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Noncontact Position Estimation Device with Optical Sensor and Laser Sources for Mobile Robots Traversing Slippery Terrains

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Abstract— **This paper describes the development of a sensing device that can be used to estimate the position of mobile robots on slippery terrains. The device consists of an optical sensor designed for a computer mouse and dual laser light sources for generating a laser speckle pattern. It detects the motion of a moving surface at a large distance from the surface, from 80 mm to 300 mm, by tracking the laser speckle pattern. The use of dual laser light sources makes the tracking robust for both large distances from the ground and different surface materials. Some fundamental experiments validated the performance of the device, which tracked surfaces of different materials with high accuracy under various height conditions. Finally, the device was mounted on our mobile robot, and simple experiments were conducted on a slippery sandy terrain to evaluate the usefulness of the device as a noncontact odometry system.**

I. Introduction

MOON/PLANETARY rovers and rescue robots are typically fitted with wide wheels or tracks so that they can traverse rough or sandy terrains such as the regolith on the moon's surface, debris fields, or rocky terrains. However, because of the slippage between mechanisms and loose terrains, it is almost impossible for such a mobile robot to use wheeled odometry to estimate its position. To provide an effective odometry system for robots with such slippage problems, some noncontact type odometry systems have been proposed. One approach is to use the optical sensor designed for a computer mouse. The characteristics of conventional optical sensors have been investigated for use in applications other than computer mice, such as mobile robots [1-2]. Some positioning methods have been proposed that use optical sensors to measure the translation and rotation displacements of the moving surface under a mobile robot [3-5]. Optical sensors can be used not only for mobile robots but also for measuring rotational motions such as those of a rotary encoder [6]. The dual use of the sensor contributes to an improvement in the robot posture accuracy [7-9]. Such positioning methods are independent of the locomotion mechanism, allowing an optical sensor to be applied to the position estimation of a Mecanum wheel robot [10]. This type of sensing device is so compact that it can also be applied not only to the motion estimation of a real car [11] but also to a small desktop robot [12]. A lens of a certain focal length with an optical sensor can be used to estimate the motion with a large height from the object surface [13]. However, in the above applications using an optical sensor with a certain optical lens for the sensor, the estimated movement varies with the distance between the sensor and the surface because of the field angle in the sensing device.

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In this study, we use an optical sensor as a position estimation device for a mobile robot on a slippery terrain for different distances between the sensor and the terrain surface. To make the system compact and applicable to measurements from large heights, the original lens system and pinhole cover part, designed for a desktop mouse, are not used in our sensing device. We have also designed the device to track different surfaces robustly by using dual laser sources. Moreover, the optical sensor that we chose detects motions with a comparatively higher speed than conventional optical sensors.

In this paper, we first present the laser speckle principle and our sensing device design in section II. Then, we report the performance of the device with dual laser sources in section III. Finally, we introduce some position estimation results for a mobile robot using the device to examine its performance.

II. Sensing Device

A. Laser speckles

Our noncontact position estimation device uses a methodology to track the laser speckle pattern (LSP). This is caused by the interference of coherent laser rays reflected from a rough surface with different heights that are much larger than the wavelength of the laser light. The LSP and its applications have been presented elsewhere in detail [14].

An LSP can be seen by a sensor either through a lens or without a lens. If enough space for a lens is available in a robot, a combination that includes a telecentric lens is appropriate for height-invariant measurement [15]. The movements of an LSP can be detected not only by the image sensor in a camera [16] but also by the optical sensor used for computer mice [17].

The motion of an LSP at a sensing plane depends on the distances of the sensor and light source to the surface on which its spot is located. If a collimated illumination of laser is adopted for the sensor, the displacement of the LSP is

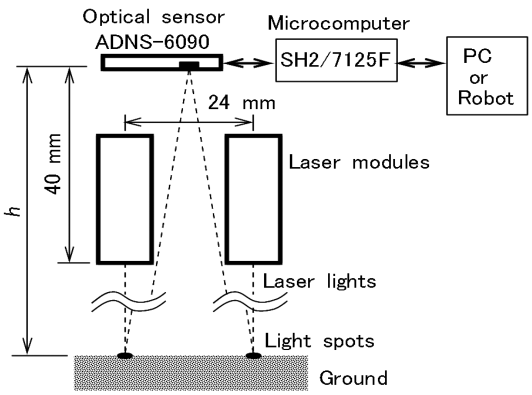


Fig. 1. Distances between the optical sensor, ground, and laser modules in sensing device.

