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164 Calibration free 3D control system based on agents

by: *Mirjana Bonkovic, Darko Stipaniev*

pp. 1641-
1646

Calibration free 3D robot control system based on agents

MIRJANA BONKOVIĆ, DARKO STIPANIČEV

Laboratory for Robotics and Intelligent Control

Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture

University of Split

Ruđera Boškovića bb, 21000 Split

CROATIA

e-mail: mirjana @fesb.hr; dstip@fesb.hr

Abstract: Robot vision is usually based on well-calibrated system in which the large numbers of calibration parameters cause error-prone and imprecise behaviour of the system. The fact that humans use a visual feedback intuitively initiated efforts to develop the robot control system based on agents for 3D control of robot arm without calibration. Using the simulator of 3-segment robot arm, the operators were able, after a period of training, to define the simple linguistic rules, which guide the robot arm to the target position. Based on the knowledge elicited from operators, the agent for 3D control of robot arm was created. Simulation and experimental results confirmed our expectations.

Key words: agents, robot positioning, visual feedback control

1. Introduction

Active vision has been the main topics in a variety of papers concerning visual servoing [1,2,3,4], visual motor model estimation [5], eye-hand coordination [6], [7], stereo-vision [8] and so on. The systems in which the basic components of the visual system are visual behaviors tightly integrated with the actions they support also fits into the active vision paradigm [5]. Such, active or behavioral vision system is characterized by permanent active agent's interaction with the world resulting with the acquisition of visual information which is not an independent open loop process but is highly related to the final task the robot is programmed to perform. Extracted visual information is usually represented in a form, which facilitates particular operations and need not represent an abstract, high level model of the world.

Vision is the most powerful sense used by humans when manipulating the objects. During grasping and manipulation, humans use efficient hand-eye coordination skill, based on visual feedback information. This complex coordination mechanism has been tuned through the whole life of human individuals[9].Therefore, vision has been considered crucial to acquire geometric and dynamic information about the environment. On the other side, almost all robot vision systems require calibration, which is known to be a difficult and error prone process [10]. Our attempt has been devoted to try to identify possible reaching task solutions, which do not acquire accurate metric estimation of the end-effector position with respect to the cameras coordinate system.

Inspired by the biological systems which hand-eye coordination skill is based only on visual feedback information, we develop this, calibration free, robot control system based on agents.

Generally, a process of a robot arm approach can be divided into two phases: a target approach phase and an execution phase.

While the executive phase relies usually on tactical sensing, the target approach phase, which is assumed to be a basic skill for a robot manipulator, is based entirely on the interpretation of visual inputs. For a specified task, two visual models are established, each for one of the mentioned approaching phases in which vision agents communicate among them and act to guide the robot system in order to perform the tasks. In this paper we describe the approach phase of a task solutions, while the execution phase is described minutely in [13], [16].

2. System overview

The system consists of a robot arm monitored by two cameras (Fig.1.), which have to be positioned to see the end effector of a robot arm and the target point. Robot end effector coordinates have to be visible at every time instances of image acquiring. Our goal has been to achieve a control through the active vision agents actions which can observe the results of its action via the changes in visual appearance. During the approaching phase, agents for plane positioning (PIPA) and for point positioning (PoPA) interactively communicate with each other, exchanging the information of their abilities to fulfill the given task; if

some of them is not capable to improve the defined behavior (move end-effector closer to the target point), it calls another and asks for help. In this stage of a task performance the robot arm is modeled as a three segment planar model of a RRR structure (Fig.2.).

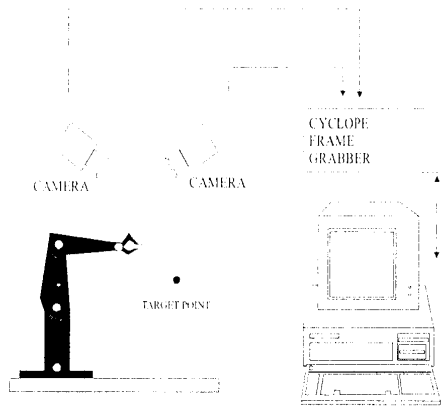


Fig.1. The system for rough target approach

The robot action reference frame is joint space, described as desired joint angles direction $x = \text{sgn}(x_1, x_2, x_3)^T$. The changes in visual appearance are recorded in a feature vector $y = (y_1, y_2, y_3)^T$.

