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Particle Display System —— Virtually Perceivable Pixels with Randomly Distributed Physical Pixels ——

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In this study, the authors propose and implement a particle display system (PDS) that consists of hundreds of randomly distributed pixels. The wireless capability of this system enables each node to move freely without distant limitation of the use of wire cables. The authors also propose effective visual presentation techniques for a display system with randomly distributed pixels. One of the optimization techniques involves the extension of a well-known phenomenon where humans can perceive two-dimensional static or moving images from a set of high-frequency flashing one-dimensional pixel arrays, such as LED arrays, as a characteristic of a human's vision system. While this technique can only extend the virtual resolution of a display in a direction perpendicular to the aligned pixels, our technique enables the display of multi-directional scrolling of two-dimensional images with randomly distributed pixels. In addition, the advantages of presenting information on a display with nonuniform pixel distribution and virtual pixels with fast flash of pixels are discussed. The proposed techniques help in reducing the cost of installing a large-scale display and the time taken for the initial preparation of the setup, which involves carrying large pixel arrays and determining the precise size and shape of the display.

1. Introduction

The innovation in display technology in recent years has opened up many possibilities for presenting information effectively in the real physical world. With this innovation, the mode of presenting information in the real world has changed and is still changing dramatically in various aspects.

Users are intuitively able to understand the information that relates to their physical environments by overlaying computer-generated information on the real world. Numerous research and art projects have been conducted in this area, Augmented Reality (AR), Pervasive Display and architecture façade display technology. For example, let us assume that an arrow sign is displayed to navigate passengers. Legacy display technology, such as that used in a flat-panel display, can provide passengers with the necessary and sufficient information. However, the display and the physical world are separated by the physical frame of the flat-panel display. On the other hand, a more effective way to navigate passengers would be to display the arrow sign on the floor where the passengers are standing and change its pattern dynamically corresponding to the movement of the passengers.

In addition to the location, the shape of the displays is also important. The appropriate size, shape, orientation, and resolution of a display change according to the information that needs to be displayed. The physical shape of the display influences the structure of the displayed information, if the display is not a conventional flat display. Poupyrev et al. discussed the relationship between the shape of a display and the displayed information for hand-held digital devices [1)].

Other problems associated with conventional large displays are that they require heavy and bulky physical structures and detailed planning and installation works. Therefore, such displays cannot be used for effective and simple visual information presentation in the real world.

On the basis of the above discussions, we define the following keycharacteristics of displays in the real world:

- on-demand position,
- on-demand resolution,
- on-demand size,
- on-demand shape,
- simple and easy installation.

In this study, a particle display system (PDS) is proposed to achieve these key characteristics. This display comprises hundreds of distributable light-emitting devices, such as wireless LED nodes, which can be controlled simultaneously in the real world. We can treat these LED nodes as pixels of conventional displays after determining their positions in the coordinates.

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Prototypes of the display were implemented using this method. In addition, two optimization methods are proposed, implemented, and evaluated to overcome the drawbacks of the display system.

2. Related Works

2.1 Basic Limitation of Existing Display System – Inflexible Hardware

As briefly explained in the above section, existing real-world display systems have several limitations.

Conventional visual displays have physical limitations. Computer displays such as a cathode ray tube (CRT) display, a liquid crystal display (LCD), and a plasma display panel (PDP) are examples of these conventional visual displays. While these displays have relatively high resolution, they are physically very bulky and inflexible. These displays are inflexible in terms of the following three characteristics:

- resolution,
- size,
- shape.

The abovementioned visual displays can provide high-resolution images, i.e., images with thousand by thousand pixels or million-order pixels. The pixels are physically structured in a matrix and fixed to a position. The *resolution distribution* is uniform; while this uniform resolution distribution is effective for creating, transferring, and displaying image data, it is sometimes ineffective (**Fig. 1**). Spatial distributions of the information or image that needs to be displayed are not always uniform, leading to an ineffective use of the resource. If the resolution is set to satisfy the representation of a high definition area, other part cannot make the best use of the potential resolution.

In the case of displays in the real world, the above problem becomes a bigger issue. The total area of the display on which information needs to be presented increases, and the information density varies. While some information such as text or graphics requires high resolution, other information such as pointing direction in the real world requires only low resolution.

