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3D display devices –
Part 62-11: Measurement methods for virtual-image type – Optical

IEC 62629-62-11:2022-11(en)

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3D display devices –
Part 62-11: Measurement methods for virtual-image type – Optical

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3D DISPLAY DEVICES –

Part 62-11: Measurement methods for virtual-image type – Optical

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The text of this International Standard is based on the following documents:

Draft	Report on voting
110/1459/FDIS	110/1473/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

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3D DISPLAY DEVICES –

Part 62-11: Measurement methods for virtual-image type – Optical

1 Scope

This part of IEC 62629 specifies the standard measuring conditions and measurement methods for determining the optical properties of the image created by 3D display devices and virtual-image optics such as head-up displays. The virtual image refers to an image in which the 3D visual information is superimposed with the outside world. Eye-wear type displays are however beyond the scope of this document.

NOTE The meaning of a virtual image in optics is in general an image formed when the outgoing rays from a point on an object always diverge. With regard to display application, a virtual image can be interpreted according to a real viewing case. When an image is viewed, even though there is no physical display (monitor, TV, screen), in front of a person's eyes, it is called virtual image.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendment-s) applies.

IEC 62629-1-2, *3D display devices – Part 1-2: Generic – Terminology and letter symbols*

3 Terms, definitions, and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62629-1-2 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
virtual image distance
distance from the centre between both eyes to the centre of a virtual image

Note 1 to entry: The eye-centre corresponds to the point where the half of the binocular spacing is located.

3.1.2
field of view
angle subtending the area of the virtual image as observed from the centre between both eyes

3.1.3
eye-box
<3D display devices – virtual-image type> three-dimensional space within which the users place both their eyes and properly see the entire virtual image

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3.1.4
look down angle
angle in a downward direction between the normal line and viewing direction from which the virtual image is viewed at the centre between both eyes

Note 1 to entry: The normal line represents a line forming a vertical angle of 90° from the centre of the eye to the virtual image plane.

3.1.5
look over angle
angle in a sideway direction between the normal line and viewing direction from which the virtual image is viewed at the centre between both eyes

3.2 Abbreviated terms

CCD charge-coupled device
CMOS complementary metal-oxide semiconductor
FOV field of view
HUD head-up display
IPD inter pupil distance
LMD light measuring device

4 Measurement systems

4.1 Measuring device

A spot LMD or an imaging LMD such as a 2D imaging colorimeter should be applied for measuring light and colour properties, for example luminance value, chromaticity coordinates, etc. The specification of the LMD applied should be described in the report as in the example given in Table 1.

NOTE If a 3D display has the characteristics of multi-view, which is explained in IEC 62629-22-1 [1][1], the aperture size of 2 mm to 5 mm is suggested and is not larger than 6 mm.

Table 1 – Example of reported specification of an imaging LMD

Image sensor type	CCD, CMOS
Resolution	1 380 × 1 030, 2 448 × 2 050,
Luminance range	0,05 cd/m^2 to 100 000 cd/m^2
Repeatability	ΔL (luminance) < 0,1 % $\Delta x, y$ (chromaticity coordinate) < 0,001
Measuring accuracy	ΔL < 3 % (for Standard Illuminant A) $\Delta x, y$ < 0,002 (for Standard Illuminant A)

The geometric property of the 3D virtual image can be estimated using the imaging LMD (multiple imaging LMDs or one imaging LMD with movement). Annex A shows a comparison of measurement items between the conventional 3D display and the virtual-image type 3D display.

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1 Numbers in square brackets refer to the Bibliography.

4.2 Measuring setup

4.2.1 Eye-box and virtual image plane

The geometric relationship between an eye-box and a virtual image plane is shown in Figure 1.

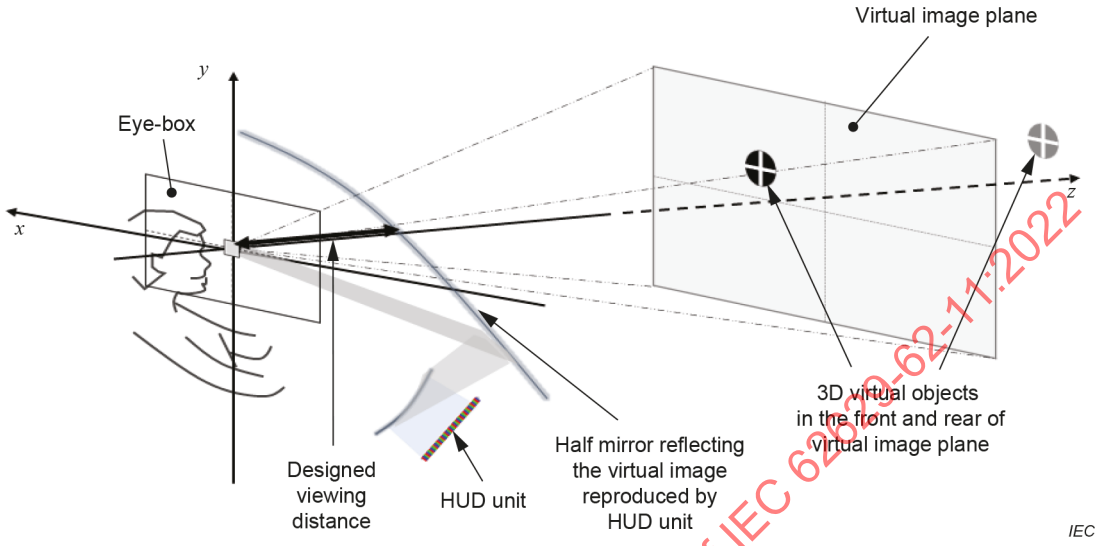

Figure 1 – Geometric relationship between an eye-box and a virtual-image plane

If users' eyes are placed in the eye-box, it is assumed that the users can view the entire virtual image without moving their head or making any other adjustment. The eye-box position can be specified by a supplier since this is varied by the application. The designed viewing distance shown in Figure 1 is the distance between the centre of the eye-box and the position on the half mirror, which should be suggested by the supplier. For the measurement, the designed viewing distance should be applied as the measuring distance.

If the eye-box location information is not provided by the supplier, this can be determined according to the method presented in 4.2.2. The measuring devices of the imaging LMD should be set up within the eye-box position. When the same left and right images without parallax are input, the plane on which the image is displayed is referred to as the virtual image plane. A 3D virtual object can be presented in the front or the back of the virtual image plane. A 3D coordinate system of xyz indicated in Figure 1 is defined in order to figure out the positions of the 3D virtual object and the virtual image plane from the eye-box of the users. The centre of the eye-box is defined as the zero position (xyz = 0).

NOTE If the supplier does not provide the eye-box position, this can be estimated by checking the geometric location where observers can view the entire virtual image plane. In general, the eye-box location is defined by the manufacturer according to the application. For example, it is determined by considering the distance from the windshield or combiner to the driver for automotive application, and the distance from the user to the half mirror for the exhibition application.

4.2.2 Determination of the eye-box

If the eye-box position is not provided by the supplier, the following method can be applied to determine the eye-box:

NOTE H1 to H9 and V1 to V7 in Figure 2 indicate examples of the position of the imaging LMD to determine the eye-box.

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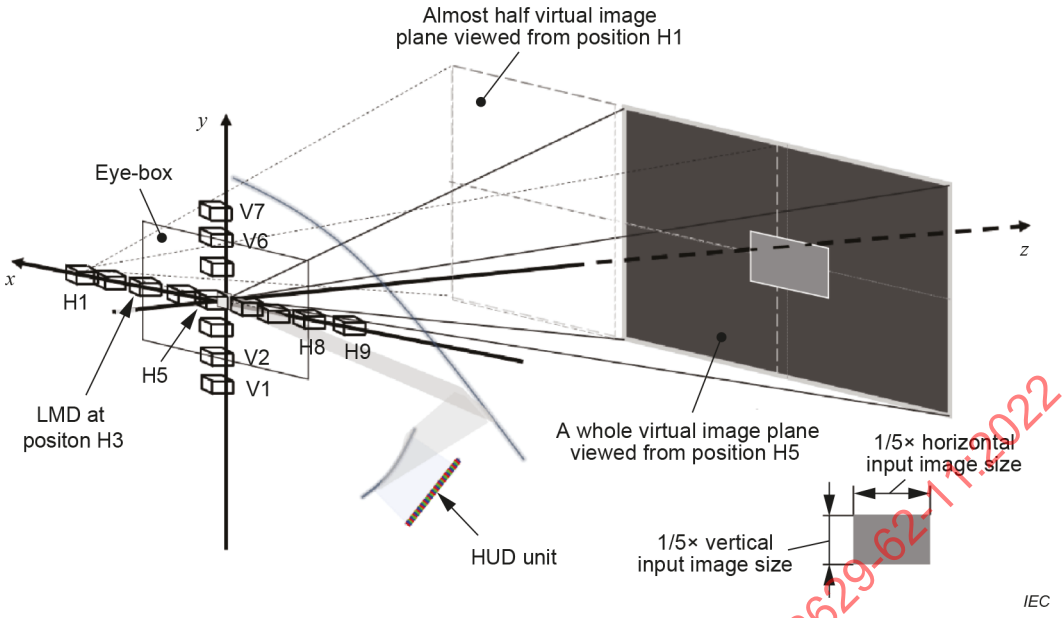

Figure 2 – Configuration for determination of the eye-box

a) a full grey input image (e.g. RGB = 50) with a white outline and a centre grey square (1 / 5 input image size in the horizontal and vertical position, e.g. RGB = 200) can be used as shown in Figure 2;

b) an imaging LMD is located at the designed viewing distance (z = 0) and should be directed to the centre point of the input image;

c) the virtual image of full grey input is captured, and the luminance of the centre grey square is measured by moving the imaging LMD in an increment of 5 mm from left to right;

NOTE 1 When the experimenter visually observes the virtual image (in Figure 2) at the designed viewing distance, the left border of the target virtual image starts to be viewed. The LMD is placed at position H1.

d) find the maximum luminance value from those measured while moving the imaging LMD, and calculate the percentage of the maximum luminance value at all imaging LMD locations;

e) the leftmost and rightmost positions, at which the full grey image with the white outline is acquired and the percentage of the maximum luminance value is greater than 50 %, are determined in the x-axis (for instance, almost half of the virtual image plane and 40 % of the percentage of the maximum luminance value are only acquired by the imaging LMD at the H1 position);

NOTE 2 The percentage of the maximum luminance value applied to find the eye-box boundary can be selected as 50 % or something else, but the value will be recorded in the report.

f) for example, the leftmost and rightmost horizontal positions to be determined are H3 and H8 in Figure 2;

NOTE 3 The left eye and right eye are located at the leftmost and rightmost positions determined through the procedures (a) to (e). Both eyes are free to be located inside the leftmost and rightmost positions.

g) the horizontal centre (x = 0) is found from the middle position of H3 and H8;

h) the virtual image of full grey input is captured and the luminance of the centre grey square is measured by moving the imaging LMD in an increment of 5 mm from the bottom through the horizontal centre (x = 0) to the top;

i) find the maximum luminance value from those measured while moving the imaging LMD, and calculate the percentage of the maximum luminance value at all imaging LMD locations;

j) the bottommost and topmost positions, at which the full grey image with the white outline is acquired and the percentage of the maximum luminance value is greater than 50 %, are determined in the y-axis;

k) for example, the bottommost and topmost vertical positions to be determined are V2 and V6 in Figure 2;

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l) the vertical centre (y = 0) is found from the middle position of V2 and V6; and

m) the zero position (xyz = 0) is finally determined.

