Controlling Robot Arm Manipulator Using Image-Based Visual Servoing without Pre-Depth Information

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***Abstract*—This paper presents an image based visual servoing of 5 degrees-of-freedom (DOF) manipulator not knowing the depth information in advance. In general, visual servoing and plant (robot) control is constructed as single algorithm, combining feature (image) Jacobian with plant Jacobian considering plant dynamics. In this paper, however, we separate visual servoing from plant control. Image information obtained from camera is transformed into angle information by using forward and inverse kinematics and these values are transferred to control module in order to manipulate robot arm. The proposed control system is verified through the experiment.**

I. Introduction

When controlling plant or system, feedback from various sensor inputs are important to get fine performance. Visual servoing [1] is one of the control methods using vision (image) data as feedback signal for control. Visual servoing can be divided into two approaches with regard to the way the vision data is used in control algorithm: image-based visual servoing (IBVS), in which the features extracted from vision data are used directly, and position-based visual servoing(PBVS), in which three dimensional coordinates is estimated from vision data. Also, depending on how many cameras are used or where the cameras are attached, there can exist a lot of configurations. In order to estimate 3D coordinates from vision data, at least two cameras are needed. Most of robot arm manipulators, however, have single camera at the end-effector. Therefore IBVS is usually used for manipulator control and the main concern is how to obtain depth (Z) information from the vision data. Various researches have been conducted for IBVS estimating depth information so far [2], [3], [4], [5], [6]. In most of cases, authors dealt with interaction matrix, i.e. feature Jacobian for IBVS and combined IBVS control with plant control algorithm. This approach can be effective in the case that a whole procedure including designing robot body and control algorithm is conducted by single person or team. However, if the scale is large, tasks cannot be done by single team. Thus role of each procedure cannot be fully understood and information can be exchanged only through some interfaces. In this paper, we separate visual servoing from plant control. Image information obtained from camera is transformed into angle information by using forward and inverse kinematics instead of Jacobians and dynamics and these values are transferred to control module in order to manipulate robot arm. The proposed algorithm is verified through experiment. The rest of paper will be organized as follows. Section II presents control schemes using IBVS in this paper. Some backgrounds regarding IBVS are introduced and main characteristics of the proposed algorithm will be described. The experimental results are shown in section III. Finally, we make a conclusion in section IV.

II. Control Scheme Design

In this paper, a 5-DOF robot arm manipulator is presented. Fig. 1 shows a brief structure of the manipulator. Since vision data from single camera at the end-effector is given as feedback signal, user cannot fully obtain the 3D position of target object. Therefore depth has to be estimated. We divide motions of the manipulator into two classes: moving in lateral direction and moving in frontal direction with respect to camera frame. The manipulator moves in lateral direction until depth is estimated, and then it approaches target object. Details of schemes are explained below.

A. Image-based Visual Servoing

In order to align the manipulator near target object, the position of target object has to be computed by using vision information from camera as in (1).

$$\begin{aligned} X_c &= \frac{(u-c_u)Z_c}{f\alpha} \\ Y_c &= \frac{(v-c_v)Z_c}{f} \end{aligned} \qquad (1)$$

Here, u, v are the coordinates of the image point expressed in pixel units and c_u, c_v are the coordinates of principal

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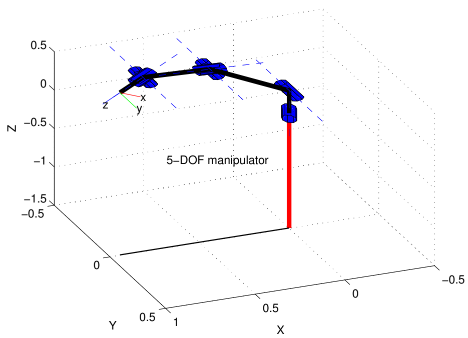


Fig. 1: 5-DOF robot arm manipulator

point of camera expressed in pixel units. X_c, Y_c, Z_c are 3-D coordinates of object with respect to camera frame. Then 3-D coordinates of target object with respect to camera frame is transformed into those with respect to base frame as in (2).

$$\begin{bmatrix} X_o \\ Y_o \\ Z_o \\ 1 \end{bmatrix} = {}^0A_1\,{}^1A_2\,{}^2A_3\,{}^3A_c\,{}^cA_4\,{}^4A_5 \begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} \quad (2)$$

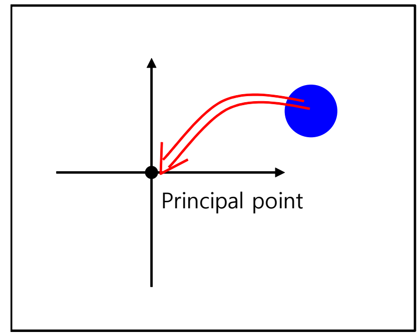
Here, X_o, Y_o, Z_o is 3-D coordinates of object with respect to base (joint 0) frame and ${}^iA_j$ is transformation matrix between joint i and j.

