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PILC Projector: Image Projection With Pixel-Level Infrared Light Communication

IKUO KAMEI[1], TAKEFUMI HIRAKI[2], (Member, IEEE), SHOGO FUKUSHIMA[3], AND TAKESHI NAEMURA[1,3], (Member, IEEE)

[1]Graduate School of Information Science and Technology, The University of Tokyo, Tokyo 1138656, Japan
[2]Graduate School of Engineering Science, Osaka University, Toyonaka 5608531, Japan
[3]Interfaculty Initiative in Information Studies, The University of Tokyo, Tokyo 1138656, Japan

Corresponding author: Ikuo Kamei (kamei@hc.ic.i.u-tokyo.ac.jp)

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ABSTRACT Invisible-light communication between a projector and multiple devices on the projection plane enables human–computer interaction applications such as movable displays and pointing devices. In this paper, we propose a pixel-level infrared light communication (PILC) projector that can project rich, invisible position-dependent information on high-contrast, full-color visible images. Although previous methods for such communication sacrificed the image quality, the amount of information, or other features, our method meets all the requirements by adding an infrared light source to a full-color DLP projector. This system alternately projects visible images and invisible data sequences with visible and infrared light, respectively. As proof of concept, we built a functional prototype and confirmed that its image contrast is more than 60 times that of a previous method while maintaining pixel-level position accuracy. In addition, we investigated flicker-perception rates in response to different amounts of embedded information and discovered that we could send rich information (up to approximately 2 kbps) with imperceptible flicker. Finally, we built a tabletop application with the proposed system, in which users can simultaneously see both an aerial photograph and a map through movable displays.

INDEX TERMS Augmented reality, digital micromirror device, human-computer interaction, visible light communication.

I. INTRODUCTION

With the remarkable progress in electrical engineering, computer devices are becoming increasingly miniaturized, and many devices exist in our daily spaces nowadays. Consequently, methods to send signals to these devices are gaining much attention. Sending position-dependent information to these devices is especially important for enabling human–computer interactions because it enables feedback to human motions.

There have been many attempts to embed position-dependent information in spaces, mainly to locate devices. In some methods [1], [2], visible markers are installed in the space and a camera is placed on each device; the device calculates its position based on how the markers appear on the camera. In other methods [3]–[5], a pattern is projected from the device, and the device's location is calculated based on the shape of the projected pattern on the walls. Although these methods are straightforward, the visible markers occasionally cause disturbance to the human eye. Therefore, some previous methods adopted high-speed projectors [6]–[9], luminance modulation [10], or color vibration [11], and these methods can be used to embed information that cannot be perceived by the human eye. However, these methods cannot provide high-quality images and send rich information simultaneously. For example, in the pixel-level visible light communication (PVLC) [8], [9], the original image and embedded data are alternately projected at a very high speed by using a digital light processing (DLP) projector, but this method degrades the contrast of projected images. On the other hand, the embedding of information using infrared light is promising because the embedded information, such as markers, would be invisible to the human eye. Several systems have been proposed to embed position data in infrared markers [12]–[16], but they were not intended to provide visual images, needed

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precise calibration, or were not capable of full-color image projection.

In this paper, we propose the pixel-level infrared light communication (PILC) method, which extends PVLC to the infrared region by projecting images via visible light and presenting information to devices via infrared light. Our method improves the quality of the image to be projected because the human eye will not see anything other than the image that was originally intended to be projected. Moreover, the transmission process of information is greatly simplified by splitting the bands for information and image projection into the infrared and visible region, respectively.

We previously demonstrated the first prototype of our system [17] by adding an infrared light source to a full-color DLP projector. We implemented our projector system inspired by previous studies which used DLP projectors with unique light sources [18]–[20]. The present paper further explores a sophisticated design of our system and its implementation. We conducted three experiments by using this prototype. First, we calculated the image contrast of the projector when projecting white and black images while embedding a certain amount of data and confirmed that the image contrast improved in comparison with PVLC. Second, we measured flicker-perception rates while changing the ratio of infrared projection time and calculated the maximum data-transfer rates without flicker perception. Finally, we evaluated the position consistency of embedded data with a projected image and confirmed that the embedded data and projected visible images are consistent with pixel-level accuracy. In addition, we designed a see-through map experience as an application of the proposed system. In the application, we combined our proposed system with a rear-projection screen on a table and a mirror. We projected an aerial photograph on the screen while a smartphone with a photodiode was placed on the screen, and we showed the corresponding map on the smartphone display.

In summary, our contributions are:

- Proposal and design of the system which enables visible high-quality image projection and infrared position-dependent data embedding from a single projector.
- Evaluation of the image contrast and position consistency of the system.
- Investigation of the trade-offs between data transfer rates and flicker-perception rates.
- Proposal and implementation of an application using the proposed system.

II. RELATED WORK

A. VISIBLE SUPERPOSITION OF DATA USING VISIBLE LIGHT

Several existing tracking techniques use visible light. TrackSense [3] projects a grid pattern to the environment and determines its position by capturing the pattern with a camera. Shadowtrack [1] uses a light-emitting rotating beacon, and receivers calculate their positions based on variations in illumination. Saito *et al.* [2] a color-coded pattern, which can serve as interior decoration, is placed on the floor, and a camera retrieves its position based on the pattern. In RFIG Lamps [4], a camera and a projector are integrated: the device position is detected with the camera, following which the signal is transmitted directionally with the projector. The reception of the signal according to the position is realized by receiving and decoding the signal from the projector. These projects can be seen as attempts to place some form of data in the environment by using visible light, but their purpose was only to send data to devices, rather than to display visual images for humans.

