IEC TR 62715-5-61

Edition 1.0 2024-08

TECHNICAL REPORT

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Flexible displays –
Part 5-61: Overview of measurement and application scenarios of stretchable displays

IEC TR 62715-5-61:2024-08(en)

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ICS 31.120

ISBN 978-2-8322-9517-5

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CONTENTS

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FLEXIBLE DISPLAYS –

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IEC TR 62715-5-61 has been prepared by IEC technical committee 110 Electronic displays. It is a Technical Report.

The text of this Technical Report is based on the following documents:

Draft	Report on voting
110/1647/DTR	110/1668/RVDTR

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 Technical Report 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/publications.

A list of all parts in the IEC 62715 series, published under the general title *Flexible displays*, can be found on the IEC website.

Future documents in this series will carry the new general title as cited above. Titles of existing documents in this series will be updated at the time of the next edition.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

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FLEXIBLE DISPLAYS –

Part 5-61: Overview of measurement and application scenarios of stretchable displays

1 Scope

This part of IEC 62715, which is a Technical Report, provides an overview of stretchable display technologies and application scenarios for stretchable displays. This document introduces special considerations for development of measurement methods for stretchable displays.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

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

3.1
stretchable display device
flexible display panel and module whose surface area and shape can change when stretched

3.2
stretchable display
device to which a stretchable display panel or module is applied

3.3
stretchability
extent to which stretchable display device can be stretched

4 Stretchable devices technology

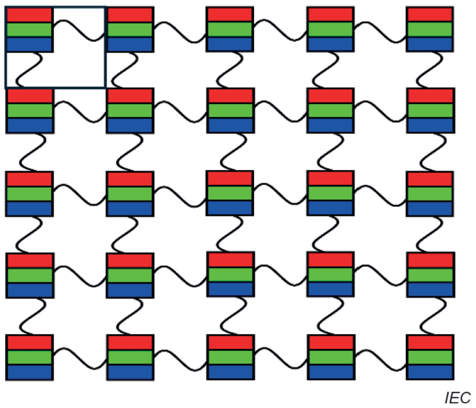
4.1 General

Various types of flexible displays have been introduced to the market [1] to [8][1]. They include foldable, rollable and slidable types. Recently, development of a new type of flexible display has been reported by academic societies as well as display industries. It is a stretchable display device. Unlike previous flexible display technologies, the size of the surface area can be changed. Furthermore, stretchable displays can have shapes with multi-curvatures in any direction. Thus, stretchable displays are often called freeform displays.

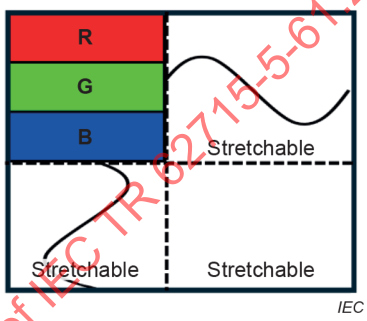
[1] Numbers in square brackets refer to the Bibliography.

4.2 Stretchable device structure

Figure 1 a) illustrates an example of the pixel structure of a stretchable display with island-bridge structure. The black square in the upper left corner of Figure 1 a) represents a single pixel. Figure 1 b) illustrates an enlarged image of the black square in Figure 1 a). A pixel consists of rigid and stretchable areas. In Figure 1 b) a pixel area is represented by four sub-areas. The upper left area represents the rigid area. It can be called a light emitting region because light emitting devices, for example light emitting diodes (LEDs) (including mini LED and micro LED) and organic light emitting diodes (OLEDs), are placed at the rigid area. This area usually remains unchanged during stretching. The remaining three sub-areas in Figure 1 b) can be stretched when external force is applied.



a) **Pixel structure**



b) **Enlarged image of white box in a)**

Figure 1 – Pixel structure of a stretchable display

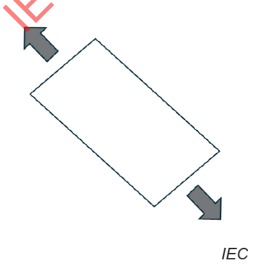
4.3 Classification of stretching types

4.3.1 General

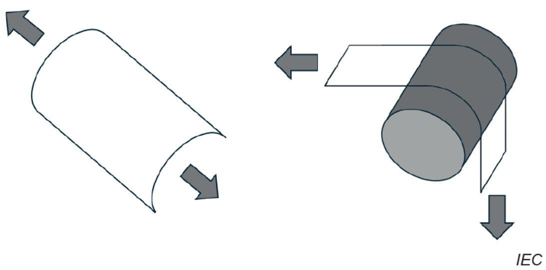
There are numerous ways to change the area and shape of a stretchable display. However, types of stretching can be grouped according to the stretching direction and shape.

