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Principle and Robotic Applications of Conical Scanning Method

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Abstract. We have proposed a surrounding environmental recognition method using conical scanning distance measurement for mobile robots. The conical scanning method has a high robustness against ambient light noise and its calculation cost is low. This report describes the principle of this method and the two implementations. The first application is the quadrupedal wheeled robot. The robot can recognize a stair in sight, approach to it and climb. A second application is the indoor-outdoor wheeled mobile robot. The robot can recognize its position and obstacles on floor from information of a laser range finder and a 3D ToF camera. The validity of this method was confirmed by these robotic applications.

1. Introduction

Various methods using stereo cameras, 2D-LiDAR or 3D-LiDAR have been proposed to recognize the environment around the running area of the robot. A Kunihiro's method using stereo cameras can obtain a wide range of information at once[1], but it is difficult to accurately recognize the environment depending on the time zone and location since ambient light and the texture around the running area become noise. According to Watanabe's method using 2D LiDAR, the area ahead of the robot can be detected by sensors installed at a fixed angle with respect to the road surface[2], but there are many erroneous detections when the posture of the robot is changed due to a rough uneven road surface. Various methods have been proposed for 3D-LiDAR-based methods. Fujii suggests a method using RANSAC[3], but because of its high calculation cost, it has low real-time performance and it is not suitable for environment recognition of autonomous mobile robot. Eguchi has proposed a method of extracting a step by comparing the horizontal distance when sensing a road surface with the distance measured beforehand[4], but this is also reported that erroneous detection occurs when the robot changes its posture.

We propose a conical scanning method. In this method, the surface of the measured target is scanned conically using a distance sensor, and the shape of the measured surface is classified according to the length (measuring distance) of the generating line of the cone and the characteristic amount of the scanning curve drawn by the scanning rotation angle[5][6][7][8]. This paper describes the principle of conical scanning method and its applications as four legged wheeled robot that moves up and down stairs, and indoor / outdoor wheeled mobile robot.

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2. Principle of conical scanning

When the distances $L(\alpha)$ to the target surface are measured while varying the scan angle α from 0 ° to 360 ° to the target surface (Figure 1), a graph as shown in Figure 2 is obtained (Hereinafter referred to as scan curve). Features (maxima, minimal value points, discontinuous points) appear in the scan curve as shown in Figure 3 depending on the shape of the region to be measured (plane, concave coupling, convex coupling, discontinuous surface). In other words, it is possible to recognize the shape of the measurement target surface from the characteristics of the scan curve. The parameters uniquely specifying the plane are three, distance dz, inclination angle γ, and inclination direction δ (Figure 4).

From Figure1 and Figure5, the feature amount dz, γ, δ of the plane by the following equation using the parameter $L_{max} \cdot L_{min} \cdot \alpha\ (L_{max})$ of the scanning curve can be calculated.

$$dz = L_{max}\cos\beta - L_{max}\sin\beta\tan\gamma \\ = L_{min}\cos\beta + L_{min}\sin\beta\tan\gamma \qquad (1)$$

$$\gamma = \alpha\tan\left\{\frac{(L_{max} - L_{min})\cos\beta}{(L_{max} + L_{min})\sin\beta}\right\} \qquad (2)$$

$$\delta = \alpha(L_{max}) \qquad (3)$$

β is the half apex angle of the cone and is a constant.