As can be seen in (1), x and y coordinates with respect to camera frame is proportional to z coordinate. Therefore depending on z coordinate, position of target object can be estimated.

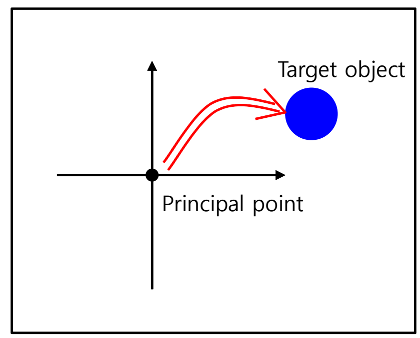
B. Estimated Displacement of the Manipulator

For alignment, robot arm manipulator moves so that the center point of target object can be located at the principal point of camera. As shown in Fig. 2, a moving distance of camera reaching the center point of target object is equivalent to a moving distance of target object reaching the principal point of camera. As for moving distance of target object, joint angles of the manipulator are fixed and the distance can be easily computed using forward kinematics from current position. However, when camera, that is, the manipulator is moving, joint angles at goal position are different from those at start position. What's more, they are not known. Based on this point, we computed moving distance of camera as if target object is supposed to move.

As mentioned before, the goal in this paper is to align the manipulator near to target object. That is, the coordinates of the center point of target object (u, v) expressed in pixel units should be located at principal points (c_u, c_v) when the manipulator arrives at goal position. Therefore moving distance of target object with respect to camera frame ΔD_t^c can be computed as in (3).



(a) target object approaches principal point of camera



(b) principal point of camera approaches target object

Fig. 2: Movement in the image plane

$$\Delta D_t^c = \begin{bmatrix} \Delta X_t^c \\ \Delta Y_t^c \\ \Delta Z_t^c \end{bmatrix} \quad (3)$$

$$\Delta X_t^c = \frac{(c_u - u)Z}{f\alpha}$$

$$\Delta Y_t^c = \frac{(c_v - v)Z}{f}$$

$$\Delta Z_t^c = 0$$

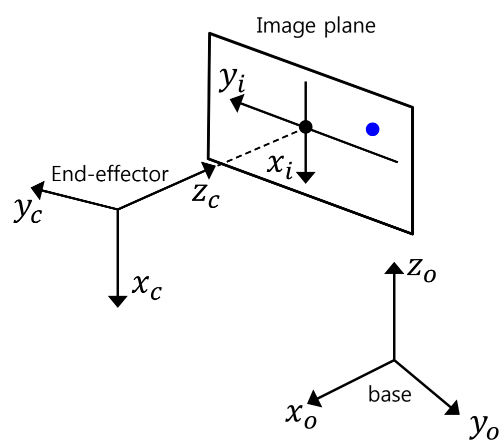
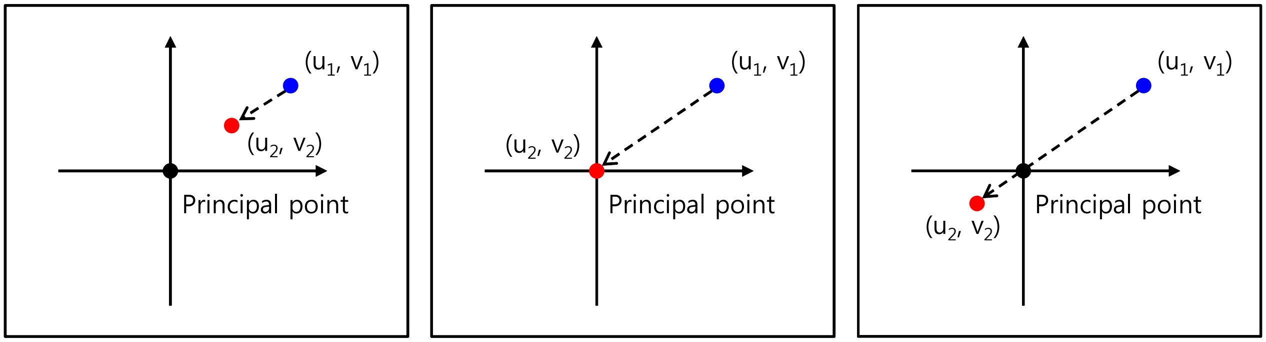


