Urban Green Space-Friendly Animation Display with Artificial Grass Gradation Control System

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This paper introduces an urban green space-friendly animation display with an artificial grass gradation control system. Recently, display devices such as a liquid crystal display (LCD) have been used in urban green spaces. However, current display devices can spoil a natural landscape in urban green spaces because they look like artificial materials. Then, it is needed to research an animation display while preserving a natural landscape. To solve this problem, we propose a grass animation display system that can mimic a natural landscape in urban green spaces. In the grass system, grass gradation can be controlled dynamically pixel by pixel. The pixel system was named a grass pixel. The grass pixel consists of artificial yellow and green grass and can change the grass gradation by moving the green grass through slits of the yellow grass. The grass animation display can be developed by using multiple grass pixels, then, the display can show gradation animations without current display devices such as an LCD and a projector. We conduct a simple evaluation of dynamic grass gradation changes depending on the grass length through image processing. In the evaluation, the grass gradation is quantified as HSV (Hue, Saturation, and Value of Brightness) values. As a result, the HSV values of the grass gradation increased or decreased simply when the grass pixel moved the grass length from minimum to maximum. Based on the results, we build a 3×3 pixels grass animation display using nine grass pixels, and the display showed several example animations. Furthermore, we evaluate five grass gradation scales depending on the grass length through image processing. To evaluate the grass gradation scales based on human cognition, we adopt a color evaluation using the CIELAB color space, which has visual uniformity. Through the evaluation, we revealed that the grass pixel can display five grass gradation scales to multiple positions. In addition, we obtained the grass length corresponding to each grass gradation scale. These results can help to use artificial grass as an animation display such as signage, advertisements, and entertainment in urban green spaces.

Main Academic Advisor: Masahiko Mikawa
Secondary Academic Advisor: Makoto Fujisawa

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Chapter 1

Introduction

1.1 Background

Recently, display devices have been installed in urban green spaces such as a park for signage and entertainment. For example, the zoo uses a digital signage application [1], and there was a projection mapping in Sosei river in Japan [2]. Furthermore, developers are exploring outdoor applications, and display devices will be used increasingly in urban green spaces.

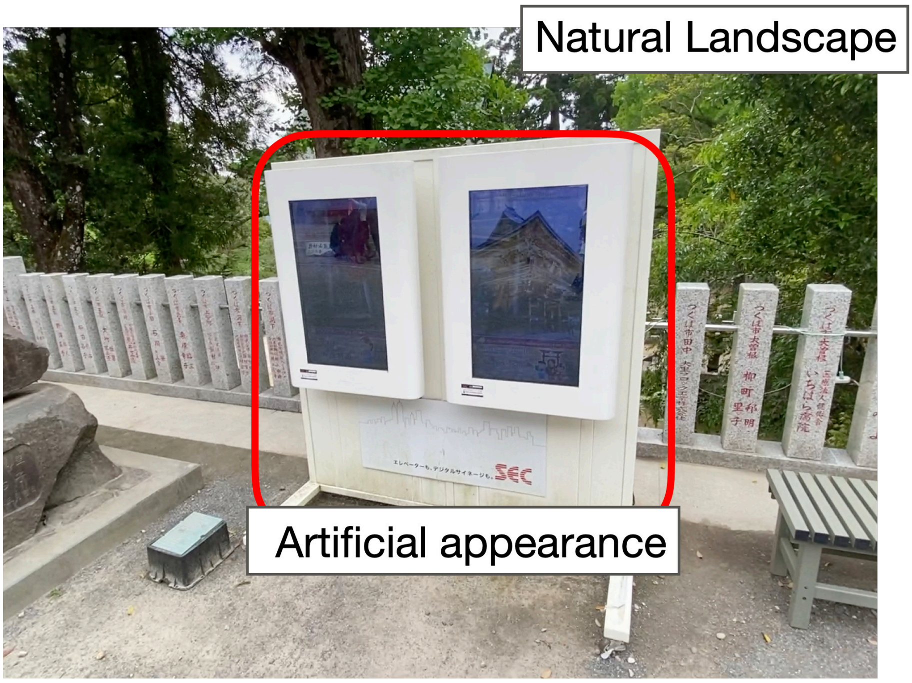


Figure 1.1: Artificial Appearance Display Device in Natural Landscape

However, current display devices can spoil a natural landscape in urban green spaces because they look like artificial materials. For example, Figure 1.1 shows the digital signage at the green space taken by us. The display devices should not destroy a natural landscape, which is important for urban green spaces. Thus, urban green spaces need a natural landscape-friendly display device.

To solve this problem, we focus on grass that is often planted in urban green spaces. By changing the shape of the grass, dots and curved lines can be drawn on the grass surface. In art fields, many artists have made multiple works as grass art. For example, there was a grass art that displayed Prince Harry and Meghan Markle's faces in the grass [3].

Since grass art can show images while preserving the a natural landscape, it is getting a lot of attention as a natural public display. Then, some researchers and artists have studied displaying computer graphics on the grass [4] [5]. However, current grass display techniques can only show static images, and there are few grass methods of playing an animation. It is because these techniques cannot switch the images quickly.

1.2 Proposed Method

We propose an urban green space-friendly animation display with an artificial grass gradation control system. The grass system can change the pixel-by-pixel grass gradation dynamically by controlling the grass length. We named the pixel system a grass pixel. In the grass pixel, artificial yellow grass is planted on the top surface of its enclosure, and artificial green grass moves go in and out the slits of the yellow grass. Depending on the length of the green grass, a viewer can see multiple grass gradation with yellow and green. Then, a grass animation display can be built by using multiple grass pixels and show a gradation animation without any display device such as a projector as shown in Figure 1.2. The grass technique can help to develop a novel animation display while preserving a natural landscape in urban green spaces as shown in Figure 1.3.

To play the gradation animation on the grass, we need to clarify the performance of the grass gradation control system. Then, the purposes of our research are described as follows.

- Purpose 1: **Evaluation of Dynamic Grass Gradation**
- Purpose 2: **Example Animation using Grass Animation Display**
- Purpose 3: **Evaluation of Grass Gradation Scales**

In the purpose 1, we reveal whether the grass gradation of the grass pixel can be changed continuously when the green grass length moves. From several angles, a digital camera captures the grass pixel moving its green length from minimum to maximum, then, the grass gradation is quantified as HSV (Hue, Saturation, and Value of Brightness) values through image processing.

Based on the results of the purpose 1, several example grass animations are created. In the purpose 2, a 3×3 pixels grass animation display is developed using nine grass pixels. In addition, we adopt a keyframe system as the grass animation display system. In the animation system, the grass length corresponds to each gradation scale subjectively.

In the example animations, we define the grass gradation scales subjectively, however, it is important to evaluate the grass gradation scales to display the animations correctly. Then, in the purpose 3, we conduct an evaluation of the grass gradation scales through image processing. To evaluate the grass gradation scales, we adopt a color evaluation with CIELAB (CIE 1976 L*a*b*) color space based on human perception. Through the evaluation, we reveal whether the grass pixel can show the grass gradation scales to multiple positions.

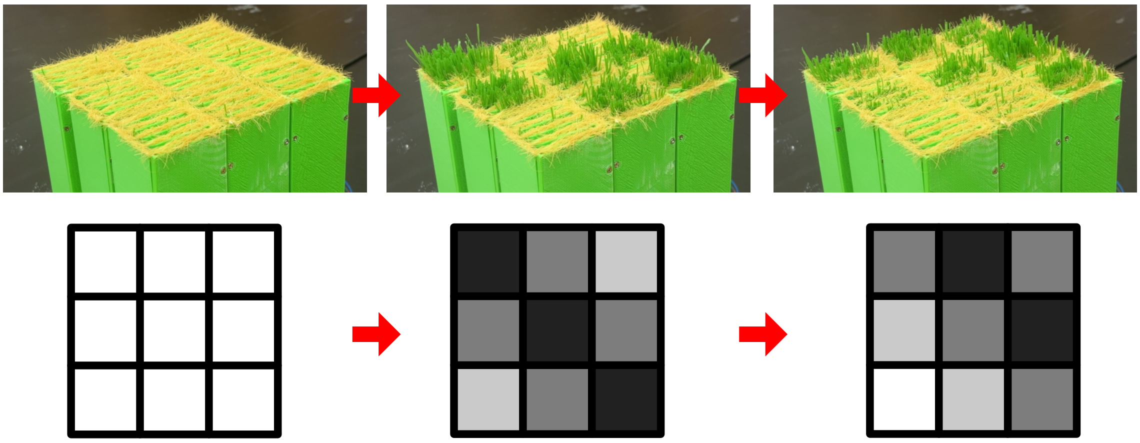


Figure 1.2: 3 × 3 Pixels Grass Animation Display

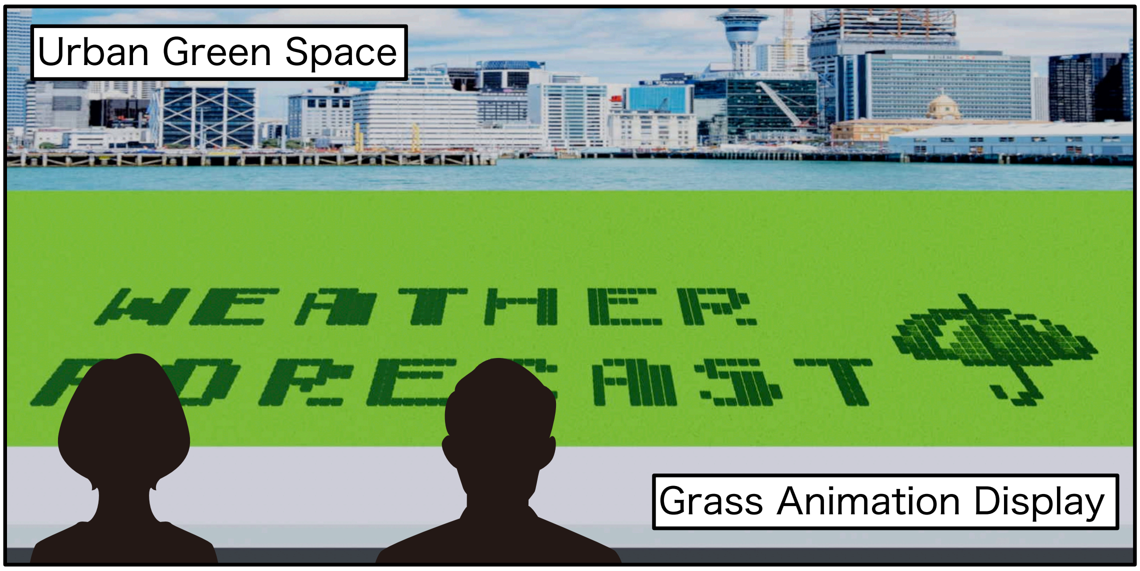


Figure 1.3: Application of Grass Animation Display (Umbrella Material [6])

Chapter 2

Related Work

2.1 Image Displaying on Grass

Figure 2.1: Grass Print Service [7]

Figure 2.2: Grass Portrait Art [4]

Currently, there are multiple methods of displaying images on the grass. Sugiura et al. proposed a method of printing a binary image on the grass [5]. In this method, the direction of the grass blades can be controlled to be raised or flatted by a servo motor rod system. As a result, the grass gradation can be lighter or darker pixel by pixel. As shown in Figure 2.1, there is a service that prints a gradation image on a large grass field by controlling the direction of the grass blades [7]. The service is used in multiple sports fields such as baseball, soccer, and so on. Ackroyd & Harvey created a grass art that can display a photography [4] as shown in Figure 2.2. To create this art work, the grass is exposed to light projected from a negative image throughout its growth. Then, the growth rate of the grass changes depending on the intensity of the light, and the grass gradation can be generated to display the photography on the grass. Scheible et al. proposed a support technique to generate a large image on the grass using a drone [8]. In the method, an artist can create a large grass work using a lawnmower while observing a bird's eye view of the grass through the drone. However, these methods only are displaying static images, and cannot show gradation animations on the grass. It is difficult for the previous works to control the grass gradation dynamically, then, currently few grass display methods can play the gradation animations.

2.2 Grass-Based Smart Material Interface

To play animations on grass, a shape-changing grass system to change the grass gradation is needed. Recently, Vyas et al. presented a novel interface idea focused on color or shapes of multiple materials, and the interface is called the smart material interface (SMI) [9]. Then, there are several grass-based SMIs. Minuto et al. presented an interface system to operate the direction of the grass blade [10] as shown in Figure 2.3. Umezu et al. proposed a hair top-based interface like the grass [11] as shown in Figure 2.4. Shape-memory alloys (SMA) allow the hair top interface to bend in various directions. These methods were developed for tangible interactions, however, there are few grass-based SMIs to control the grass gradation pixel by pixel.

Figure 2.3: Grass Blade Direction Control [10]

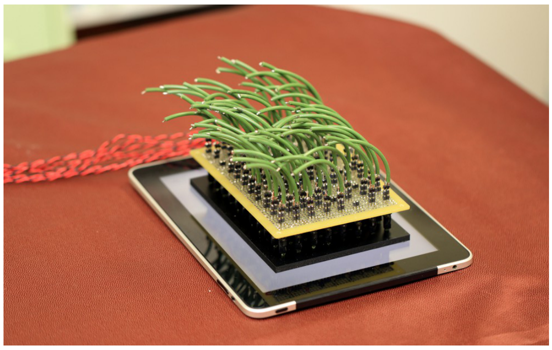


Figure 2.4: Hair top Interface like Grass [11]

2.3 Image Displaying with Natural Materials

A lot of researchers and artists have explored multiple display techniques with natural materials. The display methods can provide living environment-friendly images, then, can also help to preserve a natural landscape. Nagafuchi et al. proposed a print method on the ground using a water jet [12] as shown in Figure 2.5. Sugiura et al. presented an image print technique on fur carpet [13]. Robinson et al. proposed a small robot system that prints a static image using foodstuffs [14] as shown in Figure 2.6. In the art fields, Rozin created a wooden display art that can play the gradation animations [15] as shown in Figure 2.7. Inakadate Village in Japan creates various rice paddy arts every year [16] as shown in Figure 2.8. The rice paddy arts use multiple colored rice plants to show colorful illustrations on a paddy field. In this paper, we focus on grass as a natural material used in an urban green space-friendly display.

Figure 2.5: Water-Jet Printer [12]

Figure 2.6: Printer using Foodstuffs [14]

Figure 2.7: Wooden Animation Display [15]

Figure 2.8: Rice Paddy Art [16]

Chapter 3

Concept of Grass Gradation Control

In this paper, we designed a dynamic grass gradation control system depending on length of yellow and green grass. This chapter introduces the concept of the grass system inspired by the natural phenomenon of the grass gradation.

3.1 Grass Gradation in Natural Environment

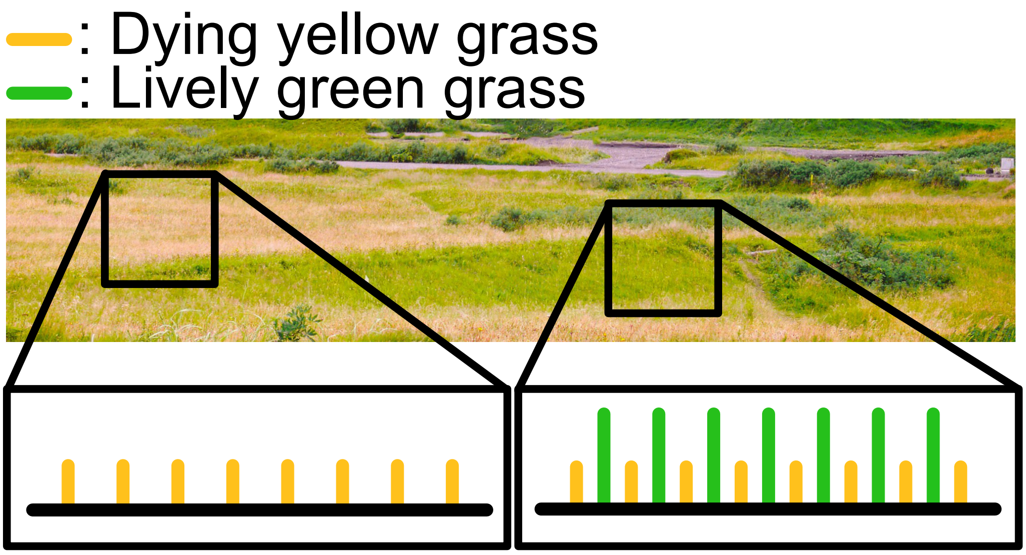


Figure 3.1: Grass Gradation by Yellow and Green Grass

To design a grass gradation control system, We focus on grass gradation by yellow grass length and green grass length as shown in Figure 3.1. In the real world, the grass has yellow and green colors. The yellow grass length cannot get bigger because the yellow grass is dying. In contrast, the lively green grass grows, then, the grass surface has multiple gradations depending on the green grass length.

3.2 Process of Grass Gradation

The grass gradation according to two different colors grass is generated by additive color mixing. The section explains additive color mixing and shows the process of the grass gradation.

3.2.1 Additive Color Mixing

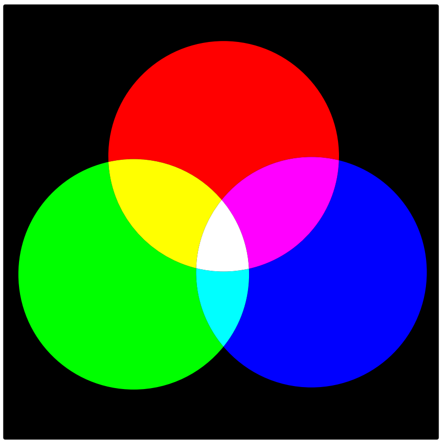


Figure 3.2: Additive Color Mixing

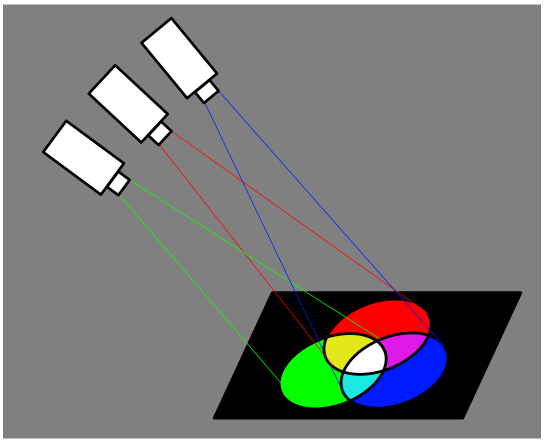


Figure 3.3: Simultaneous Additive Mixing

Additive color mixing is one of the color mixing principles using three primary colors (Red, Green, and Blue). Figure 3.2 shows an example of additive color mixing. The color mixing is characterized by the fact that color becomes brighter when another color is added to the color. For example, red, green, and blue spotlights can generate multiple colors as shown in Figure 3.3. The additive color mixing can be considered to be simultaneous additive mixing. In simultaneous additive mixing, colors are created by physically mixing colored lights. In contrast, there are ways of additive color mixing without physically mixing colors. One of the additive color mixing principles is spatial additive mixing, and the grass gradation using yellow and green grass is generated by the color mixing.

Spatial additive mixing is a color mixing principle when multiple colors are arranged in such a way that they cannot be distinguished by human retinas. In that case, a viewer recognizes a new color that has an intermediate brightness between the individual colors according to the area ratio of the colors. There is an example of spatial additive mixing as shown in Figure 3.4. In the example, all of these images are checkered patterns consisting of only red and yellow and have different densities of these colors. The left part of Figure 3.4 is coarse, then, red and yellow can be distinguished. However, the right part of Figure 3.4 is so fine that it is impossible to distinguish between the colors. Therefore, the right image looks orange color which is an intermediate color between red and yellow.

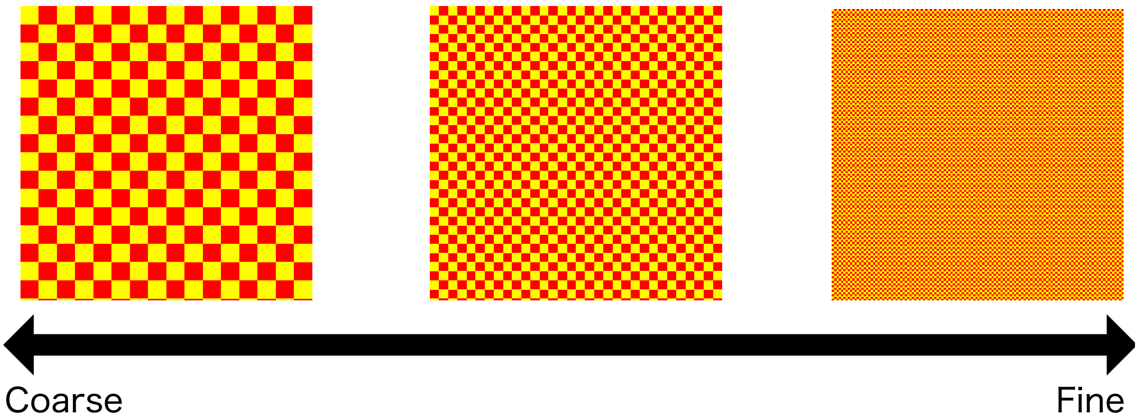


Figure 3.4: Example of Spatial Additive Mixing

3.2.2 Application of Spatial Additive Mixing

Figure 3.5: LCD using RGB pixels

Figure 3.6: Color Mixing of Clothes

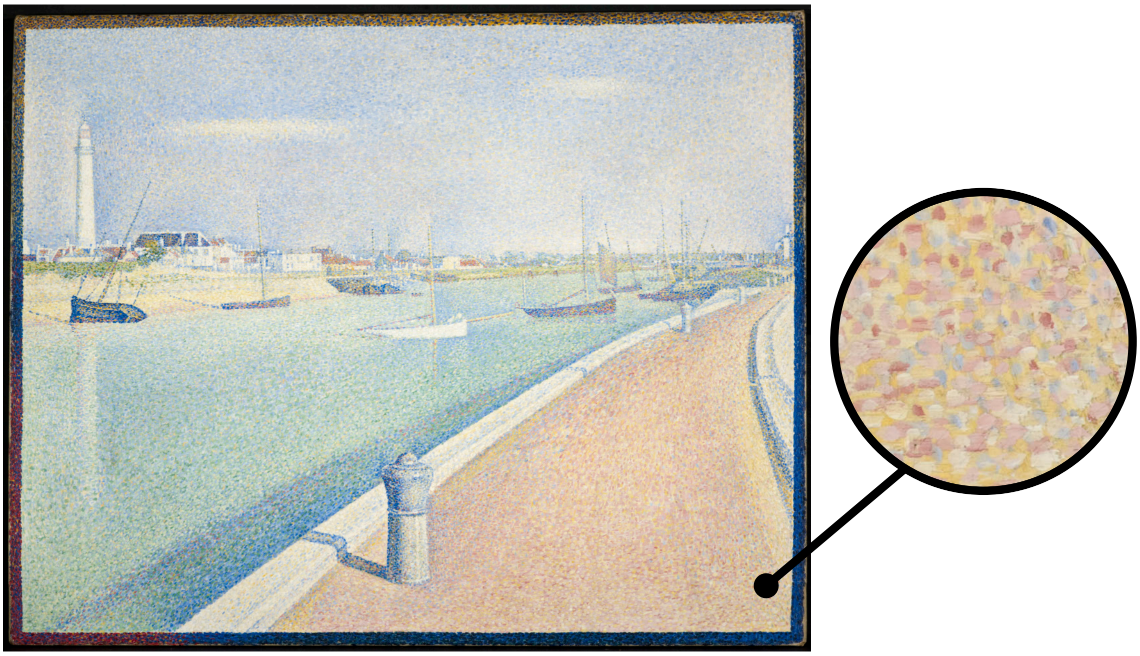


Figure 3.7: Example of Pointillism (*The Channel of Gravelines, Petit Fort Philippe* by Georges Seurat)

Spatial additive mixing is used for multiple applications. For example, a liquid crystal display (LCD) have a lot of RGB pixels and can display images by spatial additive mixing as shown in Figure 3.5. In addition, there is a method of making clothes using spatial additive mixing as shown in Figure 3.6. In the method, by interweaving threads of different colors, these colors can be mixed without dyes. In the art field, there is an art technique using spatial additive mixing. The method is called pointillism. In the method, the artwork is created by placing countless dots without lines and can be vivid and bright because paints are not mixed directly. One of the most famous artists to use pointillism is Georges Seurat (1859 – 1891). Figure 3.7 shows his work and the circle part displays the enlarged view, which shows the countless dots in the work.

3.2.3 Grass Gradation by Spatial Additive Mixing

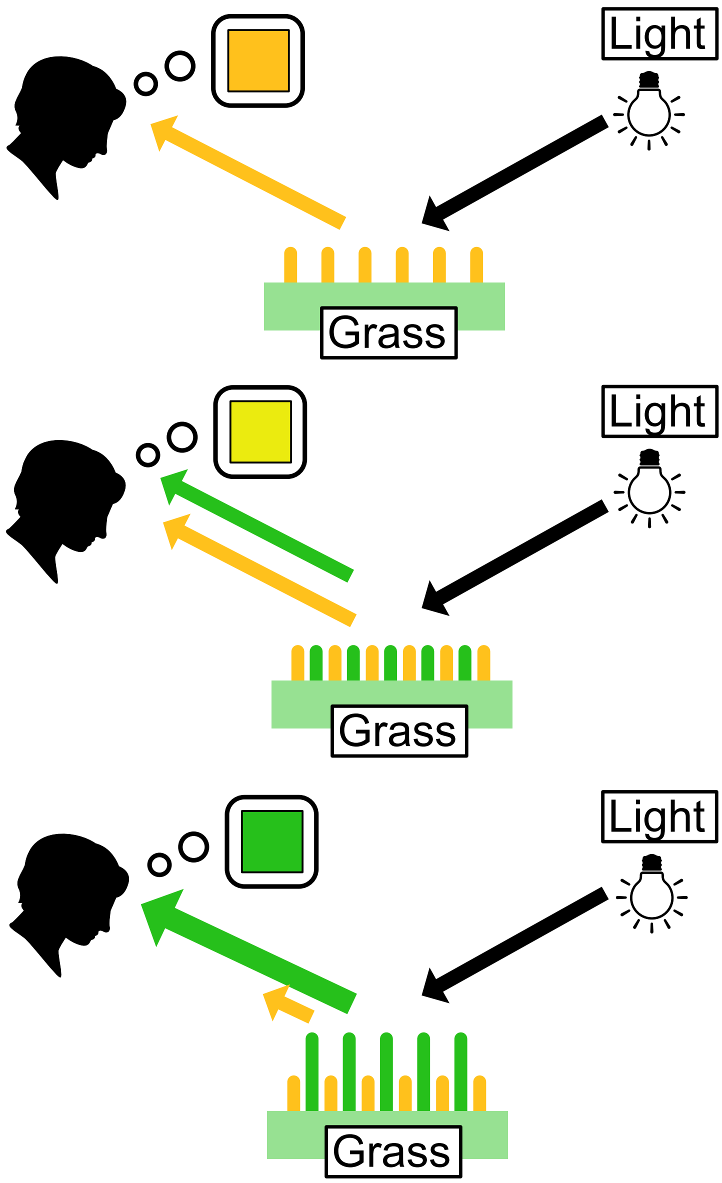


Figure 3.8: Principle of Grass Gradation with Yellow and Green

The grass gradation by the yellow and green grass is also generated by spatial additive mixing. Figure 3.8 shows how the grass gradation can be changed according to the grass length. When light is reflected by the grass, the reflected yellow and green lights can reach a viewer, then, he/she can recognize the grass gradation with yellow and green because the blades of the yellow and green grass are too small to be distinguished. In addition, as the lively green grass grows, the amount of the green reflected light increases and the grass surface color gets greener. Therefore, the viewer can see multiple grass gradation depending on the grass length.

3.3 Design of Grass Gradation Control

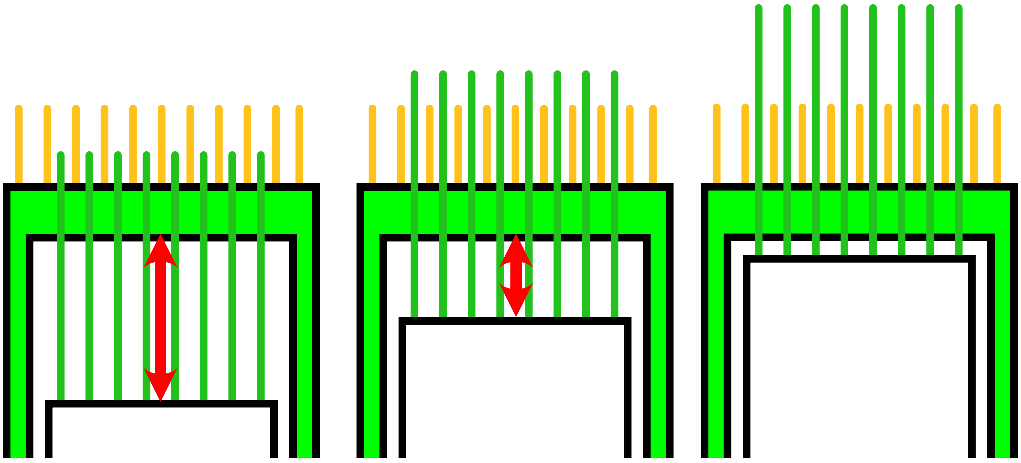


Figure 3.9: Overview of Grass Pixel

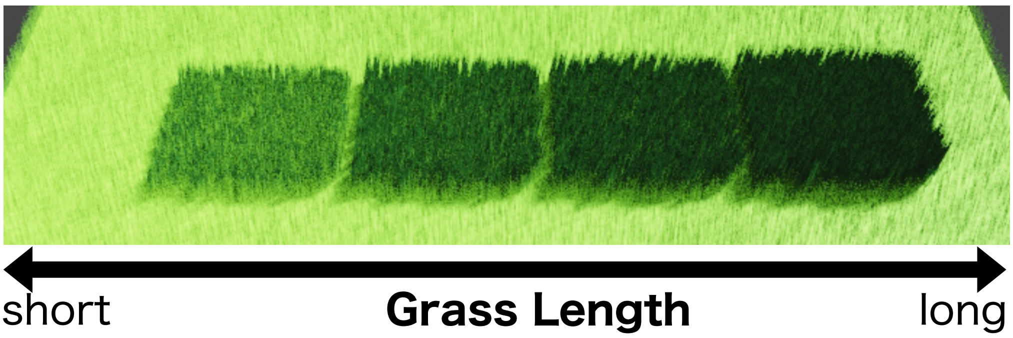


Figure 3.10: Gradation of Grass Pixel

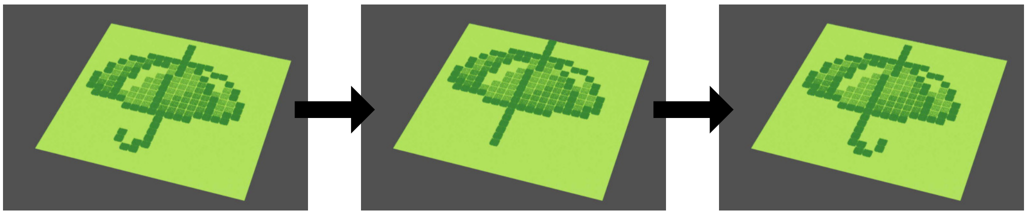


Figure 3.11: Example of Grass Animation Display

Using the natural phenomenon of spatial additive mixing, we designed a pixel-by-pixel grass system that can automatically adjust the grass length to control the grass gradation dynamically. We named the system a grass pixel. Figure 3.9 shows the overview of the grass pixel. In the grass pixel, artificial yellow and green grass are used. The yellow grass is planted on the top surface of the grass pixel. Inside the grass pixel, there is a pin that can move up and down, and the green grass is planted on the top of the pin. The vertical movement of the pin allows the green grass to go in and out the gaps of the yellow grass as if lively grass were growing out of dying grass. Then, as shown in Figure 3.10, the grass pixel can control the grass gradation pixel by pixel. Therefore, an urban green space-friendly animation display can be created by using multiple grass pixels as shown in Figure 3.11.

