

Plane Segment Finder : Algorithm, Implementation and Applications

Kei Okada Satoshi Kagami Masayuki Inaba Hirochika Inoue
Dept. of Mechano-Informatics, Univ. of Tokyo.
7-3-1, Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan.
e-mail: k-okada@jsk.t.u-tokyo.ac.jp

Abstract

This paper describes the development of a Plane Segment Finder, which is able to detect three-dimensional planar surfaces from input images in real-time. We propose an algorithm for detecting plane segments, that includes 1) Plane segment candidate extraction using 3D Hough Transformation from depth map information, 2) Fitting the plane segment candidates to the depth map in order to detect the partial plane segment, since the extracted plane segment candidates are general planes, with no boundary. To achieve real-time plane segment finding system, we apply 1) Recursive Correlation method for depth map generation, 2) Randomized Hough Transformation method for plane segment extraction. Finally, experimental results using an implementation of our system along with a humanoid robot are shown.

1 Introduction

The three dimensional recognition of environments is important for a robot that behaves in a real world. Recently many remarkable real-time depth map generation systems are developed and some of them are sold commercially [1-4].

Although the development of these real-time depth map generation systems are a remarkable achievement toward understanding real environments, there are few robots which utilize depth map information. Moreover, those robots only "recognize" obstacles and avoid them [5,6].

If we want to expand the behavior of a robot, an efficient method to extract higher level information from depth map information is required. In this paper, we propose the Plane Segment Finder (PSF), which detects planar surfaces from depth map information in real-time.

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tecting plane segments, that includes 1) Plane segment candidate extraction using Hough Transformation from depth map information, 2) fitting the plane segment candidates to the depth map to detect the partial plane segment, since the extracted plane segment candidates are general planes, with no boundary. To achieve real-time plane segment finding system, we apply 1) Recursive Correlation method for depth map generation, 2) Randomized Hough Transformation method for plane segment extraction.

PSF would be useful in a number of applications. For example, a mobile robot can recognize a floor, a wall, a table and a ceiling etc, and distinguish an obstacle from the floor or the table. A legged robot is able to climb stairs by detecting different step levels.

Finally, experimental results using an implementation of our system along with humanoid robots are shown.

2 Algorithm of Plane Segment Finder

Distance Information Measurement First, we obtain disparity information(depth map image) by finding corresponding points between two images, then calculate 3D distance information using internal/external parameters of cameras. In this paper, we utilize stereo-based disparity image generation system to acquire 3D information of the scene, but our proposed method is applicable to a variety of systems such as laser range sensors or pattern projection systems.

Plane Segment Candidates Extraction We apply the Hough Transform method of to extract plane segment candidates from distance information. The Hough Transformation method is a well-known method which is robust to noise and occlusions, and generally used for finding lines, circles etc.

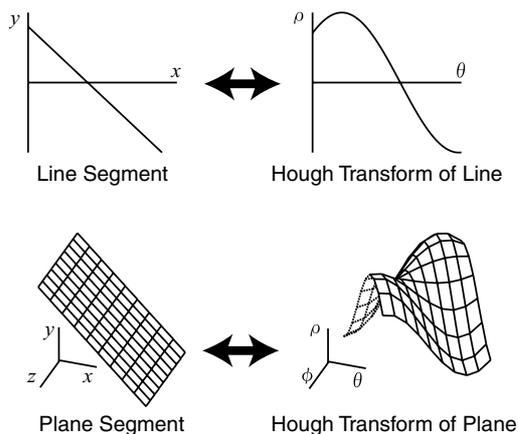


Figure 1: Comparison between Hough Transform of a 2D line and that of a 3D plane

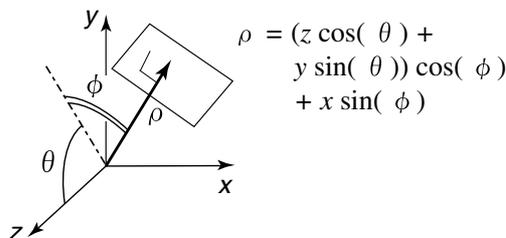


Figure 2: Parametric representation of a plane

Partial Plane Segments Detection

Extracted plane segment candidates are general planes, with no boundary. Then, we fit the plane segment candidates to the distance information to detect partial plane segments.