Display-based computing (DBC) [21] is a concept that uses a display to present not only information such as images to humans but also information such as control signals and position-measurement signals to devices such as robots. By using the DBC method, the projector can send position data to the receiver by projecting a shaded pattern around the receiver's position after its position is first searched. Augmented Coliseum [22], a mixed-reality game environment, is a system in which images and a small robot are controlled collaboratively by using the DBC method. Summet and Sukthankar [21] used the DBC method to track the locations of moving handheld displays. However, the pattern is easily visible to the human eye, thereby degrading the image outlook.

PICOntrol [5] lets users control devices with a handheld projector, which projects a control panel and 2D Gray Code [24] sequences. Each device has a photosensor and decodes the signal to retrieve its position. Although this approach enables the intuitive control of devices, users can see the coded pattern owing to the slow refresh rate of projectors.

B. INVISIBLE SUPERPOSITION OF DATA USING VISIBLE LIGHT

Humans cannot perceive light blinking at a sufficiently high frequency, and the threshold of this frequency is called critical fusion frequency (CFF) [25]. At such frequencies, we perceive the average value of illuminance. There have been several attempts to embed information by using this principle. Smart Light [6] projects position data that cannot be perceived by the human eye by arranging visible LEDs as a matrix and shifting the timing of each LED's high-speed blinking. However, the resolution of the projected image is extremely low (4 px × 5 px), making it unsuitable for displaying images and acquiring precise position information. Abe *et al.* [11] used color vibration to embed data to each pixel. Since the human eye is less sensitive to changes in color than to changes in illuminance, color vibration can be performed with conventional LCDs. However, only a small amount of information can be embedded with this method.

DLP projectors consist of light sources and a digital micromirror device (DMD) that can change each pixel's reflection at a high frequency of up to 22 kHz. Therefore, DLP projectors can embed information that can only be detected by placing a photodetector in the projection area that appears normal to the human eye. Cotting *et al.* [10] combined DLP projectors and synchronized cameras in order

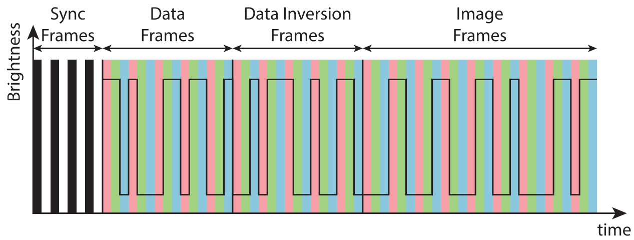

FIGURE 1. Composition of binary image frames in PVLC, which consist of synchronization frames, data frames, data-inversion frames, and image frames.

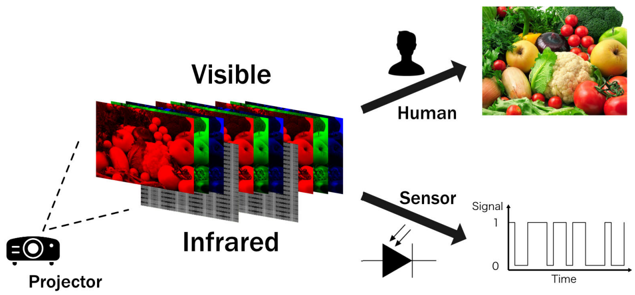

FIGURE 2. Mechanism of image projection and data transfer of the proposed system.

to track the depth of objects. However, they used projectors to track objects, which is not the objective of this paper. Le Goc *et al.* [7] projected Gray code sequences onto flat planes, and robots on the planes determined their positions by receiving and decoding the sequences. Similarly, Lee et al. used DLP projectors to calibrate projectors automatically [26] or project images on movable displays [27]. They used DLP projectors only to help devices determine their positions, and their approach cannot be applied to project an image and embed information in the same pixel. Bayer *et al.* [28] used two DLP projectors to independently stimulate short, middle, and long-wavelength-sensitive cones; however, the two projectors in the setup needed to be calibrated such that they projected on the exactly same area.

PVLC [8], [9] is a system that projects the image and information by using the data structure shown in Fig. 1. In the synchronization frames, all the pixels blink simultaneously to signal to the receiver the start of the projected sequence. In the data frames, the system sends the information independently in each pixel as a sequence of ON and OFF, and each pixel's brightness is adjusted in the data-inversion frames so that it appears as an image with 50 % brightness. In the image frames, the system projects a visual image for the human eye. Although this approach realizes image projection and data superposition from a single projector, the contrast of the projected image is not high because the human eye perceives the projected image as the sum of the synchronization, data, and image frames.

C. SUPERPOSITION OF DATA USING INFRARED LIGHT

Since visible markers are obtrusive to the human eye, the attempts mentioned above all used high-speed vibration to make them invisible. However, these markers can also be made invisible to the human eye by projecting them with infrared light. There have been several attempts to send information to devices via infrared light.

Raskar *et al.* [12] static infrared binary patterns are projected at a high frame rate, and photo-sensing tags determine their position by decoding the sequence. Lumitrack [13] projects a static binary image, and a photodetector array locates its position by scanning it. Sceptre [14] uses infrared laser pointers and an IR camera that captures laser beams emitted from the pointers, and the system calculates the location of the devices based on the shape of the laser patterns. Again, these attempts use projectors only to locate a device's position.

Chan *et al.* [15] proposed a system that simultaneously provides different information to the human eye and device by projecting with a visible-light projector and an infrared projector on the same wall. While the visible-light projector projects visual images, the infrared projector projects invisible AR markers on the projection plane. Because this system projects visible and infrared light separately and aligns them on a plane, it needs precise alignment to obtain the position on the plane.

Lee *et al.* [16] developed a projector that uses red LEDs and infrared LEDs as light sources. This projector projects visual images with the red LEDs and Gray code patterns with the infrared LEDs. With this projector, we can obtain the locations of receiver devices by decoding the infrared light signal from the projector. However, the visual images are limited to a single color, making the projector unsuitable for color images. Therefore, the development of a full-color projector system with infrared light sources remains an issue because we cannot realize such hybrid projection by simply adding light sources to the control system of a conventional projector.

