Optical design of head-up displays using CAD-compatible freeform surfaces

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Head-up displays in automobiles offer a higher level of safety, driving comfort and an enhancement of prestige as well as feeding a passion for engineering. A critical component in designing head-up displays is the imaging mirror, which is typically designed as an optical freeform surface. This article will introduce the design methods and results and also emphasize that the freeform surface can be described already in the design process in such a way that an export into custom CAD systems is easily possible without risking any severe performance.

Due to their high initial cost, head-up displays (figure 1) were primarily reserved for the military and civil aviation and only more recently have they been made available for the premium segment of the motor industry. Since then, however, large area freeform mirrors, such as those used for optical image formation and with edge lengths in excess of 100 mm, can be produced inexpensively by using injection moulding methods. In addition, small TFT displays have become an affordable image source, and their compact, directional and adjustable illumination via LEDs makes them even more attractive. The resulting lower production costs allow the application of head-up displays in all vehicle classes and simultaneously promote increased participation and supplier activity in this field.

As the optical image formation of the head-up display occurs via a reflection onto the windscreen, it is necessary to have a unique adjustment of the image formation optics for each windscreen shape common to a particular vehicle model. This requires an efficient approach to the optical design in order to minimise the development costs, but this issue is hampered by the difficulty in drawing comparisons with other optics problems in the field of conventional imaging. An additional hindrance is the lack of publicly available reference systems.

1 Functionality of a head-up display

Using a head-up display (HuD), one can present information such as velocity, navigational tips and the output of an infrared night vision camera in a form of a virtual image, this image being located within the line of sight and approximately two to three meters in front of the driver (figure 2) and overlaid on the immediate surroundings. This visualisation is achieved by reflecting the emitted light from the HuD off of the windscreen at an incidence angle in excess of 65°. According to the Fresnel reflection coefficients, for a polarisation perpendicular to the plane of incidence approximately 30% of the incident light will be reflected at the air-glass interface. The required polarisation is obtained by appropriate orientation of the liquid crystal display used for image generation (alternatively, use can be made of the laser diode scanning systems being touted for this application). As the light is also reflected at the outer surface of the windscreen, the reflection at both inner and outer sides of a parallel windscreen would create a disturbing double-image. The two images can be placed one over the other by using an appropriately angled wedged foil positioned within the laminated glass.

The image generated by the HuD overlays the image of the surroundings as seen by the driver through the windscreen. The brightness of the HuD can be controlled by adjusting the light source according to the brightness of the surroundings, for which there are sensors readily available in most vehicles. Incidentally, a virtual image is additionally formed underneath the vehicle, and is observable from

Figure 1: Head-up displays ease the visual perception of additional information and hence help improve safety and driving comfort (courtesy: BMW)
above, e.g. from a bridge looking down, over a small viewing angle. If the windscreen were a flat planar surface, it would suffice to mount the image source at a suitable angle into the dashboard and illuminate the windscreen directly without use of a mirror. This would however require the use (and installation) of a relatively large and thus expensive display. In reality the windscreen presents a curved surface for illumination, thus introducing distortion into the image, and is furthermore positioned barely a metre in front of the driver. Use of an imaging optic in the form of a mirror is thus unavoidable, and provides a means to correct any image errors introduced by the windscreen, to magnify an otherwise small source to an acceptable image size and furthermore to place the image at a distance of two to three meters in front of the driver and at a full field angle of approximately $5^\circ \times 2^\circ$. The image mirror is consequently equivalent to a conventional magnifying glass, through which the image source that serves as a display is observed. The current systems allow the virtual image to only be visible from the driving position in a relatively small area, typically $140 \times 70 \text{ mm}^2$ area, which is perpendicular to the direction of travel. This area is known as the eye box. The image mirror can be tilted in some systems in order to adjust the area to the seat height. For this relatively small eye box and the aforementioned field angle, the imaging error introduced by the windscreen can be sufficiently corrected at reasonable cost. The correction of imaging error over larger areas is however limited as the production related tolerances and deviation of the screen form are still rather large. The size of the eye box roughly corresponds to the required aperture of the image formation optics, and is thus a determining factor for the space requirements in this critical area of the dashboard. The aperture, which is relatively large if compared to other image formation systems, is also the reason why costly (conventional) glass optics can not be considered for this application.

### 2 Interaction between man and machine via HuD

Based on the previously mentioned functionality there are some obvious advantages to be gained by use of a HuD, first and foremost that useful information can be overlaid on top of the current traffic conditions visible outside the vehicle, this information remaining visible in all conditions. The need for the eyes to focus (accommodation) and mutually adjust (vergence) for the HuD image is much reduced in comparison to viewing the instrument cluster (although the gain is considerably less than the 2 s suggested in some advertising campaigns) [1]. Due to its large image distance and the reduction of visual distractions outside of the field of view, the HuD is in particular for long-sighted drivers a much more comfortable viewing technology. The HuD also helps to reduce the operational demands needed in accomplishing tasks other than driving such as answering a telephone or navigating. Reports from more “sport” oriented drivers indicate that the constant presence of the current speed in the field of vision is considered rather irritating. In general one has to be careful that the information provided by the HuD does not detract from the primary task at hand, namely that of driving the car, noting also that this form of display can draw one’s attention and lead to a situation not unlike “tunnel vision” [2]. These safety aspects are causing some automobile manufacturers to delay introduction and to also take a closer look at alternative options, such as displays that project at a similar distance but not in the driver’s line of sight. The greatest potential for HuD lies in the “augmented reality” opportunities made available, i.e. depiction of information in direct relation to the current surroundings, so-called contact analogue information [1]. For the case of automobiles this means a visual illustration of the distance to the next vehicle ahead, of the minimum braking distance or an indication of traffic signs and other road users. As is already the case for aircraft traffic, through presentation of these types of information it should be possible to avoid the disadvantages mentioned above and make a contribution to road safety, perhaps resulting in a reduction in insurance premiums for appropriately equipped vehicles [2].

