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Robot Navigation using Polarized Light Sensor without Crossed-analyzer

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Abstract
This paper provides navigation of the wheel robot using the polarized light sensor (POL-sensor) without the crossed-analyzer. The crossed-analyzer is the way to enhance the sensitivity of the sensor using some paired photodiodes. For weight saving, we make the POL-sensor composed of half the number of photodiodes compared to one using the crossed-analyzer, carry out the navigation experiment using it. And experimental results show that made POL-sensor realize the robot navigation having the same level of navigation using the magnetic sensor.

Key words
Polarized Light Sensor, Robot Navigation, Biomimetic Sensor, Wheel robot, Magnetic Sensor

1. Introduction

Insects in nature use several kinds of environmental information for their navigation of traveling to the feeding ground, the breeding site and other places [1]. For navigating our robots, we focus attention on the navigation of desert ants and bees using the polarized light of the sun. Many animals and insects use the position of the sun for their navigation. On the other hand, the polarized light can be measured, if the sun is hidden by clouds or mountains or other obstacles [2].

In space, the solar light oscillates in all direction. However, atmospheric molecules scatter it and cause polarization in the sky. We are able to know the azimuth direction by measuring oscillation directions of polarization (e-vectors), because of the pattern of polarization is symmetric about the meridian which is the line connecting the sun and zenith. Two types of microvillus which play a part in the polarization filter are arrayed orthogonally each other on the photoreceptor in the insect's ommatidium. Thus each photoreceptor has two channels about polarization. The polarization-sensitive neuron (POL-neuron) enhances sensitivity to e-vectors by measuring the difference of inputs from two channels, and this characteristic is called "crossed-analyzer".

Existing POL-sensors developed in other studies [3] use paired photodiodes to mimic the crossed-analyzer. As a result, about six photodiodes are used in a POL-sensor unit. However, it is too heavy for small robots, for example aerial robots and small wheel robots, to apply these sensors directly.

In this paper, for navigating the small flapping robot in the future, we make the prototype of the lightweight POL-sensor unit, i.e. the POL-sensor unit using less photodiodes, and carry out the navigation experiment using the wheel robot mounted it without the crossed-analyzer. Moreover our experimental results show that developed sensor realizes the same level of navigation accuracy as navigation using the magnetic sensor.

2. Polarization and Polarized Light Sensor

2.1 Polarized light

In space, the solar ray oscillates in all direction. However, atmospheric molecules and dust scatter the solar ray, and bias its oscillation plane. This phenomenon is polarization (Fig. 1), the direction of the oscillation is called "e-vector".

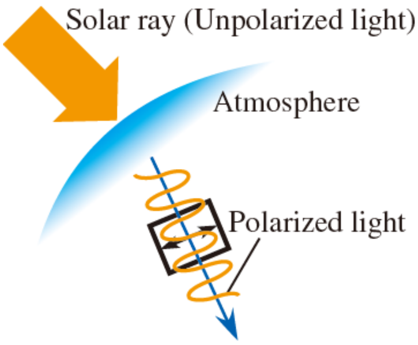

Fig.1 Polarization by the atmosphere. The solar ray (unpolarized light) is scattered by the atmosphere, transmute into the polarized light whose oscillate plane has bias.

Figure 2 shows the pattern of polarization in the sky. The polarized light expands concentrically around the sun. And the pattern of polarization is drawn symmetrically on the line through the sun and the zenith, called the solar meridian and the anti-solar meridian. The line width of dashed lines means the degree of polarization. The degree of polarization has the maximum at an angle of $\pi/2$ rad degree to the direction of the sun. Directions of dashed lines mean the directions of polarization called "e-vector".

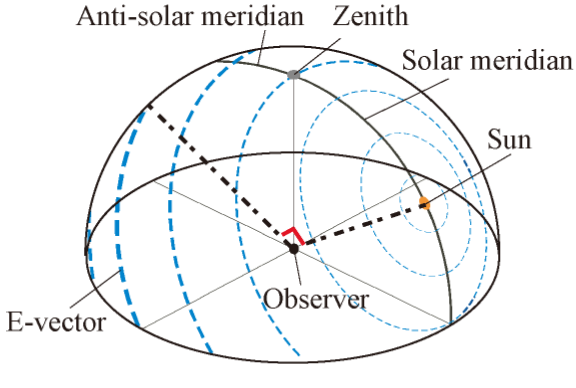

Fig.2 The pattern of polarization. Widths and directions of dashed lines are the degree and directions of polarization.