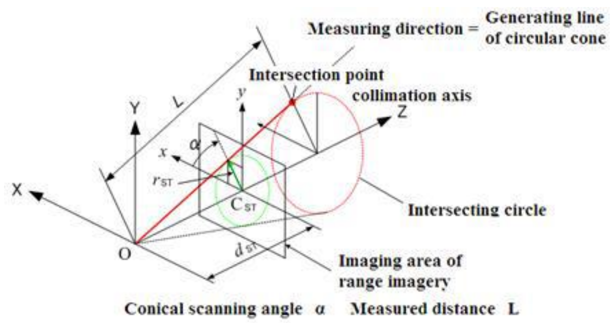


Figure 1. Principle of conical scanning

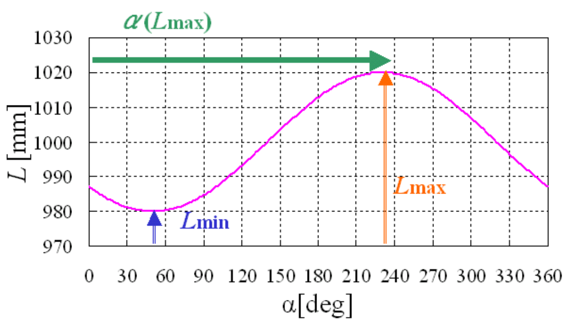
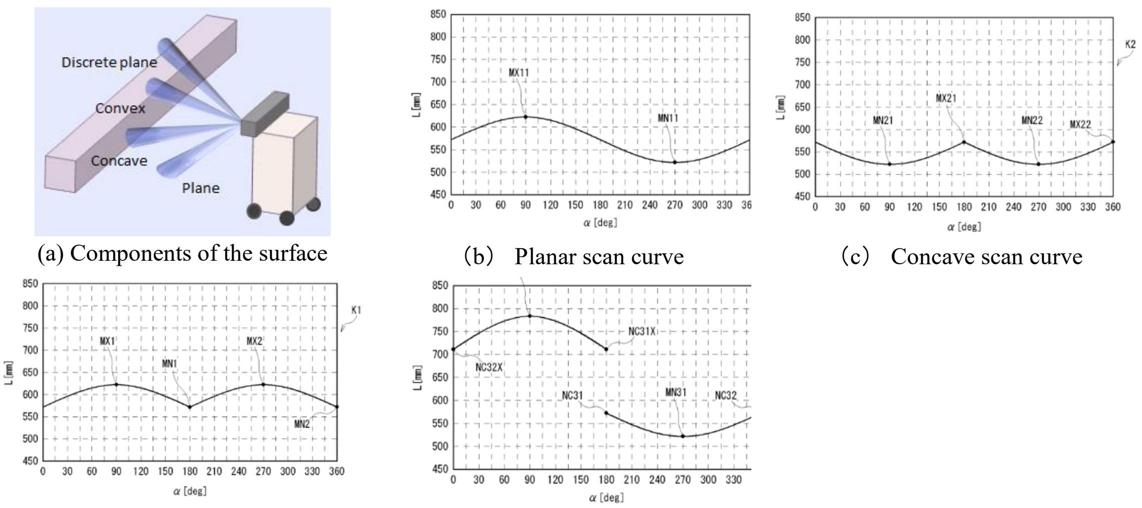


Figure 2. Example of scan curve



(a) Components of the surface (b) Planar scan curve (c) Concave scan curve

(d) Convex scan curve (e) Discrete plane scan curve

Figure 3. Scan curve in various surface shapes

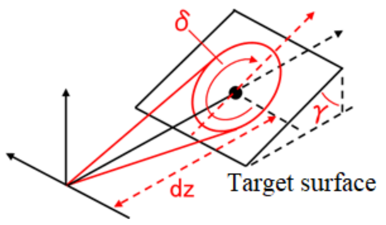


Figure 4. Parameter of plane

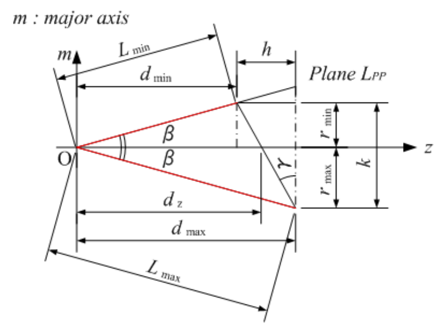


Figure 5. Parameter calculation drawing

In the following, distance image sensors are used to simultaneously measure multiple points at high speed. Conical scanning for multiple regions correspond to extracting distance on multiple circular segments within the range of the distance image sensor.

As shown in Figure 6, the center point of arbitrary *i* th and *j* th circles on the range image sensor is expressed by the following equation.

$$(x_c, y_c) = \left(\frac{w_c}{2} + \left(i - \frac{m}{2} \right) \cdot \Delta x, \frac{h_c}{2} + \left(j - \frac{n}{2} \right) \cdot \Delta y \right) \tag{4}$$

Here,

m, n: number of the circular segment in the x and y directions

Δx, Δy: spacing between the x direction and the y direction of a circular segment

w_c, h_c: number of pixels in the horizontal and vertical directions of the sensor

Based on these points, each extraction point corresponding to conical scan angle α is calculated. A scanning curve is obtained by acquiring the distance *L* of the pixel corresponding to the extraction point. For the intermediate position of the pixels, data smoothing interpolation processing by the bilinear method are performed. Parameter identification is performed for each segment, and the horizontal plane is extracted by residual evaluation and inclination direction evaluation.