4.3.2 One-axis stretching

A stretchable display device stretched in single axis is called a "one-axis stretching" display device. Figure 2 illustrates typical stretchable display devices in "one-axis stretching".



a) **Flat type**



b) **Fixed curvature type**

Figure 2 – One-axis stretching display device

4.3.3 Bi-axis stretching

A stretchable display device stretched by two axis is called a "bi-axis stretching" display device. Figure 3 illustrates the common style of a "bi-axis stretching" display device.

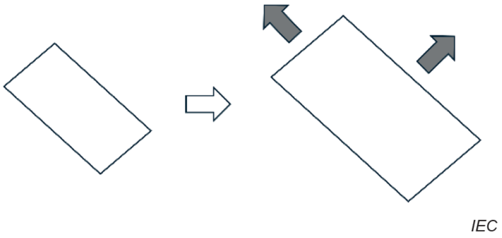


Figure 3 – Bi-axis stretching display device

4.3.4 Multi-curvature stretching

A stretchable display device stretched with more than one curvature is called a "multi-curvature stretching" display device. Figure 4 shows the common style of this kind of stretchable display device, which has two different curvatures.

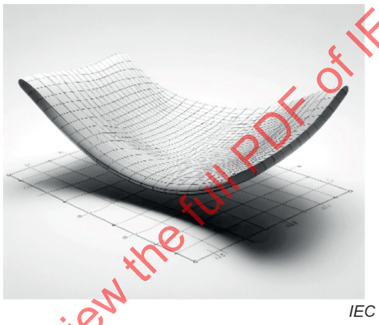


Figure 4 – Multi-curvature stretching display device

4.3.5 Others

A stretchable display device could be twisted in any direction. Figure 5 shows an example of a twisting display device.

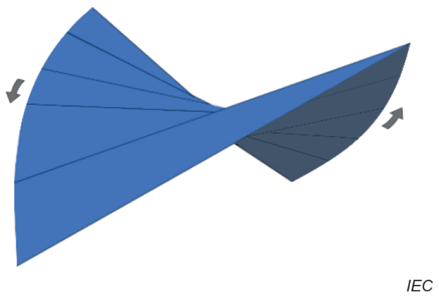


Figure 5 – Twisting display device

4.4 Application scenarios of stretchable displays

4.4.1 General

Due to their free-form characteristics, stretchable display devices are expected to be used in a wide variety of applications. Therefore, it will be a difficult task to predict or enumerate all user application scenarios of stretchable display devices. However, depending on whether the stretchable display is used only in a stretched state or not, it can be divided into a static and dynamic applications.

4.4.2 Dynamic applications

A study reported in 2017 that the 9,1-inch stretchable display was stretched to convex/concave shapes [6]. Figure 6 schematically illustrates the stretchable display with three different levels of convex shape change.

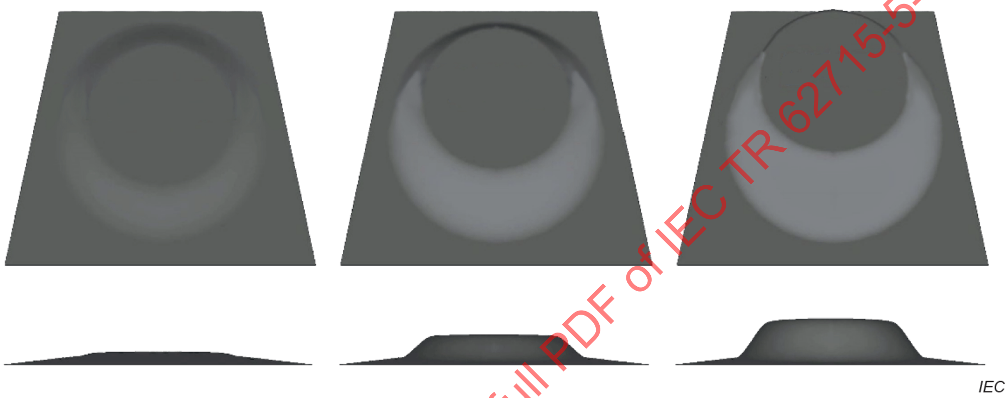


Figure 6 – Example of dynamic display applications

Stretchable display devices are suitable for wearable applications as illustrated in Figure 7 [3]. The surface of stretchable display devices can be uneven or can be twisted.

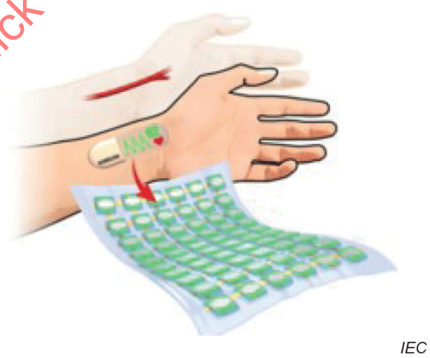


Figure 7 – Example of stretchable display for wearable application [3]

4.4.3 Static applications

Mobility applications are a key area where stretchable display devices can be used. Figure 8 conceptually illustrates how stretchable display devices can be utilized in the centre fascia of an automobile.