2.1 Hough Transform of A Plane to Extract Plane Segment Candidates

We utilized the Hough transform method for extracting plane segment candidates. The Hough Transformation method is a well-known method which is robust to noise and occlusions, and generally used for extracting lines, circles or ellipses.

For a straight 2D line segment extraction using the Hough Transform method, one edge point is transformed to a curved line in a Hough space(parameter space). In the case of our Hough transform for extracting plane segments algorithm, one distance point

on the plane is transformed to a curved surface (see Figure 1).

To apply the Hough Transform method for a plane segment extraction, we adopt the following parametric representation of a plane (see Figure 2), where ρ is the distance between a plane and the origin, ϕ is angle against the x axis, θ is angle against y the axis. (x_0, y_0, z_0) is the point on the plane.

$$\rho = (x_0 \cos(\phi) + y_0 \sin(\phi)) \cos(\theta) + z_0 \sin(\theta)$$

This equation has the following features.

1. A *point* in 3D space becomes a *curved surface* in a Hough space.
2. A *plane* in 3D space becomes a *point* in a Hough space.

Hence, to extract plane segment candidates, 1) we transform (“vote”) all 3D points in the distance information into the Hough space, 2) Detect peak points in the Hough space, which correspond to plane segment candidates in 3D space.

2.2 Partial Plane Segments Extraction

The plane segment candidates which are extracted from distance information using the Hough Transform of planes, are general plane, i.e. there is no boundary. Thus a method to detect partial plane segments from plane segment candidates is required. We utilize the following simple method:

- For each plane segment candidate:
1. Generate the virtual depth map image of the extracted plane segment candidate using parameters of the plane.
 2. Calculate distance between the virtual depth map image and the real depth map image (the input disparity image) at each pixel.
 3. If the distance is lower than the threshold, this point categorized to the partial plane segment.

3 Development of Real-time Plane Segment Finding System

For robotics applications, real-time and robustness are important features. We developed PC-based real-time Plane Segment Finding system.

Our system consists of two parts, one is depth map generation system and the other is plane segment detection system.

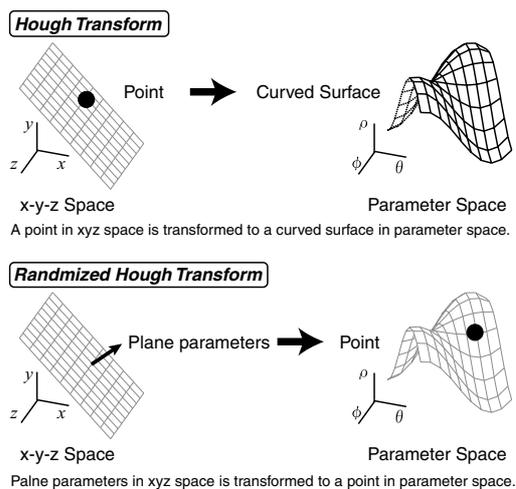


Figure 3: Randomized Hough Transform

3.1 Depth Map Generation System

Real-time Depth Map Generation

To achieve the real-time depth map generation system, we utilized following three key issues. (1) Recursive Correlation Method [2, 7], (2) Algorithmic Optimization for 2nd Level Cache, (3) Multimedia instruction set (MMX) implementation.

Reliable Depth Map Generation

Fundamentally, stereo matching suffers from occlusions or mismatches. To generate the reliable depth map, we apply the "Consistency Checking Method" [8, 9].

3.2 Plane Segment Detection System

3.2.1 Randomized Hough Transform

The Hough Transform method has the advantage that it is robust to noise. However, the computational cost and required memory size are very high.

These disadvantages are very significant problems to develop real-time system for robot applications. To cope with this problem, a method called Randomized or Probabilistic Hough Transform [10, 11] has been introduced. We apply this idea to our Hough Transformation for extracting planes.