Chapter 4

Dynamic Grass Gradation Control

This chapter introduces a dynamic grass gradation control of a grass pixel. First, we explain the hardware and software implementations of the grass pixel. Second, we evaluate the grass gradation using image processing to check whether the grass gradation can be controlled by the grass length. In addition, we create several simple animations on a 3×3 pixels grass animation display, which consists of nine grass pixels.

4.1 Implementation

4.1.1 Hardware of Grass Pixel

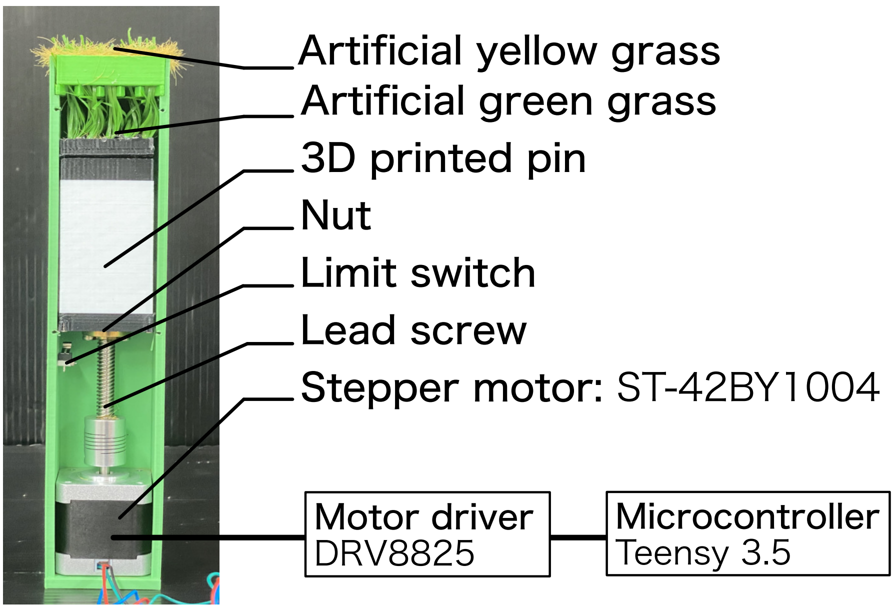


Figure 4.1: Hardware Configuration of Grass Pixel

Figure 4.1 shows the hardware configuration of the grass pixel. The dimensions of the case of the grass pixel are 50.0 (L) $\times$ 50.0 (W) $\times$ 275.0 (H) [mm]. The grass pixel consists of artificial yellow grass (length 10 [mm]), artificial green grass (length: 50 [mm]), a stepper motor (ST-42BY1004, 400 [step/rotation]), a lead screw with a nut (length: 100 [mm], pitch 2 [mm], lead 8 [mm]), a limit switch, and a three dimensional (3D) printed pin (size: 48.0

(L)× 48.0 (W) × 100.0 (H) [mm]). The stepper motor connects the 3D printed pin via the lead screw, and the pin can move vertically by working the motor. The limit switch is installed on the inner wall of the grass pixel. The green grass is attached to the pin, and the yellow grass is planted on the top of the case. The yellow grass surface has slits to move the green grass in and out the gaps as shown in Figure 4.2. The length of the green grass can be controlled from 0 [mm] to 24 [mm] as shown in Figure 4.3. The grass pixel can be worked by a microcontroller (Teensy 3.5) via a stepper motor driver (DRV8825). Table 4.1 shows the specification of the microcontroller.

Table 4.1: Specification of Teensy 3.5

CPU	ARM Cortex-M4 at 120Mhz
Flash Memory	512KB
RAM	256KB
Number of I/O pins	62
POWER	5V DC

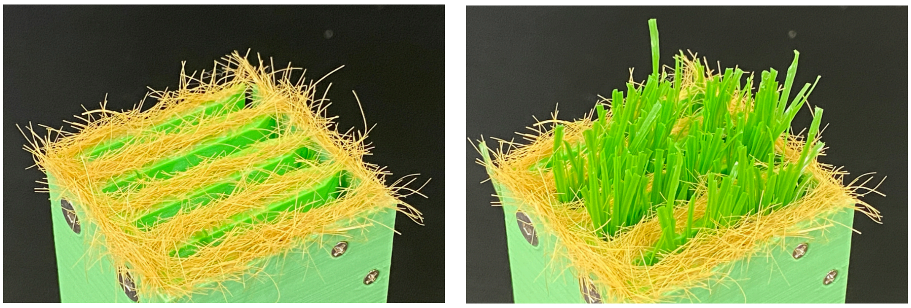


Figure 4.2: Slits for Moving Green Grass

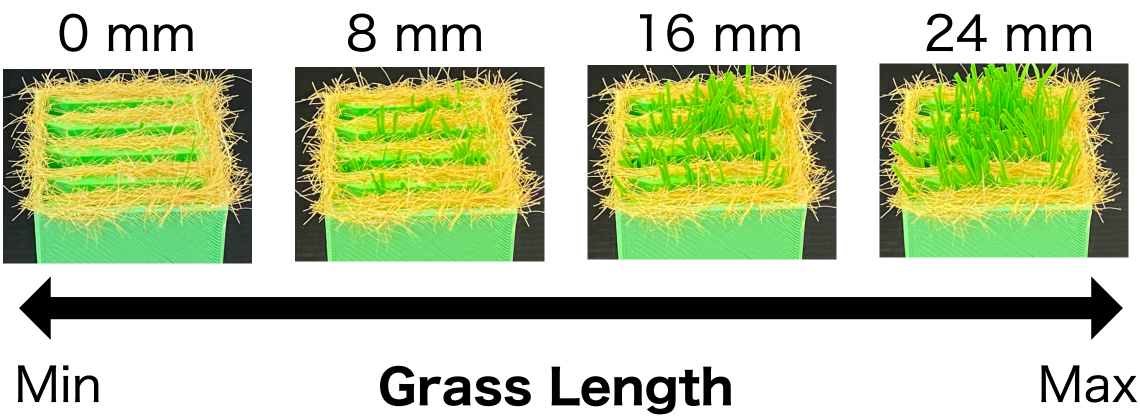


Figure 4.3: Grass Length of Grass Pixel

4.1.2 Software of Pin Control

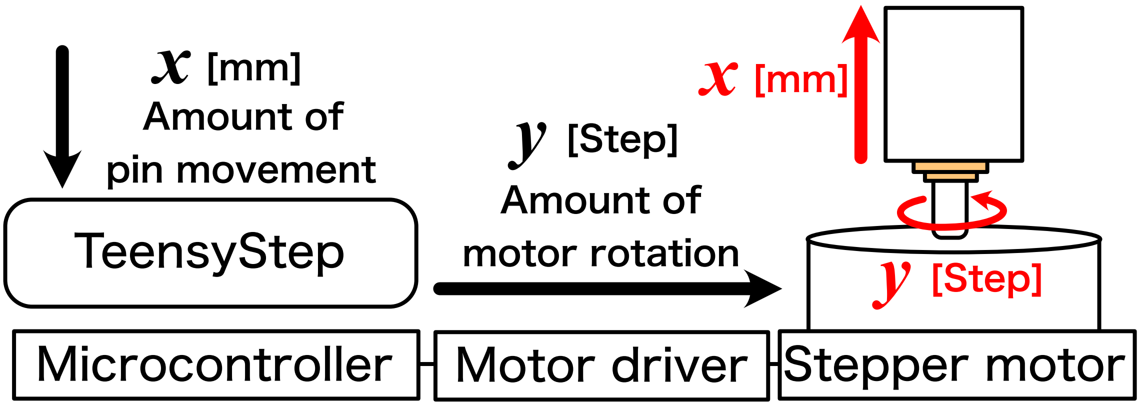


Figure 4.4: Software System for Moving Pin

The grass pixel can control the length of the grass by moving the pin. The stepper motor moves the pin, and the microcontroller needs a pin system to send steps to the stepper motor. Figure 4.4 shows the overview of the software system to move the pin. The microcontroller uses a stepper motor management software (TeensyStep [17]) to provide steps to the motor. The software can convert an amount of pin's movement [mm] to an amount of motor rotation [step]. The equation for the converting is: $y = (k/l) * x$, where x is the amount of pin's movement [mm], y is the the amount of motor rotation [step], k is the steps per a rotation [step/rotation], and l is the lead length of the pin's lead screw [mm/rotation]. When the stepper motor receives the output steps, it can move the pin of the grass depending on the step data. Finally, The length of the green grass can be controlled. In this system, the lead length of the lead screw is 8 [mm]. Then, the pin can move from 0 to 24 [mm] when the stepper motor rotates 0 to 3 [rotation].

4.2 Evaluation of Dynamic Grass Gradation

In this section, we conducted some simple grass evaluation experiments to confirm whether the grass gradation can be dynamically controlled by moving the grass length. In the evaluation, the grass gradation was evaluated through the HSV color space using image processing (OpenCV [18]).

4.2.1 HSV color space

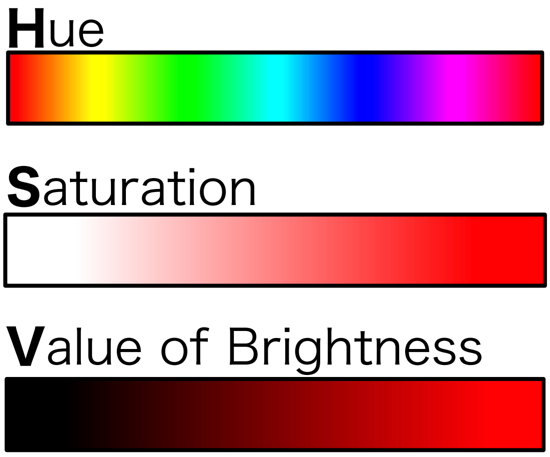


Figure 4.5: Parameters of HSV

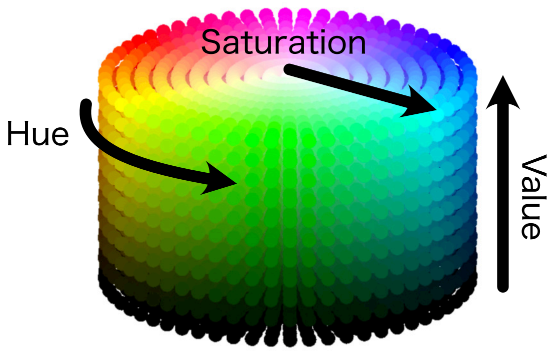


Figure 4.6: 3D HSV Model

HSV is a color space focusing on Hue, Saturation, and Value of Brightness designed by Alvy Ray Smith (1943 –) in the 1970s as shown in Figure 4.5. It can be converted from RGB color space. Figure 4.6 shows the 3D model of the HSV color space of OpenCV. We would like to observe the dynamic grass gradation changes based on saturation and brightness, then, we adopted the color space for the dynamic grass gradation evaluation.

4.2.2 Experimental Environment for Evaluation

Figure 4.7 shows the experimental environment of the dynamic grass gradation evaluation. The light sources of the environment were fluorescent lamps. In the evaluation, an iPhone 11 Pro (12 [MP], f/1.8, 26 [mm], wide-angle lens, 1080p, 60 [fps]) was used to record the grass pixel. The camera's white balance, exposure, and International Organization for Standardization speed (ISO speed) were fixed. The distance between the camera and the grass pixel was 1.331 [m], and the height of the camera was 0.975 [m] above the top of the grass pixel. In addition, the camera was located at four types of positions: Angle 0°, 30°, 60°, and 90°. At Angle 0°, the angle between the grass pixel and the camera was perpendicular. From Angle 0°, the camera was rotated around the grass pixel every 30°, and these angles were Angle 30°, 60°, and 90°, respectively. In other words, at Angle 90°, the angle between the camera and the grass pixel was parallel.

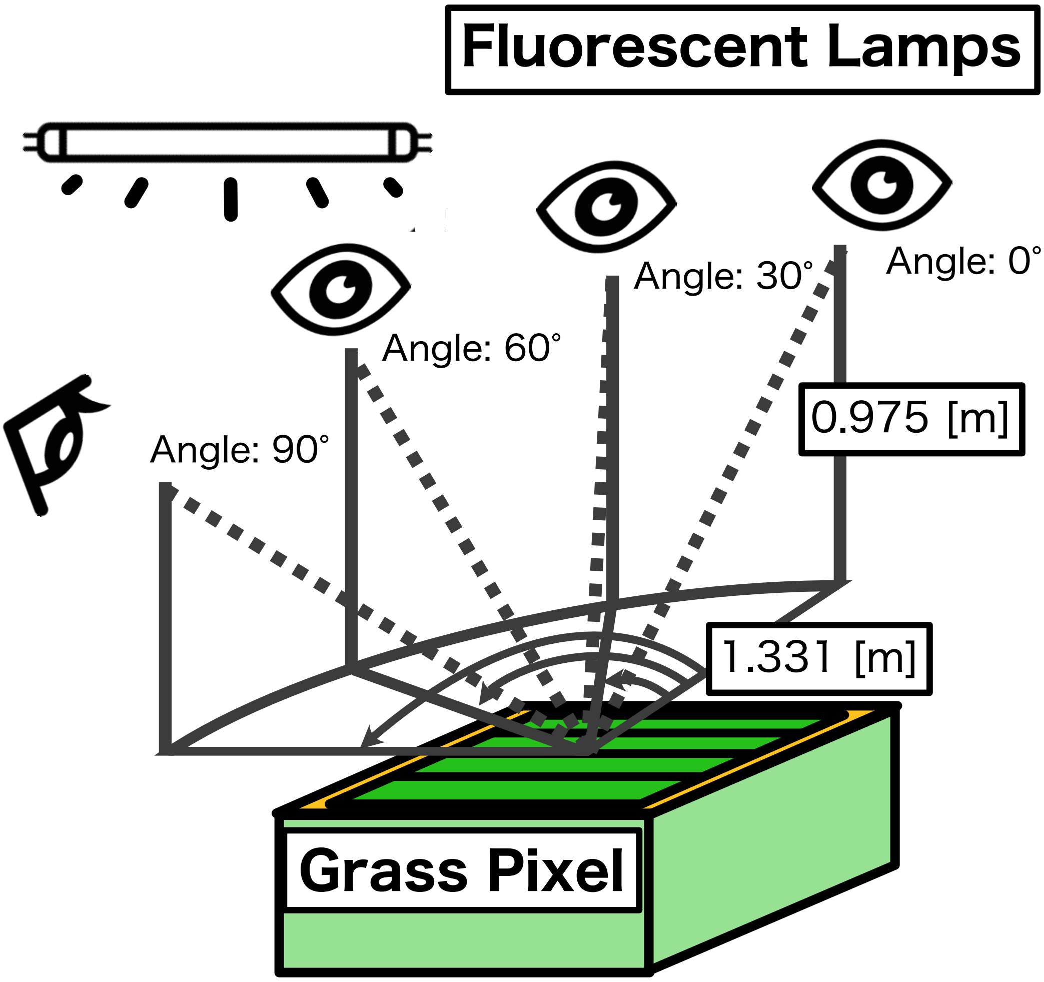


Figure 4.7: Dynamic Grass Gradation Evaluation Environment

4.2.3 Method for Evaluation

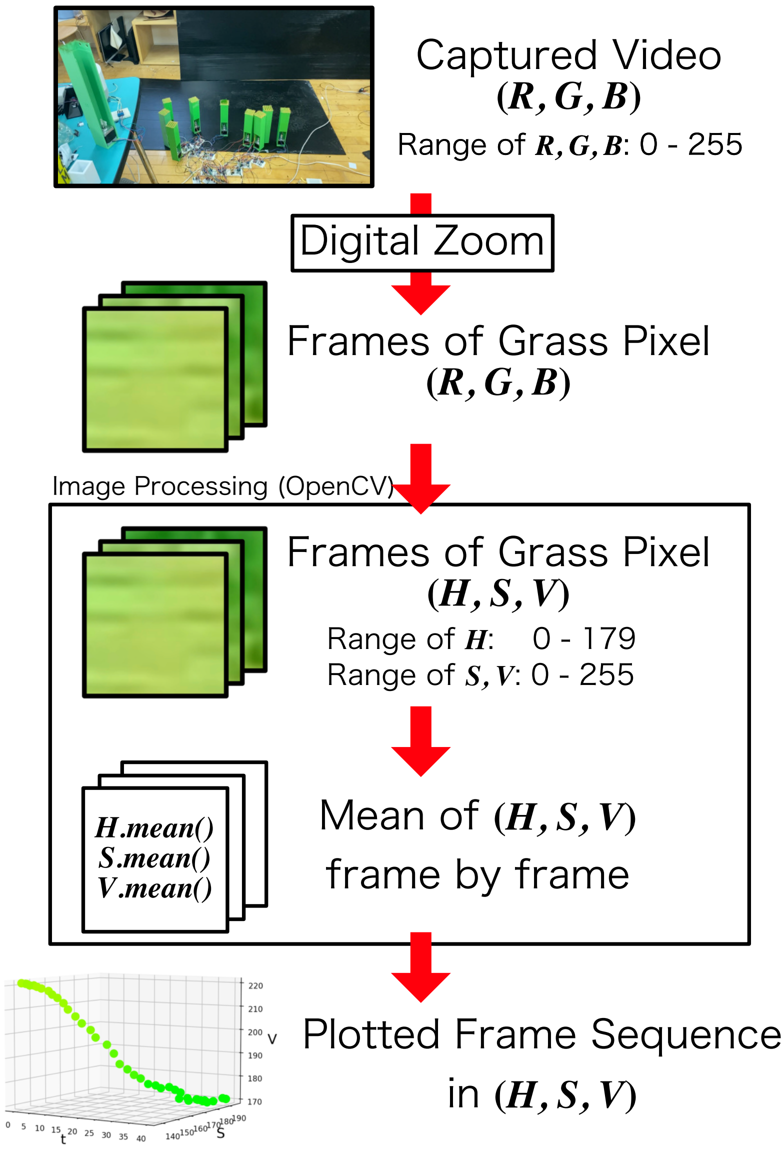


Figure 4.8: Method of Dynamic Grass Gradation Evaluation

Figure 4.8 shows the method of the dynamic grass gradation evaluation. In the experiments, the camera recorded the grass pixel that moved its length from 0 to 24 [mm] each angle. By using the captured videos, the grass gradations were plotted in the HSV color space through image processing.

Firstly, the captured videos were digitally zoomed to make the evaluation videos. The captured videos contained something other than the grass pixel. Then, as shown in Figure 4.9, the captured videos were zoomed to focus only the grass pixel surface by using a video edit software (DAVINCI RESOLVE [19]). In the evaluation, the resolutions of the original captured videos were 1920 × 1080 [px], and the captured videos were made about 41.7 times larger. Then, the zoomed videos were cropped 1000 × 1000 [px], and the cropped videos had only the grass pixel surface. Figure 4.10 shows the zoomed grass pixel each angle.

Secondly, the grass gradation was quantified frame by frame. The color spaces of the evaluation videos were converted from RGB to HSV. The convert equation of OpenCV is displayed below.

$$V = \max(R, G, B) \tag{4.1}$$

$$S = \begin{cases} \dfrac{V - \min(R,G,B)}{V} & (\text{if } V \neq 0) \\ 0 & (\text{otherwise}) \end{cases} \tag{4.2}$$

$$H = \begin{cases} 30(G-B)/(V-\min(R,G,B)) & \text{if } V = R \\ 60 + 30(B-R)/(V-\min(R,G,B)) & \text{if } V = G \\ 120 + 30(R-G)/(V-\min(R,G,B)) & \text{if } V = B \\ 0 & \text{if } R = G = B \end{cases} \tag{4.3}$$

where

$$0 \leq R, G, B \leq 255, 0 \leq S, V \leq 255, 0 \leq H \leq 179.$$

Then, the mean of the frame-by-frame HSV values were calculated as the quantified grass gradation because a color by spatial additive mixing is an average color with multiple colors.

Finally, the calculation results were plotted in the 3D space, then, the dynamic grass gradations can be visualized. The details of the graphs are explained in the next sub-section.

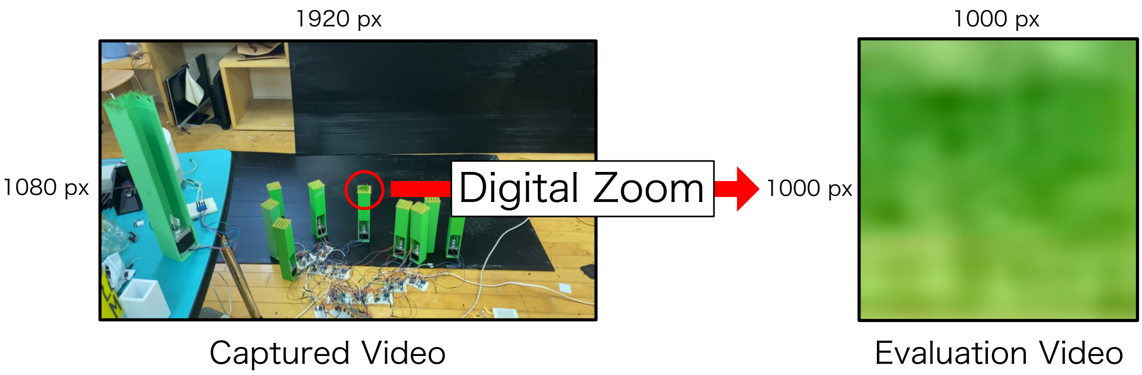


Figure 4.9: Digital Zoom of Grass Pixel

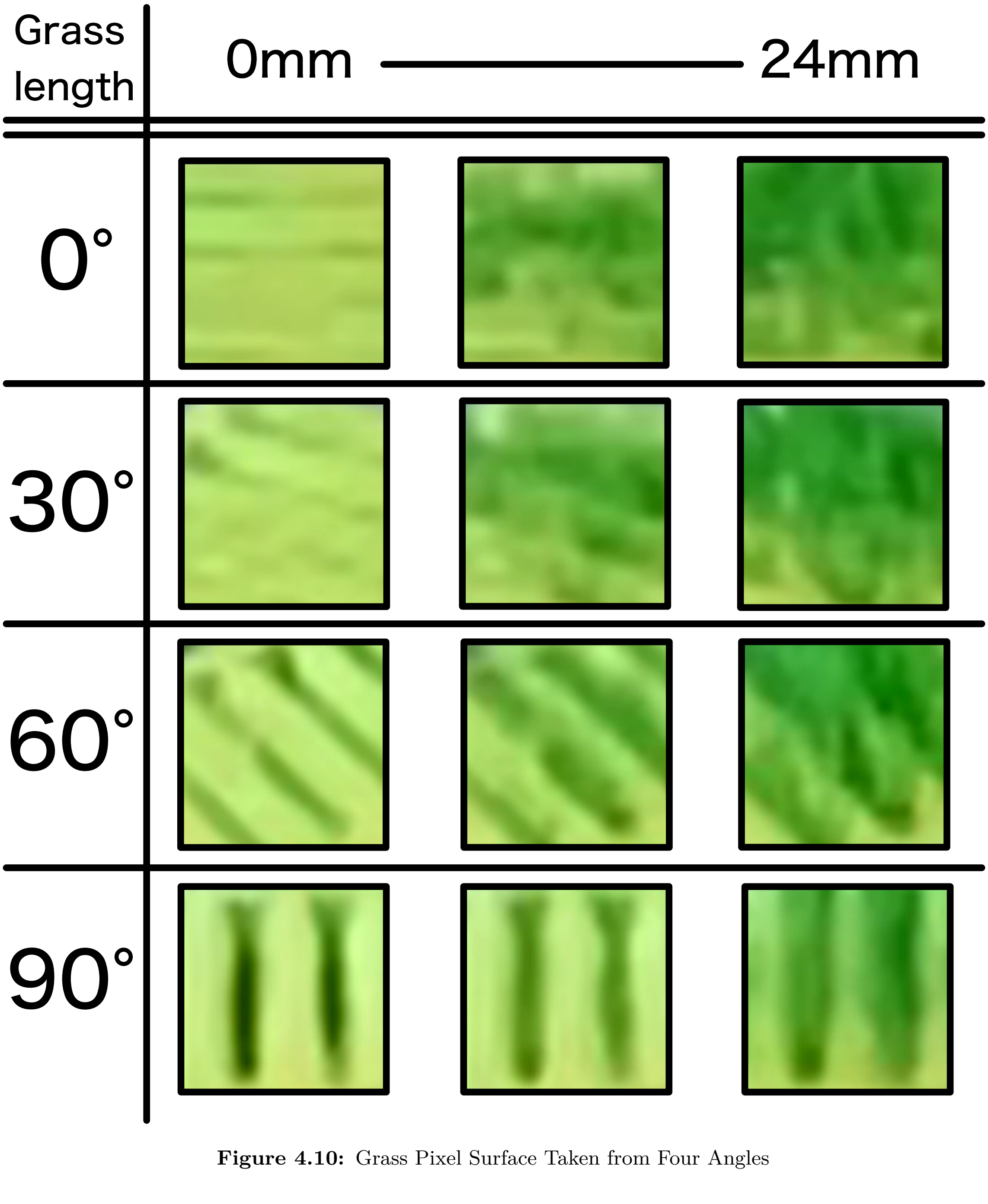


Figure 4.10: Grass Pixel Surface Taken from Four Angles

4.2.4 Result

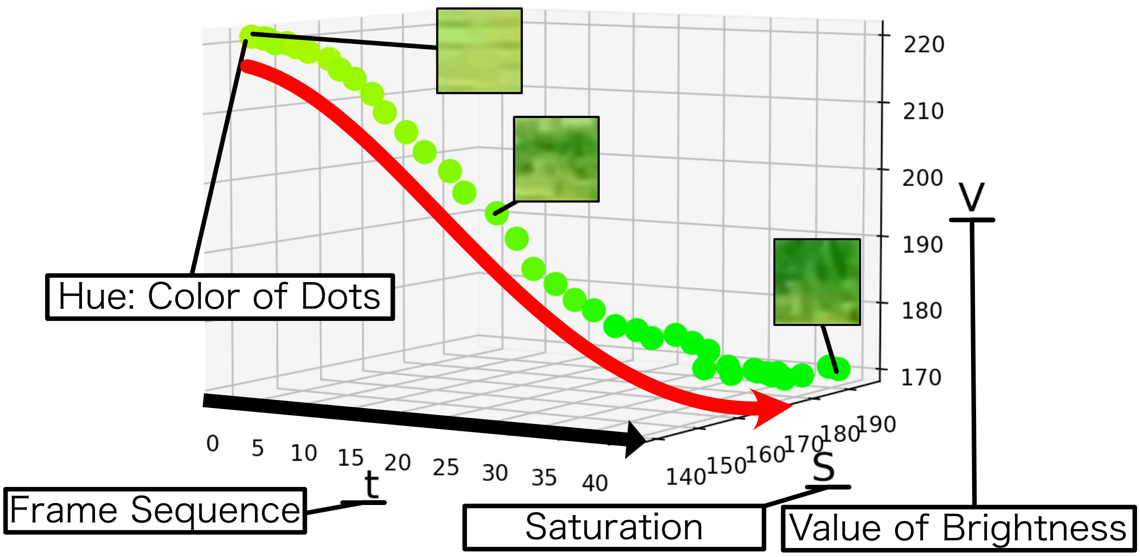


Figure 4.11: Example of Dynamic Grass Gradation Evaluation

Figure 4.11 shows how to read the graph of the dynamic grass gradation. All of the results were plotted by a visualization software with Python (Matplotlib [20]). t represents the frame sequence, and the black arrow shows the time direction of the evaluation videos. Then, when the frame sequence gets higher, the green grass length of the evaluation video becomes longer. For example, Figure 4.11 shows three frames of the evaluation video corresponding to each dot. H value is often represented by color, then, the color of the graph's dots expresses the H value. In addition, the S and V of the graph are values of saturation and brightness, respectively. Therefore, the red arrow of the graph can show the dynamic grass gradation.

Table 4.2, 4.3, 4.4, and 4.5 show the calculation results of Angle 0°, 30°, 60°, and 90°, respectively. In addition, Figure 4.12 shows all of the plotted results. As shown in Figure 4.12, the results of Angle 0°, 30°, and 60° were similar, however, the result of Angle 90° was different from the others.

In the evaluations of Angle 0°, 30°, and 60°, the HSV values monotonically increased or decreased. The S ranges of Angle 0°, 30°, and 60° were about 57, 53, and 53, and the V ranges of them were about 52, 56, 42, respectively.

In the evaluation of Angle 90°, the variation of the H values was similar to other results, however, the S and V values did not simply increase or decrease as shown in the A part of Figure 4.12. Moreover, the ranges of S and V were about 27 and 25, respectively. The S and V ranges were smaller than other results' S and V ranges. We suppose that the result of Angle 90° was caused by the slits of the grass pixel. At Angle 90°, the slits stood out from the other results as shown in the bottom part of Figure 4.10. Then, they affected the dynamic grass gradation changes of Angle 90°.