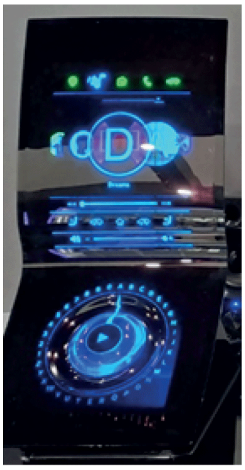


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Figure 8 – Example of stretchable display for centre fascia application

5 Considerations for development of measurement methods

5.1 General

The aim of this document is to identify critical measurement issues that are of importance for the development of the measurement standards of stretchable displays. This document focuses on the special considerations for the measurement unique to the stretchable displays.

Stretchability is a major performance factor of stretchable display devices. Especially, the measurement of stretchability in three-dimensional stretching has not yet been formally defined. In addition, measurements of luminance and colour from three-dimensional surface have not been defined.

In addition, it is worthwhile to mention the following requirements of optical measurement standards for displays.

- measurements can be made by the panel makers, set makers, testing agencies or consumer organizations by utilizing publicly available information;
- methods should be repeatable, and results can be identically reproducible;
- use of special (and very expensive) measuring devices can be undesirable.

5.2 Two-dimensional stretchability

Two-dimensional stretchability can be measured using an area ratio or length ratio. However, measurement of the elongation ratio has been widely utilized for two-dimensional stretching of stretchable display devices both in industry and academic communities. It is defined using a ratio in length as follows:

$$\varepsilon_{\text{2DLeng}}(\%) = \left(\frac{L_{\text{as}}}{L_{\text{bs}}} - 1\right) \times 100(\%) \qquad (1)$$

where

ε is the stretched ratio,

L_{as} is the length after stretching,

L_{bs} is the length before stretching.

Before and after the maximum stretching, the length of the stretchable display device is measured in the direction of the stretching. Manufacturers can declare the maximum stretching capability that satisfies the pre-determined durability conditions. It is desirable to standardize the durability conditions in future as an IEC standard, for example, IEC 62715-6-6x. The advantage of the elongation ratio is that the calculation is simple and measurement method is well established.

5.3 Controlled generation of three-dimensional stretching

3D stretchability is determined based on the measurements before and after 3D stretching. Thus, 3D stretchability depends on the types of 3D stretching applied to the stretchable displays. However, there are numerous ways to change the shape of a stretchable display by 3D stretching. This is why a unified and controlled way to create 3D stretching will first be agreed to. Furthermore, the first and second requirements specified in 5.1 will be reflected in designing a controlled generation of 3D stretching. In addition, the durability conditions will be specified (in the future by an IEC standard, for example, IEC 62715-6-6x) based on the same controlled generation of 3D stretching.

Figure 9 illustrates an example to generate a controlled 3D stretching. Figure 9 represents a cross-sectional view. An external object to generate a three-dimensional stretching is a sphere attached a to cylinder in Figure 9. It is assumed that the sphere is moved upward by an electric motor as shown in the right side of Figure 9. A fixture guide sits on the top of the stretchable display and remains unchanged during the generation of three-dimensional stretching. it is a thin but rigid plate with a circular opening. However, it is represented as two separated rectangles in the cross-sectional view of Figure 9. The fixture guide serves to limit the range of three-dimensional stretching. The diameter of the circular hole of fixture guide is bigger than the diameter of the sphere object to generate three-dimensional stretching. The half of difference in diameters of the circular hole of fixture guide and that of the sphere object can be called as a gap between the fixture guide and sphere. The use of a fixture guide is optional. When fixture guides are not utilized, the shape of three-dimensional stretching appears less steep. In addition, the durability of the deformed panel can be affected by the shape of the fixture guide and the size of the gap between the fixture guide and external object.

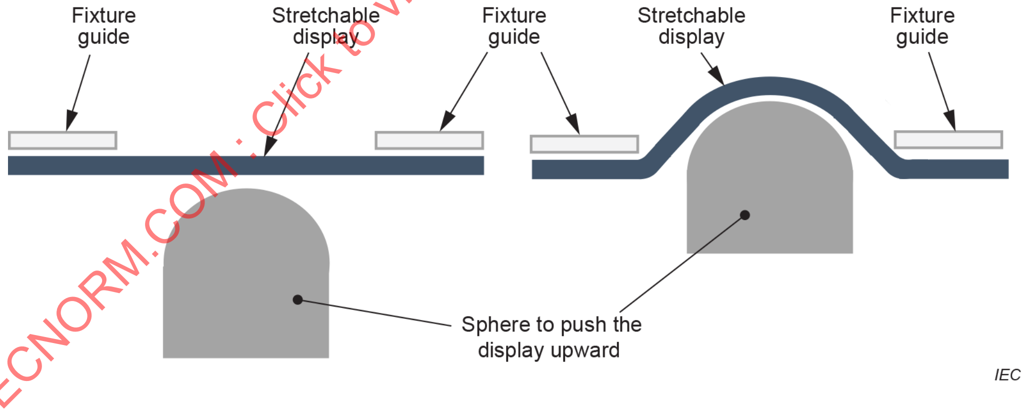

Figure 9 – An example to generate 3D dimensional stretching (sphere with fixture guide)

NOTE 1 An example of controlled stretching in Figure 9 is due to radial stretching. Circumferential stretching can also be considered for a controlled generation of 3D stretching.