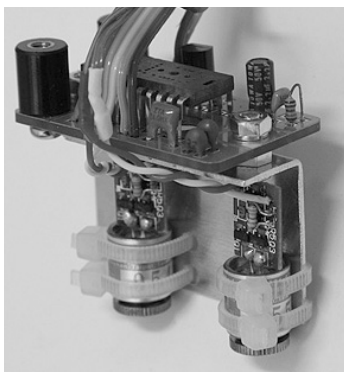


Fig. 2. Optical sensor and two laser modules.

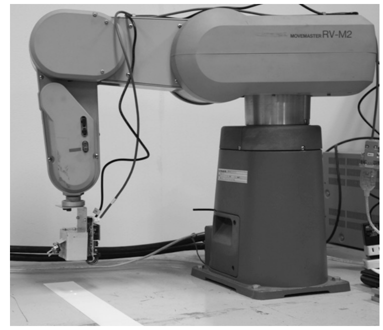


Fig. 3. Experiment environment. A robot arm moves the sensing device in a specified direction with accuracies of 0.1 mm in position and 0.1° in posture.

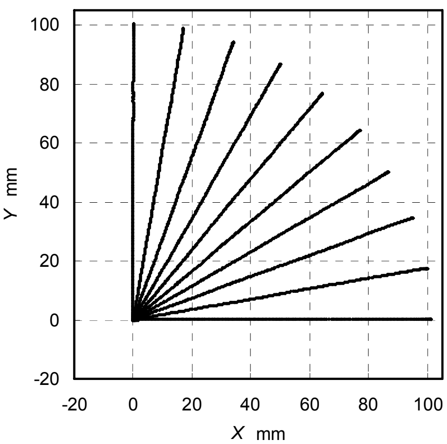


Fig. 4. Measurement result obtained by moving sensing device from origin in different directions.

theoretically independent of the distance [14]. A larger parallelism for the laser beam results in a higher invariability against distance changes. In addition, the average diameter of the LSP changes according to both the distance and diameter of the light spot [18]. It is difficult to precisely determine the parallelism of the laser beam and the diameter of the laser spot we use. Therefore, we intend to experimentally examine the sensor device while changing conditions such as the distance between the sensor and the surface in this paper.

B. Functioning scheme of sensing device

The schematic of the sensing device we have developed is shown in Figs. 1 and 2. We use an Avago ADNS-6090 [19] as an optical sensor and two laser modules emitting red beams at a wavelength of 650 nm. The laser module has a lens that allows it to emit an almost parallel beam by a laser diode. Visual observation shows that the diameter of the laser spot is 3.7 mm when the distance is from 70 mm to 500 mm. The sensor device has a maximum velocity of 65 ips (inches per second) and a resolution of 3000 cpi (counts per inch) with the normal lens system recommended by the manufacturer. The actual maximum velocity and resolution properties without the recommended lens are experimentally investigated in section III. The sensor device calculates the relative displacements in the *X*- and *Y*- directions using a 0.2-ms frame time. These displacements of delta *X* and delta *Y* are simply sent to a microcomputer SH2/7125F. A mobile robot reads the relative position displacement from the microcomputer to accumulate and estimate its position. The distance between the sensor and the ground is not sensed in our sensing device at all.

III. Fundamental Performance Tests for Device

Some tests were conducted to evaluate the fundamental performance of the sensing device used to estimate a robot's position. To evaluate the measurement accuracy of the device, its resolution was preliminarily determined by moving the device by a robot arm, *Mitsubishi RV-M2*, as shown in Fig. 3. The resolution was 288 cpi when the device was translated 200 mm in the *Y*-direction at a velocity of 50 mm/s and a height of 100 mm on a white paper with dual laser sources.

A. Translation in plane

The first test was the measurement of the translation displacement in a plane at a constant height. Fig. 4 shows the loci measured when the sensing device was moved 100 mm from the origin at a velocity of 50 mm/s to 10 different positions on a white paper by the robot arm. The average position error of the end points was 0.6% and the maximum position error was 1.5%. The device measured the planar displacement of the object surface with almost constant accuracy independent of the direction of motion.

