Uncertainty Analysis in Depth Measurement of Stereo Vision System for Sensor Fusion

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Abstract—In this paper, the geometry of uncertainty in depth measurement of stereo vision system is analyzed and visualized. A CCD sensor of the camera has a minimum unit called a pixel. Based on the pinhole camera, the camera's pixels pass through the lens and contain the most noticeable information among objects in a rectangle that increases in proportion to the distance. Also, in a stereo vision system composed of two or more cameras, the vertices of the pixels of each camera pass through the lens of the camera and contact each other to form a polygon. So, we call this polygon a uncertainty area, because human beings can't determine the exact position when a noticeable object moves within this polygon. Therefore, the core of this research is to determine the shape and size of the uncertainty area in the depth measurement of the stereo vision system made up of cameras, and the ultimate goal of this research is to obtain uncertainty information in the depth measurement of the stereo vision system and apply it to sensor fusion.

Index Terms—localization, robot, sensor fusion, camera, stereo vision system, stereo vision, depth measurement, uncertainty, uncertainty area, uncertainty analysis

I. INTRODUCTION

In recent years, cameras have been used to acquire depth (range) information as well as image information. In addition, the stereo vision system is more widely applied and is also used in robotic surgery in medical field [1]. And in recent research trends, image detection by stereo vision systems is being studied to apply to lane recognition [2], and studies are also being conducted for localization and mapping of detection targets [3]. However, the stereo vision system has a fatal disadvantage. This is the uncertainty area where the position of the object is not accurately detected. And, based on the pinhole camera model, the farther the distance between a target and the stereo vision system becomes, the more inaccurate it becomes. Therefore, it is necessary to analyze the uncertainty in the depth measurement of the stereo vision system. For this reason, previous studies have analyzed this uncertainty [4], [5] and further advanced research has been carried out in this paper. First, we obtained the coordinates and size of the uncertainty area in the 2D space, and we have found the degree of uncertainty according to the distance. Second, the shape, coordinates, and size of the uncertainty area in the 3D space were obtained. Finally, the theories were verified through experiments. The ultimate goal of this study is to find the uncertainty of the uncertainty area in the stereo vision system and apply it to sensor fusion. Therefore, it is necessary to know the size and shape of the uncertainty area in which the object to be detected exists in order to obtain the uncertainty information to be used in the sensor fusion. So, we find out the shape and size of the uncertainty area in the 2D space and propose a method to obtain the shape and size of the uncertainty area in the 3D space based on the uncertainty area in the 2D space.

II. STEREO VISION SYSTEM

A. Used Stereo Vision System

The stereo vision system was set up as shown in Fig. 1 using FLIR’s GS3-U3-50S5C-C and the two cameras of the stereo vision system were aligned.

Figure 1. Stereo vision system

In addition, the specifications of the camera (GS3-U3-50S5C-C) are shown in Table I.

<table>
<thead>
<tr>
<th>TABLE I. SPECIFICATION OF GS3-U3-50S5C-C</th>
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<tbody>
<tr>
<td>Resolution</td>
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<tr>
<td>Pixels</td>
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<tr>
<td>Sensor</td>
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<tr>
<td>Pixel size</td>
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<td>Focal length</td>
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B. Camera Model

We have assumed that the camera, which is a complicated system, is a simple system, a pinhole camera
C. Parameters

The main parameters used to obtain the position of detected object in depth measurement of stereo vision system are baseline, focal length, and disparity. Baseline(b) is the distance between the center of two cameras, focal length(f) is the distance from the camera lens to the image sensor, and disparity(d) is the difference between the pixel of two cameras where the detected object is located.

D. Coordinate System

In the stereo vision system, there are four coordinate systems. In this paper, camera coordinate system, normalized image coordinate system and pixel image coordinate system are the same as commonly used methods. And the world coordinate system is at the center of the two cameras, and the directions of the X, Y and Z axes are the same as the camera coordinate system. The unit of the world coordinate system and the camera coordinate system is meters.

