Projection-based Localization and Navigation Method for Multiple Mobile Robots with Pixel-level Visible Light Communication

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Abstract—We propose a novel method for the localization and navigation of multiple mobile robots. Our method uses coded light superimposed onto a visual image and projected onto the robots. Robots localize their position by receiving and decoding the projected light, and can follow a target using the coded velocity vector field. Localization and navigation information can be independently conveyed in each pixel, and we can change this information over time. The entire system only requires a projector to navigate the robot swarm; thus, it can be used on any projection surface. To navigate the robots, they only need to be placed within the projection area. 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 navigation of multiple mobile robots in vector fields that vary both spatially and temporally.

I. 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), which is changed either by a human or themselves. Because robots are tangible and physically manipulatable, they are more intuitive than a conventional graphical user interface [1], [2]. In robotic pattern formation, methods for creating artistic visual expressions using multiple robots have been proposed [3], [4], [5]. These methods 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 areas such as entertainment. These methods need to determine the position and state of the robots accurately. They also need to be able to navigate the robots easily and instantly on various physical surfaces to express visual information.

There remain two challenges in the localization and navigation of 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], [3], [4], [6], characteristic patterns [5], or retro-reflective materials [7]. However, it is necessary to fix the position of the cameras, calibrate them, and calculate the spatial location of robots in the camera images. Localization methods without computer vision may rely on lasers [8], [9], sonar [10], [11], or visible light communication [12]; however, these approaches have limited accuracy because of each sensor’s resolution. Second, because we often require independent control signals via wireless or wired communication in conventional methods [6], the system load increases in proportion to the number of robots; thus, robot navigation has a scalability problem. Other approaches, such as a simple direction navigation using multiple light sources [5], can navigate robots but are not able to guide them to an exact position. Thus, achieving a responsive navigation system for a large number of mobile robots without camera calibration or a heavy traffic load is not a trivial task.

In this paper, we propose a method that allows multiple mobile robots to be localized and navigated by projecting light with embedded information. The principle of pixel-level visible light communication (PVLC) [13] is utilized to embed information. The PVLC is a data communication method that uses human-imperceptible high-speed flicker from a digital light processing (DLP) projector. Utilizing this, 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 navigation, and other types of information. 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 navigation of the robots through projection. Further, the spatial deviation between the images and robots does not occur in principle. Fig. 1 shows the concept of our proposed method.

The technical contribution of this paper is two-fold: First, we propose the structure of the projection pattern for embedding data. This structure contains coordinates, control instructions, and switching mode. Second, we suggest a light receiving circuit that operates at high speeds and consumes...
low current. Further, we suggest small mobile robots that are suitable for the designed light-receiving circuit mounted onto them. Experiments in laboratory conditions demonstrate the proposed system. The results show that its projected light patterns can perform the localization and navigation of mobile robots. Besides, localization accuracy and is experimentally evaluated and an application demonstrates the effectiveness of the method.

II. RELATED WORK

We briefly review localization methods, navigation methods, and methods that combine both localization and navigation using projected light patterns for communication. We also review the PVLC method 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. Raskar et al. [14] and Lee et al. [15] localize an object with photosensors using striped pattern Gray-code images. Xiao et al. [16] use an M-sequence image, and Raskar et al. [17] use 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 of 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 navigation is performed after the robot is localized, but there are various methods using projected light for direct path guidance without localization. Fujiwara et al. [18] interactively navigates 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. [19] proposed the dynamic path navigation of a single robot using the narrow beam of a laser, although this system is not suitable for multiple robots.

Several methods implement both the localization and navigation of multiple mobile robots. Liu et al. [20] perform this task using visible light communication. Their system sends position information using general data communication, and feedback to the central system is not required. However, localization accuracy is not very high because the position is estimated from the incident angle of the light. Nii et al. [21] transmit information according to location using a high-speed LED projector; however, the image is in grayscale, and its resolution is significantly lower than our system, e.g., four by five pixels.

Various approaches in swarm robotics have demonstrated robot navigation methods that use gradient maps, and they are also able to navigate robots to specific places or into specific configurations. Fujisawa et al. [22] proposed a pheromone-based navigation method for robots. In this system, robots navigate by dripping and sensing alcohol, and Sugawara et al. [23] and Garnier et al. [24] also investigate this approach. This approach does not need an external system; however, it cannot localize the robot. Woern et al. [25] also used a projector to feed robots with light as an energy supply and navigate 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.

