Visual Servoing Using Online Calibration

Young-Sik Cho[*], Jeh-Won Lee[**], Hae-Ho Joo[**]

***Abstract*—The pose error of the robot-vision system is dependent on the camera calibration and robot kinematics. This article demonstrates that the visual servoing system can remove the steady state error of the 6-DOF serial type robot-vision system. This system uses the ECL proportional control law of the dynamic position based look and move structure. Additionally, the stability and the performance of the visual servoing system are very associated with the calibration. This article proposes the online calibration using the DLT method and shows that this method has effect on improving the performance and the stability of the visual servoing system through the experiment which makes the unstable system stable**

Index Terms— **Direct Linear Transformation, Online Calibration, Robot Vision, Visual Servoing**

I. Introduction

Vision sensor has been used in the robotic system because it is non-contact sensor and similar to the human eyes. In order to use robot-vision system, the camera calibration must be preceded.

The calibration is finding the relationship that includes image center, focal length, the transformation matrix between reference coordinates and camera coordinates. Because the image space values are transformed into the real space values by the calibration, the calibration error is directly related to the real pose error. Therefore, several effective calibration methods have been studied to reduce the calibration error.

However, the pose error cannot be overcome only by the calibration methods because of the nonlinear elements of the camera. In some case, there is the case where the calibration is impossible.

As the feedback system can overcome the limit of the open loop system, the visual servoing method was applied to cope with such problems in the robot-vision system by Y. Shirai[1] and J. Hill [2] first. Krupa[3] applied the visual servoing into the configuration control of surgical robot using a laser point. G. D. Harger[4] studied various implementation method in the real world. R. Mori[5] makes an experiment on the moving work piece in 3D space.

In this paper, we demonstrate that the precision work of 6 d.o.f. robot vision system without the steady-state error can be achieved by the experimental visual servoing. Because the calibration make effect on the performance and stability of robot-vision system., the online calibration method using DLT (Direct Linear Transformation) are used in the visual servoing. It is another object of this paper that the online calibration method using DLT can make the unstable visual servoing system stable.

II. Visual Servoing Using Online Calibration

A. Proportional Control of 6 d.o.f. visual servoing robot

ECL(End point Closed Loop) type visual servoing can cope with the calibration error because both value, the reference value and end effector pose value, are defined in the image space. In this paper, DLMS(Dynamic position based Look and Move Structure) method classified by Sanderson[6] is used as shown in Fig. 1. The control input ,when DLMS control law is used, is produced by eq. (1).

$$\mathbf{u} = KJ^{-1}\begin{bmatrix} \tilde{\mathbf{p}}_r - \tilde{\mathbf{p}}_e \\ \tilde{\theta}\,\tilde{\mathbf{s}} \end{bmatrix} \tag{1}$$

Where, K is proportional gain, J is robot Jacobian, , $\mathbf{p}_r$ and $\mathbf{p}_e$ are the position vector of reference coordinates and robot end effector coordinates respectively, $\mathbf{s}$ is the unit vector of rotation center between reference coordinates and robot end effector coordinates, θ is rotation angle, '~' is the estimated value by camera calibration

The Jacobian can be obtained from eq. (2)

$$J = [J_1, J_2, ..., J_n] \tag{2}$$

for a revolute joint,

$$J_i = \begin{bmatrix} \mathbf{z}_{i-1} \times {}^{i-1}\mathbf{p}*_n \\ \mathbf{z}_{i-1} \end{bmatrix}$$

and for a prismatic joint

$$J_i = \begin{bmatrix} \mathbf{z}_{i-1} \\ 0 \end{bmatrix}$$

where,

$$\begin{aligned} \mathbf{z}_{i-1} &= R_{i-1}[0\ \ 0\ \ 1]^T \\ {}^{i-1}\mathbf{p}*_i &= R_{i-1}\,{}^{i-1}\mathbf{r}_i \\ {}^{i-1}\mathbf{r}_i &= {}^{i-1}A_i[0\ \ 0\ \ 0\ \ 1]^T \end{aligned} \tag{3}$$

From eq. (1), $\tilde{\theta}$ and $\tilde{\mathbf{s}}$ can be obtained as follows.

