A Pyramidal Mirror System Calibration Method for Robotic Assembly

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Abstract: In case of visual sensing systems with multiple mirrors, systematic errors need to be reduced by the system calibration and the mirror position adjustment in order to enhance system measurement accuracy. In this paper, a self calibration method is presented for a visual sensing system designed to measure the three-dimensional information in deformable peg-in-hole tasks. It is composed of a CCD camera and a series of mirrors including two pyramidal mirrors. By using an image of the inner pyramidal mirror taken by the system, the error parameters of the inner pyramidal mirror could be calibrated or adjusted. Also the influence of the plane mirrors is investigated.

Keywords: self-calibration, pyramidal mirror system, deformable part assembly, visual sensing

1. INTRODUCTION

Unlike rigid parts, deformable parts can be deformed by contact forces during assembly. For successful assembly of deformable parts, information about their deformation as well as possible misalignments between the holes and their respective mating parts are essential. However, because of the nonlinear and complex relationship between parts deformation and reaction forces, it is difficult to acquire all required information from the reaction forces alone. Such information can be mainly acquired from visual sensors.

Kim et al.[1] presented a visual sensing system that can detect three-dimensional part deformation and misalignment. This system consists of only one camera and a couple of mirrors including two pyramidal mirrors. To enhance the measurement accuracy, the system needs accurate adjustment and calibration. As researches on calibration of sensing system with mirrors, Zhuang et al.[2] constructed mirror center offset model, Tamura et al.[3] used coarse-fine parameter search for error correction of mirror parameters, and Kiyono et al.[4] proposed a self-calibration method of a polygon mirror system, Kim et al.[5] used learning-based parameters estimation method.

In this paper, a self-imaging method for adjustment and calibration of the visual sensing system with multiple mirrors including two pyramidal mirrors is presented. The mirror positions of the system are adjusted and calibrated by using its self-images. The calibration of the implemented mirror system is largely divided into two stages of the calibration between the camera and the inner pyramidal mirror, and the calibration between the inner pyramidal mirror and the outer pyramidal mirror. This paper will deal with only calibration of inner pyramidal mirror. In additions, the influence of the two plane mirrors will be dealt with in together.

2. THE VISUAL SENSING SYSTEM

Fig. 1(a) illustrates the basic configuration of the sensing system. It is composed of a CCD camera, a pair of plane mirrors, and a pair of pyramidal mirrors. In order to measure three-dimensional deformation by using a camera, two views are necessary, as shown in Fig. 1(b). Fig. 1(c) illustrates an image of a peg and a hole pair. Because four images that are reflected from each face of the pyramidal mirrors are projected on the image plane of a camera, this system configuration is equivalent to that utilizes four cameras. This configuration allows the system to overcome self-occlusion.

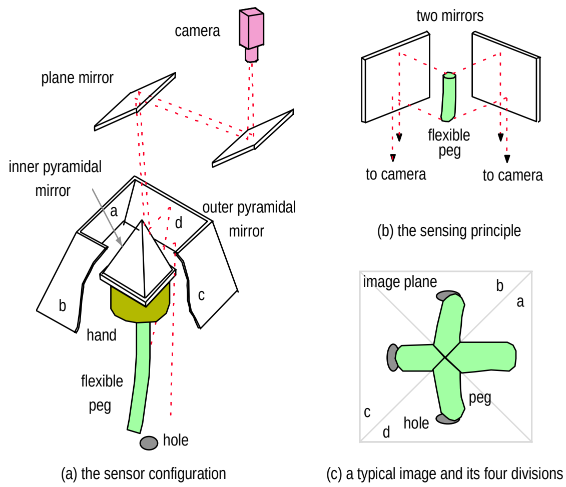

Fig 1. A schematic of the visual sensing system

3. CALIBRATION OF THE INNER PYRAMIDAL MIRROR

The calibration of the inner pyramidal mirror relative to the camera can be performed by using the image of the inner pyramidal mirror taken by the camera. A detailed system arrangement and its parameters are illustrated in Fig. 2. The parameters needed to be calibrated between the camera and the inner pyramidal mirror are three relative translational errors $C_{ex1}, C_{ey1}, C_{ez1}$ and three relative rotational errors $C_{\alpha x1}, C_{\alpha y1}, C_{\alpha z1}$.

