position should reach 80% of maximum luminosity. Maximum luminosity (EM) should be greater than 48 lux but not exceed 240 lux. The maximum luminosity (EM) of headlight used by both low and high beam should not exceed 16 times of low beam point 75R (or 75L) luminosity. In the range of 1.125m from the level of the HV point, the luminosity should not be less than 24 lux and 6 lux for 2.25m. The specification of test points and luminous intensity is shown in table 1 below.

#### Table 1: lower limit of ECE-R112 high beam test point and luminous intensity

<table>
<thead>
<tr>
<th>Test point</th>
<th>Angular coordinates degree</th>
<th>Required luminous intensity cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>I_max</td>
<td></td>
<td>Min</td>
</tr>
<tr>
<td>H-5L</td>
<td>0.0, 5.0L</td>
<td>40,500</td>
</tr>
<tr>
<td>H-2.5L</td>
<td>0.0, 2.5L</td>
<td>20,300</td>
</tr>
<tr>
<td>H-2.5R</td>
<td>0.0, 2.5R</td>
<td>20,300</td>
</tr>
<tr>
<td>H-5R</td>
<td>0.0, 5.0R</td>
<td>5,100</td>
</tr>
</tbody>
</table>

#### 3.2 SAE J3069 Illumination requirements

The test scenario of SAE J3069 is a 4 lanes road which is separated as left and right. Left represents opposing vehicles while right stands for preceding vehicles.

The width of each lane is 3.66m. Detection is done for preceding vehicles at the 3.66m from the right lane and for opposing vehicles at the 3.66m and 7.35m from the left. There are 3 measurement points.

SAE J3069 clearly specified that the measurement distance is 30 meters, 60 meters and 120 meters, and 155 meters and 100-155 meters randomly under 4 distance scenarios. Illumination of each distance is in table below which include driving status of opposing and preceding vehicles.

#### Table 2: upper limit of SAE J3069 distance and illumination.

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Maximum Illuminance</th>
<th>Maximum Illuminance</th>
</tr>
</thead>
<tbody>
<tr>
<td>155</td>
<td>0.3</td>
<td>4.0</td>
</tr>
<tr>
<td>120</td>
<td>0.3</td>
<td>4.0</td>
</tr>
<tr>
<td>60</td>
<td>0.7</td>
<td>8.9</td>
</tr>
<tr>
<td>30</td>
<td>1.8</td>
<td>19.9</td>
</tr>
</tbody>
</table>

For opposing vehicles, illumination at 155m and 120m should not exceed 0.3lux and 0.7lux should not be exceeded at 60m while 1.8lux for 30m. For preceding vehicles, illumination at 150m and 120m should not exceed 4lux, 8.9lux for 60m and 18.9lux for 30m. This design specification is quite reasonable under actual circumstance that the illumination perception is one-tenth of that received by the forward eye when viewing rear lights from rearview mirror. There another scenario is required which is light source appeared suddenly and randomly in opposing and preceding lanes with 100m to 155m and to avoid glaring within 2.5 sec.

### IV. DESIGN AND ANALYSIS

The design and analysis of the optical units of the vehicle headlight is based on the design objective conditions, specifications and methods. Use 3D software to optimize design according to reflecting surface design method. Use focus change of reflecting surface to reduce size and optimize maximum luminous efficiency, then perform ray tracing with ASAP optical analysis software to analyze lighting pattern and luminosity for complying with requirements of ECE-R112.

The light source of this lamp is multi-channel LED which include multiple luminescence dies that control brightness of individual luminescence die according to avoiding glaring demand to produce various brightness sections. The overall area of this type of LED is larger than general LED and the design is no longer based on overall light-emitting surface but on the individual one. With the exception of brightness and lighting pattern consideration, compare to traditional lamps, there is also requirements of sharpness.

For the number of illumination sections, due to requirement of automatic avoiding glaring function, at least 4 segments are needed. The design objective of illumination efficiency is based on ECE-R112 high beam. The total illumination range should be 2 degrees for up and down and 3 degrees for left and right. Dark space of avoiding glaring is based on SAE J3069, the reference of which is 1.8lux at 30m. The optical design requirement is as shown in table 3.