4.2.3 Measuring configuration for geometric property

Figure 3 illustrates the configuration of three imaging LMDs and the test pattern displayed on the virtual-image plane in the three-dimensional xyz−coordinate system for evaluating geometric characteristics of the virtual projected image.

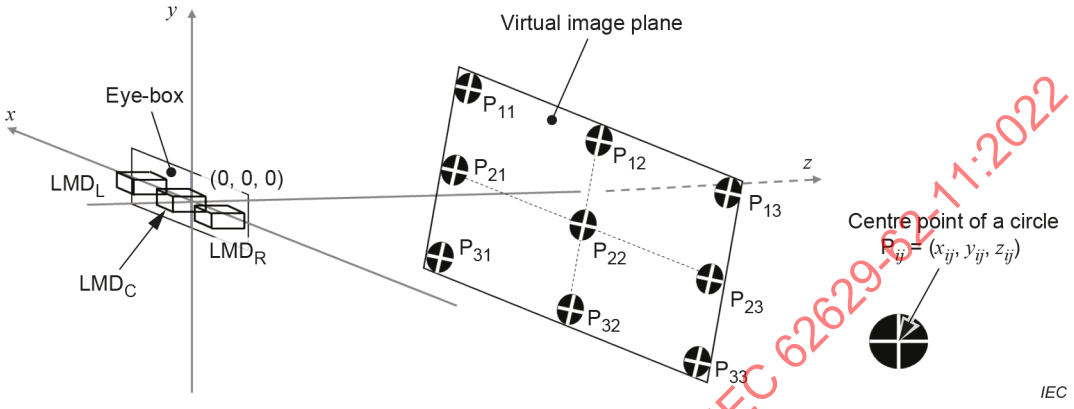

Figure 3 – Measuring setup for geometric property

The measurement items for assessing the virtual image geometry relative to a user's eyes are the look down/over angle, virtual image distance, and field of view. To ensure that projections are properly aligned, geometric distortion is also measured. The centre of the eye-box is defined to be the origin (x = 0, y = 0 and z = 0) at which the centre imaging LMD (LMD_C) is placed. The gap between the left (LMD_L) and right (LMD_R) imaging LMDs is assumed to be the same as the inter pupil distance (IPD) of a user. The average IPD of 60 mm or 65 mm can be used for this gap. The IPDs are selected to reflect mean values among both male and female examinees found in previous research [2]. The distance between the $LMD_{L(R)}$ and LMD_C is the half of the distance between the LMD_L and LMD_R. If one imaging LMD instead of three imaging LMDs is applied, the measurement can be conducted by moving the imaging LMD. The measuring point for each of the nine black circles in the test pattern is named P_{ij} (i and j = 1, 2, 3). P_{ij} can be expressed as (x_{ij}, y_{ij}, z_{ij}) in the xyz-coordinate system.

The 3D virtual image/object to be evaluated can be located on the virtual image plane or in the front/rear of the virtual image plane (Figure 1). If the 3D virtual image/object is placed on the virtual image plane, there is no parallax. On the other hand, if the 3D virtual image/object to be evaluated is located in the front or rear of the virtual image plane, there is negative or positive parallax.

Annex B describes the principle of the geometric-property measurement method applied for this document and comparisons with other measurement methods. Annex C provides the geometric calibration process for the imaging LMD. The required calibration level should satisfy the following condition.

The rotation matrix R in the calibration result of three imaging LMDs (LMD_L, LMD_C and LMD_R) in Figure 3 should be $R_L = R_C = R_R$ in theory. For the practical case, if $R_L \neq R_C \neq R_R$, there is then nonzero for the difference in the vertical pixel index of $\left| n_{ij}^{L} - n_{ij}^{R} \right|$ between the captured images by LMD_L and LMD_R where the n is vertical pixel index of the captured image of the test pattern ij. To obtain reliable results, the value of $\left| n_{ij}^{L} - n_{ij}^{R} \right|$ should be less than 1 %, that is, the difference in the vertical pixel index between the captured images by LMD_L and LMD_R should

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be less than the number of vertical pixels in the captured image/100. Details related to imaging LMD calibration are described in Annex C.

4.2.4 Test image and denotation for the captured test image

Figure 4 shows the test image composed of nine black circles and the three corresponding captured images by three imaging LMDs (LMD_L, LMD_C and LMD_R) placed in the left, centre and right positions of the eye-box. Every black circle includes a white cross in the centre. The distance between LMD_L and LMD_R is indicated by a. The measuring point(s) can be selected from the nine points of P_{11} to P_{33} as necessary.

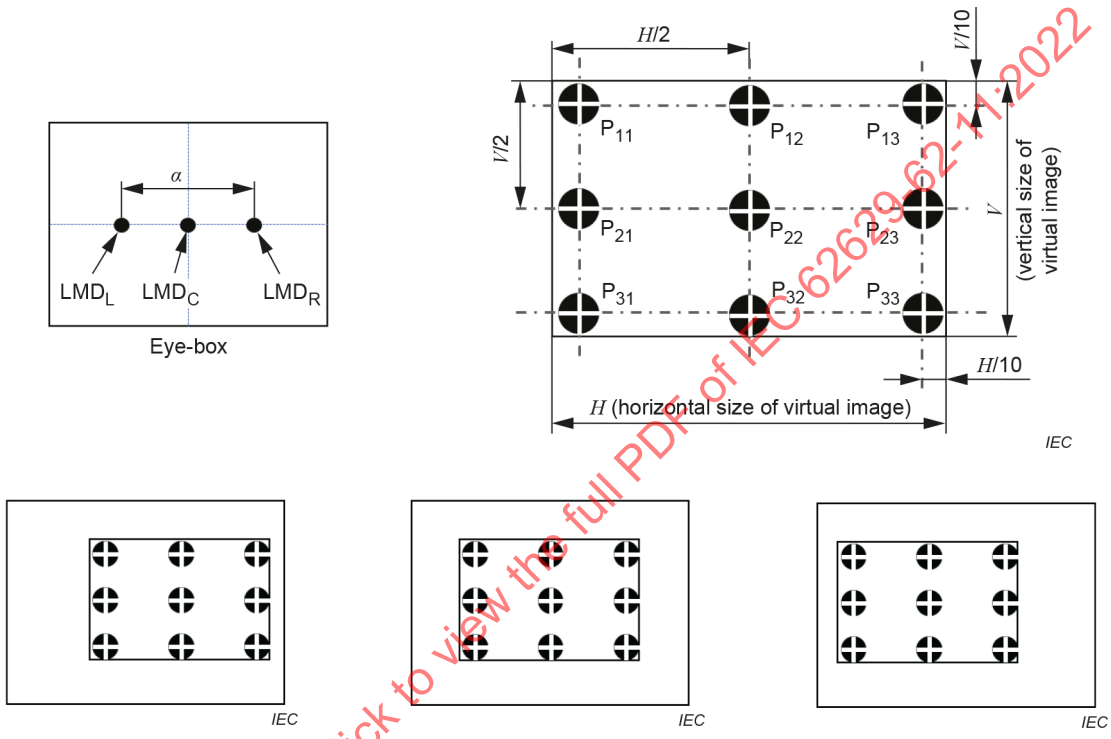

Figure 4 – Test image with nine measuring points (top right) and the three corresponding images (bottom) captured by three imaging LMDs (top left)

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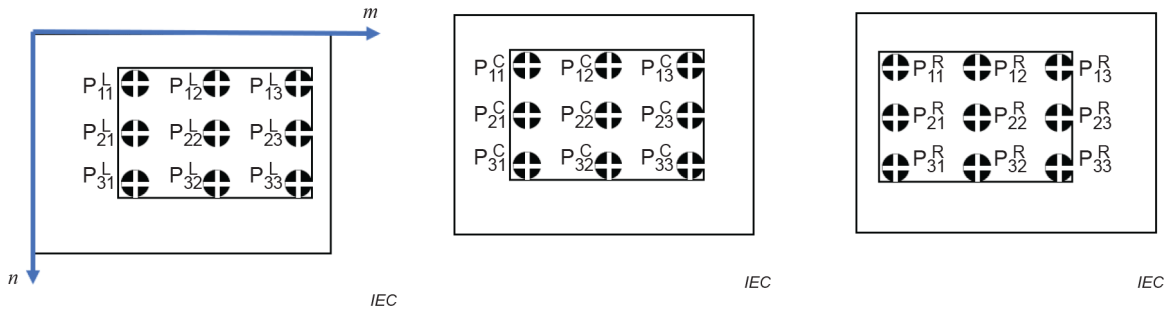

captured image by LMD_L captured image by LMD_C captured image by LMD_R

$P_{ij}^{L} = (m_{ij}^{L}, n_{ij}^{L})$ $P_{ij}^{C} = (m_{ij}^{C}, n_{ij}^{C})$ $P_{ij}^{R} = (m_{ij}^{R}, n_{ij}^{R})$

NOTE m,n: pixel index of the captured image, which is an integer.

Figure 5 – Denotation for each of the three corresponding images captured by three imaging LMDs

Figure 5 shows the denotation in terms of P_{ij}^{L}, P_{ij}^{C}, and P_{ij}^{R} for the test patterns in the three corresponding captured images by three imaging LMDs, that is LMD_L, LMD_C and LMD_R. Since P_{ij}^{L}, P_{ij}^{C}, and P_{ij}^{R} are the two-dimensional coordinates on the captured images, $P_{ij}^{L,C,R}$ is represented by ($m_{ij}^{L,C,R}$, $n_{ij}^{L,C,R}$) where m and n are pixel indexes of the captured image of the test pattern.

5 Common measurement applied for 3D virtual-image geometry

5.1 General

The 3D virtual images should be properly aligned relative to a user's eyes. The geometric property therefore shall be evaluated for the projected virtual-image plane and the 3D virtual objects (see Figure 1) that can be located in front or in back of the virtual image plane. Clause 5 introduces the common measurement method applied for the geometric property evaluation. Clause 6 and Clause 7 describe the specific procedures for evaluating the degree to which a virtual image is aligned from a user's location by focusing on four aspects: look down/over angle, field of view, distance between the user, and virtual image plane, and the distortion. Clause 8 describes the detailed procedures for determining the distance between the user and the 3D virtual object.

There is no parallax for the 3D virtual object placed on the virtual image plane, whereas there is negative or positive parallax for the 3D virtual object located in front or in back of the virtual image plane. The geometric properties for the virtual image plane (Figure 8 to Figure 11) and the 3D virtual object (Figure 12) are obtained based on the triangulation methodology. The input factors in the application of triangulation are the binocular disparity information acquired by the multiple imaging LMDs and the field of view of the imaging LMD.