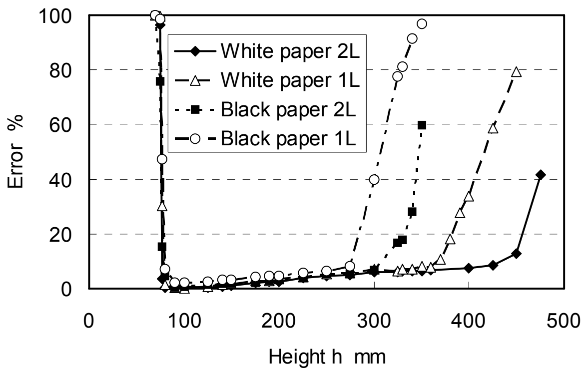
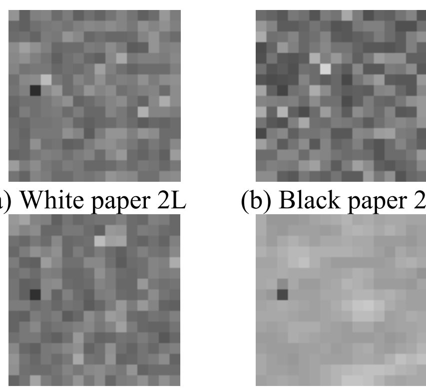


Fig. 5. Measurement errors for different distances between sensor and surface. White and black papers were used in the experiment. 2L and 1L indicate the number of laser sources used.



(a) White paper 2L (b) Black paper 2L

(c) White paper 1L (d) White paper 2L, 300 mm

Fig. 6. Image frames captured by the sensor. The distance between sensor and surface is 100 mm for (a)-(c), 300 mm for (d). 2L and 1L mean the number of laser source used. A dark pixel at left-middle in every frame is due to the defect of the sensor.

B. *Different heights*

The second test was a comparison measurement of the translation error with different heights and different laser source numbers. The sensor was translated 200 mm in the *Y*-direction at a velocity of 50 mm/s, at a specified height, *h*, above the surface. Two surface colors were used: white and black. The measurement precision at different heights is shown in Fig. 5. In this figure, 1L and 2L indicate the number of laser light sources. The error gradually increases according to the height, and suddenly escalates at a certain height. The sensor covered the widest height range on white paper with dual laser sources because this provided the strongest reflection of the light spots.

The capability of being used for a wide range of heights enables a robust positioning for mobile robots traversing loose or slippery terrains, which cause their wheels to sink. Fig. 5 shows that the measurement error remained within 5% at heights between 100 mm and 200 mm.

The contribution of the dual laser sources is also seen from a comparison of the surface quality (SQUAL) values. The SQUAL value represents the number of valid features visible to the sensor. A higher SQUAL contributes the tracking robustness to the sensor device. The SQUAL values at a height of 300 mm and the conditions of white paper with 2L, white paper with 1L, black paper with 2L, and black paper with 1L were 76, 53, 34, and 30, respectively. The SQUAL with dual laser sources was larger than that with a single laser source. Low SQUAL values below 30 caused large displacement errors.

Fig. 6 shows the image frames captured by the sensor. The images in Figs. 6(a)–(c), taken at a height of 100 mm, have visible clear features and a higher surface quality than the image in Fig. 6(d), which was taken at a height of 300 mm. The feature patterns are almost the same in the frame images taken under different conditions for the number of laser sources. The larger height made the features obscure, which was caused by the weaker luminance of the laser.

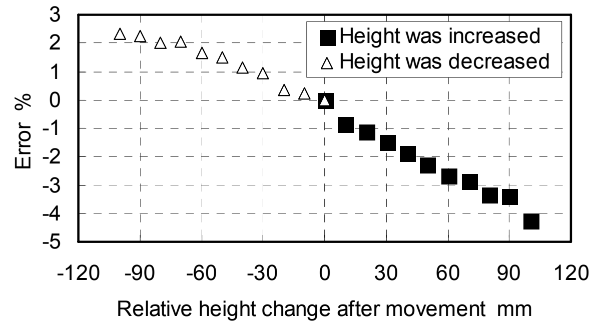


Fig. 7. Measurement error for different heights during 200-mm translation in Y-direction.

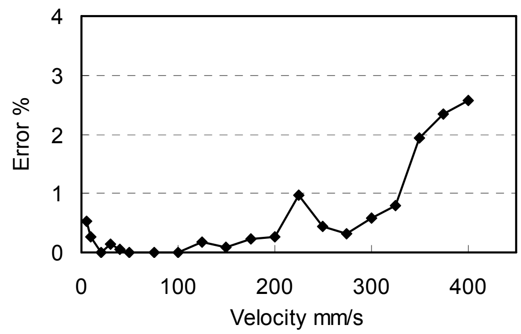


Fig. 8. Absolute error at different velocities.

