Dynamic grass color scale display technique based on grass length for green landscape-friendly animation display

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Public displays, such as liquid crystal displays (LCDs), are often used in urban green spaces. However, these display devices often tarnish the green landscape of urban green spaces due to their artificial materials. We previously proposed a green landscape-friendly grass animation display that dynamically controls the grass color pixel by pixel. The grass color is changed by moving a green grass length in yellow grass, and the grass animation display runs simple animations using grayscale images. In our previous study, the color scale is subjectively mapped to the green grass length. However, this method fails to display the grass colors corresponding to the color scale based on objective evaluations. Herein, we introduce a dynamic grass color scale display technique based on the grass length. We develop a grass color scale setting procedure to map the grass length to the five-level color scale through image processing. In the outdoor experiment of the grass color scale setting procedure, the color scale corresponds to the green grass length based on a viewpoint. Finally, we demonstrate a grass animation display to show the animations with the color scale using experimental results.

Technologies of smart cities have been researched and developed for multiple fields¹, and one of the missions of smart cities is to provide people with more opportunities to access information and improve the convenience of their community. Recently, public displays usually work in outdoor public spaces and can contribute to creating an environment that provides useful information to people easily². Liquid crystal displays (LCDs) and projectors are often used as public displays because they can show stable high-resolution animations and can be installed outdoor easily. An animation function allows public displays to provide multiple information quickly to people. In addition, people can interact with public displays using the animation function. In recent years, the effect of interactions between people and public displays has attracted much more attention, and intuitive interaction design in public spaces was discussed³. Numerous researchers and developers have explored the use of public displays in multiple scenarios, such as transportation⁴⁵, shopping⁶, public facilities⁷⁸, sports⁹¹⁰¹¹, and health¹²¹³. Public displays have also been used in urban green spaces. For example, the digital signage displays in the Manchester Science Park provide users with information such as a map and event schedules¹⁴. Moreover, an art projection mapping was created in Sosei river park using some projectors¹⁵. However, current public display devices can spoil green landscapes of urban green spaces, as most of the display devices resemble artificial materials². Numerous researchers revealed that green landscapes have a positive impact on human well-being and health¹⁶¹⁷¹⁸. Thus, green landscapes of urban green spaces must be preserved to enhance comfort in people's lives. Therefore, urban green spaces require a living environment-friendly display method to preserve their green landscapes.

Numerous researchers and artists have explored multiple living environment-friendly display methods using natural materials such as foodstuffs¹⁹, wet ground²⁰, a fur carpet²¹, and rice paddy²². In particular, displaying images using grass has been studied as a green landscape-friendly display. All current grass display methods can show a static image. Sugiura et al. proposed a print device to draw a binary static image on a grass surface using anisotropic reflection²³. The print device has multiple servo motor rods to raise or flatten the grass blades. Consequently, the grass surface can be brighter or darker pixel by pixel. There is a commercial grass service to print a static image on a large grass field, such as a soccer field²⁴. Because the direction of the grass blades can

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be adjusted by air pressure to change the grass brightness, the large static image can be displayed on the grass surface using a vehicle with an air pressure system. Scheible et al. developed a drone-aided system to create a large grass artwork. An artist can mow the grass to generate the artwork through a bird’s eye view provided by several drones. In art fields, Ackroyd & Harvey created an artwork that shows photography on the grass surface. The grass surface is exposed to light projected from a negative image of the photography throughout the grass growth. Consequently, as the grass grows, the grass color is generated to show the photography. These grass methods can show the static images in the urban green spaces to preserve the green landscapes. However, these grass methods cannot display animations, as it is difficult to dynamically change the grass color. A shape-changing-grass system is required to solve this problem. There are several smart material interfaces to bend artificial grass blades automatically actuated by shape memory alloys. However, these methods do not focus on displaying animations on the grass surface. Therefore, we focus on the smart city technology of a grass animation display system to show animations while it preserves the green landscape of the urban green spaces. For example, a landscape-friendly weather forecast application can be realized by applying the grass animation display as shown in Fig. 1.

We previously proposed a green landscape-friendly display method that realizes animations on a grass surface by dynamically controlling grass length. This method focused on a grass color consisting dying yellow grass and lively green grass in the real world. The length of the yellow grass is fixed, whereas the green grass length increases with time. Thus, multiple grass colors are generated depending on the green grass length. We designed a grass system to move artificial green grass length in artificial yellow grass using a linear actuator system pixel by pixel. The grass system was named a grass pixel. Thus, a grass animation display can be constructed by using multiple grass pixels, and the animations can be directly displayed on the grass surface without a displaying device, such as an LCD or a projector. In previous research, we developed the grass pixel with artificial yellow and green grass using a linear actuator system to control the green grass length. We also conducted a simple experiment to evaluate the grass color change of the grass pixel through image processing. Consequently, we confirmed that the grass color of the grass pixel can simply be changed from yellow to green while increasing the green grass length. Moreover, a $3 \times 3$ pixels grass animation display was created using nine grass pixels and demonstrated in several simple animations. $3 \times 3$ grayscale images were used to play the animations on the grass animation display. Because the grass color can be changed based on the green grass length, the color scale of the grayscale images was subjectively mapped to the green grass length in the demonstrations. However, we did not realize a grass color scale setting procedure to map the color scale to the green grass length based on objective evaluations.