Fig. 3: base and end-effector (camera) frame



(a) when estimated value is smaller than actual (b) when estimated value is equal to actual (c) when estimated value is larger than actual

Fig. 4: lateral movement of the end-effector

As seen in Fig. 3, the principal point of camera (black dot) moves in the reverse direction of target object (blue dot). So moving distance of camera with respect to camera frame ΔD_c^c is changed as in (4).

$$\Delta D_c^c = \begin{bmatrix} \Delta X_c^c \\ \Delta Y_c^c \\ \Delta Z_c^c \end{bmatrix} \tag{4}$$

$$\Delta X_c^c = -\Delta X_t^c = \frac{(u - c_u)Z}{f\alpha}$$

$$\Delta Y_c^c = -\Delta Y_t^c = \frac{(v - c_v)Z}{f}$$

$$\Delta Z_c^c = 0$$

Then moving distance of camera with respect to base (joint 0) frame ΔD_c^o can be computed as in (5).

$$\begin{bmatrix} \Delta D_c^o \\ 1 \end{bmatrix} = {}^0A_1 \, {}^1A_2 \, {}^2A_3 \, {}^3A_c \, {}^cA_4 \, {}^4A_5 \begin{bmatrix} \Delta D_c^c \\ 1 \end{bmatrix} \tag{5}$$

Here, note that moving distance of camera along Z axis with respect to camera frame is 0. Therefore camera, that is, robot arm manipulator always moves in lateral direction and even though Z is unknown, movement is not affected at all.

Since Z cannot be exactly measured by single camera, Z has to be estimated. In our project, while repetitively moving robot manipulator in lateral direction and returning to initial position, we estimate Z value.

As seen in Fig. 4, lateral movement of the manipulator depends on estimated Z. (u_1, v_1) is the position of target object in the image plane before lateral movement of the manipulator and (u_2, v_2) is the position of target object in the image plane after lateral movement. When estimated value is smaller than actual Z, target object before moving and after moving is located at the same quadrant in the image plane. On the contrary when it is bigger than actual Z, target object before moving and after moving is located at different quadrant. As mentioned before, the position of target object in the image plane after the movement should be located at principal points of camera. Therefore control policy of Z estimation is as follows.

- If target object before moving and after moving is located at different quadrant in the image plane, estimated Z is bigger and it should be decreased.
- Otherwise, estimated Z is smaller and it should be increased.

Fig. 5 shows the flow chart of Z estimation.

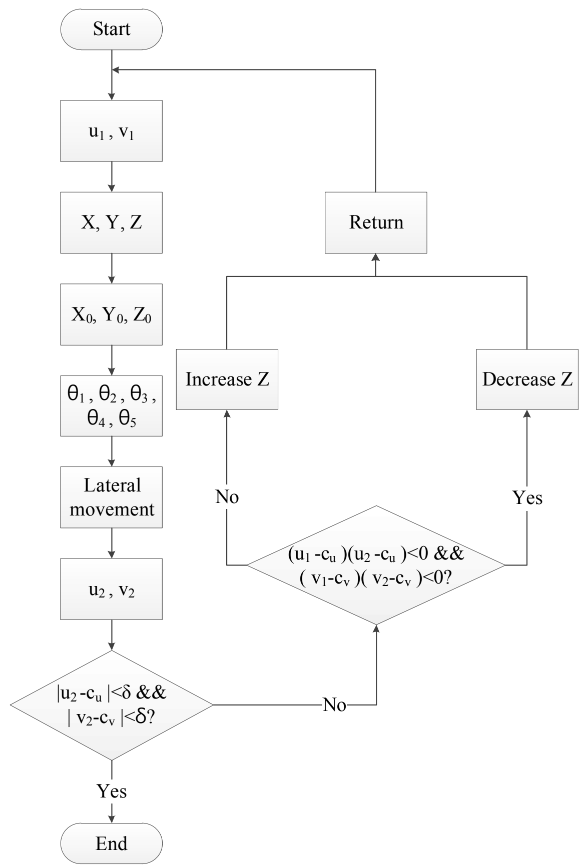
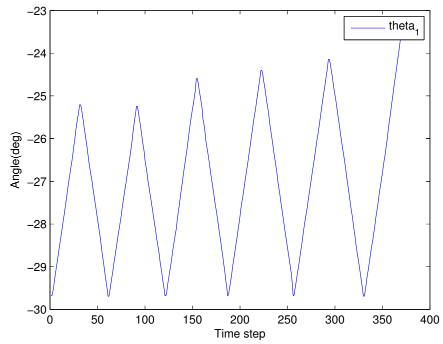


