SICE Journal of Control, Measurement, and System Integration, Vol. 11, No. 4, pp. 302–311, July 2018

Special Issue on Principles and Applications of Smart Sensing

Phygital Field: An Integrated Field with Physical Robots and Digital Images Using Projection-Based Localization and Control Method

Takefumi Hiraki *, Shogo Fukushima **, Yoshihiro Kawahara *, and Takeshi Naemura *

Abstract: Collaboration between computer graphics and multiple robots has attracted increasing attention in several fields. To enhance the seamless connection between them, the system should be able to accurately determine the position and state of the robots and to control them easily and instantly. However, realizing a responsive control system for a large number of mobile robots without complicated settings while avoiding the system load problem is not trivial. We propose a novel system, called "Phygital Field," for the localization and control of multiple mobile robots. Utilizing pixel-level visible light communication technology, our system can project two types of information in the same location: visible images for humans and data patterns for mobile robots. The system uses coded light superimposed onto a visual image and projected onto the robots. The robots localize their position by receiving and decoding the projected light and can follow a target using the coded velocity vector field. Localization and control information can be independently conveyed in each pixel, and we can change this information over time. The system only requires a projector to control the robot swarm; thus, it can be used on any projection surface. We experimentally assess the localization accuracy of our system for both stationary and moving robots. To further illustrate the utility of our proposed system, we demonstrate the control of multiple mobile robots in spatially and temporally varying vector fields. We also propose prototype applications that can provide users with novel content from collaboration between computer graphics and robot swarm.

Key Words: projection-based control, pixel-level visible light communication, digital micromirror device, robot swarm, mixed reality.

1. Introduction

Multi-robot applications that exploit the physical properties of mobile robots have attracted increasing attention in different areas. In human-computer interaction, robots are used as tangible interfaces, and they cooperatively work with computer-generated visual images by changing their state (e.g., their position and rotation) either autonomously or by human intervention [1]–[3]. Since robots are tangible and physically manipulatable, they are more intuitive than a conventional graphical user interface. In robotic pattern formation, systems have been proposed for creating artistic visual expressions using multiple robots [4],[5]. These systems can create various dynamic images using a large number of small robots with colored lights as mobile pixels, and they can be utilized in many fields, such as entertainment. The important feature of such systems is that they can accurately determine the position and state of the robots and can control them easily and instantly on various physical surfaces.

Two problems remain to be addressed to ensure seamless collaboration between computer graphics and multiple mobile robots. First, many existing methods employ external measurement systems using computer vision for localization. They recognize markers, either with infrared light-emitting diodes (LEDs) [1],[4], characteristic patterns [5], or retro-reflective materials [6]. However, it is necessary to fix the camera positions, calibrate them, and calculate the spatial location of robots in the camera images. Localization methods without computer vision may rely on lasers [7], sonar [8], or visible light communication [9]; however, these approaches have limited accuracy because of each sensor's resolution. Augmented Coliseum [10] approaches this problem using a display-based measurement and control system (DMCS) [11]. This technology obviates the need for position measurement devices and can support a large number of robots on the display; however, it requires prior initialization of tracking robots by marker-pattern images. Therefore, adding or removing robots is not allowed. We refer to this problem as the visible marker and prior initialization problem.

Second, because independent control signals via wireless or

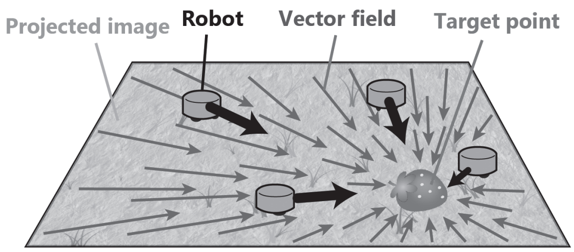

Fig. 1 Concept of Phygital Field system. An integrated system with robot swarm and computer graphics is realized by running multiple mobile robots on the projected image. Each pixel of the projected image contains various information such as the velocity vector field. The localization and control of robots are performed by projection only such that positional deviation of the images and robots does not occur in principle.

* Graduate School of Information Science and Technology, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
** PRESTO, Japan Science and Technology Agency (JST), 4-1-8 Honcho, Kawaguchi, Saitama 332-0012, Japan
E-mail: {hiraki, naemura}@nae-lab.org, s.fukushima@aist.go.jp, kawahara@akg.t.u-tokyo.ac.jp
(Received September 17, 2017)
(Revised January 12, 2018)

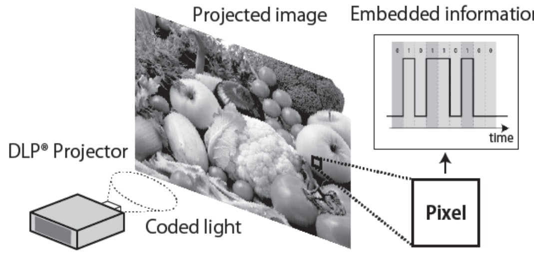

Fig. 2 Principle of PVLC. A PVLC system can superimpose data patterns on pixels using human-imperceptible high-speed flicker.

wired communication are often required in conventional methods [12], the system load increases proportionally with the number of robots, which presents a scalability problem for controlling robots. Other approaches, such as a simple direction control using multiple light sources [5], can navigate robots but cannot guide them to an exact position. Thus, realizing a responsive control system for a large number of mobile robots without camera calibration while avoiding the system load problem is not trivial. We refer to this problem as the system load problem.

We propose "Phygital Field," a system that controls a robot swarm in the field where computer graphics are projected. The system realizes robot control by embedding position and control information in projected images which is based on our proposed method [13]. Figure 1 shows the conceptual figure of our proposed system. We solved previous problems using pixel-level visual light communication (PVLC) technology [14]. PVLC is a data communication method based on human-imperceptible high-speed flicker from a high-speed digital light processing (DLP) projector. Figure 2 shows the principle of embedding imperceptible data into a visual image, which is based on pixel-by-pixel time modulation. With this technology, we can project two types of information at the same location: visible images for humans and invisible data patterns for mobile robots. Hidden data patterns can contain information such as coordinates, a velocity vector field for control, etc. Robots localize their position by decoding the information received via the projected light, which can therefore be used to control the robots. Thus, the system does not require measurement devices such as cameras, nor does it incur a high communication load, because we implement the localization and control of the robots through projection. Furthermore, the spatial deviation between the images and robots does not occur in principle. We use the control method by directly transmitting the information of the velocity vector field to the robots. Therefore, it is unnecessary for the robots to perform dynamic path planning, we can control all the robots with simple and the same program, and it is possible to simultaneously change the actions according to the positions of all the robots by updating the information embedded in the projected image.