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$$\tilde{\theta} = \cos^{-1}\frac{\tilde{i}_x + \tilde{j}_y + \tilde{k}_z - 1}{2} \tag{4}$$

$$\tilde{\mathbf{s}} = \begin{bmatrix} \dfrac{\tilde{j}_z - \tilde{k}_y}{2s\tilde{\theta}} & \dfrac{\tilde{k}_x - \tilde{i}_z}{2s\tilde{\theta}} & \dfrac{\tilde{i}_y - \tilde{j}_x}{2s\tilde{\theta}} \end{bmatrix}^T \tag{5}$$

From eq.(4) and (5), the unit vectors, **i**, **j**, **k** can be obtained from eq. (6).

$$\begin{bmatrix} \tilde{\mathbf{i}} & \tilde{\mathbf{j}} & \tilde{\mathbf{k}} & \tilde{\mathbf{p}} \\ 0 & 0 & 0 & 1 \end{bmatrix} = \tilde{R}_e \tilde{A}_e^{-1} \tilde{A}_r \tag{6}$$

where, A_e and A_r are the transformation matrix of the robot end effector coordinates and target coordinates with respect to the reference coordinates, R_e is the rotation matrix of A_e.

B. *Online Calibratin using DLT*

Eq. (1)~(6) can make the visual servoing system to track to the reference value. However, the performance of tracking depends on the calibration. So a good calibration method is needed for the system to have the high proportional gain and be stable.

In this paper, online calibration technique is used to adjust the calibration error. Fig. 1 shows the block diagram of visual serving system using the online calibration.

The feedback system basically uses DLMS type. The DLT(Direct Linear Transform)[7] calibration parameter is updated by measuring the robot joint angle and image value of robot end point. Fig. 2 shows the schematic diagram of pin-hole camera for DLT calibration.

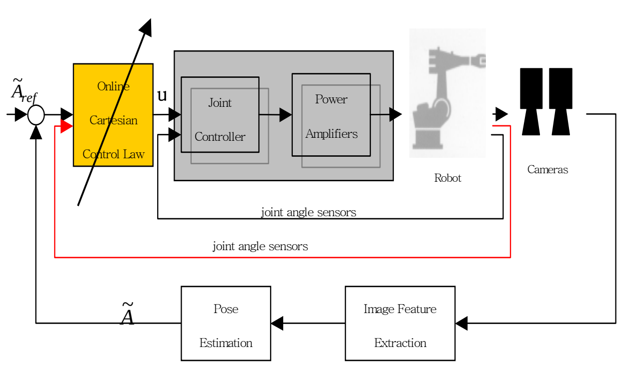

Fig. 1. Block diagram of Dynamic position based Look and Move Structure type visual servoing system using online calibration

For the calibration of camera model of Fig. 2, the number of DLT parameter is 11 and the number of necessary control point is at least 6. Where, W is reference coordinates, C is camera coordinates, **p** is the 3D position vector, **q** is the projected 2D position vector of **p**, **c** is image center, *f* is focal length, [u, v] are coordinates of image space.

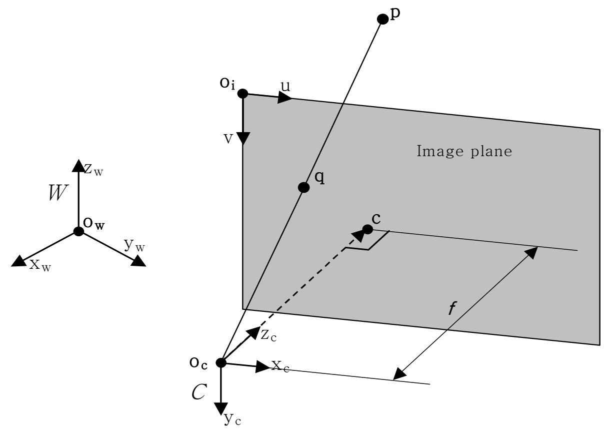

Fig. 2. Pin-hole Camera Model

DLT parameters of k th measurement, L_{1k}~$L_{11k,}$ are updated as eq. (7).

$$\begin{aligned} \mathbf{L}_k &= A_k^{-1} B_k \\ A_k &= A_{k-1} + {}_{k-1}X_k^t \, {}_{k-1}X_k \\ B_k &= B_{k-1} + {}_{k-1}X_k^t \, {}_{k-1}Y_k \, . \end{aligned} \tag{7}$$

Where, A_0 and B_0 are initial constants computed from the first calibration parameters. They are expressed by 6 control points as follows.