D. POSITION OF THIS WORK

We summarize the research projects mentioned above in Table 1. With these previous methods, it is difficult to send position-oriented data to devices precisely and transmit the information while projecting high-quality color images. In the present work, we propose a system that simultaneously solves all these problems.

III. METHOD AND IMPLEMENTATION

In this section, we propose the pixel-level infrared light communication (PILC) projector and discuss its design and prototype. In the PILC projector, visible light is used only for the projection of images and infrared light is used only for the projection of information in order to achieve both precise information presentation and high-quality video projection. In this system, the projection methods of images and information are differentiated by the wavelength of light.

Fig. 2 shows the outline of data transfer in this system. The system projects images and information signals in a

TABLE 1. Comparison of projector-device communication methods.

Method	High Resolution	High Contrast	Color Projection	Invisible Data	Rich Information	Calibration-free
RFIG Lamps [4]	✓	✓	✓	✗	✓	✗
DBC [21]	✓	✓	✓	✗	✗	✗
Smart Light [6]	✗	✓	✗	✓	✗	✓
Abe *et al.* [11]	✓	✗	✓	✓	✗	✓
PVLC [9]	✓	✗	✓	✓	✓	✓
Chan *et al.* [15]	✓	✓	✓	✓	✗	✗
Lee *et al.* [16]	✓	✓	✗	✓	✓	✓
Our work	✓	✓	✓	✓	✓	✓

time-division manner because a single DMD modulates the light from visible and infrared light sources. The image contrast does not degrade in principle, because the signal light is not added to a visual image. In addition, we can decode the information signals easily because the light of visual images and the signals can be separated by filtering out visible light appropriately. This invisibility also enables the efficient design of the binary image frames of PILC because it obviates the projection of data-inversion frames, which were necessary in PVLC to keep each pixel's brightness at a uniform value of 50%. Furthermore, flicker perception is likely to occur in PVLC because the system must group the frame blocks of the image frames and data frames. Our system can freely arrange these frames because the light of the images and signals can be separated by using a color filter, which enables us to solve the flicker problem. In our system, however, the time of projecting visible light is shorter than that in a conventional DLP projector because of the projection time of infrared light, which reduces the maximum luminance of the projected visual image. We compensated for this problem by increasing the brightness of the LED light sources.

A. HARDWARE

1) COMPONENTS

Fig. 3 shows the proposed system configuration, which consists of a PC, a DMD with its controller, a signal-conversion board, LED and laser driver boards, visible LEDs, and an infrared laser. The image to be projected and the signal to be transmitted are sent from the PC to the DMD controller in advance. When projecting, the DMD controller sends control signals to the DMD and to the LED. Of these, the DMD control signal is directly transmitted to the DMD to control the DMD, while the control signal of the LED first reaches the signal-conversion board. This board converts the combination of ON / OFF signals of R, G, and B into a combination of ON / OFF signals of R, G, B, and IR, thereby generating control signals for the visible light sources and infrared light source. The driver of each light source controls the light source based on these signals. The beam splitter integrates the light beams emitted from the two types of light sources. These reflected beams reach the DMD, pass through the lens, and are finally projected onto a projection plane.

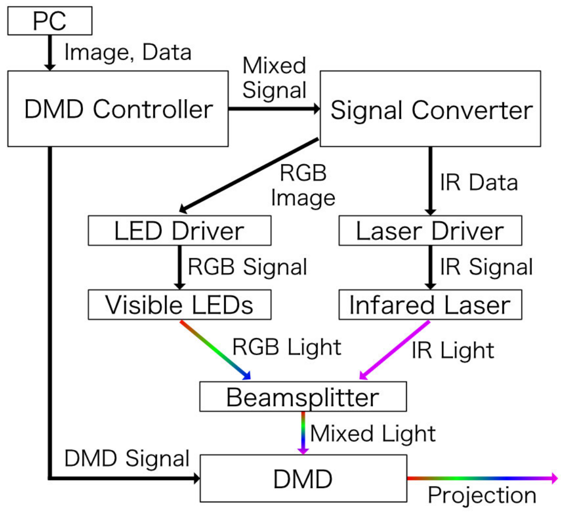

FIGURE 3. Configuration of the PILC projector system.

2) DESIGN OF THE OPTICS SYSTEM

First, we designed and implemented an optics system that integrates visible light sources and an infrared light source. We used an ultra-bright four-color LED board (SBM-160, Luminus Devices) as the visible LEDs. This LED board has red, green, blue, and white LEDs, the light intensities of which are 320 lm, 820 lm, 150 lm, and 730 lm, respectively. Further, red, green, and blue LEDs have wavelengths of 626 nm, 540 nm, and 465 nm, respectively. This board is suitable as the visible light sources because it is integrated into a small package. We designed and manufactured an LED driver board for driving these LEDs. We used the infrared laser (808 nm) built into a DLP projector (DLP LightCrafter E4500 MKII IR Laser, EKB Technologies) and used a laser driver board (LD5CHA, Wavelength Corporation) that is capable of high-power and high-speed ON / OFF control of the laser. We also used a plate-type beam splitter (75R / 25T 12.5 x 17.5, Edmund Optics), which reflects 75% of the visible light band and 25% of the infrared light band. Its reflection characteristics according to wavelength, when substituted with 70R / 30T, are shown in Fig. 4. The above components were integrated into the optics system of the DLP projector (LightCrafter E4500 MKII IR), and the DMD

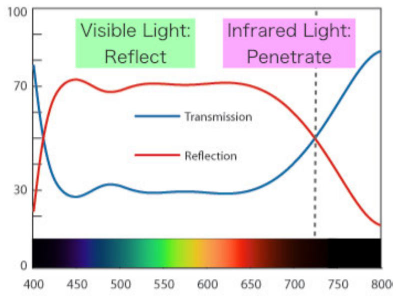

FIGURE 4. Wavelength dependence of reflectance of beam splitter [29].