Table 4.2: Result of HSV Values with Frame Sequence at Angle 0°

t	H	S	V
0	40.99	139.06	220.97
1	40.81	139.58	220.84
2	41.08	138.59	220.83
3	41.01	138.20	220.31
4	41.01	138.80	220.32
5	40.82	138.75	219.78
6	40.86	139.48	219.18
7	40.86	142.06	218.02
8	41.01	142.34	216.62
9	41.24	143.56	215.24
10	41.17	145.53	213.01
11	41.79	146.19	210.35
12	42.57	148.99	207.36
13	43.32	151.11	204.41
14	43.97	154.86	201.42
15	44.92	156.06	198.31
16	45.55	161.56	194.79
17	46.20	164.23	190.83
18	46.70	166.09	186.30
19	47.56	169.17	183.84
20	47.88	171.68	181.34
21	48.74	174.19	179.54
22	49.11	177.27	176.98
23	49.42	180.55	176.11
24	50.26	182.10	174.82
25	50.73	185.94	174.86
26	51.33	187.93	173.61
27	51.48	189.69	172.22
28	52.04	186.28	170.20
29	51.75	190.12	170.01
30	52.13	188.52	169.23
31	51.47	192.33	169.46
32	51.69	190.47	169.58
33	51.96	190.58	169.52
34	52.14	190.76	169.63
35	52.31	186.93	169.80
36	52.38	187.62	169.35
37	52.04	189.85	169.68
38	51.61	194.59	170.56
39	51.48	194.80	170.22

Table 4.3: Result of HSV Values with Frame Sequence at Angle 30°

t	H	S	V
0	42.20	132.72	228.72
1	42.13	130.82	228.29
2	41.90	132.87	228.26
3	42.05	133.84	228.63
4	42.11	134.04	227.65
5	42.03	134.83	227.02
6	42.07	135.27	226.06
7	42.09	136.21	225.00
8	42.31	136.99	222.95
9	42.75	136.62	220.62
10	42.94	139.13	218.02
11	43.51	140.84	214.92
12	44.34	142.48	212.28
13	45.28	144.92	209.21
14	45.71	148.48	205.41
15	47.02	148.78	201.74
16	47.60	152.89	198.53
17	48.31	154.91	194.89
18	48.58	159.59	192.15
19	49.02	161.63	189.37
20	49.72	166.13	187.30
21	50.02	170.14	185.08
22	51.43	169.73	183.19
23	50.89	177.15	181.21
24	52.22	175.13	179.37
25	52.26	178.18	177.09
26	52.88	179.09	175.58
27	53.21	178.87	174.31
28	52.91	182.36	173.57
29	53.35	178.55	172.69
30	53.35	179.07	172.52
31	53.23	181.15	173.09
32	52.67	184.66	172.88
33	53.02	184.15	172.80
34	53.03	182.35	172.74
35	52.95	181.79	172.81
36	52.84	183.17	172.71
37	53.01	181.88	172.40
38	52.99	183.44	172.73
39	52.79	184.41	172.26

Table 4.4: Result of HSV Values with Frame Sequence at Angle 60°

t	H	S	V
0	43.06	138.93	226.10
1	43.03	138.76	226.07
2	43.10	138.30	225.71
3	42.93	138.38	224.98
4	42.91	140.20	224.56
5	42.88	140.42	223.55
6	42.85	141.11	222.21
7	43.06	143.37	220.62
8	43.32	145.57	218.91
9	43.23	148.48	217.14
10	43.50	148.90	214.87
11	44.09	149.96	212.21
12	44.68	152.78	210.12
13	45.03	156.49	208.36
14	45.70	157.26	205.60
15	46.53	162.41	203.46
16	47.16	164.87	201.26
17	47.93	168.83	199.26
18	48.66	172.63	197.07
19	48.98	174.18	194.85
20	49.49	176.28	192.40
21	49.75	177.86	191.26
22	50.38	177.83	189.22
23	50.22	181.24	188.25
24	50.23	185.08	188.46
25	50.96	185.73	186.02
26	51.12	185.98	185.26
27	50.83	186.46	185.62
28	51.37	187.69	184.02
29	51.33	187.66	183.44
30	50.96	186.69	184.60
31	51.27	187.81	183.48
32	51.42	189.12	184.17
33	51.40	186.41	183.47
34	51.10	189.57	183.35
35	51.06	190.19	183.25
36	51.04	190.05	183.41
37	50.93	190.87	183.89
38	51.11	189.59	183.34
39	51.24	186.59	185.02

Table 4.5: Result of HSV Values with Frame Sequence at Angle 90°

t	H	S	V
0	42.95	139.77	217.00
1	42.87	138.95	216.90
2	42.95	139.31	216.87
3	42.94	138.92	217.14
4	42.89	139.70	217.28
5	42.84	140.34	217.69
6	43.03	140.90	218.15
7	43.06	141.33	218.51
8	42.86	140.91	218.48
9	42.91	138.90	219.66
10	42.91	139.61	218.64
11	43.22	140.31	218.86
12	43.51	141.50	218.57
13	43.91	141.06	218.47
14	44.14	141.51	218.20
15	44.49	141.75	216.88
16	45.17	141.54	215.24
17	45.44	144.22	214.40
18	46.13	144.78	213.01
19	46.26	147.30	211.61
20	46.40	149.04	209.98
21	46.70	151.05	207.85
22	46.88	153.40	207.30
23	46.97	155.36	205.81
24	47.19	158.92	203.97
25	47.64	159.19	201.35
26	47.56	161.80	200.46
27	48.01	162.24	198.75
28	48.26	163.02	197.41
29	48.45	163.26	195.06
30	48.61	166.06	193.61
31	48.87	164.99	192.47
32	48.99	163.07	192.42
33	48.92	166.24	193.28
34	48.98	161.94	192.46
35	48.83	163.99	192.62
36	48.72	166.73	193.14
37	48.97	164.90	193.25
38	49.00	163.50	192.35
39	48.75	164.58	192.44

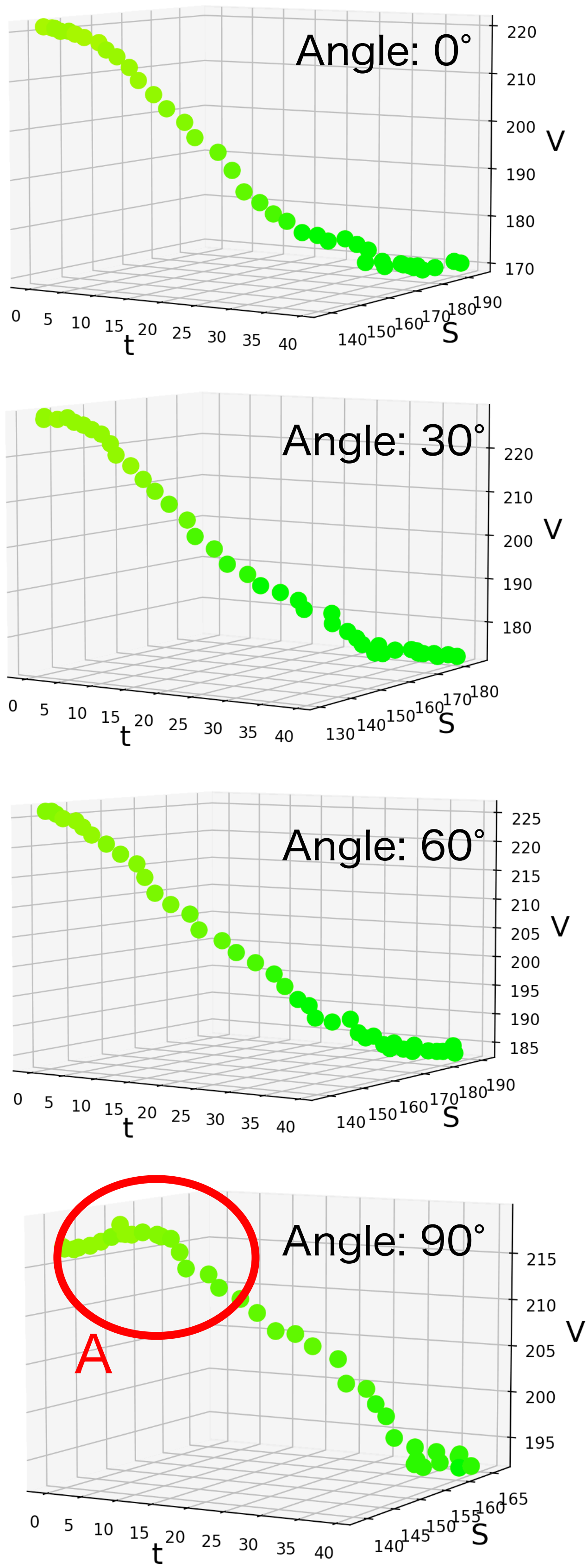


Figure 4.12: Plotted Variation of HSV Values of Grass Gradation for Each Angle

4.3 Example Animation

This section introduces several example animations using our grass method as a proof of concept. We created the following three examples to show gradation animation on the grass system: checkered pattern (Demo1), spiral (Demo2), and ware (Demo3). For the example animations, we developed a 3×3 grass animation display using nine grass pixels.

4.3.1 Animation System

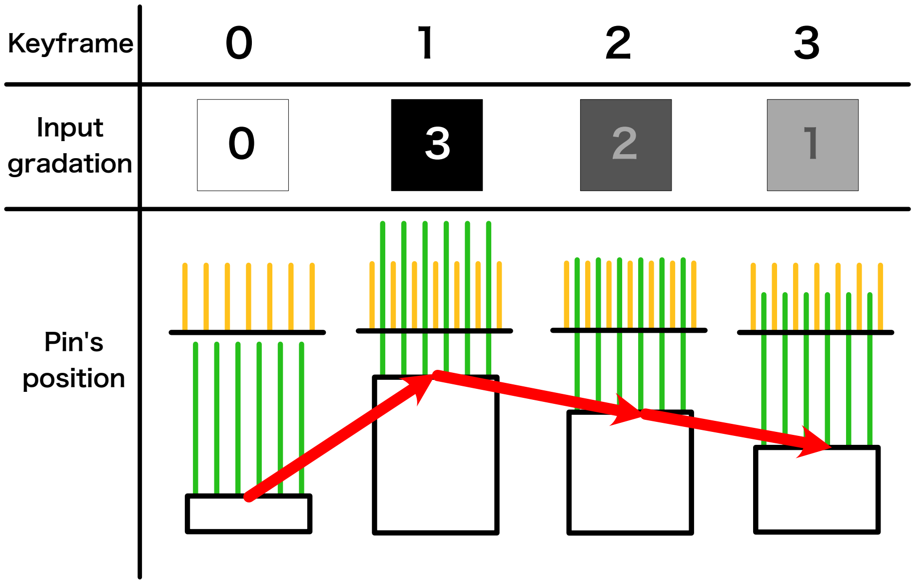


Figure 4.13: Keyframe Animation System of Grass Pixel

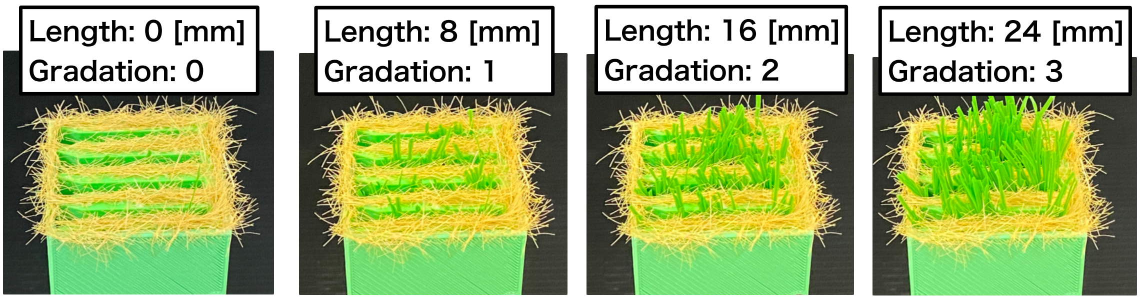


Figure 4.14: Grass Length Corresponding to Four Grass Gradation Scales

The grass pixel can change the grass gradation dynamically equal time intervals. Figure 4.13 shows the overview of the keyframe animation system of the grass pixel. In this animation system, four gradation scales were used as keyframes. For example, gradation scale 0, 3, 2, and 1 are input into the grass pixel system in turn as shown in Figure 4.13. In the animation experiments, as shown in Figure 4.14, we assigned the grass length (0, 8, 16, and 24 [mm]) for the gradation scale 0, 1, 2, and 3, respectively. Then, when the keyframe data of the gradation scales are entered into the animation system, the grass length also is set at each keyframe according to the input gradation scale. Finally, the grass length can be controlled according to the keyframe data. As a result, the grass animation display can play several gradation animations on the grass surface using the keyframe system. In the experiments, a keyframe data consists of 3×3 pixels with four gradation scales, and the grass animation display's keyframe interval is 1.0 [s].

4.3.2 Demonstration

Demo1: Checkered Pattern

As shown in Figure 4.15, the checkered pattern was displayed on the grass animation display. The animation is to see whether the grass animation display can switch between different binary images. Figure 4.16 shows the keyframes data of the checkered pattern. When the grass animation display played Demo1 animation, the checkered pattern changed smoothly.

Demo2: Spiral

Figure 4.17 shows that the grass animation display played the spiral animation. Demo2 confirms the grass animation display's ability to draw a path on the grass. The spiral path began from the top-left pixel of the grass animation display, and drew clockwise towards the display center as shown in Figure 4.18. The grass animation display can play the spiral animation clearly.

Demo3: Wave

Figure 4.19 shows the wave animation on the grass animation display. Demo3 checks that the grass animation display can show entire gradation animation. The wave movement started from the bottom-left pixel of the grass animation display as shown in Figure 4.20, and the movement of the wave spread from the bottom-left pixel of the grass animation display. The grass animation display can show the entire gradation animation in Demo3.

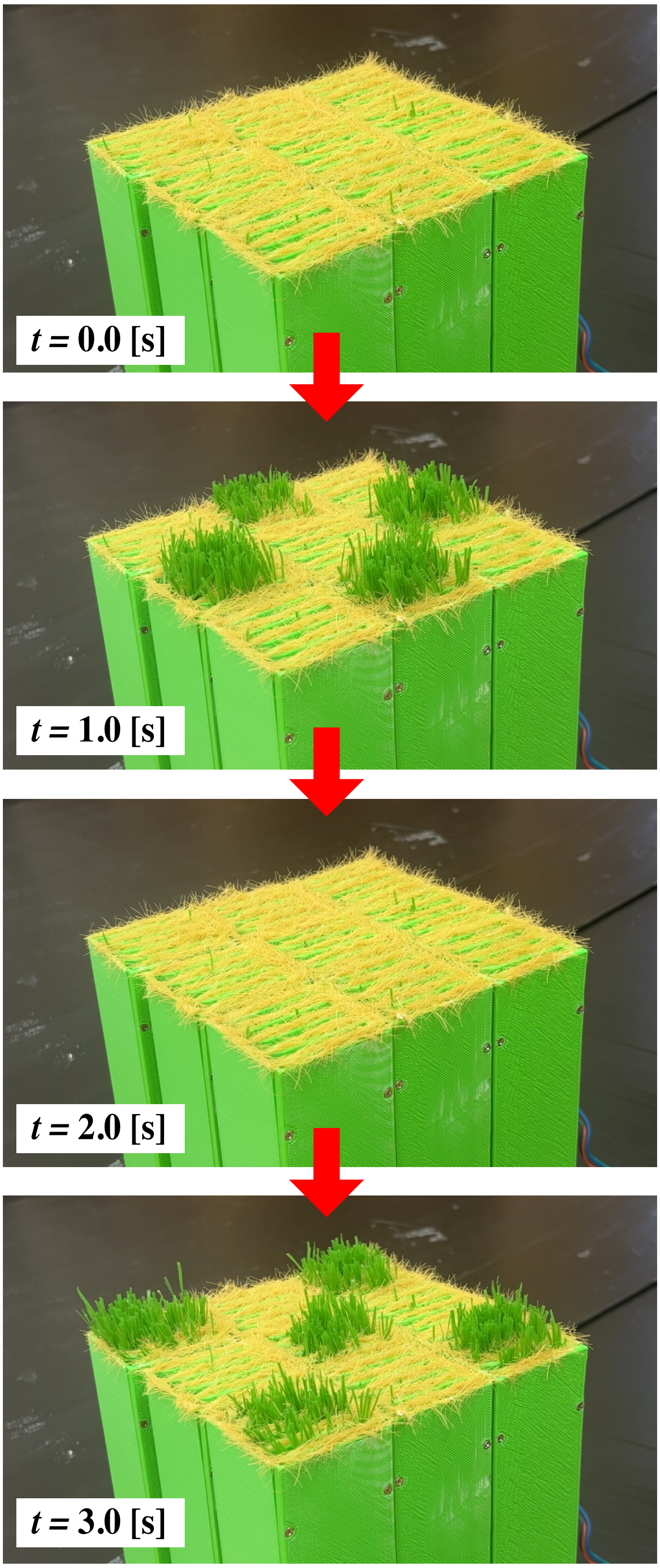


Figure 4.15: Example Animation of Checkered Pattern

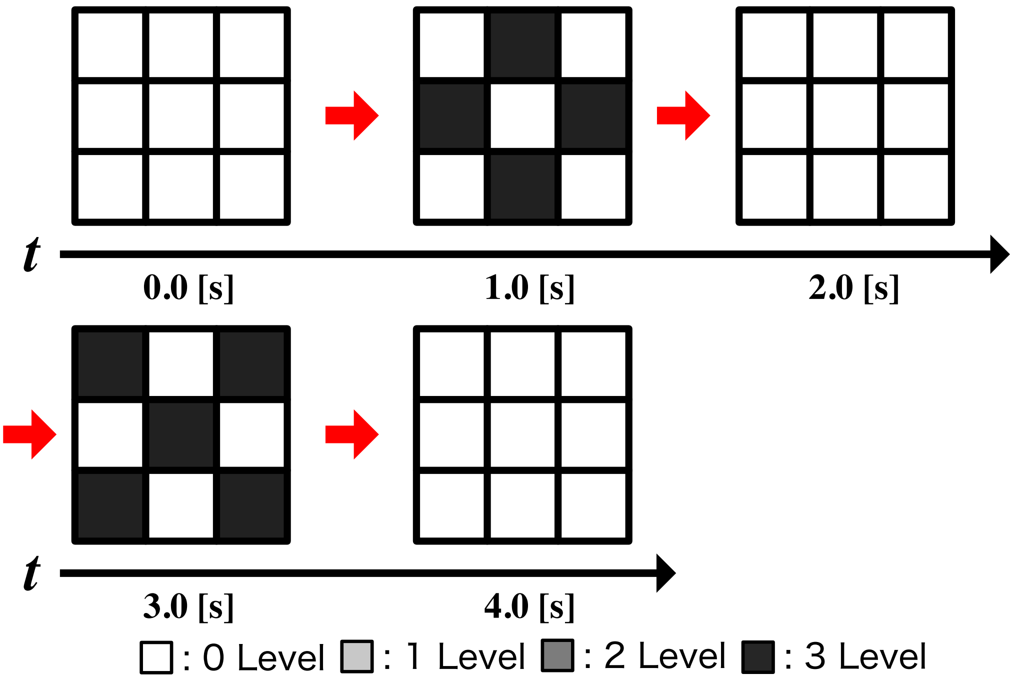


Figure 4.16: Keyframes of Checkered Pattern

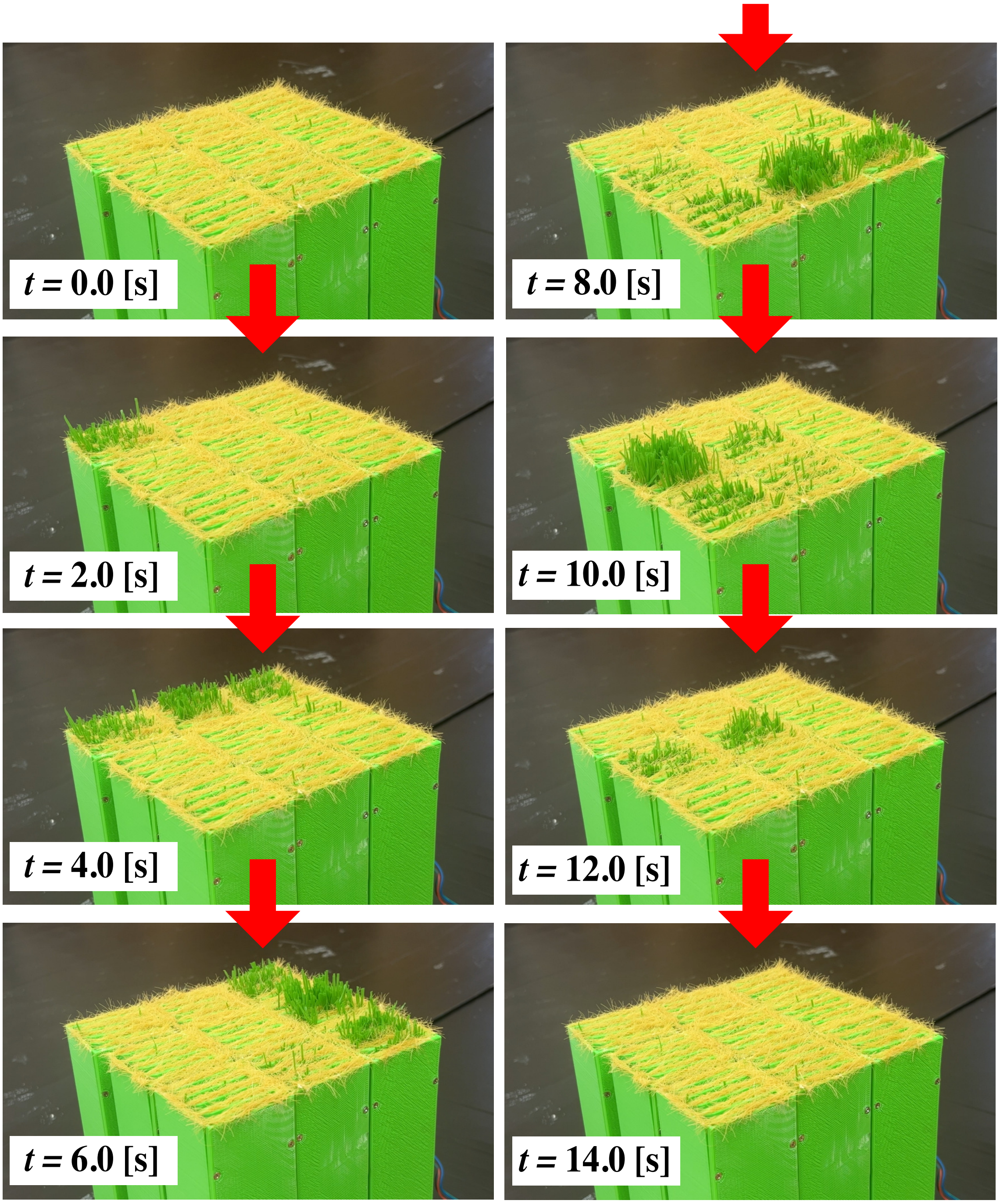


Figure 4.17: Example Animation of Spiral

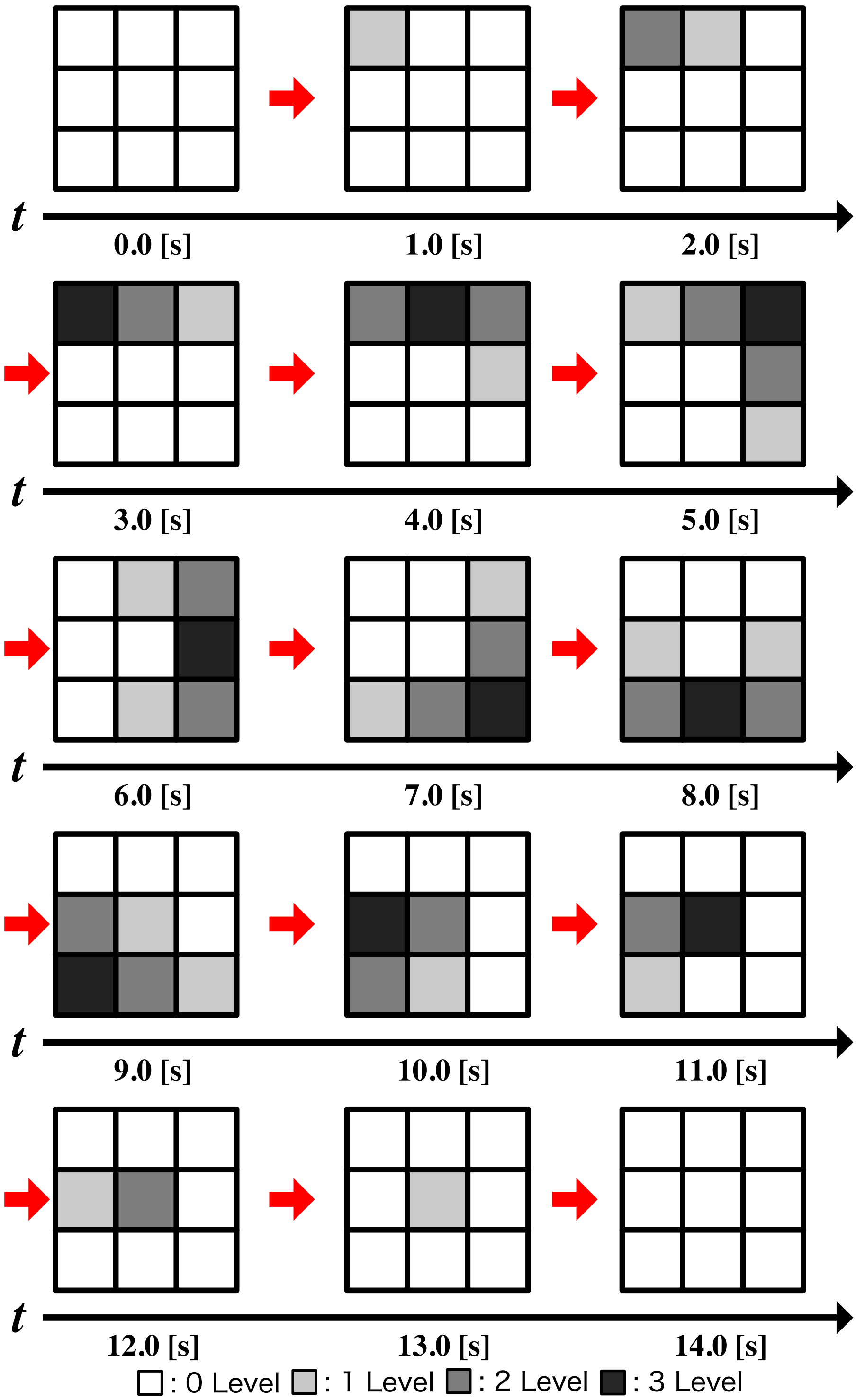


Figure 4.18: Keyframes of Spiral

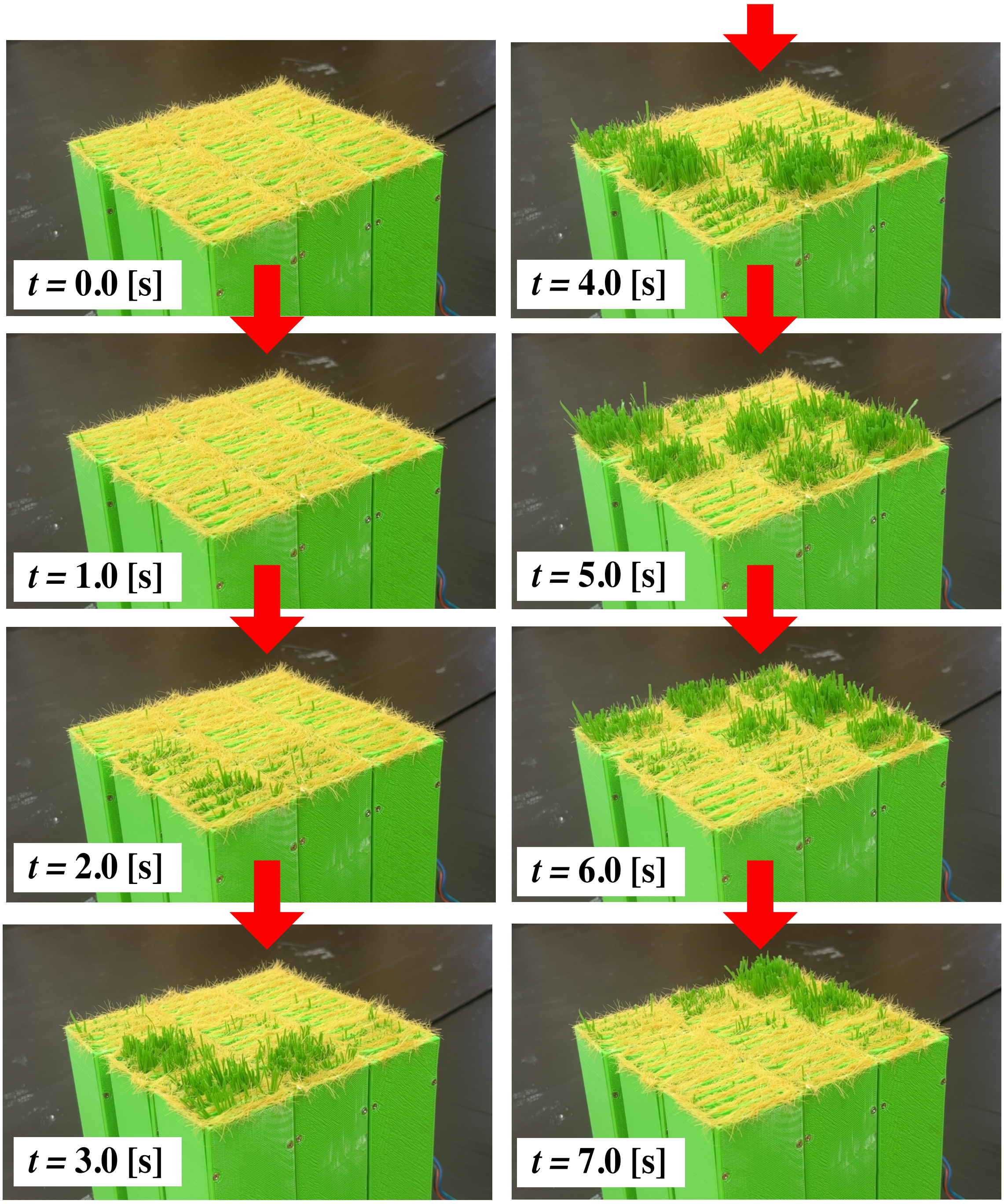


Figure 4.19: Example Animation of Wave

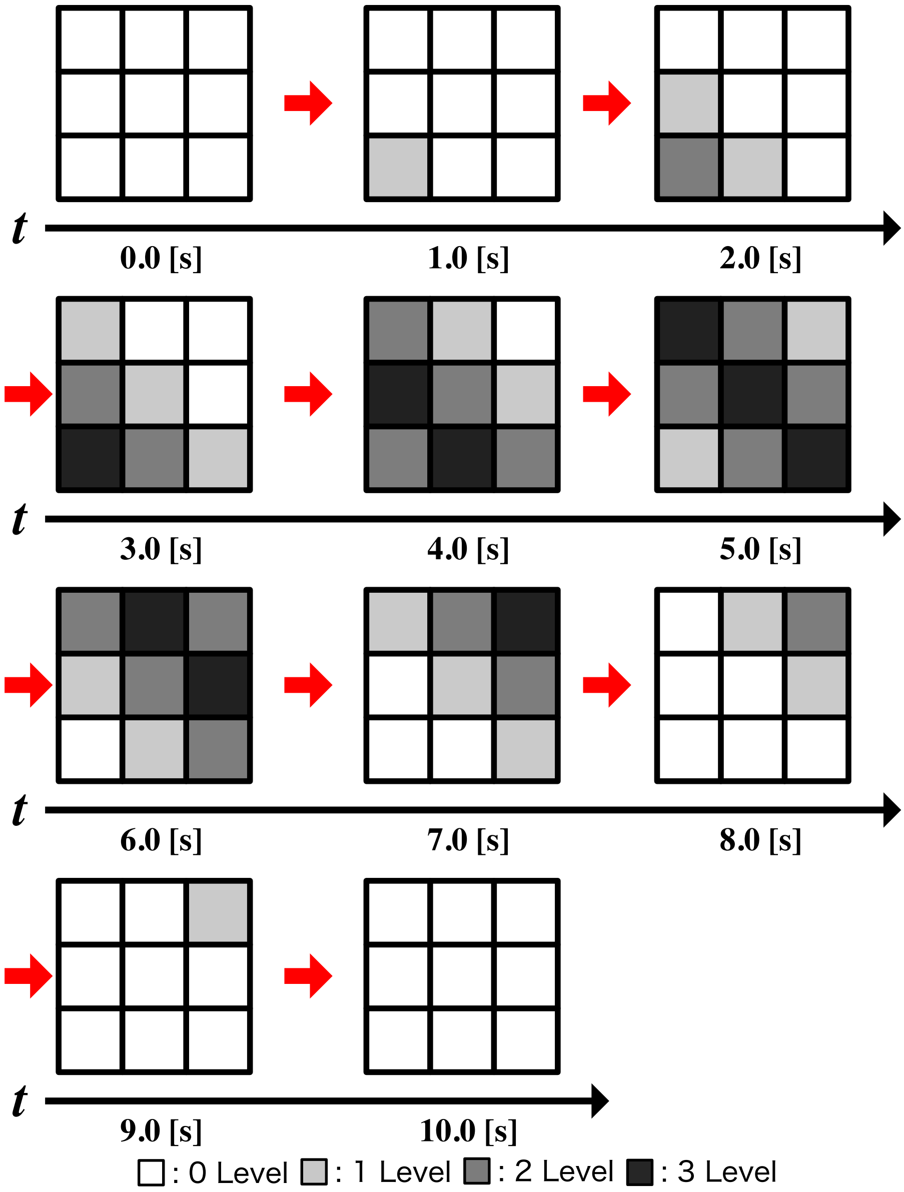


Figure 4.20: Keyframes of Wave

Chapter 5

Evaluation of Grass Gradation Scales

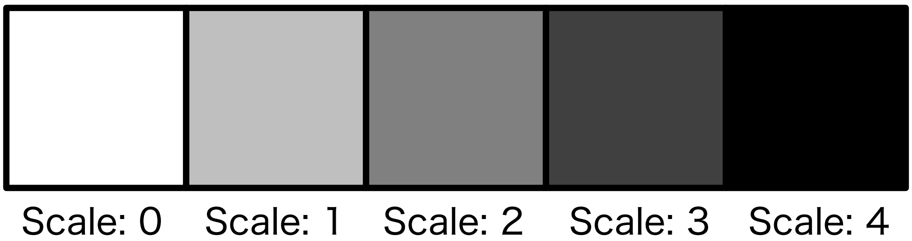


Figure 5.1: Gradation Scales

In the previous chapter, we created some example animations by setting the grass length corresponding to each grass gradation scale subjectively. To use the grass as the animation display, the grass gradation control system is needed to display correct gradation scales as shown in Figure 5.1. Then, in this chapter, we conducted an evaluation of the grass gradation scales focusing on the grass length. In the example animations, we defined 4 grass gradation scales subjectively. Through the animation experiments, we believed that the grass animation display can show more gradation scales. Then, the number of the grass gradation scales was set to 5 in the evaluation. In addition, in the previous evaluation using the HSV color space, the appearance of the grass gradation was different for each camera position, then, we evaluated the grass gradation scales of various positions.