$$A_o = \begin{bmatrix} p_{x1} & p_{y1} & p_{z1} & 1 & 0 & 0 & 0 & 0 & -q_{u1}p_{x1} & -q_{u1}p_{y1} & -q_{u1}p_{z1} \\ 0 & 0 & 0 & 0 & p_{x1} & p_{y1} & p_{z1} & 1 & -q_{v1}p_{x1} & -q_{v1}p_{x1} & -q_{v1}p_{x1} \\ & & & & & \vdots & & & & & \\ p_{x6} & p_{y6} & p_{z6} & 1 & 0 & 0 & 0 & 0 & -q_{u6}p_{x6} & -q_{u6}p_{y6} & -q_{u6}p_{z6} \\ 0 & 0 & 0 & 0 & p_{x6} & p_{y6} & p_{z6} & 1 & -q_{v6}p_{x6} & -q_{v6}p_{x6} & -q_{v6}p_{x6} \end{bmatrix}$$

$$B_o = [q_{u1}, q_{v1} \cdots q_{v6}, q_{v6}]^T \tag{8}$$

${}_{k-1}X_k$ and ${}_{k-1}Y_k$ are obtained from k-th measured control points as follows.

$${}_{k-1}X_k = \begin{bmatrix} p_{xk} & p_{yk} & p_{zk} & 1 & 0 & 0 & 0 & 0 & -q_{uk}p_{xk} & -q_{uk}p_{yk} & -q_{uk}p_{zk} \\ 0 & 0 & 0 & 0 & p_{xk} & p_{yk} & p_{zk} & 1 & -q_{vk}p_{xk} & -q_{vk}p_{xk} & -q_{vk}p_{xk} \end{bmatrix}$$

$${}_{k-1}Y_k = \begin{bmatrix} q_{uk} \\ q_{vk} \end{bmatrix} \tag{9}$$

In case of the camera model referred in this paper, eq. (7) needs the summation of 11×11 matrices and inverse matrix without regard to the number of measurement.

III. Experiments

In this paper, the position and direction of end effector coordinate coincident with those of end point of wire. We check the response of visual servoing system while increasing the proportional gain from 0.1 to 1.0, and choose the stable gain. After the intentional calibration error is inserted into the stable system, we will check the effect of the online calibration with respect to the fixed calibration. Fig. 3 shows the experimental setup.

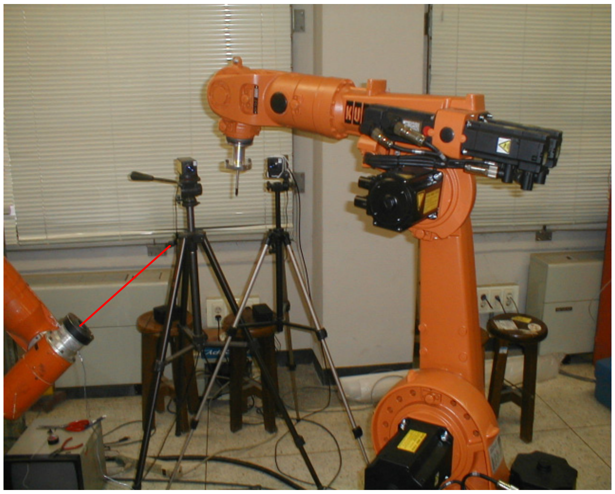

Fig. 3. Experiment System

The experimental system is consists of Robot - KR 15/2 of KUKA, Stereo Camera - XC003 model of Sony, Lens of f = 25mm and 1:1.4 of COSMICAR/PENTAX, Frame grabber - DT3133 of DATA TRANSLATION, A/D and D/A transformer - Flex Motion 6c of NI and Comi-sd104 of COMIZOA, Interface device - BK5200 of Device Net.

Table 1 shows the initial values of interior calibration of sterero camera. The initial calibration is achieved using the vanishing point. A regular hexahedron is used as the test workpiece. Eqs. (10), (11) is the results of exterior calibration. The exterior calibration using a vanishing point use rectangular plate whose size is 57.0mm ±1.0mm. Even though a large number of calibration give a good calibration results, calibration is carried out one time because the precise calibration is not required.