The display-based measurement and control system (DMCS) [26] 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. The DMCS does not require position measurement devices such as RGB or depth cameras, and it can support an unlimited number of robots on the display. However, it requires the tracking robots to be initialized by marker-pattern images beforehand; thus, adding or removing robots is not possible. This system is only for sending the coordinates of robots; we need separate channels, e.g., wireless or wired connections, to transfer other instructions such as moving other actuators.

To achieve an initialization-free and marker-free method that both localizes and navigates an unlimited number of robots, we utilize PVLC [13]. PVLC is a method that superimposes data patterns on pixels with human-imperceptible flicker using a very high-speed DLP projector. It can display a visual image containing superimposed data as bit patterns that are decodable by receiver circuits.

Fig. 2 shows the principle of embedding imperceptible data into a visual image, which is based on pixel-by-pixel pulse width modulation. When two inverted patterns are displayed alternately at high frequency, human eyes see only a flat gray image because of the persistence of vision. 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 has to be carefully designed to maintain luminance and avoid flicker.

III. METHOD AND IMPLEMENTATION

We must consider two factors when applying the PVLC principle to the localization and navigation of mobile robots. (1) We propose a projection pattern for embedding two types of information in the same location: perceptible images for humans and imperceptible data for sensors. Besides, these data include coordinates, control instructions, and other types of information. (2) We propose small mobile robots that act
A. System Overview

Fig. 3 shows an overview of our system. Our system comprises a PC, a full-color DLP projector (ViALUX STAR-07), a screen, and robots. The PC generates binary frames that include data frames for localization and navigation, and the DLP projector projects the binary frames at 12,500 fps. The robots receive the light from the projector and act according to the embedded information in each pixel. Fig. 4 shows the composition of binary frames in a sequence. The frames comprise of three blocks: synchronization, data, and luminance adjustment. The synchronization block is used to identify the start of the data sequence. The data block comprises the two-dimensional coordinates for localization and velocity vector for navigation. 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. Error does not occur even when the robot crosses pixel boundaries because of the principles of Gray-code. The luminance adjustment block maintains the time ratio of on-and-off periods to adjust the luminance of each pixel for human perception. We calculate these frames to achieve the correct ratio of synchronization to data over time.

Fig. 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 these frames (150 frames) is the number of frames per transmission unit. We set the blink frequency 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.

The data block includes 32 frames, which means we can transfer 32 bits of data for each pixel. 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). 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 to the other field information.

B. Receiver Circuit and Robot

There are three requirements for the robots in our method. They must be able to

- receive a sequence of high frequency (12,500 Hz) light pulses from the 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. 6. The robot’s length, width, and height are 72 mm, 50 mm, and 70 mm, respectively. The robot’s weight including the battery is 152 g. We developed a new receiver circuit using a photodiode instead of the phototransistor that prior systems have employed [13], [26]. We made this change because we could not obtain the required performance with a phototransistor given of the effects of rise/decay time. When using the photodiode, it is possible to obtain the required performance 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 that has a trans-impedance amplifier.

In the proposed system, it is necessary to use 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 the S2506-02 (Hamamatsu Photonics) photodiode and OPA2353UA (Burr-Brown) op-amp. The trans-impedance amplifier unit was implemented in the circuit near the chips to reduce noise. We set the trans-impedance gain to a million times 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 the comparator circuit. We use the NJM2732M (JRC) op-amp as a comparator and adjust the threshold value with an adjustable resistor. We also use the NXP Semiconductor’s LPC1114FN28 (ARM Coretex-M0, 48 MHz) as the main micro-controller. The main battery is a one-cell LiPo battery (3.7 V, 800 mAh). We also employ a 120:1 Mini Plastic Gearmotor HP with an Offset 3 mm D-Shaft Output and Extended Motor Shaft (Pololu) to drive the robot and Rainbow Products plastic pulleys (35 mm, $\Phi$ 3 mm) for the wheels.

IV. 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;
- localization accuracy while the robot is moving;
- trajectory of the robot when we set a target point.