5.1 CIELAB color space

A precision color evaluation is needed to evaluate the grass gradation scales. In Section 4.2, we quantified the grass gradation as HSV values to evaluate the grass gradation simply, however, a precision color evaluation cannot be conducted in the HSV color space because the color space does not into account human perception. Then, since CIELAB color space has visual uniformity, it is used in the grass gradation scales evaluation. This section introduces an overview of CIELAB color space and general color evaluation using the color space.

International Commission on Illumination (CIE) defines a color space to measure colors.

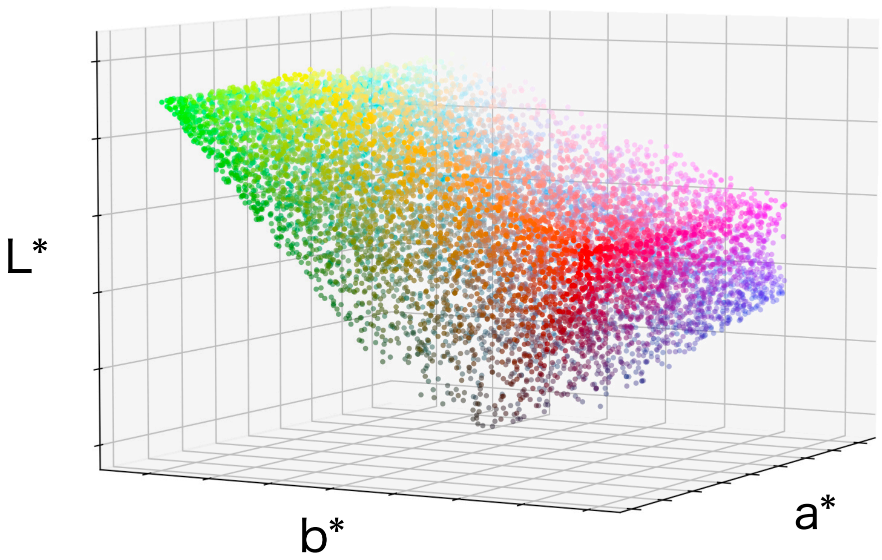


Figure 5.2: 3D CIELAB Model Based on RGB of OpenCV

The color space is CIE 1976 L*a*b* (CIELAB color space). L* is a parameter related to lightness. a* represents the complementary colors of red (+a*) and green (-a*), and b* represents the complementary colors of yellow (+b*) and blue (-b*). Figure 5.2 shows the 3D CIELAB model based on the RGB color space of OpenCV.

One of the CIELAB features is that a color difference based on human perception can be expressed. The color difference is a distance in a color space and is represented as a euclidean distance. For example, in the RGB color space, the color difference between two RGB values $(R_1, G_1, B_1), (R_2, G_2, B_2)$ is displayed as follow.

$$\text{Color Difference} = \sqrt{(R_2 - R_1)^2 + (G_2 - G_1)^2 + (B_2 - B_1)^2} \tag{5.1}$$

However, the color difference cannot be compared with other color differences in many color spaces because a range of colors that humans can distinguish is different for each color. To solve this problem, the CIELAB color space is designed based on human perception, then, allows the color difference to be compared with other color differences to evaluate color easily. This feature is the visual uniformity of the CIELAB color space.

The color evaluation using the CIELAB color space is useful to find out how similar a measured color is to a target color. The measured color is a color obtained by a measuring device such as a digital camera. The target color is a sample color compared with the measured color. The color difference between the measured color and the target color is used to evaluate the measured color as shown in Figure 5.3. The equation of the color difference between the measured color (L^*_m, a^*_m, b^*_m), and the target color (L^*_t, a^*_t, b^*_t) is displayed below.

$$\Delta E^* = \sqrt{(L^*_t - L^*_m)^2 + (a^*_t - a^*_m)^2 + (b^*_t - b^*_m)^2} \tag{5.2}$$

Then, ΔE^* is compared with a color tolerance of the target color. The color tolerance is a range of color differences between the measured color and the target color that can be regarded as the same color. As shown in Figure 5.3, the blue circle with the center as the target color represents the color tolerance. When the measured color is located outside of the blue circle, the color is different from the target color. In addition, the tolerance is set for each purpose of the color evaluation. Japan Industrial Standards (JIS) created the category of the color tolerance [21]. For example, the color tolerance is set to 20 when a pencil color is evaluated in the category. Therefore, the general CIELAB color evaluation can be conducted by comparing ΔE^* with the color tolerance, and is used in the grass gradation scales evaluation.

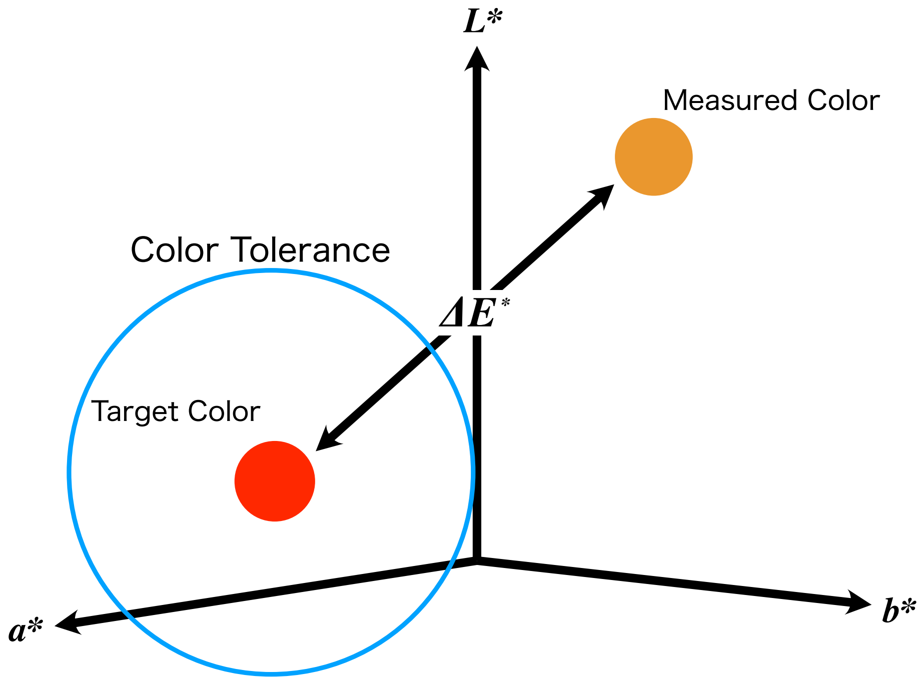


Figure 5.3: Example of Color Difference in CIELAB color space

5.2 Experimental Environment for Evaluation

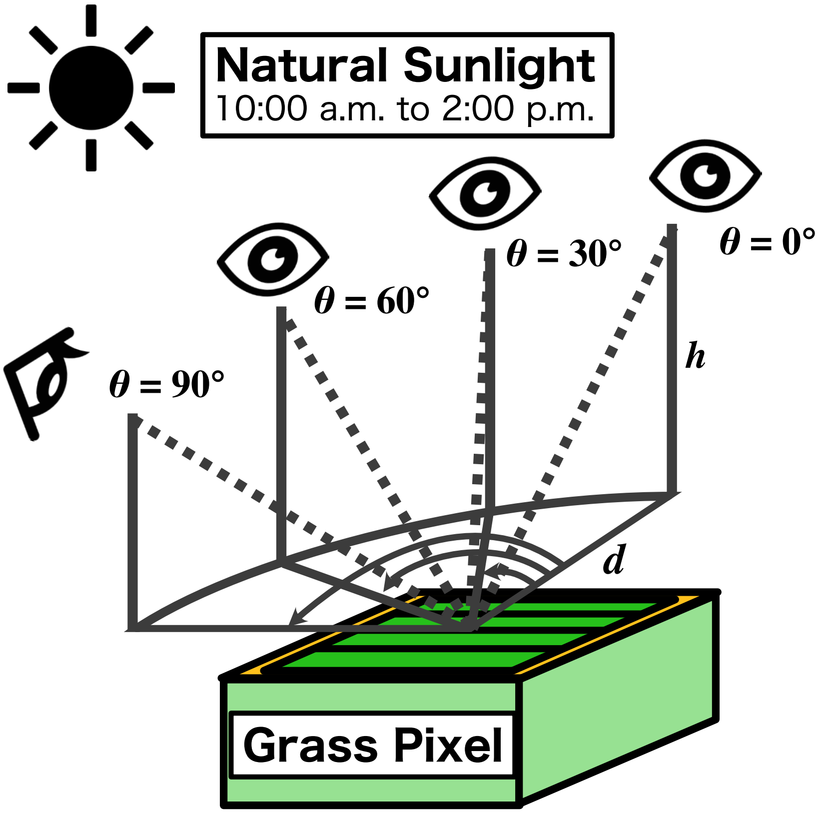


Figure 5.4: Environment of Grass Gradation Scales Evaluation

Figure 5.4 shows the environment of the evaluation. In the experiments, h, d, and θ represent the camera height, the distance between the grass pixel and the camera, and the horizontal angle between them, respectively. The evaluation camera was Nikon D7000 (16.9 [MP], f/1.8, 35 [mm], single focus lens), and the camera's white balance, exposure, and ISO speed were fixed. Since the viewer is assumed to be an adult, h was set to 1.6 and 1.7 [m]. d was set to 1.0, 2.0, and 3.0 [m] as the distance to see the grass gradation. Figure 5.5 shows the camera positions according to h and d each horizontal angle. θ was set to 0°, 30°, 60°, and 90° around the center of the grass pixel as in Section 4.2. When θ is 0° and 90°, the camera is perpendicular and parallel to the slits of the grass pixel, respectively. Therefore, the total number of the camera positions was 24 in the evaluation. To measure colors correctly, it is important to select a light source. Sato described that natural sunlight from 10:00 a.m. to 2:00 p.m. is suitable for the color evaluation in [22]. Then, the experiment was conducted between 10:00 a.m. to 2:00 p.m. on the outdoor field of University of Tsukuba, and the light source was the suitable natural sunlight. Figure 5.6 shows the scene of the evaluation on the outdoor field. In addition, the dates of the experiments when h was 1.6 and 1.7 [m] were different.

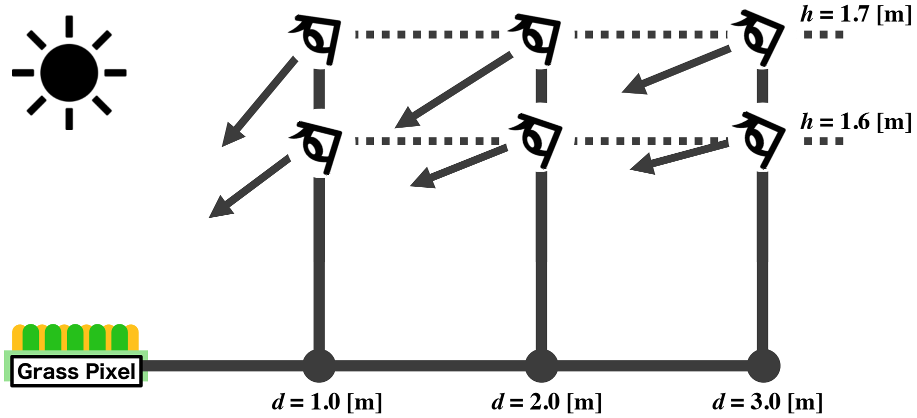


Figure 5.5: Camera Position for Each Horizontal Angle

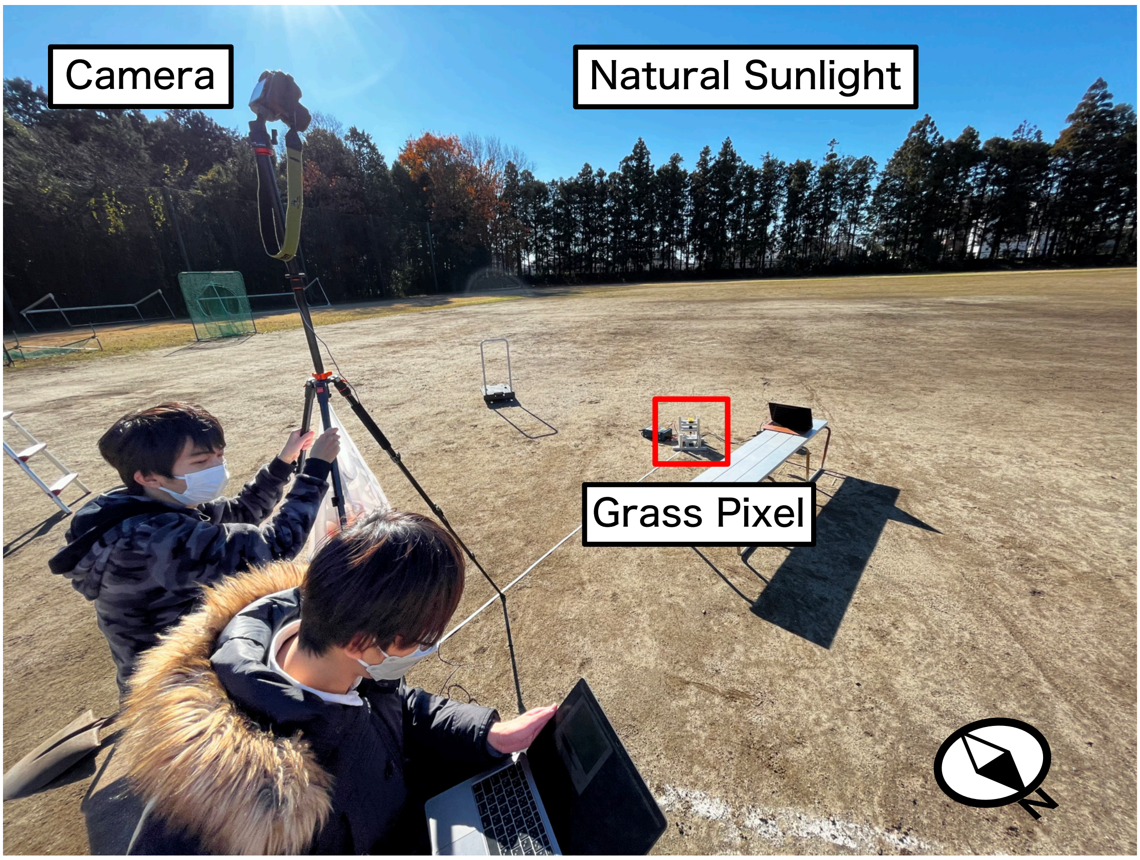


Figure 5.6: Scene of Grass Gradation Scales Evaluation

5.3 Hardware of Grass Pixel

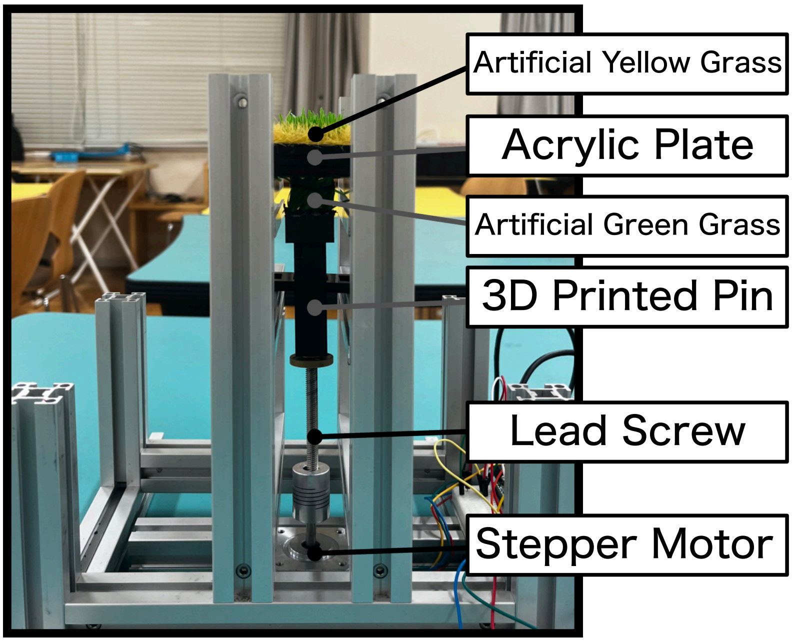


Figure 5.7: Grass Pixel for Grass Gradation Scales Evaluation

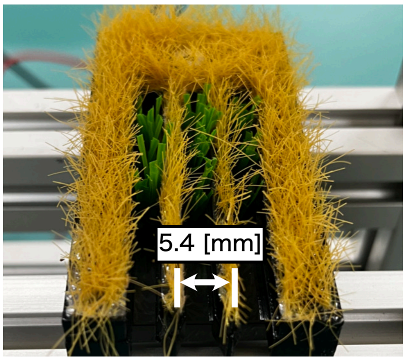


Figure 5.8: Slits of Grass Pixel

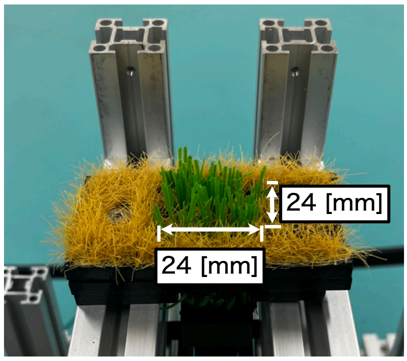


Figure 5.9: Area of Green Grass

A small and durable grass pixel was created to conduct the grass gradation scales outdoor efficiently. Figure 5.7 shows the grass pixel of the hardware specification in the evaluation. The grass pixel consists of a stepper motor (SM-42BYG011-25, 200 [step/rotation]), a lead screw with a nut (length: 100 [mm], pitch: 6 [mm], lead: 6 [mm]), a 3D printed pin (surface area: 24×24 [mm]), acrylic plates, artificial yellow grass (length: 10 [mm]) and artificial green grass (length: 50 [mm]). The yellow and green grass were planted on the acrylic plates and the 3D printed pin, respectively. As shown in Figure 5.8, the acrylic plates have three slits to move the green grass, and the width of the slit is 5.4 [mm]. The area of the grass pixel was 24×24 [mm] as shown in Figure 5.9. In the experiments, the green grass length can be controlled from 0 to 15 [mm]. To work the stepper motor, a microcontroller (Tennsy 3.5) was used via a motor driver (DRV8825).

5.4 Method for Evaluation

5.4.1 Measurement of Grass Gradation

Figure 5.10 shows the method of measuring the grass gradation of the grass pixel. Firstly, evaluation images were needed to calculate the CIELAB values of the grass gradations. The camera was located according to h, d, and θ, and the original image for evaluation was taken for each camera position. To measure the grass gradation correctly, it was needed to use the original image without the camera marker's unique image processing engine. Then, the camera captured the grass pixel as a raw image using a digital camera software (gPhoto2 [23]). Furthermore, using a python raw image management software (rawpy [24]), the raw image was developed in sRGB (standard–RGB), which is a camera device-independent RGB color space. The rawpy software is a python wrapper for the LibRaw [25]. The ranges of R, G, and B values were from 0 to 255, and the resolution of the developed original image is 4948×3280 [px]. Figure 5.11 shows the example of the developed original image. To decide the calculation area of the grass pixel surface, the developed image was cropped. The shape of the cropped area was square, and the area included only the grass pixel surface. Moreover, the crop range was different for each camera position. The cropped image was the evaluation image.

Secondly, the grass gradation was measured as the CIELAB values using the evaluation image. The means of the sRGB values in the evaluation image were calculated. To convert the sRGB values to the CIELAB values, it is needed to convert the sRGB values to the values of the CIE 1931 color space (CIE XYZ). The sRGB values to CIE XYZ values convert equation is displayed below.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \begin{bmatrix} f(R/255) \\ f(G/255) \\ f(B/255) \end{bmatrix} \tag{5.3}$$

where

$$f(t) = \begin{cases} t/12.92 & \text{if } t \leq 0.04045 \\ ((t+0.055)/1.055)^{2.4} & \text{otherwise} \end{cases} \tag{5.4}$$

where

$$0 \leq R, G, B \leq 255, \;\; 0 \leq X, Y, Z \leq 1.0, \;\; X + Y + Z = 1$$

Next, the CIELAB values were calculated using the XYZ values by the following equation.

$$L^* = 116 g(Y/Y_n) - 16 \tag{5.5}$$

$$a^* = 500[g(X/X_n) - g(Y/Y_n)] \tag{5.6}$$

$$b^* = 200[g(Y/Y_n) - g(Z/Z_n)] \tag{5.7}$$

where

$$g(t) = \begin{cases} t^{1/3} & \text{if } t > 0.008856 \\ 7.787t + 16/116 & \text{otherwise} \end{cases} \tag{5.8}$$

where X_n, Y_n and Z_n are XYZ values of white reference illuminant normalized by Y. Since the white point of sRGB is defined by Illuminant D65, the following XYZ values of D65 white point were adopted as X_n, Y_n and Z_n. Finally, the means of CIELAB values were calculated from the evaluation image as the quantified grass gradation.

$$X_n = 0.95047 \tag{5.9}$$
$$Y_n = 1.0000 \tag{5.10}$$
$$Z_n = 1.08883 \tag{5.11}$$

In the experiment, to measure the grass gradation according to the grass length, the grass pixel system was needed to move its length at regular length intervals. Since the lead length of the lead screw was 6 [mm/rotation], and the resolution of the stepper motor was 200 [step/rotation], the grass length can be controlled by 3/100 [mm/step]. In this case, it took 500 [step] when the grass length was moved from 0 to 15 [mm]. Then, in the experiments, the stepper motor worked from 0 to 500 [step] at 25-step intervals, and the grass gradation was measured each time. In other words, the grass gradation of the grass pixel was measured at 0.75-mm intervals, and 21 grass gradations were quantified as the average CIELAB values for each camera position.

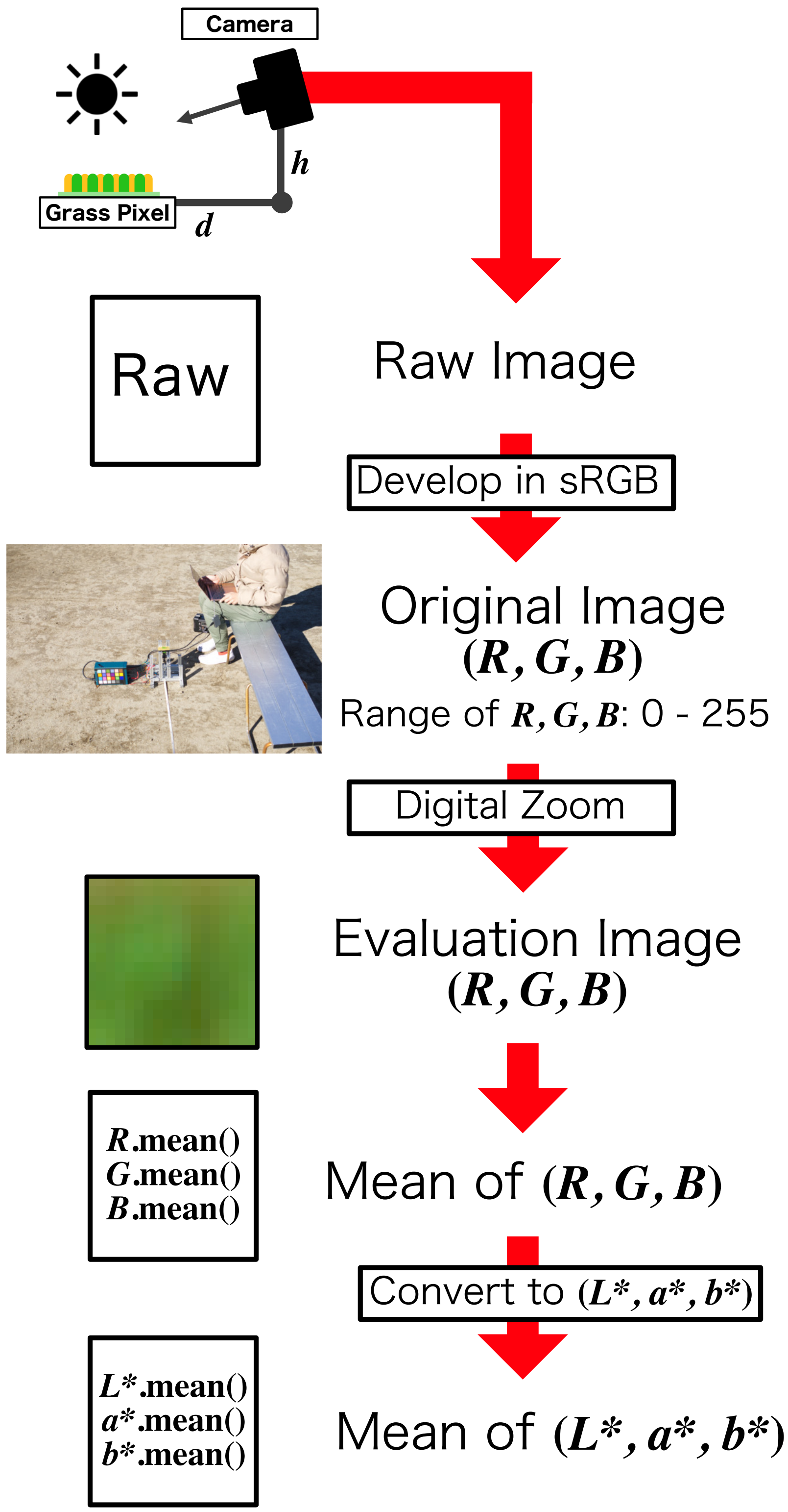


Figure 5.10: Measurement of Grass Gradation

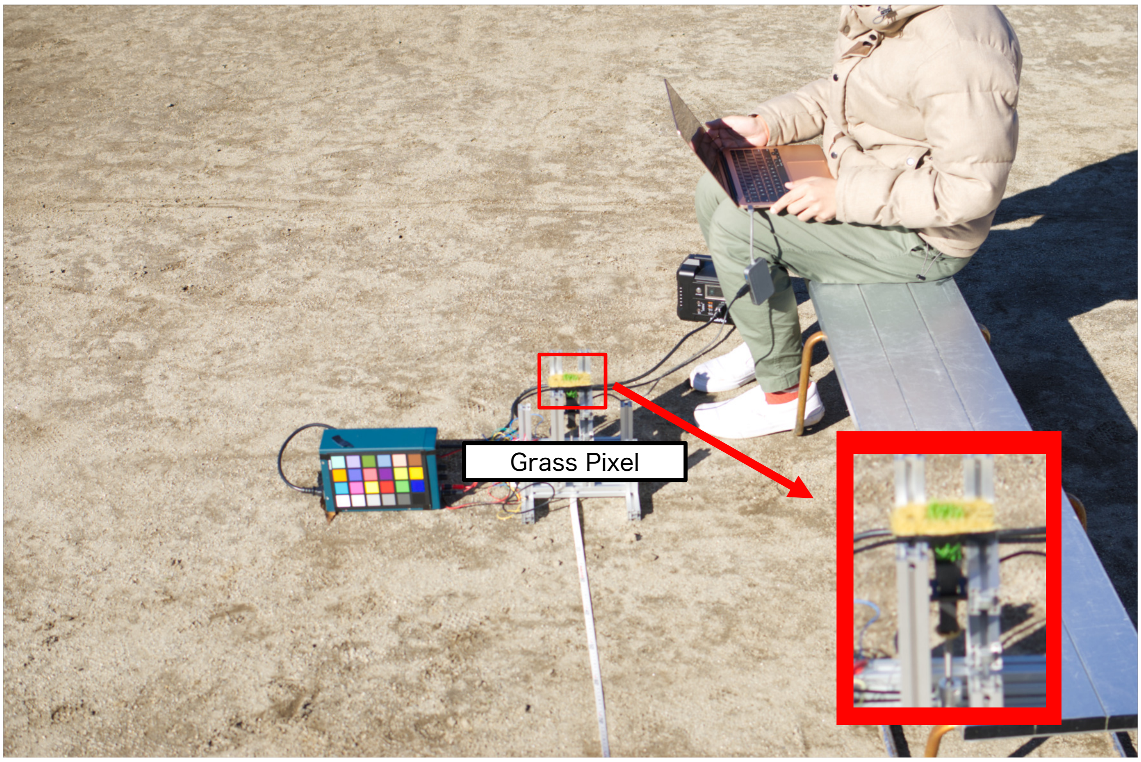


Figure 5.11: Example of Developed Original Image

5.4.2 Defining Target Grass Gradation Value

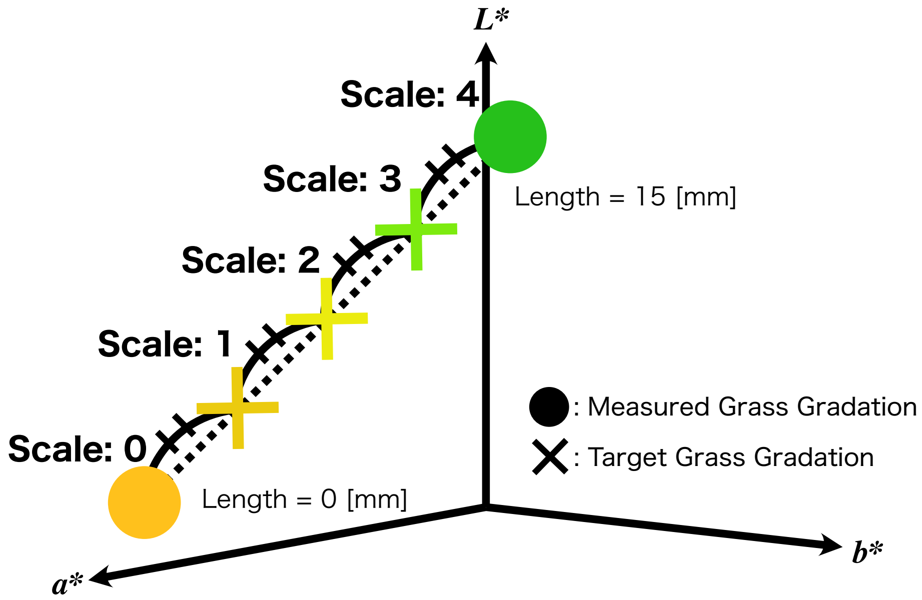


Figure 5.12: Target Grass Gradation Values

This subsection explains how to define a target grass gradation value $G_n(L_n^*, a_n^*, b_n^*)$ for each gradation scale, which is a target color values compared with the measured grass gradation value. In the experiments, the number of the grass gradation scales was five, then, G_0 and G_4 were set to the measured grass gradation values when the grass length was 0 and 15 [mm] respectively. In addition, the other target gradation values G_1, G_2, and G_3 were calculated by using G_0 and G_4. In the CIELAB color space, gradation scales such as Figure 5.1 can be defined by keeping the color difference between neighboring CIELAB values constant. Then, the equation of the target gradation values $G_n(L_n^*, a_n^*, b_n^*)$ is displayed below.

$$L_n^* = \frac{n}{5}(L_4^* - L_0^*) + L_0^* \tag{5.12}$$

$$a_n^* = \frac{n}{5}(a_4^* - a_0^*) + a_0^* \quad (n = 0, 1, 2, 3, 4) \tag{5.13}$$

$$b_n^* = \frac{n}{5}(b_4^* - b_0^*) + b_0^* \tag{5.14}$$

Finally, the target grass gradation values $G_n(L_n^*, a_n^*, b_n^*)$ can be defined. The target grass gradation values were calculated according to $h, d,$ and θ because G_0 and G_4 were different for each camera position, respectively.