If the geometric property measurement is made using other methods than that proposed by this document, these other methods shall be mentioned in the report.

5.2 Position estimation of measuring points

If the positions (P_{ij} = x_{ij}, y_{ij}, z_{ij}) for the nine points P_{11} to P_{33} on the captured image are determined in the xyz-coordinate system of Figure 3, the geometric information for the virtual

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image plane and the 3D virtual object can be deduced. In order to determine the accurate location of the 3D virtual object, Annex C introduces the reason for using three imaging LMDs (LMD_L, LMD_C and LMD_R) in Figure 3. The position z_{11} for P_{11} in the test image of Figure 3 is obtained first using LMD_L and LMD_R. The LMD_C is then used to determine the position (x_{11}, y_{11}). The detailed calculation process is described as follows.

The position z_{11} for P_{11} in the test image of Figure 3 is calculated first using a triangular relationship made of the distance (between the centre of the user's eyes and P_{11}) in the z-axis, the binocular disparity information of ($m_{11}^{L} - m_{11}^{R}$), and the LMD's field of view of θ in Figure 6. For the black circle indicated by P_{11}, the denotation in the captured images is given in Figure 7. Formula (1) and Formula (2) describe this relationship well. The binocular disparity information of ($m_{11}^{L} - m_{11}^{R}$) is obtained from the corresponding 2D image points of the two captured images by LMD_L and LMD_R. The horizontal disparity between m_{11}^{L} of the LMD_L image and m_{11}^{R} of the LMD_R image is the same as the value of a. Thus, the ratio of ($m_{11}^{L} - m_{11}^{R}$) to M can be expressed in the same way as the ratio of α to $2 \cdot \left(z_{11} \cdot \tan\frac{\theta}{2} \right)$ using the following formulae.

$$m_{11}^{L} - m_{11}^{R} : M = \alpha : 2 \cdot \left(z_{11} \cdot \tan\frac{\theta}{2} \right) \tag{1}$$

$$\frac{\alpha}{2 \cdot \left(z_{11} \cdot \tan\frac{\theta}{2} \right)} = \frac{m_{11}^{L} - m_{11}^{R}}{M} \tag{2}$$

where

M is the number of horizontal pixels in the captured image;

m_{11}^{L}, m_{11}^{R} are the horizontal pixel indexes of the captured image by LMD_L and LMD_R;

θ is the horizontal field of view of the imaging LMD;

z_{11} is the distance between the centre (0, 0, 0 in Figure 3) of LMD_L and LMD_R, and P_{11}; and

α is the gap between LMD_L and LMD_R.

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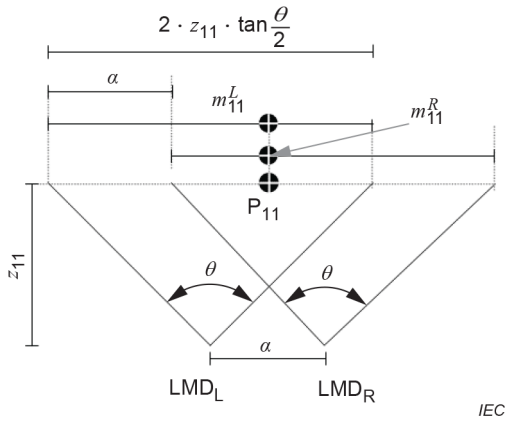

α: gap between LMD_L and LMD_R;

θ: horizontal field of view of the imaging LMD;

z_{11}: distance between the centre position (0, 0, 0 in Figure 3) of LMD_L and LMD_R; and

P_{11}: one of the black circles in the test image in Figure 4;

m_{11}^{L}, m_{11}^{R}: horizontal pixel indexes of the captured image by LMD_L and LMD_R.

Figure 6 – Geometric relationship of the black circle of P_{11} in the test image, two imaging LMDs, and the captured P_{11} (indicated by m_{11}^{L} and m_{11}^{R}) by the two imaging LMDs of LMD_L and LMD_R

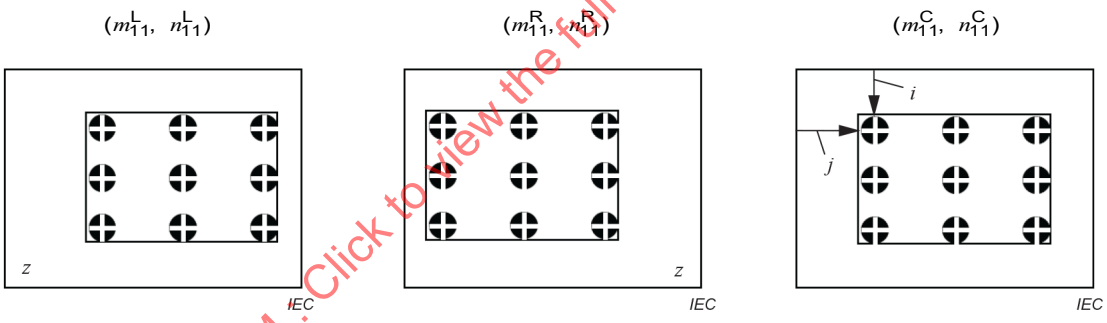

Figure 7 – Denotation for the black circle indicated by P_{11} (i and j = 1) in the three corresponding images captured by three imaging LMDs

The black circle in the top left corner (P_{11}) in Figure 7 is indicated by (m_{11}^{L}, m_{11}^{L}) in the captured image by LMD_L or by (m_{11}^{R}, m_{11}^{R}) in the captured image by LMD_R or by (m_{11}^{C}, m_{11}^{C}) in the captured image by LMD_C. From Formula (1) and Formula (2), the value of z_{11} can be obtained. The position (x_{11}, y_{11}, z_{11}) of P_{11} can then be calculated using Formula (3).

$$x_{11} = z_{11} \cdot \tan\frac{\theta}{2}\left(2 \cdot \frac{m_{11}^{C}}{M} - 1\right),\quad y_{11} = z_{11} \cdot \tan\frac{\theta'}{2}\left(2 \cdot \frac{n_{11}^{C}}{N} - 1\right),\quad z_{11} = \frac{\alpha}{2 \cdot \tan\frac{\theta}{2}} \cdot \frac{M}{(m_{11}^{L} - m_{11}^{R})} \qquad (3)$$

where

M, N are the number of horizontal and vertical pixels in the captured image;

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$m_{11}^{L}, m_{11}^{R}, m_{11}^{C}$ are the horizontal pixel indices of the captured images by LMD_L, LMD_R, and LMD_C;

n_{11}^{C} is the vertical pixel index of the captured image by LMD_C;

θ is the horizontal field of view of the imaging LMD;

θ' is the vertical field of view of the imaging LMD; and

a is the gap between LMD_L and LMD_R.

6 Measurement method for the geometry property of the virtual image plane

6.1 Measurement of virtual image distance

6.1.1 Conditions

The following detailed conditions should be applied (see Figure 8):

a) test pattern: the test image with nine circles (P_{11} to P_{33}) in Figure 3; and

b) acquisition of the test image: the three imaging LMDs located in the eye-box are used to capture three sets of the 2D image.

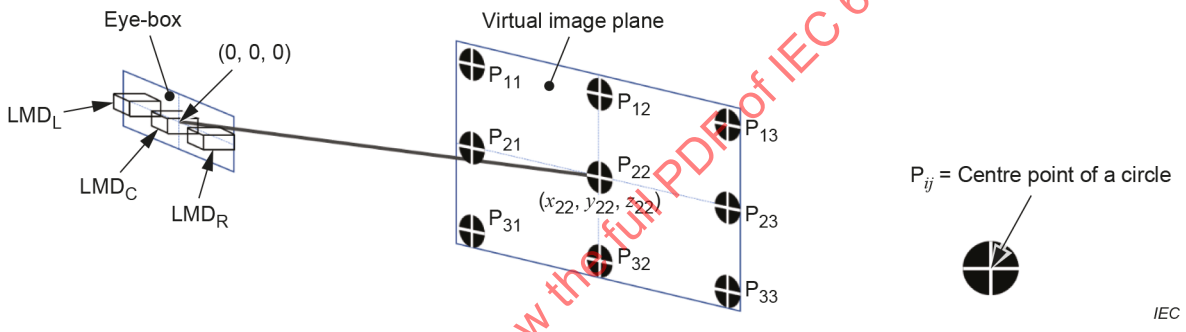

Figure 8 – Measuring condition for the virtual image distance

6.1.2 Procedures

The following measuring procedures should be carried out:

a) three test images are acquired by the three imaging LMDs: LMD_L, LMD_C and LMD_R;

b) the position (x_{22}, y_{22}, z_{22}) for P_{22} in the test image is determined according to the computation method described in 5.2; and

c) the virtual image distance between (0, 0, 0) in the eye-box and (x_{22}, y_{22}, z_{22}) in the centre of the virtual plane is calculated as follows:

$$D_{VI} = \sqrt{{x_{22}}^2 + {y_{22}}^2 + {z_{22}}^2} \tag{4}$$

6.1.3 Reports

The measurement results shall be reported with the gap (a in Figure 3 and Figure 4) that is the same as the IPD value applied to evaluate the virtual image distance as follows.

– D_{VI}, in m

– a, in mm

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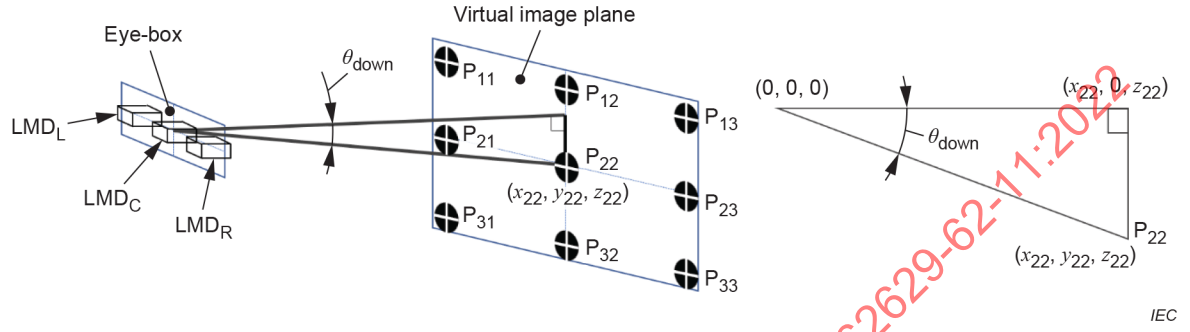
6.2 Measurement of look down/over angle

6.2.1 Conditions

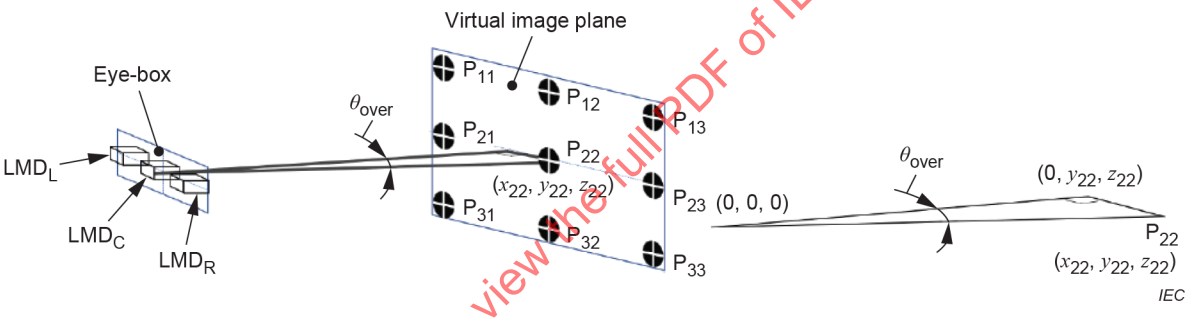
The following detailed conditions should be applied (see Figure 9):

a) test pattern: the test image with nine circles (P_{11} to P_{33}) in Figure 3; and

b) acquisition of the test image: the three imaging LMDs located in the eye-box are used to capture three sets of the 2D image.