III. 2D UNCERTAINTY AREA

A. Basic Equations of Stereo Vision System

In the stereo vision system, if the coordinates of the detected object in the pixel image coordinate system of the camera are the left camera \( P_L(X_L, Y_L) \), and the right camera \( P_R(X_R, Y_R) \), a general formula for obtaining the position of the detected object is as follows.

\[
X = \frac{bf(X_L+X_R)}{2(X_L-X_R)} \quad (1)
\]

\[
Y = \frac{bf(Y_L+Y_R)}{2(X_L-X_R)} \quad (2)
\]

\[
Z = \frac{bf}{X_L-X_R} = \frac{bf}{d} \quad (3)
\]

B. 2D Location of Uncertainty Area

The uncertainty area in the two-dimensional space formed by two specific pixels can be drawn as in Fig. 3. And the coordinates of \( P_1, P_2, P_3 \) and \( P_4 \), which are the coordinates of the uncertainty area, can be obtained by equation (4) and (5), these are expressed by (6), (7), (8), (9). \( X_L \) and \( X_R \) are the pixel coordinates of X-axis in the left and right pixel image coordinate system, and \( dv \) is the length of the pixel. Finally variable ‘b’ is baseline, variable ‘d’ is disparity, variable ‘f’ is focal length, and \( n_l \) and \( n_r \) are numbers between 0 and 1.

\[
X(n_l,n_r) = \frac{1}{2} + \frac{X_R + n_r-1}{X_L-X_R+n_l-n_r}, \quad (0 < n_l, n_r < 1) \quad (4)
\]

\[
Z(n_l,n_r) = \frac{bf}{(X_L-X_R+n_l-n_r)dv}, \quad (0 < n_l, n_r < 1) \quad (5)
\]

\[
P_1 = [X(1,1)\ Y(1,1)] = \left[\frac{1}{2} + \frac{X_R-1}{X_L-X_R} \right], \frac{bf}{(X_L-X_R)dv} \quad (6)
\]

\[
P_2 = [X(1,0)\ Y(1,0)] = \left[\frac{1}{2} + \frac{X_R}{X_L-X_R+1} \right], \frac{bf}{(X_L-X_R+1)dv} \quad (7)
\]

\[
P_3 = [X(0,0)\ Y(0,0)] = \left[\frac{1}{2} + \frac{X_R-1}{X_L-X_R} \right], \frac{bf}{(X_L-X_R)dv} \quad (8)
\]

\[
P_4 = [X(0,1)\ Y(0,1)] = \left[\frac{1}{2} + \frac{X_R}{X_L-X_R} \right], \frac{bf}{(X_L-X_R)dv} \quad (9)
\]

C. Error of Estimated Distance

The graph in Fig. 4 shows the estimated distance from the stereo vision system and the error range according to disparity when the baseline is 0.25m. The error range is obtained from the difference of the parameters \( P_2, P_4 \) of the uncertainty area in the two-dimensional space. And the disparity was adjusted by the difference of the pixel in the both cameras. From the equation (3) and the graph in Fig. 4, it can be seen that the estimation error increases as the distance to the detecting object increases.

D. Experimental Verification

The conditions of the experiment are the baseline is 0.25m and the distance from the object to cameras is about 5m away. The overall location and size of the uncertainty area including the object are shown in Fig. 5,
and a more detailed picture of the uncertainty area can be seen in Fig. 6.

Figure 5. Overall view of the uncertainty area in the 2D space

Figure 6. More detailed view of the uncertainty area in the 2D space

IV. 3D UNCERTAINTY AREA

A. Uncertainty Area in the 3D Space

Since the uncertainty area in the three-dimensional space is difficult to know how it looks, it is modeled based on the pinhole camera model, and its appearance is shown in Fig. 7.

Figure 7. Appearance of 3D uncertainty area

Also, the two cameras of the stereo vision system are perfectly aligned, and the values of \( Y_L \) and \( Y_R \) in which the detection object is located in the pixel image coordinate system of the two cameras are the same. Therefore, the equation (10) is derived by applying the pinhole camera model as shown in Fig. 8. Finally, the coordinates of the uncertainty area of the three-dimensional space can be derived substituting equation (6), (7), (8), (9) into (10).

