Calibration free visual feedback 3D robot control based on fuzzy agents

M.Bonković*, D. Stipaničev *

* LaRIS - 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

fax: +385 21 463 877

Keywords: robot positioning, fuzzy control, visual feedback, agents

Abstract

Robot visual 3D positioning is usually related with the well calibrated system in which the large numbers of calibration parameters cause errors resulting in bad system behaviour. Also, even the small changes in the robot work space needs a recalibration procedure, which is quite time consuming process. Inspired by the fact that biological organisms expose superior adaptive capabilities in motion control in comparison with present day robotic system initiated our efforts to develop the robot control system based on fuzzy agents for visual feedback 3D control of robot arm without any calibration procedure. The paper presents our ideas. The theoretical results are illustrated by simulations.

1 Introduction

Biological organisms have demonstrated their superior adaptive capabilities in motion control over present day robotic systems. For example, vision is the most powerful sense used by humans when manipulating the various types of objects. They can easily pick the fruit from the three, or, a second later, catch another one in the air if someone hit it toward them. 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] and therefore, it is reasonable to consider vision as a crucial in acquiring 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 [1].

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 calibration free, robot control system based on agents.

For a specified task, vision agents run concurrently and act to guide the robot system in order to perform its task. Consequently, robot expose reaching target property, which is, depending on the task the robot has to perform, one of the building blocks in emergent behavior/functionality of the system [7]). In Section II, short theoretical background of the emergent behavior theory and how it is relate to robot task execution is presented. Section III describes the system. In Section IV the agent control rules are explained and a controller based on fuzzy agents is applied to the robot control system simulator. The simulation results are presented in Section V. Section VI concludes the paper.

2 3D robot control as emergent behavior system

The system behavior is considered emergent if it could not be predicted from an analysis of the individual components of the system which means that the whole is greater than the sum of parts. Examples from the natural world are ants foraging for food, where they typically converge on the closest food source first before depleting others, or flocking behavior in birds. There is currently no clear definition among emergent behavior, and producing desirable emergent behavior[8]. The formal definition was proposed by Baas as:

P is an emergent property of S^2 iff

$$P = Obs^2\left(S^2\right), \quad P \notin Obs^2\left(S^1\right)$$

where S^2, is the second order structure, and it is the result R of applying interactions Int^1 to the primitives, S^1, and the observable properties of the primitives $Obs^1(S^1)$:

S^2=R(S^1, $Obs^1(S^1)$, Int^1).

This means, that a property P of the second order structure S^2 is emergent iff it is observable on S^2 but not on the low order structures. For instance, let us use the salt as a good example [11]. Sodium is a soft metal that bursts into flame on exposure to water or air, while chlorine is an asphyxiating and dangerous greenish gas. If we put them together chemically, very important spice emerge-table salt. The story is not finished at this stage. Putting a small amount of a strong taste salt on a tasteless food emerge the queue of tasty menus which worth nothing without salt.

In our example the emerging system behavior is studied on the system, which consist of a pair of CCD cameras and a robot arm. The task is to position the end effector of the manipulator using information gained from the pair of cameras arbitrary positioned around the robot. Their position is not known and the control signal, which guides the robot end-effector to the target point, is based on the visual feedback only. Fig.1. shown a schematic diagram of the system. Observing the trajectory path of the end effector, one might conclude that the joints move to reach the target. The same property is not observable by looking at the end-effector trajectory caused by individual joint movement. Therefore, reaching the target property is said to be an emergent behavior of the robot system. In this paper the strict definition of the emergent property will be define in terms of systems that contain a number of agents, each of them behave according to a traditional sequential program [8]. These agents are able to modify the system using a set of atomic actions. The different agents run concurrently exposing its own, axiomatic behavior. Our goal has been to achieve a control through the active vision agents actions, which can observe the results of their action through the changes in visual appearance. During the approaching phase, agent for plane positioning (PlPA) and agents 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. Agents' actions are defined as appropriate fuzzy control algorithm (Section IV).

3 System model and visual feedback agent based control

The robot arm is modeled as a three segment planar model of a RRR structure (Fig.2.). The main control task is to reach the target point with a robot end-effector. The robot action reference frame is a joint space, described as desired joint angles changes $x = (x_1, x_2, x_3)^T = (\Delta\theta, \Delta\varphi, \Delta\psi)^T$.