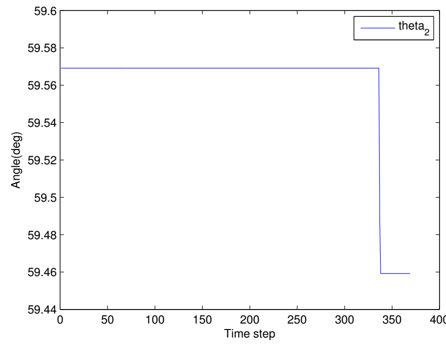
Fig. 5: Flow chart of Z estimation

III. Experimental Results

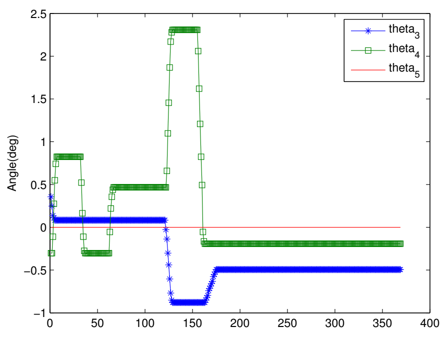
As mentioned before, we used 5-DOF robot arm manipulator attaching single camera at the end-effector for experiment. In the experiment, we set an initial guess of Z to be smaller



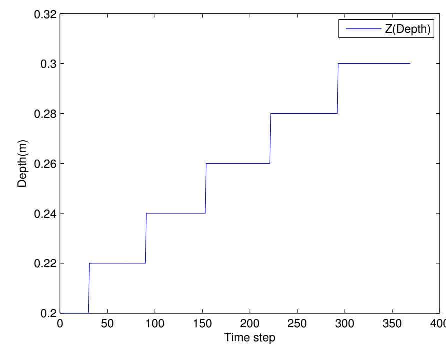
(a) θ_1



(b) θ_2

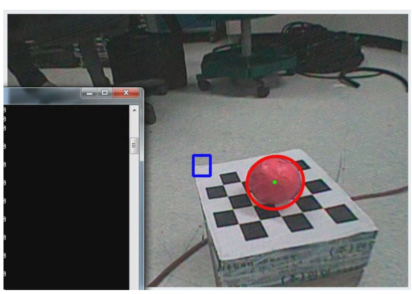


(c) $\theta_3, \theta_4, \theta_5$

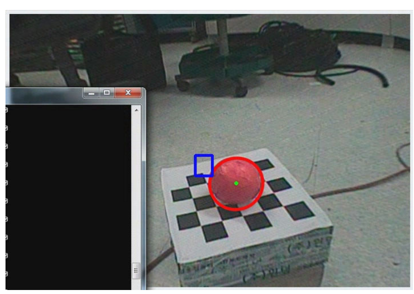


(d) estimated Z

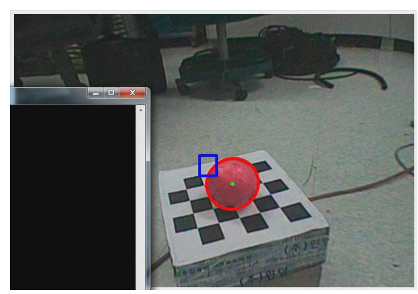
Fig. 6: Joint angle and estimated Z values during estimation