In the original Hough Transform method, each point on the input image is transformed to a curved surface, therefore we need to vote for $\Theta - \Phi$ points in

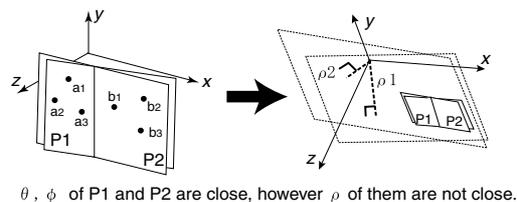


Figure 4: two planes which is "close" in $x-y-z$ coordinates are not always "close" in $\rho-\theta-\phi$ coordinates.

Hough array for each point in the distance image, Figure 3 shows this idea ($\Theta - \Phi$ is the size of the Hough array in the θ and ϕ directions).

By introducing Randomized Hough Transform method, we need to vote for S points in Hough array for each point in the distance image (S is constant, describe later).

1. Let $(d_{i,j})$ be the distance information at the point (i, j) in the input image.
2. Set window size s to initial size.
3. Calculate (ρ, θ, ϕ) from points $(d_{i,j}, d_{i+s,j}, d_{i,j+s})$, and accumulate the cell of Hough array.
4. Repeat the step (3) until s becomes maximum size S .
5. Search for peak cells in Hough Space after processing the entire image.

3.2.2 Two Stage Hough Transformation Method

The method described above seems to work well in theory, however, it is very sensitive to noise in distance information, in practice. The reason is that two planes which is "close" in $x-y-z$ coordinates are not always "close" in $\rho-\theta-\phi$ coordinates.

Figure 4 shows an example. Let us think about 6 points (a_{1-3}, b_{1-3}) in the figure, which are supposed to be lie on the same plane. However, because of noise, the extracted plane using a_{1-3} is P1, and the extracted plane using b_{1-3} is P2. In this case, because of the the position of planes and origin, parameters θ and ϕ are also very close in the representation of these planes in $\rho-\theta-\phi$ coordinates, however parameter ρ might be very different.

To cope with this problem, we propose the following two-stage method of the Hough Transformation. In the first stage, we vote into only $\theta-\phi$ space from dis-

Table 1: Accuracy of plane segments detection

	ρ [cm]	θ [degree]	ϕ [degree]
Plane 1	10.11	98.8	56.3
Plane 2	12.32	98.8	56.3
Plane 3	14.95	98.8	56.3

ρ is distance between a plane and the origin.

ϕ is angle against x axis.

θ is angle against y axis.

Table 2: Calculation time of each functions on PentiumIII-750MHz (Dual CPU machine)

Function	Time
LoG filter *1	5.92
Shift and rotate a input image	10.14
Disparity image generation *2	36.04
Distance Information Calculation	5.49
Smooth Distance Information *3	33.87
Plane Candidate Extraction *4	141.28
Plane Segment Detection	0.34
Total time of processing	233.08

(unit:msec): The size of images are 128×128 pixel.

*1 7x7 filter for 2 images.

*2 search area is 0 to 24.

*3 5x5 average filter.

*4 parameter space is $60 \times 72 \times 72$ for ρ, θ, ϕ .

tance information, and acquire normal vector of candidate planes, then we vote into ρ space.

4 System Evaluations

We placed blocks on a desk. Figure 5(A) is the input image, and the depth image is shown in Figure 5(B). Then, we detected plane segments from the depth image using PSF, Figure 5(C) shows the results of PSF. Pixels which have the same gray level are pixels on the same plane segment. These results show there are three planes in the input image.

Figure 5(D) is three-dimensional representation of the result of PSF. Each detected plane segment is rendered with a texture-map. The images shows the same 3D data from different view points, and the arrows in the images are $x - y - z$ axis(5[cm]).