The changes in visual appearance are recorded in a feature vector $y = (y_1, y_2, y_3)^T$ calculated from camera images.

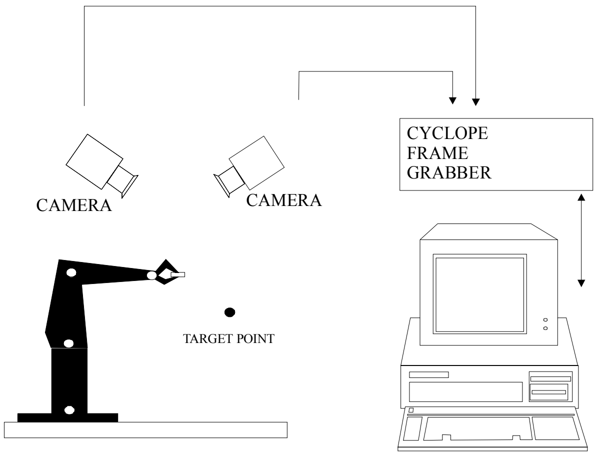


Fig.1. The system for rough target approach

The procedure is as follows:

Using image processing techniques the end effector positions are calculated on both images. After that, the virtual image plane was constructed by overlapping the points marked as target positions on both images (Fig.3.) and three characteristic values were calculated: d1, d2 and VVM: d1 and d2 are distances between end-effector positions and target positions and VVM is called the Virtual Visual Measure and it is defined as a distance between end-effector positions on the virtual images plane.

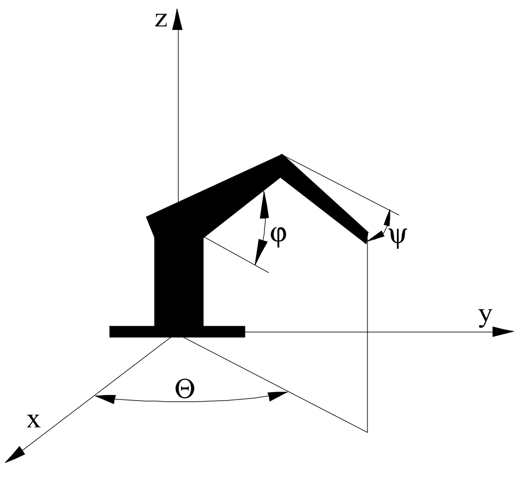


Fig.2. The robot coordinates

A feature vector y is defined as

$$y = (y_1, y_2, y_3)^T = \left[SOD, VVM, \Delta VVM \right]^T$$

where SOD=d1+d2, and ΔVVM is derivation of Virtual Visual Measure defined above.

In our previous research [11] we have designed the rules for control action based on this feature vector. The research was based on simulator of 3-segment robot specially designed for knowledge extraction about visual based robot control. Two types of control agents were defined-agent for plane positioning (PlPA) and agents for point positioning (PoPA) and their action could be described as follows:

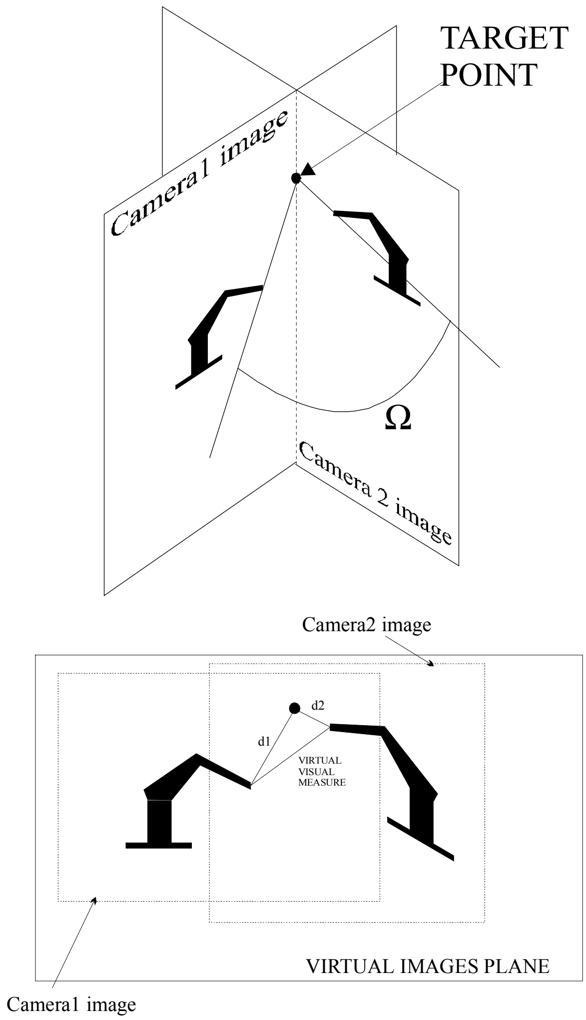


Fig.3. Construction of the virtual images plane.