With existing technologies and research projects, the size and shape of the displays are also fixed. These displays can be used for a desktop, because the use scene does not change and there is no need to change the size or shape of the display. Users can well investigate the circumstance and select an appropriate model with the best size and shape. However, in the case of real-world information displays, it is virtually impossible to determine their precise size and shape before installing them.

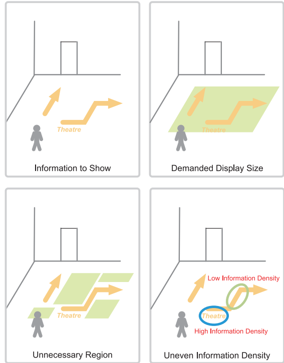


Fig. 1 Inefficiency with existing display system.

2.2 LED Array Display

Moving light dots in a space or on a retina are perceived as a two-dimensional image along their paths. Commercial LED billboards [2] and artworks [3),4] use this one or sparse one-dimensional LED array displays, for example. The key advantages of these displays are that the cost of their physical components and installation works is low. Further, these displays also have additional advantages in that they show advertisements and artwork and provide entertainment.

2.3 Flexible Display

Several commercial displays with physically flexible pixels are available, and several research projects have been conducted to develop such displays. There are primarily two types of structures, i.e., *set of strings* and *set of pixels*.

In the first type of structure, i.e., *set of strings*, light dots (usually LEDs) are used as pixels, and they are placed on a wire at regular intervals. Power is supplied to the wire. In most implementation cases, the data to be displayed is also transmitted to the pixels by the wire [5]. In some research projects, the image data is transmitted with an LED video projector using infrared (IR) LEDs[6]. A rectangular display is constructed by hanging these strings at regular intervals. Such a display can be placed in midair, such as on a stage. This allows the actors to spatially interact with the display.

The display image is created using conventional tools and techniques in rectangular frames and by simply projecting the image onto the rectangular display, *pixel by pixel*.

In the second type of structure, i.e., *set of pixels*, physically separated light dots (usually LEDs) are used as pixels. "LED throwies" are a set of small and simple electronic devices that emit static monochromatic colored light[7]. They consist of an LED, a lithium battery, and a magnet, and they can be extensively distributed in a large area for artistic use. LED throwies are designed to simply emit light until their battery discharges. "Urban pixels" are a set of wireless LED nodes that can be installed in urban spaces[8]. Each pixel unit comprises a microcontroller, an RF transceiver, bright white LEDs, a battery, and an IR sensor. Users can either change the display pattern via an SMS or interact with individual units via flashlights. While the hardware and system structure of urban pixels are similar to those of our PDS, the primary objective of urban pixels is to create a low-resolution ambient display in urban spaces. In contrast, the primary objective of the PDS is to display high-resolution images to viewers, with a small number of physical pixels.

3. Particle Display System

The key features of the PDS are its flexibility in physical shape, simple installation, and easy modification. With these features, users can benefit from the on-demand and flexible display in the real world. Furthermore, because of the inherent characteristics of the PDS, it can overcome drawbacks and even offer advantages.

3.1 Concept of Particle Display System

Figure 2 illustrates the concept of the PDS. Each pixel of this display can be physically distributed over a large area. Further, each pixel can be installed on all the surfaces in a room, on the wall, floor, all the steps of stairs, and the ceiling. The use of wireless controllability overcomes the distant limitation of the use of

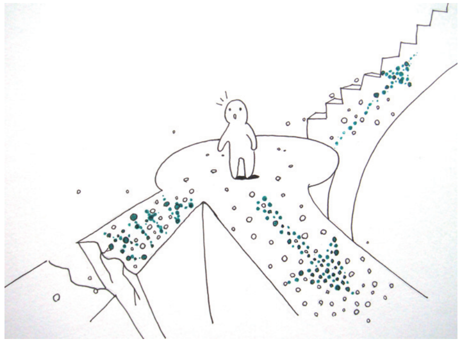


Fig. 2 Schematic of the PDS. Randomly distributed pixel light in sync and build up one image.

wire cables. The shape of the display can be designed such that it is appropriate for presenting information. The PDS can modify its resolution for illuminated graphics by changing the number and the density distribution of the distributed pixels. Users are able to change the number of pixels, depending on desirable images. For instance, displaying a single arrow requires a small number of nodes. It is possible to display more complex figures, such as alphabetic characters, by adding extra pixels.

3.2 Potential Drawbacks

The PDS may have some limitations such as *small number of pixels* and *nonuniform pixel distribution*. In the following discussion, the authors define "perceivable resolution" as *the fineness of the display that humans can perceive*.

