Localization of a Walking Robot Using a Laser Speckle Odometry

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Abstract—In this study, we propose a laser odometry to localize an underwater walking robot. In the laser odometry using optical sensors, motion is estimated by tracking laser speckle patterns. However, measurement error increases when the sensor is tilted. We describe the overview of our walking robot with the sensor, the principle of laser odometry, and the experimental results.

Index Terms—Walking robot, positioning sensor, laser speckle

I. INTRODUCTION

Exploitation of marine resources is expected in a sea-facing country such as Japan. An underwater robot which investigates the seabed for a long time is needed for such a purpose.

For performing the marine resource investigation using underwater robots, the localization of the robot is important. An inertial navigation system or ultrasonic sensor is often used for the localization in water. However, the use of expensive sensors in these sensing systems is economically inefficient.

We propose the use of a laser odometry for the localization of underwater robots. The laser odometry is a method that measures the movement of laser speckle patterns, which appear when laser light is irradiated to an object surface, with an optical sensor aligned parallel to the observation plane. Using two or more optical sensors can measure three-dimensional amounts of both the translation in the X-, Y- and Z-axes, and the rotation around the Z-axis [1]. Since the sensor does not need any external light source except the laser, it is available in dark environment such as the seabed.

In this paper, we describe a laser odometry for a walking robot with six legs to be used in the underwater. In the case of the walking robot, some measurement errors occur due to the tilt of the optical sensor rigidly fixed to the robot. To compensate this measurement error in walking, the measured value of the optical sensor is corrected by using a tilt sensor so that it corresponds to the actual movement of the robot. We explain the principle of the laser odometry, the construction of the sensor module, and also report the estimated trajectory of a real walking robot with the optical sensor.

II. OVERVIEW OF A MULTI-LEGGED ROBOT “R-3110”

A multi-legged robot is shown in Fig. 1. In order to use the laser odometry, the laser has to be radiated on the seabed. Therefore, it is required to use a locomotion method such that the robot does not roll up the sediment. The multi-legged robot using in this study can realize a multi-legged walking, in which the operating range of the legs is wide and the area of the legs touching with the seabed is small, because the legs are flared laterally. Thus, the multi-legged robot can adapt to the terrain of the seabed, and move without rolling up the sediment. Fig. 1 shows the present robot, where the angles of three attitudes of the robot are (θ, φ, ψ), the coordinate system of the robot is B=[x, y, z] and the coordinate system of the world is W=[W_x, W_y, W_z].

III. LOCALIZATION USING A LASER SPECKLE ODOMETRY

The amount of translation is measured by laser speckle odometry and the amount of Z-axis rotation is measured by a gyro sensor. It also obtains the inclination of the body by the acceleration sensor, and is corrected in consideration of the inclination of the body.

A. The Principle of Laser Speckle Odometry Measurement

The reflected light of laser radiated to an object makes laser speckle on the observation plane. The laser odometry is practiced by reading laser speckle as an image by using an optical sensor. Laser speckle is an irregular pattern generated...
by the interference of reflected lights when the laser light is radiated to an object. Since the laser lights have a same phase, when the light is radiated on an object surface having bigger unevenness than a wavelength, the reflected light is scattered. As a result, there appear a bright place and a dark place in space, where the former is generated due to the intensified phases of the reflected lights, whereas the latter is generated due to the weakened phases of them. This pattern is observed as a 2-dimensional image by an optical sensor. When the sensor moves, the laser speckle also moves, so that the amount of movement of the sensor can be measured from the amount of movement of the laser speckle. The amount of movement of a robot is measured by attaching an optical sensor and a laser module to the bottom of the robot.

B. Calculation of Laser Speckle Movements

Fig. 2 shows the measurement principle of laser odometry. The amount of movement of the laser speckle in the X-axis and Y-axis directions, is determined using the following equations [2]:

$$A_x = a_x \left( \frac{L_o \cos \theta_o + \cos \theta_o}{L_s} \right)$$
$$- a_x \left( \frac{L_o \cos \theta_o + \sin \theta_o}{L_s} \right)$$
$$- L_o \left( \varepsilon_{xx} \left( \frac{\sin \theta_o}{\cos \theta_o} \right) + \tan \theta_o \right)$$
$$- \varphi \left( \frac{\cos \theta_o}{\cos \theta_o} + 1 \right) \right)$$

(1)

$$A_y = a_y \left( \frac{L_o}{L_s} + \frac{1}{L_s} \right) - \left( \frac{L_o}{L_s} \right) \varphi \left( \sin \theta_o + \sin \theta_o \right)$$
$$- \varphi \left( \cos \theta_o + \cos \theta_o \right) - \psi \left( \sin \theta_o + \sin \theta_o \right) \right)$$

(2)

where $A_x$ and $A_y$ are the amounts of movement of the laser speckle; $a_x$, $a_y$ and $a_z$ are the translational components of the irradiated area; $\theta_o$, $\varphi$ and $\psi$ are the rotational components; $\varepsilon_{xx}$, $\varepsilon_{xy}$ and $\varepsilon_{yy}$ are the strain components; $\theta_o$ and $L_o$ are the direction and the distance from the observation plane; and $\theta_x$ and $L_x$ are the incident angle of the laser and the radius of the curvature.