In this paper, we introduce a dynamic grass color scale display technique based on grass length for a green landscape-friendly animation display. Figure 2 illustrates the concept of our proposed method. We focus on a grass color scale system that allows the animations to be played on the grass animation display, as shown in Fig. 2a. In the grass color scale system, the color scale of the input grayscale images is mapped to the green grass
length. The grass colors based on the green grass length corresponding to the color scale must be evenly separated to ensure clear animations. We develop a grass color scale setting procedure to map the grass length to the color scale through image processing, as shown in Fig. 2b. The grass color scale setting procedure provides the green grass length for each level of the color scale using the grass colors of the grass pixel measured by a digital camera at regular green grass length intervals. In the setting procedure, the CIE 1976 $L^*a^*b^*$ (CIELAB) color space and the color difference formula of CIEDE2000 are adopted to evaluate the grass color. To avoid an effect of a unique camera maker’s image processing engine, the grass color is captured as a raw image and measured in the CIELAB color space through the sRGB color space. The measured value is referred to as a measured grass color value. The measured grass colors suitable for the color scale are obtained by comparing the measured grass color values with target grass color values, which are CIELAB values of reference grass colors corresponding to the color scale. The target grass color values corresponding to minimum and maximum levels of the color scale are the measured grass color values when the green grass lengths are minimum and maximum, respectively. Then, other target color values are calculated as CIELAB values that equally divide the color difference of the CIEDE2000 between the target grass color values corresponding to the minimum and maximum levels of the color scale. Further, each target grass color value has a color tolerance. When each color tolerance includes the measured grass color value closest to each target grass color value, the measured grass pixel is considered to be capable of displaying the grass colors corresponding to the color scale. Therefore, the color scale can be mapped to the green grass length using the measured grass colors corresponding to the color scale. Then, the grass animation display can show the animation clearly by reflecting the results of the grass color scale setting procedure in the grass color scale system.

To achieve a simple grass color scale for the grass animation display, we focus on the grass pixel that show the grass color corresponding to a color scale of five levels with reference to the color scale of retro games. We conducted experiments with the grass color scale setting procedure in natural sunlight from 10:00 a.m. to 2:00 p.m., developing a grass pixel for our outdoor experiments. The green grass length was changed from 0.00 to 15.00 [mm], and the grass color of the grass pixel was measured at regular intervals of 0.75 [mm]. Moreover, the experiments were conducted at multiple camera positions focusing on a viewer’s height, a distance, and a horizontal angle between the viewer and the grass pixel. Through the experiments, the grass pixel possibilities of the color scale are clarified, such that the color scale corresponds to the green grass length for each camera position. In addition, we conducted experiments focusing on the repeatability and reliability of the grass pixel. In the experiments, we revealed that the grass pixel could show the same grass color to several camera positions when the same grass length was repeatedly inputted in natural sunlight from 10:00 a.m. to 2:00 p.m. After the
experiments, we demonstrated several animations using the results of our grass color scale experiments. In the demonstrations, a $3 \times 3$ pixels grass animation display is built using nine grass pixels, then, four animations are shown on the animation grass display using $3 \times 3$ pixels grayscale images with the color scale of five levels.

**Results and discussion**

**Grass pixel design.** Figure 3 shows an overview of a grass pixel design. The grass pixel system is developed based on a linear actuator system and can display multiple grass colors by dynamically moving the green grass length. As shown in Fig. 3a, the grass pixel consists of artificial green grass, artificial yellow grass, a surface plate, a linear guide plate, a limit switch plate, a three-dimensional (3D) printed pin, a coupling and, a motor. The motor is connected to the lead screw using the coupling, and the lead screw is jointed to the 3D printed pin. Then, the 3D printed pin with the linear guide plate can be moved vertically while the motor rotates the lead screw. The limit switch plate has a limit switch to set the home position of the 3D printed pin. The green grass is planted on the top surface of the 3D printed pin. As shown in Fig. 3b, the yellow grass is planted on the surface plate that has slits to move the green grass in and out the yellow grass as if lively green grass grows between the gaps of the dying yellow grass. Therefore, the green grass length can be changed by moving the 3D printed pin. The detailed grass pixel hardware for our experiment is described in the next subsection of the grass color scale experiments.

As shown in Fig. 3c, the grass pixel shows multiple grass colors according to the green grass length through spatial additive mixing, which is a type of additive color mixing. When light is incident on the grass pixel, green and yellow reflected lights based on the grass color are sent to the viewer. Then, the viewer recognizes an intermediate color between green and yellow when the viewer is at a distance too far away from the grass pixel to distinguish between the yellow and green grass. Moreover, the quantities of the green and yellow reflected lights can be changed according to the area ratio of the green to yellow grass. The area ratio can be changed based on the green grass length, therefore, the viewer observes multiple grass colors of the grass pixel through spatial additive mixing.

**Grass color scale setting procedure of grass pixel.** Figure 4 illustrates an overview of the grass color scale setting procedure of the grass pixel. Herein, a color scale with five levels is mapped to the green grass length of the grass pixel through the grass color scale setting procedure. In the setting procedure, the grass colors of the grass pixel are measured in the CIELAB color space, which is defined by International Commission on Illumination (CIE). $L^*, a^*$, and $b^*$ represent lightness, complementary colors of red ($+a^*$) and green ($-a^*$), and complementary colors of yellow ($+b^*$) and blue ($-b^*$), respectively. When a color is compared with another

![Figure 3. Design of grass pixel system. (a) A grass pixel is developed using a linear actuator system operated by a motor. Artificial green and yellow grass is planted on a top surface of a 3D printed pin and a surface plate, respectively. (b) The surface plate has slits to move the artificial green grass in and out of the artificial yellow grass. (c) The grass pixel displays multiple grass colors based on an area ratio of the artificial green and yellow grass through spatial additive mixing. This figure was created using Autodesk 3ds Max version 2021 (https://www.autodesk.com/products/3ds-max/features) and Serif Affinity Designer version 1.10.0 (https://affinity.serif.com/en-us/).](https://www.nature.com/scientificreports/)
color, the color difference usually represents a Euclidean distance. However, many color spaces, including HSV (Hue, Saturation, and Value of Brightness) color space, have the problem of differences in the perceived sense depending on the location of the color, even at the same color difference. In other words, the color difference that people perceive as different is expressed at different distances depending on the location of the color. In contrast, the CIELAB color space had been designed so that the same color difference provides the same perceptual difference at any color position. A color difference using a Euclidean distance between two CIELAB values $\Delta E_{ab}^*$ had been defined as CIE76 in 1976 and is displayed below:

$$\Delta E_{ab}^* = \sqrt{(L_2 - L_1)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2}$$

(1)

where $(L_1^*, a_1^*, b_1^*)$ and $(L_2^*, a_2^*, b_2^*)$ are example CIELAB values.