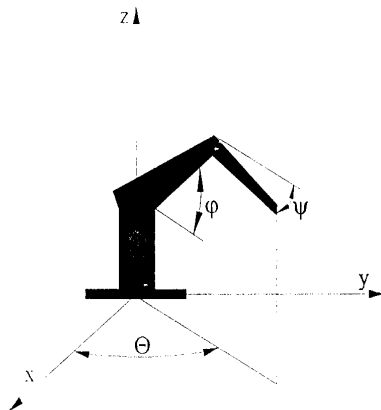


Fig.2. The robot coordinates

Visual features can be drawn from a large class of visual measurements [5], but we have found that point vectors in camera space are suitable. During the visual agents action, the characteristic point (end effector position) has been marked with bright circle for easier detection [12]. In order to speed up the computation, only parts of the camera images with marker positioned on the end-effector have been processed. Image processing has resulted with characteristic point vectors, which are the key information needed for robot control based on agents.

3. Agents control

Humans use efficient hand-eye coordination skill during grasping and/or manipulating objects, which is based only on visual feedback information. With these things in mind, we have discovered the rules for agent action, which control the robot arm movements during the approaching stage of a task execution. The process of discovering was supported by the simulator of 3-segment robot arm movement [11]. The simulator (Fig.6.) is based on a mathematical model of a scene configuration consisting of a robot arm model monitored by the two cameras. After the vector of marked target position is set, by either the scrolls of robot Cartesian (x, y, z) or cylindrical coordinates $(\alpha, \beta, \text{distance})$, the operator manually moves the robot segments, scrolling its θ, ϕ or ψ angles (Fig.2). Changing the θ angle, the robot is rotating around the main axis (around its body), while angles ϕ or ψ defines its final position in the plane defined by θ . Any movements of either target space position or robot arm are visible on the screens of the cameras as they are positioned to "see" the "process". By pressing the dialogue button named "Camera1" or "Camera2", the operator is able to change camera position coordinates, roll, pitch and yaw angles and/or zoom factor, monitoring his actions on the main window. Therefore, the simulation results could be tested for an arbitrary scene configuration, and for special case of the cameras and robot arm positions.

Using this simulator we have discovered the rules for agents action in order to perform target point rough approaching. The following statements have declared the rules:

1. Plane positioning agent action: Movement of the θ angle in the correct direction will decrease the "virtual visual measure" defined as a disparity error between end effectors positions on the, specially constructed, so-called, virtual images plane.
2. Point positioning agent action: Movement of the ϕ and ψ angle in the correct direction will decrease the sum of the differences between current and desired positions of the robot end effector in each of the camera images.

Although the "virtual images plane" has no 3D space analogues, which means that it is the plane defined with some real space points or its projections, experiments have showed that the virtual images plane consists all important elements needed for successful robot control. It has been constructed from the camera images by overlapping the points marked as target positions (Fig.3).

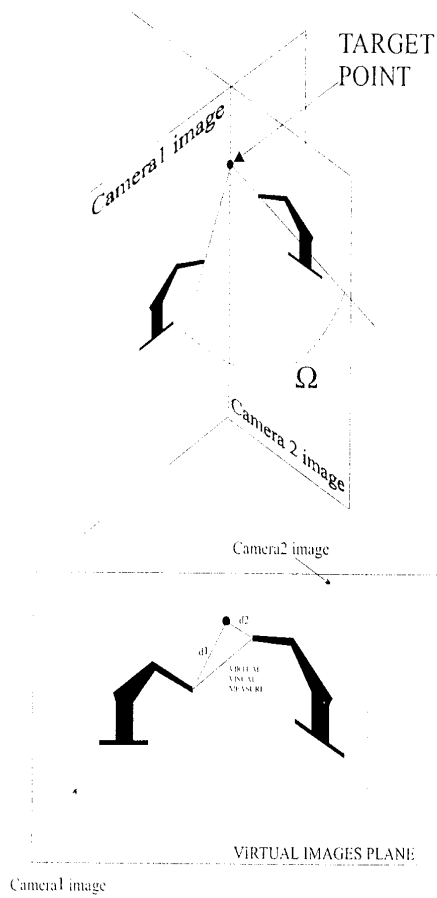


Fig.3. Construction of the virtual images plane.

