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Color-Shift Compensation for Foldable OLED Display

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Abstract:

This publication describes techniques for off-angle color-shift compensation that accommodates a user's viewing direction and use cases for devices including foldable OLED displays, particularly, foldable displays configured in an intermediate mode with a first display portion positioned in a first plane (*e.g.*, as a display) and a second display portion positioned in a second plane at an angle to the first plane (*e.g.*, as an input screen). The techniques include generating a Color Compensation lookup table (LUT) relating display input values with corresponding display output values (target color space), based on angle measurements between the first display portion and the second display portion. The Color Compensation LUT is stored on a computer-readable medium (CRM) of the device as device data. A Display Manager implemented on the CRM utilizes sensor data from sensors (*e.g.*, radar sensors, gyroscope sensors, hinge sensors) to enable off-angle color-shift compensation that compensates for a color difference between the first display portion and the second display portion.

Keywords:

color-shift compensation, organic light-emitting diode (OLED), foldable display panel, flexible OLED, flexible display, foldable smartphone, calibration, configuration, lookup table (LUT), hinge, angle, sensor

Background:

Users increasingly use mobile electronic devices as their primary computing means. As a result, consumer demand for mobile devices with larger display screens is high. To fill this demand, a new mobile device form factor is becoming popular—the foldable smartphone. Foldable smartphones have a foldable display (*e.g.*, an organic light-emitting diode (OLED) display, a flexible display) configured for use in a number of different modes, including an unfolded mode presenting a unitary screen, an intermediate mode where the foldable display is divided at a fold vertically or horizontally, and a folded mode where the foldable display folds onto itself.

In the intermediate mode, the foldable display includes a first display portion and a second display portion. The two display portions can be selectively positioned by a user relative to one another by an angle of 0° to 180° or more. This selective positioning enables a user to configure the foldable smartphone in a number of different positions within the intermediate mode. In one example configuration, the foldable smartphone has a horizontal fold enabling the device to be positioned in a configuration similar to a laptop computer, with a first display portion positioned in a first plane as a display screen and a second display portion positioned in a second plane at an angle to the first plane as an input surface (*e.g.*, virtual keyboard, touch control surface, gesture input screen). In such a configuration, the user can change the angle of the first display portion to the second display portion based on user preferences, viewing angles, and the like.

Description:

Display panels (*e.g.*, a display panel on a foldable OLED display) have a viewing angle at which the display is viewable with an acceptable visual performance. This viewing angle can be

impacted both by the position of the user's eyes relative to the displays and by the position of the first and second display portions relative to one another. For example, in Figure 1, two different positions of a user's eyes are illustrated, as are two different positions the first display portion relative to the second display portion.
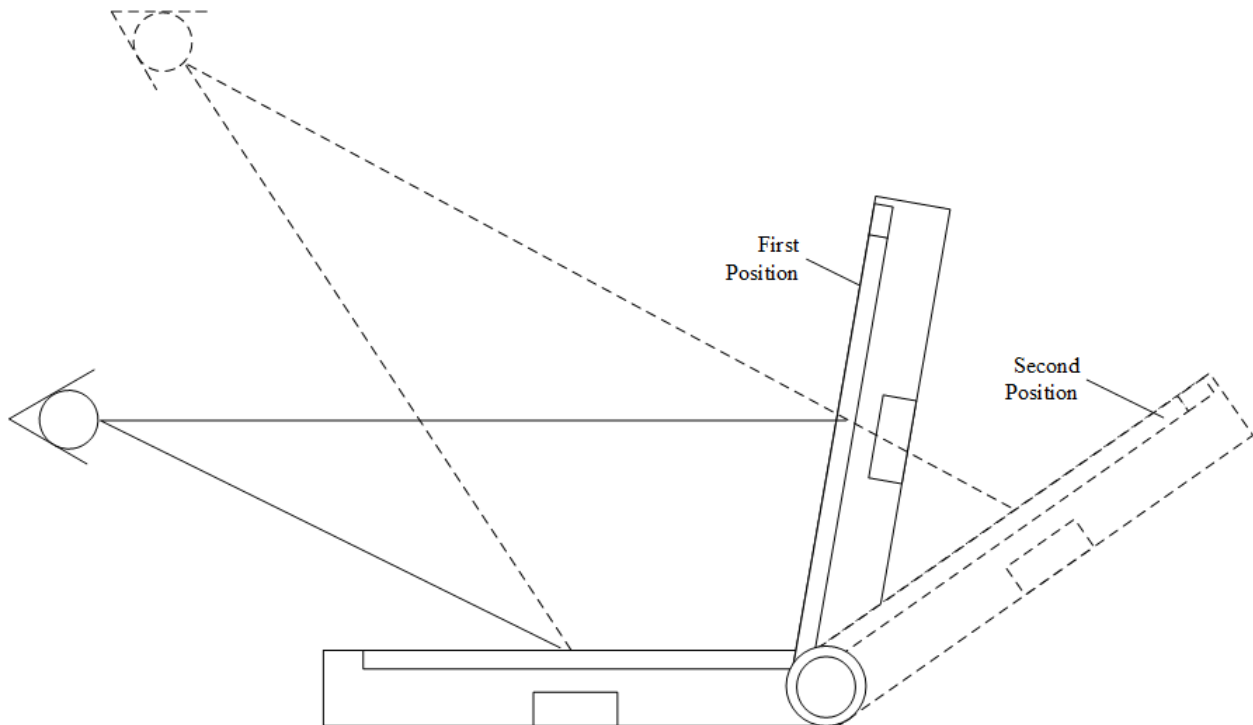