3.1 Z-axis Translational Error (C_{ez1})

Relative distance error from the optical center to the inner pyramidal mirror is just z-axis translational error C_{ez1} between the camera and the inner pyramidal mirror. If there is no inclination of the inner pyramidal mirror relative to the camera with respect to the x-axis and the y-axis, the error C_{ez1} between the designed value a_d and the actual value a_r of the distance along the optical path from the optical center O_c to the center O_1' of the bottom of the inner pyramidal mirror can be obtained by[6]

$$a_r = \left(\frac{R_l + r_l}{r_l}\right) f \qquad (1)$$
$$C_{ez1} = a_d - a_r$$

where R_l is the actual length of one side of the bottom of the inner pyramidal mirror, r_l is its length on the image plane, and f is the focal length of the camera lens. Fig. 2 and 3 show R_l, r_l, a_r.

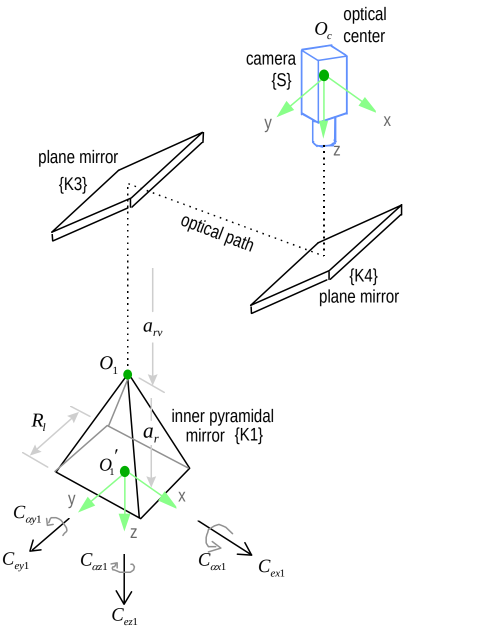

Fig 2. Calibration parameters of the inner pyramidal mirror

3.2 X, Y-axis Translational Error (C_{ex1}, C_{ey1})

Relative lateral error on the horizontal plane are x-axis and y-axis translational errors C_{ex1}, C_{ey1}. Fig. 3(a) shows the edge image of the inner pyramidal mirror when x-axis and y-axis translational errors exist. The solid lines correspond to the case the translational error exists, and the dotted lines correspond to the case of no translational errors. The translational errors C_{ex1} and C_{ey1} are given by

$$C_{ex1} = \left(\frac{a_{rv} - f}{f}\right) r_{ex} \qquad (2)$$
$$C_{ey1} = \left(\frac{a_{rv} - f}{f}\right) r_{ey}$$

where r_{ex}, r_{ey} are the errors in the x, y-direction between the origin O_i of the image plane and the image V_{ip} of the vertex O_1 of the inner pyramidal mirror, and a_{rv} is the actual distance from the optical center O_c to the vertex O_1 of the inner pyramidal mirror along the optical path. Fig. 3(a) shows r_{ex}, r_{ey}, Fig. 2 shows a_{rv}.

3.3 Relative Rotational Error with respect to Z-axis ($C_{\alpha z1}$)

If there is no relative rotational error with respect to the z-axis between the camera and the inner pyramidal mirror, every image of four sides of the bottom of the inner pyramidal mirror will become parallel to the x-axis or the y-axis of the image plane. Accordingly, the relative rotational error $C_{\alpha z1}$ with respect to the z-axis can be obtained from the angle between the one side of the bottom of the inner pyramidal mirror and the x-axis or the y-axis of the image plane, as shown in Fig. 3(b). On the other hand, if there are no rotational errors of the inner pyramidal mirror with respect to the x-axis or the y-axis, the center-line dividing the angle between the two diagonal lines of the inner pyramidal mirror into two equal parts becomes parallel to the x-axis or y-axis. And thus, in case of no rotational errors with respect to the x-axis or y-axis, $C_{\alpha z1}$ also can be obtained from the angle between the above-mentioned center-line and the x-axis or the y-axis as shown in Fig. 3(b).