However, it was found that there was a difference between $\Delta E_{ab}^*$ and visual evaluation by humans, especially at the location of color with large saturation. Thus, in 2001, CIE published an alternative color difference formula called CIEDE2000 $\Delta E_{00}^*$ according to human perception. $\Delta E_{00}^*$ can be calculated based on lightness difference, saturation difference, and hue difference, and can be corrected with weighing coefficients $(S_L, S_C, S_H)$ and constants called parametric coefficients $(k_L, k_C, k_H)$. Sharma et al. presented the color difference of $\Delta E_{00}^*$ between two example CIELAB values $(L_1^*, a_1^*, b_1^*)$ and $(L_2^*, a_2^*, b_2^*)$ as below:

$$\Delta E_{00}^* = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \frac{\Delta C'}{k_C S_C} \frac{\Delta H'}{k_H S_H}}$$

(2)

where $k_L, k_C,$ and $k_H$ are determined depending on measurement conditions, however, all of the parameters are set to 1 on the standard conditions specified for CIEDE2000. $\Delta L', \Delta C', \text{ and } \Delta H'$ can be calculated using the differences of lightness, saturation, and hue, respectively as below:

$$\Delta L' = L_2^* - L_1^*$$

(3)

$$\Delta C' = C_2^* - C_1^*$$

(4)

$$\Delta H' = 2 \sqrt{C_1^* C_2^*} \sin \left(\frac{\Delta h'}{2}\right)$$

(5)

where

$$C_i^* = \sqrt{a_i^* + b_i^*} \quad (i = 1, 2)$$

(6)

$$a_i^* = (1 + G)a_i^* \quad (i = 1, 2)$$

(7)

$$G = 0.5 \left(1 - \frac{C_{ab}^*}{\sqrt{C_{ab}^* + 25^*}}\right)$$

(8)

$$C_{ab}^* = \frac{C_{ab}^* + C_{ab}^*}{2}$$

(9)

$$C_{ab}^* = \sqrt{(a_i^*)^2 + (b_i^*)^2} \quad (i = 1, 2)$$

(10)

$$\Delta h' = \begin{cases} 0 & (C_1^* C_2^* = 0) \\ \left|h_2^* - h_1^*\right| & (C_1^* C_2^* \neq 0 \quad \left|h_2^* - h_1^*\right| \leq 180^\circ) \\ \left|h_2^* - h_1^*\right| - 360^\circ & (C_1^* C_2^* \neq 0 \quad \left|h_2^* - h_1^*\right| > 180^\circ) \\ \left|h_2^* - h_1^*\right| + 360^\circ & (C_1^* C_2^* \neq 0 \quad \left|h_2^* - h_1^*\right| < -180^\circ) \end{cases}$$

(11)

$$h_i^* = \begin{cases} 0 & (b_i^* = a_i^* = 0) \\ \tan^{-1}(b_i^*, a_i^*) & (\text{otherwise}) \quad (i = 1, 2) \end{cases}$$

(12)

In addition, the weighing coefficients $(S_L, S_C, S_H)$ and the rotation factor $R_T$ are determined as below:

$$S_L = 1 + 0.015 (L' - 50)^2$$

$$\sqrt{20 + (L' - 50)^2}$$

(13)

$$S_C = 1 + 0.045 \hat{C}$$

(14)
\[ S_H = 1 + 0.015 \tilde{C}'T \]

\[ R_T = -\sin(2\Delta \theta)R_C \]

where

\[ \tilde{L}' = \frac{L_1' + L_2'}{2} \]

\[ \tilde{C}' = \frac{(C_1' + C_2')}{2} \]

\[
\tilde{h}' = \begin{cases} 
\frac{h_1' + h_2'}{2} & (|h_1' - h_2'| \leq 180^\circ, C_1'C_2' \neq 0) \\
\frac{h_1' + h_2' + 360^\circ}{2} & (|h_1' - h_2'| > 180^\circ, (h_1' + h_2') < 360^\circ, C_1'C_2' \neq 0) \\
\frac{h_1' + h_2' - 360^\circ}{2} & (|h_1' - h_2'| > 180^\circ, (h_1' + h_2') \geq 360^\circ, C_1'C_2' \neq 0) \\
(h_1' + h_2') & (C_1'C_2' = 0)
\end{cases}
\]

\[ T = 1 - 0.17 \cos(\tilde{h}' - 30^\circ) + 0.24 \cos(2\tilde{h}') + 0.32 \cos(3\tilde{h}' + 6^\circ) - 0.20 \cos(4\tilde{h}' - 63^\circ) \]

\[ \Delta \theta = 30 \exp \left\{ - \left[ \frac{\tilde{h}' - 275^\circ}{25} \right]^2 \right\} \]

\[ R_C = 2 \sqrt{\frac{\tilde{C}'}{\tilde{C}' + 25}} \]

In this paper, we adopted the color difference of CIEDE2000 to compare two CIELAB values of the grass colors and described the color difference as below.

\[ \Delta E_{00}^* \left( (L_1^*, a_1^*, b_1^*), (L_2^*, a_2^*, b_2^*) \right) \]

where \((L_1^*, a_1^*, b_1^*)\) and \((L_2^*, a_2^*, b_2^*)\) are two example CIELAB values of the grass colors. In addition, \(k_1, k_C,\) and \(k_H\) were set to 1 because the grass color of the grass pixel was measured under natural sunlight between 10:00 a.m. and 2:00 p.m.