Figure 1: Viewing Angles on a Foldable Smartphone

Because human eyes are sensitive to relative color and luminance differences, when viewing a display panel at an "off-angle" relative to the viewing angle, the perceived color displayed on the display panel can vary substantially. Thus, when used in varying positions, an acceptable viewing angle of the first display portion may result in an off-angle view of the second display portion. This may result in differences (*e.g.*, color shift, luminance) in perceived colors between the two display portions, potentially causing a less-than-ideal user experience. This publication describes techniques for off-angle color-shift compensation that accommodates a user's viewing direction and use cases for foldable OLED displays.

Figure 2 is a right-side elevation view of an example foldable smartphone device configured in an intermediate mode. The device includes a foldable display mounted on an enclosure having a first body portion hingedly connected to a second body portion through a hinge connection. In such a configuration, a first display portion is located proximal to the first body portion, and a second display portion is located proximal to the second body portion, forming a first half and a second half of the device. Via the hinge connection, the first display portion (first half) can be positioned in a first plane at an angle relative to the second display portion (second half). While in Figure 2, the angle is illustrated as 120°, in other aspects, the angle may be 0° to 180° or more.

A device may include one or more sensors. In the foldable smartphone illustrated in Figure 2, the sensors include gyroscope sensors, a radar sensor (*e.g.*, ultrasound radar sensor), and a hinge sensor.
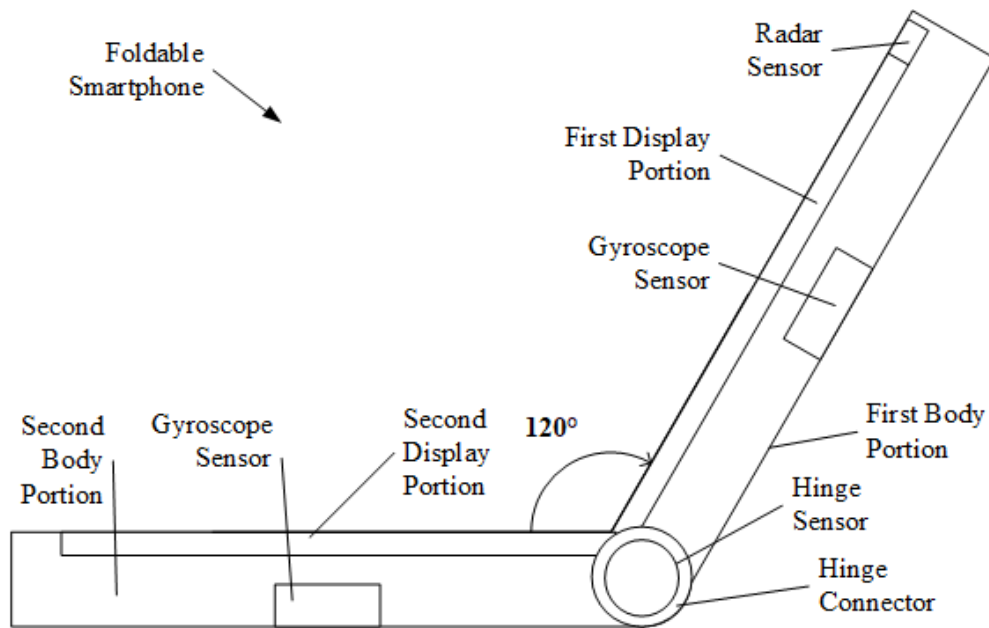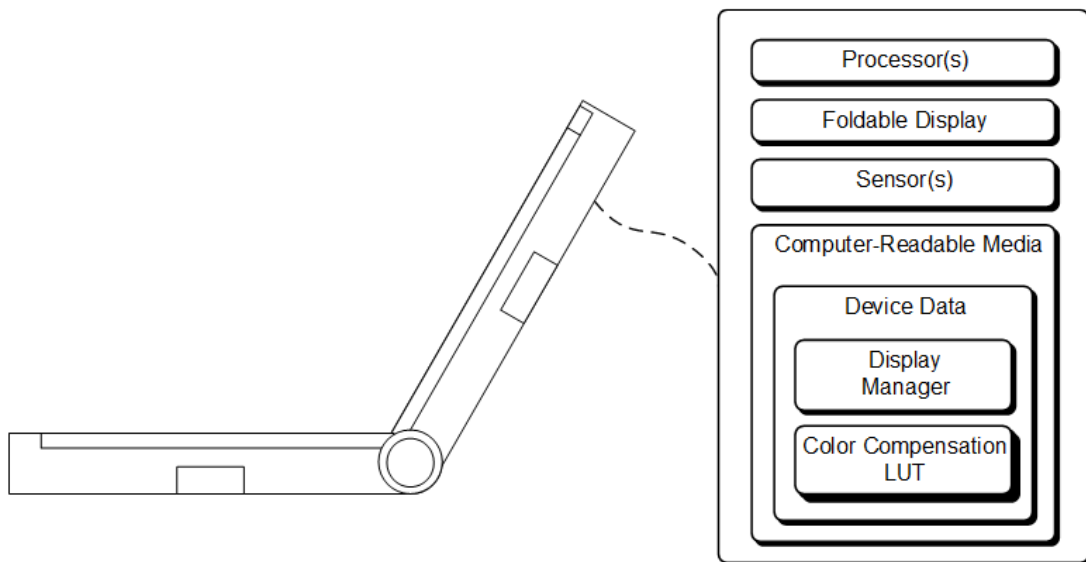

Figure 2: Foldable Smartphone in Intermediate Mode (elevation view)