C. *Height changes during translation*

The third test was for the measurement error of translation in a case where the sensing height was gradually changed. The wheels of a mobile robot typically sink into loose soil during movement. This would cause gradual changes in the height of a sensor mounted on the robot. Therefore, the measurement results from the device need to be stable when the distance between the sensor and the ground changes. Fig. 7 shows the result when the height of the sensor position gradually changed during a 200-mm displacement in the *Y*-direction. It shows that the amount of absolute error rose slightly from both increases and decreases in the height within 100 mm. However, the amount of this error was less

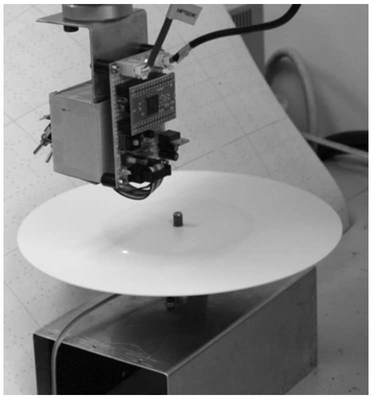


Fig. 9. Turntable driven by motor for measuring maximum velocity of tracking.

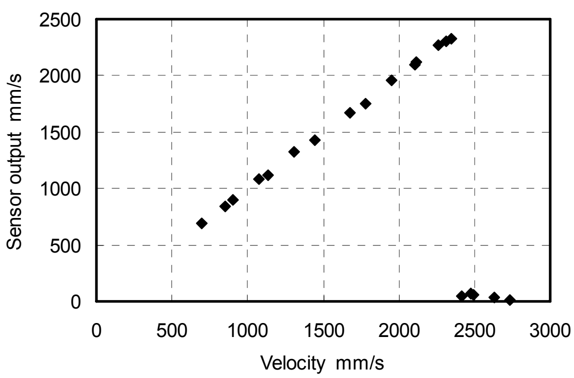


Fig. 10. Result of sensor output for surface moving at very high speed with sensor placed on plastic plate rotated by turntable.

than 5% under these conditions.

D. Different velocities

The fourth test was for the measurement error of translation in the case of fast speed. Fig. 8 shows the absolute error results when the robot arm moved the sensing device 200 mm at a specified velocity, at a height of 100 mm over a white paper. The measurement error was introduced under the conditions of high velocity, acceleration, and deceleration. The measurement accuracy reduced for high-velocity motions. However, the maximum error was less than 3% when the velocity was 400 mm/s.

E. Maximum velocity supported

The fifth test was the measurement of the maximum velocity supported by the device. The sensor was fixed on a steady robot arm, and the surface of a plastic plate was turned by an actuated turntable, as shown in Fig. 9. The rotational speed was calculated with the pulse period of a photointerrupter under the turntable. The velocity of the surface could be estimated using both the rotation rate and the radius of the sensor position. As shown in Fig. 10, the maximum velocity that can be measured by the sensing device was 2300 mm/s (approximately 8.3 km/h), which is sufficient for conventional outdoor mobile robots, including

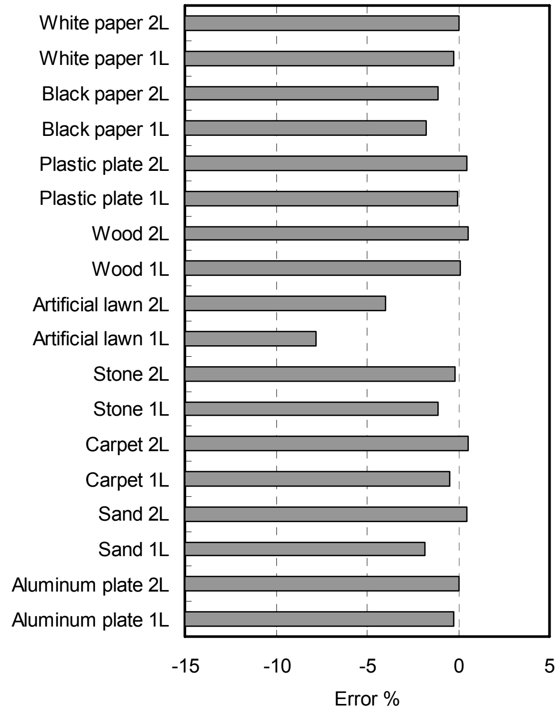


Fig. 11. Measurement error of proposed device for 200-mm displacement on different surface materials. 2L and 1L indicate the number of laser sources used.