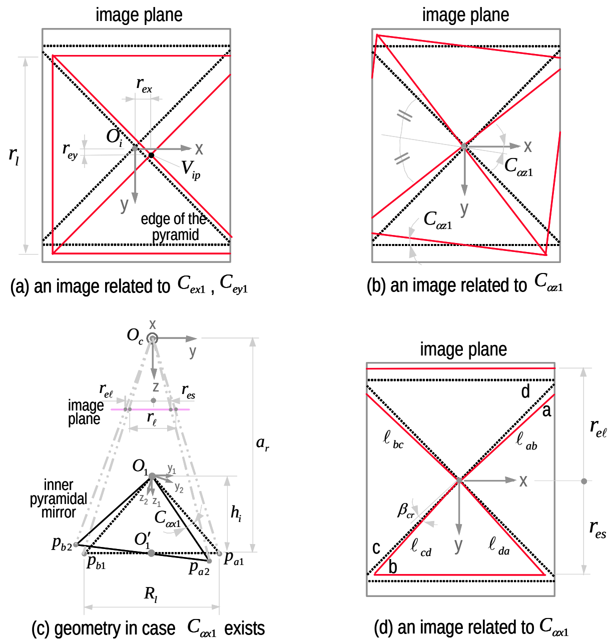

Fig 3. Some images for inner pyramidal mirror calibration

3.4 Relative Rotational Error with respect to X or Y-axis ($C_{\alpha x1}$, $C_{\alpha y1}$)

Fig. 3(c) shows the geometry related with the inner pyramidal mirror in case the relative rotational error $C_{\alpha x1}$ or with respect to x-axis exists. And Fig. 3(d) shows the edge image corresponding to Fig. 3(c). In this case, the border lines ℓ_{ab} and ℓ_{cd} between two faces of the inner pyramidal mirror do not make a straight line but intersect at an angle β_{cr} with each other. The error, $C_{\alpha x1}$ can be obtained from the information on the geometry and the image of Fig. 3(c) and Fig. 3(d). For simplification, only the rotational error $C_{\alpha x1}$ centering around the vertex O_1 of the inner pyramidal mirror is considered. The corner positions p_{a2}, p_{b2} in case $C_{\alpha x1}$ exists can be obtained by coordinate transformation from the corner positions p_{a1}, p_{b1} of the case $C_{\alpha x1}$ is equal to zero[7]. Using relative transformation, p_{a2} and p_{b2} can be obtained by

$$[p_{a2} \quad p_{b2}] = Trans(0, 0, a_r - h_i) Rot(x, C_{\alpha x1}) [{}^{O_1 y_2 z_2}p_{a1} \quad {}^{O_1 y_2 z_2}p_{b1}] \qquad (3)$$

where

$$Trans(0, 0, a_r - h_i) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & a_r - h_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$Rot(x, c_{\alpha x1}) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(C_{\alpha x1}) & -\sin(C_{\alpha x1}) & 0 \\ 0 & \sin(C_{\alpha x1}) & \cos(C_{\alpha x1}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where $Trans(0, 0, a_r - h_i)$ is the transformation corresponding to a translation by a vector $(a_r - h_i)\,\mathbf{k}$, $\mathbf{k}$ is unit vector along the z coordinate axis, $Rot(x, c_{\alpha x1})$ is the transformation corresponding to rotation about the x-axis by an angle $C_{\alpha x1}$, h_i is the height of the inner pyramidal mirror. And ${}^{O_1y_2z_2}p_{a1}$, ${}^{O_1y_2z_2}p_{b1}$ are the position vectors described with respect to the coordinate frame $O_1y_2z_2$. The transformation of Eq. (3) can be interpreted using relative transformation from left to right, as follows: the coordinate frame O_cy_z is first translated by $(a_r - h_i)\,\mathbf{k}$; it is then rotated by an angle $C_{\alpha x1}$ around the current frame x-axis; and then ${}^{O_1y_2z_2}p_{a1}$, ${}^{O_1y_2z_2}p_{b1}$ are described with respect to the current coordinate frame $O_1y_2z_2$. The transformation results p_{a2}, p_{b2} described by the coordinate frame O_cyz are obtained as follows:

$$[{}^{O_1y_2z_2}p_{a1} \quad {}^{O_1y_2z_2}p_{b1}] = \begin{bmatrix} 0 & 0 \\ \frac{R\ell}{2} & -\frac{R\ell}{2} \\ h_i & h_i \\ 1 & 1 \end{bmatrix} \tag{4}$$

$$[p_{a2} \quad p_{b2}] = \begin{bmatrix} 0 & 0 \\ \frac{R_\ell}{2}\cos(C_{\alpha x1}) - h_i\sin(C_{\alpha x1}) & -\frac{R_\ell}{2}\cos(C_{\alpha x1}) - h_i\sin(C_{\alpha x1}) \\ a_r - h_i + \frac{R_\ell}{2}\sin(C_{\alpha x1}) + h_i\cos(C_{\alpha x1}) & a_r - h_i - \frac{R_\ell}{2}\sin(C_{\alpha x1}) + h_i\cos(C_{\alpha x1}) \\ 1 & 1 \end{bmatrix}$$

Using thin lens formula[6] and the geometry of Fig. 3(c), the relationship between $p_{a2,z}$ and $p_{a2,y}$ is obtained by

$$p_{a2,z} = f\left(1 + \frac{p_{a2,y}}{r_{es}}\right) \tag{5}$$

where $p_{a2,z} = a_r - h_i + \frac{R_\ell}{2}\sin(C_{\alpha x1}) + h_i\cos(C_{\alpha x1})$, $p_{a2,y} = \frac{R_\ell}{2}\cos(C_{\alpha x1}) - h_i\sin(C_{\alpha x1})$, f is the focal length of the camera lens, and r_{es} is the distance from the vertex to the side including p_{a2} of the bottom of the inner pyramidal mirror on the image plane as shown in Fig. 3(d). Upon substituting $p_{a2,z}$, $p_{a2,y}$ into Eq. (5), it can be written as

$$a_r - h_i + \frac{R_\ell}{2}\sin(C_{\alpha x1}) + h_i\cos(C_{\alpha x1}) = f\left(1 + \frac{\frac{R_\ell}{2}\cos(C_{\alpha x1}) - h_i\sin(C_{\alpha x1})}{r_{es}}\right) \tag{6}$$

Using $\cos(C_{\alpha x1}) = \sqrt{1 - \sin^2(C_{\alpha x1})}$, Eq. (6) can be rewritten as

$$F_1\sin^2(C_{\alpha x1}) + 2F_2\sin(C_{\alpha x1}) + F_3 = 0 \tag{7}$$

with F_1, F_2, F_3 defined as

$$\begin{aligned} F_1 &= \left(\frac{R_\ell}{2} + \frac{f \cdot h_i}{r_{es}}\right)^2 + \left(h_i - \frac{f \cdot R_e}{2r_{es}}\right)^2 \\ F_2 &= (a_r - h_i - f)\left(\frac{R_\ell}{2} + \frac{f \cdot h_i}{r_{es}}\right) \\ F_3 &= (a_r - h_i - f)^2 - \left(h_i - \frac{f \cdot R_e}{2r_{es}}\right)^2 \end{aligned} \tag{8}$$

Thus, the rotational error $C_{\alpha x1}$ is given by

$$C_{\alpha x1} = \sin^{-1}\left(\frac{-F_2 \pm \sqrt{F_2^2 - F_1F_3}}{F_1}\right) \tag{9}$$

where the + sign corresponds to a positive value of $C_{\alpha x1}$ as shown in Fig. 3(c) and − sign corresponds to a negative value of $C_{\alpha x1}$.