We performed the first two experiments using a 520 mm $\times$ 400 mm screen in an assembled darkroom (Morimoto-Kasei MEDR-2518). The third experiment was conducted using a bigger screen of size 1340 mm $\times$ 1010 mm. We attached a Magnetic Encoder Pair Kit for Micro Metal Gearmotors, 12 CPR, 2.7–18 V (Pololu) to the shaft of the motors and used them as rotary encoders for the odometry. The measured values of the step size were 0.17173 mm/pulse (left) and 0.16892 mm/pulse (right). 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 running Ubuntu Linux 15.10.

A. 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 tabletop screen and obtained the position of the $x$ and $y$ coordinates using our proposed method. We selected nine points on the screen frame arranged in a $3 \times 3$ matrix. The measurement was carried out 500 times at each point. The received $(x, y)$ coordinate information is shown in Fig. 7 as three-dimensional histograms that represent the number of measurements for each point. We calculated the mode of each measurement and set it to be the center value of each axis. In Fig. 7, the value of the mode is the correct location for all points, and any outliers in the received data are only a few pixels from the position of the mode. The received data was stable, considering that over 80% of the measurements were equal to the mode at each point. As a result, the effects of the outliers in the sensor are negligible when the robot is stationary; hence, the proposed system is a stable localization method in a static state.

B. Experiment of Localization in Dynamic State

The objective of this experiment was to evaluate the accuracy of localization while the robot is moving. We compared the localization obtained using our method with that obtained using odometry. In contrast to the static state experiment, interference occurs when the robot crosses over 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 moving direction.

Specifically, the robot was set to move straight at an angle $\theta$ from the $x$ axis of $0$, $\frac{\pi}{12}$, $\frac{\pi}{6}$, $\frac{\pi}{4}$ radians. Angles larger
Fig. 8. Localization accuracy when the robot is moving. The blue line is localization using our method, and the green line is localization using odometry.

than $\frac{\pi}{4}$ are redundant because of the symmetry of the square pixel. We consistently accelerated the robot for 1.0 s, ran it at maximum speed for 1.0 s, and then stopped it. The top speed of the robot measured using odometry was about 100 mm/s. The control period for obtaining data at the receivers was 10 ms, and the time taken to renew the odometry and output the running log was 100 ms. We calibrated the coordinate systems of our method and the odometry by an affine transformation using the measured values so 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 robot’s horizontal $x$ and vertical $y$ positions with respect to time for different $\theta$. The figure shows that the localization obtained using our method almost has the same accuracy as that obtained by odometry. We conclude that localization using our method can be an alternative method to odometry when it is not necessary to perform precise localization (e.g., when moving a robotic arm).

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 (2.6 mm), which is larger than the quantization level of the odometry. A calibration error between the PVLC’s image coordinate system and original coordinate system caused a slight gap between the results of our method and the odometry. An exact transformation from the projected image to the real coordinate system is possible if the tilt of the image plane as well as the lens distortion parameters of the projector are known.

C. Experiment for Robot Navigation

We conducted the navigation experiment to evaluate the trajectory of multiple mobile robots when we set a target point. We embedded 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 about 100 mm/s, the same value as used in the preceding experiment. We changed a part of the robots’ skirts to round-shaped ones with an outside diameter of 103 mm to prevent the robots from colliding and locking together.

Fig. 9 shows the embedded velocity vector field and the resulting trajectories of the robots. The vector field was coded so that the robots moved toward a target point; namely, each vector is oriented toward the target, and the size of the vectors decrease as the robots approach it. We placed two robots in two different positions, and both of them arrived at the target point (yellow point). Our method successfully navigated them so that they followed the intended trajectory. This application allows us to move mobile robots toward a target point quickly, regardless of their initial position and angle.

Fig. 10 shows the trajectories of robots controlled by an image embedded with temporally varying velocity vector fields. The vector field was coded so that the robots moved toward a target point just as in the previous experiment. The
target in this experiment was rotated counterclockwise shown in Fig. 11; the start point is indicated by the yellow dot, and the point was moved in intervals of a second. We placed a robot on the edge of the screen. In Fig. 10, the paths for each time 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 experiments show that it is easy to perform trajectory navigation of the robots by moving the target point.

V. Conclusion

We proposed a novel localization and navigation method for multiple mobile robots by projecting an image using light with embedded information. In this paper, 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 consumes 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 our localization method can be an alternative to odometry when controlling multiple mobile robots. The third suggests that our method can perform robot navigation by moving a target point.

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References