(a) for the look down angle of θ_{down}



(b) for the look over angle of θ_{over}

Figure 9 – Measuring conditions for look down and look over angles

6.2.2 Procedures

The following measuring procedure should be carried out:

a) three test-pattern images are acquired by three imaging LMDs: LMD_L, LMD_C and LMD_R;

b) test pattern: the position (x_{22}, y_{22}, z_{22}) for P_{22} in the test image is determined according to the computation method described in 5.2; and

c) the look down/over angles of θ_{down} and θ_{over} are calculated using the position information (x_{22}, y_{22}, z_{22}) for P_{22} in the test image as follows:

$$\theta_{down} = \cos^{-1}\frac{\sqrt{x_{22}^2 + y_{22}^2}}{\sqrt{x_{22}^2 + y_{22}^2 + z_{22}^2}},\quad \theta_{over} = \cos^{-1}\frac{\sqrt{x_{22}^2 + z_{22}^2}}{\sqrt{x_{22}^2 + y_{22}^2 + z_{22}^2}} \tag{5}$$

6.2.3 Reports

The measurement results shall be reported with the gap (a in Figure 3 and Figure 4) that is the same as the IPD value applied to evaluate the look down and look over angles as follows.

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– θ_{down} and θ_{over}

– a, in mm

6.3 Measurement of field of view

6.3.1 Conditions

The following detailed conditions should be applied (see Figure 10):

a) test pattern: the test image with nine circles (P_{11} to P_{33}) in Figure 3; and

b) acquisition of the test image: the three imaging LMDs located in the eye-box are used to capture three sets of the 2D image.

6.3.2 Procedures

The following measuring procedure should be carried out:

a) three test images are acquired by three imaging LMDs: LMD_L, LMD_C and LMD_R;

b) for the horizontal FOV, the positions (x_{21}, y_{21}, z_{21}) and (x_{23}, y_{23}, z_{23}) for P_{21} and P_{23} in the test image (see Figure 10 (a)) are determined according to the computation method described in 5.2;

c) the horizontal FOV of θ_{FOV}^{H} is calculated as follows:

$$\theta_{FOV}^{H} = \cos^{-1}\frac{\left(\left\|\overline{P_{21}O}\right\|^2 + \left\|\overline{P_{23}O}\right\|^2\right) - \left\|\overline{P_{21}P_{23}}\right\|^2}{2\left\|\overline{P_{21}O}\right\|\left\|\overline{P_{23}O}\right\|} \quad (6)$$

where

O is the (0, 0, 0) position, that is, the centre of the eye-box;

$\left\|\overline{P_{21}P_{23}}\right\|$ is the distance between P_{21} and P_{23};

$\left\|\overline{P_{21}O}\right\|$ is the distance between P_{21} and O;

$\left\|\overline{P_{23}O}\right\|$ is the distance between P_{23} and O;

d) for the vertical FOV, the positions (x_{12}, y_{12}, z_{12}) and (x_{32}, y_{32}, z_{32}) for P_{12} and P_{32} in the test pattern (see Figure 10 (b)) are determined according to the computation method described in 5.2; and

e) the vertical FOV of θ_{FOV}^{V} is calculated as follows:

$$\theta_{FOV}^{V} = \cos^{-1}\frac{\left(\left\|\overline{P_{12}O}\right\|^2 + \left\|\overline{P_{32}O}\right\|^2\right) - \left\|\overline{P_{12}P_{32}}\right\|^2}{2\left\|\overline{P_{12}O}\right\|\left\|\overline{P_{32}O}\right\|} \quad (7)$$

where

O is the (0, 0, 0) position, that is, the centre of the eye-box;

$\left\|\overline{P_{12}P_{32}}\right\|$ is the distance between P_{12} and P_{32};

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$\overline{\|P_{12}O\|}$ is the distance between P_{12} and O;

$\overline{\|P_{32}O\|}$ is the distance between P_{32} and O.

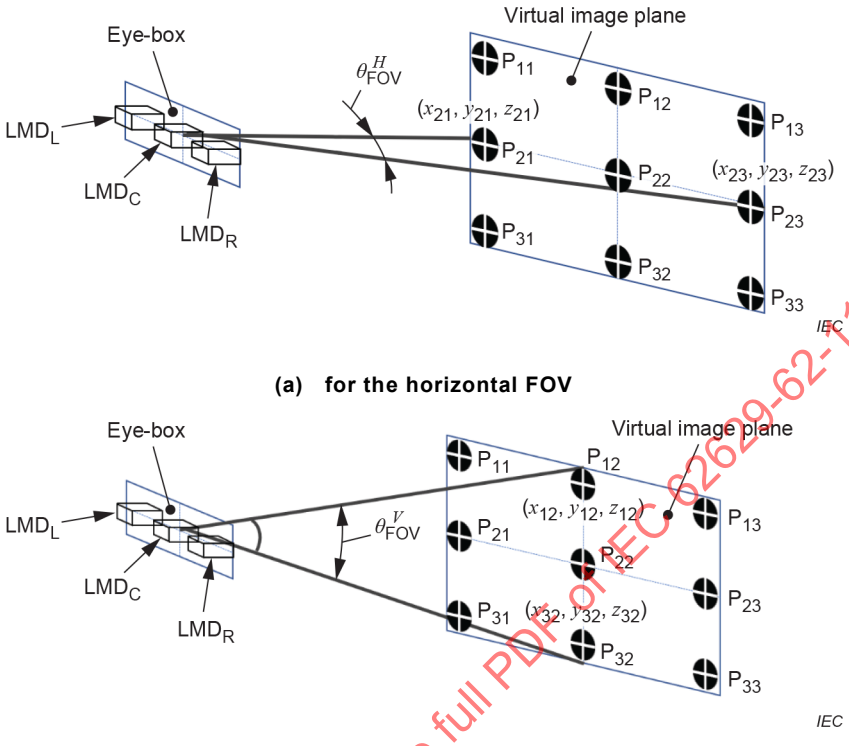

Figure 10 – Measuring conditions for field of view (FOV)

6.3.3 Reports

The measurement results shall be reported with the gap (a in Figure 3 and Figure 4) that is the same as the IPD value applied to evaluate field of view as follows.

– θ^{H}_{FOV}, θ^{V}_{FOV}

– a in mm

7 Measurement methods for the geometric distortion of the virtual image plane

7.1 General

The deviation degree in each of the horizontal and vertical directions is measured to evaluate static distortion that is caused by processes of enlargement and projection in 3D displays such as head-up displays.

7.2 Measurement of static distortion

7.2.1 Conditions

The following detailed conditions should be applied:

a) test pattern: the test image with nine circles (P_{11} to P_{33}) in Figure 11; and

b) acquisition of the test image: the three imaging LMDs located in the eye-box are used to capture three sets of the 2D image.

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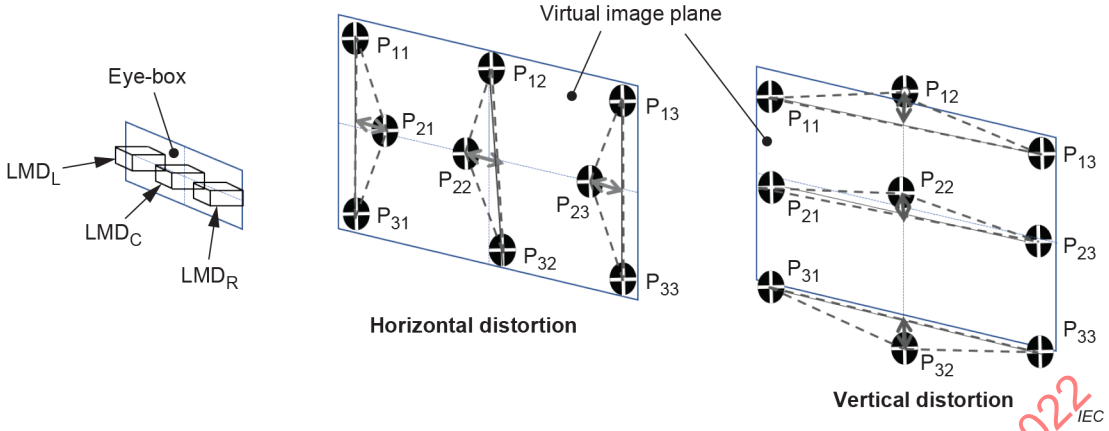

Figure 11 – Measuring conditions for evaluating static distortion

7.2.2 Procedures

The following measuring procedure should be carried out:

a) three test images are acquired by three imaging LMDs: LMD$_L$, LMD$_C$ and LMD$_R$;

b) all the positions (x_{ij}, y_{ij}, z_{ij}) for P$_{11}$ to P$_{33}$ in the test pattern are determined according to the computation method described in 5.2;

c) calculate the horizontal distortion DT_{h1} for the point P$_{21}$ from the distance between the point P$_{21}$ and the line determined by P$_{11}$ and P$_{31}$, and then repeat this calculation for the points P$_{22}$ and P$_{23}$;

d) the total and maximum horizontal distortions of DT_{ht} and DT_{hm} are calculated as follows:

$$DT_{ht} = \text{avg}\{D_{h1}, D_{h2}, D_{h3}\} \tag{8}$$

$$DT_{hm} = \max\{D_{h1}, D_{h2}, D_{h3}\} \tag{9}$$

e) calculate the vertical distortion DT_{v1} for the point P$_{12}$ from the distance between the point P$_{12}$ and the line determined by P$_{11}$ and P$_{13}$, and then repeat this calculation for the points of P$_{22}$ and P$_{32}$;

f) the total and maximum vertical distortions of DT_{vt} and DT_{vm} are calculated as follows:

$$DT_{vt} = \text{avg}\{D_{v1}, D_{v2}, D_{v3}\} \tag{10}$$

$$DT_{vm} = \max\{D_{v1}, D_{v2}, D_{v3}\} \tag{11}$$

7.2.3 Reports

The measurement results shall be reported with the gap (a in Figure 3 and Figure 4) that is the same as the IPD value applied to evaluate geometric distortion as follows.

