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스테레오 카메라의 최적 위치 및 방향

An Optimal Position and Orientation of Stereo Camera

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요 약

모션 및 무인 차량의 깊이 제어를 위해 스테레오 비전 분석을 하였다. 스테레오 비전에서 3차원 좌표의 깊이 정보는 스테레오 이미지 사이의 포인트를 식별한 후 삼각 측량을 통해 얻을 수 있다. 그러나 항상 몇몇 이유 때문에 삼각 측량의 오류가 발생한다. 비전 삼각 측량의 이러한 오류는 카메라의 위치와 방향에 주의하여 배열함으로써 완화 될 수 있다. 본 논문에서는 무인 차량을 위해 카메라의 최적의 위치와 방향을 결정하는 방법을 제시하였다.

Abstract

A stereo vision analysis was performed for motion and depth control of unmanned vehicles. In stereo vision, the depth information in three-dimensional coordinates can be obtained by triangulation after identifying points between the stereo image. However, there are always triangulation errors due to several reasons. Such errors in the vision triangulation can be alleviated by careful arrangement of the camera position and orientation. In this paper, an approach to the determination of the optimal position and orientation of camera is presented for unmanned vehicles.

Key words : sensor system(센서 시스템), active stereo vision system(능동 스테레오 비전), stereo vision (스테레오 비전), unmanned vehicle(무인 차량)

I. Introduction

A vision system is an important sensor for the unmanned vehicle such as the unmanned forklift for approaching destination. In order for the unmanned forklift to move with loads without an human beings, they need a number of sensors such as the gyro sensor, supersonic wave sensor, infrared rays sensor, and vision sensor. Out of the sensors, one of the most important sensor is the vision sensor. A number of researches were performed in application of vision sensor to the unmanned forklift [1],[2]. However, the vision sensors in the research are single vision system such that it should be used with other sensors to find depth information. However, there are always triangulation errors due to several reasons and those have been studied [3]-[6].

We focus on a stereo vision system with position and orientation errors due to several reasons. In section 2, Sensitivity for the stereo vision sensor system is

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explained. Also, System error equation is explained in section 3.

Ⅱ. Sensitivity for the stereo vision sensor system

The stereo vision sensor system is composed of two cameras capable of yawing and pitching motion as shown in Fig. 1. Each camera has two degree-of- freedom (DOF). The stereo camera is used to find the depth information between the unmanned vehicle and an object.

In this section, the system sensitivity equation to measure triangulation error of the stereo vision system is derived.

그림 1. 스테레오 비전 시스템 사진
Fig. 1 A picture of the stereo vision system

In the following two equations, x and y can be set as functions of X, Y, and Z by fixing the camera orientation variables, θ, a constant. Denoting them in function formation, we get

$$x=(X_r c\theta+Y_r s\theta)/k = f(X,Y,Z) \quad (1)$$

$$y=(-X_r s\theta c a Y_r c\theta c a Z_r S a)/k = f(X,Y,Z) \quad (2)$$

Substituting x_1, y_1, X_{r1}, Y_{r1}, and Z_{r1} into x, y, X_r, Y_r, and Z_r, respectively, in order to indicate the position and orientation of camera one, yields

$$x_1=(X_{r1}c\theta_l+Y_{r1}s\theta_l)/k_l = f_{11}(X,Y,Z) \quad (3)$$

$$y_1=(-X_{r1}S\theta_l C a_l+Y_{r1}C\theta_l C a_l+Z_{r1}S a_l)/k_l$$

$$= f_{12}(X,Y,Z) \quad (4)$$

Substituting x_2, y_2, X_{r2}, Y_{r2}, and Z_{r2} into x, y, X_r, Y_r, and Z_r, respectively, in order to indicate the position and orientation of camera two, yields

$$x_2=(X_{r2}c\theta_2 Y_{r2}s\theta_2)/k_2=f_{21}(X,Y,Z) \quad (5)$$

$$y_2=(-X_{r2}s\theta_2 c a_2 Y_{r2}c\theta_2 c a_2+Z_{r2}s a_2)/k_2=f_{22}(X,Y,Z) \quad (6)$$