2.2 Insect's navigation mechanism

Humans cannot see and recognize the pattern of the polarized light. However some insects, dessert ants and honey bees, can recognize this pattern, and figure out the direction based on it.

Such insects have compound eyes composed ommatidia, and they distinguish the pattern of polarization using the photoreceptor in the ommatidium. The rhabdomere in the photoreceptor has two channels having the difference of the direction of orthogonal microvillus. Each channel of photoreceptors responds to the polarized light whose direction of the oscillation (e-vector) has a $\pi/2$ rad difference (Fig.3). The POL-neuron enhances sensitivity to e-vectors by measuring the difference of inputs from two channels, and this characteristic is called "crossed-analyzer".

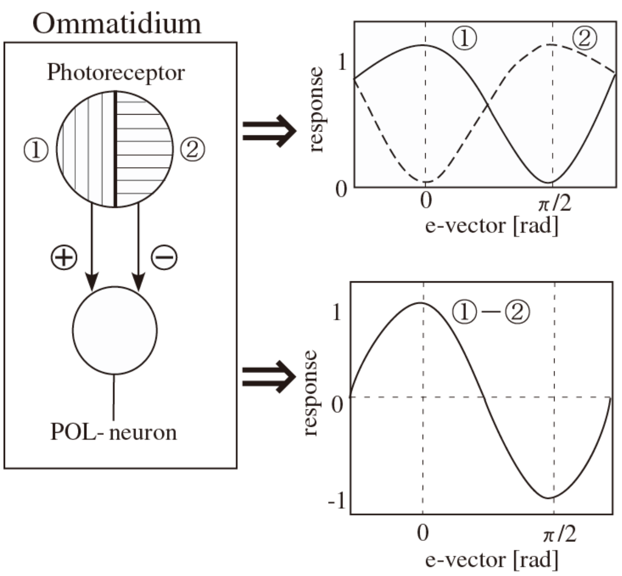

Fig.3 The mechanism of the crossed-analyzer in insect's ommatidium.

Insects figure out the direction of the meridian using the crossed-analyzer, use it as a polarization compass for their navigation. Then they can only know the direction of the meridian, cannot know the azimuth direction and the direction of the sun by the polarization compass. And the sun and the meridian move as Fig.3 over time. Thus insects figure out the position of the sun based on the solar light's characteristic that the area in the sky which is more closely to the sun abounds in the light having longer wavelength. And they navigate using the position of the sun and their biological clock.

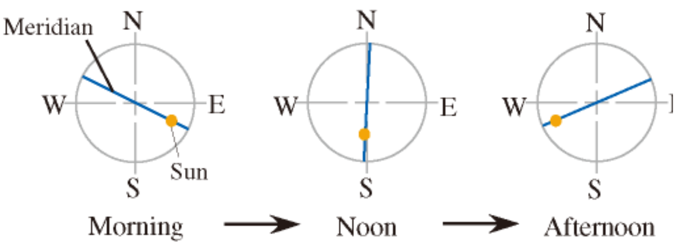

Fig.4 Change of the sun and the meridian over time.

2.3 Composition of POL-sensor unit

We construct the POL-sensor unit based on the mechanism of the insect's POL-sensor. The POL-sensors are composed of photodiodes which function as photoreceptors and polarizing filters which function as microvillus. The photodiode is covered with polarizing filter. POL-sensors are set in a $\pi/6$ rad difference each other (Fig.5). If we use the crossed-analyzer for enhancing sensitivity to e-vectors, three pairs of POL-sensors (i.e. six POL-sensors) are needed in the sensor unit. However, our wheel robot has not three pairs of POL-sensors but three POL-sensors for weight saving, is navigated without the crossed-analyzer.

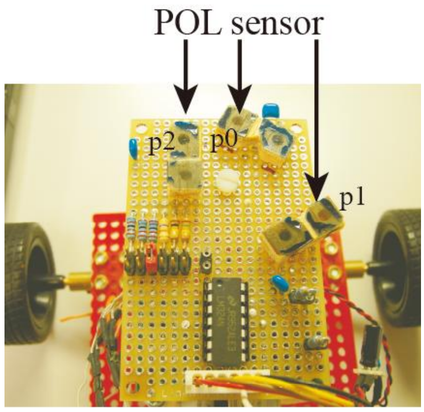

Fig.5 POL-sensor unit for wheel robot navigation.