Figure 3 is a schematic view illustrating the example foldable smartphone of Figure 2 and elements of the foldable smartphone that support the described techniques. The foldable

smartphone includes a processor(s), a foldable display, sensors, and a computer-readable medium (CRM) that includes device data. The device data includes user data, multimedia data, applications, and/or an operating system of the foldable smartphone, which are executable by the processor(s) to enable off-angle color-shift compensation that accommodates a user's viewing direction and use cases for foldable OLED displays.

During a panel calibration process, responsive to display input values, display output values (*e.g.*, $xyY_{(i)}$) are measured in a color space (*e.g.*, CIE xyY color space, CIE XYZ color space). In aspects, the display output values are measured at the center of the color gamut of the foldable display, for example, through the use of an optical instrument (*e.g.*, spectrometer). The measurements are made within the viewing angle (*e.g.*, perpendicular to the center of the foldable display) and at a number of off-angles (ϕ) outside of the viewing angle, for example, by tilting the optical instrument relative to the foldable display and/or tilting the foldable display relative to the optical instrument. In aspects, the off-angle (tilt) measurements are made in ±5° increments.

Figure 3: Foldable Smartphone in Intermediate Mode (schematic view)

Using the measurement data, a Color Compensation LUT relating display input values with corresponding display output values (target color space), based on angle measurements, is generated and stored on the CRM as device data. The Color Compensation LUT may be a sparse lookup table, and interpolation may be utilized. The Color Compensation LUT can be created on a per-panel basis or may be created based on a "golden" display panel.