There are three ways to derive the system error equation to measure the triangulation error. These ways are dependent on which camera coordinates on the image plane are used. If only xx, yx, and x_2 are used to determine the coordinates of the task, X, Y, and Z, equations (3), (4), and (5) are used. Taking partial differentiations of those equations, and expressing in matrix notation yield

$$\begin{bmatrix}\partial x_1\\ \partial y_1\\ \partial x_2\end{bmatrix} = J_1\begin{bmatrix}\partial X\\ \partial Y\\ \partial Z\end{bmatrix} \quad (7)$$

Assuming that very small errors occur in locating a scene on both of the stereo image, equation (7) can be expressed as

$$\begin{bmatrix}\Delta x_1\\ \Delta y_1\\ \Delta x_2\end{bmatrix} = J_1\begin{bmatrix}\Delta X\\ \Delta Y\\ \Delta Z\end{bmatrix} \quad (8)$$

where

$$J_1 = \begin{bmatrix}\partial f_{12}/aX & \partial f_{11}/\partial Y & \partial f_{11}/\partial Z\\ \partial f_{12}/aX & \partial f_{12}/\partial Y & \partial f_{12}/\partial Z\\ \partial f_{12}/aX & \partial f_{21}/\partial Y & \partial f_{21}/\partial Z\end{bmatrix} \quad (9)$$

in which

$$\partial f_{11}/\partial X = c\theta_l/k_1+(X_{r1}c\theta_l+Y_{r1}s\theta_l)(s\theta_l s a_l/\lambda)/k_1^2 \quad (10)$$

$$\partial f_{11}/\partial Y = S\theta_l/k_1-(X_{r1}C\theta_l+Y_{r1}S\theta_l)(C\theta_l S a_l/\lambda)/k_1^2 \quad (11)$$

$$\partial f_{11}/\partial Z = (X_{r1}c\theta Y_{r1}s\theta_1\ (c\alpha_1/\lambda)/k_1^2 \qquad (12)$$

$$\partial f_{12}/\partial X = -S\theta_1 C\alpha_1/k_1 + (-X_{r1}s\theta_1 c\alpha_1 + Y_{r1}c\theta_1 c\alpha_1 + Z_{r1}s\alpha_1)(s\theta_1 s\alpha_1/\lambda)/k_1^2 \qquad (13)$$

$$\partial f_{12}/\partial Y = c\theta_1 C\alpha_1/k_1 - (-X_{r1}s\theta_1 c\alpha_1 + Y_{r1}c\theta_1 c\alpha_1 + Z_{r1}s\alpha_1)(c\theta_1 S\alpha_1/\lambda)/k_1^2 \qquad (14)$$

$$\partial f_{12}/\partial Z = s\alpha_1/k_1 + (-X_{r1}s\theta_1 c\alpha_1 + Y_{r1}c\theta_1 c\alpha_1 + Z_{r1}s\alpha_1)(C\alpha_1/\lambda)/k_1^2 \qquad (15)$$

$$\partial f_{21}/\partial X = c\theta_2/k_2 + (X_{r2}c\theta_2 + Y_{r2}s\theta_2)(s\theta_2 s\alpha_2/\lambda)/k_2^2 \qquad (16)$$

$$\partial f_{21}/\partial Y = s\theta_2/k_2 - (X_{r2}c\theta_2 + Y_{r2}s\theta_2)(c\theta_2 S\alpha_2/\lambda)/k_2^2 \qquad (17)$$

$$\partial f_{21}/\partial z = (X_{r2}c\theta_2 + Y_{r2}s\theta_2)(c\alpha_2/\lambda)/k_2^2 \qquad (18)$$

The measurement errors in three-dimensional coordinates due to the input errors, Δx_1, Δy_1, Δx_2 in locating the projection of robot task on the image plane, are then easily determined by the following equation as

$$\begin{bmatrix}\Delta x\\ \Delta y\\ \Delta x\end{bmatrix} = J_1^{-1}\begin{bmatrix}\Delta X_1\\ \Delta Y_1\\ \Delta Z_2\end{bmatrix} \qquad (19)$$

Similarly, the measurement errors in three-dimensional coordinate due to the input errors, Δx_1, Δy_1, Δy_2 in locating the projection of robot task, are determined by following equation.