NOTE 2 The purpose of the controlled stretching example in Figure 9 is to mimic real-world applications of 3D stretching. In this case, 3D stretching is not uniform due to the use of a fixture guide. Other configurations of a controlled generation of 3D stretching with more uniform stretching rate can be considered as alternatives or additional case(s).

5.4 Examples of three-dimensional stretchability

5.4.1 General

The elongation ratio in Formula (1) cannot be directly utilized for 3D stretching. The extent of three-dimensional stretching can be measured by an area ratio or length ratio. In this document, different measurement methods of three-dimensional stretchability are introduced as examples for future standard development. In addition, experimental results for different three-dimensional stretching conditions are presented.

5.4.2 Three-dimensional stretchability measures based on length ratio

When not stretched, pixels of the stretchable display device can be represented by squares or rectangles on the same plane. After the controlled stretching by the sphere illustrated in Figure 9, a pixel becomes quadrilateral in a three-dimensional space. Simulation using the finite element method (FEM) can estimate the three-dimensional coordinates of the vertices of the stretched pixels.

Examples of three-dimensional stretchability can be explained using the schematic drawing in Figure 10. The horizontal line in Figure 10 represents a stretchable display device before stretching. As illustrated in Figure 9, the fixture guide with circular hole sits on the stretchable display device. In Figure 10, the grey shaded circle represents the cross-section of the sphere to generate 3D stretching. The red arc $\overset{\frown}{AB}$ represents the portion of the sphere above the fixture guide to create a controlled 3D stretching. The blue curved line denotes the cross-section of the stretchable display pushed up by the sphere. The red arc and blue curved line in Figure 10 are determined when the stretchable display device reaches the maximum height. Manufacturers can declare the maximum height that satisfies pre-determined durability conditions. It is desirable to standardize the durability conditions in the future as an IEC standard, for example, IEC 62715-6-6x.

The larger circle in Figure 10 denotes the boundary of the cross section of an imaginary sphere. It is assumed that the imaginary sphere passes through the three points, A', B' and the top of the stretched display. The green arc, $\overset{\frown}{A'B'}$, represents the boundary of the cross-section of the imaginary sphere above the plane defined by the fixture guide. In Figure 10, h represents the maximum height. r_{cap} is the radius of the base of the sphere cap on the plane defined by the fixture guide. It is also half the length of the chord corresponding to the red arc. r_{sph}, r_{hole}, and r_{img} are the radius of the sphere, circular hole of the fixture guide and imaginary sphere, respectively. r_{sph} is half the length of the chord corresponding to the green arc. d_{gap} is the difference between the radius of the circular hole of the fixture guide and the radius of the sphere. It represents a gap between the fixture and the sphere.

In Figure 10, the blue curved line represents the actual cross-sectional shape of the stretchable display device when it reaches the maximum height. The length of the blue curved line is determined by the data from the simulation based on the FEM. A new three-dimensional stretchability is defined as follows:

$$\varepsilon_{\text{3DLeng1}}(\%) = \left(\frac{L_{\text{bl}}}{\overline{A'B'}} - 1\right) \times 100(\%) \tag{2}$$

where

ε is the stretched ratio,

L_{bl} is the length of the blue curved line and the actual cross-sectional length after stretching;

$\overline{A'B'}$ is the cross-sectional length before stretching.

An alternative measure of the three-dimensional stretchability can be defined by Formula (3) using the ratio of red arc and its corresponding chord.

$$\varepsilon_{\text{3DLeng2}}(\%) = \left(\frac{\overset{\frown}{AB}}{\overline{AB}} - 1 \right) \times 100(\%) \tag{3}$$