– DT_{ht}, DT_{vt}

– DT_{hm}, DT_{vm}

– a, in mm

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8 Measurement method for the distance between a user and a 3D virtual object

8.1 General

The accurate depth reproduction of the 3D virtual object is important to indicate the corresponding 3D real object in the real world. Clause 8, therefore, introduces the measurement method for determining the physical distance of the 3D virtual object. The measured result represents the distance between a user and the displayed 3D virtual object. The 3D virtual objects can be reproduced in the front/back of or on the virtual image plane. For example, the virtual object of P_{22} can be displayed in the front or back of the virtual image plane in Figure 12.

8.2 Measurement method

8.2.1 Conditions

The following detailed conditions shall be applied:

a) the test circle pattern in Figure 12; and

b) acquisition of the test pattern image: the three imaging LMDs located in the eye-box are used to capture three sets of the 2D image, that is, the left, centre and right images.

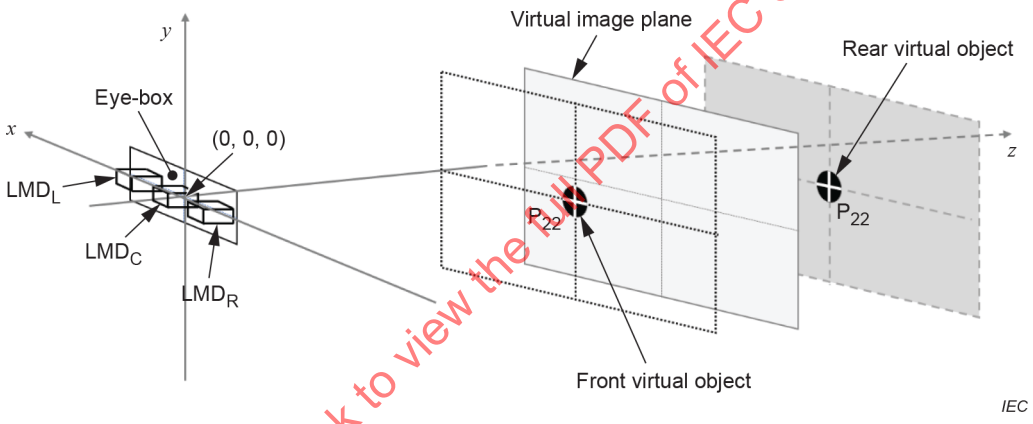

Figure 12 – Measuring conditions for the distance of the 3D virtual object

8.2.2 Procedures

The following measuring procedures shall be carried out:

a) three test images are acquired by three imaging LMDs: LMD_L, LMD_C and LMD_R in Figure 13;

b) the position (x_{22}, y_{22}, z_{22}) for P_{22} in the test pattern is determined according to the computation method described in 5.2;

c) the distance (D_{3D_object}) is calculated as the distance between (0, 0, 0) in the eye-box and (x_{22}, y_{22}, z_{22}) in the centre of the virtual plane as follows:

$$D_{3D_object} = \sqrt{{x_{22}}^2 + {y_{22}}^2 + {z_{22}}^2} \quad (12)$$

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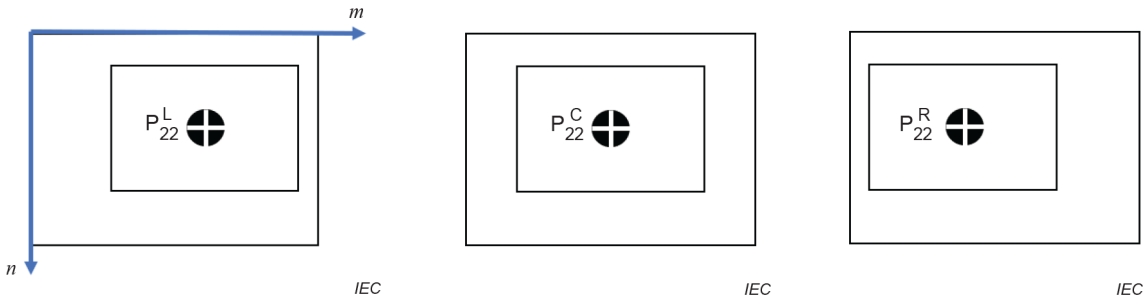

captured image by LMD_L captured image by LMD_C captured image by LMD_R

$$P_{22}^{L} = (m_{22}^{L}, n_{22}^{L}) \qquad P_{22}^{C} = (m_{22}^{C}, n_{22}^{C}) \qquad P_{22}^{R} = (m_{22}^{R}, n_{22}^{R})$$

NOTE m, n: pixel index of the captured image, which is an integer.

Figure 13 – Three images captured by three imaging LMDs for the 3D virtual object located at the back of the virtual plane

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8.2.3 Reports

The measurement results for the distance of the 3D virtual object shall be reported with the gap (a in Figure 3 and Figure 4) that is the same as the IPD value applied to evaluate the distance between a user and 3D virtual object as follows.

– D_{3D_object} (for example, in terms of dioptre (1 / m))

– a, in mm

9 Measurement methods for luminance and chromaticity

9.1 General

The reproduced 3D virtual image should have enough vivid lights and colours to be distinguishable from real-world surrounds. Clause 9 introduces the measurement method for luminance and chromaticity considering the user and the virtual-image plane configuration. The first measurement is conducted from different positions in the eye-box (see Figure 14) since users can view the virtual image within any position in the eye-box. The luminance values are evaluated at different points in the eye-box in order to find out the angular variation that explains changes in luminance up to the viewing position. The second measurement is conducted from the centre point in the eye-box against different positions in the virtual-image plane (see Figure 14). Through these first and second measurements, the luminance and chromaticity are evaluated in the uniformity aspect of both eye-box and virtual-image plane.

In addition to luminance and chromaticity measurement, the measurement method for 3D crosstalk is introduced by Annex D.

9.2 Measurement for luminance drop over the eye-box

9.2.1 Conditions

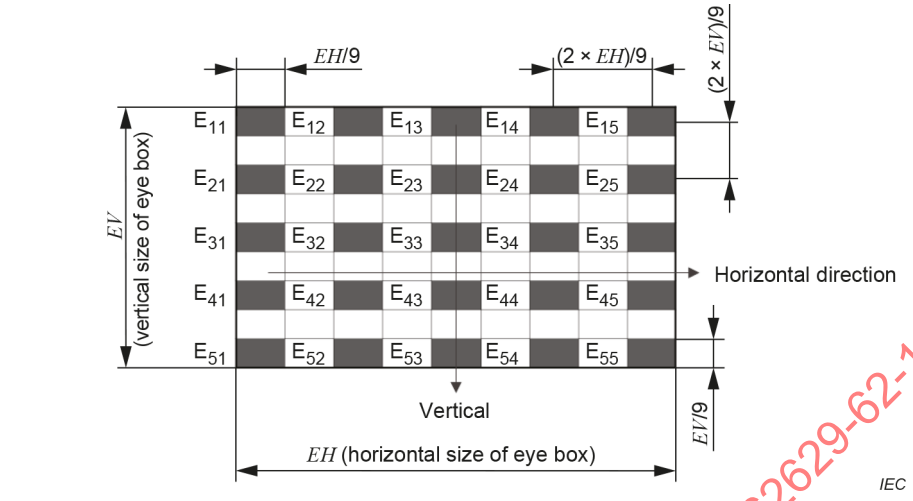
The following detailed preparations shall be applied:

a) the spot LMD is successively placed in the centre of each of the 25 positions (E_{11} to E_{55}) on the xy plane of the eye-box in a dark surround in Figure 14 (a);

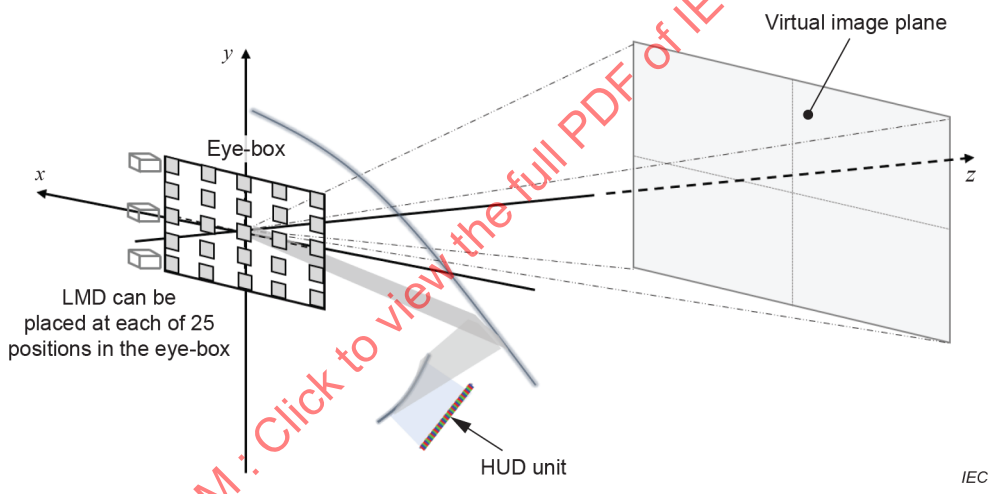
NOTE The SAE J 1757-2 [3] defines nine measurement positions inside the eye-box. If a measurement is therefore required in consideration of conformity with SAE J 1757-2 [3], the measurement can be performed at nine positions (E_{11}, E_{31}, E_{51}, E_{13}, E_{33}, E_{53}, E_{15}, E_{35}, and E_{55}) instead of 25 positions.

b) the centre position (E_{33}) of the eye-box corresponds to the zero position (xyz = 0) in Figure 3; and

c) the test signal: full white image.