$$\begin{bmatrix}\Delta x\\ \Delta y\\ \Delta x\end{bmatrix} = J_2^{-1}\begin{bmatrix}\Delta X_1\\ \Delta Y_1\\ \Delta Z_2\end{bmatrix} \qquad (20)$$

where

$$J_1 = \begin{bmatrix}\partial f_{11}/\partial x & \partial f_{11}/\partial Y & \partial f_{11}/\partial Z\\ \partial f_{12}/\partial x & \partial f_{12}/\partial Y & \partial f_{12}/\partial Z\\ \partial f_{22}/\partial x & \partial f_{22}/\partial Z & \partial f_{22}/\partial Z\end{bmatrix} \qquad (21)$$

in which

$$\partial f_{22}/\partial X = -s\theta_2 c\alpha_2/k_2 + (-X_{r2}s\theta_2 c\alpha_2 + Y_{r2}c\theta_2 c\alpha_2 + Z_{r2}s\alpha_2)(s\theta_2 S\alpha_2/\lambda)/k_2^2 \qquad (22)$$

$$\partial f_{22}/\partial Y = c\theta_2 c\alpha_2/k_2 - (-X_{r2}s\theta_2 c\alpha_2 + Y_{r2}c\theta_2 c\alpha_2 + Z_{r2}s\alpha_2)(c\theta_2 S\alpha_2/\lambda)/k_2^2 \qquad (23)$$

$$\partial f_{22}/\partial Z = s\alpha_2/k_2 + (-X_{r2}s\theta_2 c\alpha_2 + Y_{r2}c\theta_2 c\alpha_2 + Z_{r2}s\alpha_2)(c\alpha_2/\lambda)/k_2^2) \qquad (24)$$

Also all the Ax_1, Ay_1, Ax_2, and Ay_2 can be used to determine the measurement errors in three-dimensional coordinate as

$$\begin{bmatrix}\Delta x_1\\ \Delta y_1\\ \Delta x_2\\ \Delta y_2\end{bmatrix} = J_3\begin{bmatrix}\Delta X\\ \Delta Y\\ \Delta Z\end{bmatrix} \qquad (25)$$

where

$$J_3 = \begin{bmatrix}\partial f_{11}/aX & \partial f_{11}/\partial Y & \partial f_{11}/\partial Z\\ \partial f_{12}/aX & \partial f_{12}/\partial Y & \partial f_{12}/\partial Z\\ \partial f_{21}/aX & \partial f_{21}/\partial Y & \partial f_{21}/\partial Z\\ \partial f_{22}/aX & \partial f_{22}/\partial Y & \partial f_{22}/\partial Z\end{bmatrix} \qquad (26)$$

The J_3 in Eq. (26) is a four by three matrix. If the matrix $(J_3^T J_3)^{-1} J_3^T$ is applied on both sides of equation (25), we obtain

$$\begin{bmatrix}\Delta X\\ \Delta Y\\ \Delta Z\end{bmatrix} = (J_3^T J_3)^{-1} J_3^T\begin{bmatrix}\Delta x1\\ \Delta y1\\ \Delta x2\\ \Delta y2\end{bmatrix} \qquad (27)$$

Three ways of derivation of the system sensitivity equation to measure the triangulation error have been made so far. Equations (19), (20), and (27) are the matrices to measure the error in three-dimensional coordinate by the input error on the image planes. Similarly, the system error equation to measure the triangulation error is derived in next section

Ⅲ. System error equation

The depth information of the dimensional coordinates can be obtained based on the projected scene on the stereo image. Because of image resolution and possible computation errors in image correlation and human error in locating ascene on the camera image, a certain degree of inaccuracy in determining the correct depth information of the robot task in three- dimensional coordinate always occurs. In other words, if we assume that those input errors, x_1', y_1', x_2', and y_2' on the image planes occur, the corresponding errors X_1', Y_1' , and Z_1' are caused in the three-dimensional coordinate. In this approach, the system error equation to measure the triangulation error is derived in this section.