Figure 4a shows a measurement of the grass color of the grass pixel through image processing. The measurement is conducted outdoors between 10:00 a.m. to 2:00 p.m., because Sato et al. described natural sunlight at this period as suitable for evaluating colors. A digital camera is used to capture the grass color taken by the digital camera, it is necessary to capture a camera device-independent image and correct the RGB value of the recorded image for changes in a color temperature of natural sunlight. First, the digital camera captures a raw image of the grass pixel to avoid the effect of the camera maker’s unique image processing engine. Then, the raw image is developed in the sRGB (standard–RGB) color space, which is a camera device-independent RGB color space. Second, the RGB color correction of the developed image is performed using a color checker, which is a color calibration material consisting of multiple painted samples. When the digital camera captures the grass pixel, the color checker installed near the grass pixel is also captured. Then, after developing the raw image, the RGB value of the developed image is corrected toward a reference image through the color checker. In the grass color scale setting procedure, the developed image when the green grass length is minimum is set as the color correction reference image. In other words, the RGB correction allows the color temperatures of the other developed images to be corrected to the color temperature when the green grass length is minimum for each camera position. Finally, an original image is created from the raw image through the sRGB development and the RGB color correction. The original image is independent of the camera device and takes into account natural sunlight changes. Because a calculation area focusing on the grass pixel surface must be decided to measure the grass color, the original image is cropped to create a square evaluation image, which contains only the part of the grass pixel surface. The evaluation image is used to calculate the grass color value in the CIELAB color space. The average RGB value of the evaluation image is calculated and converted to the CIELAB value via the CIE 1931 XYZ color space. Therefore, the grass color of the grass pixel can be measured in the CIELAB color space, and the CIELAB value of the grass color is referred to as the measured grass color value.

The grass colors of the grass pixel are measured at regular green grass length intervals from minimum to maximum through image processing. Subsequently, a reference grass color value corresponding to the color scale is calculated using the measured grass color values. In this paper, we defined the reference grass color value as a target grass color value \(G_n (L_n^*, a_n^*, b_n^*)\). In this case, \(n\) represents a level of the color scale \((n = 0, 1, 2, 3, 4)\). As shown in Fig. 4b, both ends of the target grass color values \(G_0\) and \(G_4\) are the measured grass color values when the green grass lengths are minimum and maximum, respectively. \(G_1, G_2,\) and \(G_3\) are obtained from the CIELAB values on the line segment between \(G_0\) and \(G_4\). Then, let \(P(t)\) be the CIELAB value on the line segment between \(G_0) and \(G_4\) as below.
Figure 4. Overview of grass color scale setting procedure. (a) The grass color of a grass pixel is measured as a CIELAB value through image processing. (b) Measured grass color values are compared with target grass color values to map the grass length of the grass pixel to a color scale with five levels. (c) To calculate the target grass color value, \( t_n \) suitable for \( G_n \) is determined so that \( \Delta E^*_{00}(G_0, P(t_n)) \) is \( (n/4) \cdot \Delta E^*_{00}(G_0, G_4) \). This figure was created using Serif Affinity Designer version 1.10.0 (https://affinity.serif.com/en-us/).

\[
P(t) = (L^*(t), a^*(t), b^*(t)) \quad (0 \leq t \leq 1)
\]

(24)
\[ L^*(t) = (L_m^* - L_0^*) + L_0^* \]  \hspace{1cm} (25)

\[ a^*(t) = (a_m^* - a_0^*) + a_0^* \quad (0 \leq t \leq 1) \]  \hspace{1cm} (26)

\[ b^*(t) = (b_m^* - b_0^*) + b_0^* \]  \hspace{1cm} (27)

t represents a variable for which \( P(t) \) is the CIELAB value on the line segment between \( G_0 \) and \( G_4 \) and has a definition range from 0 to 1. \((L_m^*, a_m^*, b_m^*)\) and \((L_0^*, a_0^*, b_0^*)\) are the target grass color values \( G_0 \) and \( G_4 \), respectively. To obtain the suitable \( G_n \), it is needed to calculate \( t \) to maintain color differences between neighboring \( G_n \) constant.

Figure 4c shows how to determine \( t \) for \( G_n \). This graph of Fig. 4c represents the function of the color difference \( \Delta E^n_{00}(G_0, P(t)) \) with respect to \( t \). Since \( P(t) \) gets closer to \( G_4 \) from \( G_0 \) when \( t \) increases, \( \Delta E^n_{00}(G_0, P(t)) \) rises from 0 to \( \Delta E^n_{00}(G_0, G_4) \). \( t \) suitable for \( G_n \) can be uniquely obtained when \( \Delta E^n_{00}(G_0, P(t)) \) simply increases in the range of \( 0 \leq t \leq 1 \). However, \( \Delta E^n_{00}(G_0, P(t)) \) is nonlinear with respect to \( t \) because the color difference of CIEDE2000 is not linear with respect to a Euclidean distance in the CIELAB color space. Therefore, \( \Delta E^n_{00}(G_0, P(t)) \) is required as below to clarify whether \( \Delta E^n_{00}(G_0, P(t)) \) can increase simply. When the condition below is satisfied, \( t \) suitable for \( G_n \) can be uniquely calculated.

\[ \frac{d}{dt} \Delta E^n_{00}(G_0, P(t)) > 0 \quad (0 \leq t \leq 1) \]  \hspace{1cm} (28)

Herein, let \( t_n \) be the unique and suitable \( t \) for \( G_n \). To maintain the color differences between neighboring \( G_n \) constant, \( t_n \) and the CIELAB values of \( G_n \) can be obtained as below. In addition, the determination of \( t_n \) is also shown in Fig. 4c.

\[ \Delta E^n_{00}(G_0, P(t_n)) = \frac{n}{4} \Delta E^n_{00}(G_0, G_4) \quad (n = 0, 1, 2, 3, 4) \]  \hspace{1cm} (29)

\[ G_n = P(t_n) = (L_n(t_n), a^*(t_n), b^*(t_n)) \quad (n = 0, 1, 2, 3) \]  \hspace{1cm} (30)

Figure 4b shows how to map the color scale to the green grass length of the grass pixel. \( G_1, G_2, \), and \( G_3 \) have a color tolerance that is a range of the certain color difference centered at each target grass color value as shown by blue ellipses in Fig. 4b. When a measured grass color value is within a color tolerance, the measured and target grass colors are considered to be almost the same color. In the grass color scale setting procedure, we adopted the category of the color tolerance created by ANSI and Committee for Graphic Arts Technologies Standards (CGATS)\(^2\). The color tolerance category is called CGATS TR 016-2014 and describes several levels of the color tolerance based on CIEDE2000. In the procedure, to compare the target grass color value with the measured grass color value on an industrial-level color standard, the color tolerance of \( G_1, G_2, \) and \( G_3 \) is set to the color tolerance of 3.0 which focuses on color-critical applications, e.g., commercial printing. In this case, the target grass color value must not be included in other color tolerances to distinguish the target grass colors, then, the color difference between \( G_0 \) and \( G_4 \) must be higher than 12. To reveal whether the measured grass color value is within the color tolerance, the color difference \( \Delta E^n_{00,n} \) between the measured grass color value and \( G_n \) is needed. The equation of \( \Delta E^n_{00,n} \) is displayed below.