(a) measuring location representation in the eye-box



(b) measuring layout for luminance and chromaticity from the 25 positions in the eye-box

Figure 14 – Measuring location representation in the eye-box

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9.2.2 Procedures

The following measuring procedure shall be carried out:

a) apply the test signal of white;

b) measure the luminance of the centre point of the virtual image plane at each of the 25 points (E_{11} to E_{55}) in the eye-box shown in Figure 14 for white and black images, respectively;

c) calculate the average of luminance drop (LD^{H}_{white} and LD^{V}_{white}) for white (L_w) between the adjacent viewing positions in the horizontal and vertical directions, respectively, as follows:

$$LD^{H}_{white} = {}_{1\le i\le 5}\,\text{avg}\,{}_{1\le j\le 4}\left(\frac{L_{white}(E_{ij})}{L_{white}(E_{i(j+1)})}\times 100\right)$$
$$LD^{V}_{white} = {}_{1\le i\le 4}\,\text{avg}\,{}_{1\le j\le 5}\left(\frac{L_{white}(E_{ij})}{L_{white}(E_{(i+1)j})}\times 100\right) \quad (13)$$

where

$L_{\text{white}}(E_{ij})$ is the white luminance measured at the measuring point E_{ij};

LD^{H}_{white} and LD^{V}_{white} are the horizontal and vertical white luminance drop;

i, j are 1 to 5 for the 25-point measurement;

d) divide the luminance drop (LD^{H}_{white} and LD^{V}_{white}) for white by (2 x EH / 9) and (2 x EV / 9) respectively to estimate the luminance drop rate per centimetre in the horizontal and vertical directions:

$$LDR^{H}_{\text{white}} = \frac{LD^{H}_{\text{white}}}{(2\times EH)/9}$$
$$LDR^{V}_{\text{white}} = \frac{LD^{V}_{\text{white}}}{(2\times EV)/9} \quad (14)$$

where

LDR^{H}_{white} and LDR^{V}_{white} are the horizontal and vertical white luminance drop rate per centimetre;

e) if the luminance drop ($LD^{H}_{\text{target colour}}$ and $LD^{V}_{\text{target colour}}$) has to be evaluated for different colours such as black, red, green and blue, the test signal can be changed from white as follows:

$$LD^{H}_{\text{target colour}}(E_{ij}) = \underset{1\le i\le 5}{\text{avg}}\ \underset{1\le j\le 4}{}\left(\frac{L_{\text{target colour}}(E_{ij})}{L_{\text{target colour}}(E_{i(j+1)})}\times 100\right)$$
$$LD^{V}_{\text{target colour}}(E_{ij}) = \underset{1\le i\le 4}{\text{avg}}\ \underset{1\le j\le 5}{}\left(\frac{L_{\text{target colour}}(E_{ij})}{L_{\text{target colour}}(E_{(i+1)j})}\times 100\right) \quad (15)$$

where

$LD^{H}_{\text{target colour}}(E_{ij})$ is the luminance for the target colour measured at the measuring point E_{ij};

$LD^{H}_{\text{target colour}}$ and $LD^{V}_{\text{target colour}}$ are the horizontal and vertical target colour luminance drop;

i, j are 1 to 5 for the 25-point measurement;

f) divide the luminance drop ($LD^{H}_{\text{target colour}}$ and $LD^{V}_{\text{target colour}}$) for the target colour by (2 × EH / 9) and (2 × EV / 9), respectively, to estimate the luminance drop rate per centimetre for the target colour in the horizontal and vertical directions, as follows:

$$LDR^{H}_{\text{target colour}} = \frac{LD^{H}_{\text{target colour}}}{(2\times EH)/9}$$
$$LDR^{V}_{\text{target colour}} = \frac{LD^{V}_{\text{target colour}}}{(2\times EV)/9} \quad (16)$$

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where

$LDR^{H}_{\text{target colour}}$ and $LDR^{V}_{\text{target colour}}$ are the horizontal and vertical white luminance drop rate per centimetre.

9.2.3 Reports

The measurement results shall be reported in Table 2.

Table 2 – Example of measurement results for the average of luminance drop for white colour over the eye-box shown in Figure 14

White luminance drop rate (%) in the horizontal direction LDR^{H}_{white}	White luminance drop rate (%) in the vertical direction LDR^{V}_{white}
3.5 %	4.2 %

9.3 Measurement of the luminance and chromaticity for the virtual-image plane

9.3.1 Conditions

The luminance and chromaticity values are evaluated at different points in the virtual image plane from the centre position of the eye-box in order to estimate changes in luminance and chromaticity up to the projection position.

The following detailed preparations shall be applied:

a) the LMD is placed in the centre position (E_{33}) (as in Figure 14 (a)) of the eye-box in a dark surround in Figure 15;

b) test signal: full images of white, black, red, green, and blue;

c) measurement points in the test image: the nine points (P_{11} to P_{33}) defined in Figure 4.

NOTE If the measurement is required at a point other than the adjacent nine points at the edge, defined in Figure 4, different points can be selected according to the requirement of a user. If a measurement is required in consideration of conformity with SAE J 1757-2 [3], the measurement points for luminance uniformity are located at the position '0,2 x width/length' inward from the edge.

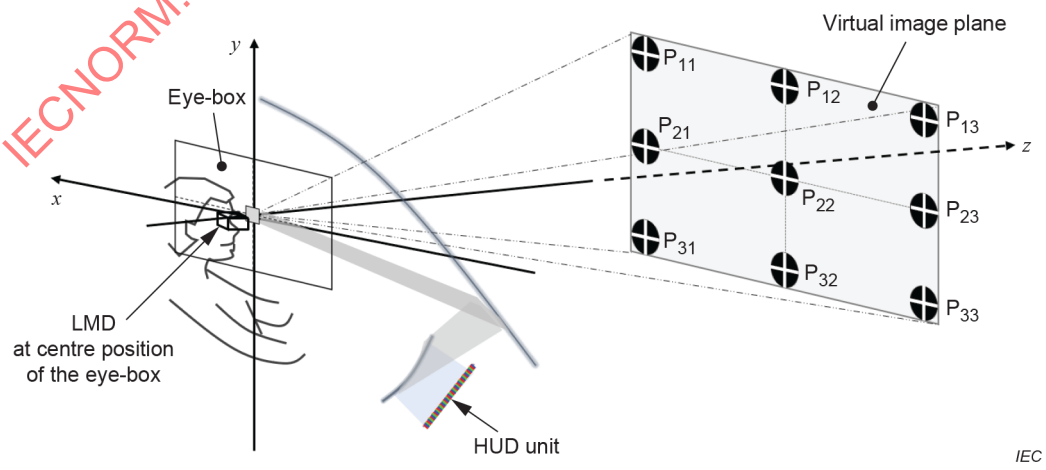

Figure 15 – Measuring condition for luminance and chromaticity from the centre point in the eye-box

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9.3.2 Procedures

The following measuring procedure shall be carried out:

a) apply the test signals of white and black;

b) measure the luminance of the nine points (P_{11} to P_{33}) in the virtual image plane shown in Figure 15 for the white and black images, respectively;

c) calculate the luminance-uniformity values for white and black images as follows:

$$L_{\text{white}} = L_{\text{white}}(P_{22})$$

$$L_{\text{black}} = L_{\text{black}}(P_{22}) \tag{17}$$

$$LU_{\text{W}} = \left(1 - \frac{\max\limits_{1\le i,j\le 3} L_{\text{white}}(P_{ij}) - \min\limits_{1\le i,j\le 3} L_{\text{white}}(P_{ij})}{\max\limits_{1\le i,j\le 3} L_{\text{white}}(P_{ij})}\right) \times 100$$

$$LU_{\text{B}} = \left(1 - \frac{\max\limits_{1\le i,j\le 3} L_{\text{black}}(P_{ij}) - \min\limits_{1\le i,j\le 3} L_{\text{black}}(P_{ij})}{\max\limits_{1\le i,j\le 3} L_{\text{black}}(P_{ij})}\right) \times 100 \tag{18}$$

where

L_{white} is the luminance value for the white image at the measuring point P_{22};

L_{black} is the luminance value for the black image at the measuring point P_{22};

LU_{W} is the luminance-uniformity value for the white image;

LU_{B} is the luminance-uniformity value for the black image;

$L_{\text{white}}(P_{ij})$ is the white luminance measured at the measuring point P_{ij};

$L_{\text{black}}(P_{ij})$ is the black luminance measured at the measuring point P_{ij}; and

i, j are 1 to 3 for the nine-point measurement;

d) measure the chromaticity coordinates of the nine points (P_{11} to P_{33}) and calculate the chromaticity difference between the two points ($u'_1v'_1$ to $u'_2v'_2$) that are farthest apart amongst the $u'v'$ coordinates measured at the measuring point P_{ij} for white and black images respectively as follows;

$$u'_{\text{white}} = u'_{\text{white}}(P_{22}),\ v'_{\text{white}} = v'_{\text{white}}(P_{22})$$

$$u'_{\text{black}} = u'_{\text{black}}(P_{22}),\ v'_{\text{black}} = v'_{\text{black}}(P_{22})$$

$$\Delta u'v'_{\text{white}} = \sqrt{\left(u'_1(\text{white}) - u'_2(\text{white})\right)^2 + \left(v'_1(\text{white}) - v'_2(\text{white})\right)^2} \tag{19}$$

$$\Delta u'v'_{\text{black}} = \sqrt{\left(u'_1(\text{black}) - u'_2(\text{black})\right)^2 + \left(v'_1(\text{black}) - v'_2(\text{black})\right)^2}$$

where

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$u'v'_{\text{white}}$	is the chromaticity coordinate for the white image at the measuring point P_{22};
$u'v'_{\text{black}}$	is the chromaticity coordinate for the black image at the measuring point P_{22}; and
$u'_1v'_1$ (white or black) and $u'_2v'_2$ (white or black)	are the chromaticity coordinates in the CIE 1976 u' and v' chromaticity diagram that are farthest apart amongst $u'v'$ coordinates measured at the measuring point P_{ij} for white and black images respectively.

e) calculate the contrast value of C at the measuring point P_{22} as follows:

$$C = \frac{L_{\text{white}}(P_{22}) - L_{\text{black}}(P_{22})}{L_{\text{black}}(P_{22})} \tag{20}$$

where

$L_{\text{white}}(P_{22})$ is the white luminance measured at the measuring point P_{22};

$L_{\text{black}}(P_{22})$ is the black luminance measured at the measuring point P_{22}.

f) apply the test signals of red, green and blue alternately;

g) measure the luminance at the measuring point P_{22} in the virtual image plane shown in Figure 15 for the red, green and blue images, respectively; and

$$\begin{aligned} L_{\text{red}} &= L_{\text{red}}(P_{22}) \\ L_{\text{green}} &= L_{\text{green}}(P_{22}) \\ L_{\text{blue}} &= L_{\text{blue}}(P_{22}) \end{aligned} \tag{21}$$

h) measure the chromaticity coordinates of the nine points (P_{11} to P_{33}) and calculate the chromaticity difference between two points ($u'_1v'_1$ to $u'_2v'_2$) that are farthest apart amongst the $u'v'$ coordinates measured at the measuring point P_{ij} for the red, green, and blue images respectively as follows:

$$\begin{aligned} u'_{\text{red}} &= u'_{\text{red}}(P_{22}),\ v'_{\text{red}} = v'_{\text{red}}(P_{22}) \\ u'_{\text{green}} &= u'_{\text{green}}(P_{22}),\ v'_{\text{green}} = v'_{\text{green}}(P_{22}) \\ u'_{\text{blue}} &= u'_{\text{blue}}(P_{22}),\ v'_{\text{blue}} = v'_{\text{blue}}(P_{22}) \\ \Delta u'v'_{\text{red}} &= \sqrt{(u'_1(\text{red}) - u'_2(\text{red}))^2 + (v'_1(\text{red}) - v'_2(\text{red}))^2} \\ \Delta u'v'_{\text{green}} &= \sqrt{(u'_1(\text{green}) - u'_2(\text{green}))^2 + (v'_1(\text{green}) - v'_2(\text{green}))^2} \\ \Delta u'v'_{\text{blue}} &= \sqrt{(u'_1(\text{blue}) - u'_2(\text{blue}))^2 + (v'_1(\text{blue}) - v'_2(\text{blue}))^2} \end{aligned} \tag{22}$$

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where

$u'v'_{red}$	is the chromaticity coordinate for the red image at the measuring point P_{22};
$u'v'_{green}$	is the chromaticity coordinate for the green image at the measuring point P_{22};
$u'v'_{blue}$	is the chromaticity coordinate for the blue image at the measuring point P_{22}; and
$u'_1v'_1$ (red, green or blue) and $u'_2v'_2$ (red, green or blue)	are the chromaticity coordinates in the CIE 1976 u' and v' chromaticity diagram that are farthest apart amongst $u'v'$ coordinates measured at the measuring point P_{ij} for red, green and blue images respectively.