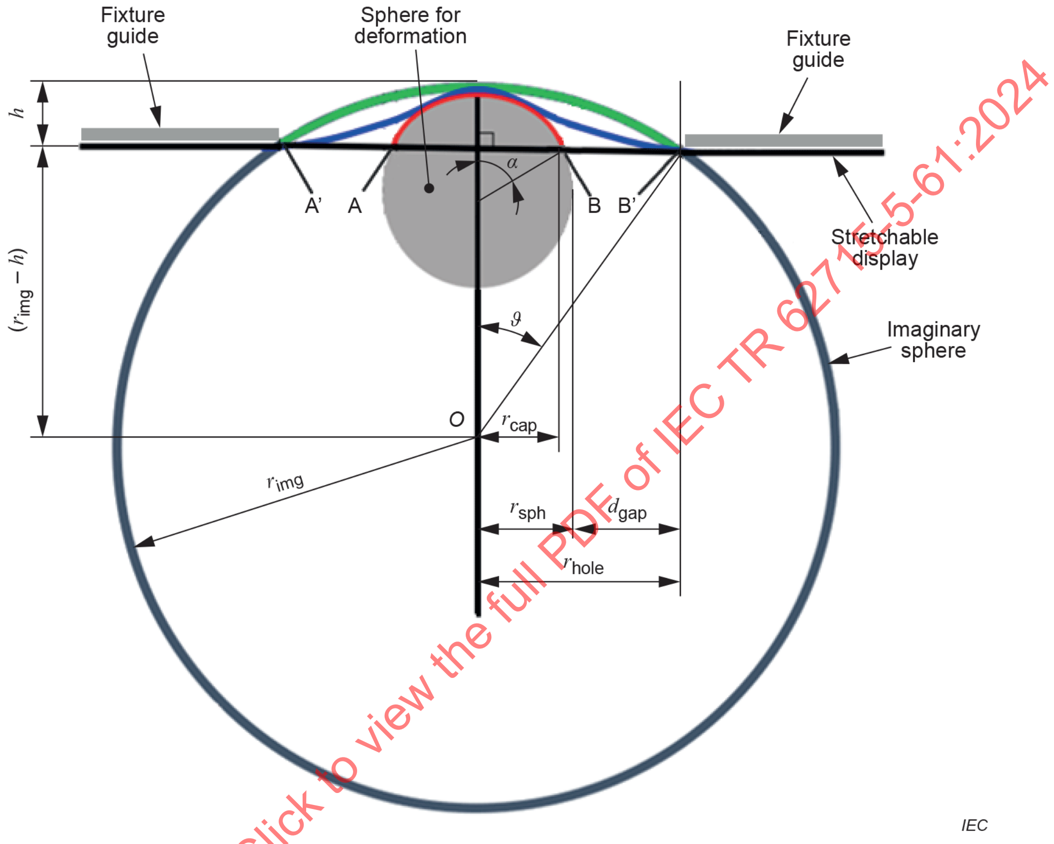

Figure 10 – Schematic cross-sectional view to explain 3D stretchability measures

$\overset{\frown}{AB}$ and $\overline{AB}$ are calculated by Formula (4) and Formula (5), respectively.

$$\overset{\frown}{AB} = 2r_{\text{sph}}\alpha = 2r_{\text{sph}} \cos^{-1}\left(\frac{r_{\text{sph}} - h}{r_{\text{sph}}} \right) \tag{4}$$

$$\overline{AB} = 2r_{\text{cap}} = 2\sqrt{r_{\text{sph}}^{2} - \left(r_{\text{sph}} - h \right)^{2}} \tag{5}$$

α in Formula (4) can be found in Figure 10. In Formula (3), it is assumed that the stretched surface of the stretchable display exactly matches with the surface of the sphere that generates 3D stretching. This assumption can deteriorate the accuracy of the calculated stretchability because the role of the gap that limits the range of 3D stretching is ignored. The new measure in Formula (3) can be calculated without the data from the simulation based on the FEM.

Another alternative measure of stretchability is defined as in Formula (6) using the ratio of the ratio of the green arc $\overset{\frown}{A'B'}$ to its corresponding chord $\overline{A'B'}$.

$$\varepsilon_{\text{3DLeng3}}(\%) = \left(\frac{\overset{\frown}{A'B'}}{\overline{A'B'}} - 1 \right) \times 100(\%) \tag{6}$$

$\overset{\frown}{A'B'}$ in Formula (6) can be calculated by substituting r_{img} in place of r_{sph} and q in place of α in Formula (4). Similarly, $\overline{A'B'}$ in Formula (6) can be determined by substituting r_{hole} in place of r_{cap} and r_{img} in place of r_{sph} in Formula (5). Unlike the measure in Formula (3), the new measure in Formula (6) partially reflects the shape of stretching caused by the sphere and the fixture guide. It is likely that the measure in Formula (6) provides better accuracy than the measure in Formula (3). The advantage of the measures based on the length ratio in Formula (3) and Formula (6) is that the two-dimensional stretchability in Formula (1) is also determined based on the length ratio. Thus, values of two- and three-dimensional stretchability measures can be compared.

The stretchability measure in Formula (2) utilizes the data from the FEM-based simulation whereas two stretchability measures in Formula (3) and Formula (6) can be calculated using the values of the parameters of three-dimensional stretching.

5.4.3 Three-dimensional stretchability measures based on area ratio

Stretchability can also be described based on the changes in surface areas. A new measure of three-dimensional stretchability based on the change in area is defined by Formula (7).

$$\varepsilon_{\text{3DArea1}}(\%) = \left[\frac{\sum_{(i,j)\in S} PA_{\text{as}}(i,j)}{\sum_{(i,j)\in S} PA_{\text{bs}}(i,j)} - 1 \right] \times 100(\%) \tag{7}$$

where

ε is the stretched ratio;

S is the set of stretched pixels by the sphere in Figure 9;

$PA_{\text{as}}(i,j)$ is the area of the (i, j)-th pixel after the three-dimensional stretching;

$PA_{\text{bs}}(i,j)$ is the area of the (i, j)-th pixel before the three-dimensional stretching.