The cost per pixel would increase since a microcontroller and other additional electronic components are required for control and communication purposes. Therefore, the total number of pixels (LED nodes) is reduced. Details of the image to be displayed may not be represented appropriately because of the nonexistent pixels, where "important information" of the image exists.

3.2.1 Nonuniform Pixel Distribution

Since the display is installed by simple manual distribution of the pixels, the pixels are not aligned in a matrix order. The simple process for distributing pixels results in the formation of a nonuniform pixel distribution. The distribution of the pixels may be noise of the represented image, because it is not *innocuous* as

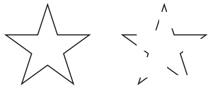


Fig. 3 "Visual completion" ("Closure" of Gestalt principles).

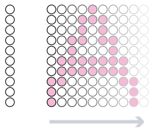


Fig. 4 Principle of a scrolling LED array display.

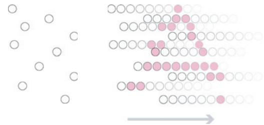


Fig. 5 Principle of a scrolling randomly distributed LED display.

medium.

The *perceivable resolution* of a figure displayed by the PDS may be lower than that of a figure displayed by an ordinary LED display in the matrix order. It can convey the necessary information to recipients using some optimizations. The challenge hereby is to enhance the display capability by adopting optimization methods by using the characteristics of the image to display's geometry, of display's spatial frequency, and of human's vision system.

3.3 Overcoming Potential Drawbacks

3.3.1 Visual Interpolation

The PDS uses a phenomenon known as "*visual completion*" [9] (**Fig. 3**). This phenomenon is also well known as the "closure" of *Gestalt principles*. A human's brain uses information that is lacking in the presented image and tends to complete the incomplete elements. If the image has a cyclic pattern, an observer can imagine the elements even if they are not present. The observer can also redeem straight lines or smooth curves, even if there is a gap (Fig. 3). In this study, this phenomenon is applied to enhance the presentation of a visual display. Since the distribution of pixels is not uniform, important information regarding the image can be conveyed by choosing the best location in the entire display.

3.3.2 Virtual Pixels

Another optimization method involves the multiplication of the number of perceivable pixels with moving images on randomly distributed pixels. **Figure 4** illustrates the principle of an ordinary one-dimensional LED array display. Observers can view the details of the image at frequencies higher than the spatial Nyquist frequency of the slit interval by using a multi-slit display. This is possible due to the spatial and temporal integration in the human's vision system [10]. This phenomenon is also observed in randomly distributed LEDs (**Fig. 5**). Some

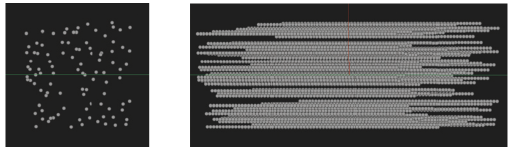
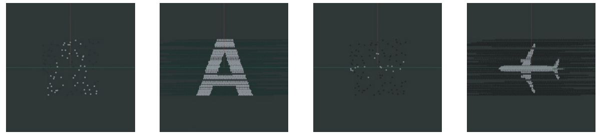


Fig. 6 Example of position of *real* pixels (LED) and *virtual* pixels (64 pixels at interspace of 0.03 × a side length of the display area).



(a) (b) (c) (d)

Fig. 7 Example of displayed images. (a): "A" without virtual pixels, (b): "A" with virtual pixels, (c): an airplane without virtual pixels, (d): an airplane with virtual pixels.

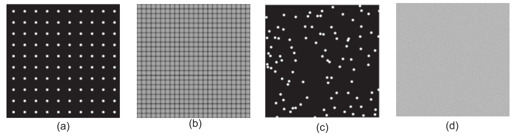


Fig. 8 Original and discrete Fourier transform (DFT) images of pixel distribution of displays. Arrangement of pixels (a) 100 pixels arranged in matrix order, (c) 100 pixels arranged in random order. (Note: the size of white dots in (a) and (c) is greater than the actual size (1 pixel dot) to make them visible.) (b) and (d) are DFT images of (a) and (c), respectively.

examples of computer-simulated images are shown in **Figs. 6** and **7**. The resolution along the axis of scrolling can be enhanced by scrolling an image on the randomly distributed pixels. In this study, these multiplied pixels and the technique employing this principle is termed "virtual pixels."

