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A Camera Pose Estimation Method Using a Single Image of Reactor Vessel Upper Head Penetration Nozzles in KSNPs

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1. Introduction

Several remotely operated robotic systems were developed for a inspection or repair of the so called J-Groove weld joining between a reactor pressure vessel head and a vessel head penetration for a sealing of the pressure boundary. In the cases of an automatic J-Groove welding by a robotic system, welding tool and nozzle should be aligned as accurately as possible for the welding tool to track the desired weld path.

As shown in Figure 1, many penetration nozzles are mounted on the inner surface of the upper head. The heights of the lower end of the nozzles are different from each other.

Figure 1. Internal view of the upper head of reactors

This paper offers a camera pose estimation method using a single image of reactor vessel penetration nozzles by assuming that the radius of a nozzle is given and the relative position between two nozzles is known priory.

Simulation results are provided to show the validity of the proposed method.

2. Pose Estimation Algorithm

In Fig. 2, C_1 and C_2 denote the circles of the lower ends of two nozzles with radius r and are located on two parallel planes, π_1 and π_2 respectively. The origin of the coordinate system $\{x_w, y_w, z_w\}$ is located at the center point of C_1 denoted by O_1 and the direction of the z_w-axis is normal to π_1. We selected the direction of x_w as pointing at the center line of the other nozzle and perpendicular to the line.

C_2 is be represented with respect to the coordinate system $\{x_w, y_w, z_w\}$ as $[d_x, 0, d_z]^T$.

We used a pin-hole camera model without radial lens distortions by assuming that such distortions are compensated for and the intrinsic parameters are known from prior camera calibration processes such as Tsai's method. Denoting a camera coordinate system by $\{x_c, y_c, z_c\}$, the image forming process can be modeled as follows.

$$\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \end{bmatrix} \begin{bmatrix} x_w \\ y_w \\ z_w \\ 1 \end{bmatrix} \equiv [\tilde{R} \mid T] \begin{bmatrix} x_w \\ y_w \\ z_w \\ 1 \end{bmatrix} \quad (1)$$

$$\tilde{R} \equiv [r_1 \; r_2 \; r_3] = Rot(z, R_z)Rot(y, R_y)Rot(x, R_x) \quad (2)$$

$$z_f \begin{bmatrix} x_f \\ y_f \\ 1 \end{bmatrix} = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = \tilde{K} \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} \quad (3)$$

In Eq. (1), $\tilde{R}$ a is 3x3 rotation matrix and T is a 3x1 translation vector between $\{x_w, y_w, z_w\}$ and $\{x_c, y_c, z_c\}$ corresponding to camera pose information

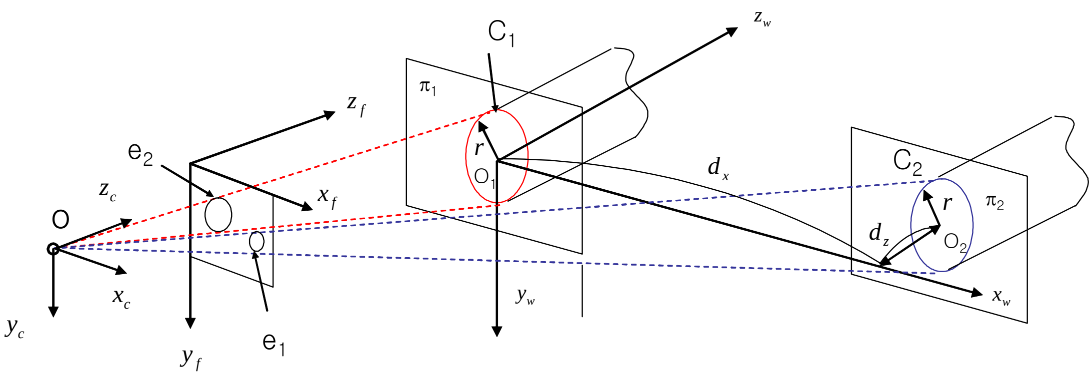

Figure 2. Coordinate systems

w.r.t. the world coordinates.

Fig.3 (a) and (b) depict two nozzles w.r.t. the world coordinates and the image coordinates respectively. l_∞ is the line at infinity of π_1 and $v_{x\infty}, v_{y\infty}, v_{z\infty}$ are the vanishing points along x_w, y_w, z_w respectively.