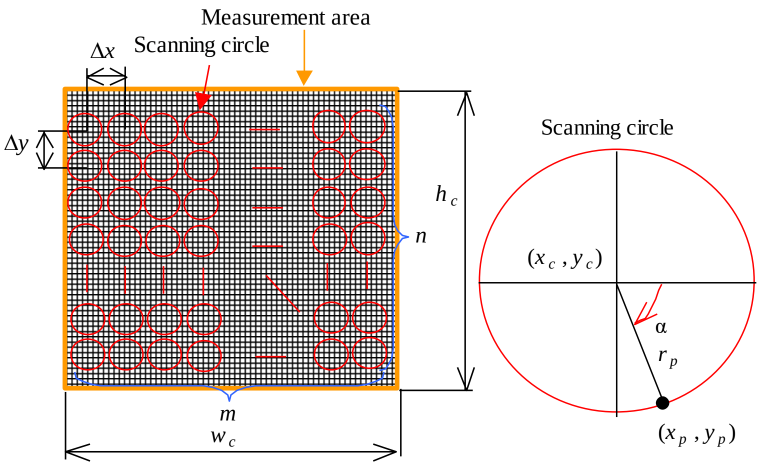


Figure 6. Image of Multiple conical scanning

3. Application for Legged wheeled robot

3.1 Overview of the legged wheeled robot.

In this section, we describe an example of applying a multiple conical scanning to staircase recognition of a four legged wheeled robot.

The appearance of the robot is shown in Figure 7. The robot has 16 DOF, with yaw, pitch axis of a hip joint, and pitch axis of a knee and a driving wheel at the toe for each leg. It supports the visually impaired person ascending and descending stairs. In the flatland, it runs with four wheel steering and four wheel driving by using driving wheels and hip joint yaw axes.

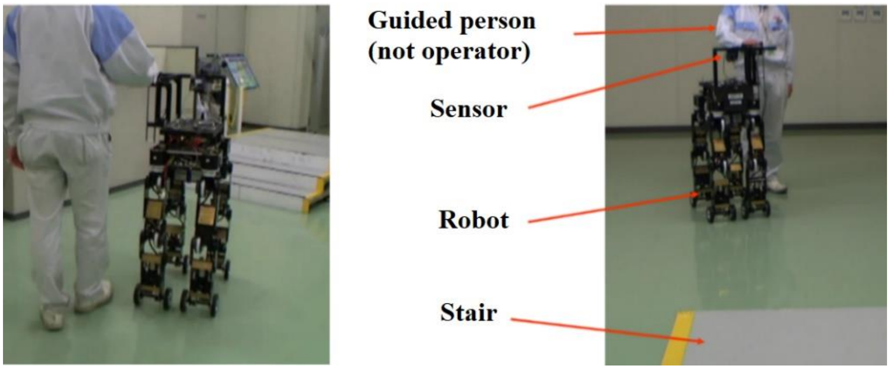


Figure 7. Appearance of leg-wheel type robot

3.2 Recognition object and recognition principle

As shown in Figure 8, the staircase information to be recognized is the stair position (S_X, S_Y), direction γ, and stair width S_W.

The staircase width is treated as the effective width within the measurement range, and the stair position is the center point of the effective width.

Figure9 shows the procedure of staircase detection. Labeling processing is executed on the image obtained by plotting the center coordinates (x_c, y_c) of the segment determined as the horizontal plane. For each extraction region, the average value Z_{ave} of the Z coordinate (height) and the variation (evaluated by the difference between the maximum value Z_{max} and the minimum value Z_{min} within the extraction region) is calculated. An extraction region in which Z_{ave} and variations are within a predetermined range is adopted as a step (first step of the stair). Line fitting is performed on the corresponding extraction region by least squares method, points on the right and left ends (x_{left}, y_{left}), (x_{left}, y_{left}) on the approximate straight line are calculated, and converted to the left and right end points (X_{left}, Y_{left}, Z_{left}),(X_{right}, Y_{right}, Z_{right}) of the robot coordinate system.

The stair position, direction, and stair width are calculated by the following equation.