Although the mentioned conclusions were result the operators get from the simulation experience, we have also confirm the rules for guiding the robot theoretically.

4. Mathematical background

The geometry is illustrated in Fig. 4. The idea of overlapping the target positions in each of the camera images has its 3D space explanations in choosing appropriate calibration planes of the cameras. Consequently, we have chosen the planes, which intersect through the target point.

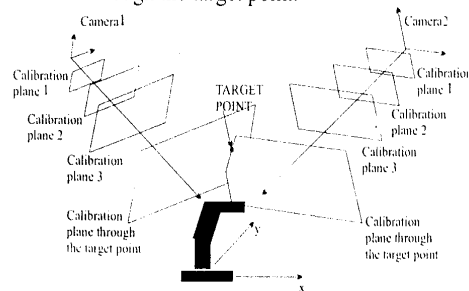


Fig.4. The geometry of the images frame

Due to different camera parameters, the images of the robot segments could be scaled with different scaled factor, but even if it is true the robot segments and the target point would be visible on the both images, as well as the distances between end effectors and target point.

For the control purpose it is only important to compare those distances on the consecutive images.

If the robot is rotated around its body for correct value of the θ angle then 2D positioning problem have occurred. During the approaching phase, the distance sum between robot's end effector and target point in the camera images would decrement until it reaches the zero value in the target point. The 2nd, experience based control rule could be explained under such 3D considerations.

On the other side, the fact used in the 1st control was not so obvious, so we have proofed the statement mathematically.

Let we consider the consequences of a rotation movement on space distance between characteristic points. If robot rotate around its body in the direction of the angle θ , then the space distance illustrated in Fig. 5., defined with

$$D^2 = (\mathbf{r}_T - \mathbf{r}_R)^T (\mathbf{r}_T - \mathbf{r}_R), \text{ or} \quad (1)$$

$$D^2 = (x_T - x)^2 + (y_T - y)^2 + (z_T - z)^2 \quad (2)$$

will decrement. The symbols, \mathbf{r}_T and \mathbf{r}_R , represent the target point vector and the vector of the robot end effector in the robot space coordination respectively, while x_T, x, y_T, y, z_T and z represent their cartesian coordinates.

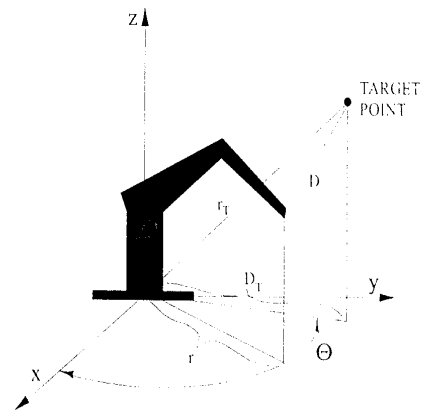


Fig.5. The space distance between robot end effector and the target point

As the pure rotation does not change the value of z , the problem could be simplified to 2D problem of finding the minimal distance between the points on the circle and the target point somewhere in the plane. The circle represents the projection of a robot end effector trajectory when robot rotates around its body, and the point is the projections of defined target point. Using mentioned simplification and powering the members of the sum, equation (2) could be expressed as:

$$f(D) = -2x_1x - 2y_1y + \text{const} \quad (3)$$

The x , y points on the circle are connected with circle equations which center is in the origin of robot coordinate system

$$x^2 + y^2 = r_c^2 \quad (4)$$

Therefore, minimal distance will occur if

$$\begin{aligned} \frac{\partial f(D)}{\partial x} &= 0, \text{ or} \\ \frac{\partial f(D)}{\partial y} &= 0. \end{aligned} \quad (5)$$