1. Plane positioning agent action: Movement of the θ angle in the correct direction decrease the "virtual visual measure" (VVM).
2. Point positioning agent action: Movement of the φ (or ψ) angle in the correct direction decrease the sum of the differences (SOD=d_1+d_2).

The agents run concurrently. The PlPA agent is activated first and it is active until the VVM decreases. When VVM start to increase again, PlPA stops and sends the message to PoPA-φ agent. PoPA-φ starts to work changing the φ angle and monitoring SOD. When SOD starts to increase, PoPA-φ stops and activates PoPA-ψ. His behaviour is the same as the behaviour of PoPA-φ agent, except he takes the control over the angle ψ. When SOD starts to increase, the first agent PlPA is activated again and so on.

As a result of their cooperative action, the robot end effector goes toward the target point and magnitude of feature vector $[\mathrm{SOD}, \mathrm{VVM}, \Delta\mathrm{VVM}]$ goes to zero. This control behavior originally obtained by simulation research was also theoretically confirmed and proved [3]. Simulations and experiments erased on classical control approach were quite successful [4] and inspired us to continue with further research.

The novelty in this paper is the application of fuzzy principles, which results in more robust control algorithm. Control actions of our PlPA and PoPA control agents were defined in terms of fuzzy procedures described minutely in the following section.

4 Fuzzy control algorithm

The control system can be treated generally as a mapping from the set of inputs X to the set of outputs: $S : X \rightarrow Y$. Input X is information extracted from sensors transformed into form suitable for further processing and outputs Y are appropriate control actions. In our case inputs were defined by feature vector X = $(x_1, x_2, x_3)^T$= =$[\mathrm{SOD}, \mathrm{VVM}, \Delta\mathrm{VVM}]^T$, defined in previous section and outputs by desired joint angle changes Y = $(y_1, y_2, y_3)^T$ = $[\Delta\theta, \Delta\varphi, \Delta\psi]^T$. The control system is considered non-deterministic if the factor of uncertainty is connected, either with input and output data (x and y) or with input and output relationship (S). 3D robot control based on uncalibrated visual feedback is such a case. Input information is not preciously defined and control actions are given by linguistic rules. In such a case the fuzzy approach could be applied because both input and output data and input and output relations could be represent with fuzzy relations [10].

The robot control system is based on three control agents:

a) PlPA (Plane positioning agent) - responsible for angle θ. It is activated first and its action is connected with VVM. If VVM decrease PlPA is active, if VVM start to increase again, PlPA stops and activates PoPA agents.

b) PoPA- φ (Point positioning agent) – responsible for angle φ. His action is connected with SOD. If SOD decrease PoPA-φ is active, when SOD start to increase, PoPA-φ stops and activates PoPA-ψ.

c) PoPA-ψ is the same as PoPA-φ except he is responsible for angle ψ.

The fuzzy control algorithm of all agents is the same. Let us defined it in terms of fuzzy relational model approach [10].

The control procedure could be seen as a sequence of mapping from the real world of inputs to the model world of inputs, from the model world of inputs to the model world of outputs and from the model world of outputs to the real world of outputs. Fig.4. shows the whole procedure schematically.

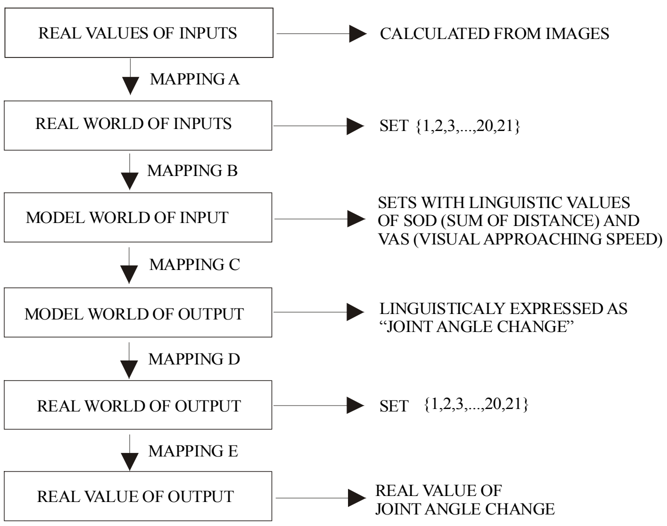


Fig.4. The whole control procedure expressed as relations between different worlds