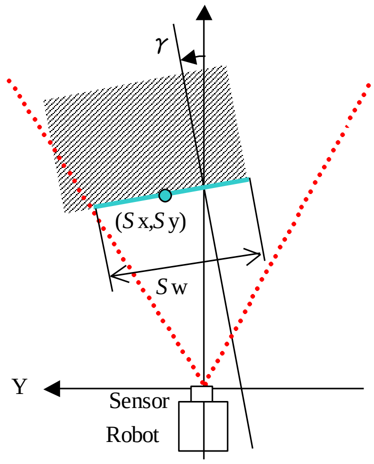


Figure 8. Information of detected stair

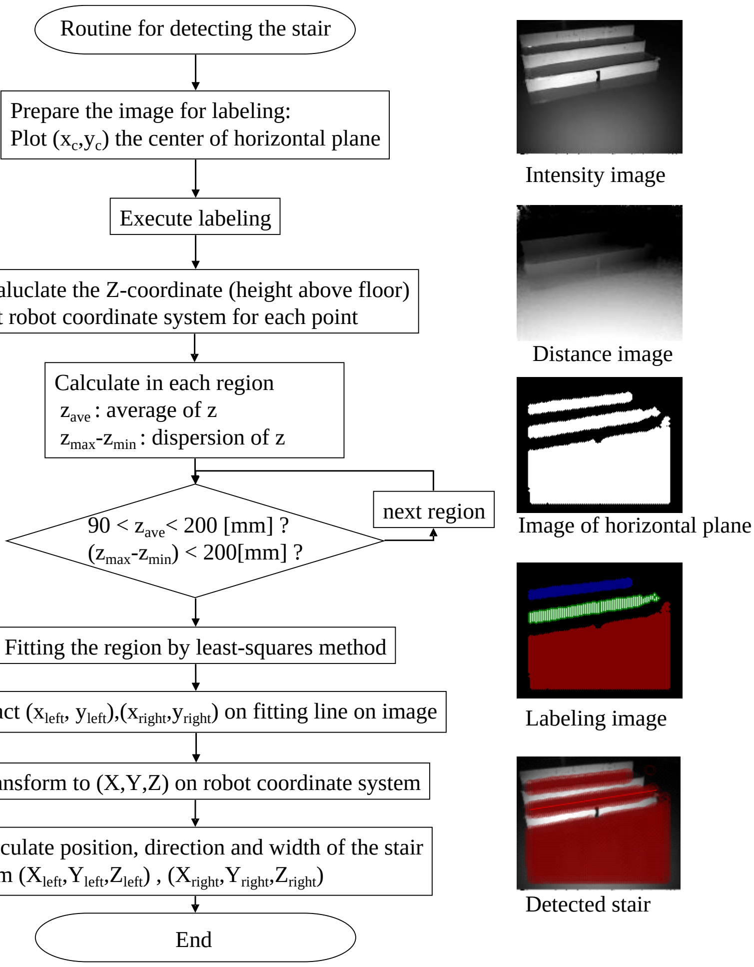


Figure 9. Flowchart to detect the stair

$$(S_X, S_Y) = \left(\frac{X_{left} + X_{right}}{2}, \frac{Y_{left} + Y_{right}}{2} \right) \tag{5}$$

$$\gamma = \tan^{-1}\left(\frac{X_{right} - X_{left}}{Y_{left} - Y_{right}} \right) \tag{6}$$

$$S_W = \sqrt{(Y_{left} - Y_{right})^2 + (X_{right} - X_{left})^2} \tag{7}$$

3.3 Recognition experiment

This algorithm is verified with TOF type distance image sensor Swiss Ranger SR-3000 (measuring range : 300 to 7500 mm, number of pixels : 176 × 144, FOV : 47.5 × 39.6 deg, frame rate : maximum 50 fps)

Experiments were carried out in both cases when facing the stairs (Figure10) and when given a predetermined angle (Figure11). Common parameters are shown in Table 1. The measurement target is a staircase with 3 steps, tread depth of 240 mm, and rise height of 120 mm.

3.3.1 Experiment when facing the stairs Table 2 shows the conditions under which recognition experiments were carried out with facing the front of the stairs. Figure12 shows recognition results of stair direction γ. Average value of 50 times and error terms of 2σ were plotted. Since it faces the front of the staircase, the ideal value of the angle is 0, but when it is 1000 mm ahead, it will be distorted as it deviates in the *Y* axis direction. It can be thought that the whole staircase can only be seen near the

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center because it is too close to the staircase. At 2000 mm ahead where the entire staircase is visible, although the dispersion depending on distance measurement accuracy is large, it is within ± 5 °.

Figure13 shows the recognition results of stair position (S_X, S_Y). The part where the whole staircase is visible are surrounded by a red dashed line.

When l_X = 1000 mm, since the whole staircase can not be seen, S_Y is narrower than the actual value, but S_X can be detected over the whole area, 2 σ = 9 mm at 1000 mm and 2 σ = about 60 mm even at 2000 mm.

3.3.2 Experiment when given a predetermined angle Table 3 shows experimental conditions when a recognition experiment is performed at a predetermined angle toward the stairs. Figure14 shows the relationship between the set angle (ideal value) of the staircase direction γ and the detection angle (experimental value). Average value of 50 times and an error term of 2σ were plotted. It was able to recognize with an accuracy of about ± 1 deg at 1000 mm ahead. As the distance gets farther, the variation becomes larger under the influence of the accuracy of distance measurement, but it is about ± 5 deg even at 2000 mm ahead.