Capability of Omni-Directional Scrolling

While this method is similar to an ordinary scrolling LED billboard (Fig. 4), it has other effects and advantages. As shown in **Fig. 8**, we can see that Fig. 8 (d) does not have directionality, while Fig. 8 (b) has strong directionality. This flat spatial frequency is suitable for multidirectional scrolling applications, because scrolls toward any direction have almost same characteristics and representation power. One possible application is to present different messages to viewers standing at different positions around the display placed on the floor.

4. Implementation

4.1 System of Wireless Particle Display System

4.1.1 System Architecture

Figures 9 and **10** show the schematic and the functional block diagram of the PDS, respectively. *The display module* consists of hundreds of distributable small circuit boards. Both the physical modules have software layers. These layers enable the integration of the two physical parts so that they can work cooperatively. *The display module* and the *control module* communicate over a wireless network (as Japanese "Extremely Low Power Radio Station" [11] at 303.2 MHz).

4.1.2 Software Setup

The displaying sequence is as follows.

(1) Distribute the Display (LED) unit in a place.

(2) The location unit calculates the position information of each node of the display (LED) unit.

(3) The communication unit controls the display (LED) unit by transmitting a light sequence to each of the display (LED) nodes.

4.1.3 Physical Setup

The physical setup of the PDS consists of the following two physical modules: the *display module* and the *control module* (Fig. 9). The control module can be divided into two subunits, namely, the *location unit* and the *communication unit,* as shown in Fig. 10.

Display Unit – Wireless LED Nodes

With the current installation, the display unit consists of several hundreds of wireless light-emitting diode (LED) nodes. Each LED node, which acts as one pixel of the display system, comprises an LED, a microcontroller, and a wireless communication module.

The components of the display unit must have the following features:

- a single-pixel display
- a wireless network device

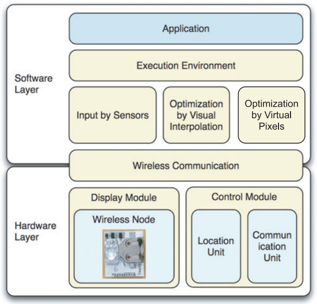


Fig. 9 Functional block diagram of the PDS.

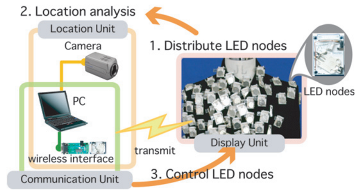


Fig. 10 Schematic of the PDS.

- a CPU to control the display and the communication unit

After developing a prototype of the first wireless LED node (**Fig. 11** left) [12], the authors redesigned the LED nodes with a super-bright full-color LED and another microcontroller for processing the pulse width modulation (PWM) of the LED and enabling additional input/output (Fig. 11 right). The specifications and system diagram of the improved LED node are shown in **Table 1** and **Fig. 12**, respectively.

With the abovementioned improvement, an LED node, i.e., one pixel of the display, could handle input/output and operations for the connected sensors/actuators. Therefore, interaction between the display and the users in the real world was enabled. First implementation is done with an acceleration sensor that enables direct input by tapping (*clicking*) the LED node.

Communication Unit

A wireless interface board is connected to the PC by an RS232C serial port with a USB-RS232C converter. This board can communicate with the wireless nodes in the same way as wireless nodes communicate with each other. The communication unit transmits a message to control the lighting pattern of the display unit. It communicates with the nodes via wireless communication at a rate of 4800 bps. It is technically difficult to transmit and display real-time animation because of the low baud rate of wireless communication.

Location Unit

The location unit consists of a PC, a wireless interface board, and a video cam-

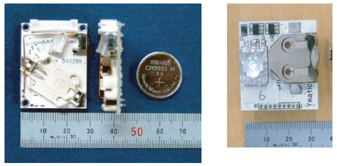


Fig. 11 Wireless LED nodes. First (left) and second (right) prototypes.

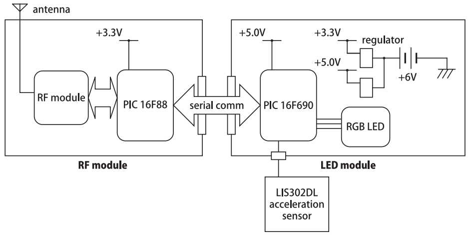


Fig. 12 Hardware diagram of input-capable LED node.

