Vision-Based Control of the RoboTenis System

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Summary. In this paper a visual servoing architecture based on a parallel robot for the tracking of faster moving objects with unknown trajectories is proposed. The control strategy is based on the prediction of the future position and velocity of the moving object. The synthesis of the predictive control law is based on the compensation of the delay introduced by the vision system. Demonstrating by experiments, the high-speed parallel robot system has good performance in the implementation of visual control strategies with high temporary requirements.

1 Introduction

The accomplishment of robotic tasks involving dynamical environments requires lightweight yet stiff structures, actuators allowing for high acceleration and high speed, fast sensor signal processing, and sophisticated control schemes which take into account the highly nonlinear robot dynamics. As a tool for the investigation of these issues, the computer vision group of the Polytechnics University of Madrid has built the RoboTenis System, which proposes the design and construction of a high-speed parallel robot that in a future will be used to perform complex tasks, i.e. playing table tennis with the help of a vision system. The RoboTenis System is constructed with two purposes in mind. The first one is the development of a tool for use in visual servoing research. The second one is to evaluate the level of integration between a high-speed parallel manipulator and a vision system in applications with high temporary requirements.

The mechanical structure of RoboTenis System is inspired by the DELTA robot [1]. The choice of the robot is a consequence of the high requirements on the performance of the system with regard to velocity and acceleration. The kinematic analysis and the optimal design of the RoboTenis System have been presented by Angel, et al. [2]. The structure of the robot has been optimized from the view of both kinematics and dynamics respectively. The design method solves two difficulties: determining the dimensions of the parallel robot and selecting the actuators. In addition, the vision system and the control hardware have been also selected. The dynamic analysis and the preliminary control of the parallel robot have been presented in [3], [4]. The dynamic model is based upon Lagrangian multipliers, and it uses forearms of non-negligible inertias for the development of control strategies. A nonlinear feedforward PD control has been applied and several trajectories have been programmed and tested on the prototype.

Using visual feedback to control a robot is commonly termed visual servoing. Visual features such as points, lines and regions can be used to, for example, enable the alignment of a manipulator / gripping mechanism with an object. Hence, vision is a part of a control system where it provides feedback about the state of the environment. For the tracking of fast-moving objects, several capabilities are required to a robot system, such smart sensing, motion prediction, trajectory planning, and fine sensory-motor coordination. A number of visual servo systems using model based tracking to estimate the pose of the object have been reported. Andersson presents one particular application: a ping-pong playing robot [5] [6]. The system uses a Puma robot and four video cameras. The vision system extracts the ball using simple color segmentation and a dynamic model of the ball trajectory. The system is accurately calibrated and the robot is controlled using the position-based approach. Other similar applications are: a catching robot presented in Burridge et al. [7] and a juggling robot presented by Rizzi and Koditschek [8]. Allen et al. [9] describe a system for tracking and grasping a moving object using the position-based servoing control. The object tracked is a toy-train on a circular trajectory. Buttazo et al. use a stand-alone configuration and a basket mounted at the end-effector of the robot to catch and object that moves in a plane [10]. Drummond and Cipolla present a system for the tracking of complex structures which employs the Lie algebra formalism [11]. The system is used to guide a robot into a predefined position (teach-by-showing approach). Concerning high-speed visual tracking, lots of new performing methods are appearing since a few years [12][13][14][15][16].

In this paper, we propose visual servoing architecture for the RoboTenis System. This architecture allows the 3D visual tracking of a ball at velocities of up to 1 m/s. The system uses a position-based visual servoing technique assuming the tricky problem of the 3D pose estimation of the target has been solved previously. The control law considers a prediction of the position and velocity of the ball in order to improve the performance of the movement of the robot. The synthesis of the predictive control law is based on the compensation of the delay introduced by the vision system (2 frames) and a constant acceleration motion hypothesis for the target and the robot. The presented experiments have been performed considering both predictions (position and velocity) and the position prediction only. The contributions of the paper include the use of a parallel robot in a vision-based tracking system, and the use of prediction of the movement of the target to improve tracking performance.

This paper is organized as follows. Section 2 describes the visual servo control structure. Experimental results are presented in Section 3. Finally, in Section 4 some concluding remarks are given and future work is also discussed.

2 Visual Servoing Arquitecture

This application considers an eye-in-hand configuration within dynamic look-and-move position-based scheme [6]. The task is defined as a 3D visual tracking task, keeping a constant relationship between the camera and the moving target (ball). We assume that the task is referenced with respect to a moving target that is located in the workspace of the robot and that the mobile target lays in the camera field of view so that it can always be seen as the task is executed.