Based on the distance and angle to the staircase calculated by this algorithm, the legged wheeled robot generated the approach trajectory, approached the stairs, and could move up and down.

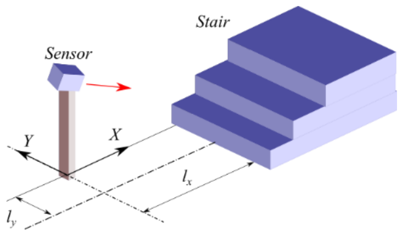


Figure 10. Experimental environment to measure the stair

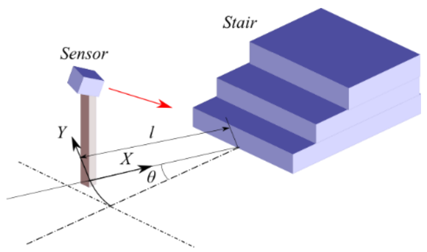


Figure 11. Experimental environment to measure the stair

Table 1. Parameter for multiple conical scanning

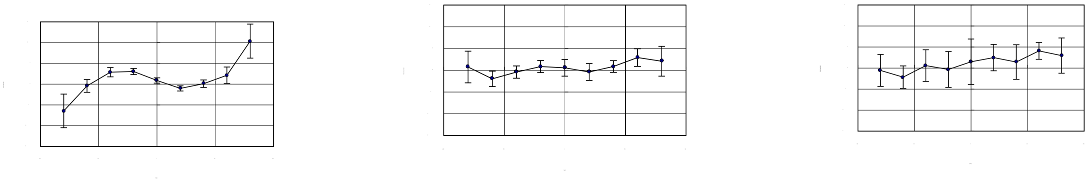
Radius of conical scan r_p	5 (pixel) (β=1.3625(deg))
Interval of conical scanning angle $\Delta\alpha$	5.625 (deg) (divided into 64)
Number of segment $m \times n$	74 × 121
X-axis Scanning interval Δx	2 (pixel)
Y-axis Scanning interval Δy	1 (pixel)
Descending vertical angle of sensor	30 (deg]
Height of the sensor	750 (mm)

Table 2. Experimental condition

X-coordinate of stair position l_x	1000, 1500, 2000 (mm)
Y-coordinate of stair position l_y	-800~+800(mm) (per 200)
Direction of stair γ	0 (deg)

Table 3. Experimental condition

Distance stair l	1000, 1500, 2000 (mm)
Direction of stair γ	-20 ~ +20 (deg) (per 5)



(a) 1000mm (b) 1500mm (c) 2000mm

Figure 12. Experimental results of γ

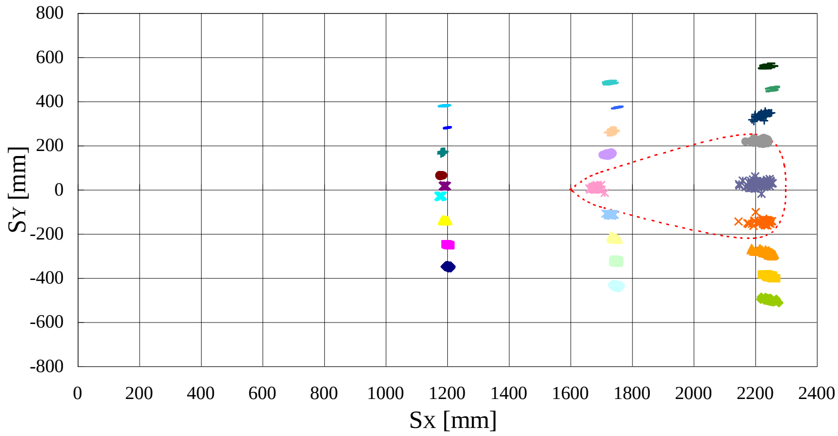
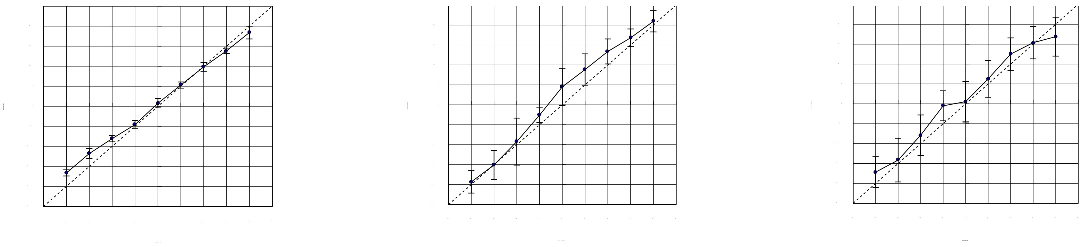