5.4.3 Comparison between Color Difference and Color Tolerance

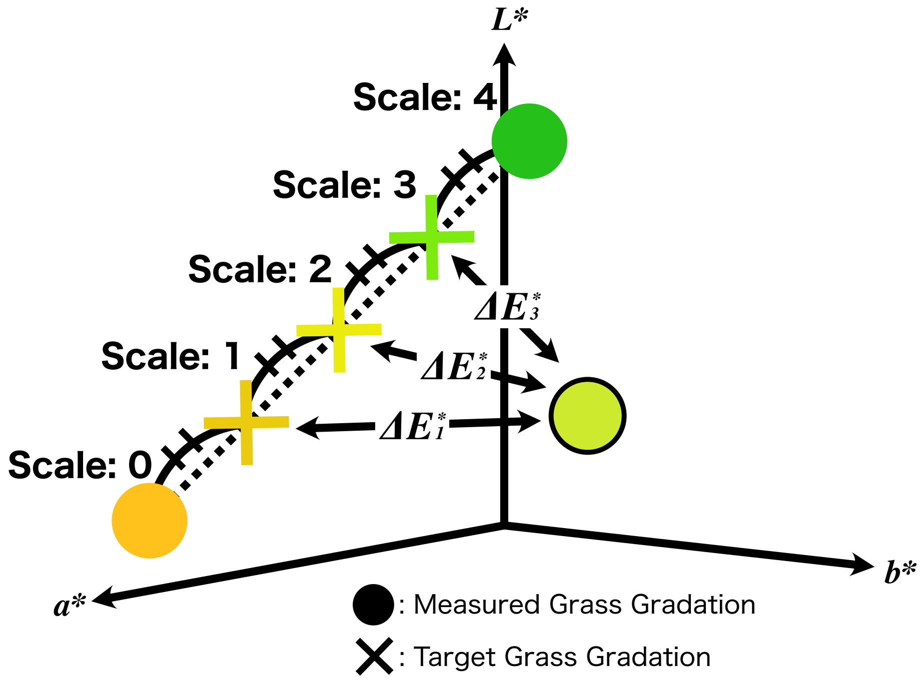


Figure 5.13: Comparison between Measured and Target Grass Gradation

In this subsection, we reveal whether the grass pixel can display five gradation scales by comparing the measured values with the target values for each camera position.

Firstly, the color difference between the measured and target values was calculated as shown in Figure 5.13. In the evaluation, the color differences between the measured values and G_1, G_2, and G_3 were set to $\Delta E_1^*, \Delta E_2^*$, and ΔE_3^*, respectively. In addition, the color differences of G_0 and G_4 were not needed because the grass gradation scale 0 and 4 were defined by the measured values when the grass length was the minimum (0 [mm]) and the maximum (15 [mm]). Then, the minimums of $\Delta E_1^*, \Delta E_2^*$, and ΔE_3^* were calculated to obtain the measured values closest to G_1, G_2, and G_3, respectively.

Secondly, the minimum of $\Delta E_1^*, \Delta E_2^*$, and ΔE_3^* were compared with the color tolerance. It was necessary to select a color tolerance for an grass animation display. In the evaluation, the category of the color tolerance created by Japan Industrial Standards (JIS) was used [21], then, we adopted the color tolerance of 5 defined as the color difference between two colors that can be regarded as nearly identical when they are compared over time. Therefore, when the minimums of $\Delta E_1^*, \Delta E_2^*$, and ΔE_3^* were contained within five as the color tolerance, the grass pixel can display five gradation scales in the experiments.

Finally, these comparisons were calculated for each camera position to investigate whether the grass pixel can show five gradation scales. Moreover, the grass length corresponding to each gradation scale was obtained when the grass pixel can display five gradation scales.

5.5 Results

Table 5.1 and 5.2 show the target grass gradation values according to the camera height of 1.6 and 1.7 [m] respectively. The target grass gradation values were calculated by using Eqs. (5.12, 5.13, 5.14) and the measured values when the grass length was the minimum and the maximum according to h, d, θ. Then, $\Delta E_1^*, \Delta E_2^*$, and ΔE_3^* based on h, d, θ were obtained by using the target grass gradation values. In addition, all measured grass gradation values and the color differences are listed in Appendix.

Table 5.1: Target Grass Gradation Values ($h = 1.6$)

d [m]	θ [degree]	$G_0(L_0^*, a_0^*, b_0^*)$	$G_1(L_1^*, a_1^*, b_1^*)$	$G_2(L_2^*, a_2^*, b_2^*)$
1.0	0	[35.42, -1.22, 25.46]	[34.28, -6.17, 26.77]	[33.13, -11.12, 28.08]
2.0	0	[40.03, 0.22, 28.59]	[39.40, -6.49, 30.24]	[38.77, -13.21, 31.89]
3.0	0	[56.08, 1.45, 38.82]	[54.24, -6.3, 39.53]	[52.40, -14.05, 40.24]
1.0	30	[32.84, -2.19, 24.81]	[32.58, -7.17, 26.84]	[32.31, -12.14, 28.86]
2.0	30	[49.19, -0.82, 34.29]	[46.04, -6.87, 34.53]	[42.89, -12.92, 34.78]
3.0	30	[52.82, 0.39, 35.66]	[50.77, -6.43, 36.73]	[48.72, -13.26, 37.81]
1.0	60	[39.61, -3.4, 28.53]	[38.84, -8.63, 30.46]	[38.07, -13.87, 32.39]
2.0	60	[50.98, -1.8, 33.78]	[49.24, -8.02, 35.41]	[47.50, -14.24, 37.04]
3.0	60	[52.30, -0.16, 35.00]	[49.89, -6.64, 35.93]	[47.47, -13.12, 36.85]
1.0	90	[33.85, -2.6, 24.31]	[32.45, -6.18, 25.28]	[31.05, -9.76, 26.24]
2.0	90	[31.66, -1.45, 22.93]	[32.07, -5.82, 25.05]	[32.49, -10.19, 27.17]
3.0	90	[43.19, -0.85, 29.63]	[42.17, -4.97, 30.56]	[41.16, -9.08, 31.49]

d [m]	θ [degree]	$G_3(L_3^*, a_3^*, b_3^*)$	$G_4(L_4^*, a_4^*, b_4^*)$
1.0	0	[31.98, -16.08, 29.38]	[30.83, -21.03, 30.69]
2.0	0	[38.14, -19.93, 33.54]	[37.50, -26.65, 35.18]
3.0	0	[50.56, -21.8, 40.94]	[48.72, -29.55, 41.65]
1.0	30	[32.05, -17.12, 30.88]	[31.79, -22.1, 32.90]
2.0	30	[39.75, -18.98, 35.02]	[36.60, -25.03, 35.27]
3.0	30	[46.67, -20.08, 38.89]	[44.62, -26.9, 39.97]
1.0	60	[37.30, -19.1, 34.32]	[36.52, -24.33, 36.25]
2.0	60	[45.76, -20.46, 38.67]	[44.03, -26.68, 40.30]
3.0	60	[45.05, -19.61, 37.78]	[42.64, -26.09, 38.71]
1.0	90	[29.66, -13.34, 27.20]	[28.26, -16.91, 28.16]
2.0	90	[32.90, -14.56, 29.29]	[33.32, -18.93, 31.41]
3.0	90	[40.14, -13.19, 32.42]	[39.13, -17.3, 33.35]

Table 5.2: Target Grass Gradation Values ($h = 1.7$)

d [m]	θ [degree]	$G_0(L_0^*, a_0^*, b_0^*)$	$G_1(L_1^*, a_1^*, b_1^*)$	$G_2(L_2^*, a_2^*, b_2^*)$
1.0	0	[49.65, -1.40, 33.80]	[48.10, -8.24, 35.35]	[46.55, -15.07, 36.90]
2.0	0	[57.37, -0.34, 37.91]	[54.95, -8.06, 39.10]	[52.53, -15.79, 40.28]
3.0	0	[64.66, 1.96, 43.85]	[61.68, -5.71, 43.45]	[58.69, -13.37, 43.05]
1.0	30	[47.69, -1.72, 32.70]	[45.95, -8.57, 34.37]	[44.21, -15.42, 36.04]
2.0	30	[56.58, 0.18, 37.90]	[54.13, -7.61, 39.08]	[51.69, -15.40, 40.26]
3.0	30	[62.59, 0.46, 40.55]	[59.75, -7.43, 41.80]	[56.91, -15.31, 43.04]
1.0	60	[43.51, -2.48, 31.03]	[42.05, -8.42, 32.48]	[40.58, -14.36, 33.92]
2.0	60	[53.37, -1.75, 35.20]	[51.53, -9.02, 37.10]	[49.69, -16.29, 39.00]
3.0	60	[58.23, 0.43, 39.41]	[57.12, -6.59, 41.09]	[56.00, -13.62, 42.77]
1.0	90	[38.88, -1.13, 28.41]	[39.75, -6.40, 31.17]	[40.63, -11.67, 33.93]
2.0	90	[44.58, 3.46, 34.09]	[46.30, -2.72, 36.52]	[48.02, -8.89, 38.94]
3.0	90	[54.20, -2.56, 34.90]	[52.45, -7.30, 36.18]	[50.70, -12.04, 37.47]

d [m]	θ [degree]	$G_3(L_3^*, a_3^*, b_3^*)$	$G_4(L_4^*, a_4^*, b_4^*)$
1.0	0	[45.00, -21.91, 38.45]	[43.45, -28.75, 40.00]
2.0	0	[50.12, -23.51, 41.46]	[47.70, -31.23, 42.64]
3.0	0	[55.70, -21.03, 42.65]	[52.71, -28.69, 42.25]
1.0	30	[42.47, -22.28, 37.71]	[40.73, -29.13, 39.38]
2.0	30	[49.24, -23.19, 41.44]	[46.80, -30.98, 42.63]
3.0	30	[54.06, -23.20, 44.28]	[51.22, -31.08, 45.52]
1.0	60	[39.11, -20.30, 35.37]	[37.65, -26.25, 36.82]
2.0	60	[47.85, -23.55, 40.90]	[46.01, -30.82, 42.80]
3.0	60	[54.89, -20.64, 44.45]	[53.77, -27.67, 46.14]
1.0	90	[41.50, -16.95, 36.69]	[42.38, -22.22, 39.44]
2.0	90	[49.74, -15.07, 41.37]	[51.46, -21.25, 43.80]
3.0	90	[48.95, -16.79, 38.76]	[47.20, -21.53, 40.04]

Table 5.3 and 5.4 show the minimums of ΔE_1^*, ΔE_2^*, and ΔE_3^* according to h, d and θ. The tables were created based on the color differences listed in Appendix. Most of the minimum color differences were under five that was the color tolerance. Therefore, the grass pixel can show five grass gradation scales to most camera positions in the evaluation. However, when (h, d, θ) was (1.6 3.0, 90) and (1.7, 3.0, 90), the minimum of ΔE_2^* was 6.16, 5.13, respectively. These minimum color differences were over the color tolerance.

Table 5.3: Minimum of Each Color Difference ($h = 1.6$)

d [m]	θ [degree]	min(ΔE_1^*)	min(ΔE_2^*)	min(ΔE_3^*)
1.0	0	2.34	1.51	1.15
1.0	30	2.13	1.46	0.70
1.0	60	2.39	0.98	0.92
1.0	90	1.96	3.31	1.81
2.0	0	1.06	0.86	2.15
2.0	30	2.67	2.78	0.34
2.0	60	1.80	2.83	0.70
2.0	90	1.69	4.28	2.96
3.0	0	2.25	1.49	0.95
3.0	30	1.78	1.87	2.39
3.0	60	2.81	3.72	2.56
3.0	90	3.30	6.16	3.87

Table 5.4: Minimum of Each Color Difference ($h = 1.7$)

d [m]	θ [degree]	min(ΔE_1^*)	min(ΔE_2^*)	min(ΔE_3^*)
1.0	0	0.47	1.67	2.95
1.0	30	1.49	1.04	1.88
1.0	60	1.39	1.19	0.84
1.0	90	1.76	2.47	1.06
2.0	0	0.79	1.10	0.92
2.0	30	0.92	1.91	0.87
2.0	60	3.43	3.48	1.47
2.0	90	1.12	0.86	2.49
3.0	0	1.90	1.60	1.23
3.0	30	0.83	0.75	1.94
3.0	60	2.78	4.20	4.53
3.0	90	4.66	5.13	1.26

Based on Table 5.3 and 5.4, the grass length corresponding to the gras gradation scale 0, 1, 2, 3 and 4 was determined for each camera position as shown in Table 5.5 and 5.6. In addition, the grass lengths when (h, d, θ) were (1.6, 3.0, 90) and (1.7, 3.0, 90) are also shown in the tables with failed labels. Figure 5.15, 5.16, 5.17, 5.18, 5.19, 5.20 show the plotted measured grass gradation values and the target grass gradation values in the CIELAB color space based on Table 5.3 and 5.4. In addition, Figure 5.14 shows an example of the plotted results. The dot point represents the measured grass gradation, the cross point represents the target grass gradation. The blue sphere represents the color tolerance each target grass gradation, then, when the dot point is within the blue sphere, the measured grass gradation can be regarded as the target grass gradation of the blue sphere. Furthermore, Figure 5.21, 5.22, 5.23, 5.24, 5.25 and 5.26 show the evaluation images arranged in order of the grass gradation scales when the color differences were minimums according to h, d and θ.

Table 5.5: Grass Length Corresponding to Each Grass Gradation Scale ($h = 1.6$)

d [m]	θ [degree]	Grass Length of Scale 0 [mm]	Grass Length of Scale 1 [mm]	Grass Length of Scale 2 [mm]	Grass Length of Scale 3 [mm]	Grass Length of Scale 4 [mm]
1.0	0	0.00	5.25	7.50	10.50	15.00
1.0	30	0.00	3.75	6.75	9.75	15.00
1.0	60	0.00	4.50	7.50	12.00	15.00
1.0	90	0.00	3.00	6.75	10.50	15.00
2.0	0	0.00	5.25	7.50	11.25	15.00
2.0	30	0.00	4.50	7.50	9.75	15.00
2.0	60	0.00	4.50	6.75	10.50	15.00
2.0	90	0.00	2.25	5.25	9.75	15.00
3.0	0	0.00	6.00	9.75	11.25	15.00
3.0	30	0.00	5.25	7.50	10.50	15.00
3.0	60	0.00	4.50	7.50	10.50	15.00
3.0	90	0.00	1.50	3.75 (Failed)	12.75	15.00

Table 5.6: Grass Length Corresponding to Each Grass Gradation Scale ($h = 1.7$)

d [m]	θ [degree]	Grass Length of Scale 0 [mm]	Grass Length of Scale 1 [mm]	Grass Length of Scale 2 [mm]	Grass Length of Scale 3 [mm]	Grass Length of Scale 4 [mm]
1.0	0	0.00	5.25	7.50	11.25	15.00
1.0	30	0.00	3.75	7.50	10.50	15.00
1.0	60	0.00	3.75	7.50	9.75	15.00
1.0	90	0.00	3.00	6.75	10.50	15.00
2.0	0	0.00	5.25	7.50	10.50	15.00
2.0	30	0.00	5.25	8.25	10.50	15.00
2.0	60	0.00	3.00	6.75	9.75	15.00
2.0	90	0.00	4.50	7.50	12.00	15.00
3.0	0	0.00	6.00	7.50	11.25	15.00
3.0	30	0.00	5.25	8.25	11.25	15.00
3.0	60	0.00	4.50	6.75	12.00	15.00
3.0	90	0.00	1.50	9.00 (Failed)	12.75	15.00

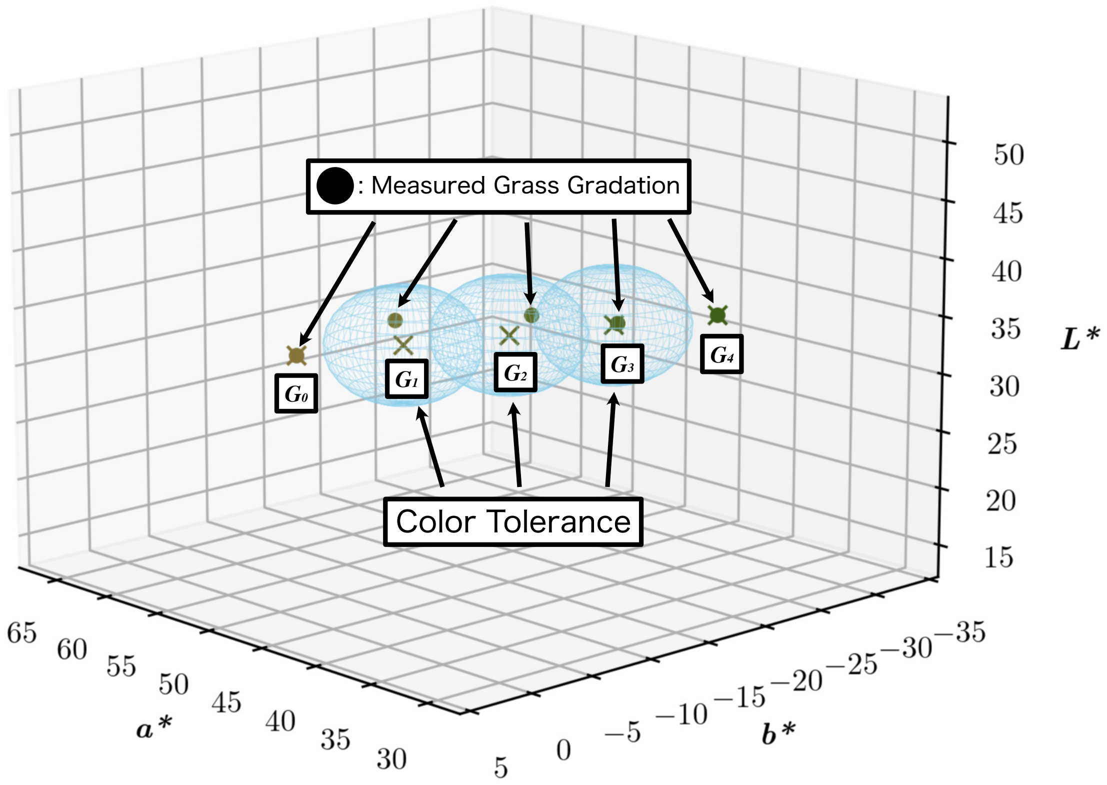
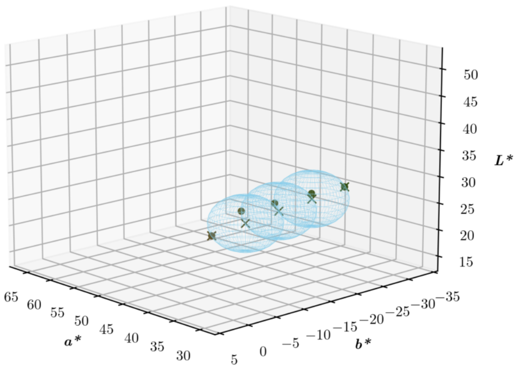
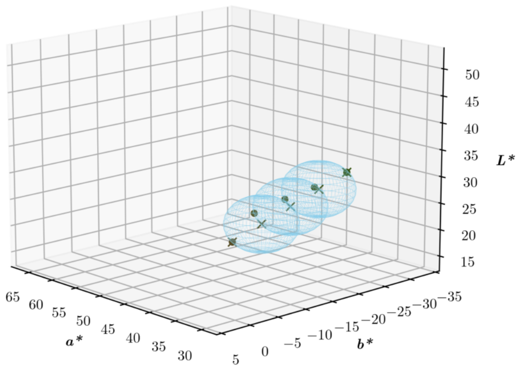


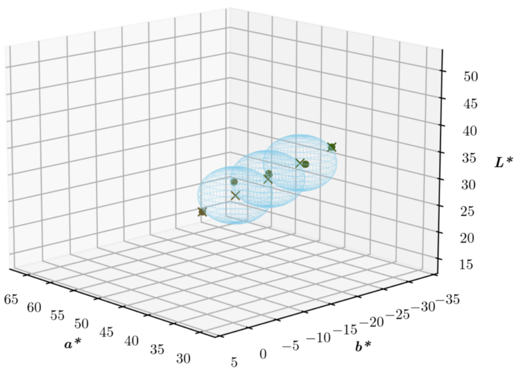
Figure 5.14: Example of Plotted Measured and Target Grass Gradation Values



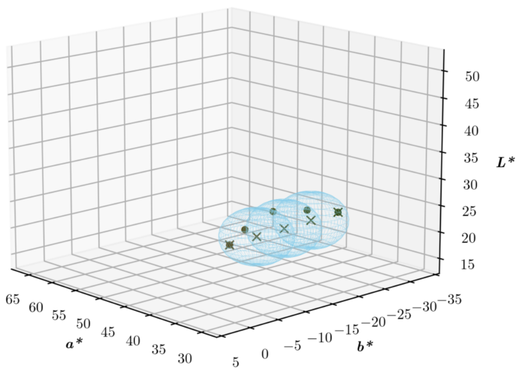
$(h, d, \theta) = (1.6,\ 1.0,\ 0)$



$(h, d, \theta) = (1.6,\ 1.0,\ 30)$

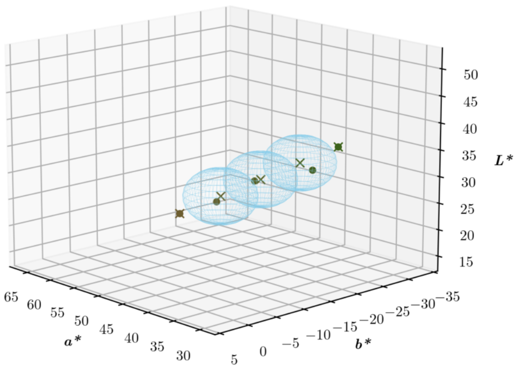


$(h, d, \theta) = (1.6,\ 1.0,\ 60)$

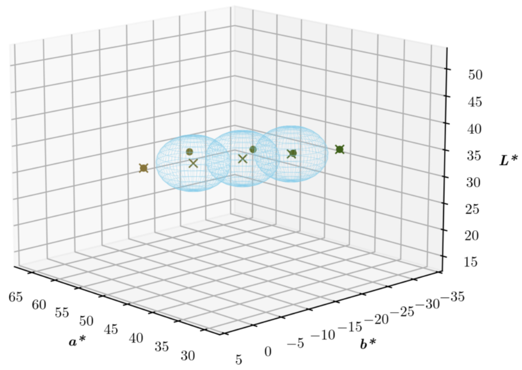


$(h, d, \theta) = (1.6,\ 1.0,\ 90)$

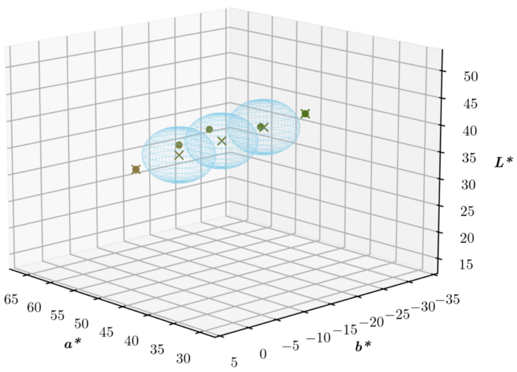
Figure 5.15: Plotted Minimum of Each of ΔE_1^*, ΔE_2^*, and ΔE_3^* $(h = 1.6, d = 1.0)$



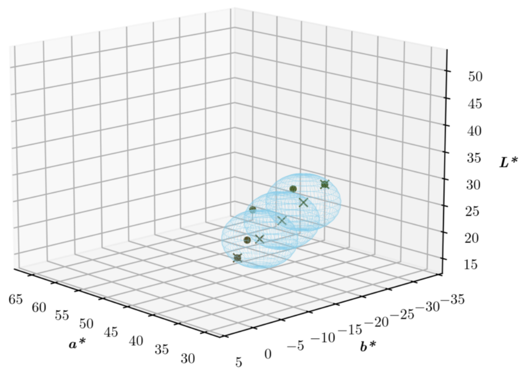
$(h, d, \theta) = (1.6,\ 2.0,\ 0)$



$(h, d, \theta) = (1.6,\ 2.0,\ 30)$

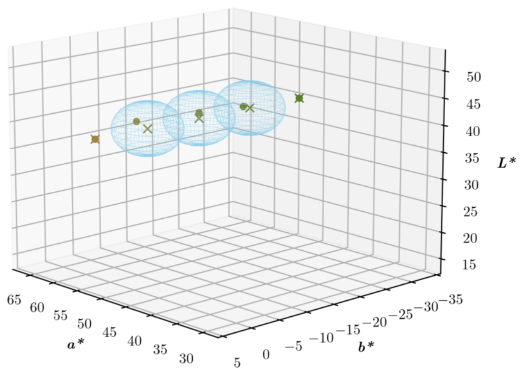


$(h, d, \theta) = (1.6,\ 2.0,\ 60)$

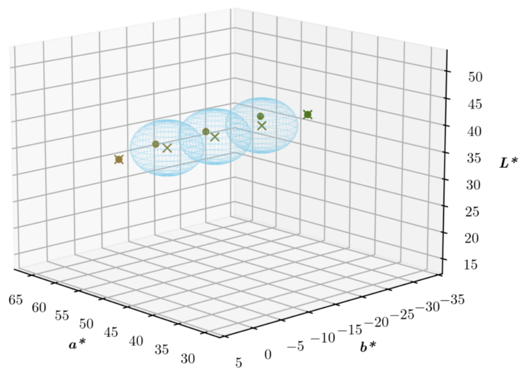


$(h, d, \theta) = (1.6,\ 2.0,\ 90)$

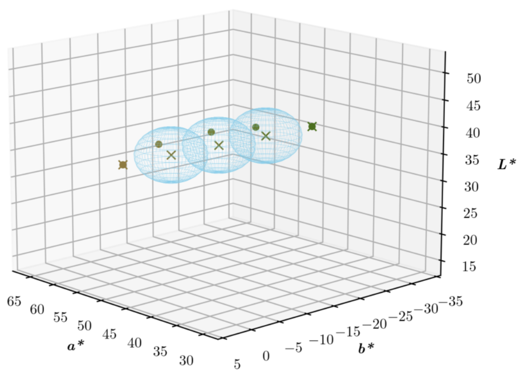
Figure 5.16: Plotted TMinimum of Each of ΔE_1^*, ΔE_2^*, and ΔE_3^* $(h = 1.6, d = 2.0)$



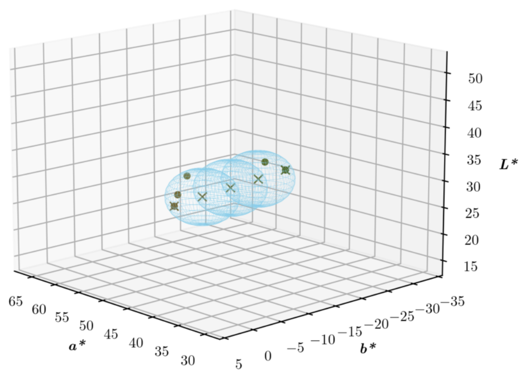
$(h, d, \theta) = (1.6,\ 3.0,\ 0)$



$(h, d, \theta) = (1.6,\ 3.0,\ 30)$

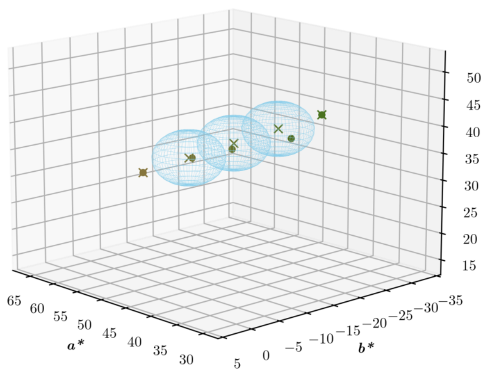


$(h, d, \theta) = (1.6,\ 3.0,\ 60)$

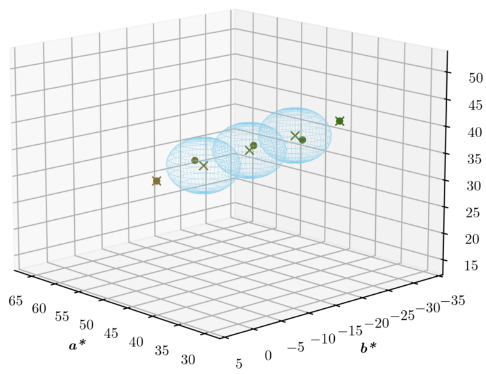


$(h, d, \theta) = (1.6,\ 3.0,\ 90)$

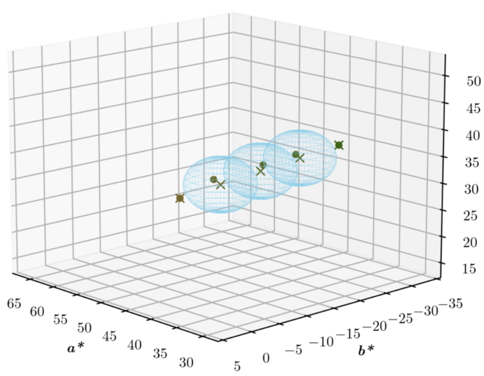
Figure 5.17: Plotted Minimum of Each of ΔE_1^*, ΔE_2^*, and ΔE_3^* $(h = 1.6, d = 3.0)$