9.3.3 Reports

The measurement results shall be reported in Table 3.

Table 3 – Example of measurement results for white (black) luminance, contrast, uniformity of white (black) luminance, and chromaticity coordinates in the measurement configuration of Figure 15

Luminance		Contrast	Uniformity of		Chromaticity coordinates			
white luminance	black luminance		white luminance	black luminance	White	Red	Green	Blue
(L_W)	(L_B)	(C)	(LU_W)	(LU_B)	u' v'	u' v'	u' v'	u' v'
cd/m^2	cd/m^2		%	%				

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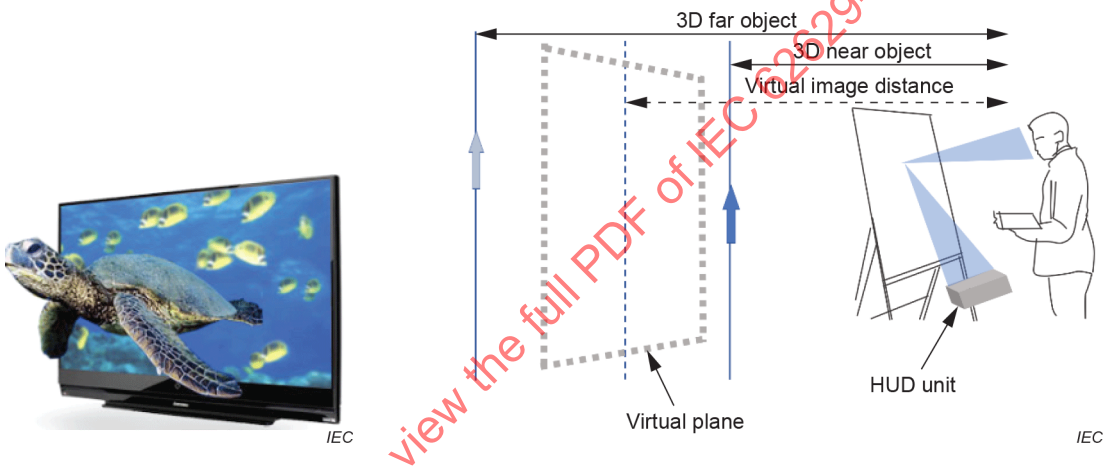
Annex A
(informative)

Comparison of measurement items between the conventional 3D display and the virtual-image type 3D display

The 3D effect is implemented for 3D displays by using depth cues such as occlusion, relative size, shading, distance to horizon, texture gradient, linear perspective, binocular disparity, and motion perspective, among others. The most common depth cue is binocular disparity, that is, deviation in the retinal images of the left and right eyes due to the slightly different viewing angle between two eyes against the same object. In the conventional 3D display shown in Figure A.1 (a), users recognize the stereoscopic image that is positioned in the front and back depth directions from the 2D display. On the other hand, the position of the 2D virtual image plane is determined by the optical system design for the 3D HUD, and 3D virtual content can be produced so that it is located in the direction of the depth before and behind the virtual image plane (see Figure A.1 (b)).



(a) conventional flat-panel type **(b) illustration of 3D HUD**

Figure A.1 – Example of 3D displays

The biggest differences between a traditional 3D display and a 3D HUD is (1) the reproduction image plane viewed by observers (actual 3D display versus virtual image plane projected from the actual 3D display by the optical system) and (2) the correlation with real objects in the viewing surroundings (non-correlation versus correlation). These differences raise the need for the development of new measurement methods for 3D HUD. The optical-characteristics measurement methods are well defined in the IEC 62629-12-1 [4] and 62629-22-1 [1] for traditional stereoscopic and autostereoscopic 3D displays, respectively. Contrary to the conventional 3D displays, the new measurement methods, particularly with regard to geometry and spatial distortion, are required for 3D HUD. It is therefore attempted to develop an optical-property measurement method for 3D HUD using the concept of binocular disparity, and its results are suggested for the development of this document. Table A.1 compares measurement items between the conventional standards (IEC 62629-12-1 [4] and 62629-22-1 [1]) for 3D displays and the current document.

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Table A.1 – Comparison of measurement items

Measurement items	IEC 62629-62-11 (Virtual 3D – Optical)	IEC 62629-12-1 [4] (Stereoscopic 3D – Optical)	IEC 62629-22-1 [1] (Autostereoscopic 3D – Optical)
Reproduction image plane viewed by observers	Virtual 3D image plane	Actual 3D display with glasses	Actual 3D display without glasses
Correlation with real object	Correlation	Non-correlation	Non-correlation
Viewing area	Eye-box	Non-specification	Non-specification
3D crosstalk (X-talk)	Interocular X-talk for multi-view display (see Annex D)	Interocular X-talk at screen centre for two-view display Interocular X-talk screen position dependency	X-talk (luminance component ratio) for two-/multi-view display X-talk related property for multi-view display: (1) offset X-talk, (2) 3D pixel X-talk
3D virtual image geometry	Virtual image distance Look down/over angle Field of view	None	None
3D virtual image distortion	Static distortion	None	None
Distance between 3D virtual object and user	Distance from user to 3D virtual image	None	None
Luminance	Luminance Luminance uniformity	Luminance Luminance uniformity Interocular luminance difference	Maximum luminance direction Luminance Screen luminance uniformity Angular luminance variation
Colour (chromaticity)	Chromaticity	White chromaticity White chromatic uniformity Interocular chromatic difference Colour gamut	White chromaticity White chromaticity uniformity on screen Angular chromaticity variation
Contrast	Contrast	Contrast ratio Interocular contrast difference	

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Annex B
(informative)

Comparison of the optical-property measurement methods for virtual images

Table B.1 compares different optical-property measurement methods to determine the virtual image distance: this document, ISO 9241-305 [5] and SAE J 1757-2 [3]. Figure B.1, Figure B.2 and Figure B.3 illustrate the measurement concept applied for this document, ISO 9241-305:2008, 6.11.1 in particular [5], and SAE J 1757-2 [3], respectively. The triangulation principle is applied for this document and ISO 9241-305 [5] whereas the actual vertical screen with orthogonal horizontal and vertical rulings, which is called paravan thereafter, is used for SAE J 1757-2 [3].

The variable factors dependent on the virtual image distance and the constant factor unchanged by that distance are described in each of the three methods in Table B.1. The virtual image distance is evaluated using the binocular disparity information obtained from the multiple imaging LMDs in Figure B.1 for this document (see 5.2). The rotation angle of the LMD obtained from the goniometric measurement configuration is used to evaluate the virtual image distance in Figure B.2 for ISO 9241-305 [5]. The paravan is moved to the position where both the virtual image and the grating pattern in the paravan are in focus in order to measure the virtual image distance in Figure B.3 for SAE J 1757-2 [3]. There is however limitation in the measurement of the geometric property for the 3D virtual objects with parallax (see Figure 12) since the binocular disparity information cannot be measured by the proposed method in SAE J1757-2 [3]. For the HUD providing the tilted virtual-image plane, there are practical difficulties in measuring the virtual image distance using the physical paravan.

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Table B.1 – Comparison of the optical-property measurement methods for virtual images

	IEC 62629-62-11	ISO 9241-305:2008 [5] (particularly 6.11.1)	SAE J 1757-2 [3]
Scope	This document specifies the standard measuring conditions and measurement methods for determining the optical properties of the virtual-image created by 3D display devices such as head-up displays. It can also be applied for the 3D superimposed visual information on the external field.	In 6.11.1. Applicability: Monocular and binocular (both eyes, separate optics, identical images) near-to-eye displays, which produce a virtual image. This procedure does NOT apply to stereoscopic vision (different image for each eye) or two-eye monocular (one large optics for both eyes) devices.	This SAE standard provides measurement methods to determine HUD optical performance in typical automotive ambient lighting conditions.
Principle applied for the measurement method	Triangulation	Triangulation	Focus on virtual image on physical paravan
Number of imaging LMDs	1 LMD with movement (or 3 LMDs)	1 LMD with movement (or 2 LMDs)	1 LMD
Variable factor dependent on virtual image distance	Binocular disparity information in the multiple images captured by LMDs	LMD rotation angle based on goniometer	Position of the paravan
Constant factor unchanged by the virtual image distance	Distance between multiple LMDs (see 5.2) and the field of view of the LMD	Distance between two LMDs	LMD position
Method to determine virtual image distance	Triangulation using the binocular disparity information between multiple images using LMDs and field of view of the LMD	Triangulation using the rotation angle of the LMD and the distance between two LMDs	Moving the paravan to the position where both the virtual image and the grating pattern in the paravan are in focus

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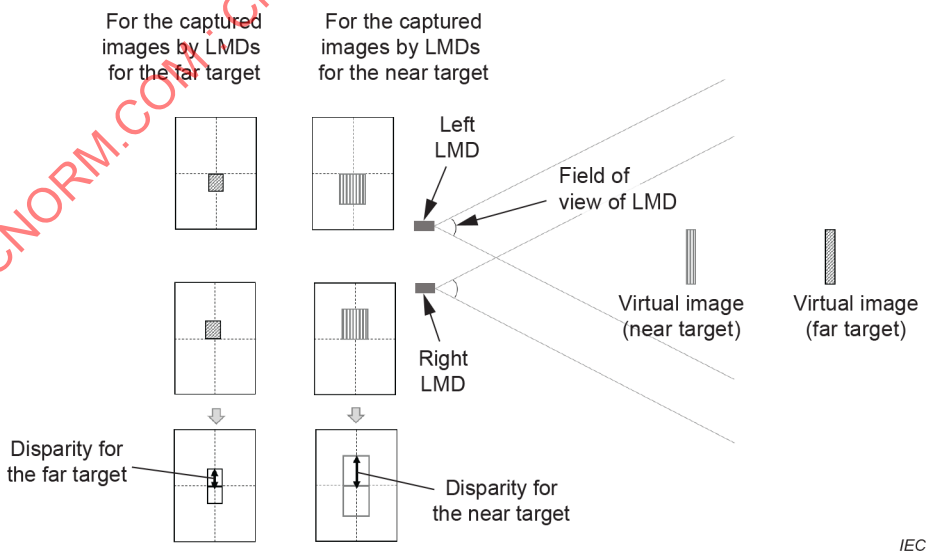