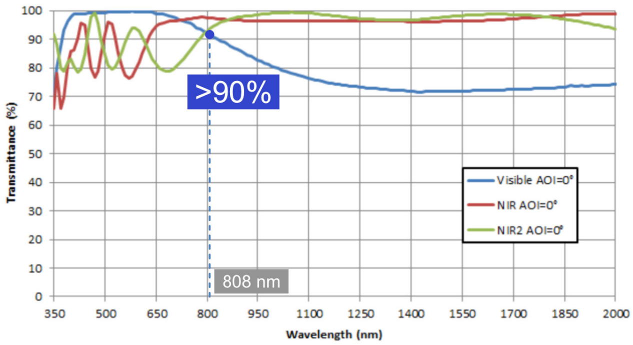

FIGURE 5. Wavelength dependence of reflectance of the DMD. The characteristics of the DMD we used (DLP4500FQE) are shown by the blue line, which corresponds to Visible AOI = 0° (blue line). AOI is abbreviation for angle of incidence [30].

(DLP4500FQE, Texas Instruments) was incorporated in this optics system in advance. Although this DMD is assumed to have specifications for application in the visible light band, it has a reflectance of 90% or more at a wavelength of 808 nm, which is used in our system, and can sufficiently withstand practical use. The reflection characteristics of the DMD are shown in Fig. 5.

Fig. 6 shows the implemented optics system. Our projection system integrates the light from the visible light sources and infrared light source and enables the simultaneous projection of the image and information.

3) DESIGN OF THE SIGNAL CONVERSION BOARD

A DMD controller board has three control outputs for the RGB light sources, but our system requires a control output for an infrared light source in addition to those for the RGB light sources. Therefore, the number of control signals is insufficient for our system. We noticed that we need not turn on two or more RGB light sources simultaneously, and simply switching them sequentially is sufficient when projecting visual images. In other words, the DMD controller has eight (2^3) combinations of ON and OFF states of the three signals, but we need only four combinations (each color ON and all OFF); the others are unnecessary for the image projection. We realized the control of all the light sources by replacing one of the remaining four combinations with a control signal for the infrared light source. In our implementation, we chose

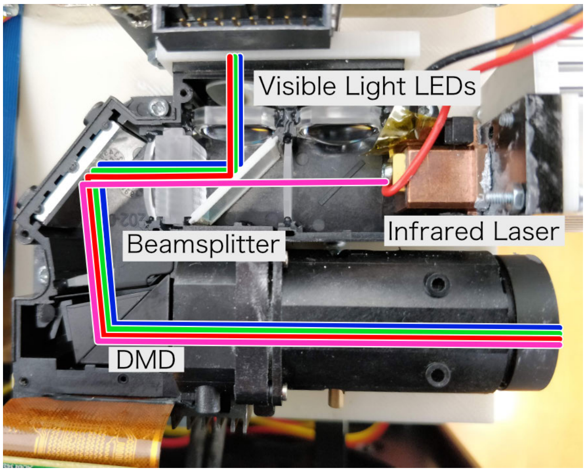

FIGURE 6. Internal structure of the implemented optics system. The light from the visible LEDs and infrared laser is integrated at the beam splitter, and the DMD spatially modulates this light.

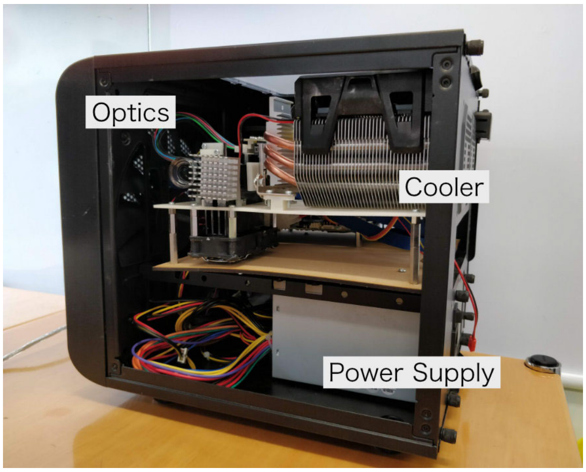

FIGURE 7. Implementation of the PILC projector. The optics system, a signal-conversion board, a DMD controller board, a power supply, and a cooler are integrated in a PC cabinet.

"yellow" (red and green) to represent the ON state of the infrared light source.

4) INTEGRATION

We integrated the optics system, the signal-conversion board, a power supply, and a DMD controller board (LC4500, Keynote Photonics) in a PC cabinet (Core V1, Thermaltake). Fig. 7 shows a photograph of the entire projector system.

B. SOFTWARE

1) CONTROL SOFTWARE

We operated the PILC projector via commands from the DMD controller board and sent the instructions to this controller through software (DLP LightCrafter 4500 EVM GUI). We need to drive the red, blue, and green light sources when projecting images and drive the infrared light source when projecting information while applying binary image frames

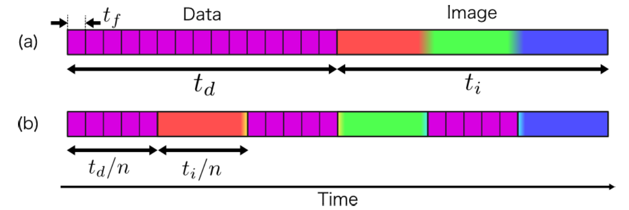

FIGURE 8. **Projection time chart of each pixel in PILC. (a) The standard case in which the data sequence is not divided. t_f is the projection time of each binary frame, t_d is the projection time of the data sequence, and t_i is the projection time of the visible image. (b) Time chart when the information sequence is divided into n subsequences.**

to a DMD. As described in Section III-A3, we can drive the infrared light source by sending the signal to turn on ''yellow'' light. Therefore, we can use the PILC system by loading images and information to be projected as well as the settings of projection patterns on the DMD controller; this method is identical to the method of using DLP LightCrafter 4500.