Table 1 shows the accuracy of the detected plane segments for each 3 blocks. From the results, we can

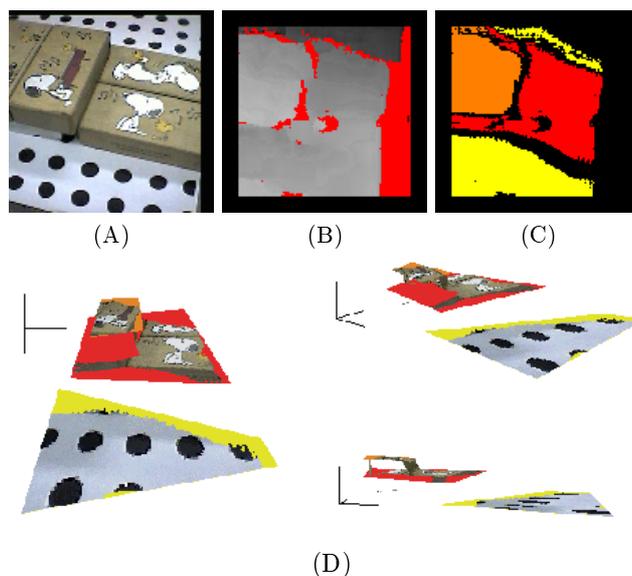


Figure 5: A) Input image. B) Depth map (Brighter is closer). C) Result of plane segment detection.

see that the distances between each plane are 2.21[cm], 2.62[cm] respectively, where the real height of block is 2.5[cm].

Table 2 shows the calculation time of the developed system. The system is able to detect planes at a rate of up to 4[Hz]. The size of input image is 128×128 pixels, and window size of correlation is 21, disparity size is 32. The size of Hough space is 100 for ρ and 72 for θ, ϕ .

5 Applications of PSF

To demonstrate that the Plane Segment Finder can be an effective tool for real-world robots, we show a placing a cup behavior and a climbing a step behavior of a humanoid based on the detected partial plane segment information.

5.1 Placing A Cup Behavior of A Humanoid

We utilized a wheel type humanoid robot called H3, which has 4 D.O.F. for each arm, 1 D.O.F for each hand, and 3 D.O.F for head.

In Figure 6, first the robot search for a horizontal plane to place a cup, then reach to the plane, finally



Figure 6: exp

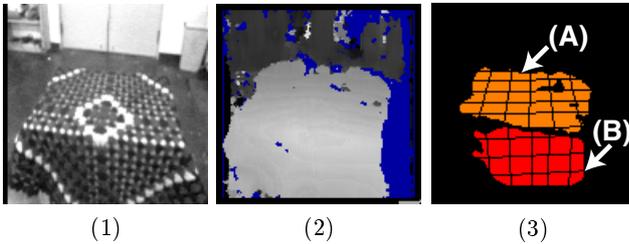


Figure 7: (1) Input image. (2) Depth map (Brighter is closer). (3) Result of plane segment detection.

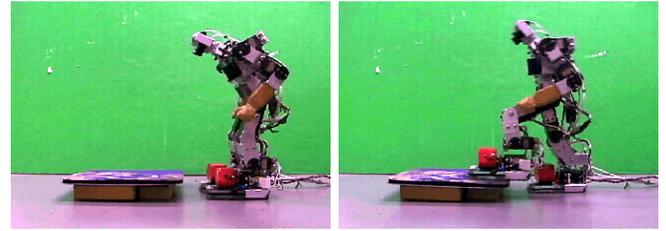
the robot place a cup.

Figure 7 shows processing image during the experiment. Figure 7(1) is input image, (2) is depth image, and (3) is the result of plane segment detection. In Figure 7(3), two plane segments (A) and (B) are detected. From the pitch angle of the robot head, the robot recognize plane (A) as a horizontal plane, and plane (B) as a vertical plane.

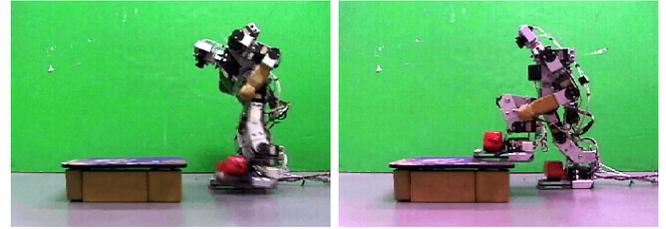
5.2 Climbing A Step Behavior of A Humanoid

We utilized a humanoid typed robot for experiments, which is developed using a remote-brained robotics approach. humanoid has 16 D.O.F., 4 D.O.F. in each leg, 3 D.O.F in each hand and 2 D.O.F. for neck, and 2 TV cameras in the head.