Whether or not it is stretched can be determined by checking the z-coordinate in the three-dimensional coordinates of the vertexes of the corresponding pixel by the simulation by the FEM. The shape of the pixel before stretching is square or rectangle. Regardless of the position, the pixel area is the same. However, the pixel after the stretching has the shape of quadrilateral in a three-dimensional space. Thus, the pixel area can be calculated using the three-dimensional coordinates of the vertices of the quadrilateral estimated by the simulation with FEM.

The second measure based on the area ratio can defined by Formula (8).

$$\varepsilon_{\text{3DArea2}}(\%) = \left(\frac{2\pi r_{\text{sph}} h}{\pi r_{\text{cap}}{}^{2}} - 1 \right) \times 100(\%) \tag{8}$$

The nominator inside the parenthesis in Formula (8) represents the area after 3D stretching. More specifically, it is the surface area of the sphere cap defined by the plane of the fixture square in Figure 10. The sphere cap is a portion of the sphere to generate the controlled 3D stretching. The denominator inside the parenthesis in Formula (8) represents the area before the stretching. It is the base area of the sphere cap cut by the surface of the fixture guide. The base of the sphere cap is a circle whose radius is r_{cap}.

Another measure of stretchability is defined as in Formula (9) using the imaginary sphere defined in Figure 10.

$$\varepsilon_{\text{3DArea3}}(\%) = \left(\frac{2\pi r_{\text{img}} h}{\pi r_{\text{hole}}{}^{2}} - 1 \right) \times 100(\%) \tag{9}$$

The nominator inside the parenthesis in Formula (9) is the surface area of the sphere cap corresponding to the green arc of the imaginary sphere in Figure 10. The imaginary sphere is assumed to be cut by the plane of the fixture guide. The denominator inside the parenthesis in Formula (9) is the area of the base of the sphere cap of the imaginary spere. The base of the sphere cap is a circle whose radius is $r_{\text{hole}}\mathrm{d_b}$.

Candidates of new measures in Formula (7) to Formula (9) are defined based on the area ratio. The stretchability measure in Formula (7) utilizes the data from the FEM-based simulation whereas two stretchability measures in Formula (8) and Formula (9) can be calculated using the values of the parameters of 3D stretching.

5.4.4 Performance evaluation of three-dimensional stretchability measures

Among the six different measures of 3D stretchability described above, two in Formula (2) and Formula (7) are determined based on the three-dimensional pixel coordinates estimated from the FEM based simulation. The three-dimensional pixel coordinates can also be estimated using the optical measurements. However, these methods to estimate the pixel coordinates are computationally expensive.

Furthermore, the data required to running the simulation program are only available to the manufacturers, Thus, it might not be publicly available to the other stakeholders. In addition, when the simulation or optical measurement are executed by independently developed programs, it can be difficult to guarantee that the same result values can be obtained for the same input data. These can be reasons for the reluctance to adopt Formula (2) and Formula (7) as standard measurement methods of an international standard because it is difficult to satisfy the first and second requirements specified in 5.1. However, the values of 3D stretchability measurements calculated using the FEM simulation as in Formula (2) can be utilized for evaluating the accuracy of other measurements defined in Formula (3) and Formula (6). Similarly, the 3D stretchability in Formula (7) can be utilized for evaluation of the candidates of the measures in Formula (8) and Formula (9).

Even with the controlled stretching shown in Figure 9, the values of 3D stretchability depend on the values of the parameters such as the radius of the sphere, radius of the circular hole in the fixture guide and the maximum height. Table 1 lists twenty-one different combinations of parameters to cover the variety of three-dimensional stretching. The first column represents the parameter set number ranging from 1 to 21. For each of twenty-one cases, simulation based on FEM is carried out to determine the measures in Formula (2) and Formula (7).

The values of the parameters in Table 1 are chosen to examine the effects of each of three parameters. For example, the effects of the gap d_{gap} can be examined against the fixed values of r_{sph} and h. The parameter set numbers 7,10 and 13 can compare the effect of different gap values (5 mm, 7 mm and 10 mm) for the combination of the diameter of sphere ($2\ r_{\mathrm{sph}} = 2 \times 45 = 90$ mm) and the height ($h = 5$ mm). Similar comparisons can be made using the data from the parameter set numbers of 8, 11, and 14 as well as 9, 12, and 15. Effects of r_{sph} can be examined by the parameter set numbers 3, 6, 9, 18, 21. In these cases, d_{gap} remains 5 mm and h has 10 mm.