Substituting (3) and (4) in (5), results with

$$\begin{aligned} x_R^2 &= \frac{x_{RT}^2}{D_T^2} = K^2 x_{RT}^2 \\ y_R^2 &= \frac{y_{RT}^2}{D_T^2} = K^2 y_{RT}^2 \end{aligned} \quad (6)$$

where, D_T is a constant space distance between target point projections and robot coordinate system origin. Relating the robot coordinate system and camera coordinate frame results with known transformations

$$r_R = Rr_C + T \quad (7)$$

where R is a rotation matrix, T is a translation matrix and r_C is a point vector in respect to the camera coordinate frame, assuming that the projective geometry of the camera is modeled by perspective projection. Consequently, the robot end effector cartesian coordinates is

$$x_R = r_{11}u_1 + r_{12}v_1 + r_{13}f_1 + t_1 \quad (8)$$

and the target point is

$$x_{RT} = r_{11}u_{1T} + r_{12}v_{1T} + r_{13}f_1 + t_1 \quad (9)$$

Substituting relations (8) and (9) in (6)

we have

$$\frac{u_1^2}{u_{1T}^2} = \frac{v_1^2}{v_{1T}^2} = \frac{u_1v_1}{u_{1T}v_{1T}} = \frac{u_1}{u_{1T}} = \frac{v_1}{v_{1T}} = K^2 = a \quad (10)$$

Analogue procedure for the second camera frame results with

$$\frac{u_2^2}{u_{2T}^2} = \frac{v_2^2}{v_{2T}^2} = \frac{u_2v_2}{u_{2T}v_{2T}} = \frac{u_2}{u_{2T}} = \frac{v_2}{v_{2T}} = K^2 = a \quad (11)$$

On the virtual images plane, second camera coordinates have been translated for vector, which components are

$$u = u_{1T} - u_{2T}, \text{ and}$$

$$v = v_{1T} - v_{2T} \quad (12)$$

Therefore, the distance between end-effectors on the virtual images plane could be expressed as:

$$D_{VIRT}^2 = [(u_1 - u_2) - (u_{1T} - u_{2T})]^2 + [(v_1 - v_2) - (v_{1T} - v_{2T})]^2 \quad (13)$$

Finally, (10), (11) and (12) result with

$$u_1 = u_{1T}; v_1 = v_{1T}; u_2 = u_{2T}; v_2 = v_{2T} \quad (14)$$

Substituting (14) in (13), we get:

$$D_{VIRT}^2 = [a - 1]^2 [(u_{1T} - u_{2T})^2 + (v_{1T} - v_{2T})^2]$$

which means that minimal distance point on the virtual images plane, when a approaches to desired value ($a=1$), would be characterised with zero distance between end effectors. The more important is that if a is not equal one, than D_{VIRT} would reached minimal value exactly for $a=1$. Consequently, the θ angle and the robot "body" segment define the plane, which intersects the target point together with two camera image planes taken into consideration. Under these circumstances, approaching to the target point with changing the θ values would decrease the distance between end effectors on the constructed virtual images plane, which is completely related to the agents actions which are based on the rules formed by the operators' experience.

5. Simulation results

We have simulated described robot control system based on agents. If the position of the cameras are determined in relation to the robot coordinate system with the origin in the base of the robot body, first camera is positioned at point $X=0, Y=-1130, Z=0$,

while the second camera coordinates are defined with $X=1640, Y=-700$ and $Z=0$. Fig. 6. shows the results of simulations and the main window of the simulator for the robot arm final position for two different target space positions. For the first target position, defined by $X=790, Y=-208$ and $Z=1289$ (Fig. 6a), the robot control results with the $\theta, \phi,$ and ψ angles, and with appropriate error distance from robot end-effector to the goal position on the images of both cameras. The simulation traces of direction angles need in both cases approx. the same number of iterations for reaching the target position. The system capability to reach the target point has not been determined by robot or target start position, or start robot joint angles. As the simulation results has been encouraged, we have successfully verified the results experimentally.