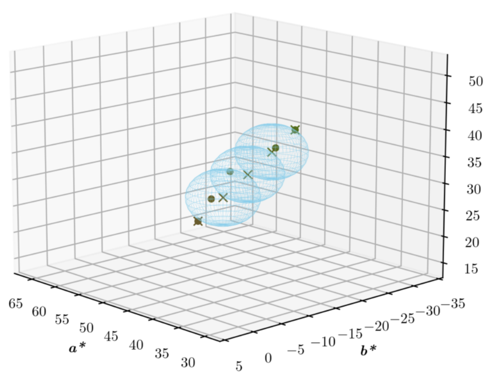
$(h, d, \theta) = (1.7,\ 1.0,\ 0)$



$(h, d, \theta) = (1.7,\ 1.0,\ 30)$

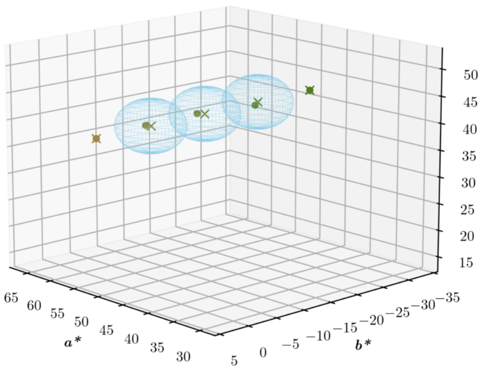


$(h, d, \theta) = (1.7,\ 1.0,\ 60)$

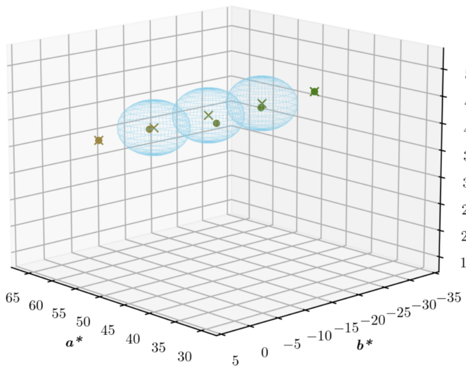


$(h, d, \theta) = (1.7,\ 1.0,\ 90)$

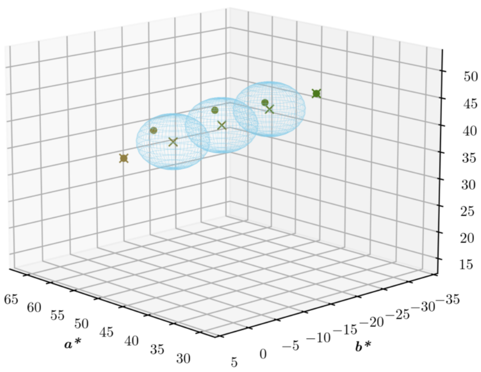
Figure 5.18: Plotted Minimum of Each of ΔE_1^*, ΔE_2^*, and ΔE_3^* $(h = 1.7, d = 1.0)$



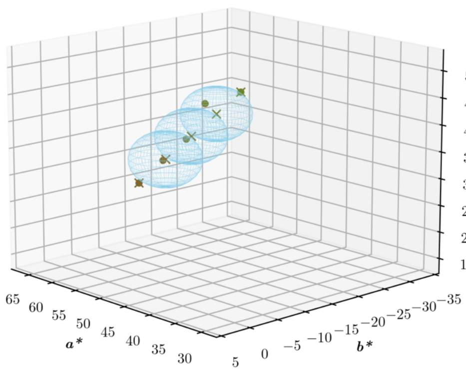
$(h, d, \theta) = (1.7,\ 2.0,\ 0)$



$(h, d, \theta) = (1.7,\ 2.0,\ 30)$

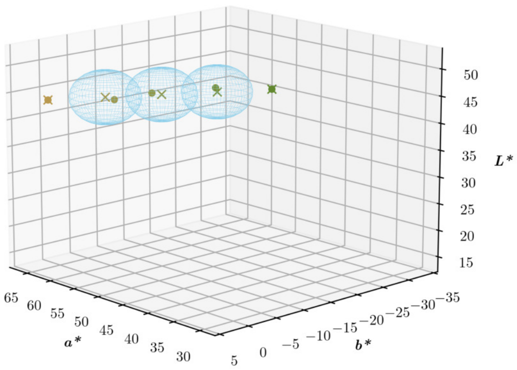


$(h, d, \theta) = (1.7,\ 2.0,\ 60)$

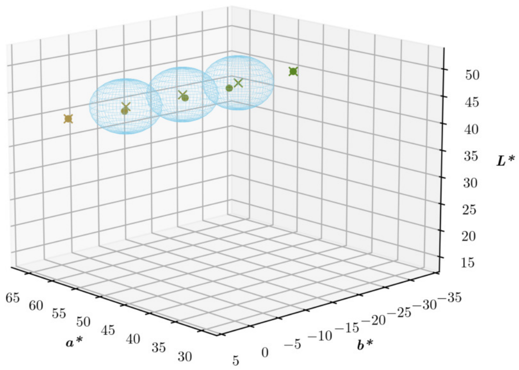


$(h, d, \theta) = (1.7,\ 2.0,\ 90)$

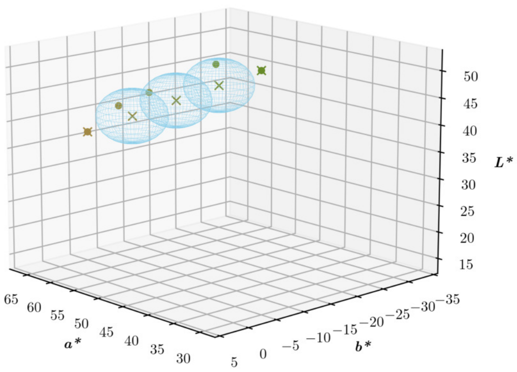
Figure 5.19: Plotted Minimum of Each of ΔE_1^*, ΔE_2^*, and ΔE_3^* $(h = 1.7, d = 2.0)$



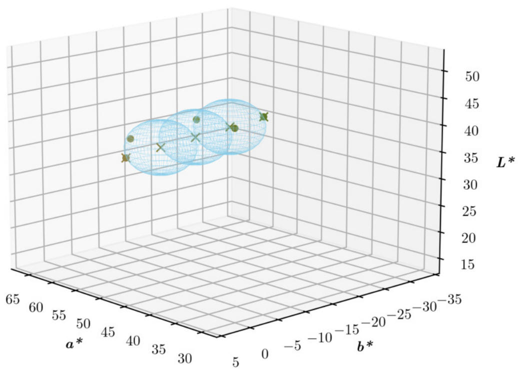
$(h, d, \theta) = (1.7,\ 3.0,\ 0)$



$(h, d, \theta) = (1.7,\ 3.0,\ 30)$



$(h, d, \theta) = (1.7,\ 3.0,\ 60)$



$(h, d, \theta) = (1.7,\ 3.0,\ 90)$

Figure 5.20: Plotted Minimum of Each of ΔE_1^*, ΔE_2^*, and ΔE_3^* $(h = 1.7, d = 3.0)$

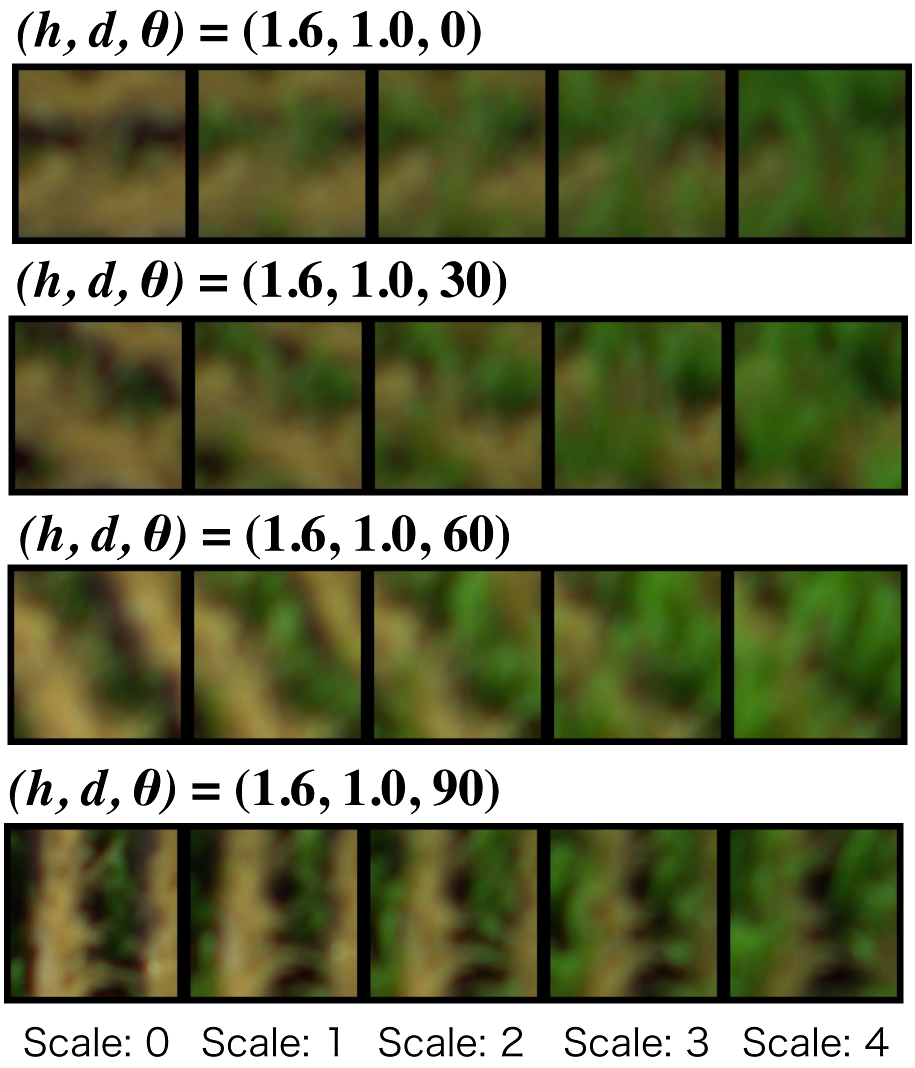


Figure 5.21: Evaluation Images in Order of Grass Gradation Scales ($h = 1.6, d = 1.0$)

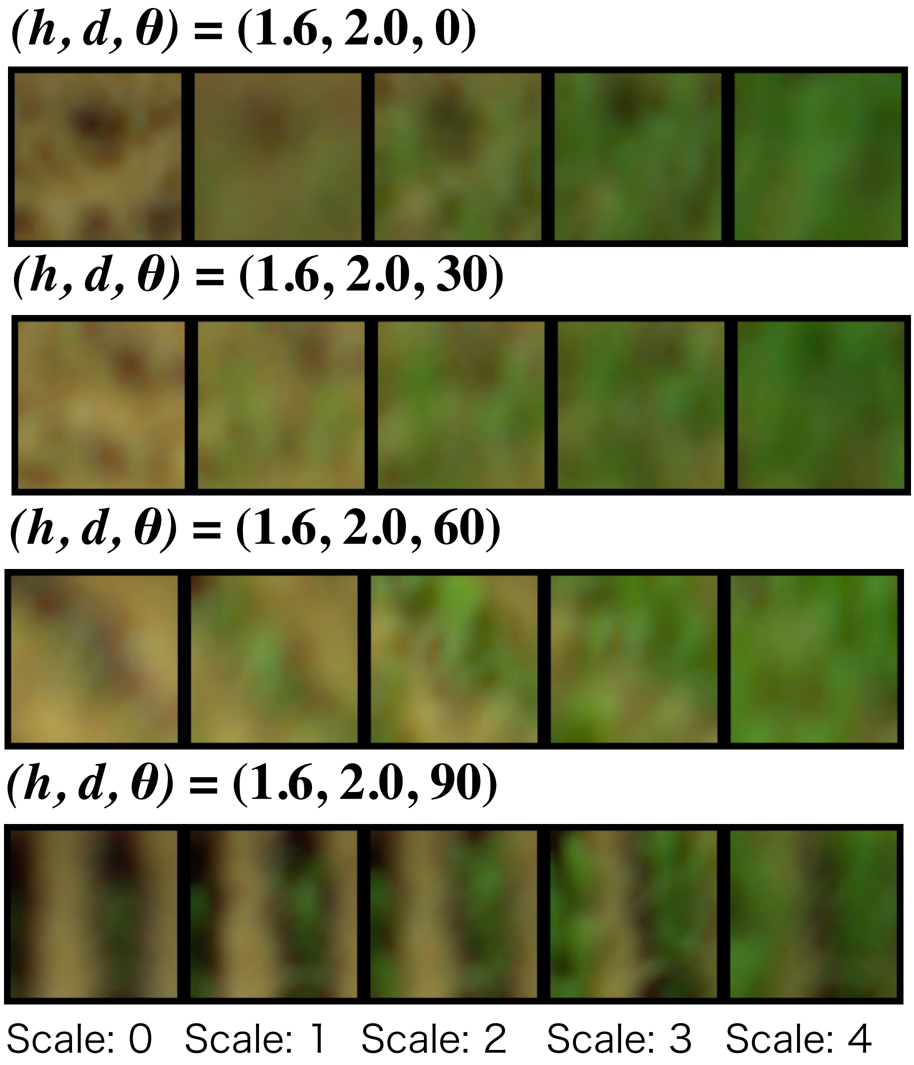


Figure 5.22: Evaluation Images in Order of Grass Gradation Scales ($h = 1.6, d = 2.0$)

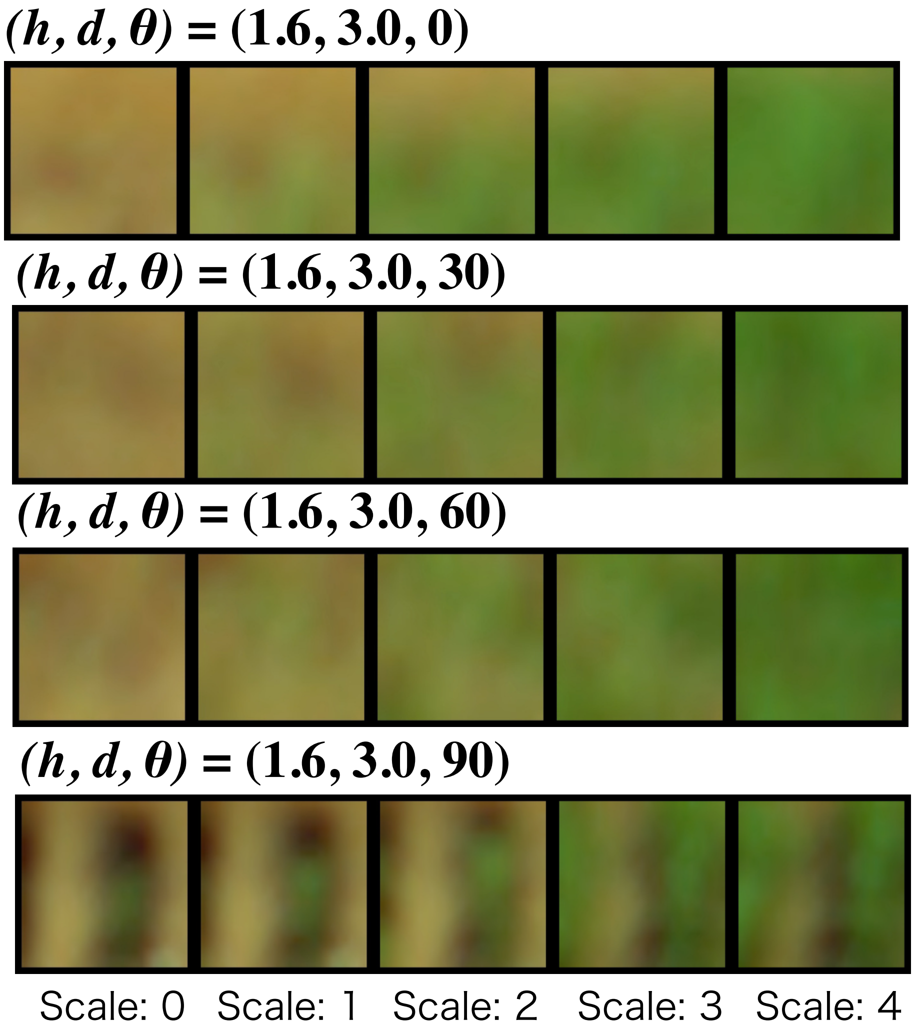


Figure 5.23: Evaluation Images in Order of Grass Gradation Scales ($h = 1.6, d = 3.0$)

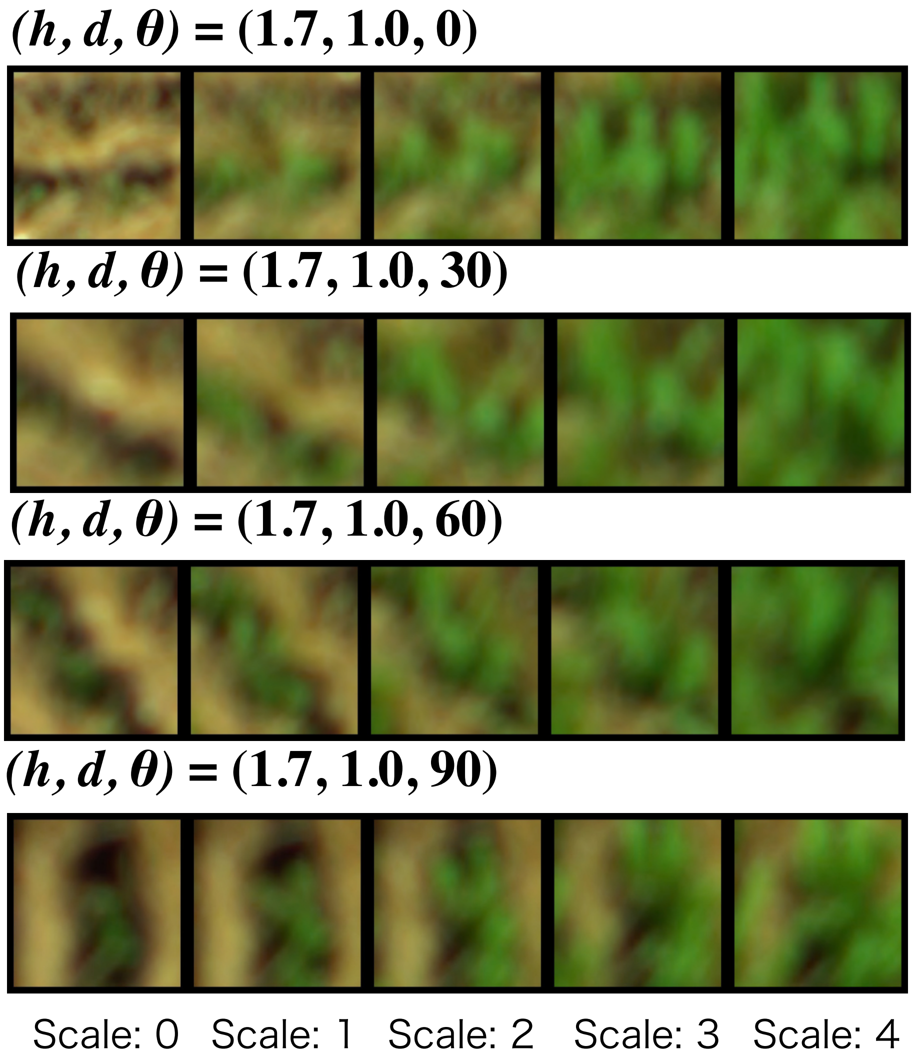


Figure 5.24: Evaluation Images in Order of Grass Gradation Scales ($h = 1.7, d = 1.0$)

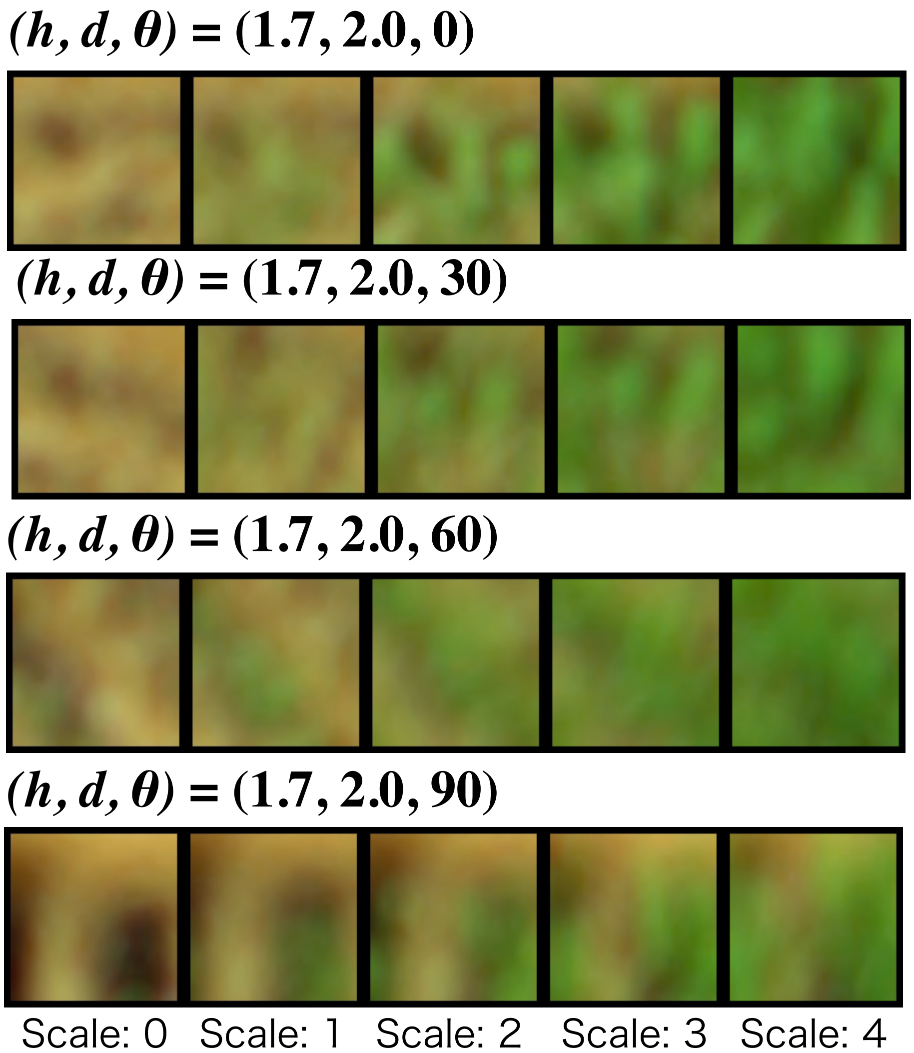


Figure 5.25: Evaluation Images in Order of Grass Gradation Scales ($h = 1.7, d = 2.0$)

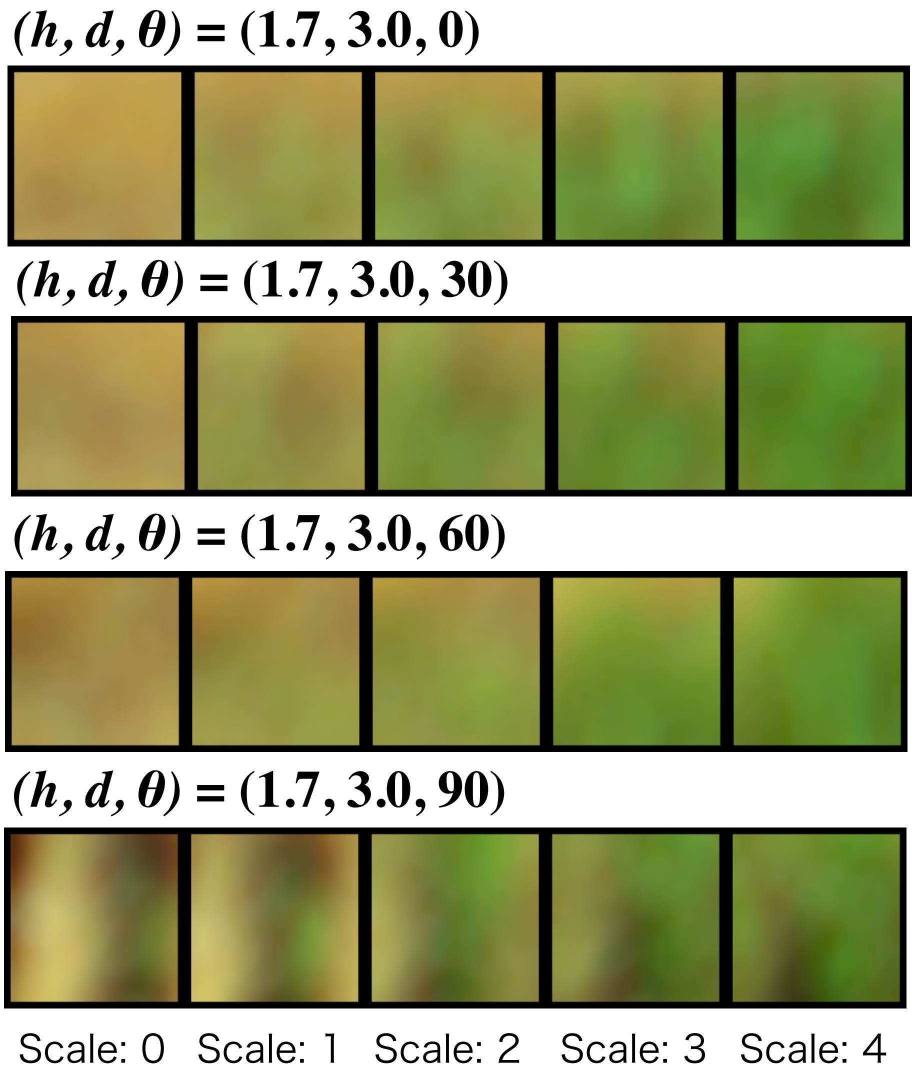
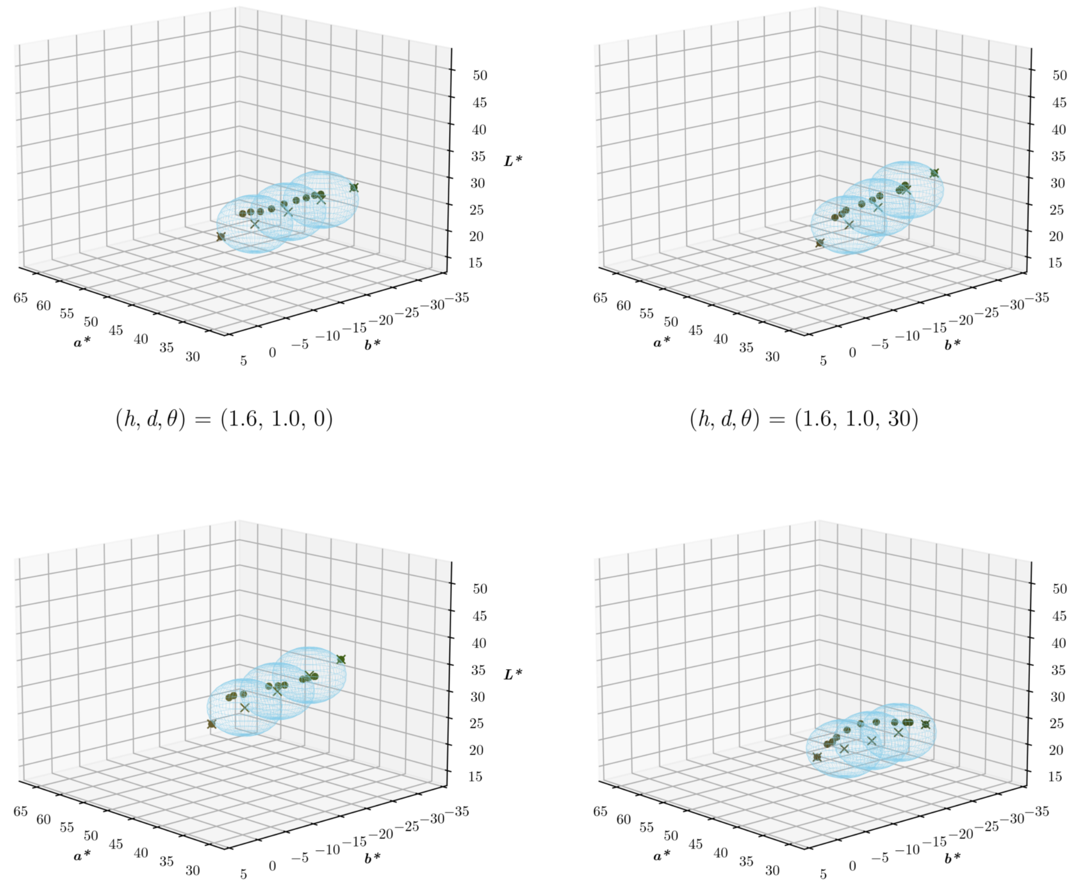


Figure 5.26: Evaluation Images in Order of Grass Gradation Scales ($h = 1.7, d = 3.0$)

5.6 Detailed Results

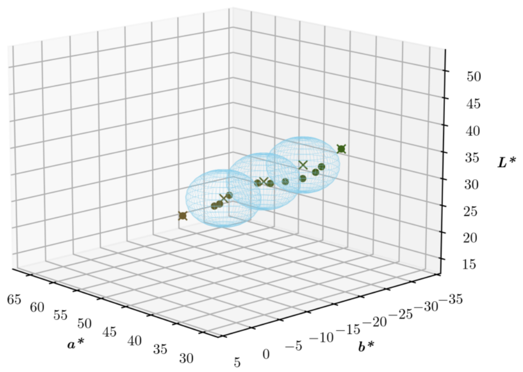
Figure 5.27, 5.28, 5.29, 5.30, 5.31, and 5.32 show the plotted measured grass gradation values corresponding to top three smallest color difference for each target grass gradation. In the experiments, most of the minimums of the color differences were under the color tolerance. Furthermore, there were other measured grass gradation that was under the color tolerance of the target grass gradation.