The coordinate frames for the proposed visual servoing system are shown in Figure 1. $\sum_w$, $\sum_e$ and $\sum_c$ are the global, end-effector and camera coordinate frames. ${}^c p_b$ is the relative pose of camera to target object. The pose of the end-effector with respect to the global coordinate frame ${}^w p_e$ is known with ${}^w R_e = I$ and ${}^w T_e$ obtained from the forward kinematic model of the robot. The transformation matrix between the camera and end-effector coordinate frames (kinematics calibration), ${}^e p_c$, is known assuming that ${}^c T_e = 0$.

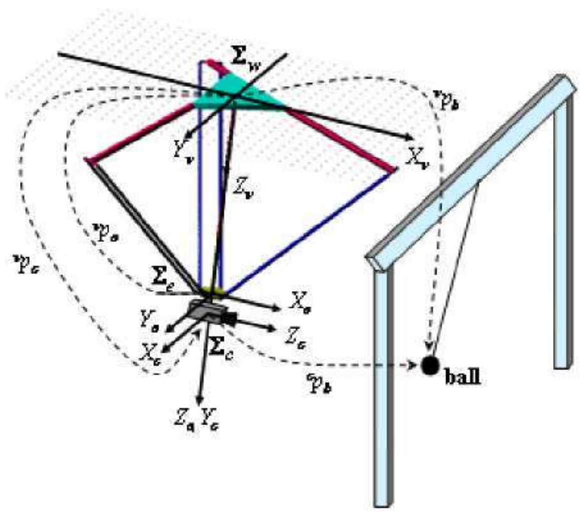

Fig. 1. Coordinate frames for the proposed visual servoing system

Fig. 2 shows a representation of the visual servo loop at an instant k. The reference position vector ${}^c p_b^*(k)$ of the control loop is compared to ${}^c p_b(k)$, this value is obtained with the vision system and the vector ${}^w p_c(k)$. The controller generates the control signal ${}^w V_e(k)$, a 3x1 vector that represents velocity references signals for each component of ${}^w p_e(k)$. This reference signals are expressed in the Cartesian space. So they must be converted into the joint space in order to be applied to the three joint-level velocity control loops of the robot. This transformation is computed by means of the jacobian matrix of the robot [4].

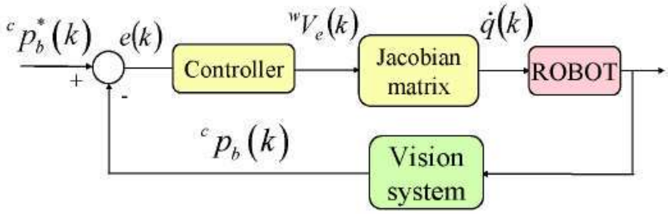

Fig. 2. Block diagram of the visual servo loop

2.1 Modeling the Visual Servoing

From Figure 2, the task error at an instant k is defined as

$$e(k) = {}^{c}p_b^*(k) - {}^{c}p_b(k) \tag{1}$$

which can be expressed by

$$e(k) = {}^{c}p_b^* - {}^{c}R_w\left({}^{w}p_b(k) - {}^{w}p_c(k)\right) \tag{2}$$

The basic idea of control consists of trying to determine that the task error approximately behaves like a first order decoupled system, i.e.

$$\dot{e}(k) = -\lambda e(k) \tag{3}$$

with $\lambda > 0$. Differentiating (2), the following vector $\dot{e}(k)$ is obtained:

$$\dot{e}(k) = -{}^{c}R_w\left({}^{w}v_b(k) - {}^{w}v_c(k)\right) \tag{4}$$

Using (2) and (4) in (3) it gives

$${}^{w}v_c(k) = {}^{w}v_b(k) - \lambda {}^{c}R_w^T\left({}^{c}p_b^* - {}^{c}p_b(k)\right) \tag{5}$$

where ${}^{w}v_c(k)$ and ${}^{w}v_b(k)$ represent the camera and ball velocities respectively.

Since ${}^{w}v_e(k) = {}^{w}v_c(k)$ the control law can be written as

$${}^{w}v_e(k) = {}^{w}v_b(k) - \lambda {}^{c}R_w^T\left({}^{c}p_b^* - {}^{c}p_b(k)\right) \tag{6}$$

Note that (6) has two components: a component of motion prediction of the ball ${}^{w}v_b(k)$ and a component of the trajectory tracking error $({}^{c}p_b^* - {}^{c}p_b(k))$.

