An Application of Augmented Reality Head-Up Display

Shun-Wen Cheng*, Yi-Feng Su, Jih-Tao Hsu
Automotive Research & Testing Center, No.6, Lugong S. 7th Rd., Lukang, Changhua County 50544, Taiwan (R.O.C.)
E-mail: zonacheng@artc.org.tw

1. Introduction

Head up display (HUD) is a semi-transparent display system that projects information directly on windscreen, as to allow the driver for vital information while keeping his eyes on the road for better safety. The most commonly seen HUD products in the market are of single optical path system that is unable to provide display information that is projected with perceptive depth and lack multifunctional warning. With increasing attention on onboard safety system, the quantity provided to the driver increases dramatically and traditional HUD systems are no longer up for the job. Also, the short virtual image distance leads easily to overlapped focus of driver and eventually eyestrain. In light of needs in future cars, a dual optical path HUD system was proposed to project image directly on the road ahead using augmented reality, as shown in Fig. 1. A face recognition system was incorporated to adjust the position of image projected in real time based on the elevation and position of the driver. Future expansion is possible to allow projection of other vehicle information on this platform.

![Fig. 1 Scheme of HUD projection](image)

2. Methodology

The image to be projected should be able to cover the road ahead in order to produce a picture corresponding to lane lines. However, the challenge is to fit the size of projector in the limited space in a car. Therefore, the law of Etendue conservation was introduced in the study. A multi-optical path approach was adopted to realize a virtual image display system covering a large range with only a single image input and splitting element framework. The system works by splitting the original image using the splitting element. The split optical paths generate deflection and cross one another. Therefore, the subsequent placement of optical element at where the optical paths meet effectively minimizes the size of optical element. The dual image splitting allows display of dual images or overlapping into a large-area image display.

2.1 Optical System Design

The projector consists 4 parts, the image source, splitting element, concave mirror and combiner. The splitting element was a bi-prism that deflects and crosses the optical paths of the image source, thus achieving image splitting along X-axis. Fig. 2 shows how the optical paths are split. The concave mirror magnifies the split images and projects them on the combiner, and an enlarged virtual image is created.
The upper half of the bi-prism in Fig. 2 is zoomed in to show the relationship between the deflection angle of the optical path of display and the incident optical path. When a beam of light is shot horizontally into the prism, it is projected at a $\delta_0$ angle below the normal line. The angle between the incident light and the normal of the first side of the bi-prism is equal to the apex angle, $\alpha$, and the function of angle of emergence, $\delta_0$, refraction index, $n$, and vertex angle, $\alpha$, is obtained as Eq. (1).

$$\delta_0 = \sin^{-1}\left(\sin \alpha \sqrt{n^2 - \sin^2 \alpha} - \cos \alpha \sin \alpha \right)$$

(1)

The half field of view angle of driver’s eyes has to be 22° in order to achieve the size of image large enough to cover the lane lines. Therefore, the angle of emergence of the prism, $\delta_0$, was set at 22°. The specifications of the bi-prism are provided in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>BK7</th>
</tr>
</thead>
<tbody>
<tr>
<td>apex angle,$\alpha$</td>
<td>30°</td>
</tr>
<tr>
<td>$\delta_0$</td>
<td>$\pm 22.323^\circ$</td>
</tr>
<tr>
<td>length</td>
<td>100mm</td>
</tr>
<tr>
<td>width</td>
<td>50mm</td>
</tr>
<tr>
<td>height</td>
<td>28.8mm</td>
</tr>
</tbody>
</table>

With this projector structure, the lens imaging formula of the theory of geometric optics was used to calculate the specifications and focal range of the concave mirror. From the designed projector structure shown in Fig. 3, the total projection distance, $T$, of this structure was determined as Eq. (3).

$$T = D + \left[ S + S' \right]$$

(2)

$$\frac{1}{S} + \frac{1}{S'} = \frac{1}{f}$$

(3)