Measuring results are shown in Fig.6 measured by three POL-sensors shown in Fig.5. Red dots, green dots and blue dots mean the value of POL-sensor output when these sensors measure the polarized light in a given angle. Three curves composed of each colored dots are drawn by results measured in rotating 2π rad, and shape like the sine function. These phases have about $\pi/3$ rad differences each other as with the layout of POL-sensors.

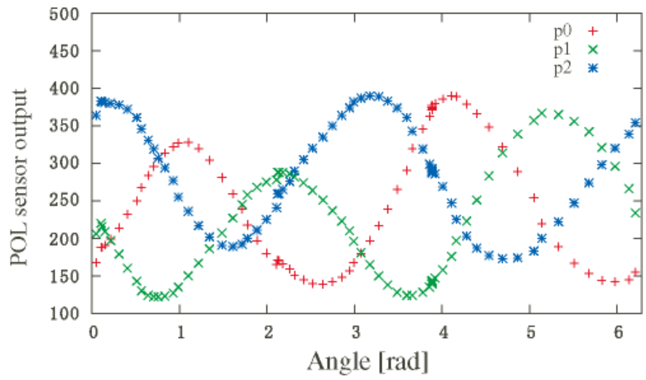

Fig.6 Measuring results by the POL-sensor unit in Fig.5. The horizontal axis is rotate angles of the sensor unit. The vertical axis is output values from the POL-sensor.

In the zenith, the direction of the oscillation of the polarized light crosses the meridian at right angles independent of the position of the sun. Thus we can know the angle between the North-South axis and the robot's direction by measuring the polarization in the zenith using the POL-sensor. By this way, only the direction of the North-South axis is shown, we cannot get the azimuth direction. For navigating the robot, the azimuth direction is calculated using both measuring results by POL-sensor and the rotational angle of the robot measured by the rotary encoder mounted on the wheel robot.

Before navigating the robot, we calibrate the POL-sensor and the rotary encoder, and make the look-up table for the rotate angle of the POL-sensor from 0 to 2π rad. The azimuth direction $\theta_{pol}(t)$ is calculated from following equations (1) or (2) based on the value estimated from the look-up table and the encoder output $\theta_{enc}(t)$.

$$\theta_{pol}(t)=(\theta_{p0}(t)+\theta_{p1}(t)+\theta_{p2}(t))/3 \qquad (0 \le \theta_{enc}(t) \le \pi) \quad (1)$$
$$\theta_{pol}(t)=(\theta_{p0}(t)+\theta_{p1}(t)+\theta_{p2}(t))/3+\pi \qquad (\pi \le \theta_{enc}(t) \le 2\pi) \quad (2)$$

Here, $\theta_{p0}(t)$, $\theta_{p1}(t)$ and $\theta_{p2}(t)$ are the estimated angles by POL-sensor p1, p2 and p3 using the look-up table.

3. Wheel robot and experiment system

Figure 7 shows the wheel robot for navigation experiments. This wheel robot has two drive wheels driven by two independent motors attached the rotary encoder, the micro computer (sh2 Tiny) for control, the POL-sensor unit and the 2D magnetic sensor shown in Fig.8. To reverse two wheels each other realizes turning the robot, because of the front part of the robot is sustained by a caster. The wireless communication module is mounted for communication between the wheel robot and PC for taking experimental data and sending commands.

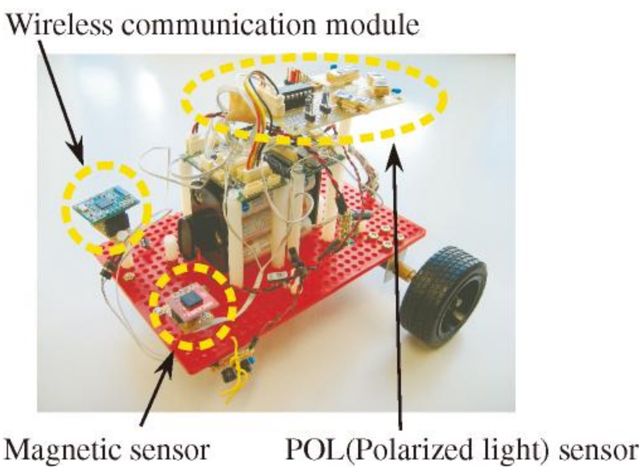

Fig.7 Over view of the wheel robot for navigation experiment. Rear wheels of the robot are driven by independent two DC motors. Mounted sensors are the POL sensor, the magnetic sensor for navigation and rotary encoder attached on DC motors for the odometry. The magnetic sensor is used in the navigation experiment for compare to POL-sensor.