A fundamental aspect in the performing of the visual servoing system is the adjustment of λ parameter. This parameter is based on the future positions of the camera and the ball. The future position of the ball according to the coordinate frame Σ_w at an instant $k+n$ can be written as

$${}^{w}p_b(k+n) = {}^{w}\hat{p}_b(k) + {}^{w}\hat{v}_b(k)Tn \tag{7}$$

where T is the sampling time. In addition, the future position of the camera according to the coordinate frame Σ_w at an instant $k+n$ is

$${}^{w}p_c(k+n) = {}^{w}p_c(k) + {}^{w}v_c(k)Tn \tag{8}$$

and λ is defined by

$$\lambda = \frac{1}{Tn} \quad (9)$$

The basic architecture of visual control is shown in Fig.3. The control law considers a prediction of the position and velocity of the ball in order to improve the performance of the movement of the robot. The synthesis of the predictive control law is based on the compensation of the delay introduced by the vision system z^{-r}

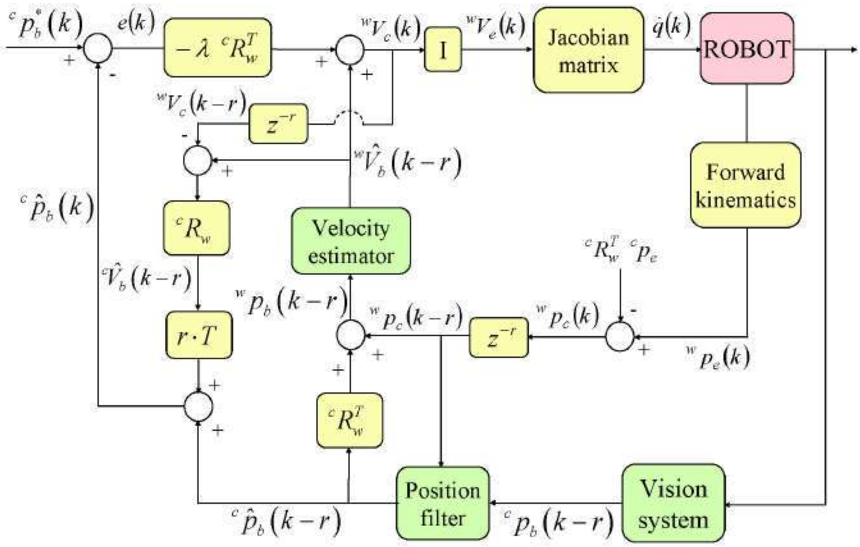

Fig. 3. Visual servoing architecture proposed for the RoboTenis System

2.2 Experimental Setup

The experimental setup is shown in Fig. 4. The control architecture of the RoboTenis System uses two control loops: one inner control loop that allows the velocity control of the robot to low level, and one external control loop that allows the 3D tracking of the ball using the information gives by vision system. The two control loops are calculated in a DSPACE card. The velocity loop is running at 0.5 ms and the vision loop at 8.33 ms. Other computer is employed for the acquisition and processing of the image in Windows 98 platform. The information given by the vision system is transmitted to the DSPACE card using a serial communication channel.

In order to minimize the delay in the vision loop, the acquisition of a new image is made in parallel to the processing of the previous image.

Image processing is simplified using a dark ball on a white background. The camera captures 120 non-interlaced images per second. At this frame rate, the resolution is limited to 640x240 pixels. Indeed, with a sampling rate of 120 Hz, the image transfer, image processing and control must no take more than 8.33 ms. In the RoboTenis System, all these tasks take about 5 ms.

A pinhole camera model performs the perspective projection of a 3D point into the image plane. The camera is pre-calibrated with known intrinsic parameters. Features extracted (centroid and diameter) together with the knowledge of the ball geometry (radius); give the pose estimation of the ball according to the camera. The position and velocity of the ball are estimated using the Kalman filter.

The control program takes the estimated position and velocity of the ball, the joints positions and, using (6) it calculates the control actions in order to be applied to the three joint-level velocity control loops of the robot.

3 Experimental Results

In this section, results related to the realization of visual tracking tasks using a parallel robot are presented. The results show the performance of the visual servoing algorithm proposed for the RoboTenis system.