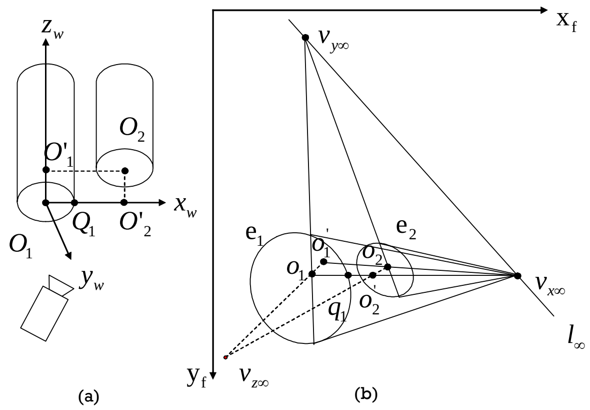

Figure 3. Two nozzles and their image

Generally, two of the four intersection points of the elliptic images, e_1 and e_2, that are the projected elliptical images of C_1 and C_2 are complex-conjugate and can be represented by z and $\bar{z}$ satisfying the following equation.

$$z^T\tilde{K}^{-T}\tilde{K}^{-1}z = 0. \quad \bar{z}^T\tilde{K}^{-T}\tilde{K}^{-1}\bar{z} = 0 \tag{4}$$

Because z and $\bar{z}$ are on l_∞, l_∞ can be obtained as follows.

$$l_\infty = z \times \bar{z} \tag{5}$$

By a pole-polar relation, o_1 and o_2, that are the projected points of O_1 and O_2 are obtained by using 3x3 ellipse matrixes $\tilde{e}_1, \tilde{e}_2$ as follows.

$$o_1 = \tilde{e}_1^{-1} l_\infty, \quad o_2 = \tilde{e}_2^{-1} l_\infty \tag{6}$$

If we define $d(x, y)$ as the distance between two points x and y, $v_{x\infty}, v_{y\infty}, v_{z\infty}$ can be retrieved by the following equations.

$$z^T\tilde{K}^{-T}\tilde{K}^{-1}v_{z\infty} = 0 \tag{7}$$

$$cr(o_1, q_1, o'_1, v_{x\infty}) = \frac{d(o_1, o'_1)}{d(o_1, v_{x\infty})}\frac{d(q_1, v_{x\infty})}{d(q_1, o'_1)} = \frac{d_x}{d_x - r} \tag{7}$$

$$v_{y\infty} = \tilde{e}_1^{-1}(o_1 \times v_{x\infty}) \tag{8}$$

Reconstruction procedure of $\tilde{R}$ is as follows;

$$r_1 = \tilde{K}^{-1}v_{x\infty} / \left\|\tilde{K}^{-1}v_{x\infty}\right\|, r_2 = \tilde{K}^{-1}v_{y\infty} / \left\|\tilde{K}^{-1}v_{y\infty}\right\|, r_3 = r_1 \times r_2 \tag{9}$$

T can also be reconstructed by the following equations.

$$s_1 o_1 = \tilde{K}T, \; s_2 o_2 = \tilde{K}(r_1 d_x + r_3 d_z + T) \tag{10}$$

3. Simulation

As geometric parameters of two nozzles, we used r =57mm, d_x =349mm, d_y = -125mm. Fig. 4 shows $v_{x\infty}, l_\infty, o_1, o'_1, o_2, o'_2$ obtained by a Simulation. Pose estimation results for several cases are provided by Table 1 and it shows that the pose estimation errors are vary with real camera poses.

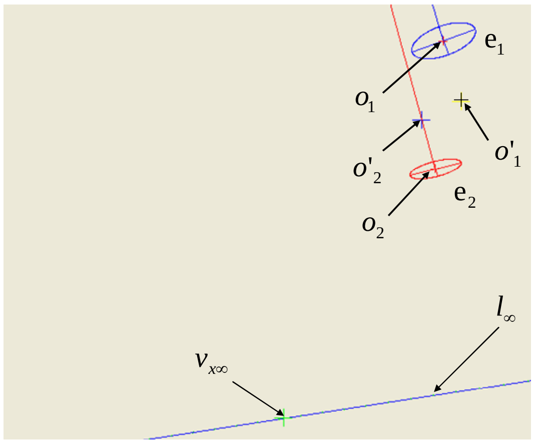

Figure 4. $v_{x\infty}, l_\infty$ by Simulation

Table 1. Pose estimation results Simulation

	Simulation #1		Simulation #2	
	real	result	real	result
t_1 (mm)	-10	-9.9	400	410.1
t_2 (mm)	-200	-197.8	-300	-307.6
t_3 (mm)	1000	988.8	1200	1230.2
R_x (deg)	20	20.2	20	17.1
R_y (deg)	-20	-19.8	-60	-60.6
R_z (deg)	80	79.4	60	63.4

4. Conclusion

We proposed a camera pose estimation method using a single view of two penetration nozzles of a reactor vessel head in order to provide a relative pose of a camera w.r.t. the reactor head. The estimated relative camera pose should be combined with the tool pose w.r.t. the camera in order to get the tool pose w.r.t. the reactor head. The simulation results are not satisfactory but we expect that the better results could be produced if truncation errors are reduced. Experimental works will be performed as a further work.

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