Table 1 Specification of the Improved LED node.

RF	303.2 MHz
CPU (RF communication)	Microchip PIC16F88
CPU (LED control)	Microchip PIC16F690
LED	RGB full color (EP204K-35RGB) Total Flux 1.4 (lm) Intensity Level 3.7 (cd)
Power Supply	Series of two CR2032 3 V Lithium Coin Battery (6 V)
Size	W39 mm × H34 mm × D12 mm
Weight	11.0 g (exclude battery)

era. This unit calculates the position information of each node of the distributed display (LED) unit, with the following sequence:

- It sends a message to each LED node and turns the LED on.
- It captures a video stream using the camera.
- It calculates the position of the lighting LED node from the captured image.

The locating system of the LED nodes is employed with a GUI for easy operation.

4.2 Optimization by Visual Interpolation

Optimization by visual interpolation was carried out after vanilla implementation [12]. The author's hypothesis is that the key information about a figure can be obtained from its "contours" and, especially, its "vertices." Therefore, by representing the contours and vertices selectively, the key information about an image to be displayed can be conveyed effectively. Two types of optimizations, i.e., optimization A and optimization B, were carried out on the basis of this hypothesis.

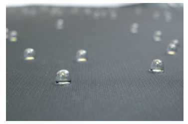


Fig. 13 Embedded LEDs.

Fig. 14 Front view of randomly distributed LED display.

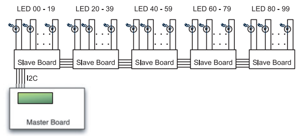


Fig. 15 Hardware setup of randomly distributed LED display with virtual pixels.

4.3 Optimization by Virtual Pixels

Prior to developing a hardware-based display, simulation software was implemented. This simulation software can display a set of colored points in a three-dimensional coordinate system. The color of the points is set from an imported image file to be displayed, including the simulation of virtual pixels. While the virtual pixel display requires a high refresh rate, the refresh rate of computer screens (LCD panels) is low (60 frames per second). Therefore, this simulation software is used as a previewer and a sequence generator for the hardware-based installation of the display.

A hardware-based evaluation system is developed with 100 LEDs as randomly distributed pixels and a set of printed circuit boards with PSoC CY8C29466 mixed-signal arrays (Cypress Inc.) (**Figs. 14**, **15**, **16**). The display area is 400 × 400 mm in size. The pixels of the display are ϕ5 mm white LEDs E1L55-AW0C2 (Toyoda Gosei Co., Ltd.) These LEDs are embedded into a 2 mm thick plastic board, as shown in **Fig. 13**. The rear view of the wired, randomly distributed LED display is shown in Fig. 16. This display is installed with wired and embedded LEDs to ensure that the conditions are the same throughout the evaluation processes.

The system consists of one master board and five slave boards. The sequence number and the parameters of the display, i.e., "flash interval" and "frame interval" (**Fig. 17**), can be controlled with switches and variable resistors on the master board. The flash interval sets the duration of one flash of a sequence, and the frame interval sets the time cycle of the display. The master board sends out a command that contains the sequence number and the flash interval. The sequence of each pixel is stored in the ROM of the microcontroller. The micro-

Fig. 16 Rear view of the randomly distributed LED display.

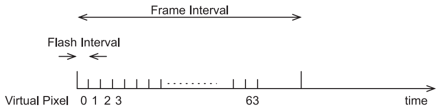


Fig. 17 "Flash Interval" and "Frame Interval".

controller on the slave boards reads the sequence in the ROM and flashes the LEDs with the provided flash time interval. 20 white LEDs are directly driven by each slave board.

5. Evaluation

5.1 Evaluation of Optimization by Visual Interpolation

The authors carried out two computer-based simulations and one real-world experiment. The computer-based simulations use large numbers of randomly distributed pixels (100, 500, 1000, 2000, 5000, 10000 pixels) with 320×240 (pixels) field. The virtual pixels are randomly distributed on a computer, which works in the same way as the actual system. The image to be displayed is a filled star (**Fig. 18**, 92×87 pixels).