TABLE 1. INTERIOR CALIBRATION RESULT OF STEREO CAMERA

	LEFT CAMERA	RIGHT CAMERA
c_u	307.2954	310.1756
c_v	274.7008	269.5568
f	2700.8918	2506.1164

$$A_{Left} = \begin{bmatrix} -0.2457 & -0.1351 & 0.9599 & -775.2718 \\ -0.9391 & 0.2120 & -0.2703 & -652.1875 \\ -0.2401 & -0.9679 & 0.0748 & 1315.7796 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{10}$$

$$A_{Right} = \begin{bmatrix} 0.1002 & 0.01703 & 0.9948 & -811.1724 \\ -0.9537 & 0.2866 & 0.0912 & -868.3046 \\ -0.2835 & -0.9579 & 0.0450 & 1305.9446 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{11}$$

Fig. 4 ~ Fig. 6 shows the experimental result of visual servoing system when an intentional calibration error is not given and the proportional control gain is 0.1. Fig. 4 shows the trajectory of robot end effector and reference input measured by the right camera. Fig. 5 and Fig. 6 shows the time response of u(t) and v(t) of the right camera respectively.

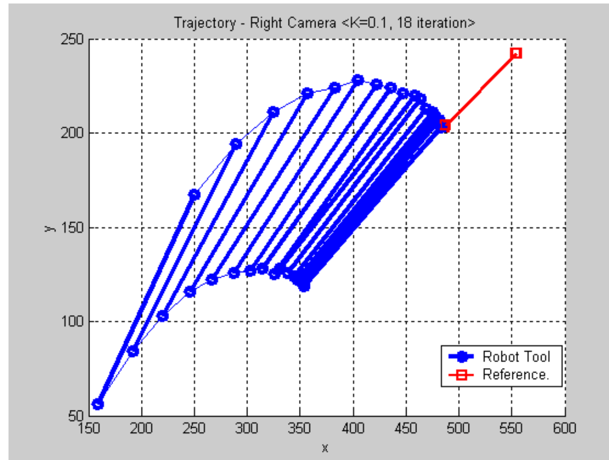

Fig. 4. Robot End Effector Trajectory w.r.t Right Camera (K=0.1, without Calibration Offset)

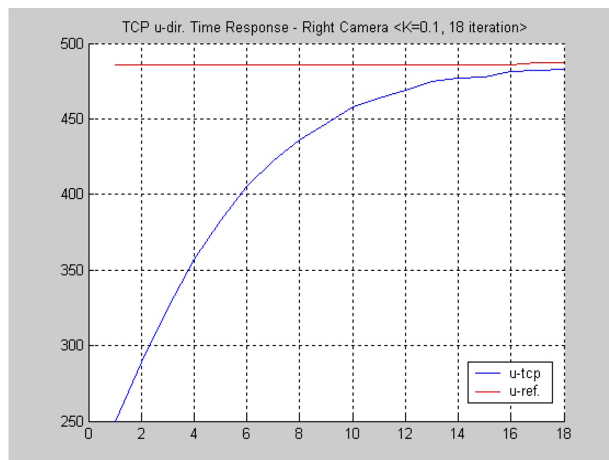

Fig. 5. Robot End Effector u(t) Response w.r.t Right Camera (K=0.1, without Calibration Offset)

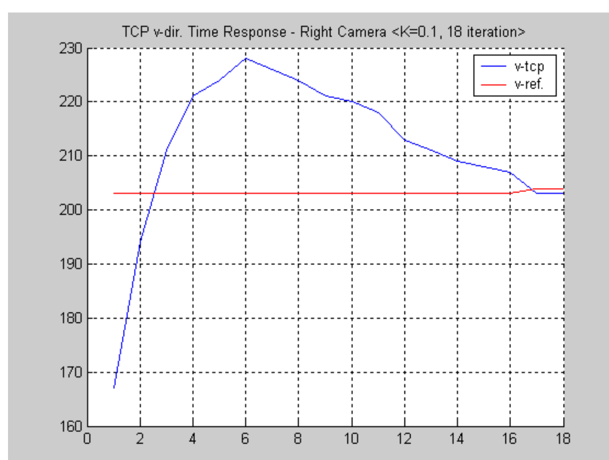

Fig. 6. Robot End Effector v(t) Response w.r.t Right Camera (K=0.1, without Calibration Offset)

When the proportional gain is 0.1, v(t) shows the response of a sluggish and some overshoot. Even though the calibration error exists initially, 6 dof robot carry out the errorless operation using the visual servoing.

As the proportional gain is increasing, the converge speed is faster and v(t) show more overshoot response. However, u(t) does not show overshoot response. The unstable response occurs when the proportional gain becomes above 0.7.