The first procedure (mapping A) is transformation of real inputs (SOD-sum of distances and VVM-virtual visual measure) calculated from images and expressed in pixels, in new inputs $\overline{\text{SOD}}$ and $\overline{\text{VAS}}$ (visual approach speed) defined on discrete support set conceived as a set of integers form 1 to 21. The transformation equations are different for approaching ($\Delta\,\text{VVM} \le 0$) and moving from the target ($\Delta\,\text{VVM} \ge 0$). For the approaching case $\Delta\,\text{VVM} \le 0$ equations are:

$$\overline{\text{SOD}} = r_1 * \text{SOD} \tag{1}$$

$$\overline{\text{VAS}} = r_2 + \left(\frac{\text{VVM}[k] - \text{VVM}[k-1]}{\text{VVM}[k-1]}\right) * r_3 \tag{2}$$

where r_1, r_2 and r_3 are transformation coefficients. SOD is always positive, while VAS indicates that robot motion is directed to the target, or from the target. Consequently, r_2 has been used to shift a zero value to integer 11. The coefficients values were r_1=2/150, r_2=10 and r_3=0.9. When VVM starts to increase, which means that robot end effector is not any more approaching the target point, but it is moving from the target, experiments have shown that equation (2) is not any more adequate. We have found a new heuristic formula

$$\overline{\text{VAS}} = r_2 + \left(a\tan\left(\frac{\text{VVM}[k] - \text{VVM}[k-1]}{\text{JAC}[k-1]} * r_4\right)\right) \tag{3}$$

where r_4 is coefficient (r_4=0.9) and JAC (Joint angle changes) is appropriate output value for that agent (for PlPA, JAC=$\Delta\theta$, for PoPA-φ, JAC=$\Delta\varphi$ and for PoPA-ψ, JAC=$\Delta\psi$) in previous time instant.

The model world of these new inputs ($\overline{\text{SOD}}$ and $\overline{\text{VAS}}$) is linguistic description of their possible values:

$\overline{\text{SOD}}$={CENTRE, CLOSE, MIDDLE, FAR}

$\overline{\text{VAS}}$={BIG TO TARGET, MIDDLE TO TARGET, SMALL TO TARGET, ZERO, SMALL FROM TARGET, MIDDLE FROM TARGET, BIG FROM TARGET}

The relations between real world of this new discrete inputs and their model world (mapping B) are defined on Fig.5.a) and b) in terms of degrees to which each element from real world (integer from 0 to 21) belongs to each element of model world (linguistic values).

For example the relation between real world of inputs {1,2,3….,21} and model world value "CLOSE" could be defined with relational Table I:

REAL WORLD MODEL WORLD	1	2	3	4	5	6	7	8
"CLOSE"	0	0.2	0.4	0.6	0.8	1	0.8	0.6

REAL WORLD / MODEL WORLD	9	10	11	12	13	14	….	21
"CLOSE"	0.4	0.2	0	0	0	0	0	0

Table I: An example of input relations

The third relation (C) is mapping from the model world of inputs (linguistic input values) and model world of output (linguistic output values). Output is defined as $\overline{\text{JAC}}$ -"joint angle change" and it could be either $\Delta\theta$, $\Delta\varphi$ or $\Delta\psi$ (see Fig.2.). Its linguistic values are: DG-decrease great, DM-decrease midium, DL-decrease little, NC-no change, IL-increase little, IM-increase midium, IG-increase great, and they are shown in Fig.5.c. Relation between linguistic inputs and linguistic output (mapping C on Fig.4.) are defined by two sets if IF….THEN rules of the form:

If the $\overline{\text{SOD}}$ is "CLOSE", and

the $\overline{\text{VAS}}$ is "SMALL"

and ΔVVM is negative (approaching)

then $\overline{\text{JAC}}$ should be "DECREASE LITTLE",

or if

ΔVVM is positive (moving from the target)

$\overline{\text{JAC}}$ should be "DECREASE GREAT".