In summary, the main contributions of this study are:

- The integrated system with robot swarm and computer graphics based on the control of a robot swarm by embedding information on the position and the velocity vector field in the projection image using PVLC technology.
- Evaluation of laboratory conditions for demonstrating the proposed system. The results show that its projected light patterns can perform the localization and control of mobile robots.
- Prototype applications that demonstrate the effectiveness of the method, which can provide users with novel content from the collaboration between computer graphics and a robot swarm.

2. Related Work

We briefly review localization methods, control methods, and methods that combine both localization and control using projected light patterns for communication. We also review the PVLC technique utilized in the proposed method.

Localization methods using projected structured light and photosensors are common in the context of user interface and motion capture systems. "Radio frequency identity and geometry" lamps [15] and Lee et al. [16] localize an object with photosensors using striped pattern Gray-code images. Lumitrack [17] uses an M-sequence pattern image, and Prakash [18] uses a special projection device that has transparent glass slides of Gray-code patterns and multiple LEDs that can flicker at a very high frequency. In all these methods, a receiver can estimate its two-dimensional position from spatial light patterns; however, it is not trivial to directly add more information such as control commands for robots or images other than signal patterns, which are meaningless to human eyes.

Usually, robot control is performed after the robot is localized, but there are various methods using projected light for direct path guidance without localization. Fujiwara et al. [19] interactively control line-follower robots by letting users draw lines with hand gestures. Line-follower robots do not know their location but instead run along a path that is visually defined. Hara et al. [20] proposed the dynamic path control of a single robot using a narrow laser beam. VisiCon [21] proposed a robot manipulation method by using a hand-held projector. However, these approaches are not suitable for multiple robots.

Several methods implement both the localization and control of multiple mobile robots. Liu et al. [22] perform this task using visible light communication (VLC). Their system sends position information using general data communication, and feedback to the central system is not required. However, the localization accuracy is not very high because the position is estimated from the incident angle of the light. Nii et al. [23] transmit information according to location using a high-speed LED projector; however, the image is grayscale, and its resolution is significantly lower than that in our system, e.g., four by five pixels.

Various approaches in swarm robotics have demonstrated robot control methods that use gradient maps, and they are also able to control robots to specific places or into specific configurations. Igarashi et al. [24] proposed a robot control method using a dipole field. The computational load is small in this approach; however, the movement paths of robots are limited. Fujisawa et al. [25] proposed a pheromone-based control method for robots. In their system, robots are controlled by sensing alcohol, and Sugawara et al. [26] and Garnier et al. [27] also investigated this approach. This approach does not need an external system; however, it cannot localize the robot. Woern et al. [28] also used a projector to feed robots with light as an energy supply and control them by the projected pixel patterns. However, this is an autonomous distributed control system so that the robots' speed is not very fast and they cannot synchronize with the projected image.

DMCS [11] also achieves both localization and control. It consists of a conventional display device and multiple mobile robots with several photosensors evenly spaced on a robot's surface. DMCS does not require position measurement devices such as color or depth cameras, and it can support an unlimited number of robots on the display. However, DMCS must detect the initial positions and directions of robots to decide the display positions of marker-pattern images for tracking robots. This initialization is necessary every time when a robot is added to the projection area, and it takes several seconds for each robot; thus, adding or removing robots is not possible. Yasu et al. [29] proposed the robot control method using field projection. This approach does not require the initialization; however, it requires projection of pattern images on the entire screen and cannot project visible images for humans.

To achieve an initialization-free and marker-free method that both localizes and controls an unlimited number of robots, we utilize PVLC [14]. PVLC is a method that superimposes data patterns on pixels with human-imperceptible flicker using a very-high-speed DLP projector. PVLC can display a visual image containing superimposed data as bit patterns that are decodable by receiver circuits. When two inverted patterns are displayed alternately at high frequency, human eyes see only a flat gray image because of the persistence of vision effect. Although human eyes cannot distinguish each image, a receiver with a photosensor can detect the images as different signals. The embedding algorithm for determining the on and off periods must be carefully designed to maintain luminance and avoid flicker.

3. Method and Implementation

We must consider two factors when developing the Phygital Field system.

1. A projection pattern for embedding two types of information in the same location: perceptible images for humans and imperceptible data for sensors. Moreover, these data may include coordinates, control instructions, and other types of information.
2. Small mobile robots that act based on the light from a high-speed DLP projector.

We particularly propose a light-receiving circuit that meets our requirements for fast response and low power consumption.

3.1 System Overview

Figure 3 shows an overview of our system. Our system comprises a PC, DLP projector, screen, and robots. The PC generates binary frames that include data frames for localization and control, and the DLP projector projects these frames.

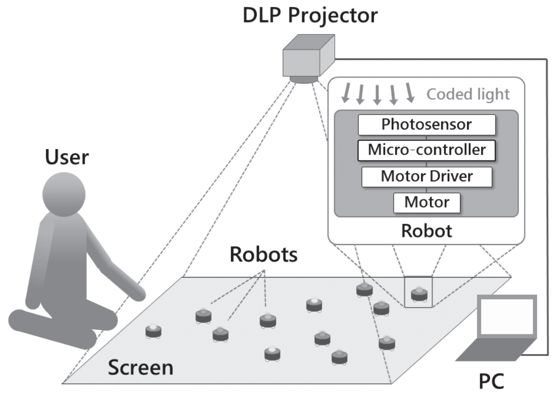

Fig. 3 System overview.

3.2 Hardware

3.2.1 Projector

We constructed a PVLC system that can display color images by using a DLP projector (ViALUX, STAR-07). This projector can control the LED light sources of three colors (red, green, and blue) in synchronization with the control of a digital micromirror device by using control software (ALP Ver. 4.2 Core Program).

3.2.2 Receiver circuit

We developed a new receiver circuit using a photodiode instead of the phototransistor that prior systems have employed [11],[14]. We made this change because we could not obtain the required responsiveness with a phototransistor, owing to the effects of rise/decay time. When using the photodiode, it is possible to obtain the required responsiveness even at low voltage and without consuming much power, but the output current is small. Thus, we also designed and implemented a receiver circuit using op-amps, which has a trans-impedance amplifier.