$\sin \alpha = \frac{2}{S}$

$\cos \alpha = \frac{2}{S'}$

Where D is the distance that the image travels from the prism to driver’s eyes. However, to project an image on the combiner, the projection has to be a virtual image. Therefore, $S'$ needs to be corrected to be negative. Later the focal length of the projector, $f$, is determined using Eq. (3), and then a proper focal length is selected for experiment to determine the preliminary specifications of the elements. The preliminary specifications of the mirror set calculated are provided in Table 2. To meet the demand of onboard applications, an LCD display for onboard use was selected for system image input with the specifications shown in Table 3.
### Table 2 Preliminary specifications of mirror set

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>486nm–656nm</td>
</tr>
<tr>
<td>spot-size</td>
<td>8mm</td>
</tr>
<tr>
<td>Focal length</td>
<td>263mm–265mm</td>
</tr>
<tr>
<td>Image distance</td>
<td>7000mm</td>
</tr>
</tbody>
</table>

### Table 3 Display specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>320H x 240V</td>
</tr>
<tr>
<td>Screen size</td>
<td>3.5”</td>
</tr>
<tr>
<td>Back light</td>
<td>LED</td>
</tr>
<tr>
<td>Display size</td>
<td>71.12mm x 53.34mm</td>
</tr>
</tbody>
</table>

#### 2.2 Simulation of Optical Design

Zemax, an optical imaging design program, was used to import the preliminary data in the tables above. Optimized parameters were used for optimization. Fig. 4 provides the system output optical path after optimization. The spot-size of element was 8mm, similar to the pupil of a human eye. The combiner was placed 500mm from the driver’s eyes, and the concave mirror was placed 200mm from the combiner. The concave mirror and combiner used here were of standard spherical surface and planar surface rotating against Y-axis, respectively. The concave mirror was 130mm from the bi-prism. The image input element was 60mm from the bi-prism. The imaging location was 2m and the size of image was 10.1 inch.

![Fig. 4 Optical path of mirror set after optimization](image)

Parameters such as field curvature, distortion and lateral color were used to examine the imaging quality of the structure. Fig. 5 (a) provides the field curvature and distortion values. The maximum distortion was -0.52%, still within the range of ±1%. Fig. 5 (b) is the lateral color diagram where the horizontal axis is the lateral color, vertical axis is the image height and the three colored lines are the three wavelengths set in the system. The diagram shows that the lateral color values in all the fields of view were less than the size of a pixel (222.25μm). Fig. 5(c) is the analysis of binocular FOV range. Its binocular FOV was 18.16° x 9.58°. The imaging quality parameters achieved the level recognizable for human eyes.
Fig. 5 Parameters used for examination of mirror set quality: (a) field curvature and distortion; (b) lateral color; (c) FOV range analysis.

The optimized element parameters were imported into an optical program to examine the changes in optical paths and verify the structure volume that is smaller than that of a typical single optical path projector. The image sizes were all 10.1", enough to cover the lane lines. Fig. 6 (a) shows the optical path crossing as they passed the bi-prism. The concave mirror was placed where the optical paths crossed one another. The size of concave mirror was 38.5mmx28mmx11mm. The size of display used in typical traditional single optical path structure was 38.5mmx52mmx11mm. By comparing the structure proposed and the single optical path structure of a traditional HUD, the concave mirror was 53.8% smaller in size.

Fig. 6 Simulation of volumetric size of concave mirror: (a) dual optical path structure; and (b) single optical path structure.
2.3 Augmented Reality Algorithm

For augmented reality display, human eye detection and multiple-image coordinate conversion technology were introduced to calculate where the virtual image was displayed. The fitted road lines and front car information were projected through the projector. The conversion of coordinates is shown in Fig. 7. The system had to convert 2-D information into 3-D projection using the multiple-image coordinate conversion formulae of Eq. (3) and (4) in order to overlap the lane lines and front car on the windshield on the position in the real space (World Coordinate).

\[
U_p = \frac{U_e H_c x e_a}{e_c H_c x e_a - e_c x} + U_{p0}
\]

\[
V_p = \frac{e_c e_a H_c y a}{e_c H_c y a - e_c y} + V_{p0}
\]