When the laser beam is irradiated perpendicularly to the measuring surface without distortions, it results in $\varepsilon_{xx} = 0$, $\varepsilon_{xy} = 0$, $\varepsilon_{yy} = 0$, $L_s = \infty$, $\theta_o = 0$, $\psi = 0$ and $\Omega_y = 0$, so that the above equation is reduced to

$$A_x = a_x \cos \theta_o - a_z \sin \theta_o$$

(3)

$$A_y = a_y + L_o \psi \sin \theta_o$$

(4)

C. Calculation of the Movements

The position of the optical sensors $O_1$ and $O_2$, and one of the laser module are shown in Fig. 3. The distance from the sensor to the ground is defined as $h$, and the distance on the X-axis from the optical sensor to the laser module is defined as $D$. The coordinate system of the sensor is $S=[X, Y, Z]$ as shown in Fig. 3. Each sensor is placed in axis symmetry around the laser module. Using Eq. (3) and Eq. (4) in the case of $D = L_o \sin \theta_o$, the small measured values $x_1$ and $y_1$ in the sensor $O_1$ are expressed as follows:

$$x_1 = a_x \cos \theta_o - a_z \sin \theta_o$$

(5)

$$y_1 = a_y + D \psi$$

(6)

The small measured values $x_2$ and $y_2$ in the sensor $O_2$ are expressed similarly as follows:

$$x_2 = a_x \cos \theta_o + a_z \sin \theta_o$$

(7)

$$y_2 = a_y - D \psi$$

(8)
The small movements in the X- and Y-axes of the radiated area are expressed, using Eq. (5) to Eq. (8), as

\[
a_x = \frac{x_1 + x_2}{2\cos\theta_0} \tag{9}
\]

\[
a_y = \frac{y_1 + y_2}{2} \tag{10}
\]

Movements \((x, y)\) are purchased by accumulating the small movements \((a_x, a_y)\).

D. Correction in consideration of tilt of the sensor

It is already known that laser odometry can measure the translational distance without the effect of the altitude variation [3]. Therefore, it can not be measure only the movement amount in the X- or Y-plane direction of the sensor when measuring the translational movement in a state of tilting the sensor. From this, it needs to perform a correction in consideration of the attitude of the robot. The correction formulas are shown by the following equations:

\[
a_x = \frac{x_1 + x_2}{2\cos\theta_0 \cos\varphi_y} \tag{11}
\]

\[
a_y = \frac{y_1 + y_2}{2\cos\theta_x} \tag{12}
\]

where \(\theta_x\) and \(\varphi_y\) are the tilt angles of the sensor.

IV. EXPERIMENT OF TRANSLATIONAL DISTANCE MEASUREMENT

In previous studies, there was an error when localization was estimated by using the laser speckle odometry for a multi-legged robot [4]. Since the robot swings when walking, the optical sensor can no longer maintain a parallel between the sensor and the ground surface. Therefore, measuring the tilt by an acceleration sensor, it my improve the measurement accuracy by applying a correction if the observation surface is not parallel to the sensor. However, we did not have an experiment using any real robots, so that it was impossible to check whether the localization error was able to be reduced. In what follows, an accuracy improvement in localization is confirmed by using the laser speckle odometry, considering the inclination movement path of a multi-legged robot.

A. Experimental Environment

An experimental environment is shown in Fig. 4, in which the experimental equipment is composed of a laser sensor module, a 9-axis sensor, a walking robot “R-3110,” a microcontroller, and a PC. The sensor unit shown in Fig. 5. The laser sensor module consists of one laser module and two optical sensors, where the optical sensors are arranged symmetrically around the laser module. The distance in the X-axis direction from the laser module to the light receiving portion of the optical sensor is 10 [mm]. The MPU-9250 with 9-axis sensor, which includes a gyro sensor, an acceleration sensor, and a compass sensor, is placed in the center of the robot. The experiment was conducted in room 511, the 5th floor of Okayama University Research Building. The floor is a glossy plane and the experiments were in a state where the lighting in the room was turned off to approximate an actual seabed environment.
B. Experimental Method

The laser sensor module is placed at the center of the robot, and in parallel to the observation surface. The optical sensor is placed at the height of 65 [mm] measured from the observation plane when the robot took the home position. The robot navigates 1000 [mm] straight in the Y-axis from the initial position, taking the measured values of the sensor. Then, the actual moving distance and the measured value are compared each other, to check the accuracy of the localization of the walking robot, where the number of trials was 3 times.

C. Experimental Result

One of the measured Y-axis direction date when the robot navigated 1000 [mm] straight in the Y-axis is shown in Fig. 6. Averaged actual values in the Y-axis direction is 1057 [mm], whereas the average actual measured value is the 1030 [mm]. Averaged actual values in the X-axis direction is 12 [mm], whereas the average measured value is the 0 [mm]. Averaged actual rotation angle around the Z-axis is 5.1 [deg], whereas the average measured rotation angle is 6.2 [deg].

D. Consideration

There exists 2.6 [%] error between the actual value and the measured value of the Y-axis. This error can’t be ignored when performing long-range localization. However, since the fluctuation was not observed on the error of three measurements, it is considerable that a correction is possible.

The actual moving distance in the X-axis direction is not 0 [mm], so that it is considered to be a shift when setting the robot to an initial position.

The difference between the actual value and the measured value in the Z-axis rotation angle was observed. Since in this time, the measured distance was short, the influence was small; but this difference is considered to cause a large error in the long-range self-position specified. As the cause of this error, it is considered that the processing of the offset error of the gyro sensor is not going well. Such an offset is an averaged sensor value when the robot is stationary. However, the offset is changed by the temperature around the sensor. The offset value changes in the start of the experiment and the last time. Therefore, it is considerable to reduce the error by focusing on the latest offset.

V. CONCLUSION

In this paper, we have explained the principle of the laser odometry, the construction of the sensor module, and also reported the estimated trajectory of a real walking robot with the optical sensor, indicating the usefulness of the proposed method. In future, we will conduct a localization underwater by using a waterproofed real machine.

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