Figure B.1 – Illustration of the measurement concept applied for this documenta

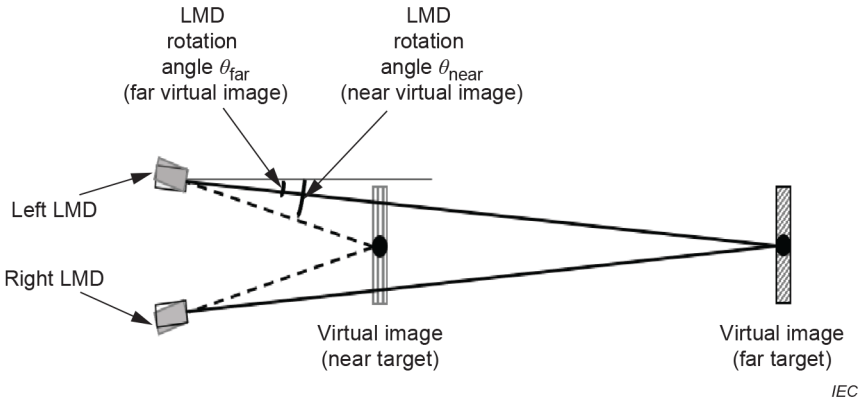

Figure B.2 – Illustration of the measurement concept applied for ISO 9241-305:2008, 6.11.1 [5]

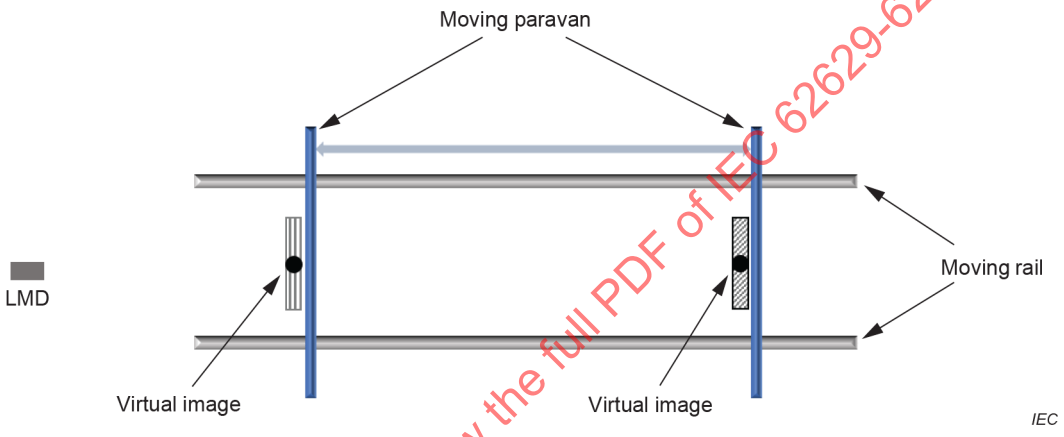

Figure B.3 – Illustration of the measurement concept applied for SAE J 1757-2 [3]

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Annex C
(informative)

Additional information for geometric property measurement of 3D virtual images using imaging LMDs

C.1 General

In 5.2, the measurement method is defined for the geometric property of 3D virtual images using three imaging LMDs. The background for the selection of three imaging LMDs is introduced in Annex C. The possibility of error in the determination of the virtual-object location by the application of two imaging LMDs is also explained. The geometric calibration process of the imaging LMD is also provided in Clause C.3.

C.2 Reasons for the necessity of using three imaging LMDs

A 3D HUD is made up of a real 3D display and the optical components of lens and mirror. The lights from the circle reproduced on the real 3D display (R in Figure C.1) do not converge into one virtual position due to aberration by the lens in the HUD unit that can lead to two virtual circles of A and B in Figure C.1. As a result, the 3D virtual-object location can be estimated to be C based on triangulation using the two virtual circles of A and B. The error in estimating the position of a virtual object due to lens aberration cannot be detected because the number of corresponding positions between two LMDs is only one (C in Figure C.1). There is therefore no way to determine the accurate location of the corresponding virtual circle against the circle presented on the real 3D display using two LMDs. This limit can be overcome by increasing the number of imaging LMDs.

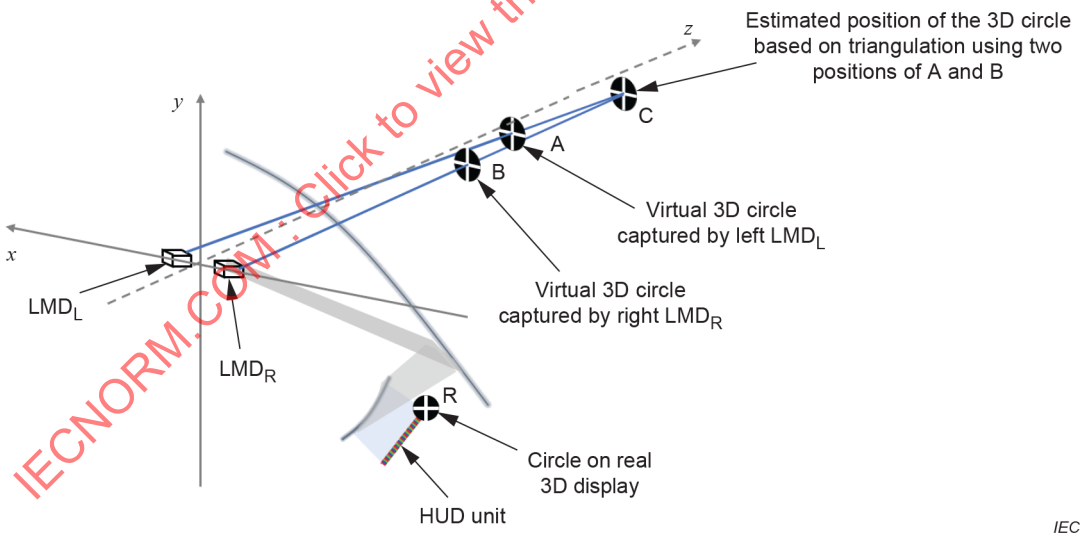

Figure C.1 – Limit in the determination of the location of a 3D virtual object using two imaging LMDs

Three imaging LMDs with the same gap can prevent a wrong estimation by determining the location of the virtual object that satisfies the condition described in Formula (C.1). In this condition, the disparity values between “left and centre” and “centre and right” imaging LMDs are identical, indicating that three imaging LMDs can capture the 3D virtual object at the same position (E in Figure C.2).

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$$\left\| m_{ij}^{\mathrm{L}} - m_{ij}^{\mathrm{C}} \right\| = \left\| m_{ij}^{\mathrm{L}} - m_{ij}^{\mathrm{R}} \right\| \tag{C.1}$$

where

m_{ij}^{L}, m_{ij}^{C}, and m_{ij}^{R} are the pixel indices of the captured images (by left, centre, and right LMDs) for the corresponding 3D virtual circle of the R on the real 3D display in Figure C.2.

The details about the pixel index of the captured image by imaging LMDs are given in Figure 5. In conclusion, the erroneous determination of the 3D virtual-object position due to lens aberration can be solved using three imaging LMDs.

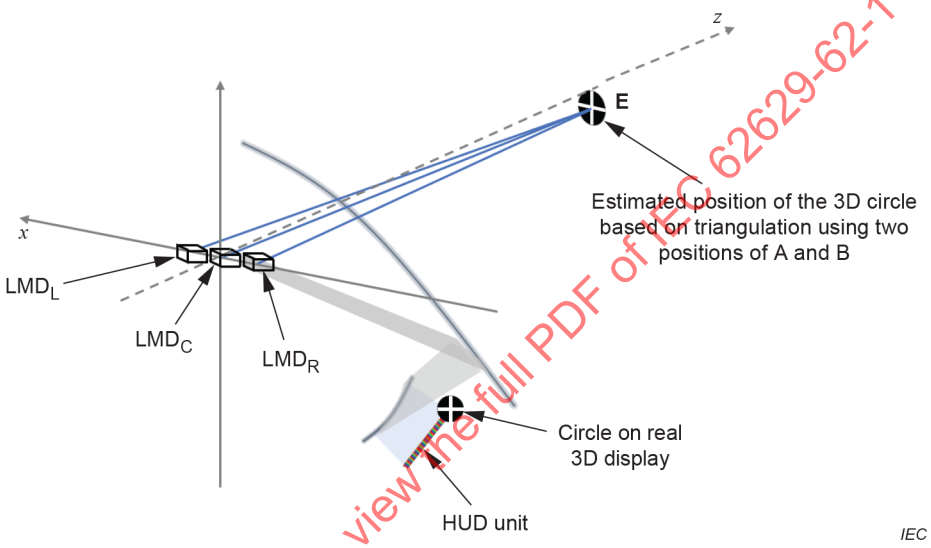

Figure C.2 – Determination of the location of a 3D virtual object using three imaging LMDs

C.3 Geometric calibration process for the imaging LMDs

The imaging LMD is used to measure the geometric locations of the virtual image plane (see Figure 1) and the 3D virtual object that can be placed in the front/back of the virtual image plane (see 8.2). The imaging LMD image is obtained by projecting points in 3D space onto a 2D image plane. The actual 2D image is greatly affected by the mechanical parts inside the imaging LMD, such as the lens, the distance between the lens and the image sensor, and the angle formed by the lens and image sensor. When calculating the position where 3D points are projected on the image or conversely restoring the 3D spatial coordinate from the image coordinate, accurate calculation is possible only by removing these internal factors.

An imaging LMD calibration process is executed to align the imaging LMDs at the centre of the eye-box (see Figure C.3). The imaging LMD calibration estimates the intrinsic and extrinsic parameters. The extrinsic parameters are related to the geometrical relationship between the imaging LMD and the external space, such as the installation height and direction (pan, tilt) of the imaging LMD. The intrinsic parameters refer to the internal parameters of the imaging LMD itself, such as the focal length, aspect ratio, and centre point of the imaging LMD.

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To determine these parameters, the following procedures can be applied:

a) calculate the intrinsic matrix:

$$\text{Intrinsic matrix} = \begin{bmatrix} f_x & 0 & C_x \\ 0 & f_y & C_y \\ 0 & 0 & 1 \end{bmatrix} \tag{C.2}$$

where

f_x and f_y are the focal lengths expressed in pixel units in x and y directions;

(C_x, C_y) is a principal point that is the optical centre of the imaging LMD lens;

b) calculate the field of view from the intrinsic matrix:

$$\text{FOV}_x = 2\tan^{-1}\frac{w}{2f_x},\ \text{FOV}_y = 2\tan^{-1}\frac{h}{2f_y} \tag{C.3}$$

where

w and h are the horizontal and vertical resolution;

c) calculate the extrinsic matrix for three imaging LMDs:

$$\text{2DLMD}_{\text{left}} = [R_1, T_1],\ \text{2DLMD}_{\text{centre}} = [R_2, T_2],\ \text{2DLMD}_{\text{right}} = [R_3, T_3] \tag{C.4}$$

where

R and T are a rotation and a translation matrix; and

d) calculate a (the gap between the left and right imaging LMDs) from the extrinsic matrix:

$$\begin{bmatrix} a \\ 0 \\ 0 \end{bmatrix} = \|T_3 - T_2\| + \|T_1 - T_2\| \tag{C.5}$$

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