6. Experimental results

The experimental setup is composed of a manipulator and two cameras (Fig.1.). We have used robot MICROROBOT TechMower of a RRR structure [15]. The vision system consists of a CYCLOPE-II frame grabber board, plugged into a standard PC/486 computer and connected to a pair of CCD cameras. For the control requirements purpose it is necessary to mark with the mouse the same target point on the images of cameras. It may cause the difficulties if the point has not marked in the space, too. Therefore, we have used a thin wire connected to the third camera mounted in front of the arm. The wire had been moved before the robot started to approach the target point. During the visual servoing process, the characteristic points have been marked with bright circle on the dark background for easier detection [12]. Image processing has resulted with characteristic point coordinates which are built in the virtual visual measure. In order to speed up the computation only parts of the camera images with markers have been processed.

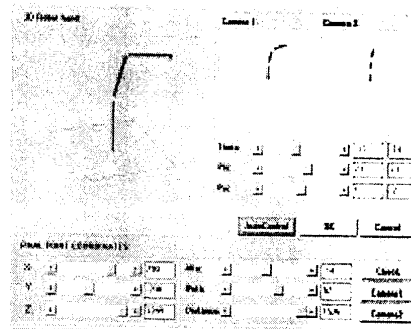
In all the experiments performed the stereo cameras were static and their position was manually adjusted to cover the required work space (i.e., both the target and the robot end effector should be present in the field of view when experiment is initiated).

Figure 7. shows the start and the final frame of the sequences captured by both of the cameras. Figure 8. shows the distance between the robot end effector and the target. The effect of the control applied is the zeroing the difference between image coordinates of the end-effector and the target. It also stopped the robot arm when the difference is less then 10 pixels.

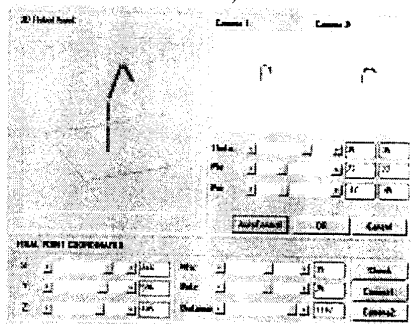
7. Conclusions

This paper shows how agents can be effectively used to control a reaching task in a simple and reliable manner avoiding any calibration procedure. The

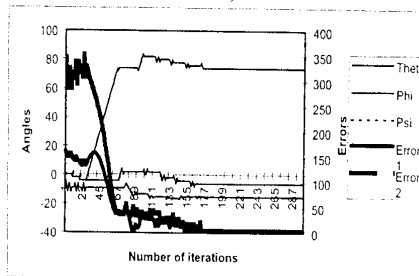
results have been achieved with robot of RRR structure, but it can be easily transferred to any structure.



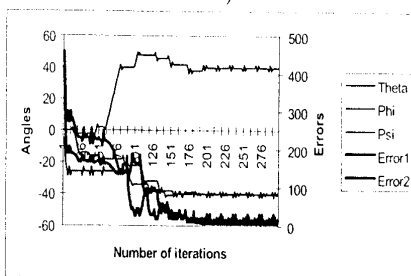
a)



b)



c)



d)

Fig.6.a)&b) main window of the simulator for final robot positions; c)&d) simulation results for robot control system based on agents

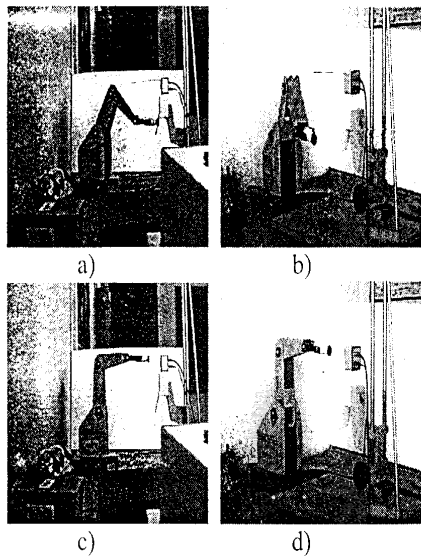


Fig.7.a)&b) Image frames of start robot positions;
c)&d) Image frames of end robot positions