#### Table 3: Optical design requirements

<table>
<thead>
<tr>
<th>Illumination sections</th>
<th>Total illumination range</th>
<th>Single illumination sections</th>
<th>Maximum brightness</th>
<th>Dark space brightness</th>
<th>LED brightness</th>
<th>LED control</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 segments</td>
<td>6° x 4’</td>
<td>4° x 4’</td>
<td>&gt; 40,500 cd</td>
<td>&lt; 1.8 lx @ 30m</td>
<td>250 lm</td>
<td>Independent</td>
</tr>
</tbody>
</table>

Light source used by illumination module is 6 chip and light source of individual chip is about 3.2 x 1mm. Reduce lens curvature and lens weight to decrease process difficulty and supporter load with longer focal length to process projection function. The diameter of lens is 30mm to cover main divergent rays; the simulation of lens size is shown in figure 2.
In order to get high light utilization, optical system uses single lens as design objective. Spherical lens commonly used has curved focal plane which causes out of focus of edge light source and light source image to be blurred and unequally amplified so that the edge segment are more likely to interfere with other surrounding dark spaces. For ADB system, it is necessary to cope with the situation to comply with regulatory requirements.

To deal with the bending problem of focal plane, i.e. spherical aberration, aspheric surface (various curvature in each area), corrections of cemented doublet (materials with different refractive index) and increasing lens are usually used. With a single lens, spherical aberration can be processed by changing curvature of lens as discontinuous or by adjusting relative angle of light source and lens [9].

Lens design is divided into two parts: optical surfaces of light-gathering and refractive. Light-gathering optical surface is used to collimate the light irradiated form the LED, and refractive optical surface is used to redirect the collimated light to meet light source image and its illumination properties of design requirements [10].

Adjust the curvature of the lens, and apply a compensation design at the corresponding LED die position and main light-emitting range to reduce the aberration caused by the bending of the focal plane to further correct the aberration.

When light enters refractive at a large angle of incidence, there is no ideal convergence effect. The light refraction will be different from the simplified ideal situation which needs to be described by the optical paraxial refraction equation stated by Snell's law:

\[ n(y_c + u) = n'(y_c + u') \]  

Where:
- \( n \) is the refractive index of the incident space
- \( n' \) is the refractive index of the emergence space
- \( y_c \) is the height of the light on the incident optical surface
- \( y_c' \) is the height of the light on the emergence optical surface
- \( u \) is the slope of incidence and optical axis
- \( u' \) is the slope of emergence and optical axis

When determining the behavior of a ray in an optical system, only need to ensure the height \( y \) and slope \( u \) of the ray on each optical surface. When the light is transmitted through the optical system, the slope is extremely small and angle of light and optical axis is the same as tangent value of the angle to get translation equation to give \( y \) value from one optical surface to next one.

\[ y = y_{c-1} + tu \]  

\[ y_{c-1} + tu = \frac{y}{n} + \frac{t}{n(u + u')} \]  

\[ y = \frac{n'y + u' + \frac{t}{n}}{n} \]  

\[ y = \frac{y_{c-1} + tu}{n} \]  

\[ y = y_{c-1} + tu \]  

\[ y = \frac{y_{c-1} + tu}{n} \]  

Introduce the focusing force parameters of the lens surface to describe the lens ability to converge the light and it is related to the curvature and refractive index of the optical surface to get the following equation:

\[ u = \frac{2k - y}{w} \]  

And express the

This equation can explain the height of the light incident on the lens surface with a focusing force of \( \varphi \) and express the slope. Continuous use of this paraxial translation and refraction equation can determine the paraxial light passing through the optical system.

Therefore, the paraxial refraction equation (1) uses the translation equation (2) to describe the light traveling on the optical surface of each focusing force, and is the following light tracing equation:

\[ y = y_{c-1} + \frac{t}{n}(n'u' + y\varphi) \]  

Give system \( y, nu \) of the first optical surface and use refraction equation to calculate \( n'u \) of the second optical surface to reckon light height of the second optical surface. To calculate optical aberration caused by different incidence light height, it is necessary to design incidence surface with various angles corresponding to different positions to adjust refraction angle at various locations to correct the included angle between emergence light and optical axis to improve optical aberration.

Using non-sequential optical simulation software ASAP and the result show that lighting pattern of each segment are hardly affected and the brightness is more concentrated. The dark section is darker (25% difference) that is in line with the expected improvement.

The illumination effect of a single module (6 segments) has illumination range of 4 degrees up and down, 3.75 degrees left and right at 25m, center brightness reaches 40,500cd which comply with brightness requirement of high beam HV point of ECE-R112. The high beam illumination range of the regulation requires 6 degrees for left/right and 2 degrees for up/down. Therefore, each side of headlight is designed with two modules and a center distance of 40mm. Left illumination module is tilted by 5 degrees while 3 degrees for right module. It is expected to produce 12 segments illumination effect with range of 2 degrees up/down and 7.5 degrees left/right. Two modules are overlapped at HV position to avoid insufficient brightness due to light emitting gap of the die.
Comprehensive simulation analysis shows that the size of a single lens is about 30mm with 16mm in thickness, so that a segment can have an illumination range of about 2 degrees up, down, left and right at 25m, and the light source image is clear. With the compensation structure, the tangent is more obvious, and meets the SAE J3069 dark area brightness minimum requirement of 0.3 lux.