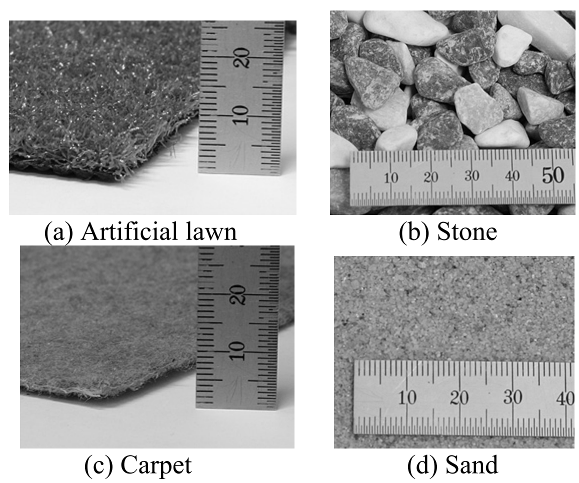


Fig. 12. Some examples of various surface materials used in experiment.

our robot.

F. Different surface materials

The sixth test was for the measurement capability in the case of different surface materials. Fig. 11 shows the error in the *Y*-direction estimated by the device after it traveled 200 mm in the *Y*-direction at a velocity of 50 mm/s and a height of 100 mm. The labels 2L and 1L in the figure indicate the number of laser sources turned on for the device. The surfaces for some materials are shown in Fig. 12. The dual laser sources made the tracking more robust against different surface materials compared to the single source, particularly

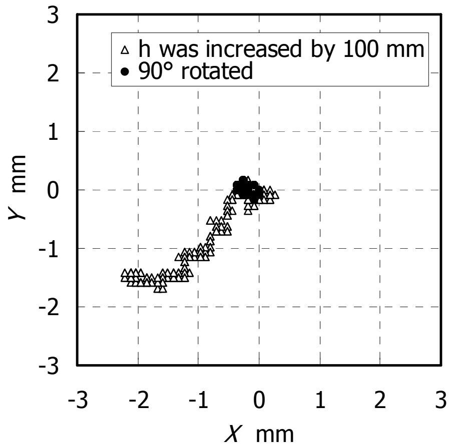


Fig. 13. Measurement results for sensor moved 100 mm in height direction and rotated 90° along Z-axis.

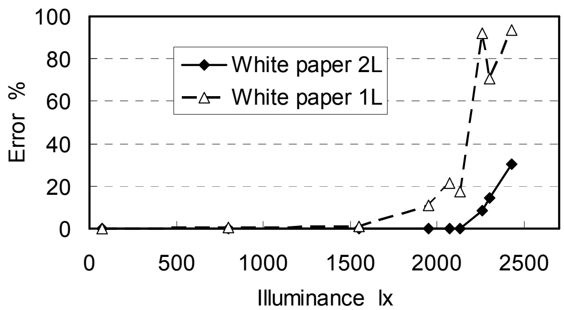


Fig. 14. Measurement errors for different surface illuminances. 2L and 1L indicate the number of laser sources used.

in the results for artificial lawn. Artificial lawn greatly reduced the luminance of the laser spot, so that the sensor struggled with tracking. For stone, the measurement error was less than 1.1% even though two laser sources were projecting two spots with different heights. The device could estimate motions even on patternless surfaces such as paper, plastic plates, and aluminum plates however the device could not estimate any movements on mirror. The absolute error of the device with dual laser sources was less than 4% over different surfaces shown in Fig. 11.

G. *Movements unsupported by the device*

The seventh test was used to determine the measurement behavior in a case where the sensor was moved in unsupported ascent and rotation directions. Fig. 13 shows the tracks of the position measured when the robot arm moved the sensing device with two types of motions. In the first, only the height was changed by 100 mm, while in the other, the device was rotated by 90° with the position fixed. The rotation of the sensor was produced by a rotation of the wrist joint of the robot arm. The last position was –2.1 mm in the X, –1.4 mm in the Y when it was moved in the height direction, while –0.3 mm in the X, –0.1 mm in the Y when it was rotated. These experimental results indicate that the device counts few displacements for movements that they were not designed to support.

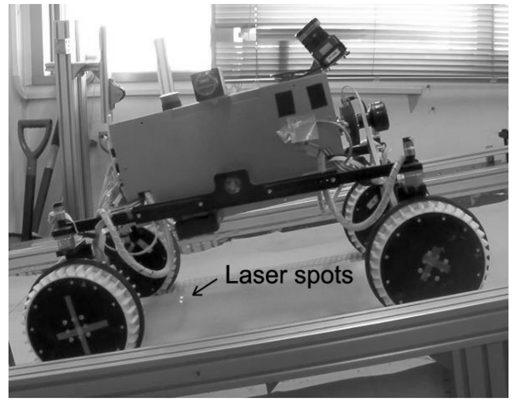


Fig. 15. Rover vehicle with proposed sensing device climbing 10° inclined sandy terrain.