\[ \Delta E^n_{00,n} = \Delta E^n_{00}(G_n, (L_m^*, a_m^*, b_m^*)) \quad (n = 1, 2, 3) \]  \hspace{1cm} (31)

where \((L_m^*, a_m^*, b_m^*)\) is the measured grass color value. Then, \( \Delta E^n_{00,1}, \Delta E^n_{00,2}, \) and \( \Delta E^n_{00,3} \) are calculated and compared with the color tolerance of 3.0. When the \( \Delta E^n_{00,n} \) of the measured grass color value is smaller than this color tolerance, the measured grass color value can be almost the same color as \( G_n \). Therefore, the grass pixel is regarded as displaying the grass colors corresponding to the color scale by adopting each grass length whose \( \Delta E^n_{00,n} \) is smaller than the color tolerance. In addition, the green grass length can likewise be mapped to the color scale. The detailed experimental environment of the grass color scale setting procedure is described in the next subsection of the grass color scale experiments.

**Grass color scale experiments.** Experimental environment. We conducted an evaluation experiment to map the color scale to the green grass length using the grass color scale setting procedure. Figure 5a shows our experimental environment based on multiple camera positions. We used a digital camera, Nikon D7000 (resolution: 16.9 [MP]), with a single focus lens (AF-S DX NIKKOR 35 mm f/1.8G, focal length: 35 [mm], maximum aperture: f/1.8). The camera’s aperture (f/4.0), shutter speed (1/640), and International Organization for Standardization speed (ISO100) were fixed. In addition, a color checker (Datacolor Spyder CHECKER 24) was installed near the grass pixel to correct the RGB value of the captured image. The experiment was conducted on the playground of the University of Tsukuba in natural sunlight from 10:00 a.m. to 2:00 p.m. As shown in Fig. 5a, \( h, d, \) and \( \theta \) represent the camera height from the grass pixel surface, the distance between the grass pixel and the digital camera, and the horizontal angle between them, respectively. Because the viewers are assumed to be an adult and a child, \( h \) was set to 1.2, 1.6, and 1.7 [m]. \( d \) was set to 1.0, 2.0, and 3.0 [m] as a distance to observe the grass color of the grass pixel. \( \theta \) was set to 0°, 30°, 60°, and 90° around the center of the grass pixel. Furthermore, when \( \theta \) was 0° and 90°, the digital camera was perpendicular and parallel to the slits of the grass pixel, respectively. Figure 5b shows the grass pixel configuration in our grass color scale experiment. The surface
The area of the grass pixel was 24 × 24 [mm], and the slit width of the yellow grass surface was 5.4 [mm]. The artificial yellow grass length was 10.00 [mm], and the artificial green grass length could be varied from 0.00 to 15.00 [mm]. The grass pixel in our experiment consisted of a stepper motor (SM-42BYG011-25, 200 [step/rotation]), a lead screw with a coupling (length: 100.0 [mm], pitch: 6.0 [mm], lead: 6.0 [mm]), a 3D printed pin (dimension: 24 × 24 × 70 [mm]), and a limit switch. Moreover, a limit switch plate, a guide plate, and a surface plate were created by a laser cutting device and a 3D printing device. The grass pixel was operated by a microcontroller (Teensy 3.5) via a stepper motor driver (DRV8825). The grass color of the grass pixel was measured for each camera position while moving the grass length at 0.75 [mm] intervals from 0.00 to 15.00 [mm], as shown in Fig. 5c. Then, the color scale was mapped to the green grass length using the measured grass color values for each camera position through the grass color scale setting procedure.

**Experimental results.** As a result, the grass pixel is regarded as displaying the grass colors corresponding to the color scale, and the green grass length was mapped to the color scale at 30 camera positions out of 36. In these experiments, since $\frac{d}{dt}E_0^*(G_0, P(t))$ were positive in the range of $0 \leq t \leq 1$ in all camera positions, $G_1$, $G_2$, and $G_3$ can be uniquely obtained for each camera position, respectively. For example, Fig. 6 shows $\frac{d}{dt}E_0^*(G_0, P(t))$ at $(h, d, \theta) = (1.2, 1.0, 0), (1.2, 3.0, 0)$. Since both results of $\frac{d}{dt}E_0^*(G_0, P(t))$ were positive even though these results decreased in the range of $0 \leq t \leq 1$, $G_1$, $G_2$, and $G_3$ can be uniquely obtained at $(h, d, \theta) = (1.2, 1.0, 0), (1.2, 3.0, 0)$. Figure 7 shows examples of the experimental results. These examples illustrate the number of measured grass
color values included within the color tolerance of $G_1$, $G_2$, and $G_3$ out of 21 measured grass color values, respectively. In other words, the number represents the number of the grass length of the grass pixel corresponding to each level of the color scale. When this number is greater than or equal to 1 for each of $n = 1, 2, 3$, the color scale with five levels can be mapped to the green grass length of the grass pixel. In addition, as examples of results of mapping the measured grass colors of the grass pixel to the color scale, Fig. 7 also shows the color difference of $\Delta E^*_0$, the grass lengths and the images of the grass pixel based on the measured grass color values closest to $G_1$, $G_2$, and $G_3$, respectively. In this case, the color differences of $\Delta E^*_0$, $\Delta E^*_0$, and $\Delta E^*_0$ are minimal. Furthermore, Fig. 7 shows plotted measured and target grass color values in the CIELAB color space. Each dot marks the measured grass color value and represents the measured grass color. Each cross mark is the target grass color value and represents the target grass color. The blue ellipsoid centered on the cross mark represents the color tolerance of 3.0.