2) RESTRICTIONS OF EMBEDDED DATA

Although various types of information can be embedded in each pixel by using PILC, there are restrictions on the information to be embedded in terms of the minimum projectable time of a single frame, flicker perception, and spatial continuity of information sequences. We discuss the details of these three restrictions below. In this section, we call the ON / OFF pattern of infrared light to be embedded in each pixel as ''information sequence.'' Fig. 8 (a) shows a time chart of the rays projected on each pixel in PILC.

a: MINIMUM PROJECTABLE TIME OF A SINGLE FRAME

The length per frame of the information sequence (referred to as t_f) cannot be shorter than a fixed time. This fixed time is mainly due to the performance limit of the DMD, and it is 235 μs in our PILC projector. This time can be shortened to 30 μs if we use a high-performance DMD (DLP7000, Texas Instruments), but it is impossible to project shorter binary image frames. Thus, the minimum projection time of a frame t_f determines the maximum information-transfer rate at the time of information-sequence projection.

b: FLICKER PERCEPTION

The time of the data sequence (t_d) must be shorter than a certain time depending on t_i, which is the projection time of the visible image. This is because infrared-light sequences invisible to the human eye are projected in the gap between visible-light sequences. If the information sequence is too long, the flicker of visible light will be perceived by the human eye, causing discomfort to humans. We can determine the percentage of time that can be used to project information from the upper limit of the length of infrared sequences. However, the limit at which this flicker starts to be perceived by the human eye depends on the fatigue conditions of individuals, surrounding environment, and projected images, making it difficult to establish a unified standard. Therefore, we determined this limit through experiments.

For reducing the flicker perceived by the human eye without changing the t_d mentioned above, we can divide the projection of the information sequence and visual image into several parts in order, as shown in Fig. 8 (b). By dividing the sequence into n subsequences, the effective flicker frequency is increased by a factor of n, which makes it difficult for the human eye to perceive flicker; conversely, compared to the case without such division, the length of the sequence t_d can be extended by a factor of n in principle. However, in reality, the divided subsequences have differences in color and brightness, and the human eye can perceive these differences. Therefore, the maximum length of the information sequence is increased by a factor less than n even if the projection sequence is divided into n subsequences.

c: SPATIAL CONTINUITY OF INFORMATION SEQUENCES

The information sequence of a pixel needs to be similar to the information sequence of the surrounding pixels, which is because the size of a light receiver is usually larger than that of a pixel, and the information sequence of several pixels is received simultaneously. As a result, the light signals are mixed on a plane of the receiver, so that it is nearly impossible to decode this mixed signal if an information sequence changes greatly for each pixel. Therefore, the embedded information needs to change continuously or do not change.

We tackled this problem by using Gray code, which Bitner *et al.* [24] used to acquire position information, as an embedding method of information that satisfies the continuity of information sequences mentioned above. Gray code has a property that the inter-symbol distance between adjacent bit strings of numerical values is 1 when converting an integer into a bit string. Therefore, for example, by expressing position information (x, y) on a plane as a set of integers, encoding x and y individually with Gray code, and projecting it as an information sequence, the continuity of the information sequence is ensured.

3) DATA TRANSFER RATES AND FRAME RATES

The data-transfer rates of PILC projectors can be calculated as follows. First, the transfer rates when projecting data sequences is $1/t_f$. When we consider image sequences, the average data-transfer rates are as follows.

$$\text{Data-transfer Rate} = \frac{1}{t_f} \cdot \frac{t_d}{t_d + t_i}. \tag{1}$$

Since the data sequence and image sequence cannot be projected simultaneously, the brightness of the projected image is lower than that of conventional DLP projectors. The brightness ratio can be calculated as follows.

$$\text{Brightness Ratio} = \frac{t_i}{t_d + t_i}. \tag{2}$$

Therefore, there is a trade-off relationship between the data-transfer rates and brightness.

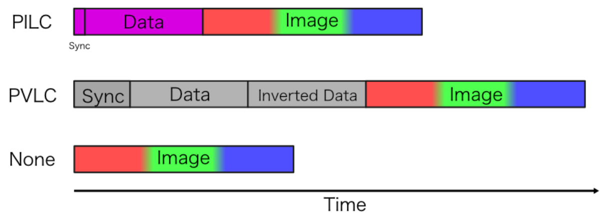

FIGURE 9. Projection patterns with PILC, PVLC, and image-only projection (none).

For comparison, we also calculated the data-transfer rates of PVLC projectors. PVLC projectors project an inverted data sequence immediately after projecting the ON / OFF patterns in order to make the brightness of the data-transfer frames the same at each pixel. Therefore, when we adopt the same DMD, data sequences, and image sequences, projecting the ON / OFF patterns takes twice the time taken by a PILC projector to project data. Therefore, the data-transfer rate of a PVLC projector is calculated as follows.

$$\text{PVLC's data transfer rates} = \frac{1}{t_f} \cdot \frac{t_d}{2t_d + t_i} \tag{3}$$

Compared with the data-transfer rates of PVLC, PILC achieves higher transfer rates.

IV. EXPERIMENTS

We conducted three experiments to evaluate the performance of the PILC projector.