Figure 13. Experimental results of (S_X,S_Y)



(a) 1000mm (b) 1500mm (c) 2000mm

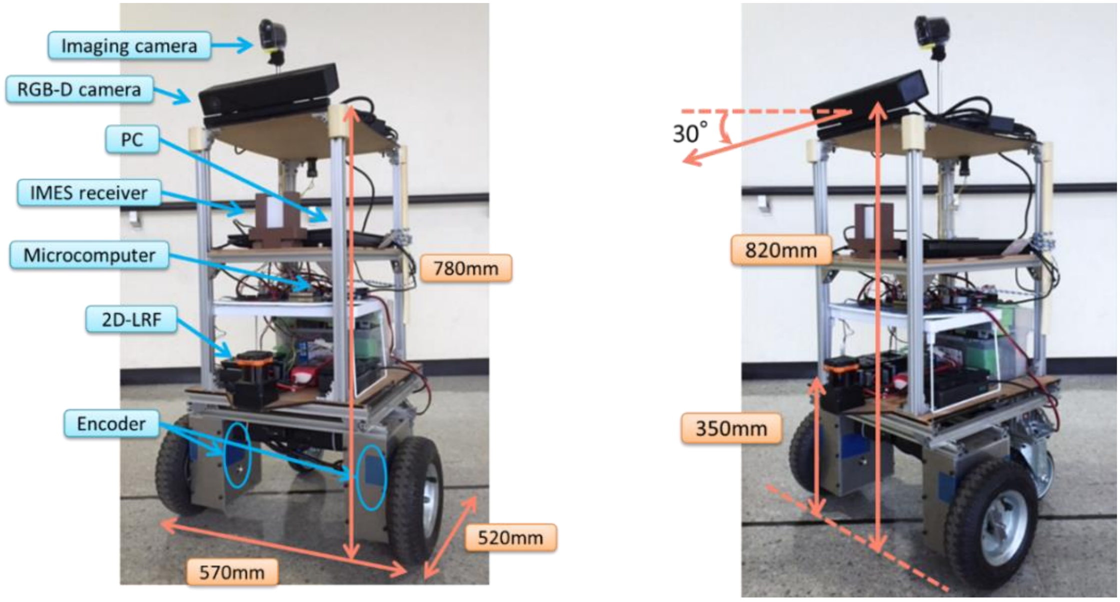
Figure 14. Experimental results of γ

4. Application for indoor and outdoor mobile wheeled robot

4.1. Overview of the mobile robot

In this section, we describe an example of applying a conical scanning to indoor and outdoor autonomous mobile robot "KANACO (Kanamori Autonomous Navigation And COmmunication robot)" (Figure 15). This robot is an independent two-wheel drive type robot. Two air tires with a wheel diameter of 210 mm are attached to the front wheels and two casters with a wheel diameter of 125 mm are attached to the rear wheels in order to overcome small steps in the running area of the robot, such as the groove of the automatic door and the boundary between the asphalt and the side groove lid. The hardware consists of a PC, left / right motor unit, motor driver, control circuit, various sensors.

The sensor using for conical scan is Kinect v2 (color image resolution : 1920 × 1080, color frame rate : 30 fps, depth image : 512 × 424, Depth frame rate : 30 fps, Depth sensing method : TOF (Time Of Flight), Depth range : 500 mm to 8000 mm, a horizontal viewing angle of 70 degrees, and a vertical viewing angle of 60 degrees).



(a) Appearance and dimension (b) Height and angle of sensor

Figure 15. Overview of the robot

4.2. Extension and verification of conical scan

When the conical scanning method was used outdoors, a lot of noise was included in the measured scanning curve, and the correct shape could not be classified and the feature amount could not be calculated in some cases. Therefore, we developed a scan curve fitting method applying weighted M-estimation[9] in order to realize robust environmental recognition. Furthermore, in order to process in real time, a scan curve parallel processing algorithm using GPU (NVIDIA Geforce GT 740 M) was implemented.

A flowchart of the implemented algorithm is shown in Figure16. First, using the depth information acquired from the distance image sensor, scanning curve of each scanning circle are acquired and transmitted to the GPU. Each thread of the GPU obtains the scan curve of the designated scan circle and then performs M-estimation of the quartic equation. After M-estimation, the number of extreme values is judged. If the number of extreme values is 3, it is determined to be a region other than the plane, that is, a running dangerous region. If the number of extreme values is 2, it is determined to be a flat area, and it is judged whether it is a travel safety area or a danger area according to the inclination angle and inclination direction of the measurement surface. Thereafter, parameters of the target surface obtained by each thread are transmitted to the CPU. By repeating this series of processing, the robot consecutively recognizes the surrounding environment.