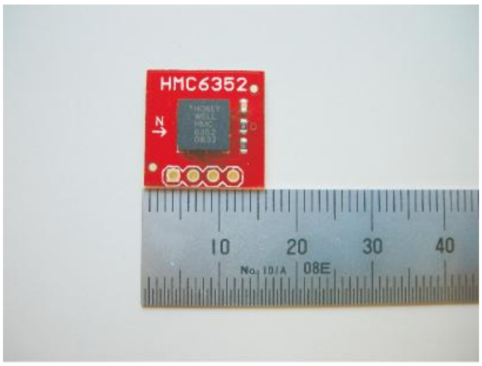

Fig.8 2D magnetic sensor HMC6352 for navigation.

In the navigation experiment, the robot's position is estimated by the odometry [4] using rotary encoders. The odometry is the way to estimate the distance and the position based on the history of traveling. Dessert ants use not only the polarization but also the odometry for traveling and feeding activity [5].

The velocity $v(\tau)$ and the angler velocity $\omega(\tau)$ at given time τ are calculated as

$$v(\tau)=(R_w/2)(\omega_r(\tau)+\omega_l(\tau))=(v_r(\tau)+v_l(\tau))/2 \qquad (3)$$
$$\omega(\tau)=(R_w/D)(\omega_r(\tau)-\omega_l(\tau))=(v_r(\tau)-v_l(\tau))/D \qquad (4).$$

Here, R_w, $\omega_r(\tau)$, $\omega_l(\tau)$, $v_r(\tau)$, $v_l(\tau)$ and D are the wheel radius, the angler velocity of right and left wheels, the translational velocity of right and left wheels and the distance between wheels as shown in Fig.9.

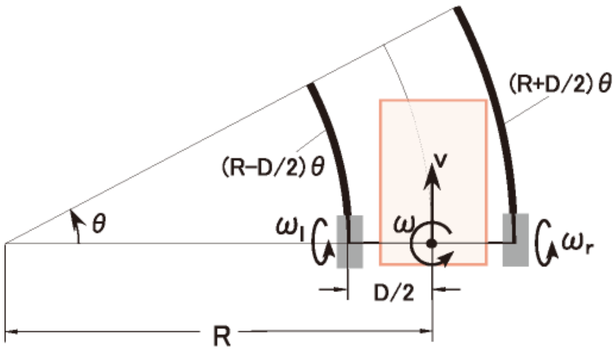

Fig.9 Parameters of the robot in turning.

Then the position and the angle of the traveling direction ($x(t)$, $y(t)$, $\theta(t)$) are calculated from following equations base on Fig.10. In following equations, t_0 is the start time of traveling.

$$\theta(t)=\int_{t_0}^{t}\omega(\tau)d\tau+\theta(t_0) \qquad (5)$$

$$x(t)=\int_{t_0}^{t}v(\tau)\cos(\theta(\tau))d\tau+x(t_0) \qquad (6)$$

$$y(t)=\int_{t_0}^{t}v(\tau)\sin(\theta(\tau))d\tau+y(t_0) \qquad (7)$$

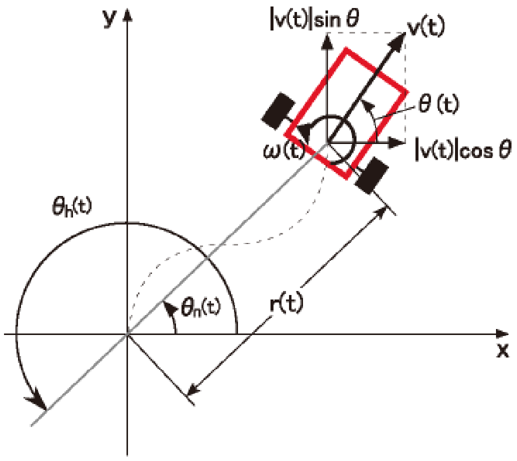

Fig.10 the position of robot and the angle of traveling direction.