The proposed system requires a photodiode with sufficient sensitivity to the range of visible light. Furthermore, the op-amps must have a large gain–bandwidth product and small input bias current because of the characteristics of the circuits. To meet these requirements, we chose S2506-02 (Hamamatsu Photonics) as bottom-side photodiodes, S6775 (Hamamatsu Photonics) as top-side photodiodes, and OPA2353UA (Texas Instruments) as an op-amp. The sizes of the light receiving surfaces of these photodiodes are 2.77 mm × 2.77 mm (S2506-02) and 7 mm × 7.8 mm (S6775), respectively. The larger one of this surface size and the size of a pixel of projected images is a spatial resolution of the received pixel-level information. The trans-impedance amplifier unit was implemented in the circuit near the chips to reduce noise. We set the trans-impedance gain to one million and placed a non-inverting amplifier unit after the trans-impedance amplifier unit to adjust sensitivity. An adjustable resistor adjusts the gain of the non-inverting amplifier.

A receiver adjustment circuit is used as a comparator circuit. We use an NJM2732M (JRC) op-amp as a comparator and adjust the threshold value with an adjustable resistor.

3.2.3 Robot

There are three requirements for the robots in the Phygital Field. They must be able to

- receive a sequence of high frequency (12,500 Hz) light pulses from a DLP projector;
- analyze the signal and acquire their positions and control data from the sequence;
- move based on the positions and velocity vectors.

To meet these requirements, we developed the robot shown in Fig. 4. The robot's length, width, and height are 72 mm, 50 mm, and 70 mm, respectively. The robot's mass, including the battery, is 152 g. The robot consists of three boards: a main board,

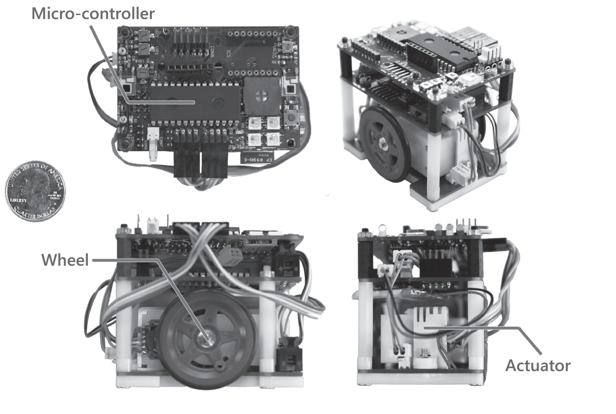

Fig. 4 Prototype mobile robot: (upper right) overall view, (lower right) front view, (upper left) top view, and (lower left) side view.

chassis board, and expansion board. Thanks to this feature, we can easily change the module configuration, such as changing the information presentation method.

The main board consists of a microcontroller, receiver adjustment circuit, and power supply circuit. We use a 50 MHz ARM microcontroller (NXP Semiconductor, LPC1114FN28) as the main microcontroller. This board is compatible with the mbed platform, which is the ARM prototyping development environment, and the designer can easily code the robot program. The main battery is a one-cell Li-Po battery (3.7 V, 800 mAh). The robot can run for approximately 1 h of continuous usage with this battery.

The chassis board is constituted by a receiver circuit for the bottom side and a motor driver circuit, and it is possible to mount a motor and a wheel. The receiver circuit incorporates what was described in the previous section, and it is installed to support the rear projection. The motor driver circuit is configured using a motor driver IC (Rohm, BD6211F) and a logic IC (Toshiba Semiconductor, TC74HC08AF). We also employ a 120:1 Mini Plastic Gearmotor HP (Pololu) to drive the robot and plastic pulleys (35 mm, Φ 3 mm) with rubber rings (Φ 30 mm) for the wheels.

The expansion board is composed of a microcontroller, information presentation elements, receiver circuit for the top side and its adjustment circuit, as well as a radio communication module. The microcontroller is the same as the main board (LPC1114FN28), and it can be programmed in the mbed platform development environment. The board has a full-color LED (World Semi, WS2812B), speaker (DB Products, UM1515IA), and mp3 playback module (WTV020M01) as information presentation elements. The light-receiving circuit for the top side and its adjusting circuit are installed to support the front projection, and these circuits are the same as those of the chassis board. The radio communication module is a Bluetooth communication module (Microchip, RN42-I/RM) and the robots use it for information feedback to the projection system. The main board and expansion board communicate using the I^2C protocol.

3.3 Software

3.3.1 Frame structure of projection images

PVLC frames consist of three blocks: synchronization, data, and luminance adjustment. The synchronization block is used to identify the start of the data block. The data block is a block

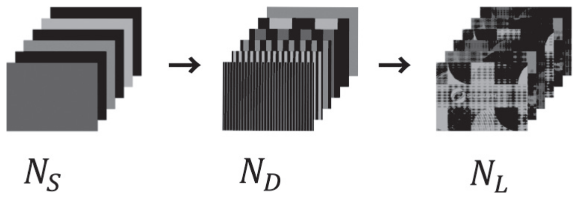

Fig. 5 Composition of binary frames in a sequence.

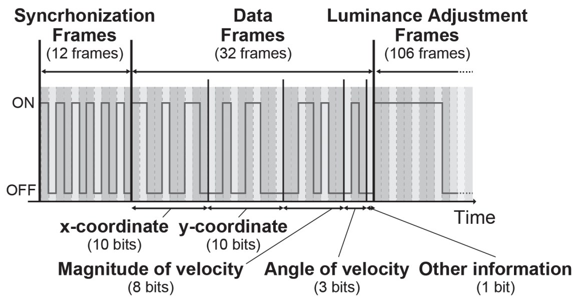

Fig. 6 Time series of a sequence.

for data embedded in accordance with the pixel position. The luminance adjustment block maintains the time ratio of the on to off periods to adjust the luminance of each pixel for human perception.

Figure 5 shows a time series of the sequence in detail. Here, N_S, N_D, and N_L are the number of frames for synchronization, data, and luminance adjustment, respectively. To balance control and contrast, we set N_S to 12, N_D to 32, and N_L to 106. The total number of frames (150 frames) is the number of frames per transmission unit. We refer to this unit as the binary frame unit in this study. We set the binary frame-rate of the projector to 12,500 Hz. In this case, the actual refresh rate of the images that a human sees is 12,500 / 150 = 83 Hz, and the data transfer rate is 2,656 bps. Figure 6 shows the composition of binary frames in a binary frame unit. In the synchronization block, the start of the data block is indicated by embedding 12 bits of information on the whole projection image. The data block comprises the two-dimensional coordinates for localization and velocity vector for control. The data block includes 32 frames, which means we can transfer 32 bits of data for each pixel. The user can optimize the design of the data block according to the performance of the robots and the design of applications. To express the coordinates, we assign 10 bits each for the horizontal (x) and vertical (y) coordinates, as the resolution of the projector is XGA (1024 × 768). This coordinates information is used to obtain the position information acquired by the two sensors of each robot. The robots calculate its orientation by calculating arctangent from this position information. For the remaining 12 bits, 8 bits are assigned for the magnitude of the velocity vector, 3 bits for the direction of the velocity vector, and 1 bit for the other field information. The velocity vector is converted into polar coordinates and decomposed into inclination and radial components (magnitude and direction). To avoid receiving errors caused by interference at the pixel boundaries, we encode the data with Gray code before transmission. Gray code can suppress the effect of mixture of adjacent multiple pixel values because of its principles. In the luminance adjustment block, the luminance of each pixel is calculated from the luminance information of the image to be projected, whereby the block is constructed.