Table 1. Absolute error in displacement estimated by conventional odometer and proposed sensing device on sandy terrain inclined at 10°.

Trial	Actual [mm]	Absolute error [%]	
		Mechanical odometer	Proposed sensing device
1	1030	37.9	3.9
2	950	40.0	1.1
3	970	37.1	0.0
Average		38.3	1.7

Table 2. Absolute error in displacement estimated by conventional odometer and proposed sensing device on sandy terrain inclined at 12°.

Trial	Actual [mm]	Absolute error [%]	
		Mechanical odometer	Proposed sensing device
1	970	175.3	1.0
2	910	193.4	2.2
3	900	163.3	3.3
Average		177.3	2.2

H. *Different illuminances*

The eighth test was for the inspection of the maximum surface illuminance which the sensing device endures. The device was translated 200 mm in the Y-direction at a velocity of 50 mm/s, at a height of 100 mm on a white paper. The absolute error at different illuminances is shown in Fig. 14. In this figure, 1L and 2L indicate the number of laser light sources. The error exceeds 10% at an illuminance of 1950 lx for single laser source, while 2300 lx for dual laser sources. Some cover will be required for the device under strong illuminance conditions such as outdoor environment.

IV. Measuring on Slippery Terrain

From the above performance tests, we concluded that the device is reasonably effective at estimating a robot's position. Therefore, we mounted it on our mobile robot and evaluated the performance of the sensing device in loose soil.

The sensing device was installed on the body of a rover vehicle that was developed by our research group. This vehicle is 810 mm in length, 510 mm in width, 430 mm in height, and has a weight of approximately 24 kg. The diameter of the wheels is 100 mm. The optical sensor was attached 150 mm above the ground surface.

We conducted traversing experiments with the rover on an inclined sandy slope, as shown in Fig. 15. The rotational velocity of the four driving wheels was set at 7.5 rpm, giving the rover a speed of 40 mm/s without slippage. Two laser spots can be seen near the rear-left wheel in this figure. The rover gradually sank up to 30 mm into the loose terrain with large slippage while traversing this terrain, thus degrading the reliability of wheel odometers for the rover.

Table 1 shows the actual displacement as measured by a scale and the estimation errors of a wheel odometer and the proposed sensing device as the rover climbed a sandy slope with an inclination of 10°. The average measurement error of the wheel odometer was 38.3%, while that of the sensing device was 1.7%. Table 2 shows the measurement results when the slope inclination was 12°. The rear wheels of the rover slipped much more than in the case of the 10° slope. The average measurement error of the wheel odometer was 177.3%, while that of the sensing device was 2.2%, which was considerably much better than the wheel odometer.

These results prove that the sensing device we have developed provides more robust odometry against wheel slippage and sinkage in a mobile robot than the conventional wheel odometer.

V. Conclusion

In this paper, we have presented a sensing device that uses an optical sensor, designed for a computer mouse, and dual laser light sources to estimate the position of a robot traversing slippery terrains.

First, we explained laser speckles, which are used for noncontact sensing at a large distance from the ground surface. Second, we presented our developed sensing device and investigated its performance robustness against different surfaces and height changes by moving the device using a robot arm. The results of this experiment showed that the measurement error remained within 5% at heights between 100 mm and 200 mm. Another experiment showed that the maximum velocity of the sensing device was 2300 mm/s (approximately 8.3 km/h), which is sufficient for a conventional mobile robot. Moreover, the absolute error of the device with dual laser sources was less than 4% for different surfaces. Third, we introduced our simple results to show that our mobile robot can traverse even loose soil. The precision of the position estimated by the proposed device was considerably higher than that of the wheel odometry on the slippery terrain. The average measurement error of the sensing device was 2.2% in the experiment with our rover vehicle.

This sensing device is so compact, inexpensive, and simple that it can be easily used in mobile robots for estimating their position. Since, in principle, the device does not estimate the rotational displacement caused by a posture change in a mobile robot, other sensors are required to estimate the rotational displacement, for example gyroscopes. Using many such sensing devices, including laser sources, may improve the estimation accuracy of a mobile robot's position or enable three-dimensional odometry.

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