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Influence of geometry of HUD optical system on screen luminance distribution

Abstract. HUD screens are an element that enables simultaneous observation of the environment and reading the information displayed on it. This allows for increased safety especially in the movement of vehicles. This paper will present an analysis of the luminance distribution on the screen as dependent on the geometry of the optical system and ambient lighting.

Streszczenie. Ekrany HUD to element umożliwiający jednoczesną obserwację otoczenia i odczytywanie wyświetlanych na nim informacji. Pozwala to na zwiększenie bezpieczeństwa zwłaszcza w ruchu pojazdów. W artykule zostanie przedstawiona analiza rozkładu luminancji na ekranie w zależności od geometrii układu optycznego i oświetlenia otoczenia. (Wpływ geometrii układu optycznego HUD na rozkład luminancji ekranu).

Keywords: optoelectronics, lighting technique, optical measurements, HUD.

Słowa kluczowe: optoelektronika, technika oświetleniowa, pomiary optyczne, HUD.

Introduction

In recent years, we can notice the increasing use of HUD displays. They are one of the types of head-up displays. They give the possibility to simultaneously observe the environment and receive additional information. This solution allows to increase the level of safety. Application in which such displays have been used for years is aviation, automotive and can be used in teleoperate systems for robotic applications [1-2]. What both cases have in common is the need to provide information to the driver or pilot in a way that is minimally distracting. However, with a poorly designed display, the losses can outweigh the gains. If the image seen by the driver is unreadable, obstructs vision, or causes glare it can result in a loss of attention to the road. Keep in mind that HUD displays should perform at their best both day and night. Examination of luminance distribution and luminance contrast allows us to determine how well the image is visible under different lighting conditions. Additionally, an analysis of the above parameters was conducted as a function of viewing angle and ambient light level [1-4].

The purpose of the study was to analyze the effects of HUD screen plate geometry and system geometry on the uniformity and luminance contrast of the observed images on the translucent screen. Screens made of a parallel-walled plate that was tilted at different angles and under different ambient light conditions were studied.

Construction of a test bench

A test rig was built to conduct the study. The design is shown in Figure 1. FFF printing technology was used to make the body. This allowed for quick and easy prototyping. This technology was chosen because the part dimensions made it difficult and expensive to print in other technologies such as SLA. Black PLA was used as a printing material to reduce light reflection from the structural elements. The material was chosen because of the satisfying mechanical properties, and the ease of printing this material. The screen was made of PMMA sheet. Two screens were evaluated with sheet thicknesses of 0.75 mm and 3 mm. PMMA is a material with high transparency and at the same time high refractive index, which allows for a high Fresnel reflectance value. All the materials used resulted in a lightweight and robust design. SAMSUNG Galaxy Tab A 10.1 SM-T510 tablet was used as the image source. One of the main design considerations was the ability to change

the angle of inclination of the screen, and easy replacement of the screen plate for an element of different thickness. The device was equipped with an inductive charging module. The completed test stand is shown in Figure 2.

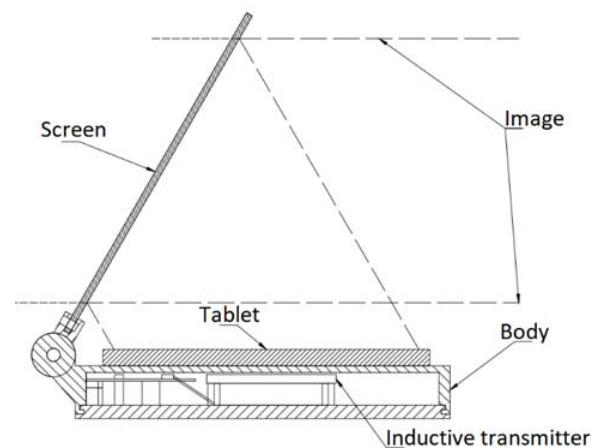


Fig. 1. HUD screen assembly drawing.



Fig. 2. HUD screen.

Geometry of the designed system

The reflectance value of the HUD screen was determined. At the angle of incidence of light flux equal to 60°, it is equal to 9% on one plane. This results in a

transparency of 83 % on two planes and a total reflectance of 17%. The calculations were conducted according to formulae (1-7).