The distance $r(t)$ from the origin to the robot position and the angle $\theta_n(t)$ between the x-axis and the line to the robot are calculated as

$$r(t)=(x(t)^2+y(t)^2)^{(1/2)} \quad (8).$$
$$\theta_n(t)=\arctan(y(t)/x(t)) \quad (9).$$

The direction of the home position to return $\theta_h(t)$ is given by add π to $\theta_n(t)$ as

$$\theta_h(t)=\theta_n(t)+\pi. \quad (10)$$

The wheel robot is navigated from a given position to the home position based on $\theta_h(t)$ calculated using encoder outputs. Two motors are controlled by PID controller to reduce the angler error $\theta_e(t)$ close to 0. The angler error $\theta_e(t)$ is the error between the reference angle $\theta_h(t)$ and the azimuth angle measured by the magnetic sensor $\theta_{mag}(t)$ or POL-sensors $\theta_{pol}(t)$.

4. Navigation Experiment using the magnetic sensor

Navigation experiments are carried out along the following steps.

1. Calibration of sensors and encoders at the home position.
2. Start the travel controlled by commands from the PC.
3. Switch from manual control to autonomous control using the magnetic sensor or POL-sensors.
4. Return to the home position by autonomous control.

For comparing the navigation accuracy using the POL-sensor with the other sensor, we carry out the navigation experiment using the magnetic sensor.

Figure 11 shows experimental results of navigation using the magnetic sensor. After switching to autonomous control, the estimated home direction $\theta_{mag}(t)$ closes to $\theta_h(t)$. The distance between the robot and the home position $r(t)$ increases once, however, it closes to zero. That trajectory is shown in the bottom graph in Fig.11, says that the wheel robot turned and closed to the home position by autonomous control.

5. Navigation Experiment using the POL-sensor

Figure 12 shows experimental results of navigation using the POL-sensor. In this experiment, the direction estimated by POL-sensor $\theta_{pol}(t)$ closes to the reference direction to the home position estimated by encoders $\theta_h(t)$. And the distance between the robot and the home position $r(t)$ also closes to zero.

The distance $r(t)$ seems to increase by the autonomous control in the trajectory of the robot. It is caused that the ratio of x and y axes in the trajectory graph is not 1-for-1. Actually, the robot returns to the home position, the distance $r(t)$ also decrease to the same level of the navigation result using the magnetic sensor.