A. CONTRAST IMPROVEMENT

The contrast of visual images is expected to be improved in the PILC projector because it uses infrared light for projecting information, as opposed to the PVLC projector, which uses only visible light. In order to confirm this hypothesis, we projected white and black images with PILC and PVLC, and we measured the brightness of the projected images. In this experiment, we embedded position information in images in units of one pixel. The resolution of the DLP projector we used is 912 px × 1,140 px. We used 21 data frames in total, of which 10 frames were used for x coordinates and 11 frames for y coordinates. For comparison, we also measured the brightness when only visual images are projected without sending information.

Fig. 9 shows the projection of one cycle with each projection method (PILC, PVLC, and image only). In PILC, we projected a binary frame for synchronization and 21 binary frames for the data projected via infrared light, and we performed image projection with visible light. In PVLC, we projected five binary frames for synchronization, 21 binary frames for data, and then 21 binary frames for averaging the illuminance, following which we finally performed image projection. We set the projection time of a binary frame as 235 μs, which is the minimum exposure time with our prototype. We also set the projection time of the image as 4,500 μs,

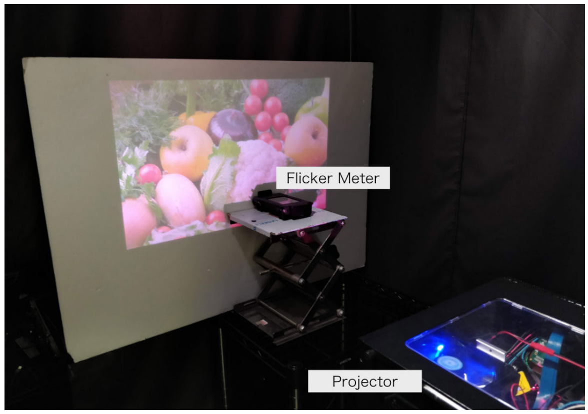

FIGURE 10. Setup of the contrast-measurement experiment. We projected the image on a screen, measured the brightness, and calculated the contrast ratios.

TABLE 2. Illuminance and contrast of the projected image for each information-embedding method.

	PILC	PVLC	Image only
White image [Lx]	59.6	91.0	76.6
Black image [Lx]	0.467	48.6	0.254
Contrast ratio	128	1.87	301

which is the minimum projectable time for 7-bit RGB color images.

We placed the projector 40 cm away from a screen in a dark room and measured the brightness at the center of the screen by using a flicker meter (MK350N, UPRTek). Fig. 10 shows the setup of this experiment. We measured the brightness five times with each method and calculated the average value. The results are listed in Table 2. The contrast ratio of PILC was 128, which is much higher than that of PVLC (1.87). This difference is straightforward to understand even if a general image is projected, as shown in Fig. 11.

There are two reasons why the contrast ratio of PILC is inferior to the case in which only an image is projected. One is that the brightness when projecting a white image with PILC is 0.77 times that observed when projecting only the image because the average brightness is reduced according to to the extent of infrared-light projection. Actually, we can estimate the brightness ratio as 0.72 by substituting $t_d = 235 \times 22 = 5,170\mu$s and $t_i = 13,500\mu$s into Eq. (2). Thus, we confirmed that there is no significant difference between the estimated and experimental values. The second reason is that the illuminance is slightly higher when projecting a black image with PILC because the wavelength of infrared light (808 nm) is very close to that of visible light, making a certain amount of infrared light visible to the human eyes. This problem can be solved using a far-infrared light source, although we need to change the photodiodes such that they can receive the signals.

(a) (b) (c)

FIGURE 11. **Image-quality deterioration of general images with PILC and PVLC. The image with information is superimposed using (a) PILC and (b) PVLC. (c) The image without superimposed information for comparison.**

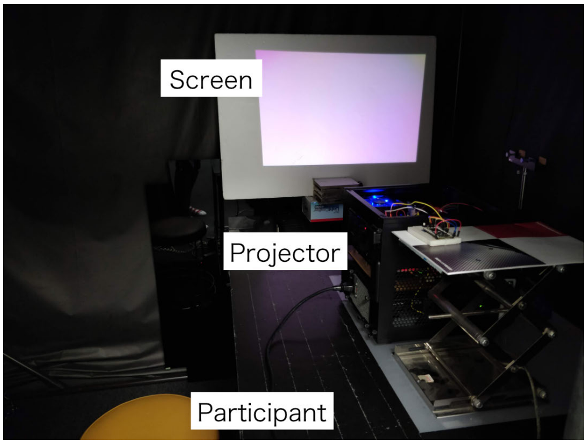

FIGURE 12. **Setup of the flicker-measurement experiment. The PILC projector and screen were placed in a dark room, and participants sitting on a stool watched the image projected on the screen.**

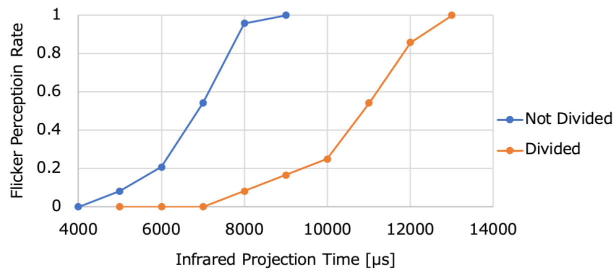

FIGURE 13. **Change of flicker-perception rate with information-sequence projection time and sequence division.**

B. FLICKER MEASUREMENT

In order to calculate the maximum data-transfer rate without flicker perception, we projected various pattern sequences and asked participants whether they noticed any flicker in the projected images. The participants were eight males and females aged 23 to 28 (average 24.5 years old).