The values of the measures based the length ratio in Formula (3) and Formula (6) are compared with the values of the measure in Formula (2). Figure 11 illustrates the graph of the percent errors for the length ratio-based measures in Formula (3) and Formula (6).

The percent errors is calculated by Formula (10).

$$E(\%) = \frac{1}{n}\sum_{i=1}^{N}\left|\frac{M_{\mathrm{cal},i}}{M_{\mathrm{ref},i}} - 1\right| \times 100(\%) \qquad (10)$$

where

N is the number different configurations of 3D stretching. In this case, $N = 21$;

$M_{\mathrm{cal},i}$ is the value of the measures under evaluation with the i^{th} configuration;

$M_{\mathrm{ref},i}$ is the value of the reference measures with the i^{th}configuration.

When the measures in Formula (3) and Formula (6) are evaluated, the value of Formula (2) serves as the reference data. Similarly, when the measures in Formula (8) and Formula (9) are evaluated, the value of Formula (7) is utilized as the reference data.

In Figure 11, the horizontal axis represents the values of the measure in Formula (2) sorted in ascending order. When the values of the measure under evaluation are the same as those of the reference measure, the percent error has a value of 0 for all 21 cases. It can be noticed from Figure 11 that the measures in Formula (3) yield quite different values for the 21 cases of 3D stretching. However, the measure in Formula (6) generates relatively consistent values for the 21 cases. The average of percent errors for the measure defined in Formula (6) is 4,5 %.

Similarly, the values of the area ratio-based measures in Formula (8) and Formula (9) are compared with the values of the measure in Formula (7). Figure 12 illustrates the graph of the percent errors for the area ratio-based measures in Formula (8) and Formula (9). The horizontal axis represents the values of the measure in Formula (7) sorted in ascending order. Like the case of the measure defined in Formula (3), the measure in Formula (8) generates much larger errors than the measure in Formula (9). The percent errors for the measure defined in Formula (9) are an incentive to variations in the conditions of the three-dimensional stretching. However, the average of percent errors for the area ratio-based measure in Formula (9) is 62,6 %, which is much larger than that of the length ratio-based measure in Formula (6).

Table 1 – Different configurations of controlled stretching (all numbers in mm)

Parameter sets (in mm)				Length-based measures			Area-based measures		
No.	$2r_{sph}$	d_{gap}	h	Formula (2)	Formula (6)	Formula (3)	Formula (7)	Formula (9)	Formula (8)
1	25	5	5	4,99	5,35	15,91	5,06	8,16	25,00
2	25	5	7,5	10,85	11,82	26,48	11,04	18,36	42,85
3	25	5	10	18,38	20,51	39,76	18,73	32,65	66,66
4	35	5	5	3,25	3,26	10,75	3,18	4,93	16,66
5	35	5	7,5	7,12	7,25	17,29	7,01	11,11	27,27
6	35	5	10	12,16	12,68	24,83	12,05	19,75	40,00
7	45	5	5	2,17	2,18	8,13	2,13	3,30	12,50
8	45	5	7,5	4,80	4,88	12,84	4,74	7,43	20,00
9	45	5	10	8,30	8,59	18,07	8,23	13,22	28,57
10	45	7	5	1,87	1,90	8,13	1,77	2,87	12,50
11	45	7	7,5	4,16	4,25	12,84	3,96	6,46	20,00
12	45	7	10	7,22	7,49	18,07	6,90	11,49	28,57
13	45	10	5	1,50	1,57	8,13	1,45	2,36	12,50
14	45	10	7,5	3,35	3,51	12,84	3,25	5,32	20,00
15	45	10	10	5,85	6,19	18,07	5,70	9,46	28,57
16	55	5	5	1,44	1,57	6,53	1,48	2,36	10,00
17	55	5	7,5	3,25	3,51	10,21	3,33	5,32	15,78
18	55	5	10	5,70	6,19	14,21	5,85	9,46	22,22
19	65	5	5	1,16	1,18	5,46	1,07	1,77	8,33
20	65	5	7,5	2,59	2,64	8,48	2,41	4,00	13,04
21	65	5	10	4,55	4,67	11,71	4,25	7,11	18,18