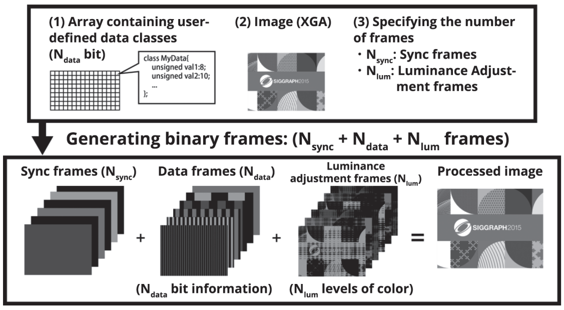

Fig. 7 Software framework of Phygital Field.

3.3.2 PVLC design framework

Many interactive applications using PVLC have been proposed, and various functions such as bit-wise operations and brightness calculation per pixel are required for designing these applications. These previous applications were implemented on an ad hoc basis, and thus efficient and reusable application design was impossible. Therefore, we designed and implemented a framework that makes it easy to implement applications embedded with arbitrary information in projection images. Figure 7 shows the structure of our software framework. Thanks to this framework, application designers can implement an application without having to think about complicated binary frame generation calculation, and so on, by preparing the images and information to be projected and embedded.

4. Experiments & Results

In this section, we describe the experiments to evaluate our proposed method. The purpose of the experiments was to evaluate the localization accuracy when the robot is stationary; the localization accuracy while the robot is moving; and the trajectory of the robot when we set a target point and a velocity vector field. We performed the experiments using a 1340 mm × 1010 mm screen in an assembled darkroom (Morimoto-Kasei MEDR-2518). To transmit data from the robot, we used XBee 802.15.4 (Digi International) wireless communication devices, and we analyzed the transmitted data on a Lenovo ThinkPad X240.

4.1 Experiment of Localization in Static State

This experiment was carried out to evaluate the accuracy of localization when the robot is stationary. We placed the static robot at various points on the screen and obtained the x and y coordinates of its position using our proposed method. We selected nine points on the screen frame arranged in a 4×4 matrix. The measurement was carried out 1000 times at each point. Since the values were constant at all 1000 measurements, it was found that the proposed method can acquire position coordinate information stably in a stationary state. As a result, we can receive the coordinates information stably with expected accuracy using the proposed system; hence, the proposed system can accurately localize robots in a static state.

4.2 Experiment of Localization in Dynamic State

The objective of this experiment was to evaluate the accuracy of localization while the robot is moving. We installed the robot on the linear actuator (Oriental Motor, EZSM6D085AZMC) and acquired position information using our method while operating at a constant speed. The movable range of the linear actuator was 850 mm, and the speed was set to 100 mm/s.

In contrast to the static state experiment, interference occurs when the robot crosses pixel boundaries. Because the pixels are square and tiled, we tested four directions of movement with respect to the pixel to determine the robustness of the localization to direction of movement. Specifically, we installed the linear actuator at angles with respect to the x-axis of $\theta = 0$, $\frac{\pi}{12}$, $\frac{\pi}{6}$, and $\frac{\pi}{4}$ radians. Angles larger than $\frac{\pi}{4}$ radians are redundant because of the symmetry of the square pixel.

The control period for obtaining data at the receivers was 10 ms, and the output cycle of the operation log of the linear actuator was 100 ms. We calibrated the coordinate systems of our method and the linear actuator by an affine transformation using the measured values such that we could evaluate them in the same real coordinate system in mm. We also set the initial (x, y) values to zero.

The top and bottom rows in Fig. 8 respectively show the receiver's horizontal x and vertical y positions with respect to time for different θ. Figure 8 shows that the localization obtained using our method almost has the same accuracy as that obtained by the linear actuator. The coordinate values obtained by our method are slightly noisy, and this is due to discretization error caused by the physical size of the photosensors (about 8 mm). We conclude that localization using our method could be a possible method when precise localization is not required (e.g., when moving a robotic arm).

4.3 Experiment for Robot Control

We conducted a control experiment to evaluate the trajectory of multiple mobile robots when we set a target point. We em-

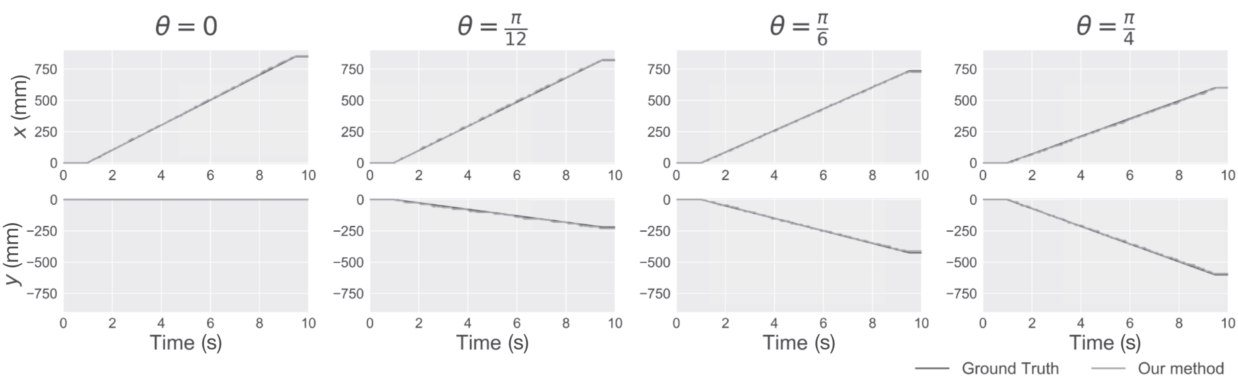

Fig. 8 Localization accuracy when the sensor is moving. The dark gray line is localization using the linear actuator (ground truth), and the light gray line is localization using our method.