When all of segments are turned on, with computer simulation analysis, the brightest point is 52,334cd, the simulated value at 25R test point is about 52,310cd, the simulated value at 5R test point is about 51,687cd and the simulated value at 5L test point is about 49,609cd with 2 degrees up/down, 7.5 degrees left/right illumination range which meet high beam regulation of ECE-R112. In terms of overall performance, the brightness is greater than lower limit of regulations. With its avoiding glaring and warning lighting capabilities, the optical performance and functionality are better than traditional lamps. Combine with image recognition system, it is a vehicle intelligent headlight system that meets the safety requirements of night driving in the future.

When a single segment is turned off, the bright section on both sides will not be have large halation which affect dark section with 0cd lowest brightness to produce obvious avoiding glaring section to avoid glare to another driver.

Turn off a segment with a 0 cd range of 1.5 degrees to the left and right; the illumination range is similar to bright section due to sufficient sharpness of light source image. The width is about 32.48m at 155m, 12.58m at 120m, 6.28m at 60m, and 3.14m at 30m which means only 1 segment needs to be turned off with 19m and above and 2 segments should be turned off with less than 19m.

When the upper row of segments are used for avoiding glaring, the lower raw segments keeps a certain degrees of road illumination for more delicate avoiding glaring control. As another function of intelligent headlight, spot light can be projected on the objects that require warning, such as pedestrian who intends to cross the road, to bring driver's attention without affecting other road users.

Overall, this design has successfully produced 12 segments of multichannel LED Intelligent headlight, while meeting the high beam requirements of ECE-R112 and optical performance requirements of SAE J3069 with maximum brightness of 52,334cd and 2 degrees up/down, 7.5 degrees left/right and 1.5 degrees for avoiding glaring. According to distance, turn off 1 ~ 2 segments to cover avoiding glaring for width of 2m for another drivers to avoid hazards of glare to meet requirements of regulation, standard and pedestrian waring achieving driving safety.
### Table 4: Simulation results of illumination system

<table>
<thead>
<tr>
<th>Optical design objective</th>
<th>Simulation result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illumination sections</td>
<td></td>
</tr>
<tr>
<td>Total illumination range</td>
<td>12’ x 4’</td>
</tr>
<tr>
<td>Single illumination</td>
<td>4’ x 4’</td>
</tr>
<tr>
<td>Maximum brightness</td>
<td>&gt; 40,500 cd</td>
</tr>
</tbody>
</table>
| Dark space brightness    | < 1.8 lx (1,620 cd)@
|                          | 30m               |
| Dark space               | --                |

**CONCLUSION**

Due to the vigorous development of automotive electro optical technology, driving safety has become the focus of research today. The function of intelligent headlight on autonomous car is not only to illuminate the roads but also to communicate with outside world. With commercialization of various high pixel light source such as DLP, MEMS, it will be the illumination representative equipment of high value and effectiveness and also meet the demand of ADB illumination. This equipment has more diversified functions and added values. It also means that intelligent headlight which not only improves safety of autonomous car but also improves safety of entire road environment and can be the replacement of traditional ones.

In this study, we successfully design two illumination modules that have 12 on/off segments ADB system optical design meets high beam regulation of ECE-R112 and requirements of SAE J3069. At 30~155m, it can prevent strong light from hitting other driver's eyes in opposing or preceding vehicles while keep illumination distance of high beam that is of great help to improve safety of night driving.

For the ADB system, the technical level established in this study mainly corresponds to the optical design of the multi-channel LED light source. The traditional optical design focus on uniform distribution of luminance and the design meets the regulations and bases on non-imaging optical design. For intelligent headlight, optical design is based on imaging optic. Light source image should have certain degree of sharpness to meet requirement of projection image and upper limit of brightness in dark area of SAE J3069. The design structure on a single lens can overcome the optical aberration and increase utilization of light.

This study completes optical design of intelligent headlight which can show clear images in optical simulation and comply with high beam illumination standard and have ADB function. In the future, it will combine the image recognition system to achieve interactive display of the vehicle and road environment to let others know the driving intention of the vehicle. Through identification system works with firmware to control on/off of light source which can to determine other vehicles to produce section where needs to avoid glaring and make the smart lamp technology more complete.

### REFERENCES