All together 32 rules were used, 16 for approaching case $\dot{VVM} \le 0$ and 16 for case when robot end effector is going from the target (Table II).

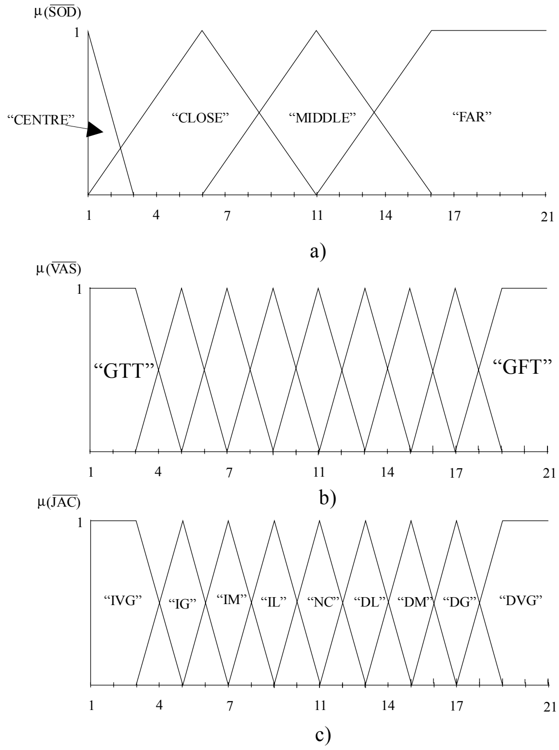


Fig.5. Relations between input and output real world and model world

a) For input $\overline{\text{SOD}}$

b) For input $\overline{\text{VAS}}$

c) For output $\overline{\text{JAC}}$

		Distance			
		CENT.	CLOSE	MIDD.	FAR
VAS	ZERO	DG	DM	DL	NC
	SMALL	DM	DL	NC	IL
	MIDD.	DL	NC	IL	IM
	BIG	NC	IL	IM	IG

a) The Table for $\dot{VVM} \le 0$ (DG-decrease great; DM-decrease middle, DL-decrease little; NC-no change; IG-increase great; IM-increase middle; IL-increase little)

		Distance			
		CENT.	CLOSE	MIDD.	FAR
VAS	ZERO	DVG	DG	DG	NG
	SMALL	DG	DG	DG	DG
	MIDD.	DM	DM	DM	DM
	BIG	DL	DL	DL	DL

b) The Table for $VVM \geq 0$ (DG-decrease very great)

Table II: The control algorithm

The fuzzy inference mechanism was classical one, based on Mamdani's definition of fuzzy compositional rule of inference (max-min). Let us explain the procedure through one example: In time instant k the calculated $\overline{SOD}=2$ and $\overline{VAS}=7$. From Fig.5.a. we can see that two linguistic values have degree of fulfilment bigger than zero: "CENTRE" $\alpha_1 = 0.5$, and for "CLOSE" $\alpha_2 = 0.2$. The end effector is moving toward the target ($\overline{VAS} \leq 11$ and $\overline{VVM} \geq 0$) so from Fig.5.b. it could be seen that only $\overline{VAS}$ expressed as "MIDDLE TOWARD THE TARGET" has a degree of fulfilment bigger than zero ($\beta_1 = 1$). Consequently, two rules from Table II a) have been trigerred:

Rule 1: $\overline{SOD}$="CENTRE" and $\overline{VAS}$="MIDDLE" resulting in $\overline{JAC}$="DECREASE LITTLE"

Rule 2: $\overline{SOD}$="CLOSE" and $\overline{VAS}$="MIDDLE" resulting in $\overline{JAC}$="NO CHANGE"

In terms of degrees of fulfilments (min principle)

$$\gamma_I = \min(\alpha_1, \beta_1) = \min(0.5, 1) = 0.5 \text{ and}$$

$$\gamma_{II} = \min(\alpha_2, \beta_2) = \min(0.2, 1) = 0.2 .$$

γ_I is applied to $\overline{JAC}$=DECREASE LITTLE and γ_{II} to $\overline{JAC}$=NO CHANGE.