Optimization A

Search for a position in the 320×240 pixel field, where the sum of randomly distributed pixels, i.e., four pixels from the contours, is the largest (**Fig. 19** left).

$$S_n = \sum_{k=1}^{n} (x_k | \text{within 4 pixels from contours}) \tag{1}$$

Optimization B

Search for a position in the 320×240 pixel field, where the sum of randomly distributed pixels, i.e., four pixels from the contours and four times the number within four pixels from the vertices, is the largest (Fig. 19 right).

$$S_n = \sum_{k=1}^{n} (x_k | \text{within 4 pixels from contours}) + 4\sum_{k=1}^{n} (x_k | \text{within 4 pixels from vertices}) \tag{2}$$

Fig. 18 Image to be Displayed (Filled Star).

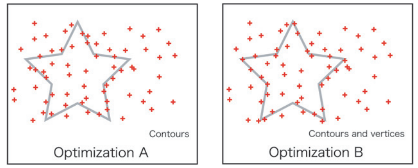


Fig. 19 Optimization Methods A and B.

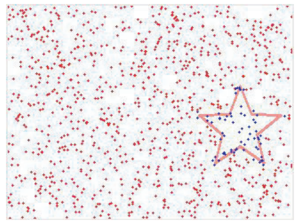


Fig. 20 Optimized location by optimization B with 1000 pixels.

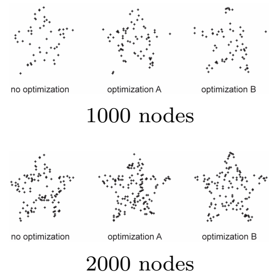


Fig. 21 Displaying position so that there are more nodes on the representation of a star with 1000 and 2000 pixels.

Eleven ordinary students answered the grading of *"how well a figure is represented"* by sliding a bar on a computer screen with a mouse. The numerical value was scaled from 0 to 100, and the average of the score is shown in **Fig. 22**. The application of the optimization method makes it easy to understand the original figure (**Figs. 20**, **21**). Both the optimizations improved the score in most cases, and the score obtained by optimization B was higher than that obtained by optimization A, in most cases (Fig. 22). For example, with 1000 pixels (Fig. 21), we can determine the difference between the representations with and without optimization. In the case of optimization B, a clear image of the star can be obtained, while in the absence of optimization, the edges of the star cannot be observed clearly.

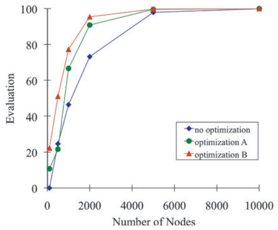


Fig. 22 Averages of evaluation of each optimization method.

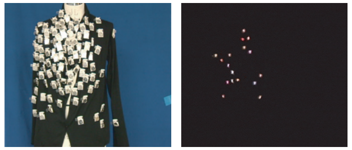


Fig. 23 Distributed pixels (LED nodes) (left) and the displayed star (right).

From the above result, it can be concluded that a figure can be well represented by conditioning the displaying position so that there are more nodes on the contours of the figure and, especially, on the vertices.

Real World Experiment

On the basis of the results of simulations carried out with optimizations A and B, the authors performed a real-world experiment with the better method, i.e., optimization B. Representation in the real environment (**Fig. 23**) was contrary to that expected by the authors. It was found that 100 pixels were not sufficient to represent a complicated figure such as a star. Because of a failure in wireless communication, the right arm of the star was not represented, as shown in Fig. 23; this resulted in a poor representation of the star. Even though the representation was not perfect, observers could guess or understand what the original figure represented, and they could even see clear contours of the star, which were reconstructed by the human's vision system.

5.2 Characteristic Evaluation of Particle Display System with Virtual Pixels

When the spatial or temporal frequency of visual stimuli changes, the visibility of the displayed pattern also varies with the display. To determine the relationship between the spatial or temporal frequency and the visibility of the PDS by optimization with virtual pixels, a display experiment that involved the scrolling of alphabet "A" was performed to determine the characteristics of the display (**Figs. 24**, **25**).

The subjects who performed the above experiment were eight ordinary men and women in their 20 s and 30 s. In this experiment, the experimenter varied the

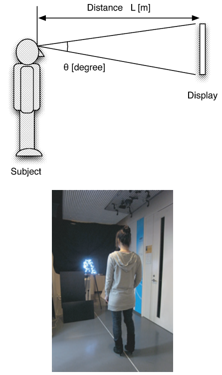


Fig. 24 Spatial arrangement of experiment.

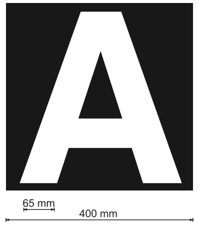


Fig. 25 Size of the character "A".