Fig. 7 ~ Fig. 9 are the experimental results when the proportional gain is 0.5 and the intentional calibration errors are given by 30°, 300mm in x-direction and z-direction respectively and the online calibration is not given. Fig. 7 shows the trajectory of robot end effector and reference input measured by the right camera. Fig. 8 and Fig. 9 shows the time response of u(t) and v(t) of the right camera respectively. We can observe that the system become unstable by Fig. 7 ~ Fig. 9

The system becomes unstable at 0.7 proportional gain when intentional calibration error is not given. On the other hand, the system become unstable at 0.5 proportional gain when intentional calibration error is given. A bigger calibration error results a lower proportional gain for unstable system. Therefore, a small calibration error is required for a good performance of visual servoing system.

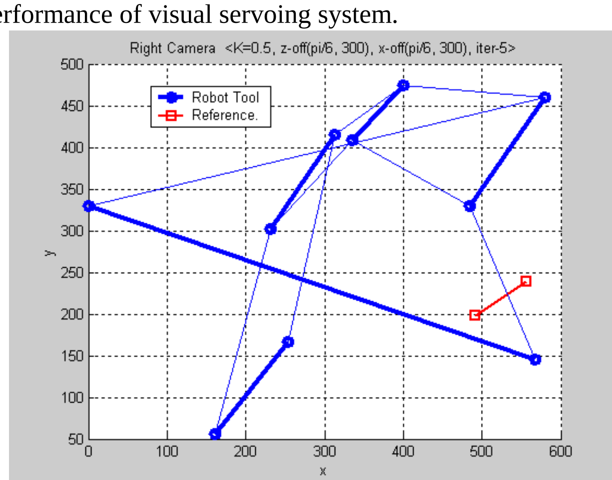

Fig. 7. Robot End Effector Trajectory w.r.t Right Camera
(K=0.5, with x and z-dir Offset, without Online Calibration)

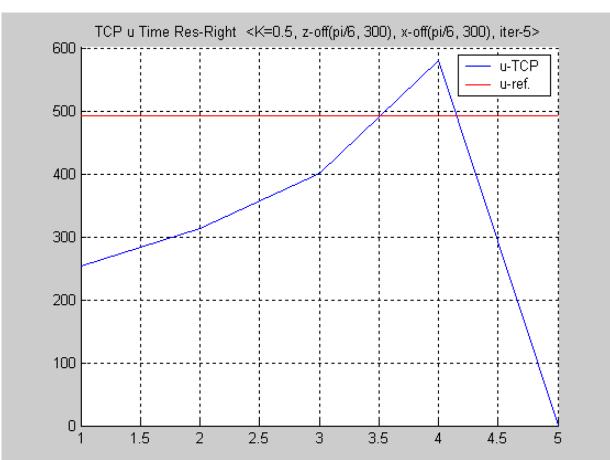

Fig. 8. Robot End Effector u(t) Response w.r.t Right Camera
(K=0.5, with x and z-dir Offset, without Online Calibration)

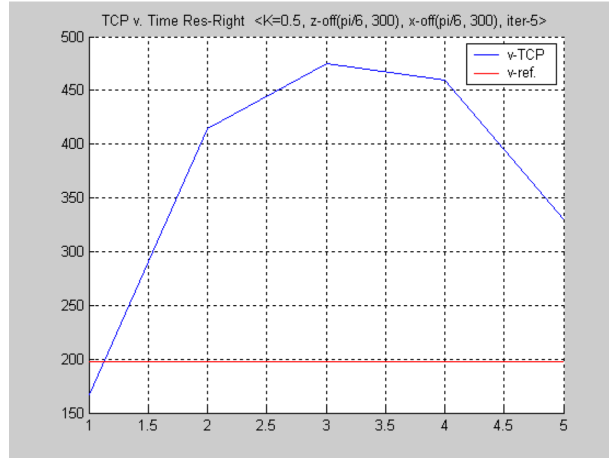

Fig. 9. Robot End Effector v(t) Response w.r.t Right Camera
(K=0.5, with x and z-dir Offset, without Online Calibration)

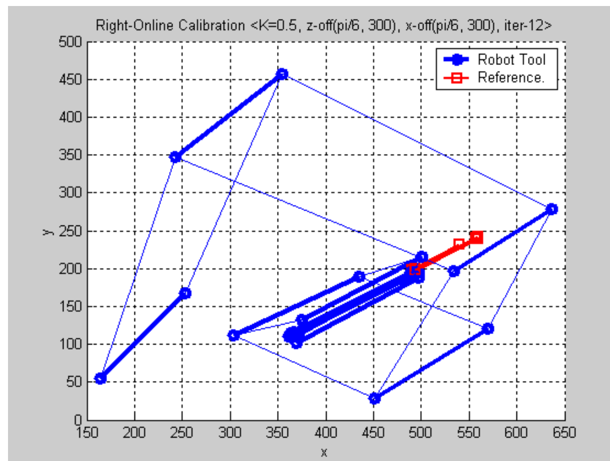

Fig. 10. Robot End Effector Trajectory w.r.t Right Camera
(K=0.5, with x and z-dir Offset, with Online Calibration)