$$(1) \quad r_s = \frac{\sin(\theta_1 - \theta_2)}{\sin(\theta_1 + \theta_2)}$$

$$(2) \quad r_p = \frac{\operatorname{tg}(\theta_1 - \theta_2)}{\operatorname{tg}(\theta_1 + \theta_2)}$$

$$(3) \quad r_s = \frac{n_o \cdot \cos \theta_1 - \sqrt{n_e^2 - n_o^2 \sin^2 \theta_1}}{n_o \cdot \cos \theta_1 + \sqrt{n_e^2 - n_o^2 \sin^2 \theta_1}}$$

$$(4) \quad r_p = \frac{n_e^2 \cdot \cos \theta_1 - \sqrt{n_e^2 - n_o^2 \sin^2 \theta_1}}{n_e^2 \cdot \cos \theta_1 + \sqrt{n_e^2 - n_o^2 \sin^2 \theta_1}}$$

$$(5) \quad \rho_s = r_s^2$$

$$(6) \quad \rho_p = r_p^2$$

where: θ_1 – angle of incidence on the boundary surface, θ_2 – angle of refraction off the boundary surface, r_p –

reflection coefficient of amplitude of wave with polarization p (vector \vec{E} is parallel to the incident surface of the light ray), r_s – reflection coefficient of amplitude of wave with polarization s (vector \vec{E} is perpendicular to the incident surface of the light ray), n_o – refractive index of the medium from which the light ray falls, n_e – refractive index of the medium on which the light ray falls, ρ – reflectance.

For incident unpolarized radiation (when the contributions of the two polarization components are equal), the reflectance is the average of the reflectances of the two polarization components. This is described by the following formula:

$$(7) \quad \rho = \frac{\rho_p + \rho_s}{2}$$

Calculations were performed in the geometric system shown in Figure 3. The results of the calculations are shown in Figure 4.

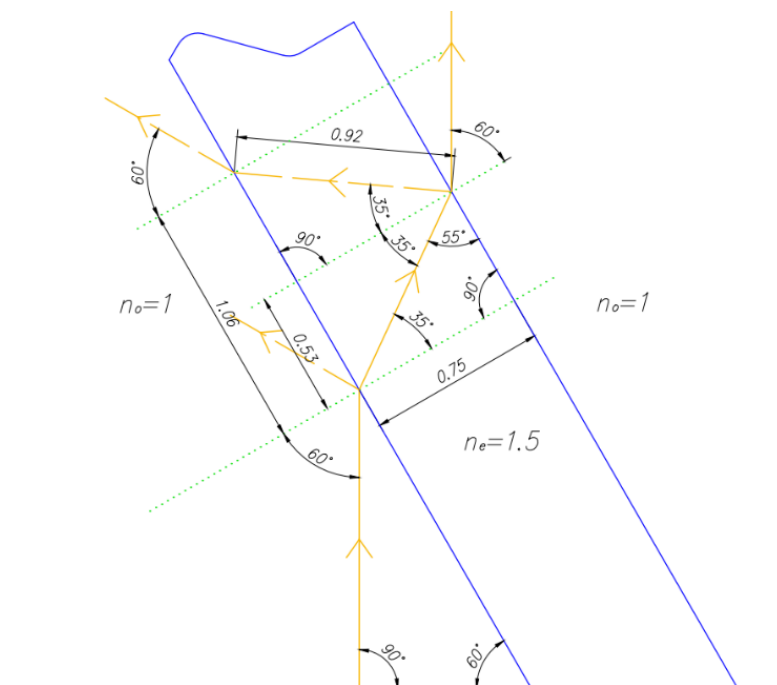


Fig.3. Cross section of the tested HUD screen.

The use of a 3mm thick screen caused a 4.2 mm shift between the images reflected from both screen surfaces. Therefore, we chose a screen 0.75 mm thick, in which the shift between the images reflected from the two surfaces is only 1mm, which allows us to provide higher contrast and readability of the displayed images.

Another way to eliminate the double-image effect is to use a screen with variable thickness. More widely, the propagation of light in optical elements of different shapes is presented in publications [5-7].

Due to the way humans perceive images, only the first reflections from both surfaces of the HUD screen were possible to observe. The screen material suppresses multiple reflections quite strongly. Their effect is to reduce the luminance contrast observed on the HUD screen. Mainly a small angular divergence rays are involved in the formation of an image in the eye. Rays emitted from the

tablet screen in other directions change the observed luminance of background.

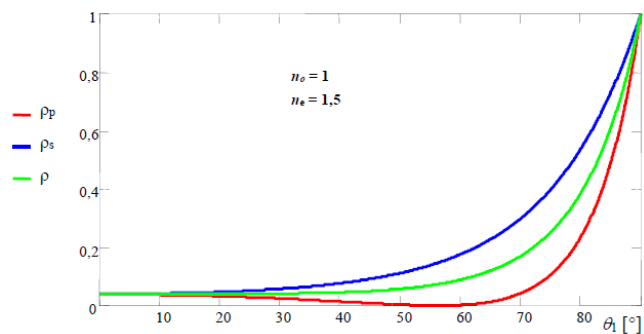


Fig.4. Dependence of the reflectance value on the angle of incidence on the screen from a medium with a lower refractive index.