The system error equation is based on equations (6) and (7). If only x_1, y_1, and x_2 are used, the system error equation can be expressed as the following matrix by setting $xx_1 = x_1+x_1'$, $yy_1 = y_1+y_1'$, $xx_2 = x_2+x_2'$, and $yy_2 = y_2+y_2'$,

$$A'\begin{bmatrix} X_r1+X_1' \\ Y_r1+Y_1' \\ Z_r1+Z_1' \end{bmatrix} = \begin{bmatrix} \lambda xx_1 \\ \lambda xx_1 \\ \lambda xx_2+P' \end{bmatrix} \tag{28}$$

where A' =

$$\begin{bmatrix} xx_1 s\theta_1 s\alpha_1+\lambda c\theta_1, & -xx_1 c\theta_1 s\alpha_1+\lambda s\theta_1, & xx_1 c\alpha_1 \\ yy_1 s\theta_1 s\alpha_1-\lambda s\theta_1 c\alpha_1, & -yy_1 c\theta_1 s\alpha_1+\lambda c\theta_1 c\alpha_1, & yy_1 c\alpha_1+\lambda s\alpha_1 \\ xx_2 s\theta_2 s\alpha_2+\lambda c\theta_2, & -xx_2 c\theta_2 s\alpha_2+\lambda s\theta_2, & xx_2 c\alpha_2 \end{bmatrix} \tag{29}$$

If only x_l, y_1, and y_2 are used, the system error equation can be expressed as,

$$B'\begin{bmatrix} X_{r1}+X_1' \\ Y_{r1}+Y_1' \\ Z_{r1}+Z_1' \end{bmatrix} = \begin{bmatrix} \lambda xx_1 \\ \lambda xx_1 \\ \lambda xx_2+q' \end{bmatrix} \tag{30}$$

where B' =

$$\begin{bmatrix} xx_1 s\theta_1 s\alpha_1+\lambda c\theta_1, & -xx_1 c\theta_1 s\alpha_1+\lambda s\theta_1, & xx_1 c\alpha_1 \\ yy_1 s\theta_1 s\alpha_1-\lambda s\theta_1 c\alpha_1, & -yy_1 c\theta_1 s\alpha_1+\lambda c\theta_1 c\alpha_1, & yy_1 c\alpha_1+\lambda s\alpha_1 \\ yy_2 s\theta_2 s\alpha_2-\lambda s\theta_2 c\alpha_2, & -yy_2 c\theta_2 s\alpha_2+\lambda c\theta_2 c\alpha_2, & yy_2 c\alpha_2+\lambda s\alpha_2 \end{bmatrix} \tag{31}$$

If all the variables, xx_1, yy_1, xx_2 and yy_2 are used, the system error equation can be expressed as,

$$C'\begin{bmatrix} X_{r1}+X_1' \\ Y_{r1}+Y_1' \\ Z_{r1}+Z_1' \end{bmatrix} = \begin{bmatrix} \lambda xx_1 \\ \lambda yy_1 \\ \lambda xx_2+p' \\ \lambda yy_2+q' \end{bmatrix} \tag{32}$$

where C' =

$$\begin{bmatrix} xx_1 s\theta_1 s\alpha_1+\lambda c\theta_1, & -xx_1 c\theta_1 s\alpha_1+\lambda s\theta_1, & xx_1 c\alpha_1 \\ yy_1 s\theta_1 s\alpha_1-\lambda s\theta_1 c\alpha_1, & -yy_1 c\theta_1 s\alpha_1+\lambda c\theta_1 c\alpha_1, & yy_1 c\alpha_1+\lambda s\alpha_1 \\ xx_1 s\theta_1 s\alpha_2+\lambda c\theta_2, & -xx_2 c\theta_2 s\alpha_2+\lambda s\theta_2, & xx_2 c\alpha_2 \\ yy_2 s\theta_2 s\alpha_2-\lambda s\theta_2 c\alpha_2, & -yy_2 c\theta_2 s\alpha_2+\lambda c\theta_2 c\alpha_2, & yy_2 c\alpha_2+\lambda s\alpha_2 \end{bmatrix} \tag{33}$$

$$P' = (xx_2 s\theta_2 S\alpha_2+\lambda c\theta_2)(X_{o2}-X_{o1})+(-xx_2 C\theta_2 S\alpha_2+\lambda s\theta_2)(Y_{o2}-Y_{o1})+xx_2 c\alpha_2(Z_{o2}-Z_{o1}) \tag{34}$$

$$q' = (yy_2 s\theta_2 s\alpha_2-\lambda s\theta_2 C\alpha_2)(X_{o2}-X_{ol})+(yy_2 c\theta_2 s\alpha_2+Xc\theta_2 c\alpha_2)(Y_{o2}-Y_{o1})+(yy_2 c\alpha_2+\lambda s\alpha_2)(Z_{02}-Z_{0l}) \tag{35}$$

The procedure of deriving the system error equation is quite similar to that of system sensitivity equation, so that only equation (32) which uses all the input variables is derived.