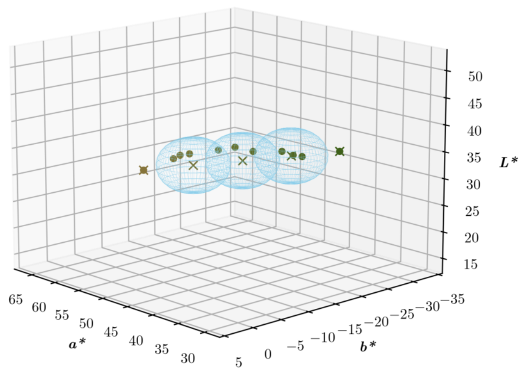
$(h, d, \theta) = (1.6, 1.0, 0)$ $(h, d, \theta) = (1.6, 1.0, 30)$

$(h, d, \theta) = (1.6, 1.0, 60)$ $(h, d, \theta) = (1.6, 1.0, 90)$

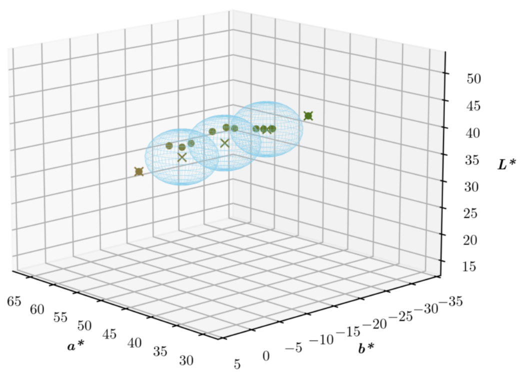
Figure 5.27: Plotted Measured Grass Gradation Values Corresponding to Top Three Smallest Color Difference for Each Target Grass Gradation ($h = 1.6, d = 1.0$)



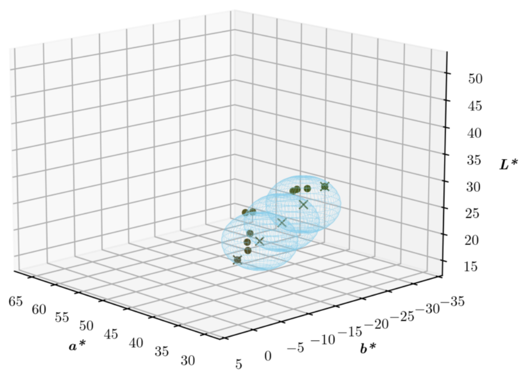
$(h, d, \theta) = (1.6,\ 2.0,\ 0)$



$(h, d, \theta) = (1.6,\ 2.0,\ 30)$

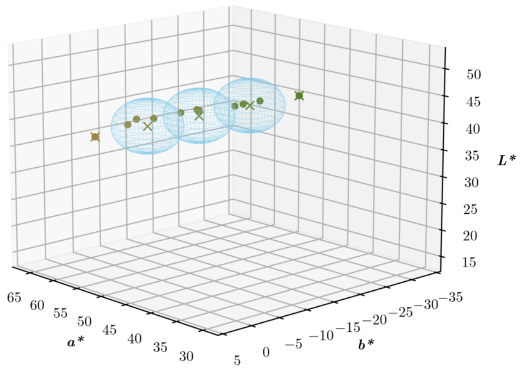


$(h, d, \theta) = (1.6,\ 2.0,\ 60)$

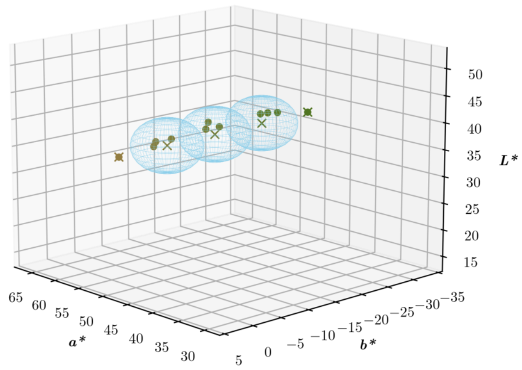


$(h, d, \theta) = (1.6,\ 2.0,\ 90)$

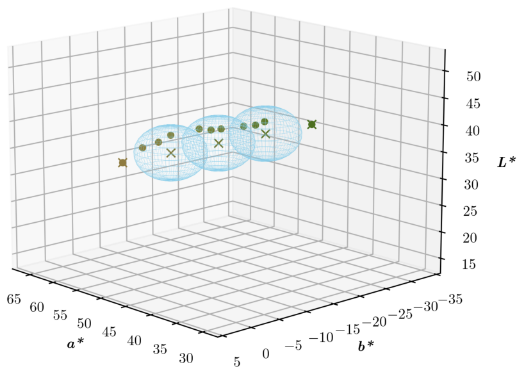
Figure 5.28: Plotted Measured Grass Gradation Values Corresponding to Top Three Smallest Color Difference for Each Target Grass Gradation ($h = 1.6, d = 2.0$)



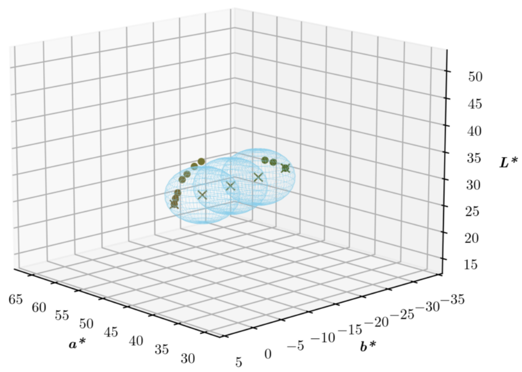
$(h, d, \theta) = (1.6,\ 3.0,\ 0)$



$(h, d, \theta) = (1.6,\ 3.0,\ 30)$

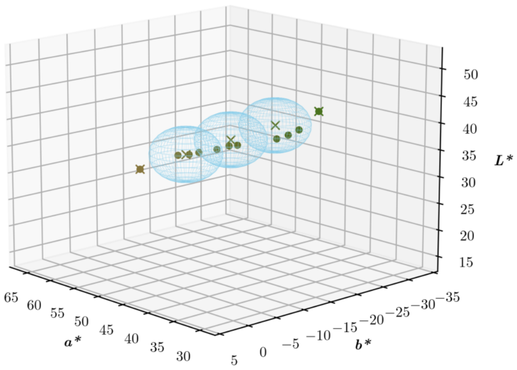


$(h, d, \theta) = (1.6,\ 3.0,\ 60)$

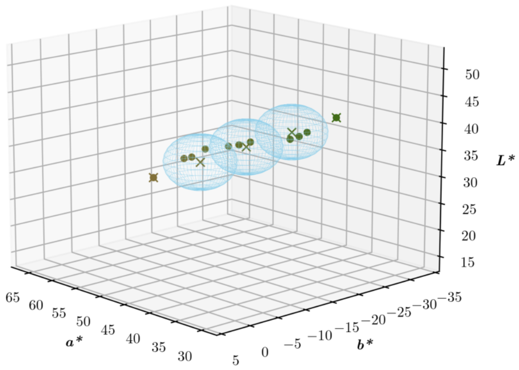


$(h, d, \theta) = (1.6,\ 3.0,\ 90)$

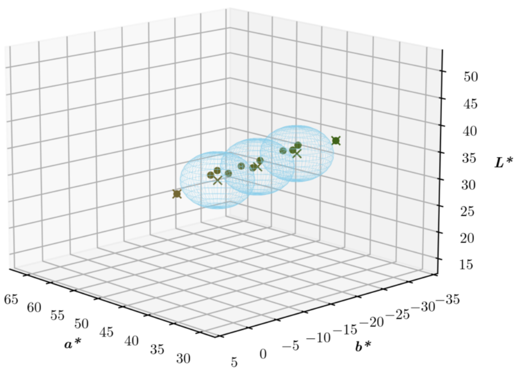
Figure 5.29: Plotted Measured Grass Gradation Values Corresponding to Top Three Smallest Color Difference for Each Target Grass Gradation ($h = 1.6, d = 3.0$)



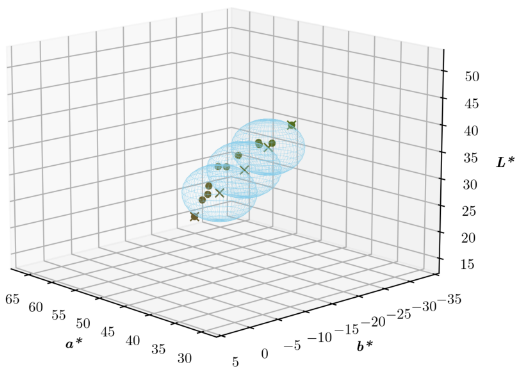
$(h, d, \theta) = (1.7, 1.0, 0)$



$(h, d, \theta) = (1.7, 1.0, 30)$

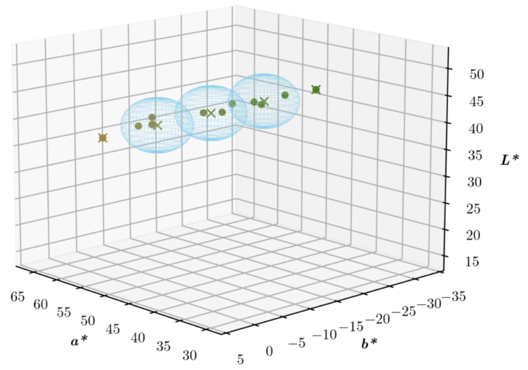


$(h, d, \theta) = (1.7, 1.0, 60)$

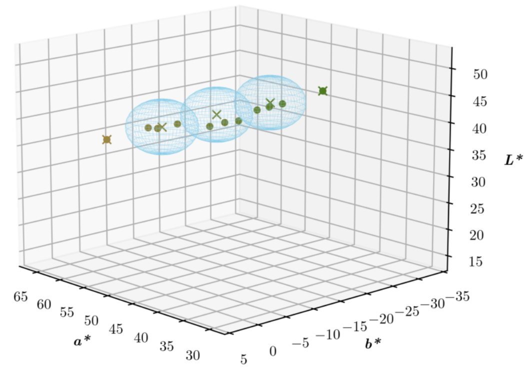


$(h, d, \theta) = (1.7, 1.0, 90)$

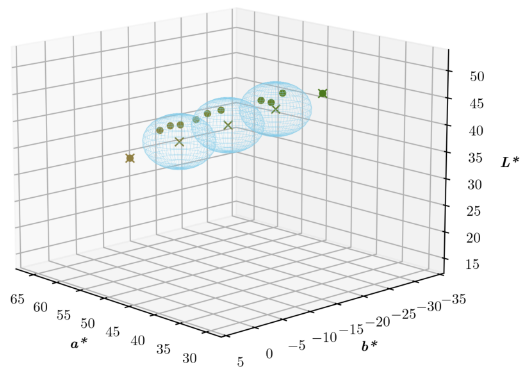
Figure 5.30: Plotted Measured Grass Gradation Values Corresponding to Top Three Smallest Color Difference for Each Target Grass Gradation ($h = 1.7, d = 1.0$)



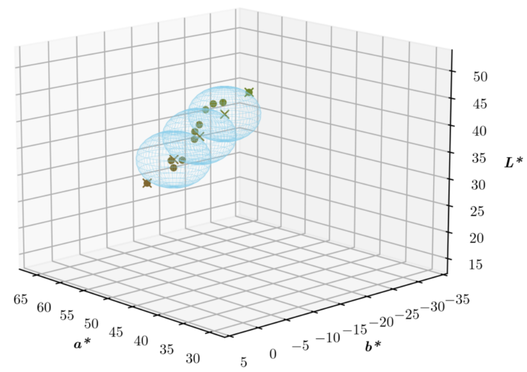
$(h, d, \theta) = (1.7,\ 2.0,\ 0)$



$(h, d, \theta) = (1.7,\ 2.0,\ 30)$

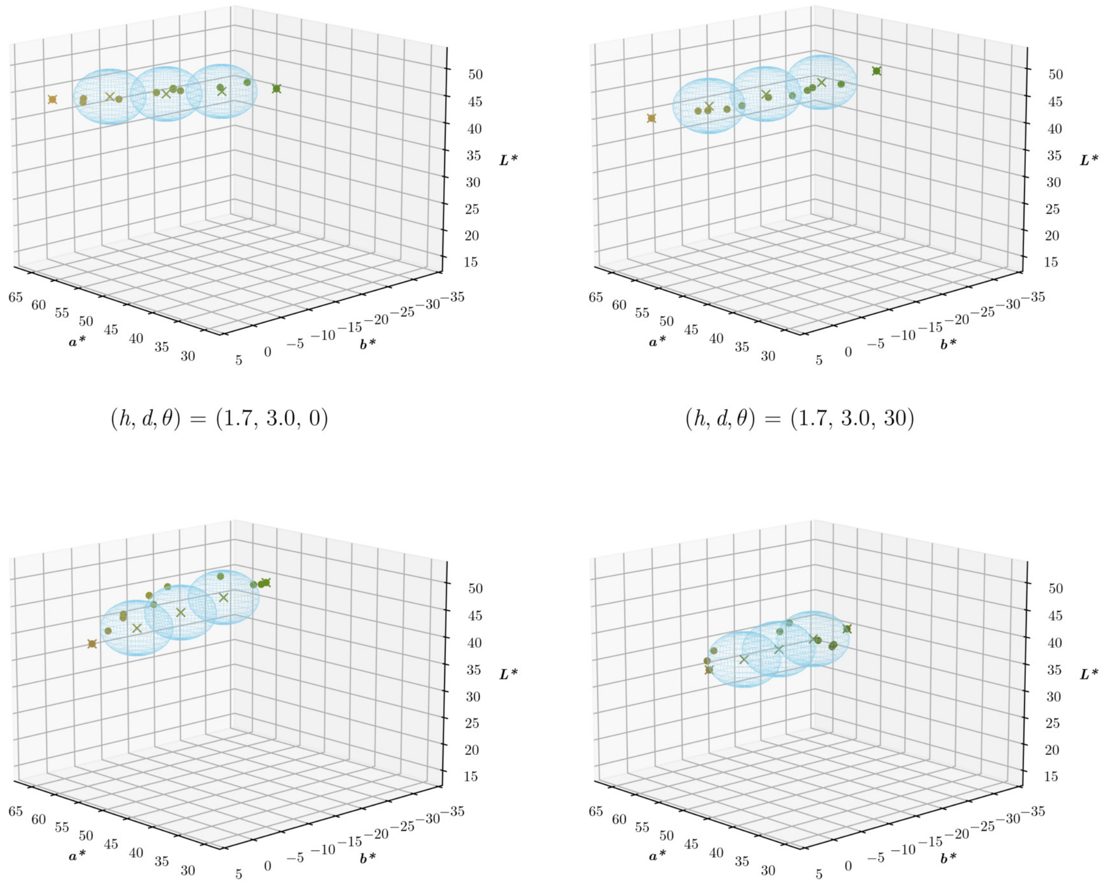


$(h, d, \theta) = (1.7,\ 2.0,\ 60)$



$(h, d, \theta) = (1.7,\ 2.0,\ 90)$

Figure 5.31: Plotted Measured Grass Gradation Values Corresponding to Top Three Smallest Color Difference for Each Target Grass Gradation ($h = 1.7, d = 2.0$)



$(h, d, \theta) = (1.7,\ 3.0,\ 0)$ $(h, d, \theta) = (1.7,\ 3.0,\ 30)$

$(h, d, \theta) = (1.7,\ 3.0,\ 60)$ $(h, d, \theta) = (1.7,\ 3.0,\ 90)$

Figure 5.32: Plotted Measured Grass Gradation Values Corresponding to Top Three Smallest Color Difference for Each Target Grass Gradation ($h = 1.7, d = 3.0$)

5.7 Discussion

As shown in Figure 5.3 and 5.4, it is possible for the grass pixel to show five grass gradation scales to multiple positions. In addition, as shown in Figure 5.5 and 5.6, the grass length can be obtained corresponding to each grass gradation scale based on h, d and θ. However, the grass length corresponding to each grass gradation scale the were different for each camera position. Then, Table 5.5 and 5.6 are not much helpful to develop a grass animation with wide viewing angles as shown in Figure 5.33. However, we revealed that there were also several measured grass gradations that were within the color tolerance for each target grass gradation as shown in Figure 5.27, 5.28, 5.29, 5.30, 5.31, and 5.32. It means that there is a possibility of the grass gradation scales control that passes the color tolerance of multiple camera positions simultaneously.

In addition, the range of the target grass gradation values was different for each camera position. It was because the target grass gradations were defined by the measured grass gradation values. In particular, the range tended to be smaller when the evaluation images included the slits of the grass pixel. When θ was 90°, the range of the target values was smaller than other results when θ was $0°, 30°, 60°$. For example, as shown in Figure 5.16, the range when (h, d, θ) was (1.6, 2.0, 90) was smaller than the range when (h, d, θ) was (1.6, 2.0, 0). In addition, when (h, d, θ) was only (1.6, 3.0, 90) and (1.7, 3.0, 90), the minimum of ΔE_2^* was over the color tolerance. Moreover, when d was 1.0 [m], the evaluation images included the slits because the camera was too close to the grass pixel. Then, the range of the target grass gradation was also smaller than other results when d was 2.0, 3.0. For example, the range when (h, d, θ) was (1.6, 1.0, 30) was smaller than the range when (h, d, θ) was (1.6, 2.0, 30) as shown in Figure 5.15 and 5.16. As in the previous evaluation using the HSV color space, the slits also have an effect on the grass gradation scales. To show grass gradation scales widely, it is necessary to develop the grass pixel that hides its slits.

The L^* values of the target grass gradations when h was 1.7 [m] tended to be higher than the L^* values when h was 1.6 [m]. For example, the L^* values of the target grass gradations when (h, d, θ) was (1.7, 2.0, 0) were bigger than when (h, d, θ) was (1.6, 2.0, 0) as shown in Figure 5.16 and 5.19. However, the dates of the experiments when h was 1.6 and 1.7 [m] were different, then, we suppose that the results were caused by the weather of the experiment. To solve this problem, an image correction system based on the weather is needed before analyzing the evaluation images.

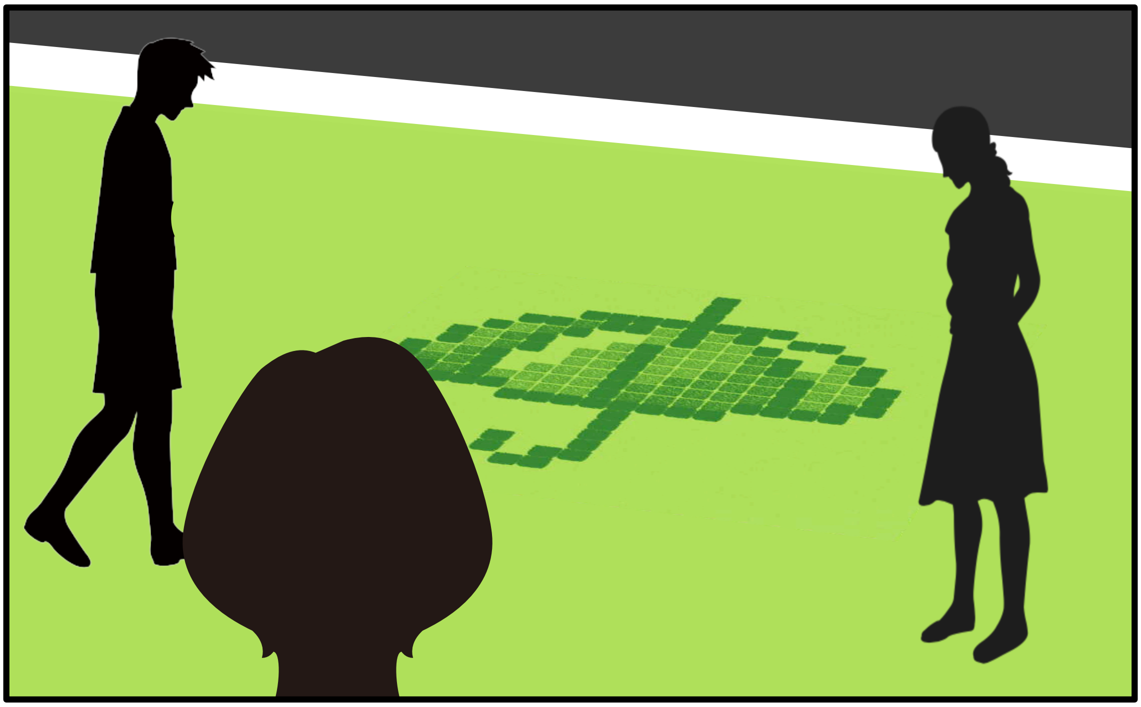


Figure 5.33: Grass Animation Display with Wide Viewing Angles

Chapter 6

Future work

Figure 6.1: Weather Forecast Application with Grass Animation Display

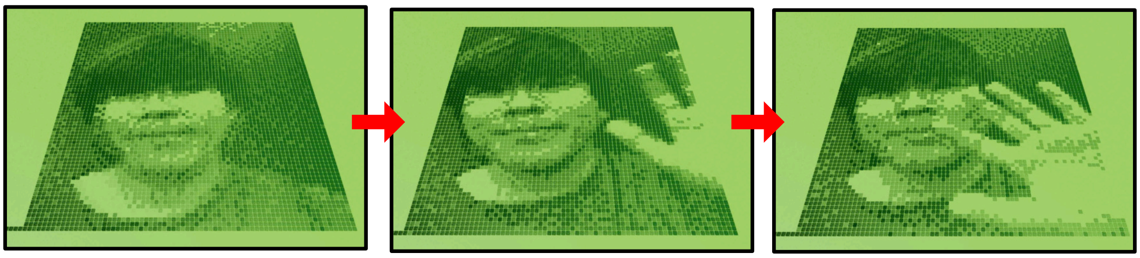


Figure 6.2: Live-Action Images Displayed on Grass

Our proposed method can help to develop a natural landscape-friendly grass animation display device in urban green spaces. Figure 6.1 shows the example application of the display device. The application is a weather forecast application in an urban green space. In the application, the text and the umbrella on the grass; thus, the green space can be useful while preserving the natural landscape. In addition, if the number of the grass pixel is increased, live-action images can be displayed on the grass surface as shown in Figure 6.2. We believe that the grass animation display device can be applied to multiple landscape-friendly applications, such as advertisements, guide maps, and entertainments in urban green spaces.

Chapter 7

Limitation

7.1 Speed and Resolution

In Section 4.3, the keyframe intervals is 1.0 [s]. To play animation smoothly, the grass keyframe animation system is needed to make the keyframe interval small. However, when the speed of the grass animation display increases, the stepper motors cannot synchronize with other stepper motors. Moreover, the animation system cannot work a lot of stepper motors simultaneously, then, it is difficult for the current grass animation display to display even a letter. To solve these problems, the grass animation display needs a system to control a lot of motors simultaneously and quickly.

7.2 User Evaluation

In this paper, we conducted several quantified evaluations of the spatial additive mixing of the grass gradation through image processing. Since spatial additive mixing is related to human cognition, we evaluated the grass gradation control system using the CIELAB color space, which has visual uniformity. However, user evaluations are also needed to improve the grass animation display. In addition, it is necessary to evaluate whether the grass animation display is friendly to a natural landscape in urban green spaces as future work. In that case, it is needed to evaluate the impression of the grass animation display with experimental participants.

7.3 Outdoor Installation

Outdoor installation of the grass animation display is challenging for various reasons. For example, it is not easy to embed the grass animation display in the ground because of the height of its enclosure. Moreover, the grass animation display needs to be durable from the outside environment such as rain and wind.

Chapter 8

Conclusion

We proposed an urban green space-friendly animation display with an artificial grass gradation control system. We designed a pixel-by-pixel dynamic grass gradation control system, which was named a grass pixel. The grass pixel consisted of artificial yellow and green grass, displayed multiple grass gradations with yellow and green by moving the green grass length through slits in the yellow grass. Then, a grass animation display can be developed by using multiple grass pixels and can show gradation animations on the grass surface without any display device such as a projector. We conducted a simple evaluation of continuous changes in the grass gradation of the grass system through image processing. In the evaluation, the grass gradation was quantified as HSV values, which can express gradations of saturation and brightness. As a result, the HSV values of the grass gradation increased or decreased simply when the grass pixel moved the green grass length from minimum to maximum. In addition, we created several simple example animations using a 3×3 pixels grass animation display. A gradation image keyframe system was adopted as the animation system of the grass animation display. Furthermore, we evaluated five grass gradation scales depending on the grass length through image processing. To evaluate the grass gradation scales based on human cognition, we adopted a color evaluation with the CIELAB color space, which has visual uniformity. As a result, we revealed that the grass pixel can show five grass gradation scales to multiple positions, and obtained the grass length corresponding to the grass gradation scales for each camera position. As future work, we will develop a stable grass animation display system to control a lot of grass pixels simultaneously and quickly. Moreover, we will evaluate the grass animation display by experimental participants focusing on the performance and the impression when the display is installed outdoor.

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Moreover, I would like to thank Yuichi Kato, a member of Social Robotics Laboratory for developing a grass gradation evaluation software using the CIELAB color space. Thanks to his software, I was able to proceed with the evaluation efficiently.

Finally, I would like to express my thanks to members of our seminar, my family, and my friends.

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Appendix

Table 8.1: Measured Values and Color Differences when (h, d, θ) is $(1.6, 1.0, 0)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	35.42	-1.22	25.46	5.25	10.50	15.75
0.75	35.70	-1.62	25.76	4.88	10.12	15.36
1.50	35.91	-2.26	25.97	4.31	9.52	14.76
2.25	36.13	-3.09	26.53	3.60	8.71	13.93
3.00	36.46	-3.95	27.12	3.13	7.97	13.12
3.75	36.40	-4.86	27.57	2.63	7.09	12.19
4.50	36.34	-5.92	28.17	2.51	6.12	11.12
5.25	35.81	-6.87	28.38	2.34	5.04	10.02
6.00	35.13	-7.96	28.40	2.57	3.76	8.76
6.75	34.54	-9.44	28.69	3.80	2.28	7.15
7.50	34.10	-11.30	29.22	5.69	1.51	5.23
8.25	33.58	-13.01	29.55	7.41	2.43	3.46
9.00	33.21	-14.52	29.79	8.94	3.80	2.03
9.75	32.98	-15.85	29.97	10.28	5.10	1.19
10.50	32.68	-16.69	30.04	11.13	5.92	1.15
11.25	32.39	-17.91	30.29	12.40	7.18	2.09
12.00	32.06	-18.75	30.47	13.30	8.07	2.89
12.75	31.22	-19.74	30.30	14.35	9.10	3.85
13.50	31.02	-20.16	30.44	14.83	9.58	4.33
14.25	30.88	-20.69	30.51	15.37	10.13	4.88
15.00	30.83	-21.03	30.69	15.75	10.50	5.25

Table 8.2: Measured Values and Color Differences when (h, d, θ) is $(1.6, 1.0, 30)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	32.84	-2.19	24.81	5.38	10.76	16.14
0.75	33.61	-2.91	25.67	4.53	9.86	15.22
1.50	34.26	-4.13	26.62	3.48	8.55	13.86
2.25	34.44	-5.20	27.33	2.76	7.42	12.67
3.00	34.30	-6.24	27.93	2.24	6.30	11.50
3.75	34.04	-7.20	28.38	2.13	5.26	10.42
4.50	34.14	-8.07	28.88	2.73	4.47	9.50
5.25	33.85	-9.14	29.29	3.40	3.40	8.34
6.00	33.63	-10.39	29.57	4.36	2.31	7.04
6.75	33.14	-11.88	30.04	5.73	1.46	5.42
7.50	33.15	-13.26	30.41	7.09	2.09	4.04
8.25	32.80	-14.75	30.81	8.56	3.29	2.49
9.00	32.32	-16.03	30.98	9.79	4.43	1.13
9.75	32.41	-16.68	31.29	10.51	5.15	0.70
10.50	32.54	-17.40	31.58	11.28	5.92	0.90
11.25	32.39	-18.34	31.80	12.23	6.86	1.56
12.00	31.88	-18.81	31.83	12.69	7.31	1.94
12.75	32.05	-19.58	32.13	13.51	8.13	2.76
13.50	31.57	-20.64	32.23	14.55	9.17	3.80
14.25	31.75	-21.57	32.74	15.58	10.20	4.83
15.00	31.79	-22.10	32.90	16.14	10.76	5.38

Table 8.3: Measured Values and Color Differences when (h, d, θ) is $(1.6, 1.0, 60)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	39.61	-3.40	28.53	5.63	11.26	16.89
0.75	40.13	-4.28	29.63	4.62	10.19	15.80
1.50	40.88	-5.18	30.63	4.01	9.30	14.84
2.25	40.90	-6.40	31.28	3.15	8.06	13.55
3.00	40.79	-7.61	31.99	2.68	6.83	12.23
3.75	40.60	-8.28	32.26	2.55	6.14	11.50
4.50	39.89	-9.36	32.49	2.39	4.86	10.24
5.25	39.86	-10.45	33.07	3.34	3.92	9.11
6.00	39.00	-11.74	32.92	3.96	2.38	7.68
6.75	38.70	-12.92	33.37	5.18	1.50	6.40
7.50	38.04	-14.00	33.36	6.15	0.98	5.24
8.25	37.59	-14.75	33.46	6.93	1.47	4.44
9.00	37.57	-16.01	33.85	8.22	2.64	3.13
9.75	37.54	-16.76	34.31	9.09	3.52	2.35
10.50	36.85	-17.43	34.11	9.72	4.14	1.74
11.25	36.64	-18.22	34.19	10.52	4.92	1.10
12.00	36.39	-19.25	34.31	11.55	5.96	0.92
12.75	36.13	-20.49	34.69	12.87	7.27	1.85
13.50	36.38	-21.71	35.35	14.18	8.56	2.96
14.25	36.55	-23.01	35.82	15.51	9.88	4.26
15.00	36.52	-24.33	36.25	16.89	11.26	5.63

Table 8.4: Measured Values and Color Differences when (h, d, θ) is $(1.6, 1.0, 90)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	33.85	-2.60	24.31	3.96	7.92	11.88
0.75	33.38	-3.41	24.58	3.00	6.96	10.92
1.50	34.15	-4.01	25.48	2.76	6.57	10.49
2.25	34.16	-4.71	26.02	2.38	5.93	9.80
3.00	33.75	-5.29	26.44	1.96	5.23	9.06
3.75	33.83	-6.05	27.02	2.22	4.69	8.39
4.50	33.62	-6.82	27.44	2.54	4.08	7.62
5.25	33.67	-7.82	27.96	3.37	3.68	6.86
6.00	34.70	-8.89	28.83	5.00	4.56	6.92
6.75	33.26	-9.87	28.69	5.09	3.31	5.22
7.50	33.64	-10.94	29.40	6.41	4.25	5.15
8.25	32.07	-11.56	28.91	6.50	3.38	3.45
9.00	31.55	-12.42	28.86	7.25	3.77	2.68
9.75	32.19	-13.22	29.35	8.14	4.79	3.32
10.50	30.66	-13.56	28.69	8.32	4.54	1.81
11.25	31.58	-14.77	29.41	9.57	5.95	3.26
12.00	29.92	-14.93	28.58	9.69	5.79	2.12
12.75	29.72	-15.47	28.50	10.20	6.29	2.50
13.50	27.77	-15.54	27.51	10.70	6.77	2.92
14.25	27.44	-16.12	27.48	11.34	7.42	3.57
15.00	28.26	-16.91	28.16	11.88	7.92	3.96