On the other hand, in case the rotational error $C_{\alpha y1}$ with respect to y-axis exists, it can be obtained by using the same method as the one described above for $C_{\alpha x1}$. The best thing is to adjust the positions and orientations of the inner pyramidal mirror in order that no error happens, not to calibrate the errors that happened. Therefore, the first thing is to adjust accurately if there is the way to do so. In case of $C_{\alpha x1}$ and $C_{\alpha y1}$, they can be made to nearly zero by adjusting the orientations of the inner pyramidal mirror so that the border lines ℓ_{ab} and ℓ_{cd}, ℓ_{bc} and ℓ_{da} make a straight line respectively. If their values result in zero, the other calibration parameters of the inner pyramidal mirror such as C_{ez1} and $C_{\alpha z1}$ can be calibrated more simply. In this implementation, the rotational errors $C_{\alpha x1}$ and $C_{\alpha y1}$ were made to zero by accurate adjustment of the inner pyramidal mirror.

4. THE INFLUENCE OF THE PLANE MIRRORS

There are two plane mirrors between the camera and the inner pyramidal mirror. Their positions and orientations of course have an influence on the image of the inner pyramidal mirror taken by the camera. We will investigate how the image of the inner pyramidal mirror changes according to the position and orientation parameters of two plane mirrors respectively. Fig. 4, 5, 6 show the coordinate frames and the geometry related with the influence of the plane mirrors.

First, the translational errors of the plane mirror A in the x'_a or y_a-direction and the translational errors of the plane mirror B in the x'_b or y_b-direction don't change the plane of the corresponding plane mirror at all. In other words, they don't have an influence on the image of the inner pyramidal mirror at all even though they exist. Therefore, there is no need to take them into consideration as the calibration parameters of the sensing system.

On the other hand, from the viewpoint of the image of the inner pyramidal mirror taken by the camera, the translational error t'_{za} of the plane mirror A in the z'_a- direction leads to the same result as the x-axis translational error $C_{ex1} = -t'_{za}/\sin\alpha_a$ and the z-axis translational error $C_{ez1} = -t'_{za}/\sin\alpha_a$ of the inner pyramidal mirror. Fig. 4(a) shows the influence of the z'_a- axis translational error t'_{za}. And the z'_b- axis translational error t'_{zb} of the plane mirror B has the same effect as $C_{ex1} = -t'_{zb}/\sin\alpha_b$ and $C_{ez1} = -t'_{zb}/\sin\alpha_b$ as shown in Fig. 4(b). Here α_a, α_b are the inclination angles of the plane mirror A and B.

Next, the rotation of the plane mirror A and B with respect to z'_a- axis and z'_b- axis respectively don't change the plane of the corresponding mirror at all. Therefore they don't have an influence on the relationship between the actual object space and the camera image space, and they don't need to be taken into consideration as the calibration parameters.