In equation (33), the system error can be expanded into two equations as, $C' = C + C_1$ where C is decided (32) and (37), and C_1 matrix is expressed as,

$$C_1 = \begin{bmatrix} x_1{}'s\theta_1 s\alpha_1, & -x_1{}'c\theta_1 s\alpha_1, & x_1{}'c\alpha_1 \\ y_1{}'s\theta_1 s\alpha_1, & -y_1{}'c\theta_1 s\alpha_1, & y_1{}'c\alpha_1 \\ x_2{}'s\theta_2 s\alpha_2, & -x_2{}'c\theta_2 s\alpha_2, & x_2{}'c\alpha_2 \\ y_2{}'s\theta_2 s\alpha_2, & -y_2{}'c\theta_2 s\alpha_2, & y_2{}'c\alpha_2 \end{bmatrix} \quad (37)$$

The matrix on the left side of the equation (32) can be expanded into the following matrices,

$$C'\begin{bmatrix} X_{r1}+X_1' \\ Y_{r1}+Y_1' \\ Z_{r1}+Z_1' \end{bmatrix} = C\begin{bmatrix} X_{r1} \\ Y_{r1} \\ Z_{r1} \end{bmatrix} + C_1\begin{bmatrix} X_{r1} \\ Y_{r1} \\ Z_{r1} \end{bmatrix} + C'\begin{bmatrix} X_{r1}' \\ Y_{r1}' \\ Z_{r1}' \end{bmatrix} \quad (38)$$

From equation (38), the following equation yields

$$C'\begin{bmatrix} X_1' \\ Y_1' \\ Z_1' \end{bmatrix} = -C_1\begin{bmatrix} X_{r1} \\ Y_{r1} \\ Z_{r1} \end{bmatrix} + \begin{bmatrix} \lambda x_1' \\ \lambda y_1' \\ \lambda x_2 + p' - p \\ \lambda y_2 + q' - q \end{bmatrix} \quad (39)$$

where

$$P'\text{-}P = X_2{}'S\theta_2 S a_2(X_{o2} - X_{o1}) - x_2{}'c\theta_2 S a_2(Y_{o2} - Y_{o1}) + x_2{}'c a_2(Z_{o2} - Z_{o1}) \quad (40)$$

$$q'\text{-}q = y_2{}'s\theta_2 s a_2(Xo_2 - Xo_1) - y_2{}'c\theta_2 a_2\ (Yo_2 - Yo_1) + y_2{}'c a_2(Zo_2 - Zo_1) \quad (41)$$

All the terms of equation (39) have four rows. Dividing the first, second, third, and fourth row of both sides of equation (39) by x_1', y_1', x_2', and y_2' respectively yields

$$\begin{bmatrix} c_1'/x_1' \\ c_2'/y_1' \\ c_3'/x_2' \\ c_4'/y_2' \end{bmatrix}\begin{bmatrix} X_1' \\ Y_1' \\ Y_1' \end{bmatrix} = \begin{bmatrix} -s\theta_1 s\alpha_{1,} & c\theta_1 s\alpha_{1,}, & -c\alpha_{1,} \\ -s\theta_1 s\alpha_{1,} & c\theta_1 s\alpha_{1,}, & -c\alpha_{1,} \\ -s\theta_1 s\alpha_{1,} & c\theta_1 s\alpha_{1,}, & -c\alpha_{1,} \\ -s\theta_1 s\alpha_{1,} & c\theta_1 s\alpha_{1,}, & -c\alpha_{1,} \end{bmatrix}\begin{bmatrix} X_{r1} \\ Y_{r1} \\ Z_{r1} \end{bmatrix}$$