Fig. 12 shows the setup of the experiment. We installed the PILC projector and a screen 50 cm apart in a dark room. The PILC projector projected a white image and an infrared-light image alternately, as shown in Fig. 8(a). Participants sat on a stool next to the projector and reported whether the projected image appeared to flicker. For the sake of simplicity, it is assumed that the infrared light is fully turned on for t_d (time for projecting the data sequence), under the assumption that the infrared light is completely invisible to the human eye. We fixed t_i (time for projecting visible image) at $t_i = 4,500 \times 3 = 13,500\mu s$ and changed t_d to investigate the upper limit of the second restriction described in Section III-B2. In order to investigate whether flickering is reduced by dividing information sequences, we established another condition by dividing t_i and t_d into three, as shown in Fig. 8(b). We checked the upper limit of t_d for which visual images do not flicker on changing t_d under these two conditions.

We set t_d as $t_d = 3,000, 4,000, \cdots, 9,000\,[\mu s]$ under the condition that the information sequence was not divided and as $t_d = 5,000, 6,000, \cdots, 13,000\,[\mu s]$ when it was divided into three. We measured the flicker perception thrice in total for each t_d in a random order for each participant in order to offset the effect of order. The participants stated whether they could perceive flicker. We calculated the flicker-perception rate for each t_d as the average of the participants' statements.

Fig. 13 shows the result of flicker-perception rate. Regardless of whether the information sequence was divided, it was confirmed that the flicker-perception rate tends to increase as t_d increases. From the figure, we obtained the value of t_d at which the flicker-perception rate exceeds 0.5: $t_d = 7,000\mu s$ when the information sequence was not divided, and $t_d = 11,000\mu s$ when it was divided. Although the division of the information sequence reduces flicker as expected, the upper limit of t_d increased by a factor of 1.57, rather than 3, when we divided the information sequence into 3. We considered that this mismatch was due to the difference in illuminance and color among the projected portions of the divided visible light, as described in Section III-B2. The critical flicker frequencies calculated from these results are 48.7 Hz and 40.8 Hz when the sequence was not divided and divided, respectively. This is consistent with the reported values of 20–60 Hz [25].

Following Eq. (1), the maximum data-transfer rates were calculated as follows ($t_f = 235\mu s$).

$$\text{Data Transfer Rates (not divided)} = 1.45\,[\text{kbps}]$$
$$\text{Data Transfer Rates (divided)} = 1.91\,[\text{kbps}]$$

These transfer rates are sufficient to send pixel-level position data and several bits of other data as well.

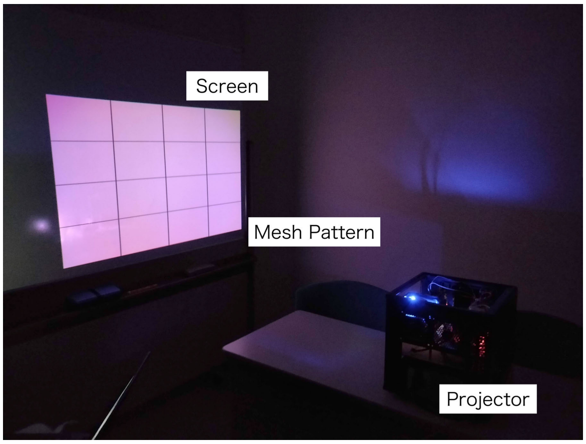

FIGURE 14. Setup of the experiment to measure the consistency of a projected image and embedded data. A visible mesh pattern was projected along with infrared position data, and infrared-light receivers decoded the data into (x, y) coordinates at the intersection points. The decoded coordinates were then compared to the coordinates of the intersection points of the original mesh image.

C. POSITION ACCURACY

We conducted this experiment to confirm whether the invisible information superimposed on the visual images can be correctly received as data. We embedded the position (x, y) of each pixel of an image as invisible information. We installed light receivers at multiple points on a screen, which decoded the information as position data, and then we verified the accuracy of these position data.

The setup of the experiment is shown in Fig. 14. We installed the PILC projector 70 cm away from a screen and projected a grid image that divided an image into 4×4 areas. We projected the position information as a data sequence of binary frames by using Gray code. We designed the light receiver using a photodiode (S6775, Hamamatsu Photonics) attached with an IR cut-off filter (IR80, FUJIFILM). We obtained the position information by placing the receiver on a stable stand so that light from each point of intersection is incident on the receiver at nine crossing points. We received the position information 100 times at each point. Since the optical system of visible and infrared light is the same, the information embedded in infrared light is positionally consistent with visible image. However, when practically communicating via light, a few communication errors are observed owing to interference among neighbor pixels and large sensor size that receives data from multiple pixels simultaneously. This experiment tries to demonstrate that such miscommunication is avoided when this setup is employed.

The situation of the experiment is shown in Fig. 14. We installed the PILC projector 70 cm away from a screen and projected a grid image that divided a whole image into 4×4 areas We projected the position information as a data sequence of binary frames using Gray code. We designed the light receiver using a photodiode (Hamamatsu Photonics, S6775) attached with an IR cut-off filter (FUJIFILM, IR80). We obtained the position information by placing the receiver on a stable stand so that each point of intersections hits the receiver on nine crossing points. We received the position information 100 times at each point.

TABLE 3. Results of the position-accuracy experiment.

Position	Target	Result	Deviation
Top-left	$(228, 285)$	$(221, 282)$	$(-7, -3)$
Top-center	$(456, 285)$	$(453, 277)$	$(-3, -8)$
Top-right	$(684, 285)$	$(682, 287)$	$(-2, +2)$
Middle-left	$(228, 570)$	$(221, 565)$	$(-7, -5)$
Center	$(456, 570)$	$(458, 565)$	$(+2, -5)$
Middle-right	$(684, 570)$	$(685, 565)$	$(+1, -5)$
Bottom-left	$(228, 855)$	$(226, 853)$	$(-2, -2)$
Bottom-center	$(456, 855)$	$(453, 853)$	$(-3, -2)$
Bottom-right	$(684, 855)$	$(682, 853)$	$(-2, -2)$

Table 3 lists the results. The same position value was obtained in all 100 measurements for each point. The results show that we can acquire the position information of each point stably when the receiver is in a stable state, and the deviation from the target value is within 10 pixels at every point. Note that the size of a light-receiving surface of the photodiode (6 mm $\times$ 7 mm) is 6 px $\times$ 14 px when converted to projected image pixels, and both vertical and horizontal deviations are approximately accommodated in this range. Therefore, we conclude that the expected accuracy of position information is sufficient. This accuracy is equal to that of PVLC system [31].