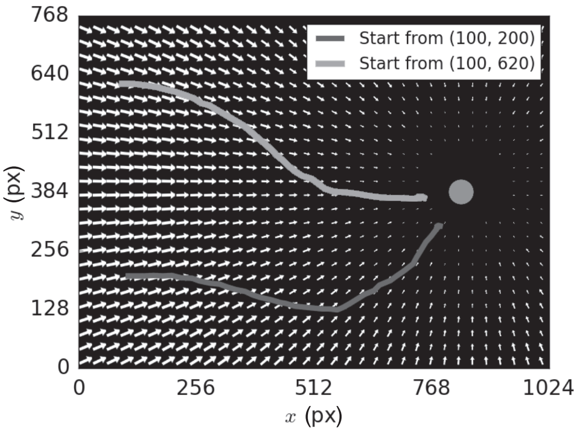

Fig. 9 Temporally static and spatially varying velocity vectors embedded in the image so that the robots move toward a target point.

bedded the data regarding the absolute position and velocity vector field into the images and observed the behavior of multiple mobile robots placed on the screen. The maximum speed of the robots was limited to approximately 100 mm/s, the same value as used in the preceding experiment. We changed part of the robots' skirts to round-shaped ones with an outer diameter of 103 mm to prevent the robots from colliding and locking together.

First, we conducted an experiment in the case of using the image embedded with a temporally static and spatially varying velocity vector field. The vector field was coded so that the robots moved toward a target point; that is, each vector is oriented toward the target, and the size of the vectors decreases as the robots approach it. We placed two robots in two different positions, and both of them arrived at the target point. Figure 9 shows the embedded velocity vector field and the resulting trajectories of the robots. This figure suggests that our method successfully controlled the robots so that they followed the intended trajectory.

Next, we conducted an experiment using the image embedded with temporally and spatially varying velocity vector field. The vector field was coded so that the robots moved toward a target point, just as in the previous experiment. The target point in this experiment was rotated counterclockwise, as shown in Fig. 10; the start point is indicated by the yellow dot, and the point was moved at 1 s intervals. Table 1 shows the settings of the coordinates of the target point and the color in figures in this experiment. We placed a robot on the lower left corner of a screen. Figure 11 shows the trajectories of robots controlled by an image embedded with temporally varying velocity vector fields. In Fig. 11, the paths for each period are colored to match the color of the target point over that period. The robots moved toward the target point in each period, and they smoothly followed the point. The results of these two experiments show that it is easy to perform trajectory control of the robots by moving the target point.

5. Application

We created some applications involving a swarm of robots and visible projected images by designing two modes of affecting the robots.

By solving the visible marker and prior initialization problem, Phygital Field realizes initialization-free and marker-free localization and control in applications. This feature allows the robots to recover instantly from irregular user manipulation such as brushing aside and obstructing. Furthermore, users can add and remove robots at will and control robots without the need for positional displacement.

By solving the system load problem, the system can control any number of robots existing in the projection image. The robot swarm control method using the embedded velocity vector field allow them to operate with a simple and the same program without dynamic path planning, and we can change the movement of the robots at the same time by updating the embedded information.

Thanks to these characteristics, applications can provide users with novel content from the collaboration between computer graphics and robot swarms. In developing the applications, we replaced part of the skirt with a round-shaped component whose outer diameter is 103 mm to prevent robots from colliding and becoming locked onto each other. An appearance of a swarm of robots in an application is shown in Fig. 12 (a).

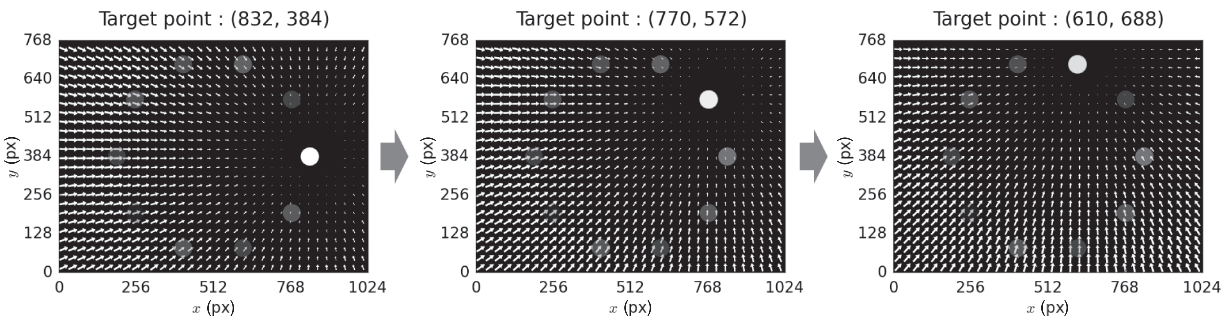

Fig. 10 Appearance of change in the target point and vector field over time. This corresponds to the state of the target point and vector field at t = 0 s to 1 s, t = 1 s to 2 s, and t = 2 s to 3 s from the left of this figure. The target point was rotated counterclockwise, and it was transferred in 1 s intervals. The vector field is constructed and embedded to concentrate at the target point at each instant.

Table 1 Setting the coordinates of the target point and the grayscale color of the point in the figure.

Time: t (s)	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10
Coordinates (px)	(832, 384)	(770, 572)	(610, 688)	(414, 688)	(254, 572)	(192, 384)	(254, 196)	(414, 80)	(610, 80)	(770, 196)
Point color										

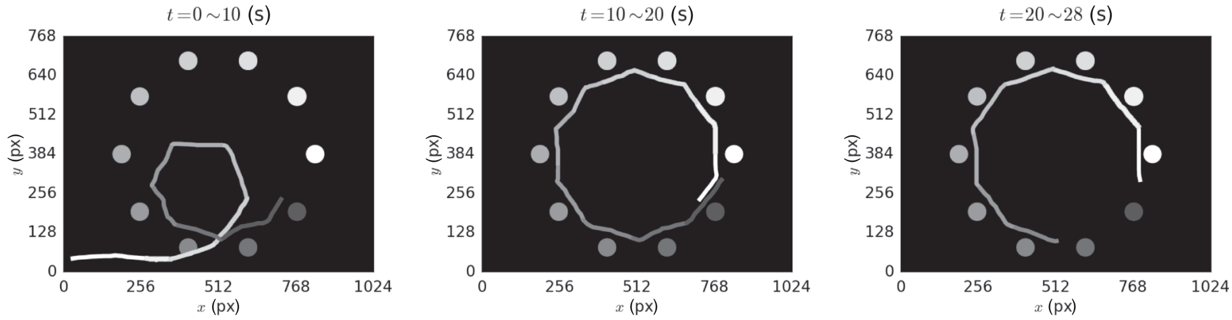

Fig. 11 Appearance of movement of the target point over time and the state of the trajectory of the robot moved at that time. Temporally and spatially varying velocity vectors were embedded so that the robots move toward and follow a target point. After a certain time has passed since starting moving ($t > 9$ s), it can be seen that the robot closely follows the movement of a target point.