Figure 7 shows an example of the successful experimental result when $(h, d, \theta) = (1.2, 1.0, 0)$. In this result, the minima of $\Delta E^*_0$, $\Delta E^*_0$, and $\Delta E^*_0$ were within the color tolerances of $G_1$, $G_2$, and $G_3$, respectively. Number of the measured grass color values included in the color tolerance of $G_1$, $G_2$, and $G_3$ were 5, 5, and 6, respectively. When the measured grass color values based on the minima of $\Delta E^*_0$, $\Delta E^*_0$, and $\Delta E^*_0$ are adopted, the green grass lengths corresponding to the color scale can be 0.00, 5.25, 8.25, 10.50, and 15.00 [mm] in the order of the color scale. As shown in Fig. 7, the result at $(h, d, \theta) = (1.2, 3.0, 0)$ was likewise successful. Number of the

![Figure 7](https://affinity.serif.com/en-us/) and Matplotlib version 3.2.2 (https://matplotlib.org).
measured grass color values included in the color tolerance of \(G_1\), \(G_2\), and \(G_3\) were 2, 2, and 3, respectively. In addition, the green grass lengths can be 0.00, 6.00, 8.25, 12.00, and 15.00 [mm] in the order of the color scale when the measured grass color values based on the minima of \(\Delta E_{1980}^{*}\), \(\Delta E_{1990}^{*}\) and \(\Delta E_{2000}^{*}\) are used. Moreover, the plotted images show that some measured grass color values are within the color tolerances as shown in Fig. 7a and b.

Figure 8c shows the experimental results when \(\theta\) was 60° and 90°, then the trajectory of the measured grass color values at \(\theta = 60°\) and 90° was more curved than at \(\theta = 0°\) and 30°. For example, as shown in Fig. 7b and c, the plotted results at \((h, d, \theta) = (1.2, 3.0, 90)\) were more curved than at \((h, d, \theta) = (1.2, 3.0, 0)\).


The green grass lengths can be 0.00, 6.00, 8.25, 12.00, and 15.00 [mm] in the order of the color scale when the digital camera and the grass pixel were at short distances to each other. For example, shown as in Fig. 7a and b, the dot colors at \((h, d, \theta) = (1.2, 1.0, 0)\) were darker than at \((h, d, \theta) = (1.2, 3.0, 0)\).

When \(\theta = 60°\) and 90°, the slits appeared strongly in the evaluation image because the horizontal angle between the digital camera and the slits was closer to parallel when \(\theta\) increased. Then, the trajectory of the measured grass color values at \(\theta = 60°\) and 90° was more curved than at \(\theta = 0°\) and 30°. For example, as shown in Fig. 7b and c, the plotted results at \((h, d, \theta) = (1.2, 3.0, 90)\) were more curved than at \((h, d, \theta) = (1.2, 3.0, 0)\).

Then, \(G_2\) at \((h, d, \theta) = (1.2, 3.0, 90)\) cannot be mapped to the measured grass color value because the minimum of \(\Delta E_{1980}^{*}\) was 3.94, which were higher than the color tolerance of 3.0. In addition, the minima of \(\Delta E_{1980}^{*}\) and \(\Delta E_{2000}^{*}\) at \((h, d, \theta) = (1.6, 2.0, 60)\) were also 3.17 and 3.37 over the color tolerance of 3.0, respectively as shown in Fig. 7d. Furthermore, the results at \((h, d, \theta) = (1.2, 2.0, 90), (1.6, 3.0, 90)\) and \((1.7, 3.0, 60)\) likewise failed to map the green grass length to all the levels of the color scale simultaneously. These results were attributed to the curved trajectories of the measured grass color values caused by the black slits in the evaluation images. Moreover, \(\Delta E_{1980}^{*}(G_0, G_4)\) at most camera positions were over 12, however, \(\Delta E_{1980}^{*}(G_0, G_4)\) at \((h, d, \theta) = (1.6, 1.0, 90)\) was 11.94 under 12. Then, the measured grass color values corresponding to the color scale cannot be determined because the target grass color value was included in the color tolerance of other target grass color values.

The camera position of the result included \(d = 1.0\) and \(\theta = 90°\), then, we suppose the result was caused by the color difference between \(G_0\) and \(G_4\) reduced by the black slits of the grass pixel.

**Repeatability and reliability of grass pixel.** We conducted simple experiments on revealing whether the grass pixel can show the same grass color when the same grass length was repeatedly inputted to confirm the repeatability and reliability of the grass pixel. Figure 8a shows the experimental environment based on the grass color scale experiments and Fig. 8b shows the photo of the environment of the experiments. In the experiments, the same digital camera and the grass pixel were used as in the grass color scale experiments. \(h, d\), and \(\theta\) represent the height of the digital camera, the distance from the digital camera to the grass pixel, and the horizontal angle between them as in the grass color scale experiment, respectively. \(h\) and \(d\) were 1.2 [m] and 2.0 [m]. Moreover, \(\theta\) were 0°, 30°, 60°, and 90°. The experiments were conducted on the playground of the University of Tsukuba in natural sunlight from 10:00 a.m. to 2:00 p.m. The grass colors were measured while moving the grass length in the following order: 0.00, 3.75, 7.50, 11.25, and 15.00 [mm]. Then, this process was repeated 10 times for each camera position. After the measurements, the mean of the measured grass color values for each grass length and camera position was calculated as a reference grass color value. Then, the reference grass color value was compared with 10 measured grass color values at the same grass length and camera position. In the experiments, to reveal the repeatability and reliability of the grass pixel using the tightest color tolerance, the color tolerance of the reference grass color values was set to a color difference of 2.0, which is defined by CGATS TR 016-2014 as a color difference for the most color-critical applications, e.g., proofing. In other words, when the measured grass color values are more within the color tolerance, the grass colors of the measured grass color values can be approximately the same and the grass pixel has repeatability and reliability.