### 3 Optical Design

#### 3.1 System analysis

By using differential geometrical methods in describing the optical image formation of a small bundle of rays on freeform surfaces [3, 4], an initial system for the HuD optics can be determined, even taking in account the curvature of the windscreen. Moreover, the image mirror is described by using a non-symmetrical rotational paraboloid. This system is illustrated in figure 3. As this initial representation only considers small bundles of rays, the distortion is not yet taken into account. This initial system can be subjected to a first analysis via ray tracing, and for this

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1 “Contact analogue” means that the display of information correlates directly with the environment, for example as is the case for an aircraft’s artificial horizon. For instance, an approximate estimation of the braking distance could be depicted using augmented reality in form of colours overlaid on the surroundings instead of just through numbers – such information is then called contact analogue. The same is true for a navigational arrow overlaid on the surroundings at the point where a turn should be made. The illustration of current speed is however not contact analogue – information thrown up onto the HuD from the instrument cluster is additive.
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purpose various exit pupils within the eye box have been colour-coded (as shown in figure 4), correlating to various positions of the eye. In comparison with eyepieces or head-mounted displays [5], the position of the exit pupils in HuD varies over a significantly larger area. The different positions of the exit pupils allow the study of the effects of horizontal head movement, particularly the change of distortion so produced. For short, this effect is called dynamics. In addition, the coding allows the study of vergence by comparing the image points for both, left and right positions of the eyes. The image points are coded with corresponding colours. Lastly, the image definition for each eye position is observed.

Figure 5 shows the result of a beam calculation for nine horizontal and five vertical object points according to the eye positions given above. For this visualisation, the image space rays are extended into the virtual image plane, where they are analysed. In this approach, a ‘targeted’ beam calculation (so-called ray aiming) is essential as the proper direction of the beam travelling from the object point is initially unknown, instead the required point of incidence of the beam in the eye box is known. The illustration in figure 5 indicates clearly that the system does not fulfil the requirements regarding distortion. Moreover, the dynamics of the distortion (identifiable by the length of the arrows), the vergence and the difference in the corresponding colour pairs, is clearly very large. Only the focus, which is rendered by the expansion of the image point lies in the range of a few angular minutes and would therefore be tolerable.

3.2 CAD-compatible freeform surface definition

Prior to optimisation of the image mirror, an adequate surface definition has to be reached. The current format in standard software for optical design is a polynomial description. It is thus practical to describe the surfaces within the optics software using a NURBS-basis. The data exchange using CAD-systems can then be achieved via standardised formats such as STEP or IGES. However, surface description in this way has never been offered by commercial programs for designing imaging systems, which is why the study and observations made here are performed using a MATLAB-based software [8].

3.3 Optimisation of the optical design

The previously calculated system falls well short of requirements regarding distortion correction. These requirements, coupled together with an acceptable image focus, can not be entirely compensated by a single imaging optic – at very best a minimisation is possible. The distortion can be separated into distortion dynamics, vergence and absolute distortion (cf. 3.1). The result of an optimisation, by which the surface parameters are varied and the distortion components together with the image focus are minimised, is shown in figure 6. Compared to the start system (shown in figure 5), the result is clearly better. For the same level of image focus, the degree of distortion has been significantly reduced. The remaining parabolic-like distortion error can not be further reduced using a single imaging mirror, but can be compensated by introducing a complementary distortion in the source image (“image warping”). Following optimisation, a tolerance study of the developed design is necessary, although this procedure will not be discussed here. In addition, it is also prudent to perform an analysis of the surface curvature of the mirror in order to check for excessive curvature. Curvature analysis is often performed as a matter of course in CAD systems when using converted surface data, as it is often the conversion itself that is responsible for spurious effects. Utilising the CAD compatible B-splines for the initial description and optimisation of the surface is thus highly favourable.
Figure 7 shows the process of the average curvature (in dioptres) over the surface of the mirror. At the chosen points on the surface, the two principal directions of curvature and their magnitudes are illustrated by arrows.

Of interest is a comparison of the design of the imaging mirror using the traditional polynomial description process and the CAD compatible B-splines method adopted here. A polynomial description allows faster convergence on the optimal design, although the final result using the B-spline description was slightly better. In essence, the B-spline method, while providing similar results, does provide for considerably easier handling and compatibility.

4 Demonstrator

In addition to the optical design for HuDs for the automotive industry, a design for a demonstrator with a simple, flat windshield was developed. The image mirror is produced using precision diamond milling a suitable aluminium alloy. For production, the surface data of the optical design was converted directly into NC-commands. The optical path in the demonstrator was folded using a flat mirror. A simple LED matrix type of display was chosen as the image source. The demonstrator shown in figure 8 illustrates the principle and has been integrated into a driving simulator for the study of interaction between man and machine.

Literature:


[7] Protokoll und Anwenderberichte zum Thema Freiformflächen, 4th meeting of the optic design technical group from bayern photonics and the Optic Design and Simulation Society from Photonics BW on 19th October 2006 in Ulm


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