Using the max principle and definitions from Fig 5.c) the cumulative JAC relation is defined as:

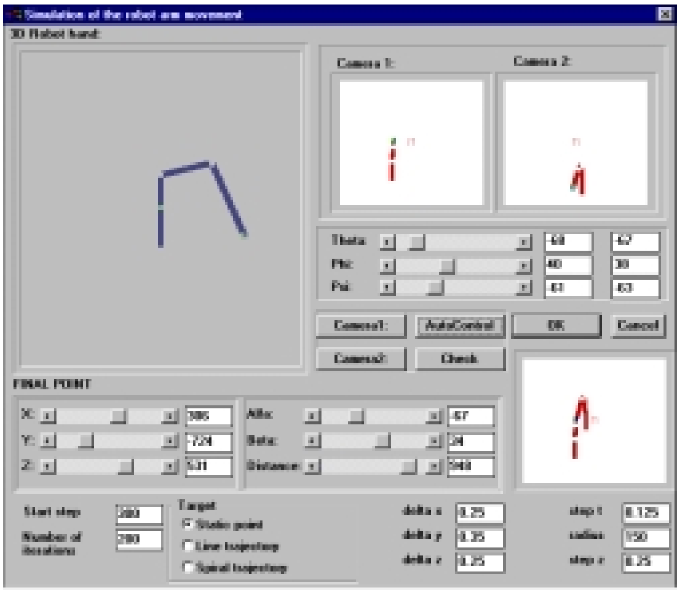
REAL WORLD MODEL WORLD									
$\overline{JAC}$	0	0	0.5	0.5	0.5	0.2	0.2	0	0

Table III. Relation from the model world of output and real world of output

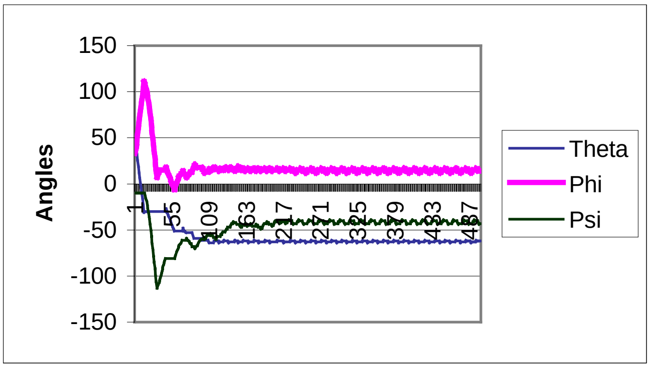
This relation is mapping D from Fig.4. and it connect model world of output and real world of output. The final relation (mapping E) is the relation between elements of **real world of output** (set {1,2,3,…21}) and **real values of output** (real values of JAC-real joint change). It is expressed relatively according to JAC in previous time instant and it could be the same as previously, greater or smaller. Its appropriate value is calculated using the centre of gravity method. For example, JAC calculated from values from Table III results with JAC=9.5 which means that the motor has to be decrease 15% according to its previous value (JAC=11 means no change, and JAC>11 means increase the motor voltage).

5 Simulation results

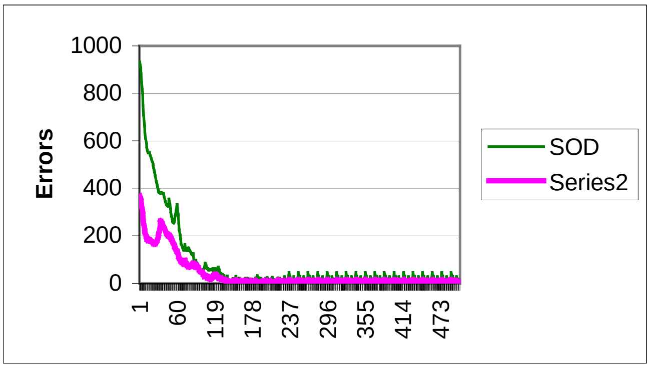
The described robot control system has been simulated. The simplest task was to position the robot end-effector in static point inside the robot workspace. That is illustrated with two examples. Cameras were positioned arbitrary. Fig. 6. shows the results of simulations and the main window of the simulator for the robot arm final position for



a)



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 for static target point

Static target space positions. Fig. 6.b.) shows the result of robot control angles and Fig.6.c.) appropriate error distances from robot end-effector to the goal position on both camera images. The end effector reaches the target in approximately 100 iterations.

Dynamic condition have been also tested for a curve trajectory tracking (Fig.7). Robot end-effector has followed the target after it had approached closely to the point. Time instances have been determined with image acquisition frequency.