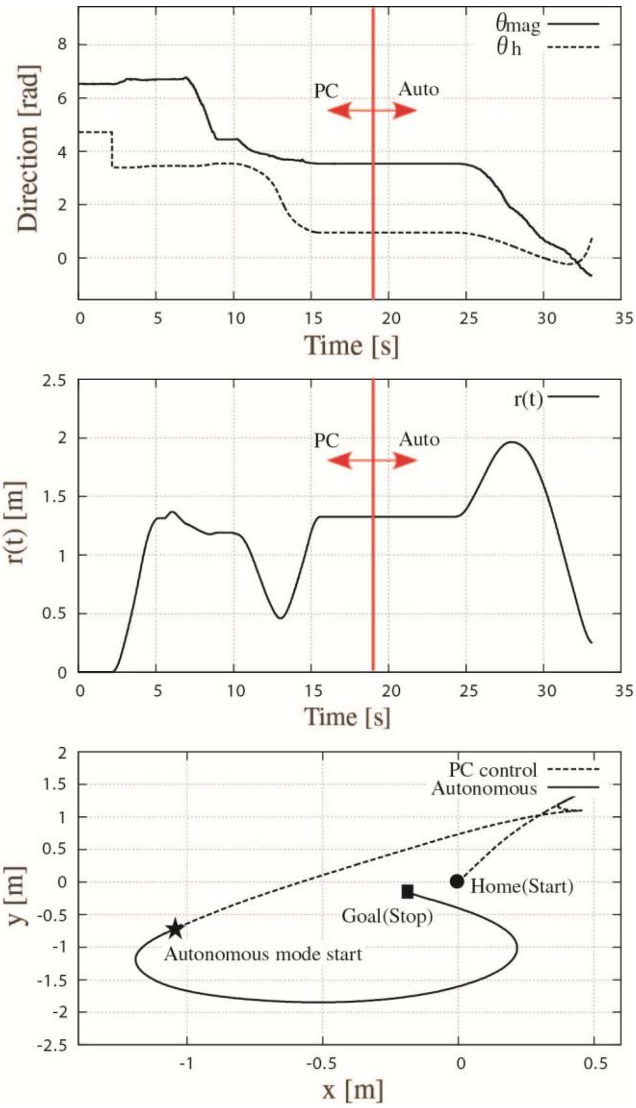

Fig.11 Experimental results of navigation using the magnetic sensor. Upper: Directions estimated by odometry $\theta_h(t)$ and the magnetic sensor $\theta_{mag}(t)$. Middle: The distance between the wheel robot and the home position. Bottom: The trajectory of the wheel robot controlled by the manual control (dashed line) and the autonomous control (solid line). The ratio of x and y axes in the trajectory graph is not 1-for-1.

6. Conclusions

This paper has presented navigation of the wheel robot using the prototype of the light weight POL-sensor. This prototype is composed of unpaired three photodiodes and measures polarization without the crossed-analyzer. In the navigation experiment, the robot has been navigated using the POL-sensor measuring the direction without the crossed-analyzer. The navigation experiment using the magnetic sensor also has been carried out. The comparison of two kinds of experimental results has shown that the autonomous control using the POL-sensor realized the same accuracy level of navigation using the magnetic sensor.

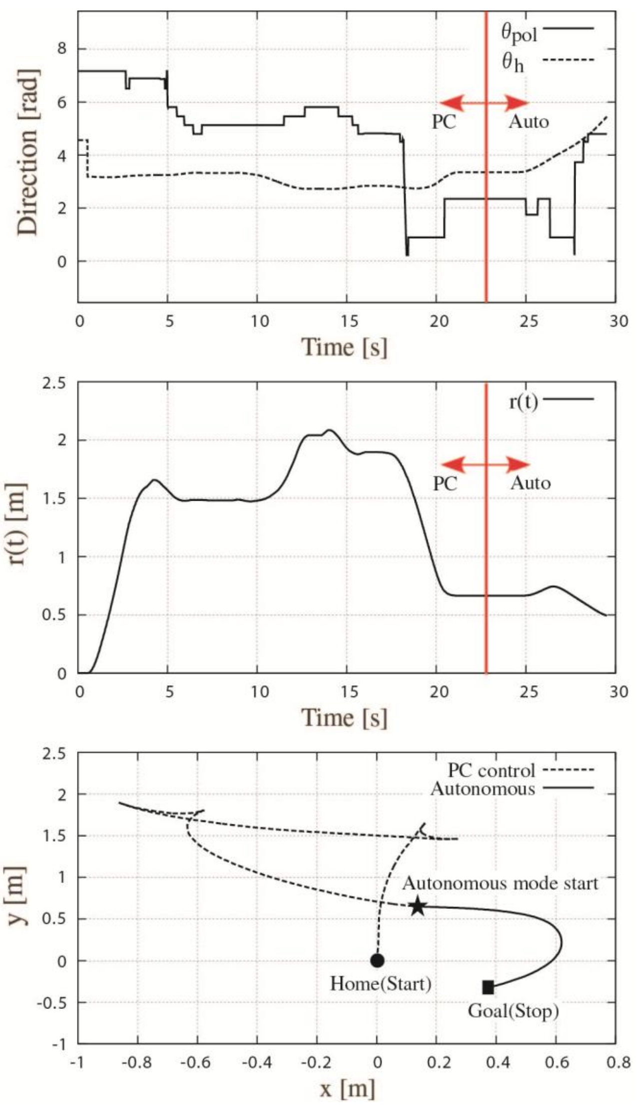

Fig.12 Experimental results of navigation using the POL-sensor. Upper: Directions estimated by odometry $\theta_h(t)$ and the POL-sensor $\theta_{pol}(t)$. Middle: The distance between the wheel robot and the home position. Bottom: The trajectory of the wheel robot controlled by the manual control (dashed line) and the autonomous control (solid line). The ratio of x and y axes in the trajectory graph is not 1-for-1.

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