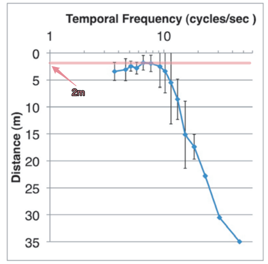


Fig. 26 Characteristic evaluation of PDS and virtual pixels. Error bars are SD.

scrolling speed of the alphabet, and the subjects were asked to answer a question, i.e., "what is the distance range from where you can see the image clearly without making any intentional effort?" "Intentional effort" involves approaches such as moving the eyes quickly to follow the moving alphabet or narrowing of the eyes.

Prior to the main part of the experiment, presentation with a flash speed of 10 [ms] was shown to the subjects that were standing at a distance of 10 [m] from the display, as the standard of "clear image." This condition was defined as "a condition under which most people can see a very clear image without making any intentional effort," with a preliminary experiment. The luminous intensity of one LED is 1400 [mcd]. Ambient light illuminance is 120 [lux].

Experiment Result

Figure 26 shows the result of the display experiment. The average of the closest distance to the display is plotted. If a subject cannot see a clear image, the trial does not calculate the average and distribution.

This confirms that the PDS with virtual pixels can be used as a general visual display with appropriate configuration.

5.3 Design Principle and Calculation of Required Pixel Density

The required pixel density of the display is determined by carrying out the characteristic evaluation. The view angle of the display is expressed in the following equation.

$$View\ Angle = \arctan\left(\frac{D}{L}\right)(\text{rad}) \quad (3)$$

where L (m) is the distance between the display and a viewer, and D (m) is the length of a side of a square. Therefore, the pixel density (pixels/rad^2) of this display is expressed in the following equation.

$$Pixel\ Density = \frac{m}{(\arctan(\frac{D}{L}))^2} \simeq \frac{m}{(\frac{D}{L})^2} = \frac{m \cdot L^2}{D^2}(\text{pixels/rad}^2) \quad (4)$$

where m is the sum of the pixels. It is assumed that D/L is sufficiently small.

Here, Fig. 26 shows that a distance of 2 [m] is required to obtain a clear image with this setup. With the above equation, the required pixel density of the PDS is expressed as

$$Pixel\ Density \simeq \frac{100 \cdot L^2}{0.4^2} = 625 \cdot L^2 = 2500(\text{pixels/rad}^2) \quad (5)$$

6. Discussion

6.1 Flexible Display - Overcoming the Limitations in Shape and Potential Low Resolution

PDS enables flexible placement of a display in the real world, such as architecture façades and vast public spaces on real objects. PDS can be installed effortlessly and quickly since it comprises physically separated pixels.

Several methods are developed for placing physical pixels. First, implementation with fully wireless pixel nodes, the implementation in this paper is done with this method. The PDS worked well with small-scale applications and temporary installation with physical pixels of the order of a few hundreds. Evaluations were carried out by placing wireless nodes on the floor or attaching these nodes to clothes with adhesive tapes. However, it was found that the PDS was not suitable for large-scale and long-term applications. Therefore, to solve this problem, we are now studying the feasibility of ensuring easy and fast attachment and detachment using electromagnets. Second, one of the practical solutions is to use a *partially wired* PDS. This is also favorable as power supply is an unsolved problem as discussed later. Only power is supplied by a soft, flexible, and cuttable two-dimensional net/cloth; therefore, the display can be installed with enough flexibility in position, size, shape, and resolution, as in Refs. 13)–15).

Locating is another challenge. At present, the PDS is installed with on-board LEDs, an off-the-shelf FireWire camera, and a simple computer vision process. Such a PDS is cost effective, because neither does it require any additional physical components on the LED nodes nor does it require a special projector/camera. As the drawback is relatively slow locating, in future, the PDS will be installed with high-speed optical devices. *Smart dust* communicates with optical transmitters and receivers. It has a passive transmitter with a corner-cube retroreflector, an active transmitter with a laser diode and beam steering, and a receiver with a photodetector [16),17)]. *Pushpin computing* uses an IR module for short-range communication [13),18)]. Projectors with both visible light and IR light are popular in recent research projects. Some of these approaches are carried out with binary gray-codes with an off-the-shelf video projector and photosensors [19)], gradient fiducial markers with an off-the-shelf video projector [20)], a high-speed video projector using a digital mirror device (DMD) [21)] technology [22)], a modified IR LED video projector [6)], a custom high-speed LED array projector [23)], passive binary-masked LED projectors as the transmitters, and photosensors as the receivers [24)]. The operation speeds of an LED projector and a DMD video projector are considerably higher (kHz or more) than those of ordinary projectors.