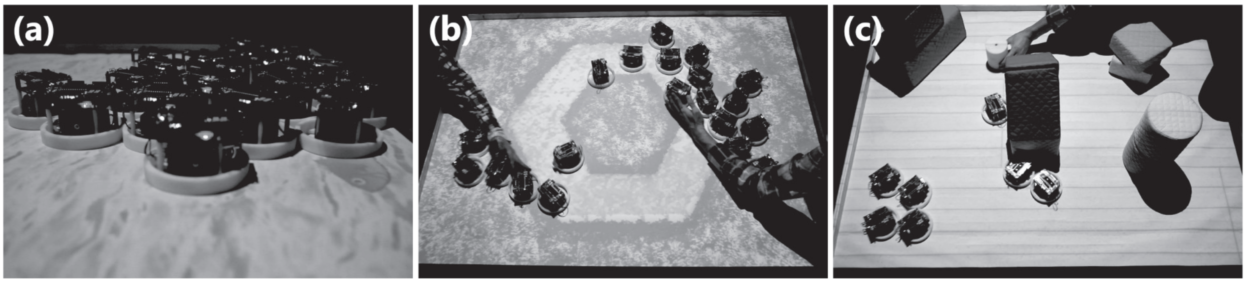

Fig. 12 Appearance of the sample applications of Phygital Field. (a) Appearance when a swarm of robots was controlled by coded light. (b) Appearance of a sample application in which robots are affected by the virtual environment. This represents an interaction between moving robots and users' hands. (c) Appearance of a sample application in which robots encounter a real environment. A user is manipulating a physical object and navigating a swarm of robots in the field with real blocks.

5.1 Interaction Between Robots and Virtual Environment

Figure 12 (b) shows a sample application in which robots are affected by the virtual environment. The light gray and dark gray areas displayed in the image are intended to imitate a circular road and forest, and two types of velocity vector fields were embedded in each zone: the robots were sent instructions to circulate along the road in a clockwise direction, and to move toward the road when located within the forest area. All of the robots moved rapidly toward the road, following which they proceeded clockwise along the road. The robots can realize these actions without path planning by using the embedded velocity vector field. This confirmed that the robots were successfully controlled such that they followed the intended trajectory. The robots followed these instructions even when we attempted to use our hands to obstruct their movement, thereby confirming that they are only controlled by information they receive via the projection.

Figure 13 shows a virtual seesaw application. When a user tilts the virtual wood board, then the robots slip down according to the board as a slope. The system realizes the control of the robots synchronized with the projected image by changing the vector field used for controlling the robots at the same time as changing the image of the seesaw board. The user can enjoy interaction with the robots changing their movements according to the virtual seesaw by manipulating the tilt of a seesaw board. These two applications are forms of interaction realized by the state of the virtual environment and its change affecting the operation of the robots.

5.2 Interaction Between Robots and Real Environment

Figure 12 (c) shows a sample application in which robots encounter a real environment, which has the spatially and temporally varying code embedded in visual images. This code contains two-dimensional coordinates and a velocity vector that is generated in real time in accordance with the position of a physical target the user is holding onto. By manipulating the physical target, the user can control a swarm of robots toward the virtual goal and avoid the physical obstacle blocks. The orientation of a robot becomes disordered when it collides with a block; however, the characteristics of the system allow it to continue along its intended path.

Figure 14 shows a sample game application in which the player can control the robots by manipulating the physical object as an avatar of the player. The player can clear the game by manipulating a physical object and guiding the robots from the start area (the lower-left corner of the game field) to the goal area (the upper-right corner of the field). The robots behave as a character following the avatar and perform actions that are influenced by the virtual objects in the form of the flowing river or enemy characters existing in the game field. The system realizes these actions by calculating and embedding the superposition of a vector field concentrating with the physical object and concentrating/diffusing vector fields with the virtual objects. Thus, the player has to think about these effects while controlling the object. The robots change their movement according to both the real and virtual environment in these two applications.

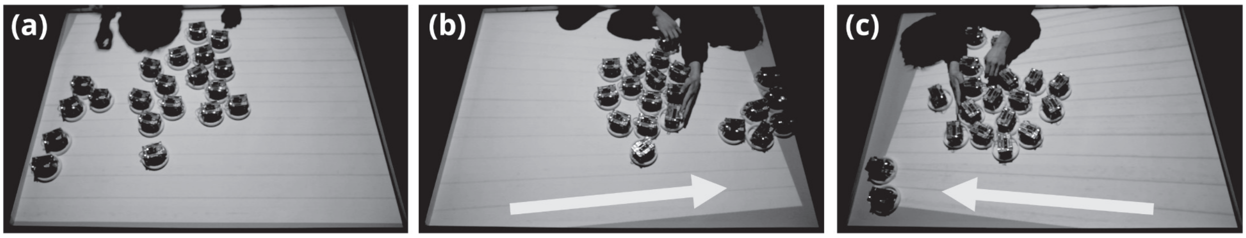

Fig. 13 Appearance of a virtual seesaw application. A virtual gravity act in a direction parallel to the virtual seesaw board. When a user tilts the board, then a robot swarm slips down according to the board as a slope. (a) When the board is horizontal, the robots do not move. (b) When the board tilts to the right, the robots move to the right according to the tilt. (c) When the board tilts to the left, the robots move to the left as well.

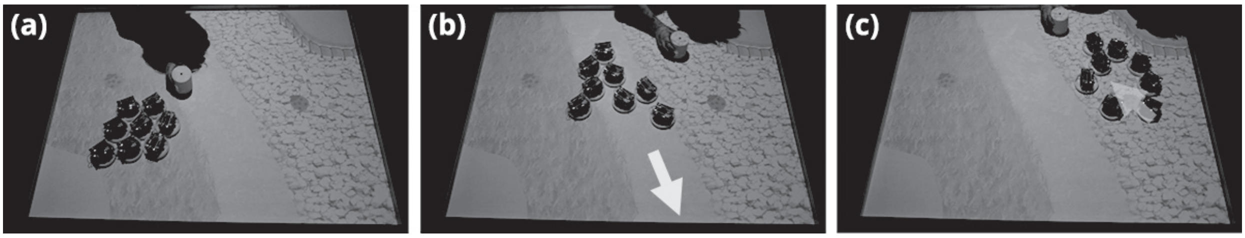

Fig. 14 Appearance of a sample game application. The player manipulates a physical object and guides the robots from the start area (the lower-left corner of the game field) to the goal area (the upper-right corner of the field). (a) In a normal field zone, the robots move toward the direction of the object. (b) In a river zone, the robots try to head toward the object, but they are swept along the river at the same time. (c) If there is an enemy in the field, the robots move toward the direction of the object while avoiding the enemy.