$$+\begin{bmatrix} \lambda \\ \lambda \\ \lambda + (P' - P)/Y_2' \\ \lambda + (q' - q)/Y_2' \end{bmatrix} \quad (42)$$

where we set the matrix C' as

$$C' = \begin{bmatrix} C_1' \\ C_2' \\ C_3' \\ C_4' \end{bmatrix} \quad (43)$$

We set k' as

$$k' = \lambda k \quad (44)$$

Substituting θ_1, a_l X_{o1}, Y_{o1}, and Z_{o1} into θ, α, X_0, Y_0, and Z_0, respectively, to indicate camera one coordinate, yields

$$k_1' = \lambda k_1 = -s\theta_1 S a_1 X_{r1} + c\theta_1 s a_1 Y_{r1} - c a Z_{r1} + \lambda \quad (45)$$

Substituting θ_2, a_2, X_{o2}, Y_{o2}, and Z_{o2} into θ, α, X_c, Y_c, and Z_0, respectively, to indicate the camera two coordinate, yields

$$k_2' = \lambda k_2 = -s\theta_2 s a_2 X r_2 + c\theta_2 S a_2 Y_{r2} - c a_2 Z_{r2} + \lambda \quad (46)$$

Rearranging equation (42) yields

$$\begin{bmatrix} C_1'/x_1' \\ C_2'/y_1' \\ C_3'/x_2' \\ C_4'/y_2' \end{bmatrix}\begin{bmatrix} X_1' \\ Y_1' \\ Z_1' \end{bmatrix} = \begin{bmatrix} k_1' \\ k_1' \\ k'_2 + (p' - p)/x_2' \\ k'_2 + (q' - q)/y_2' \end{bmatrix} \quad (47)$$

If we set

$$D = \begin{bmatrix} C_1'/x_1' \\ C_2'/y_1' \\ C_3'/x_2' \\ C_4'/y_2' \end{bmatrix} \quad (48)$$

the D matrix is a four by three matrix. In order to get the errors, X_1' , Y_1', and Z_1' of depth informations in the three-dimensional coordinate affected by the input errors, X_1', Y_1' and Z_1' on the image plane in the camera coordinates, the least squares method should be applied. The least squares method is applied by pre- multiplying on each side of the above equation by $(D^TD)^{-1}D^T$, which yields

$$\begin{bmatrix} X_1' \\ Y_1' \\ Z_1' \end{bmatrix} = (D^T D)^{-1} D^T \begin{bmatrix} k_1' 1 \\ k_1' 1 \\ k'_2 + (p' - p)/x_2' \\ k'_2 + (q' - q)/y_2' \end{bmatrix} \quad (49)$$

The purpose of the optimal arrangement of position and orientation of stereo camera is to decide the best stereo camera arrangements to produce the least triangulation error as mentioned before. The depth error X_1', Y_1', and Z_1' in three-dimensional coordinates is affected by the variation of the ten explicit variables, Xrl, Y_{rl}, Z_{rl}, X_{r2}, Y_{r2}, Z_{r2}, x_1, y_1, x_2, y_2, and four implicit variables, α_1, θ_1, α_2, and θ_2. Here the aiming angles of the stereo camera to the task and the mapped position of robot task on the camera image plane are dependent on each other. In other words, x_1, y_1, x_2, y_2 can be treated as implicit variables and at the same time α_1,θ_1,α_2 and θ_2 can be set as explicit variables.

In order to solve the optimization problem, the limits of the image plan should be set within the image plane size, because the image of task can not be mapped out of the image plane. The smallest absolute value of the error, X_1' , Y_1', and Z_1' in three-dimensional coordinate in equation (49) should be obtained. If the absolute value of the error is set ERR, the expression is

$$ERR = sqrt(X_1'^2 + Y_1'^2 + Z_1'^2) \quad (50)$$

In order to find the minimum value of the equation (50), a program based on the "complex" method of M. J. Box is used [6]. The program finds the minimum of a multi variable, nonlinear function subject to nonlinear inequality constraints.

Ⅳ. Conclusion

A stereo vision analysis was performed for motion and depth control of unmanned vehicles. In this paper, a system error equation for the stereo vision is derived. Also, an approach to the determination of the optimal position and orientation of camera which produce the least triangulation error equation is presented.

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