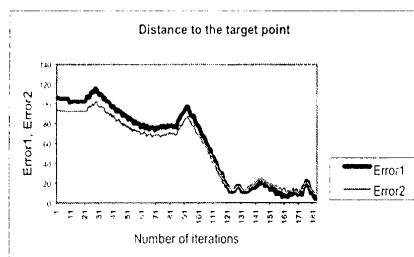


Fig.8. The curve of the distance between end effector and the target point

The proposed approach has been based on a continuous use of visual information. The trajectory of the arm are continuously controlled on the basis of the measured distance between features. The solution presented here is limited by the fact that we have used only consecutive steps between θ , ϕ and ψ movement for performing task, but simplicity of the proposed algorithm is an advantage, specially in technical systems. The principles following the described experiment could be very interesting in all cases in which accurate calibration is impossible or time consuming.

For final positioning, promising experiments were done with fuzzy displacement vector based control [13], [14].

References:

[1] Peter I. Corke, "Visual Control of Robots", John Wiley & Sons Inc. 1996.

- [2] B. Espiau, R. Horaud, "Visual Servoing with Calibrated Cameras: A Review, VIGOR, Esprit-IV reactive LTR project number 26247.
- [3] S. Hutchinson, G.D.Hager, P.I. Corke "A Tutorial on Visual Servo Control", IEEE Trans. On Robotics and Automation, Vol.12, No. 5., October 1996.
- [4] E. Grosso, "Robust Visual Servoing in 3-D Reaching Tasks", IEEE Trans. On Robotics and Automation, Vol.12, No. 5., October 1996.
- [5] M. Jagersand, R. Nelson, "On-line Estimation of Visual-Motor Models using Active Vision", In Proc. ARPA Image Understanding Workshop 96.
- [6] P. Allen, A. Timcenko, B. Yoshimi, and P. Michelman, Automated tracking and grasping of a moving object with a robotic hand-eye system. *IEEE Trans. on Robotics and Automation*, 9(2):152-165, 1993.
- [7] G.D.Hager, W.C.Chang, A.S.Morse, Robot Hand-Eye Coordination Based on Stereo Vision, IEEE . Control Systems, 1995.
- [8] E.Grosso, M. Tistarelli, "Active_Dynamic Stereo Vision", IEEE Trans. On Pattern Analysis and Machine intelligence, Vol.17, No. 9., September 1995.
- [9] A. Pozne, A. Bajec, S. Kovačević, N. Pavešić, "Uncalibrated Robot Vision System, Speech and Image Understanding", Proc. of 3rd Slovenian-German and 2nd SDRV Workshop, April 24-26, 1996. Ljubljana, Slovenia, pp. 291-300.
- [10] Billibon H. Yoshimi, P.K.Allen, Alignment using an Uncalibrated Camera System, IEEE Trans. On Robotics and Automation, Vol.11, No.4., August 1995.
- [11] M. Bonković, S.Nikolić, D. Stipaničev, "Knowledge Elicitation for Robot Arm Intelligent Controller". Proc. of Mipro 98, Opatija, 1998.
- [12] M. Cecić, I. Visković, Z. Čukušić, "Vehicle Position Detection by Using Video Camera Signal Processing" (in Croatian), p.p. 220-223, Korema, Zagreb, 1993.
- [13] M. Bonković, D. Stipaničev, "Image Displacement Vector Determination by Fuzzy Set Comparator", Proc. Of SoftCOM '98, p. 587-593, Split – Bari – Dubrovnik, 1998.
- [14] M. Bonković, D. Stipaničev, M. Štula, "2D Motion Analysis by Fuzzy Pattern Comparator", F. Solina, A. Leonardis (Eds.), Proc. Of 8th Int. Conf., CAIP'99, Ljubljana, Slovenia 1999.
- [15] Microbot TeachMover Robot, User Manual, Microbot, Inc., 1984.
- [16] Mirjana Bonković, Intelligent 3D robot control using visual feedback, PhD thesis, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, 2000.