Measurements of distribution, uniformity of luminance contrast on the screen

The constructed HUD display was evaluated using the test bench shown in Figure 5.

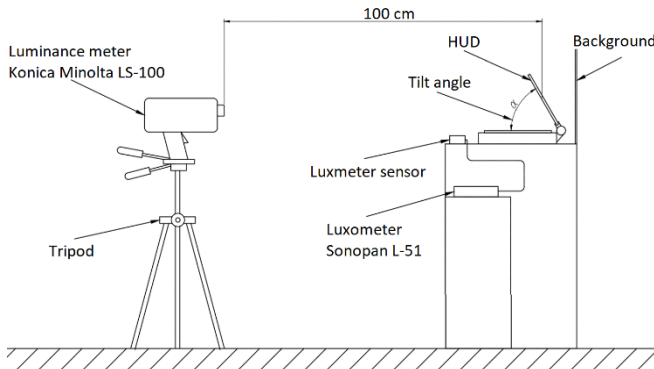


Fig.5. Test rig for measuring luminance uniformity and contrast.

Testing was conducted in a photometric darkroom. Tests were conducted to measure the luminance uniformity of the tablet screen and HUD screen.

The luminance uniformity relationship of the HUD screen was measured on an on-screen uniform white and black. The following formula was used to calculate the luminance uniformity:

$$(8) \quad \delta = \frac{L_{\min}}{L_m} [-]$$

where: δ – luminance uniformity, L_{\min} – minimum luminance [cd/m²], L_m – average luminance [cd/m²].

The average luminance was determined as the arithmetic mean of 32 evenly spaced points on the screen. The points were arranged analogously to the checkerboard shown in Figure 7, and a uniformly white or black image was displayed on the screen. The calculated luminance uniformity values are shown in Table 1.

Table 1. Results of luminance uniformity measurements of the displays at maximum (345 cd/m²) brightness

	All black screen	All white screen
Tablet display	0.864	0.896
Screen HUD		
$\alpha = 30^\circ$	0.581	0.755
$\alpha = 45^\circ$	0.583	0.661
$\alpha = 60^\circ$	0.597	0.594

The result of measuring the luminance uniformity dependence of the HUD working uniform screen in white and black is shown in Figure 6.

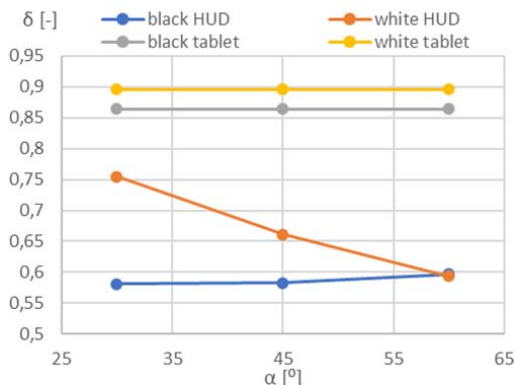


Fig.6. Dependence of luminance uniformity on the HUD screen on the angle of this screen.

The luminance contrast measurements of the screen and the HUD screen were performed next. The measurements were performed by displaying a checkerboard (8x4) (Fig. 7.) of white and black fields on the screen. To calculate the luminance contrast the following formula was used:

$$(9) \quad c = \frac{L_o - L_b}{L_b} [-]$$

where: c – luminance contrast, L_o – object luminance [cd/m²], L_b – background luminance [cd/m²].

The total luminance contrast was calculated as the average value over the area of the entire screen. The results of calculating the luminance contrast values are included in Table 2. Then, based on these values, the dependence of the luminance contrast on the angle of the HUD screen was plotted, which can be found in Figure 8.

Table 2. Luminance contrast measurement results

Display brightness level:	Minimum		Maximum	
	Vertical	Horizontal	Vertical	Horizontal
Tablet display	181.68	179.46	200.9	206.95
Screen HUD $\alpha = 30^\circ$	21.95	22.29	27.05	29.56
Screen HUD $\alpha = 45^\circ$	-	-	29.69	29.75
Screen HUD $\alpha = 60^\circ$	-	-	19.62	19.89

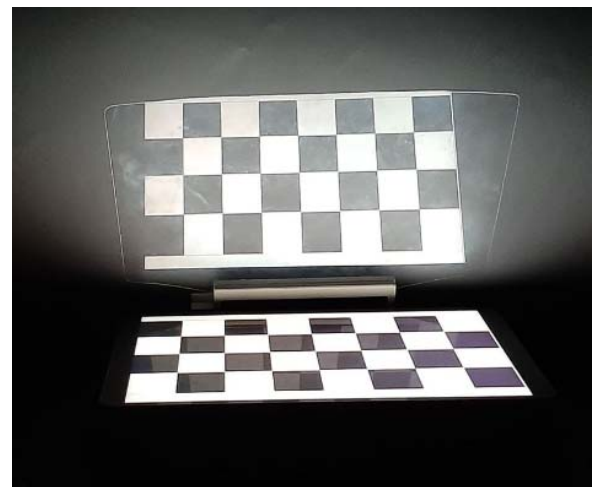


Fig.7. Images of the checkerboard displayed from the tablet on the HUD screen.