6. Exhibition

6.1 Overview

We exhibited the implemented applications at the Emerging Technologies session, SIGGRAPH Asia 2016. SIGGRAPH Asia is an international academic conference convened by the ACM SIGGRAPH organization, which has been held annually since 2008. The conference focuses on computer graphics and interactive techniques, and the total number of attendees was 5,200. Most SIGGRAPH Asia participants have academic backgrounds and are interested in computer graphics. The Emerging Technologies session ran for three days with a total exhibition time of 18 h (10 am to 4 pm every day). We exhibited the application in which a robot swarm follows the virtual object (fish) as the target (Fig. 12 (a)) and the application in which the robots circle the road (Fig. 12 (b)). The appearance of the exhibition is shown in Fig. 15.

We observed the visitor's behavior from the following perspective:

- Response to the projected image: we observed user behavior and responses when the visitor saw the projected image with embedded information that humans cannot perceive.
- Response to the application: we observed how the visitor responds to the application realized by a collaboration between computer graphics and a robot swarm.

6.2 Findings and Discussion

Our system operated steadily through the three-day exhibition. In the exhibition, no participant reported that they perceived flickering of the projection image. Thus, we assumed that our data-embedding method functioned effectively.

Most visitors who saw our application recognized that the robots were running around the field made by computer graphics without discomfort. This shows the achievement of realizing the seamless connection between the projected image and the robots. Additionally, some visitors stated that the movement of the robots feels like that of living things. For example, one visitor commented that the robots are like a fish in Swimmy (Swimmy is a picture book written by Leo Lionni, and there are scenes in which small fish swim in the sea in a swarm to appear as a big fish).

As another distinctive behavior, it was observed that some visitors shadowed the projected image with their own hands and bodies. This behavior was observed especially frequently in children. The robots existing in a shadow area stop their operation at that position, because our system controls the robots by the projection light. Therefore, the users can stop the operation for some robots in the swarm in the field freely and easily. It was also observed that children moved the hand up and down to change the size of the shadow and stopped the movement of the robots existing in a much larger area than the size of their own body. This behavior suggests the possibility of being able to operate and control a part of a robot swarm using a shadow as an interface that allows the users to intuitively change the

Fig. 15 Appearance of the exhibition.

position and shape.

A few participants asked us, "Will the robots recognize the image of the road and run?," when they were looking at the application where the robots orbit the road. This recognition is incorrect because the robots are controlled by the information embedded in the projected image. This erroneous recognition suggests that the participants felt that the robots were just running in the area of the road as there was no misalignment of the image and information in our system.

7. Conclusion

In this study, we proposed Phygital Field, which is a system that controls a robot swarm in a field where computer graphics are projected. To satisfy the requirements of the system, we explored a novel localization and control method for multiple mobile robots by projecting an image using light with embedded information. We specifically proposed a structure for the projection pattern that embeds data containing coordinates, control instructions, and other types of information. We also introduced a light-receiving circuit that operates at high speed and draws little current, as well as small mobile robots that are suitable for the designed light-receiving circuit mounted onto them.

We performed three experiments to evaluate our method. The first experiment shows that our localization method is stable in a static state. The second shows that our localization method can be used when controlling multiple mobile robots. The third suggests that our method can perform robot control by moving a target point. In addition, we proposed prototype applications that can provide users with novel content from collaboration between computer graphics and a robot swarm, and we observed the users' behavior through the exhibition of these applications. These efforts suggest that we can easily design an integrated environment for physical robots and digital images to preserve the seamless connection between them.

Acknowledgments

This work was supported by JST CREST, JST ERATO Grant Number JPMJER1501, JSPS KAKENHI Grant Number JP16H01739, and Grant-in-Aid for JSPS Fellows JP17J04216, Japan. We thank Issei Takahashi, Takuya Umedachi, and Rei Kawakami for their advice and reviews of our paper.

References

[1] D. Rosenfeld, M. Zawadzki, J. Sudol, and K. Perlin: Physical objects as bidirectional user interface elements, *IEEE Computer Graphics and Applications*, Vol. 24, No. 1, pp. 44–49, 2004.

[2] J. Patten: Thumbles: Robotic tabletop user interface platform, http://www.pattenstudio.com/thumbles/, 2014.

[3] M. Le Goc, L.H. Kim, A. Parsaei, J.-D. Fekete, P. Dragicevic, and S. Follmer: Zooids: Building blocks for swarm user interfaces, *Proc. the 29th Annual Symposium on User Interface Software and Technology*, pp. 97–109, 2016.

[4] J. Alonso-Mora, A. Breitenmoser, M. Rufli, R. Siegwart, and P. Beardsley: Multi-robot system for artistic pattern formation, *Proc. 2011 IEEE International Conference on Robotics and Automation*, pp. 4512–4517, 2011.

[5] A. Becker, G. Habibi, J. Werfel, M. Rubenstein, and J. McLurkin: Massive uniform manipulation: Controlling large populations of simple robots with a common input signal, *Proc. 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 520–527, 2013.

[6] O. Kilinc, G. Kucukyildiz, S. Karakaya, and H. Ocak: Image processing based indoor localization system, *Proc. 22nd Signal Processing and Communications Applications Conference*, pp. 1654–1657, 2014.

[7] K. Lingemann, A. Nüchter, J. Hertzberg, and H. Surmann: High-speed laser localization for mobile robots, *Robotics and Autonomous Systems*, Vol. 51, No. 4, pp. 275–296, 2005.

[8] D. Navarro, G. Benet, and M. Martinez: Line based robot localization using a rotary sonar, *Proc. 2007 IEEE Conference on Emerging Technologies & Factory Automation*, pp. 896–899, 2007.

[9] X. Liu, H. Makino, and K. Mase: Improved indoor location estimation using fluorescent light communication system with a nine-channel receiver, *IEICE Transactions on Communications*, Vol. E93-B, No. 11, pp. 2936–2944, 2010.

[10] M. Kojima, M. Sugimoto, A. Nakamura, M. Tomita, M. Inami, and H. Nii: Augmented coliseum: An augmented game environment with small vehicles, *Proc. First IEEE International Workshop on Horizontal Interactive Human-Computer Systems*, pp. 3–8, 2006.

[11] M. Sugimoto, K. Kodama, A. Nakamura, M. Kojima, and M. Inami: A display-based tracking system: Display-based computing for measurement systems, *Proc. 17th International Conference on Artificial Reality and Telexistence*, pp. 31–38, 2007.

[12] A. Sudsang, F. Rothganger, and J. Ponce: Motion planning for disc-shaped robots pushing a polygonal object in the plane, *IEEE Transactions on Robotics and Automation*, Vol. 18, No. 4, pp. 550–562, 2002.