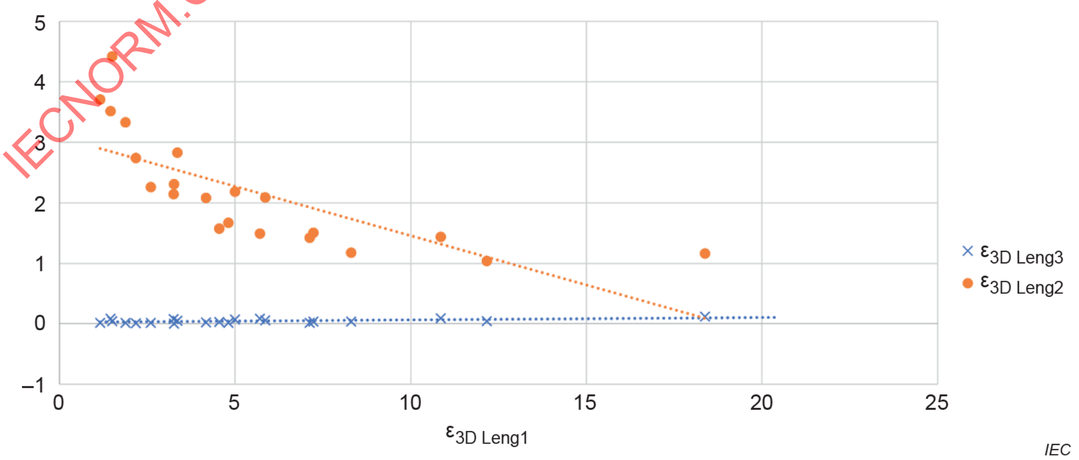

Figure 11 – Performance comparison of length ratio–based measures

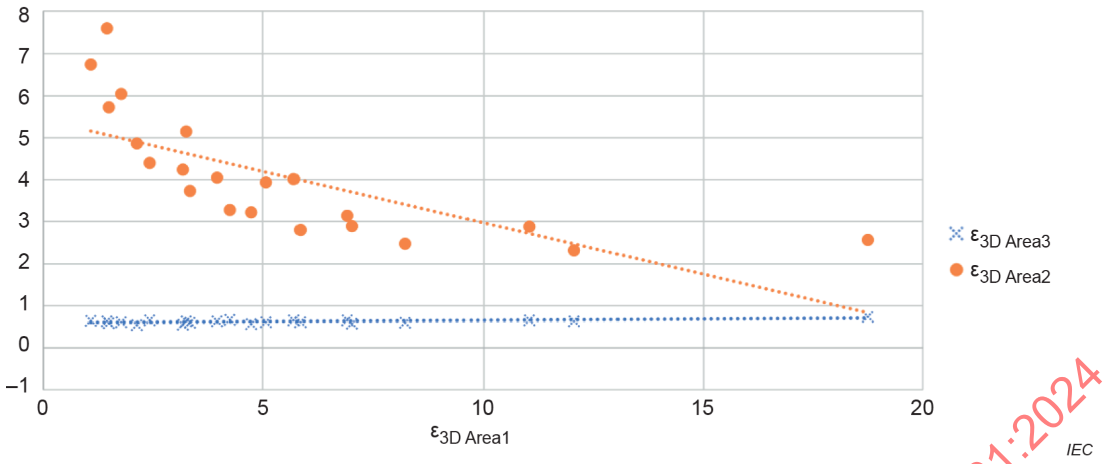

Figure 12 – Performance comparison of area ratio–based measures

5.5 Luminance and colour measurement from three-dimensional surface

The luminance and colour of emissive and reflective displays are traditionally measured over a flat measurement area (for example see IEC 62977-2-1 [11]). Similar methods are applied to transparent displays (see for example IEC TR 62977-2-5 [12]). In these measurements, at least 500 display pixels are generally required to ensure a reliable sampling of the pixelated measurement area. The flat display surface and relatively small measurement field (≤ 2°) enables the spatial average of the measurement area without the influence of the viewing direction. The viewing direction dependence of emission can be characterized separately by measuring the same measurement area at different inclination angles. When the display surface is curved, the contribution of the viewing direction will increase with larger measurement areas and smaller radius of curvatures. In IEC 62715-5-1 [10], the influence of the viewing direction was limited by measuring displays with a single radius of curvature of 35 mm or greater in a static mechanical state. It is feasible that similar limitations could be applied for 3D surfaces with multi-curvature for a given measurement area.

Photometers and colorimeters are typically designed to be focused on the display surface. Light measuring devices (LMDs) are generally adjusted for best focus along their optical axis. However, a stretchable display can change from a nominal flat surface to a 3D surface. An LMD aligned and focused on the centre of a stretchable surface will start to get increasingly out of focus when the display is stretched to its extreme convex and concave shape. Optical imaging systems have a depth of field (DOF) which defines the distance about a nominal focus position where the display is still observed as being in focus. As the measurement surface gets further away from the LMD's nominal focus plane, increasing measurement errors can occur. However, radiometric optical designs are less sensitive to focusing. In the example shown in Figure 13, a spot spectroradiometer was focused at normal incidence on a flat LCD display 45 cm away. The LCD displayed a full screen white pattern. The plot shows the luminance change over a ±5 cm object distance as the LMD is moved closer or further away from the LCD (with the LMD focus held constant). The example shows that the measured luminance for this spot LMD generally remained within 0,5 % of the luminance value at the nominal focus position. This luminance variation was within the expected stability of the LCD display. The colour variations over these object distances were also within the measurement tolerance of the LMD. Although this example shows the feasibility of using spot LMDs for luminance and colour measurements of 3D stretched displays, it is best to confirm this for any given LMD optical design and measurement configuration.