In addition, the dependence of contrast values on ambient and background lighting conditions was examined. When a white surface with a high reflectance value was placed behind the screen, the measured luminance contrast value was 3.3. This case corresponds to the extreme most unfavorable situation with regard to the readability of the HUD screen. However, with a uniform background, it allowed to read the presented information from the HUD screen. Under intermediate conditions similar to those encountered during use, an average luminance contrast of 12.

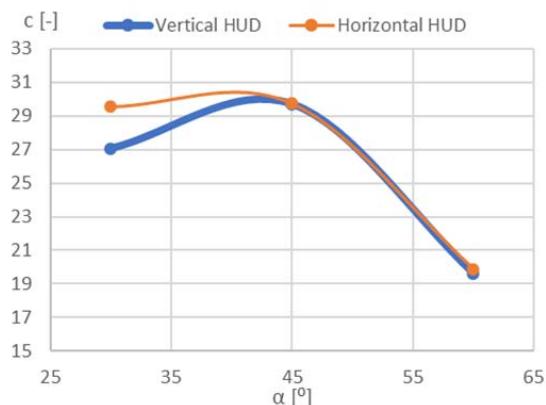


Fig.8. Dependence of the luminance contrast on the HUD screen on the tilt angle of this screen.

Analysis

The first step of the work carried out was the design and then manufacturing of the HUD display which was the object of research. During the initial design phase technologies and materials were selected from which the device will be made. This allowed us to optimize the body geometry already during the design in order to minimize the number of supports needed. The finished body design was made using 3D printing in FFF technology from black PLA. The results were satisfactory. Next, a bench was made to measure luminance uniformity and contrast. The measurement of the luminance distribution on the tablet screen used as the reference image source had a uniformity of 0.864 for the black screen and this was 4% lower than the uniformity of the tablet with a white display which is 0.896. Measurements were performed in a photometric darkroom. The ambient illuminance during the black screen display was above zero, indicating that the black screen also emits light. This is due to the technology in which the display was made, i.e., TFT. On the translucent screen, a reflectivity of 17% was achieved. The uniformity of the tablet is 11% higher than the uniformity of the HUD screen at the light level of 323 lx and bright background, and 34% higher at the minimum light level and bright background. This is due to the geometry of the layout. As the angle of the HUD screen increases, the uniformity of the white screen decreases by 21.3%. The lowest uniformity for the white screen was obtained at 60° of screen tilt, which was 0.594, while the highest uniformity was obtained at 30°, which was 0.755. The uniformity of the black HUD screen increases with increasing the tilt angle by only 2.7%. The lowest uniformity for the black screen was obtained at 30° of screen tilt, which was 0.581, while the highest uniformity was obtained at 60°, which was 0.597. The differences in the uniformity comparison between the tablet and HUD screen are due to the difference in distance between the tablet screen surface and the top and bottom edges of the HUD screen. The luminance contrast measurements were conducted at a screen luminance of 345.2 cd/m². The result of the total average luminance contrast of the tablet, and the HUD screen calculated from two horizontally or vertically adjacent fields differ by 3%.

Summary

Due to the geometry of the layout, it is not possible to obtain a uniform luminance contrast value over the entire screen area. Decreases in luminance contrast were observed near the edges. In addition to providing the highest possible luminance contrast value, it is also important to provide color contrast. Colors which contrast well with the surroundings should be selected in the

displayed images. Apart from the color, it is also worth choosing a font that will make the information easier to read. [8-10]. It is also worth paying attention to the arrangement of the elements displayed on the screen so that they are within the central field of vision, while not impeding the observation of the environment [11-16]. With regard to requirements, it is important to consider issues related to both technical parameters and those related to the readability and content of the information conveyed. It is also important to take into account studies of what content should be conveyed through HUD screens. Displaying an excessive amount of information can cause information overload. The question of what information is necessary for the observer (driver) in a specific context must be answered. In order to ensure adequate readability, the requirements for achieving a luminance contrast of at least level 3 must also be met, which was met in the system studied. [2, 13-16] HUD screens are proving to be especially useful, and their widespread use can significantly increase safety.

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