[13] T. Hiraki, S. Fukushima, and T. Naemura: Projection-based localization and navigation method for multiple mobile robots with pixel-level visible light communication, *2016 IEEE/SICE International Symposium on System Integration*, pp. 862–868, 2016.

[14] S. Kimura, R. Oguchi, H. Tanida, Y. Kakehi, K. Takahashi, and T. Naemura: PVLC projector: Image projection with imperceptible pixel-level metadata, *ACM SIGGRAPH 2008*, Article No. 135, 2008.

[15] R. Raskar, P. Beardsley, J. van Baar, Y. Wang, P. Dietz, J. Lee, D. Leigh, and T. Willwacher: RFIG lamps: Interacting with a self-describing world via photosensing wireless tags and projectors, *ACM Transactions on Graphics*, Vol. 23, No. 3, pp. 406–415, 2004.

[16] J.C. Lee, P.H. Dietz, D. Maynes-Aminzade, R. Raskar, and S. E. Hudson: Automatic projector calibration with embedded light sensors, *Proc. the 17th annual ACM symposium on User interface software and technology*, pp. 123–126, 2004.

[17] R. Xiao, C. Harrison, K.D. Willis, I. Poupyrev, and S.E. Hudson: Lumitrack: Low cost, high precision, high speed tracking with projected m-sequences, *Proc. the 26th annual ACM symposium on User interface software and technology*, pp. 3–12, 2013.

[18] R. Raskar, J. Barnwell, S. Nayar, M. Inami, P. Bekaert, M. Noland, V. Branzoi, E. Bruns, H. Nii, B. DeDecker, Y. Hashimoto, J. Summet, D. Moore, Y. Zhao, J. Westhues, and P. Dietz: Prakash: Lighting aware motion capture using photosensing markers and multiplexed illuminators, *ACM Transactions on Graphics*, Vol. 26, No. 3, pp. 36.1–36.11, 2007.

[19] T. Fujiwara and Y. Iwatani: Interactions with a line-follower: An interactive tabletop system with a markerless gesture interface for robot control, *Proc. 2011 IEEE International Conference on Robotics and Biomimetics*, pp. 2037–2042, 2011.

[20] K. Hara and S. Maeyama: Navigation using one laser source for mobile robot with optical sensor array installed in pan and tilt mechanism, *Proc. 2008 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, pp. 257–262, 2008.

[21] K. Hosoi, V.N. Dao, A. Mori, and M. Sugimoto: VisiCon: A robot control interface for visualizing manipulation using a handheld projector, *Proceedings of the international conference on Advances in computer entertainment technology*, pp. 99–106, 2007.

[22] X. Liu, E. Umino, and H. Makino: Basic study on robot control in an intelligent indoor environment using visible light communication, *Proc. 2009 IEEE International Symposium on Intelligent Signal Processing*, pp. 323–325, 2009.

[23] H. Nii, M. Sugimoto, and M. Inami: Smart light-ultra high speed projector for spatial multiplexing optical transmission, *Proc. 2005 IEEE Conference on Computer Vision and Pattern Recognition - Workshops*, Vol. 3, pp. 95–95, 2005.

[24] T. Igarashi, Y. Kamiyama, and M. Inami: A dipole field for object delivery by pushing on a flat surface, *Proceedings of 2010 IEEE International Conference on Robotics and Automation*, pp. 5114–5119, 2010.

[25] R. Fujisawa, H. Imamura, T. Hashimoto, and F. Matsuno: Communication using pheromone field for multiple robots, *Proc. 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 1391–1396, 2008.

[26] K. Sugawara, T. Kazama, and T. Watanabe: Foraging behavior of interacting robots with virtual pheromone, *Proc. 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Vol. 3, pp. 3074–3079, 2004.

[27] S. Garnier, F. Tache, M. Combe, A. Grimal, and G. Theraulaz: Alice in pheromone land: An experimental setup for the study of ant-like robots, *Proc. IEEE Swarm Intelligence Symposium 2007*, pp. 37–44, 2007.

[28] H. Woern, M. Szymanski, and J. Seyfried: The I-SWARM project, *Proc. the 15th IEEE International Symposium on Robot and Human Interactive Communication*, pp. 492–496, 2006.

[29] K. Yasu, N. Nagaya, T. Tokiwa, M. Sugimoto, and M. Inami: A control method for robots with display-based computing, *Transactions of the Virtual Reality Society of Japan*, Vol. 16, No. 2, pp. 181–188, 2011 (in Japanese).

Takefumi Hiraki

He received his B.S. and M.S. degrees from the University of Tokyo, Japan, in 2014 and 2016, respectively. He is currently a Ph.D. student at the Graduate School of Information Science and Technology, the University of Tokyo. His research interests lie in the areas of human-computer interaction, virtual reality, and ubiquitous computing. He is a student member of IEEE and ACM.

Shogo Fukushima

He received a Ph.D. in engineering from the University of Electro-Communications in 2013. He was a visiting student of Camera Culture Group at MIT Media Lab supported by "Japan Society for Promotion of Science (JSPS) Research Fellowships for Research Abroad," and a project researcher of Graduate School of Information Science and Technology at the University of Tokyo. He is currently a researcher at Japan Science and Technology Agency (JST) PRESTO and a visiting researcher at Digital Human Research Group Human Informatics Research Institute, National Institute of Advanced Industrial Science (AIST). His research interests are IA (Intelligence amplification), virtual reality, entertainment computing and human emotions. He is a member of ACM.

Yoshihiro Kawahara (Member)

He received the B.S., M.S., and Ph.D. degrees in Information and Communication Engineering from the University of Tokyo, Japan, in 2000, 2002, and 2005, respectively. Currently, he is an Associate Professor in the Department of Information and Communication Engineering, the University of Tokyo. He joined the faculty in 2005. From 2011 to 2013, he was a Visiting Scholar at the Georgia Institute of Technology, USA. Further, he was a Visiting Assistant Professor at the Massachusetts Institute of Technology, USA, in 2013. His research interests lie in the areas of computer networks and ubiquitous and mobile computing. He is a member of IEICE, IEEE, and ACM.

Takeshi Naemura

He received a Ph.D. in electrical engineering from the University of Tokyo, Japan, in 1997. Currently, he is a Professor in the Interfaculty Initiative in Information Studies, the University of Tokyo. He was a visiting assistant professor of computer science at Stanford University, USA, supported by "Japan Society for Promotion of Science (JSPS) Postdoctoral Fellowships for Research Abroad" from 2000 to 2002. His research interest includes virtual reality and human interface. He is a member of IEICE, IEEE, and ACM.