To overcome the potential low resolution of the PDS, two solutions are proposed. The first solution involves the use of "visual interpolation" of the human's vision system, wherein viewers can clearly see and understand the complete image that is not actually depicted. The second solution involves the use of virtual pixels, wherein viewers can see a very clear image by scrolling images on randomly distributed pixels. One advantage of the PDS over conventional one-dimensional displays is its omni-directional scrolling.

6.2 Cost

Although at present, the PDS is considered to be expensive, it can be made cost effective.

First, the number of LED nodes required is less than the required resolution. By adopting these two methods, one pixel of the PDS does much more work than one pixel of the existing displays. Second, only necessary and sufficient pixels for the information to be displayed are needed because of the on-demand resolution, size, and shape of the PDS. Third, the PDS does not require a large structure to build a large-scale display; however, it requires only small LED nodes. It is cost-effective to use small LED nodes because they can be stacked and packed in a small box, and they can be handled by a small number of people that install and manage the PDS. On the other hand, ordinary large-scale displays require bulky and large-sized structures to support themselves. The cost of these displays is high for transportation, handling, and installation.

In addition, the flexibility of the PDS makes it cost effective. Simple and on-site installations are possible owing to the flexibility of the PDS. Since there is no need for strict alignments, the PDS can be installed in a very fast, simple, and easy manner. In the case of an unexpected move or installations in a non-stable environment, the PDS can be reused by relocating the LED nodes. On the other hand, in the case of conventional large-scale displays, it is necessary to carry out a detailed preliminary planning, which cannot be changed later.

Therefore, the representation power of the PDS increases, and it also becomes cost effective for a real world display (**Fig. 27**).

6.3 Power Supply

Our proposed PDS can be applied to relatively short periods and small-scale applications. However, for longer periods and larger-scale applications, other power sources should be considered. Power supply is an unanswered question in the field of distributed wireless modules, and there are a number of power sources, such as primary/secondary batteries, micro-fuel cells, heat engines, radio active, solar cells, thermo-electronic conversion, and vibrational excitation [25),26)]. The most probable solution would be to use power sources such as solar cells and secondary batteries, as in Ref. 27). Pushpin computing involves the use of two insulated prongs that are inserted into a polyurethane foam substrate to make an electrical contact with two conductive planes (power and ground) [13)]. Two-dimensional communication can provide not only 54 Mbps communication but also 10 W power supply via a thin and flexible sheet without wiring [28),29)].

6.4 Future Direction

With our current setup, we could readily install the PDS with an accelerometer on a wireless LED node. This PDS enables interaction between a user and the display, where the user interacts using his/her body (**Fig. 28**); this enables intuitive manipulation and encourages involvement. Interaction design with physically separated pixels must be different from that of ordinary large displays. We intend to explore the interaction methods to develop a display for a three-dimensional presentation and multi-viewer application.

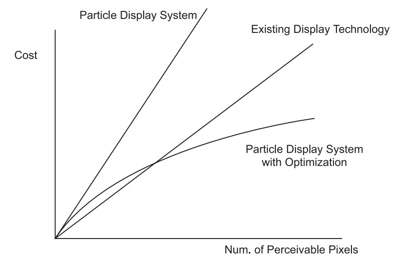


Fig. 27 Cost comparison chart between existing displays and the PDS.

Fig. 28 Interaction with accelerometer.

7. Conclusion

In this paper, the authors have described a PDS, which is a physically distributable visual display suitable for representations and annotations in the real world. The physically distributable pixels allow for the installation of a display with characteristics such as on-demand position, resolution, size, and shape. Further, the installation becomes simple, easy, and inexpensive. In addition, in this study, two methods to overcome the potential drawbacks of the PDS are proposed, implemented, and evaluated. Visual interpolation for the PDS selectively displays *important* information with nonuniform pixels. Virtual pixels of the PDS virtually enrich the perceivable pixels with rapid flash of pixels. Drawbacks that include the presence of a small number of pixels and nonuniform pixel distribution are overcome using these two methods.

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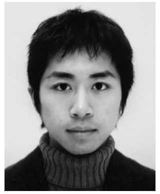

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