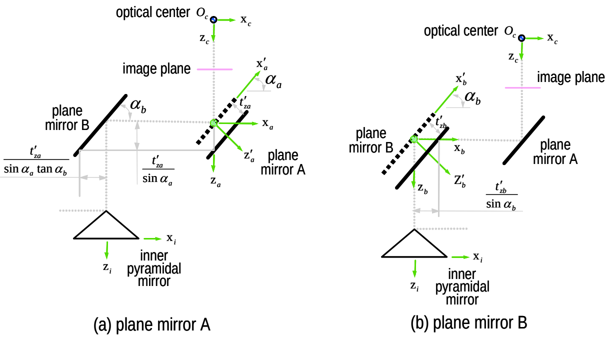

Fig 4. The influence of translation of the plane mirrors

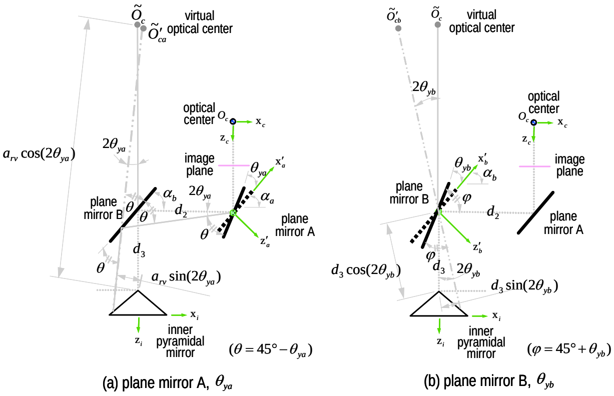

Fig 5. The influence of y-axis rotation of the plane mirrors

Next, the influence of the rotational error θ_{ya}, θ_{yb} of the plane mirror A and B with respect to y_a- axis, y_b- axis is shown in Fig. 5. The error θ_{ya} has the equivalent effect to the rotational error $C_{\alpha y1}=2\theta_{ya}$ with respect to y-axis and the translational error $C_{ex1}=(d_2+d_3)\sin(2\theta_{ya})$ in the x-direction and the translational error $C_{ez1}=-(d_2+d_3)(1-\cos(2\theta_{ya}))$ in the z-direction of the inner pyramidal mirror. And θ_{yb} has the equivalent effect to the rotational error $C_{\alpha y1}=-2\theta_{yb}$ with respect to y-axis and the translational error $C_{ex1}=-d_3\sin(2\theta_{yb})$ in the x-direction and the translational error $C_{ez1}=-d_3(1-\cos(2\theta_{yb}))$ in the z-direction of the inner pyramidal mirror.

Finally, Fig. 6 shows the influence of the rotational error θ'_{xa}, θ'_{xb} of the plane mirror A and B with respect to x'_a- axis, x'_b- axis. The error θ'_{xa} has the equivalent effect to the rotational error $C_{\alpha x1}=2\theta'_{xa}$ with respect to x-axis and the translational error $C_{ey1}=-(d_2+d_3)\sin(2\theta'_{xa})$ in the y-direction and the translational error $C_{ez1}=-(d_2+d_3)(1-\cos(2\theta'_{xa}))$ in the z-direction of the inner pyramidal mirror. And the error θ'_{xb} has the equivalent effect to the rotational error $C_{\alpha x1}=-2\theta'_{xb}$ with respect to x-axis and the translational error $C_{ey1}=d_3\sin(2\theta'_{xb})$ in the y-direction and the translational error $C_{ez1}=-d_3(1-\cos(2\theta'_{xb}))$ in the z-direction of the inner pyramidal mirror. Here d_2 is the distance between two centers of the plane mirror A and B, and d_3 is the distance from the center of the plane mirror B to the vertex of the inner pyramidal mirror.

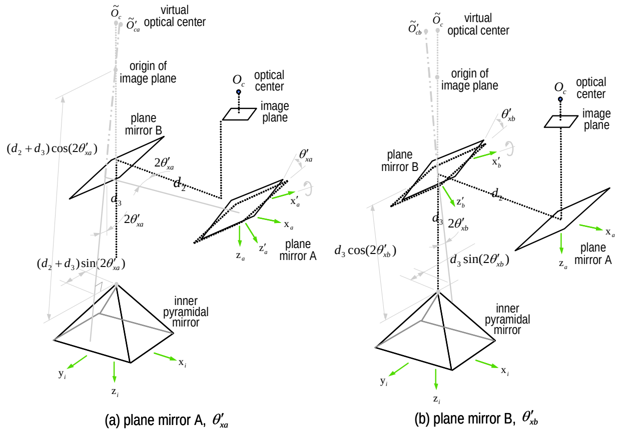

Fig 6. The influence of x-axis rotation of the plane mirrors

As we can see in the above results, the errors of the plane mirrors have no influence on the relationship between the actual object space and the camera image space or have the equivalent effect to the combination of some of the errors of the inner pyramidal mirror. Considering the objective of the system calibration, which is to obtain the accurate mapping relationship between the actual object space and the camera image space, the positions and orientations of the plane mirrors are not indispensable for the system calibration. Instead they can be replaced with the errors of the inner pyramidal mirror. On the other hand, the positions and orientations of the plane mirrors can be adjusted so that there are no errors in them by direct and indirect measurement using various gauges. This will make the calibration of the inner pyramidal mirror simpler and easier.

5. CONCLUSIONS

In order to enhance the accuracy of a measurement system, systematic errors need to be reduced by the system calibration or adjustment. In this paper, a self-imaging method for calibration and adjustment of a visual sensing system with pyramidal mirrors was presented. By using an image of the inner pyramidal mirror taken by the system, the error parameters of the inner pyramidal mirror could be calibrated or adjusted. Also the influence of the plane mirrors was investigated.

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