Eq. (3) shows that the position of projection changes with where the driver’s head and eyes are. Therefore, to minimize the error in projection position due to the changes in driver’s head position, the facial deflection angle and 3D positions of facial features of the driver were calculated by considering the relative spatial relations of eyes and nose and using Eq. (3). This increased the accuracy of overlapping error correction and made the projection more accurate. \( H_c \) was the elevation of camera from ground level, \( D_c \) was the result of infrared ranging, \( f \) was the focal length of the camera’s lens, \( h_e \) was the \( Y \) coordinate of the 2D image of the eyes, and \( h_{pe} \) was the height of eyes in relation to the horizontal position of camera estimated based on the pinhole imaging principle of camera. From all of the above, the elevation of eyes was the sum of \( H_c \) and \( h_{pe} \), and the distance of eyes was the infrared ranging result, \( D_c \).
3. **Experiment Result**

As shown in Figure 9 about system structure configuration chart, video camera, optical machine module (including source of image, bi-Prism, plane mirror, concave mirror and combiner), and DSP module are installed on top of dashboard for driver to identify safety message of preceding vehicle and reminder message of integrated forward collision warning (FCW), lane departure warning (LDW) and navigation. Integrated message screens will then be input to a 3.7” LCD Display monitors as part of basic structure of dual paths. Tests performed included: (1) virtual image display: to verify the effect of nighttime virtual image display; and (2) correction test for intelligent display position errors: the 3D position of driver was used to correct the position of projection.

![Fig. 9 AR-HUD system structure](image)

**3.1 Virtual image display: to verify the effect of nighttime virtual image display**

A single concave mirror was used to receive the image transmitted through the two optical paths and 2 combiners were used to reflect lights into the driver’s eyes, thus enabling the viewing of virtual image displayed. The experiment setup is shown in Fig. 10.
Actual display performance of AR HUD system through experimental platform as presented in Figure 11, where the display area can cover up-front lane, clearly detect current location of up-front lane marking of travelling vehicle, warning message of safety distance away from preceding vehicle, integrated messages of driving speed and speed limit, and displayed image can be overlapped with screen of actual lane. The accuracy recognition rate of lane deviation warning system for good-quality roads such as Expressway reaches up to 98.2% and Highway reaches up to 98.6%; projected lane image perfect in line with actual lane represents a tolerance less than a marking width at ±15cm.

![Fig. 10 Experiment setup and display result](image)

![Fig.11 Sample image demonstrating the performance of AR-HUD system](image)

3.2 Correction test for intelligent display position errors

The 3D position of driver was used to correct the position of projection. The facial feature position information and detection algorithm proposed was used to detect the position of driver’s face in 3D space. The experiment result is shown in Table 4. The accuracy was 91% for the distance from eyes to camera, 98% for eye elevation from ground level and 91-98% for 3D estimation of face position, which is good enough for typical scenarios of use. Fig. 12 provides real-time correction of projection.
Table 4 The accuracy of detecting the position of driver’s face in 3D space

<table>
<thead>
<tr>
<th></th>
<th>experiment value of the eye distance</th>
<th>experiment value of the eye height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual value</td>
<td>63.4 cm</td>
<td>121.65 cm</td>
</tr>
<tr>
<td>of the eye</td>
<td></td>
<td>Actual value of the eye height</td>
</tr>
<tr>
<td>distance</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>69 cm</td>
<td>122 cm</td>
</tr>
<tr>
<td>Accuracy rate</td>
<td>91.88%</td>
<td>99.71%</td>
</tr>
</tbody>
</table>

Fig. 12 Calculation process of face feature position detection

4. Conclusion

An image-splitting multi-optical path structure was proposed for onboard HUD systems. A symmetric pair of right-angle prisms were placed in front of the display to form a dual optical path structure. The simulation result proved that this multi-optical path technique allowed the need for large area display (10.1”). The overall image covered the entire width of a lane and was incorporated with safety information useful for driving, thus realizing a display platform of augmented reality. Virtual imaging was introduced in the system design and the image produced was projected 2m in front of driver to minimize the eyestrain caused to the driver while reading information projected. The optical simulation proved that the size of concave mirror used in the proposed system was 53.8% smaller than those used in traditional single optical path systems. The face position estimation and multiple-image coordinate conversion technology were incorporated to project the image information of augmented reality on windscreen. The estimation of face position was 91~98% accurate as the overlapping images were corrected in real time with the position and elevation of the driver. This augmented reality system provided good display effect as the driver’s head moved in different angles and elevations, thus realizing a information display system of increased safety and comfort.
5. Reference