An example Color Compensation LUT generation includes operations of:

(a) measuring, in the CIE xyY (or CIE XYZ) color space, a color response ($xyY_{(i)}$) at multiple hinge angles (ϕ) (*e.g.*, $\phi=0$, ϕ_1, ϕ_2, ϕ_3, …, $\phi_{(i)}$, …, ϕ_{max});

(b) computing the color difference ($\Delta xyY_{(i)}$) between the measured color response ($xyY_{(i)}$) and a target color response ($xyY_{(target)}$) (*e.g.*, the display output value of main display within the viewing angle of a user);

(c) converting (*e.g.*, using matrices, using a lookup table) the color difference ($\Delta xyY_{(i)}$) from the CIE xyY (or CIE XYZ) color space to corresponding RGB values ($\Delta RGB_{(i)}$); and

(d) generating a Color Compensation LUT from the RGB values ($\Delta RGB_{(i)}$).

The device data also includes executable instructions of a Display Manager that can be executed by the processor(s). The processor(s) performs operations, under the direction of the Display Manager, to enable off-angle color-shift compensation that accommodates a user's viewing direction and use cases for foldable OLED displays.

In use, the Display Manager detects that the foldable display is in an intermediate mode. For example, where the foldable smartphone has a horizontal fold enabling the device to be positioned in a configuration similar to a laptop computer, with a first display portion positioned in a first plane and a second display portion positioned in a second plane at an angle to the first

plane. In such a configuration, the first display portion is configured as a display screen and the second display portion is configured for use as an input screen (*e.g.*, virtual keyboard, touch control surface, gesture input screen). Responsive to detecting an intermediate mode use, the Display Manager may utilize the Color Compensation LUT to perform color-shift compensation that compensates for a color difference between the first display portion and the second display portion. The Display Manager may use one or more sensor inputs from one or more sensors to determine that the foldable smartphone is in the intermediate mode.

In another aspect, the Display Manager determines the type of use of one or more of the display portions when a foldable display is in an intermediate mode. For example, the Display Manager may determine that a user is operating the first display portion as a display screen, and the user is operating the second display portion as an input screen. The Display Manager may utilize one or more sensor inputs from one or more sensors to determine the type of use of one or more of the display portions. Responsive to detecting the type of use of one or more of the display portions when a foldable display is in an intermediate mode, the Display Manager may utilize the Color Compensation LUT to perform color-shift compensation that compensates for a color difference between the first display portion and the second display portion.

Figure 4 is an overall block diagram illustration of an example use case. The main block where the color-shift compensation process takes place is outlined in Figure 4 with a dashed line. In the main block, a processor (*e.g.*, graphics processing unit (GPU)) of the device receives input display data (*e.g.*, image data, video data, graphic data, on-screen display data). The GPU generates a first display output for display on a first display portion and a second display output for display on a second display portion. For example, the first display output of a user interface of a messaging application and the second display output of a virtual keyboard.
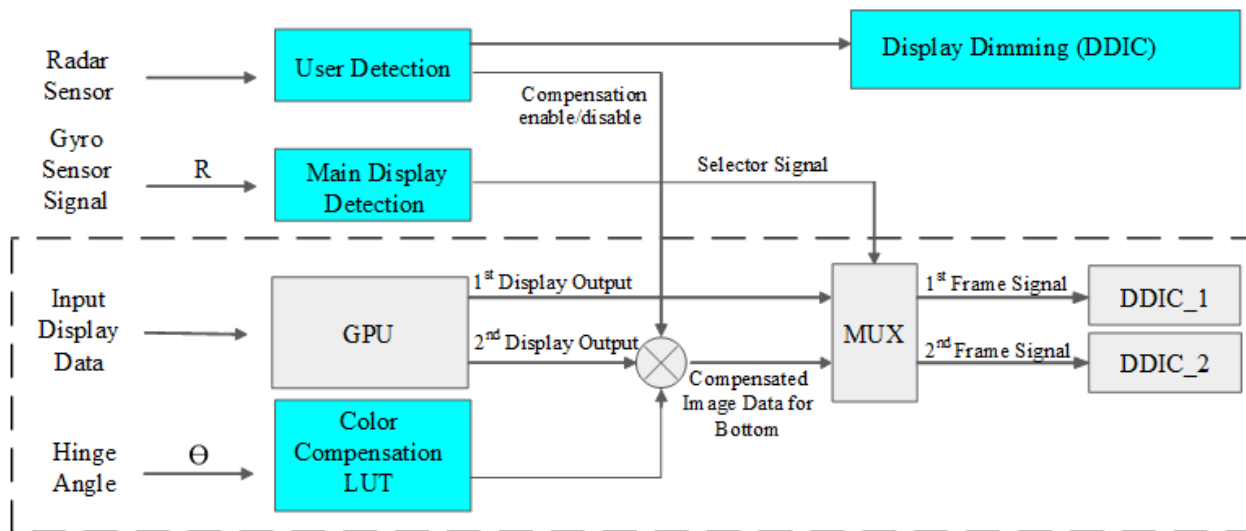
Figure 4: Overall Block Diagram Illustration of an Example Use Case.