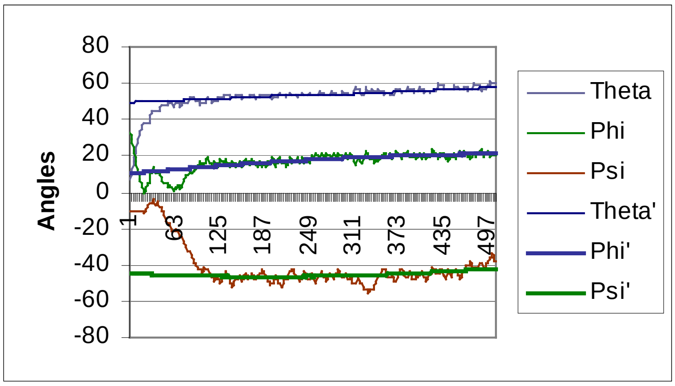
The effect of the control applied is the zeroing the difference between image coordinates of the end-effector and the target. It also stopped the robot arm when the difference is less then 5 pixels.

6 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 other structure.

The proposed approach has been based on a continuous use of visual information. The trajectory of the arm is 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, especially in technical systems. The principles following the described simulations 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 [5], [6].



a)

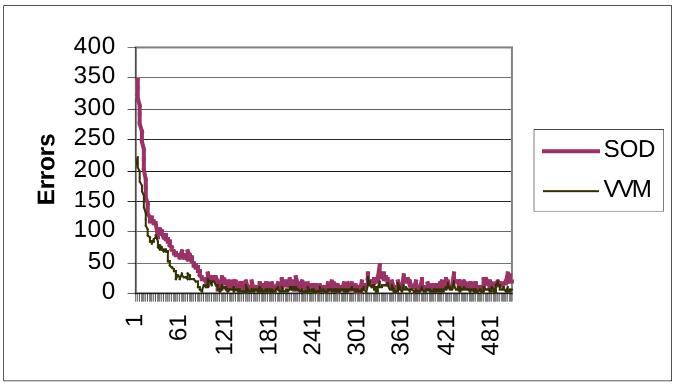


Fig.7.a)&b) simulation results for curve trajectory tracking

References

[1] Billibon H. Yoshimi, P.K.Allen, Alignment using an Uncalibrated Camera System, IEEE Trans. On Robotics and Automation, Vol.11, No.4., August 1995.

[2] Bonković, M., Nikolić, S., Stipaničev, D., “Knowledge elicitation for Robot Arm Intelligent Controller”, Proc of MIPRO 99, Opatija, Croatia.

[3] Bonković M., Stipaničev D.: Calibration free 3D robot control system based on agents, in book V.V.Kluev, N.E.Mastorakis (Eds.), Advances in Signal Processing, Robotics and Communications, Electrical and Computer Engineering Series, A Series of Reference Books and Textbooks, pp. 381-387, WSES, 2001.

[4] M.Bonković, Intelligent 3D robot control using visual feedback, PhD thesis, Faculty of Electrical Engineering and Naval Architecture, University of Split, 2000.

[5] M. Bonković, D. Stipaničev, “Image Displacement Vector Determination by Fuzzy Set Comparator”, Proc. Of SoftCOM ’98, p. 587-593, Split – Bari – Dubrovnik, 1998.

[6] 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, Lju Ljubljana, Slovenia 1999.

[7] Brooks, Rodney A., “Integrated System Based on Behaviors”, SIGART Bullentin, 1991.

[8] Kristensen, L., K. (2000). Aintz: A study of Emergent Properties in a Model of Ant Foraging. In: Proceedings of the Seventh Conference on Artificial Life (ALIFE 7), vol. 1, p. 353-361.

[9] Pozne A., Bajec A., Kovačević S., Pavešić N., "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] D.Stipaničev, Fuzzy relational models for intelligent control, in book R Janus et al. (editors) “Mathematical and Intelligent Models in System Simulations”, J.C.BALTZER AW, 1991, pp.275-279.

[11] Thornley, www. visi. com/ ~thornley /david / philosophy/ definitions. html

Acknowledgements

This work is supported by the ministry of science and technology of Republic Croatia through project 023021 “Complex systems control by intelligent methods”. Especially thanks to Ivana Ivanišević who has contributed to algorithm programming and simulation research.