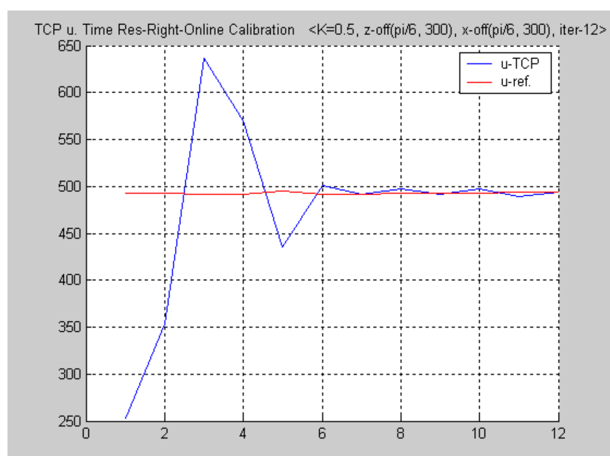

Fig. 11. Robot End Effector u(t) Response w.r.t Right Camera
(K=0.5, with x and z-dir Offset, with Online Calibration)

Fig. 10 ~ Fig. 12 are the experimental results when the online calibration scheme is applied with the same conditions of Fig. 7, ~ Fig. 9. Fig. 10 shows the trajectory of robot end effector and reference input measured by the right camera. Fig. 11 and Fig. 12 shows the time response of u(t) and v(t) of the right camera respectively. In these figures, we can observe that the position error is decreasing and finally become a zero as the time pass.

These figures demonstrate the effect of the online calibration scheme on the visual servoing.

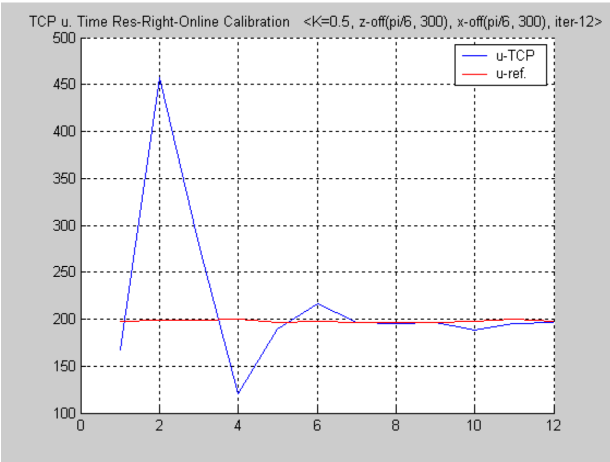

Fig. 12. Robot End Effector v(t) Response w.r.t Right Camera (K=0.5, with x and z-dir Offset, with Online Calibration)

The pictures of both camera shows the position and direction of robot end effector coincide with those of workpiece as shown in Fig. 13

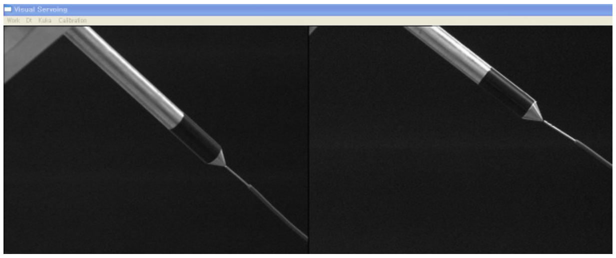

Fig. 13. Left Camera and Right Camera Image of Robot End Effector and Target Work of Steady State.

IV. Conclusions

In this paper, we show that 6 dof serial type robot can accomplish a precision work by the online calibration scheme even if the calibration error is exist in the Dynamic Position Based Look And Move Structure type visual servoing system.

Therefore, in case of the calibration is not permitted when the environment is frequently changed, this scheme is very useful in the visual servoing system.

It is verified experimentally that the performance and stability is depends on the accuracy of calibration by experiment. The online calibration can compensate the degrade of the performance and stability due to the calibration error

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