The hinge connection includes a hinge sensor. The hinge sensor determines a hinge angle (*e.g.*, the angle between the first display portion and the second display portion) and generates hinge angle data. Examples of hinge sensors include strain gauges, mechanical hinge encoders, and electrical hinge encoders. Aspects of a foldable smartphone (*e.g.*, a Display Manager implemented on the CRM of the device) may use hinge angle data within techniques for off-angle color-shift compensation that accommodates a user's viewing direction and use cases for foldable OLED displays. The Display Manager, using the hinge angle data received from the hinge sensor and values from the Color Compensation LUT, determines a color-shift compensation (color correction) to apply. For example, using hinge angle data, a display input value corresponding to a target display output value can be selected from the Color Compensation LUT. The selected display input value determines a color-shift compensation to apply (*e.g.*, by a mixer) to a source image signal (*e.g.*, the second display output) to generate a desired output color gamut on a display portion, described as compensated image data for bottom in Figure 4.

Aspects of a foldable smartphone (*e.g.*, a Display Manager implemented on the CRM of the device) may use a gyro sensor signal (*e.g.*, x, y, z rotation angle data) from one or more

gyroscope sensors within techniques for off-angle color-shift compensation that accommodates a user's viewing direction and use cases for foldable OLED displays. For example, the gyro sensor signal can represent information indicative of a vertically-oriented first display portion and a horizontally-oriented second display portion. The device (*e.g.*, the Display Manager) can use a gyroscope sensor signal to determine which side of the foldable display is the main display and which side is the sub-display (*e.g.*, input screen), thereby determining the color-shift compensation target (here, the sub-display). In the aspect illustrated in Figure 4, a multiplexer (MUX) receives a selector signal that indicates which display is the main display. The MUX receives the first display output and generates a first frame signal for a first display driver integrated circuit (DDIC_1), and the MUX receives the second display output and generates a second frame signal for a second display driver integrated circuit (DDIC_2). DDIC_1 generates a driving signal and data for driving the first display portion, and DDIC_2 generates a driving signal and data for driving the second display portion. Alternatively, a single DDIC receives the first and second frame signals and drives both display portions.

Aspects of a foldable smartphone (*e.g.*, a Display Manager) may use radar sensor data generated by a radar sensor. Radar sensor data may indicate the presence of a user and/or a position of a user. The device (*e.g.*, used by the Display Manager) may utilize radar sensor data to determine if color-shift compensation needs to be enabled or disabled, and a compensation enable/disable signal may be sent to the mixer, as illustrated in Figure 4. For example, if a user is not detected, color-shift compensation may be disabled. The device can also use radar sensor data to trigger, via a display driver integrated circuit, the dimming of a display portion, changing the refresh rate of a display portion, turning off a display portion, and the like.

The device may also use radar sensor data to determine a viewing angle selected by the user for the primary display portion and/or the best viewing angle. For example, the device may perform viewing angle detection to compensate for users having different heights and/or a user holding the device in an atypical position. The foldable smartphone may determine, by using a radar sensor, the position and/or height of the user's head with respect to the foldable display. In use, the user's head typically forms a normal angle to the display. Knowing the hinge angle, the location of the user's head, and that a user typically adjusts the hinge angle for the best viewing angle, a viewing angle difference can be estimated. The larger the hinge angle, the smaller the viewing angle difference. Viewing angle difference is inversely-proportional to the hinge angle.

In an example operation sequence, the foldable smartphone starts in a folded (closed) state where the first and second display portions are facing one another. A user then opens the foldable smartphone. A hinge sensor determines the degree (angle) to which the first display portion and the second display portion are positioned. Gyro sensors determine the positioning of the device (*e.g.*, that the device is held in an intermediate mode with the first display portion positioned in a first plane as a display screen and a second display portion positioned in a second plane at an angle to the first plane as an input surface). A radar sensor then determines the presence and position of a user.

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