Table 8.5: Measured Values and Color Differences when (h, d, θ) is $(1.6, 2.0, 0)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	40.03	0.22	28.59	6.94	13.89	20.83
0.75	40.31	-0.55	28.65	6.23	13.17	20.11
1.50	40.30	-0.51	28.81	6.22	13.16	20.11
2.25	39.93	-1.67	28.77	5.07	12.01	18.95
3.00	39.56	-2.55	28.89	4.17	11.11	18.05
3.75	39.95	-3.36	29.37	3.30	10.24	17.18
4.50	39.45	-4.87	29.28	1.89	8.77	15.71
5.25	39.40	-5.80	29.45	1.06	7.83	14.77
6.00	39.85	-7.97	30.33	1.55	5.57	12.50
6.75	39.59	-9.62	30.98	3.22	3.80	10.72
7.50	39.31	-12.60	31.62	6.26	0.86	7.66
8.25	38.39	-14.08	31.48	7.75	1.04	6.20
9.00	37.47	-15.99	31.57	9.78	3.08	4.45
9.75	36.99	-17.54	31.77	11.40	4.68	3.19
10.50	36.58	-18.36	31.79	12.30	5.60	2.81
11.25	36.36	-20.54	32.49	14.55	7.74	2.15
12.00	36.66	-21.98	33.14	15.99	9.10	2.56
12.75	36.98	-23.36	33.40	17.33	10.42	3.62
13.50	36.80	-24.36	33.98	18.44	11.51	4.65
14.25	36.41	-25.17	33.93	19.27	12.36	5.53
15.00	37.50	-26.65	35.18	20.83	13.89	6.94

Table 8.6: Measured Values and Color Differences when $(h, d, \ \theta\ )$ is $(1.6, 2.0, 30)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	49.19	-0.82	34.29	6.83	13.65	20.48
0.75	49.72	-1.76	35.08	6.32	13.09	19.89
1.50	49.41	-2.97	35.24	5.20	11.91	18.70
2.25	49.06	-4.31	35.51	4.08	10.62	17.38
3.00	48.44	-5.47	35.49	2.94	9.32	16.07
3.75	48.44	-6.65	35.87	2.75	8.45	15.11
4.50	48.05	-7.97	35.91	2.67	7.24	13.82
5.25	47.53	-9.71	36.37	3.69	5.86	12.18
6.00	46.27	-11.62	36.19	5.04	3.89	9.90
6.75	45.27	-13.73	36.50	7.17	3.04	7.76
7.50	43.50	-15.44	35.79	9.02	2.78	5.22
8.25	42.32	-17.30	35.96	11.17	4.57	3.22
9.00	40.97	-18.42	35.72	12.67	5.90	1.51
9.75	39.71	-19.29	35.14	13.96	7.13	0.34
10.50	38.75	-20.08	34.91	15.09	8.27	1.49
11.25	37.97	-20.59	34.63	15.91	9.11	2.43
12.00	37.26	-21.59	34.48	17.14	10.35	3.65
12.75	36.74	-23.12	34.59	18.72	11.91	5.14
13.50	36.17	-23.64	34.40	19.45	12.65	5.90
14.25	36.54	-24.70	34.97	20.21	13.38	6.56
15.00	36.60	-25.03	35.27	20.48	13.65	6.83

Table 8.7: Measured Values and Color Differences when $(h, d, \ \theta\ )$ is $(1.6, 2.0, 60$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	50.98	-1.80	33.78	6.66	13.32	19.98
0.75	50.70	-2.55	33.93	5.86	12.52	19.18
1.50	51.32	-3.61	34.84	4.91	11.50	18.15
2.25	51.67	-5.01	35.73	3.88	10.21	16.80
3.00	51.57	-6.51	36.68	3.05	8.74	15.24
3.75	51.40	-7.60	37.09	2.76	7.70	14.13
4.50	49.85	-8.57	37.02	1.80	6.14	12.68
5.25	49.80	-10.17	37.34	2.94	4.68	11.13
6.00	50.01	-11.97	38.35	4.98	3.63	9.50
6.75	49.76	-14.06	38.74	6.91	2.83	7.55
7.50	49.24	-16.12	39.16	8.93	3.32	5.58
8.25	48.30	-16.85	39.00	9.57	3.36	4.43
9.00	47.20	-18.11	38.89	10.86	4.30	2.76
9.75	46.49	-19.18	38.86	11.99	5.36	1.49
10.50	45.69	-19.81	38.89	12.79	6.14	0.70
11.25	45.02	-20.83	38.89	13.93	7.28	0.86
12.00	45.36	-22.65	39.56	15.69	9.04	2.40
12.75	44.20	-23.12	39.02	16.31	9.67	3.10
13.50	43.38	-23.67	39.01	17.09	10.48	4.01
14.25	45.28	-25.72	40.40	18.81	12.17	5.56
15.00	44.03	-26.68	40.30	19.98	13.32	6.66

Table 8.8: Measured Values and Color Differences when (h, d, θ) is $(1.6, 2.0, 90)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	31.66	-1.45	22.93	4.87	9.75	14.62
0.75	31.82	-2.21	23.49	3.94	8.81	13.68
1.50	31.83	-3.43	24.03	2.62	7.49	12.36
2.25	32.88	-4.33	25.05	1.69	6.24	11.07
3.00	33.73	-5.65	26.03	1.93	4.85	9.52
3.75	34.78	-5.06	27.07	3.46	5.62	9.94
4.50	36.58	-7.46	28.56	5.94	5.11	8.03
5.25	36.03	-8.31	28.67	5.91	4.28	7.01
6.00	40.94	-10.63	31.77	12.12	9.63	9.28
6.75	37.00	-10.88	30.42	8.87	5.60	5.62
7.50	36.97	-11.71	30.73	9.53	5.92	5.17
8.25	36.25	-12.87	30.76	9.98	5.85	4.03
9.00	36.43	-13.92	31.37	11.16	6.86	4.15
9.75	35.21	-14.87	31.11	11.33	6.69	2.96
10.50	35.00	-15.38	31.35	11.81	7.12	3.05
11.25	36.41	-16.61	32.33	13.72	9.12	5.07
12.00	34.33	-16.70	31.32	12.75	7.93	3.28
12.75	35.67	-17.88	32.34	14.54	9.80	5.29
13.50	34.17	-18.07	31.66	14.08	9.23	4.42
14.25	35.13	-19.01	32.41	15.40	10.59	5.87
15.00	33.32	-18.93	31.41	14.62	9.75	4.87

Table 8.9: Measured Values and Color Differences when (h, d, θ) is $(1.6, 3.0, 0)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	56.08	1.45	38.82	8.00	15.99	23.99
0.75	56.32	1.13	38.79	7.75	15.74	23.74
1.50	56.57	0.76	38.86	7.46	15.45	23.44
2.25	56.83	0.62	39.07	7.41	15.37	23.36
3.00	56.60	-0.75	39.39	6.04	13.98	21.96
3.75	56.86	-1.22	39.58	5.72	13.60	21.56
4.50	56.46	-3.20	39.25	3.82	11.62	19.58
5.25	56.34	-4.58	39.72	2.72	10.27	18.21
6.00	56.30	-6.08	40.42	2.25	8.88	16.75
6.75	55.46	-8.47	40.26	2.60	6.36	14.21
7.50	54.52	-11.22	40.11	4.96	3.54	11.33
8.25	54.35	-12.38	40.70	6.19	2.61	10.16
9.00	53.74	-14.84	40.95	8.67	1.72	7.65
9.75	53.43	-14.93	40.87	8.77	1.49	7.45
10.50	51.58	-19.98	40.99	14.01	6.03	2.09
11.25	51.27	-21.24	41.21	15.32	7.34	0.95
12.00	50.62	-23.85	41.41	18.02	10.03	2.10
12.75	49.99	-26.69	41.77	20.95	12.96	4.99
13.50	49.70	-27.75	41.70	22.03	14.03	6.05
14.25	48.80	-29.00	41.58	23.44	15.44	7.44
15.00	48.72	-29.55	41.65	23.99	15.99	8.00

Table 8.10: Measured Values and Color Differences when $(h, d, \ \theta\ )$ is $(1.6, 3.0, 30$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	52.82	0.39	35.66	7.21	14.41	21.62
0.75	53.15	0.96	36.70	7.76	14.93	22.12
1.50	53.42	-0.17	37.00	6.81	13.93	21.11
2.25	53.04	-1.22	36.54	5.69	12.85	20.04
3.00	53.09	-1.73	37.35	5.27	12.33	19.50
3.75	52.08	-4.57	36.61	2.28	9.39	16.58
4.50	51.92	-5.02	36.62	1.83	8.92	16.11
5.25	52.30	-5.68	37.28	1.78	8.39	15.54
6.00	51.74	-8.02	37.41	1.98	6.06	13.16
6.75	51.36	-11.00	37.90	4.75	3.47	10.26
7.50	50.52	-13.22	38.33	6.97	1.87	7.89
8.25	49.93	-15.17	38.54	8.97	2.38	5.90
9.00	49.40	-16.83	38.82	10.69	3.77	4.25
9.75	50.67	-13.80	39.50	7.87	2.63	7.47
10.50	48.32	-21.41	40.01	15.53	8.45	2.39
11.25	47.89	-22.34	40.10	16.51	9.40	2.83
12.00	47.15	-23.54	40.06	17.80	10.65	3.69
12.75	46.49	-24.92	40.17	19.28	12.10	5.01
13.50	45.98	-25.58	40.39	20.07	12.89	5.74
14.25	44.84	-26.59	39.89	21.25	14.04	6.83
15.00	44.62	-26.90	39.97	21.62	14.41	7.21

Table 8.11: Measured Values and Color Differences when $(h, d, \ \theta\ )$ is $(1.6, 3.0, 60)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	52.30	-0.16	35.00	6.98	13.96	20.94
0.75	51.38	-0.72	35.10	6.17	13.13	20.10
1.50	52.25	-1.40	35.67	5.75	12.71	19.69
2.25	52.41	-2.57	36.37	4.81	11.66	18.61
3.00	52.61	-3.96	36.84	3.94	10.51	17.41
3.75	54.04	-5.23	37.94	4.83	10.33	16.96
4.50	52.33	-6.59	37.32	2.81	8.16	14.92
5.25	52.43	-8.89	38.12	4.04	6.64	13.02
6.00	52.23	-10.99	38.34	5.50	5.42	11.23
6.75	51.55	-13.31	38.50	7.34	4.40	9.07
7.50	50.56	-14.59	38.31	8.32	3.72	7.47
8.25	49.78	-15.73	38.40	9.42	3.81	6.14
9.00	50.69	-17.60	39.34	11.51	6.05	6.18
9.75	48.32	-18.61	38.68	12.38	5.84	3.53
10.50	47.40	-19.96	38.74	13.83	7.09	2.56
11.25	45.25	-23.19	39.62	17.58	10.68	4.04
12.00	46.96	-21.21	39.23	15.22	8.45	2.88
12.75	43.75	-23.35	38.37	17.97	10.99	4.01
13.50	47.61	-26.15	40.99	20.28	13.67	7.72
14.25	42.45	-25.39	38.53	20.34	13.36	6.39
15.00	42.64	-26.09	38.71	20.94	13.96	6.98

Table 8.12: Measured Values and Color Differences when (h, d, θ) is $(1.6, 3.0, 90)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	43.19	-0.85	29.63	4.34	8.67	13.01
0.75	43.72	-1.56	30.36	3.75	8.02	12.34
1.50	44.23	-2.43	31.04	3.30	7.34	11.59
2.25	46.33	-3.43	32.35	4.78	7.71	11.56
3.00	45.66	-4.51	32.63	4.08	6.51	10.29
3.75	45.93	-5.64	33.31	4.71	6.16	9.55
4.50	47.77	-6.67	34.46	7.03	7.64	10.24
5.25	46.57	-7.50	34.07	6.17	6.20	8.74
6.00	46.71	-8.91	34.64	7.27	6.39	8.15
6.75	47.12	-10.24	35.23	8.61	7.14	8.09
7.50	51.71	-12.32	37.75	14.03	12.69	12.77
8.25	46.53	-12.67	35.73	10.25	7.73	7.21
9.00	45.75	-13.33	35.50	10.35	7.43	6.40
9.75	45.05	-14.21	35.47	10.86	7.57	5.87
10.50	45.85	-15.08	36.17	12.14	8.95	7.09
11.25	43.64	-15.39	35.36	11.57	7.81	5.07
12.00	47.67	-17.29	37.52	15.18	12.09	9.97
12.75	41.77	-16.02	34.50	11.74	7.59	3.87
13.50	40.76	-16.61	34.24	12.29	8.03	3.92
14.25	41.44	-17.69	34.61	13.37	9.16	5.17
15.00	39.13	-17.30	33.35	13.01	8.67	4.34

Table 8.13: Measured Values and Color Differences when (h, d, θ) is $(1.7, 1.0, 0)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	49.65	-1.40	33.80	7.18	14.37	21.55
0.75	50.58	-2.38	34.47	6.41	13.53	20.70
1.50	49.69	-2.87	34.49	5.66	12.83	20.01
2.25	49.72	-3.55	34.75	4.99	12.15	19.32
3.00	49.15	-4.46	34.97	3.93	11.09	18.27
3.75	48.92	-5.64	35.15	2.73	9.89	17.07
4.50	48.45	-7.08	35.37	1.21	8.36	15.54
5.25	47.65	-8.39	35.40	0.47	6.94	14.12
6.00	47.09	-9.68	35.60	1.77	5.58	12.74
6.75	46.19	-12.15	35.86	4.39	3.12	10.17
7.50	45.60	-13.85	36.28	6.22	1.67	8.37
8.25	44.78	-14.63	36.45	7.29	1.88	7.55
9.00	43.91	-17.59	36.75	10.34	3.65	4.78
9.75	43.02	-19.53	36.94	12.49	5.68	3.44
10.50	42.71	-20.00	36.88	13.03	6.24	3.38
11.25	42.29	-21.77	37.31	14.86	7.94	2.95
12.00	42.35	-23.85	37.80	16.82	9.77	3.35
12.75	42.87	-25.54	38.52	18.35	11.21	4.21
13.50	43.32	-27.10	39.29	19.86	12.68	5.51
14.25	43.50	-28.07	39.78	20.84	13.65	6.47
15.00	43.45	-28.75	40.00	21.55	14.37	7.18

Table 8.14: Measured Values and Color Differences when (h, d, θ) is $(1.7, 1.0, 30)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	47.69	-1.72	32.70	7.26	14.53	21.79
0.75	48.35	-2.95	33.98	6.13	13.31	20.55
1.50	46.94	-3.32	33.43	5.43	12.68	19.95
2.25	47.50	-5.65	34.81	3.34	10.38	17.61
3.00	47.22	-6.78	35.19	2.34	9.19	16.40
3.75	46.66	-7.68	35.32	1.49	8.16	15.37
4.50	46.57	-10.03	36.30	2.49	5.89	12.99
5.25	46.14	-11.43	36.58	3.62	4.47	11.51
6.00	45.20	-13.04	36.49	5.00	2.62	9.71
6.75	44.66	-14.47	36.55	6.42	1.17	8.19
7.50	44.14	-16.08	36.85	8.11	1.04	6.47
8.25	43.00	-17.79	36.69	9.95	2.73	4.63
9.00	41.91	-19.54	36.93	11.96	4.79	2.90
9.75	41.04	-20.59	37.06	13.26	6.15	2.30
10.50	40.64	-21.91	37.44	14.68	7.53	1.88
11.25	40.81	-23.60	37.81	16.25	9.03	2.13
12.00	40.82	-25.23	38.21	17.84	10.59	3.41
12.75	41.09	-26.35	38.53	18.89	11.63	4.38
13.50	41.10	-27.74	38.96	20.29	13.03	5.77
14.25	40.80	-28.50	39.29	21.16	13.89	6.63
15.00	40.73	-29.13	39.38	21.79	14.53	7.26

Table 8.15: Measured Values and Color Differences when (h, d, θ) is $(1.7, 1.0, 60)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	43.51	-2.48	31.03	6.29	12.58	18.87
0.75	45.23	-3.49	32.65	5.87	11.90	18.10
1.50	45.16	-4.16	33.23	5.33	11.20	17.37
2.25	44.56	-5.28	33.67	4.20	9.92	16.07
3.00	42.99	-6.61	33.30	2.21	8.15	14.39
3.75	42.54	-7.61	33.50	1.39	7.04	13.28
4.50	42.37	-8.67	34.09	1.66	5.97	12.15
5.25	41.26	-9.68	33.66	1.90	4.74	10.98
6.00	41.16	-11.90	34.50	4.12	2.60	8.69
6.75	40.04	-12.94	34.22	5.24	1.55	7.51
7.50	40.41	-14.64	35.07	6.94	1.19	5.82
8.25	39.82	-16.58	35.24	8.89	2.68	3.80
9.00	40.05	-18.56	36.10	10.95	4.76	2.11
9.75	39.49	-19.91	36.00	12.28	6.02	0.84
10.50	39.86	-21.18	36.59	13.59	7.36	1.68
11.25	39.49	-22.31	36.88	14.80	8.55	2.54
12.00	39.06	-23.29	36.83	15.78	9.51	3.32
12.75	38.36	-23.73	36.17	16.17	9.88	3.59
13.50	38.41	-24.66	36.54	17.13	10.84	4.56
14.25	37.98	-25.60	36.83	18.19	11.90	5.61
15.00	37.65	-26.25	36.82	18.87	12.58	6.29

Table 8.16: Measured Values and Color Differences when (h, d, θ) is $(1.7, 1.0, 90)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	38.88	-1.13	28.41	6.02	12.03	18.05
0.75	39.62	-1.91	29.28	4.87	10.86	16.87
1.50	39.65	-2.36	29.89	4.24	10.20	16.20
2.25	40.12	-3.65	30.48	2.86	8.75	14.74
3.00	40.22	-4.70	31.18	1.76	7.50	13.49
3.75	41.40	-5.97	32.10	1.94	6.04	11.90
4.50	42.53	-7.36	33.10	3.51	4.79	10.29
5.25	42.78	-8.06	33.62	4.23	4.22	9.49
6.00	43.41	-9.53	34.35	5.77	3.54	8.01
6.75	42.65	-10.32	34.32	5.80	2.47	7.13
7.50	43.35	-13.15	35.56	8.82	3.50	4.37
8.25	43.71	-13.27	36.21	9.39	4.15	4.31
9.00	42.24	-15.31	36.24	10.54	4.59	1.85
9.75	42.71	-16.45	37.01	11.99	6.05	1.35
10.50	41.70	-17.88	37.16	13.09	7.08	1.06
11.25	42.69	-16.24	37.45	12.04	6.12	1.57
12.00	43.14	-17.77	38.19	13.78	7.85	2.37
12.75	42.41	-19.28	38.14	14.88	8.87	2.89
13.50	43.05	-20.09	38.94	16.08	10.09	4.16
14.25	42.66	-21.92	39.24	17.73	11.72	5.71
15.00	42.38	-22.22	39.44	18.05	12.03	6.02

Table 8.17: Measured Values and Color Differences when (h, d, θ) is $(1.7, 2.0, 0)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	57.37	-0.34	37.91	8.18	16.36	24.54
0.75	57.46	-1.09	38.03	7.48	15.66	23.84
1.50	57.35	-2.04	38.25	6.53	14.70	22.88
2.25	57.30	-2.32	38.77	6.22	14.37	22.54
3.00	56.79	-3.45	38.75	4.98	13.14	21.31
3.75	55.94	-5.16	38.62	3.10	11.28	19.46
4.50	56.20	-5.74	39.15	2.64	10.76	18.92
5.25	55.28	-7.38	39.31	0.79	8.89	17.07
6.00	55.51	-7.60	40.53	1.61	8.71	16.82
6.75	54.34	-11.69	40.56	3.96	4.48	12.58
7.50	53.45	-15.18	40.26	7.37	1.10	9.05
8.25	52.20	-17.55	40.19	9.94	1.80	6.44
9.00	52.31	-19.56	41.30	12.00	3.91	4.52
9.75	50.96	-22.38	41.35	15.03	6.86	1.41
10.50	49.82	-22.72	41.10	15.66	7.49	0.92
11.25	49.31	-26.76	42.14	19.76	11.59	3.42
12.00	49.68	-28.51	42.74	21.43	13.27	5.18
12.75	50.01	-30.28	43.54	23.18	15.06	7.08
13.50	49.36	-30.68	43.12	23.64	15.49	7.40
14.25	48.42	-31.07	42.85	24.21	16.04	7.87
15.00	47.70	-31.23	42.64	24.54	16.36	8.18

Table 8.18: Measured Values and Color Differences when (h, d, θ) is $(1.7, 2.0, 30)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	56.58	0.18	37.90	8.25	16.50	24.75
0.75	56.79	-0.18	37.73	8.00	16.24	24.49
1.50	56.68	-0.84	38.39	7.26	15.50	23.75
2.25	56.07	-0.94	38.46	6.97	15.22	23.47
3.00	55.92	-3.08	38.72	4.88	13.11	21.36
3.75	55.21	-4.19	38.75	3.60	11.84	20.09
4.50	54.81	-5.71	39.17	2.02	10.24	18.48
5.25	54.02	-6.69	39.02	0.92	9.10	17.34
6.00	53.18	-9.54	39.46	2.19	6.10	14.34
6.75	51.83	-11.23	39.09	4.29	4.34	12.46
7.50	50.57	-13.10	38.81	6.55	2.94	10.51
8.25	50.16	-15.47	39.11	8.81	1.91	8.11
9.00	49.76	-17.71	39.04	11.01	3.25	6.00
9.75	49.39	-20.82	40.55	14.11	5.89	2.54
10.50	48.92	-22.67	40.83	16.04	7.80	0.87
11.25	48.41	-24.73	41.13	18.17	9.93	1.78
12.00	47.85	-26.44	41.58	20.01	11.77	3.54
12.75	48.67	-28.15	42.53	21.54	13.30	5.12
13.50	47.34	-28.40	41.86	22.05	13.80	5.56
14.25	47.17	-29.07	42.09	22.77	14.52	6.27
15.00	46.80	-30.98	42.63	24.75	16.50	8.25

Table 8.19: Measured Values and Color Differences when (h, d, θ) is $(1.7, 2.0, 60)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	53.37	-1.75	35.20	7.74	15.47	23.21
0.75	53.14	-2.84	35.76	6.52	14.25	21.99
1.50	53.44	-4.02	36.72	5.36	13.03	20.74
2.25	54.12	-6.11	38.19	4.04	11.13	18.73
3.00	54.38	-8.05	38.75	3.43	9.48	16.96
3.75	54.13	-9.71	39.31	3.49	7.94	15.28
4.50	53.59	-11.07	39.33	3.67	6.52	13.83
5.25	53.11	-13.52	39.87	5.53	4.49	11.38
6.00	52.72	-15.26	40.72	7.32	3.63	9.62
6.75	52.30	-17.43	40.99	9.30	3.48	7.57
7.50	52.52	-18.85	41.85	10.97	4.77	6.69
8.25	51.48	-21.60	42.16	13.57	6.44	4.31
9.00	50.10	-22.88	42.21	14.85	7.35	2.69
9.75	48.94	-23.74	41.88	15.70	8.03	1.47
10.50	50.69	-24.97	43.41	17.18	9.79	4.04
11.25	49.25	-26.20	43.11	18.35	10.74	3.72
12.00	48.59	-27.53	43.14	19.69	12.03	4.62
12.75	47.25	-28.20	42.31	20.34	12.61	4.90
13.50	47.26	-29.15	43.07	21.43	13.71	6.03
14.25	46.50	-29.85	42.81	22.18	14.45	6.72
15.00	46.01	-30.82	42.80	23.21	15.47	7.74

Table 8.20: Measured Values and Color Differences when (h, d, θ) is $(1.7, 2.0, 90)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	44.58	3.46	34.09	6.86	13.71	20.57
0.75	41.40	2.94	32.23	8.63	15.13	21.85
1.50	40.68	0.90	31.09	8.61	14.54	21.05
2.25	43.21	0.82	33.47	5.60	12.15	18.91
3.00	44.35	-1.27	33.86	3.60	9.87	16.61
3.75	45.69	-2.10	35.29	1.50	8.06	14.88
4.50	47.23	-3.07	36.02	1.12	6.57	13.38
5.25	46.48	-4.37	35.97	1.75	5.63	12.42
6.00	49.55	-2.24	38.70	3.94	6.83	13.11
6.75	49.23	-5.12	38.78	4.41	3.96	10.29
7.50	48.31	-8.22	38.51	6.19	0.86	7.56
8.25	49.15	-9.04	39.56	7.58	1.29	6.32
9.00	49.70	-10.41	40.38	9.26	2.68	4.77
9.75	54.49	-7.89	43.15	11.74	7.78	8.79
10.50	51.36	-10.66	41.86	10.83	4.77	4.72
11.25	51.26	-12.96	42.30	12.76	6.18	2.76
12.00	51.60	-14.67	42.97	14.58	7.90	2.49
12.75	51.35	-16.29	42.94	15.85	9.04	2.56
13.50	50.58	-20.04	42.72	18.90	12.05	5.22
14.25	51.39	-19.89	43.57	19.25	12.39	5.55
15.00	51.46	-21.25	43.80	20.57	13.71	6.86

Table 8.21: Measured Values and Color Differences when (h, d, θ) is $(1.7, 3.0, 0)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	64.66	1.96	43.85	8.23	16.47	24.70
0.75	63.97	0.58	41.70	6.92	14.98	23.16
1.50	63.84	0.65	42.56	6.78	14.95	23.16
2.25	63.68	-1.05	41.19	5.55	13.42	21.56
3.00	63.81	-0.19	43.08	5.93	14.14	22.37
3.75	63.08	-2.01	42.32	4.11	12.20	20.40
4.50	63.09	-2.10	42.86	3.92	12.10	20.32
5.25	63.33	-2.38	43.44	3.71	11.93	20.17
6.00	61.82	-7.42	42.65	1.90	6.73	14.92
6.75	61.06	-9.93	42.95	4.30	4.18	12.33
7.50	60.23	-12.94	43.11	7.38	1.60	9.29
8.25	59.49	-15.32	43.40	9.86	2.14	6.89
9.00	58.40	-15.72	43.27	10.54	2.38	5.99
9.75	61.76	-10.47	43.61	4.77	4.26	12.21
10.50	59.45	-15.30	43.60	9.85	2.14	6.92
11.25	56.68	-21.62	43.09	16.69	8.50	1.23
12.00	55.31	-25.49	43.54	20.79	12.60	4.57
12.75	54.56	-28.54	43.98	23.92	15.75	7.71
13.50	54.27	-29.82	44.18	25.24	17.08	9.04
14.25	53.25	-29.99	43.20	25.70	17.49	9.30
15.00	52.71	-28.69	42.25	24.70	16.47	8.23

Table 8.22: Measured Values and Color Differences when (h, d, θ) is $(1.7, 3.0, 30)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	62.59	0.46	40.55	8.47	16.95	25.42
0.75	62.34	0.97	41.16	8.81	17.26	25.73
1.50	62.55	-0.57	41.38	7.42	15.87	24.34
2.25	63.15	-0.31	41.68	7.89	16.31	24.76
3.00	62.68	-1.50	41.68	6.62	15.03	23.49
3.75	61.19	-4.19	40.98	3.63	12.09	20.56
4.50	60.04	-5.69	41.16	1.87	10.29	18.76
5.25	59.66	-7.10	41.04	0.83	8.89	17.35
6.00	58.19	-9.26	41.13	2.50	6.47	14.87
6.75	57.83	-11.68	41.40	4.68	4.09	12.45
7.50	58.55	-11.60	42.27	4.37	4.13	12.59
8.25	56.71	-15.63	42.38	8.77	0.75	8.24
9.00	54.91	-18.47	42.54	12.08	3.77	5.11
9.75	54.03	-19.70	42.80	13.58	5.26	3.79
10.50	54.30	-20.69	43.24	14.41	5.98	2.73
11.25	53.95	-21.36	43.67	15.21	6.76	1.94
12.00	52.52	-25.44	43.81	19.51	11.06	2.76
12.75	51.82	-27.32	44.12	21.55	13.09	4.70
13.50	51.53	-29.42	44.37	23.62	15.15	6.72
14.25	51.17	-29.98	44.22	24.26	15.80	7.38
15.00	51.22	-31.08	45.52	25.42	16.95	8.47

Table 8.23: Measured Values and Color Differences when (h, d, θ) is $(1.7, 3.0, 60)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	58.23	0.43	39.41	7.31	14.62	21.93
0.75	58.06	1.24	40.85	7.89	15.12	22.41
1.50	58.26	-0.65	40.58	6.07	13.34	20.64
2.25	59.78	1.24	43.34	8.57	15.34	22.45
3.00	58.58	-2.70	41.08	4.16	11.34	18.63
3.75	59.28	-3.10	42.59	4.37	11.01	18.18
4.50	59.38	-6.08	42.62	2.78	8.27	15.36
5.25	59.55	-6.31	43.21	3.24	8.14	15.13
6.00	60.16	-7.92	44.31	4.62	7.22	13.77
6.75	59.69	-11.92	43.85	6.53	4.20	9.97
7.50	60.41	-11.76	45.39	7.49	5.45	10.50
8.25	62.90	-9.10	46.95	8.61	9.24	14.27
9.00	60.26	-15.02	46.46	10.48	5.80	8.03
9.75	62.44	-12.53	47.96	10.53	8.34	11.63
10.50	59.67	-17.46	47.26	12.76	6.96	6.39
11.25	59.82	-18.71	47.96	14.19	8.21	6.36
12.00	57.63	-22.57	47.51	17.22	10.25	4.53
12.75	54.12	-25.60	46.05	19.88	12.57	5.27
13.50	53.44	-26.40	46.09	20.76	13.45	6.16
14.25	53.90	-26.99	46.03	21.23	13.92	6.61
15.00	53.77	-27.67	46.14	21.93	14.62	7.31

Table 8.24: Measured Values and Color Differences when (h, d, θ) is $(1.7, 3.0, 90)$

Grass Length [mm]	L^*	a^*	b^*	ΔE_1	ΔE_2	ΔE_3
0.00	54.20	-2.56	34.90	5.22	10.43	15.65
0.75	54.57	-2.55	36.46	5.21	10.30	15.47
1.50	56.61	-5.51	37.25	4.66	8.82	13.72
2.25	57.45	-7.01	38.58	5.56	8.50	12.96
3.00	57.87	-8.25	39.33	6.34	8.32	12.36
3.75	58.65	-9.36	39.77	7.45	8.70	12.26
4.50	59.00	-10.51	40.32	8.38	8.91	11.95
5.25	59.11	-11.51	40.88	9.18	9.09	11.65
6.00	58.86	-11.69	41.40	9.36	9.07	11.45
6.75	58.84	-13.18	42.01	10.46	9.39	11.02
7.50	58.20	-14.59	40.62	10.29	8.53	9.69
8.25	56.78	-15.42	40.67	10.24	7.66	8.18
9.00	54.14	-15.38	39.29	8.82	5.13	5.40
9.75	54.23	-17.26	40.49	10.99	6.98	5.58
10.50	56.60	-18.21	42.55	13.30	9.93	8.66
11.25	53.38	-18.74	40.22	12.17	7.72	5.06
12.00	52.83	-19.07	40.59	12.57	7.98	4.86
12.75	49.14	-17.91	38.24	11.30	6.12	1.26
13.50	46.94	-18.47	37.46	12.51	7.44	2.92
14.25	46.35	-18.18	38.02	12.61	7.54	3.04
15.00	47.20	-21.53	40.04	15.65	10.43	5.22