The control objective consists in keeping a constant relationship between the camera and the moving target. The distance was fixed to [600, 0, 0]T mm. The

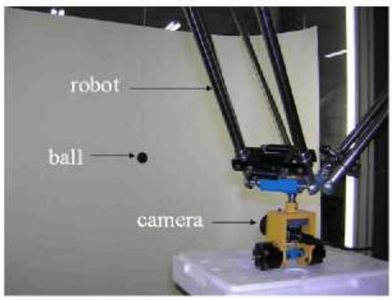

Fig. 4. Experimental setup

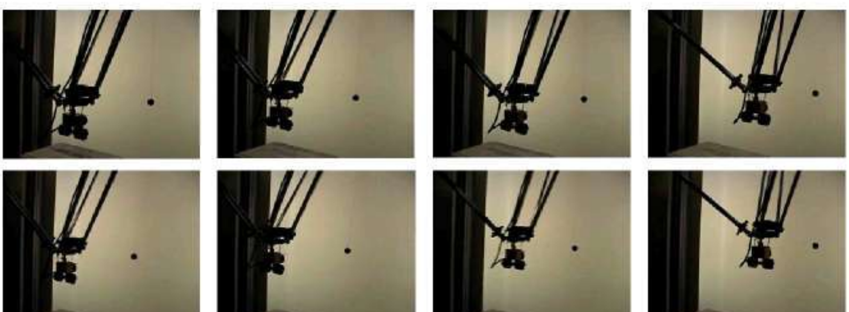

Fig. 5. 3D visual tracking of a ball using a parallel robot

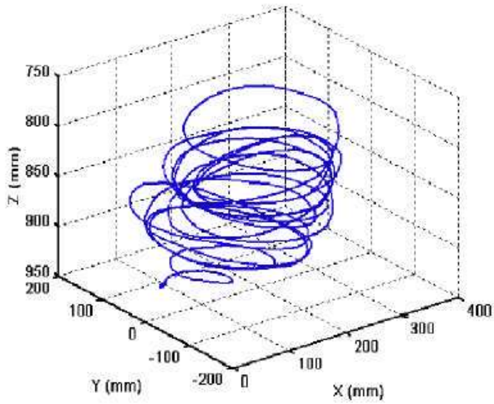

Fig. 6. Movement of the end-effector in the workspace

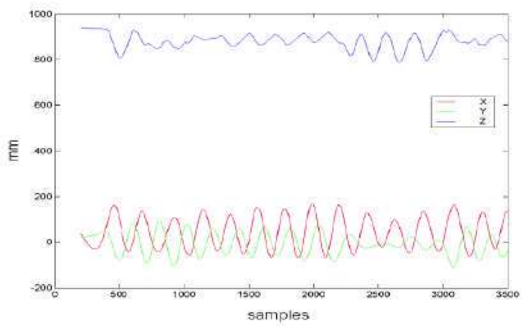

Fig. 7. Behaviour of the end-effector for the 3D visual tracking of the ball

ball is hold by a thread to the structure of the robot and it moves by means of a manual drag (Fig. 4). Different 3D trajectories have been executed. The tests have been made with speeds of up to 1000 mm/s.

For example, in Fig. 5 is represented the space evolution of the ball and the end-effector for one trial. This figure shows a sequence of eight images taken during a tracking task. Fig. 6 and Fig. 7 show the space evolution in the position of the end-effector and a time history, respectively. The nature of the motion causes appreciable variations of the velocity of the ball difficult to predict, which increases the difficulty of the tracking task.

3.1 Performance Indices

We propose two performance indices for the validation of the visual controller (6). These indices are based on the tracking error and the estimated velocity of the ball. Given the random nature of the made tests, the proposed indices are:

- *Tracking relation:It is defined as the relation between the average of modulate of the tracking error and the average of modulate of the estimated velocity of the ball, it is*

$$TrackingRelation = \frac{\frac{1}{N}\sum_{k=1}^{N} e(k)}{\frac{1}{N}\sum_{k=1}^{N} {}^{w}\hat{v}_b(k)} \tag{10}$$

This index isolates the result of each trial of the particular features of motion of the ball.