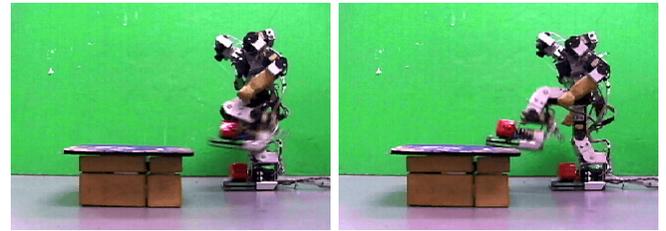
In Figure 8(1)-(3), the robot is able to recognize the height of the step using PSF, then lifts up its leg. Figure 9 shows that the humanoid is able to climb the step using PSF.



(1) The height of the step is 2.5cm



(2) The height of the step is 5.0cm



(3) The height of the step is 7.5cm

Figure 8: The humanoid recognizes the height of the step using PSF, then lift up the leg to climb.

6 Concluding Remarks

In this paper, we described an algorithm and implementation of a Plane Segment Finder, real-time partial plane segment detection system. The proposed algorithm includes 1) Hough transformation for plane segment to extract plane segment candidates from depth map information, 2) fitting the plane segment candidate into depth map to detect the partial plane segment. To realize real-time PSF system, we apply 1) the Recursive Correlation method to depth map generation, 2) the Randomized Hough Transformation method for plane segment extraction.

We consider that PSF would be useful in a number of applications. For example, a mobile robot can recognize a floor, a wall, a table etc, and detect objects on the floor or the table. In this paper, we showed a placing a cup behavior and a climbing a step behavior

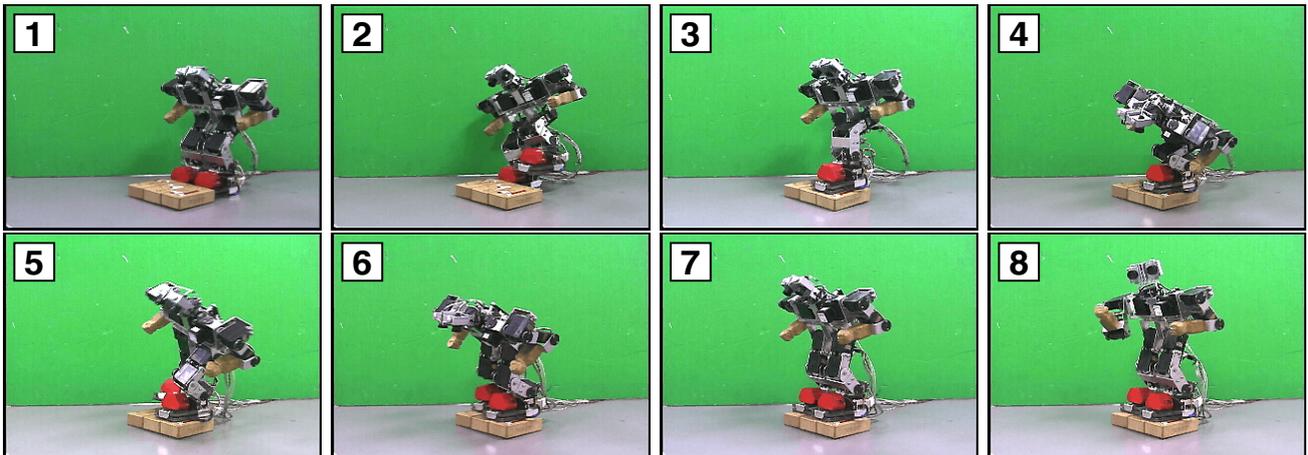


Figure 9: Experimental results: Climbing a step behavior of a humanoid using PSF.

of a humanoid.

In our experiment, we used only one step not stairs, however the height of the step is previously unknown and calculated using PSF. The contribution of this experiment is that humanoid robots will be able to climb any stairs with PSF, in spite of unknown step height or number of steps.

We believe extracting plane segments can be applied to a number of applications and expand the behavior of robots in the real-world.

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