Table 4 shows the results of the processing speed executed under the four conditions. The average of 100 frames was taken as the average processing speed. Under all conditions, the parallel processing by the GPU realized about 20 to 30 times faster than sequential processing by the CPU. These are sufficient processing speeds exceeding 30 fps and real time processing can be realized.

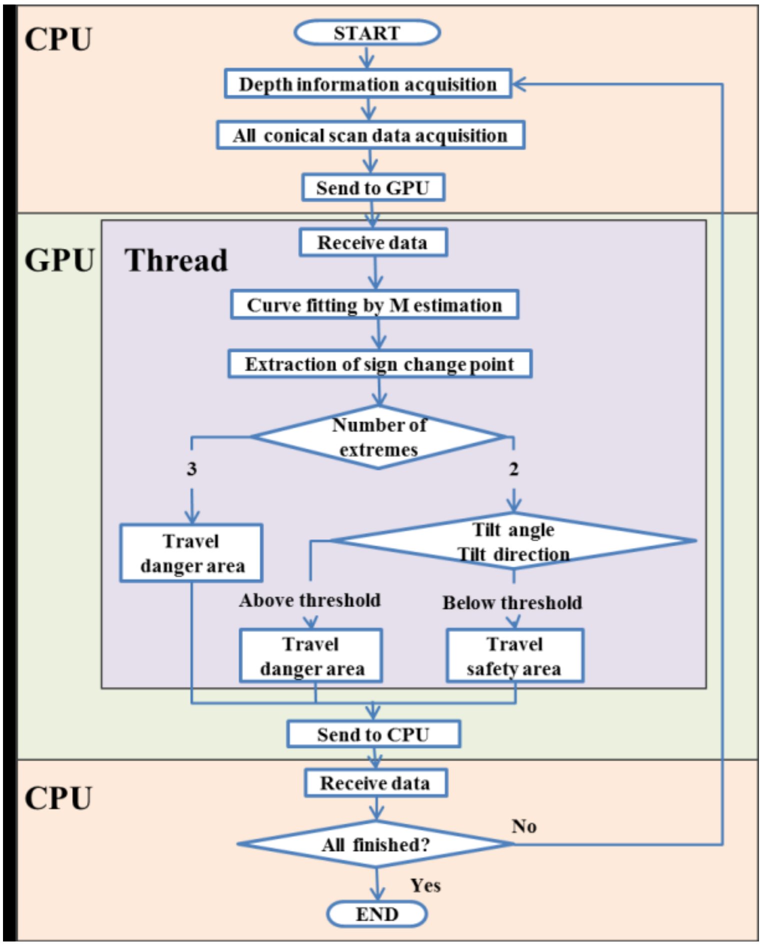


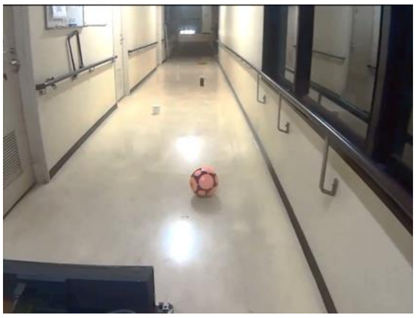
Figure 16. Flow chart of environment recognition algorithm

Table 4. Example of processing speed result

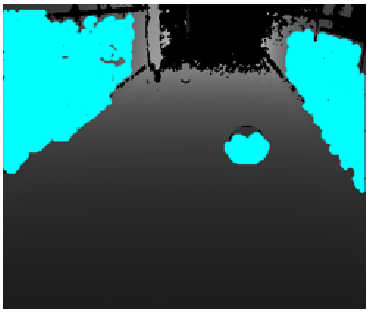
Radius of scan circle (pixel)	Average processing speed CPU only (msec/frame)	Average processing speed with GPU (msec/frame)
5 (3933 scan circle)	899.78	27.42
7 (2009 scan circle)	463.35	15.62
9 (1147 scan circle)	265.03	13.95
11 (775 scan circle)	170.79	7.43

4.3 Indoor and outdoor running experiments

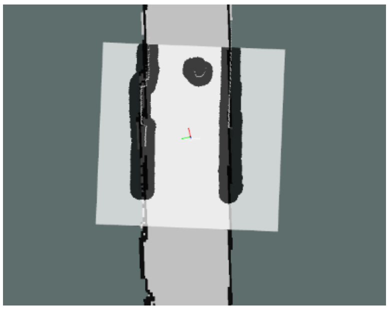
Figure17 shows an example of obstacle detection indoors. In the situation (a) where a soccer ball is placed in the corridor, the running danger area is indicated by light blue in (b) according to the surrounding environment recognition result. (c) is an overlay of the traveling dangerous area on the planar map created by SLAM from the measurement data of the 2D LRF, and the dangerous area is treated as an obstacle.