Figure 8c shows the experimental results when \(\theta\) were 0°, 30°, 60°, and 90°. In these graphs, the reference grass color value for each grass length and camera position is set as the origin. The upper and the lower limits of \(a^*\) and \(b^*\) are set to 6 and -6. In addition, them of \(L^*\) is set to 3 and -3. In other words, each parameter in these graphs represents the difference of each parameter between the reference and measured grass color values. The blue ellipsoid of each graph is the color tolerance of 2.0 of the reference grass color value. Blue dots are the measured grass color values within the color tolerance, and red dots are not included in the color tolerance. As shown in Fig. 8c, most of the measured grass color values were included in the color tolerance of 2.0 at all angles. Although some of the measured grass color values were not within the color tolerance, they were located around the blue ellipsoid of the grass tolerance. Therefore, since the grass pixel can show the grass color stably with the grass length, the experiments revealed the repeatability and reliability of the grass pixel.

**Demonstration for grass animation display.** We made several demonstrations of the grass animation display using the results of our grass color scale experiments. Figure 9a shows a 3 × 3 pixels grass animation display was constructed using nine grass pixels (dimension: 315.0 × 315.0 × 260.0). In this display, the surface area of the grass pixel was 40 × 40 [mm]. The slit width and the moving range of the green grass length were the same as those of the grass pixel used in our grass color scale experiments. Because the color scale was mapped to the green grass length through the grass color scale experiments, the grass animation display can show a 3 × 3 pixels image using a 3 × 3 pixels grayscale image. Then, the animation was played on the grass animation display by changing the displayed images to other images with time. In the grass animation display, a keyframe animation system was adopted to change the displayed images as shown in Fig. 9b. In the animation system, the grayscale images were set in the order of the keyframes, and the levels of the color scale for each grass pixel were set in keyframe order. Then, the green grass length was determined pixel by pixel for each keyframe using the results of the grass color scale experiments. Therefore, each grass pixel can change the grass color corresponding to the color scale by moving its green grass length in keyframe order, and the grass animation display can play
the animations by changing the displayed images. In the demonstrations, we captured the grass animation display at \((h, d, \theta) = (1.7, 2.0, 0)\) and adopted the green grass lengths suitable for the color scale. In the grass color scale experiments at the same camera position, the measured grass color value of these green grass lengths was included within the color tolerance of 3.0 of each \(G_n\). The grass animation display played four animations, and the keyframe interval of the animation system was 1.0 [s].

Figure 8. Simple experiments on repeatability and reliability of grass pixel. (a, b) The camera height and the distance between the camera and the grass pixel were fixed. The horizontal angles between them were 0°, 30°, 60°, and 90°. The experiments were conducted the playground in the University of Tsukuba under natural sunlight from 10:00 a.m. to 2:00 p.m. (c) Since most of the measured grass color values were within the blue ellipsoid of the color tolerance of the reference grass color value for each camera position, the experimental results revealed that the grass pixel can show the grass color stably with the grass length. This figure was created using Serif Affinity Designer version 1.10.0 (https://affinity.serif.com/en-us/) and Matplotlib version 3.2.2 (https://matplotlib.org).
of the gaps for moving the green grass length does change hardly when it is viewed at additive color mixing of the grass pixel. To solve this problem, the grass pixel needs to be such that the appearance of the grass colors corresponding to the color scale to a viewer at another position. Hence, to achieve a wide-field procedure. However, it is not evident whether the optimized grass pixel based on a camera position can show holes of the grids to widen the viewing angle of the grass color display.

When the grass pixel was developed, we tried a grass pixel with holes of matrix-like grids. However, it was difficult to insert the green grass evenly into all of the holes of the grids. Thus, in this paper, the slits were adopted to facilitate the insertion of the green grass into the holes. In future work, we will design a grass pixel with the slit to facilitate the insertion of the green grass into the holes of the grids.

Limitation and future work

In this paper, the grass color scale can be controlled by adjusting the grass length of the grass pixel. On the other hand, another method of showing a color scale is spatial dithering. Using the spatial dithering, a wide range of the color scale can be expressed with a limited number of the color scale. In particular, it is possible to display intermediate colors even using the color scale with 2 levels like electronic ink (E ink). Although the spatial dithering using the color scale of 2 levels can help the grass animation display show the color scale without adjusting the grass length, multiple grass pixels are needed to show an input level of a single pixel. In this paper, it was difficult to use the spatial dithering in the grass animation display because the grass animation display had only nine grass pixels. However, with the spatial dithering, the more levels of the color scale the grass animation display can control, the wider the apparent color scale can be shown. In future work, we are going to develop a grass system with multiple motors to show a wide color scale using the spatial dithering and adjusting the grass length.

This paper showed the grass color characteristics of the grass pixel through the grass color scale experiments using the digital camera. Moreover, BRDF (Bidirectional Reflectance Distribution Function) model is also useful to confirm the grass color behavior of the grass pixel depending on the viewer's position. However, since the brightness and the angle of incidence of sunlight were not measured in the grass color scale experiments, it was impossible to build the BRDF model of the grass pixel using the 36 camera data of the experiments. In the future, we are planning to measure and model the BRDF of the grass pixel based on the viewer's positions, the grass colors, and the grass length.

In the demonstrations, the response time to change the grass pixel from minimum and maximum of the grass color scale was 1.0 [s]. However, a faster response time is needed to play the animations on the grass animation display smoothly. This problem can be solved using a high-speed motor with a rotary encoder system. In future work, we are going to develop a high-speed grass pixel system to play smooth animations.

The grass color scale experiment results of \( \theta = 60^\circ \) and \( 90^\circ \) showed that the slits of the grass pixel affected the additive color mixing of the grass pixel. To solve this problem, the grass pixel needs to be such that the appearance of the gaps for moving the green grass length does change hardly when it is viewed at \( \theta = 0^\circ \), \( 30^\circ \), \( 60^\circ \), and \( 90^\circ \). For example, holes of matrix-like grids are similar in appearance when they are viewed from multiple positions. When the grass pixel was developed, we tried a grass pixel with holes of matrix-like grids. However, it was difficult to insert the green grass evenly into all of the holes of the grids. Thus, in this paper, the slits were adopted to facilitate the insertion of the green grass into the holes. In future work, we will design a grass pixel with the holes of the grids to widen the viewing angle of the grass color display.