B. Equation of 3D Uncertainty Area

If all the coordinates of the uncertainty area in three-dimensional space shown in Fig. 9 are derived in the manner described earlier, each coordinate can be expressed as equation (11), (12), (13), (14), (15), (16), (17), (18). \( P^U \) is the coordinates of the top surface of the uncertainty area in the 3D space, and \( P^D \) is the coordinates of the bottom surface of the uncertainty area in the 3D space. \( Y_L \) is the pixel coordinates of Y-axis in the left pixel image coordinate system.

\[
P^U = \left[ b \left( \frac{1}{2} + \frac{X_R - 1}{X_L - X_R + 1} \right), b \frac{Y_L}{X_L - X_R}, \frac{bf}{(X_L - X_R) dv} \right]
\]

\[
P^D = \left[ b \left( \frac{1}{2} + \frac{X_R - 1}{X_L - X_R + 1} \right), b \frac{Y_L}{X_L - X_R}, \frac{bf}{(X_L - X_R) dv} \right]
\]

C. Experimental Verification

The experimental conditions of the experiment are the baseline of the stereo vision system is 0.25m, and the detected object is located between the two cameras and is 0.33m above the stereo vision system, and the distance from the stereo vision system is about 5m away. The uncertainty area in the 3D space created by applying the experimental conditions can be seen in Fig. 10 and is highlighted by red lines.
V. EXPERIMENT & ANALYSIS

A. Experimental Setup

We set up a stereo vision system using two FLIR’s GS3-U3-50S5C-C cameras, set the baseline as 0.25m, and then aligned the two cameras. In addition, a XY-table, designed to move freely forward, backward, left and right without shaking, was placed at a distance of 5m from the stereo vision system. On the XY-table, there is the target consisting of a white dot with a diameter of 0.15cm on a black background. And a parameter ‘a’, which is the distance from the XY-table to the target, is set and moved as shown in Fig. 11. The conception of the experimental setup can be seen in Fig. 11, and the actual configuration of the experiment can be seen in Fig. 12.

B. Experiments and Results

Experiments were conducted to confirm the uncertainty area in depth measurement of the stereo vision system. The left and right camera images obtained from the experiment were as shown in Fig. 13 and the results obtained by adjusting the variable ‘a’ are shown in Fig. 14, Fig. 15, Fig. 16. First, when the variable ‘a’ is set to 13cm, the target is located at $P_L(1275,1171)$ and $P_R(1203,1171)$ in the pixel image coordinate system of the both cameras, and can be seen in Fig. 15. Third, when the variable ‘a’ is set to 16.2cm, the target is located at $P_L(1275,1171)$ and $P_R(1203,1171)$ in the pixel image coordinate system of the both cameras, and can be seen in Fig. 16.

C. Analysis

The target was detected by adjusting the parameter ‘a’. In the experiments, the target has moved a distance of up to 3.2cm and the target exists in the uncertainty area formed by the coordinates $P_L(1275,1171)$ in the pixel image coordinate system of the left camera and the coordinate $P_R(1203,1171)$ in the pixel image coordinate system of the right camera. In Fig. 17, the blue circles are the camera, and the uncertainty area including...
the target is expressed through simulation. As can be seen in Fig. 17 and Fig. 18, a circle with a diameter of 0.15 can be placed in the uncertainty area, and in the uncertainty area of polygon shape slanted at 6°, the circle can move up to 3.4cm in the Z-axis direction, and is completely get out of it when moving more than 3.4cm. Therefore, it seems reasonable that the circle located on the XY table moved up to 3.2cm in the Z-axis direction.

![Figure 17](image1.png)

**Figure 17.** Location of the uncertainty area including the target

![Figure 18](image2.png)

**Figure 18.** Coordinates of the uncertainty area including the target

D. Conclusion

We have extended the uncertainty area from 2D space to 3D space and proposed a method to obtain size and coordinates. Therefore, in this paper, the size and the coordinates of the uncertainty area in the 2D space and the 3D space were obtained and visualized using the proposed method. And the experiments have also shown that it is very reasonable to obtain the size and coordinates of the uncertainty area using the proposed method. Finally if the proposed method is used, the reliability and uncertainty of the object detected in the stereo vision system can be expressed, and the reliability and uncertainty can be applied to the sensor fusion.

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