(a) Robot viewpoint image



（b） Surrounding environment recognized image

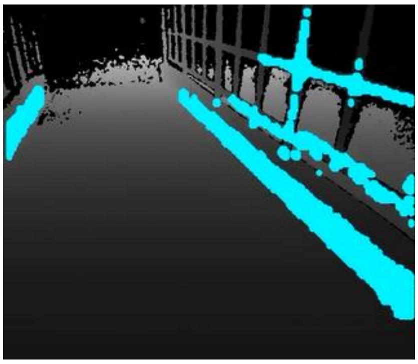


（c） Local map

Figure 17. Soccer ball detection during indoor driving

An outdoor running experiment was continued. Figure18 shows a state of running on a wheelchair slope. The slope was a surface with unevenness and the posture of the robot was easy to change. Also, because there are steps and fences on both sides, the road width was very narrow. The surrounding environment recognized image shows that the robot recognized steps on both sides. In addition, it was possible to stably determine whether the robot is in safe traveling area or dangerous area even when the posture of the robot changes. Figure 19 is a scene to avoid a bicycle. The spokes of the wheels with high metallic luster could not be recognized because the depth data did not return, but since tires with low gloss were able to be extracted stably, avoidance action were able to be taken safely. Figure20 is a state of running in a narrow passage surrounded by a short metal pole and a curb. There were a plurality of places where the point cloud could not be acquired due to the high metallic luster, but by performing scan curve fitting by M-estimation, it was possible to determine the travel dangerous area robustly against noise. By using our algorithm which is also robust to outdoor peculiar noise, the robot was able to autonomously travel safely about 350 m to the goal point by following the trajectory as shown in Figure 21.

(a) RGB image



(b) Recognized image

Figure18. Traveling on a slope

(a) RGB image (b) Recognized image

Figure 19. Bicycle detection

(a) RGB image (b) Recognized image

Figure 20. Driving a narrow passage

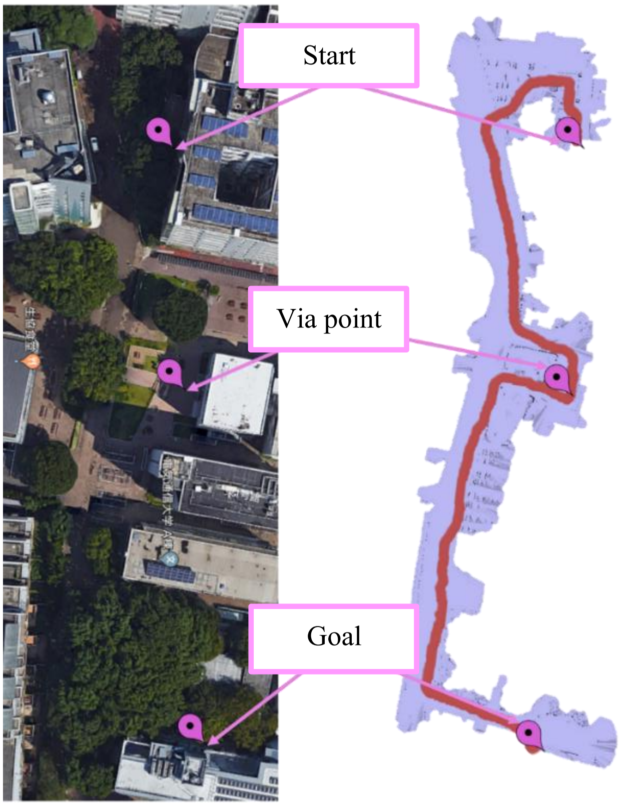


Figure 21. Example of outdoor driving test result

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5. Conclusion

We discussed the basic principle of the conical scanning method for detecting the distance to the plane and the attitude of the plane and the algorithm for recognizing the surrounding environment by multiple conical scanning processes. This algorithm was applied to a quadruped wheel type robot, the robot recognized the stairs and approached, realized the ascent and descent operation. In addition, when applied to indoor and outdoor wheeled robots, the robust against ambient light noise by M-estimation and real-time peripheral environment recognition by GPU processing was implemented, the navigation to the destination was realized and the utility of this method was shown.

Acknowledgements

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