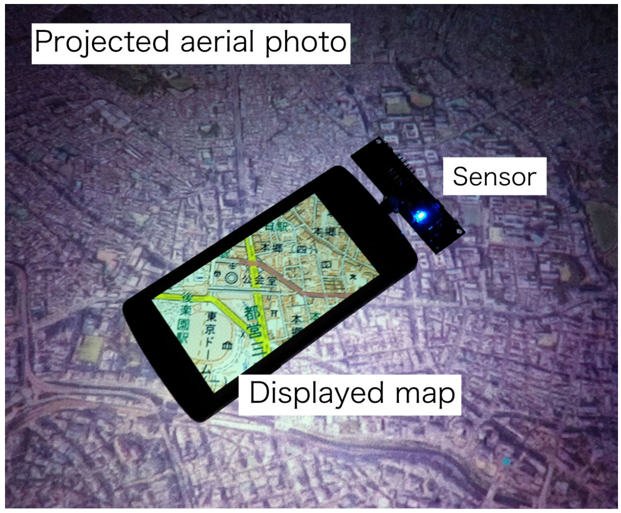

FIGURE 15. Application that superimposes an aerial photograph and map on a smartphone display.

V. APPLICATION

PILC projectors can project high-quality color images and position-dependent information without positional deviation. We implemented a see-through map application that shows this interactivity based on the characteristics of PILC. This application allows us to check map information by using the display of a smartphone that can be freely moved on a

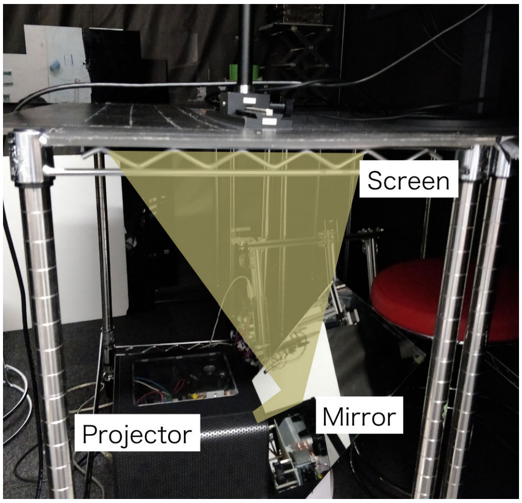

FIGURE 16. **Configuration of devices in the application.**

projected aerial photograph, as shown in Fig. 15. We superimposed the position information on the projected image (color aerial photograph), and two light receivers connected to the display device (smartphone) acquired this information. The position and tilt of the display on the screen are calculated from the position information of the two receivers, and the map area that is within the edges of the display is appropriately cut out and displayed. Fig. 16 shows the configuration of the devices.

VI. CONCLUSION

In this paper, we proposed the pixel-level infrared light communication (PILC) system, which performs the superimposed projection of video and information by using a visible light source and an infrared light source in a hybrid manner. We designed the PILC framework by improving the pixel-level visible light communication (PVLC) system. We developed a prototype, investigated its performance, and created an application based on the prototype. In principle, PILC projectors do not cause misalignment between the images and information, and they do not require alignment even if the system is moved. In addition, the embedded information is invisible to the human eye, and we achieved high-resolution, high-contrast, and full-color image projection. Our system will enable the design of new forms of interaction with projected videos. In the future, we will implement the projection of dynamic images or videos, instead of still images, and investigate the perception, efficiency of information transfer, and accuracy of information acquisition.

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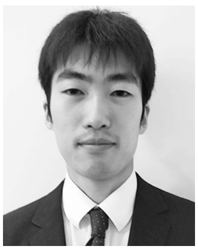

IKUO KAMEI received the B.S. degree from The University of Tokyo, Japan, in 2019, where he is currently pursuing the master's degree with the Graduate School of Information Science and Technology. His current research interests include augmented reality, human–computer interaction, and ubiquitous computing.

TAKEFUMI HIRAKI (S'16–M'19) received the Ph.D. degree in information and communication engineering from The University of Tokyo, Japan, in 2019. He is currently a Japan Society for the Promotion of Science (JSPS) a Research Fellow with the Graduate School of Engineering Science, Osaka University. His current research interests include augmented reality, human–computer interaction, and ubiquitous computing. He is a member of the ACM.

SHOGO FUKUSHIMA received the Ph.D. degree in engineering from The University of Electro-Communications, in 2013. He was a Visiting Student with the Camera Culture Group, MIT Media Lab supported by the ''Japan Society for Promotion of Science (JSPS) Research Fellowships for Research Abroad,'' and a Project Researcher with the Graduate School of Information Science and Technology, The University of Tokyo. He is currently an Assistant Professor with the Interfaculty Initiative in Information Studies, The University of Tokyo. His current research interests include intelligence amplification (IA), virtual reality, entertainment computing, and human emotions. He is a member of the ACM.

TAKESHI NAEMURA (M'01) received the Ph.D. degree in electrical engineering from The University of Tokyo, Japan, in 1997. He was a Visiting Assistant Professor in computer science with Stanford University, USA, supported by the ''Japan Society for Promotion of Science (JSPS) Postdoctoral Fellowships for Research Abroad,'' from 2000 to 2002. He is currently a Professor with the Inter Faculty Initiative in Information Studies, The University of Tokyo. His current research interests include virtual reality and human interface. He is a member of the ITE, IEICE, and ACM.