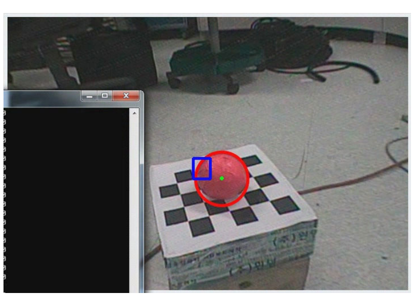
(a) Initial position



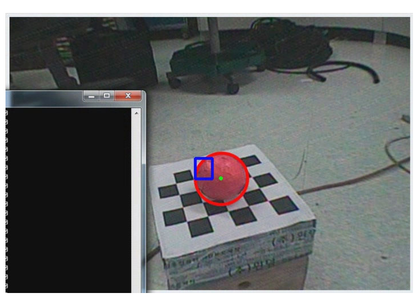
(b) After 1st iteration



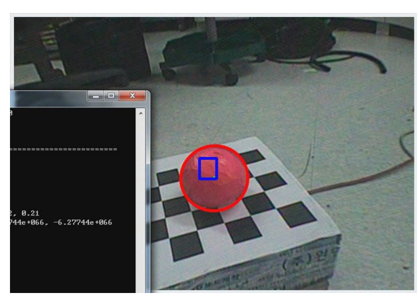
(c) After 2nd iteration



(d) After 3rd iteration

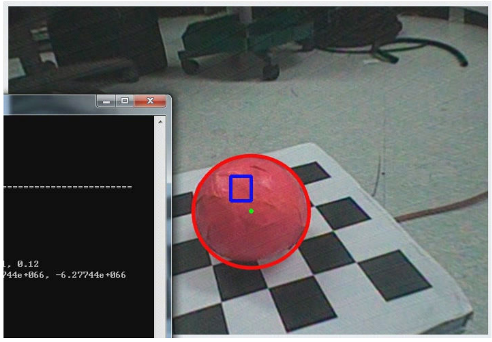


(e) After 4th iteration

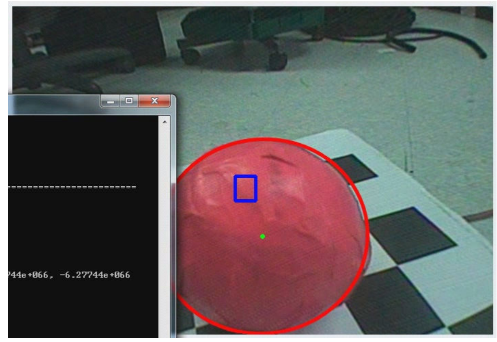


(f) After 5th iteration

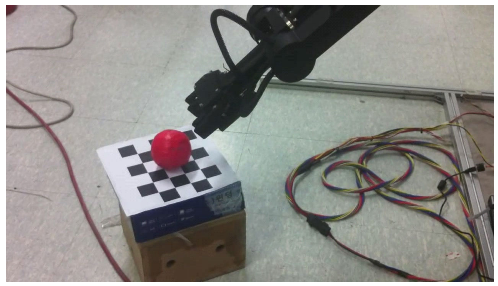
Fig. 7: Z estimation sequence



(a) After 1st Step



(b) After 2nd Step



(c) Final position of manipulator

Fig. 8: Alignment in 3 steps

than actual value and center point of target object not to be within the boundary of principal point. So, through the Z estimation equation and flow chart of estimation mentioned above, it is expected that estimation value becomes larger to be adjusted to actual value. It took 5 iterations to obtain depth value. After each iteration, estimated z becomes larger, moving distance of camera becomes larger, and therefore distance between principal point of camera and target object became smaller. After 5 continuing iterations, the center point lies within the boundary of principal point of the camera and iteration stops. Values of joint angles and estimated Z during estimation and some of video sequences during estimations are shown in Fig. 6 and Fig. 7 respectively.

After finishing the z estimation, manipulator alignment begins. In Fig. 8, manipulator alignment divided into 3 steps is shown. After each step, the size of target object in the image gets bigger because distance between camera at the end-effector and target object is shorter.

IV. Conclusion

In this paper, we developed IBVS of 5-DOF robot arm manipulator not knowing depth information. Different from existing approaches, IBVS proposed in this paper is separated from plant control and does not use feature Jacobian. So by using forward and inverse kinematics, robot arm manipulator estimates depth information while moving in lateral direction. After estimation, the manipulator approaches target object. Through the experiment, it is shown that the manipulator estimates depth value in 5 iterations and approaches the target object in 3 steps.

Acknowledgment

This paper was supported by KAIST, Hanoool robotics, and KACST under the joint project(G01100245).

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