The color scale with five levels can be mapped to the green grass length through the grass color scale setting experiments. However, it is not evident whether the optimized grass pixel based on a camera position can show the grass colors corresponding to the color scale to a viewer at another position. Hence, to achieve a wide-field...
In addition, we conducted the grass pixel experiments under natural sunlight from 10:00 a.m. to 2:00 p.m. to evaluate the grass color under standard conditions. However, we did not reveal whether the experimental results of the color scale can be used except from 10:00 a.m. to 2:00 p.m., e.g., morning and evening environments. In the future, we will clarify a color scale mapping method of the grass pixel from morning to evening.

Furthermore, user evaluations are likewise important because the spatial additive mixing of the grass pixel is based on human perception. We are planning user evaluations to reveal whether the grass pixel can display the color scale clearly based on psychophysical aspects. Moreover, herein, we constructed the $3 \times 3$ pixels grass animation display, which can play several primitive animations with the color scale. In the future, we plan to create a grass animation display to show graphical animations such as texts and icons.

**Conclusion**

We proposed a dynamic grass color scale display technique based on a grass length for a green landscape-friendly animation display. We designed a grass color scale setting procedure using image processing to map a color scale with five levels to the green grass length of the grass pixel. The grass color scale setting procedure yields the green grass length corresponding to the color scale using the measured grass color values of the grass pixel at regular green grass length intervals. We experimented with the grass color scale setting procedure under natural sunlight between 10:00 a.m. and 2:00 p.m. at multiple camera positions based on a viewer's height, a distance, and a horizontal angle between the viewer and a grass pixel. As a result, we revealed that the grass pixel can be regarded to

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**Figure 10.** Demonstration results of a $3 \times 3$ pixels grass animation display using results of grass color scale setting experiments at $(h, d, \theta) = (1.7, 2.0, 0)$. (a) The response time to change the grass pixel from minimum and maximum of the grass color scale was 1.0 [s]. (b) Four animations of (i) path of letter N, (ii) cross, (iii) rain, and (iv) wave were played on the pixels grass animation display. This figure was created using Serif Affinity Designer version 1.10.0 (https://affinity.serif.com/en-us/).
show the grass colors corresponding to the color scale at 30 camera positions out of 36, which can be mapped to the green grass length. In addition, we also conducted the experiments on the repeatability and reliability of the grass pixel under natural sunlight between 10:00 a.m. and 2:00 p.m. at several camera positions. As a result, the experimental result revealed the grass pixel can show the same grass colors across the camera positions when the same grass length was repeatedly inputted. Several demonstrations were constructed using the experimental results to play the animation with the color scale on the grass animation display. In the demonstrations, a 3 × 3 pixels grass animation display was built using nine grass pixels and played several animations (e.g., path of letter N, cross, rain, and wave). In our future study, we will aim to improve the grass color scale display technique based on human perception through user evaluations. Furthermore, we will develop a wide-field grass animation display to show graphical animations with the color scale, such as text and icons.

Methods

Grass pixel implementation. The hardware of the grass pixel was designed by the computer-aided design software (Autodesk FUSION 360). The limit switch plate, the guide plate, and the part of the surface plate were made of black acrylic sheets (thickness: 5 [mm]). The acrylic sheets were cut by the diode laser cutter (NEJE Master 2S plus). The laser cutter was operated by the laser cutter software (LASERGRBL). The 3D printed pin and the part of the surface plate were made by the fused deposition modeling (FDM) 3D printer (Creality Ender-3 Pro) using black filament (ANYCUBIC Filament, material: polyactic acid (PLA), diameter: 1.75 ± 0.02 [mm]). The 3D printer was operated by the 3D printer slicer software (Ultimaker Cura). The frameworks of the grass pixel system were made of aluminum frames (YUKI LABORATORY LECOFRAME). The printed circuit board (PCB) for the grass pixel was designed by the PCB design software (Autodesk Eagle).

Software of grass color scale setting procedure for grass color scale experiments. The software of the grass color scale setting procedure was developed based in Python3. The digital camera was controlled by the camera management software (gPhoto2). The raw image was developed in sRGB color space using the Python raw image management software (rawpy). The RGB values of the developed image were corrected with the color correction Python library (PlantCV). The computer vision library (OpenCV) was used to crop the developed image and calculate the average CIELAB values of the evaluation image. The image processing library (scikit-image) was used to calculate the color difference of CIEDE2000. The formula manipulation system (Mathematica) was used to calculate $E_0$. The hardware of the grass pixel was designed by the computer-aided design software (Autodesk FUSION 360). The limit switch plate, the guide plate, and the part of the surface plate were made of black acrylic sheets (thickness: 5 [mm]). The acrylic sheets were cut by the diode laser cutter (NEJE Master 2S plus). The laser cutter was operated by the laser cutter software (LASERGRBL). The 3D printed pin and the part of the surface plate were made by the fused deposition modeling (FDM) 3D printer (Creality Ender-3 Pro) using black filament (ANYCUBIC Filament, material: polyactic acid (PLA), diameter: 1.75 ± 0.02 [mm]). The 3D printer was operated by the 3D printer slicer software (Ultimaker Cura). The frameworks of the grass pixel system were made of aluminum frames (YUKI LABORATORY LECOFRAME). The printed circuit board (PCB) for the grass pixel was designed by the PCB design software (Autodesk Eagle).

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Author contributions
K.T. designed and implemented the grass color control system. K.T., Y.K., A.M., M.M., and M.F. conceived the grass gradation scale setting procedure. Y.K. and A.M. implemented the software of the grass color scale setting procedure. K.T. designed and implemented the grass color control system. K.T., Y.K., A.M., M.M., and M.F. conceived the grass gradation scale setting procedure. Y.K. and A.M. implemented the software of the grass color scale setting procedure. K.T. conducted the animation demonstrations. All authors discussed the results. K.T. wrote the initial manuscript, and M.M reviewed the manuscript.

Competing interests
The authors declare no competing interests.

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