- *Average of the tracking error by strips of the estimated velocity of the ball: we have defined 5 strips:*

$$\begin{array}{l} Estimated\,velocity < 200mm/s \\ < 200mm/s < Estimated\,velocity \leq 400mm/s \\ < 400mm/s < Estimated\,velocity \leq 600mm/s \\ < 600mm/s < Estimated\,velocity \leq 800mm/s \\ Estimated\,velocity > 800mm/s \end{array} \tag{11}$$

3.2 Predictive Control Versus Proportional Control

With the purpose of validating (6), we propose to compare the performance of the RoboTenis System using (10) and (11) for the two following cases:

- *Predictive control law: It considers the predictive component of (6), is to say:*

$${}^{w}v_e(k) = {}^{w}\hat{v}_b(k) - \lambda^{c}R_w^T\left({}^{c}p_b^* - {}^{c}\hat{p}_b(k)\right) \tag{12}$$

- *Proportional control law: It does not consider the predictive component of (6), is to say:*

$${}^{w}v_e(k) = -\lambda^{c}R_w^T\left({}^{c}p_b^* - {}^{c}\hat{p}_b(k)\right) \tag{13}$$

Table 1 and Table 2 present the results obtained for the indices (10) and (11) when the control laws (12) and (13) are applied. The results present the average of 10 trials made for each algorithm of control. A high performance of the system using the predictive control algorithm is observed, given by a smaller tracking relation and a smaller error by strips.

Fig. 8 and Fig. 9 show the evolution in the tracking error and the estimated velocity of the ball when (12) is applied to the RoboTenis System. Whereas Fig. 10 and Fig. 11 show the evolution in the tracking error and the estimated velocity of

Table 1. Predictive control vs proportional control tracking relation

Algorithm	tracking relation
Proportional	40.45
Predictive	20.86

Table 2. Predictive control vs proportional control error by strips (V in mm/s)

Algorithm	$V < 200$	$200 < V < 400$	$400 < V < 600$	$600 < V < 800$	$V > 800$
Proportional	6.36	13.72	20.11	26.22	32.56
Predictive	4.21	8.19	9.50	11.38	13.54

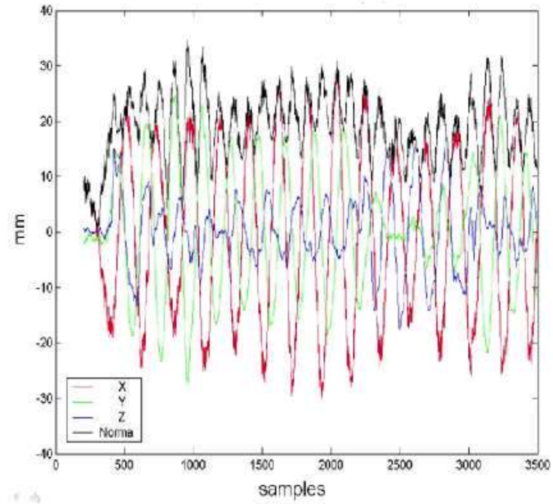

Fig. 8. Proportional Control Law: tracking error

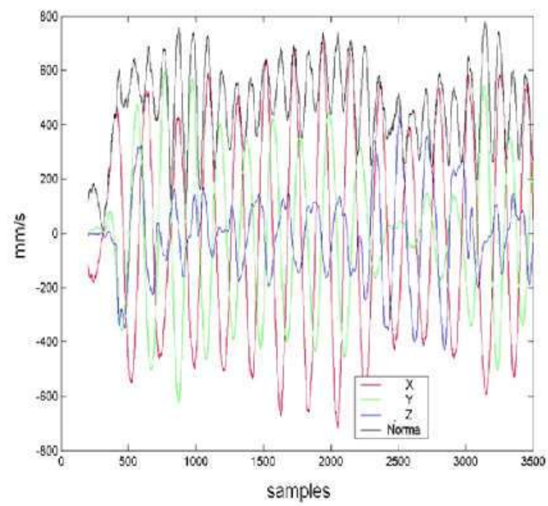

Fig. 9. Proportional Control Law: estimated velocity of the ball

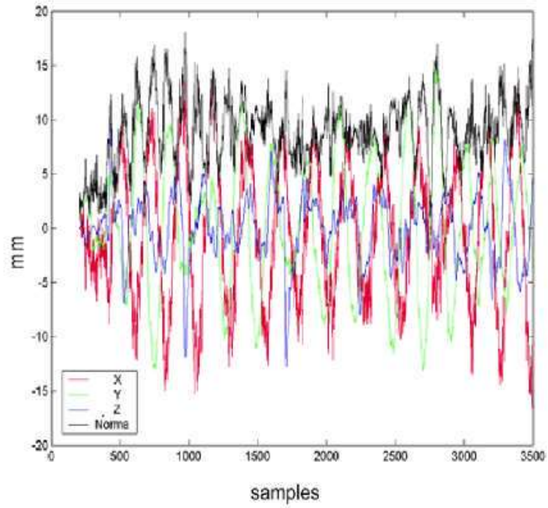

Fig. 10. Predictive Control Law: tracking error

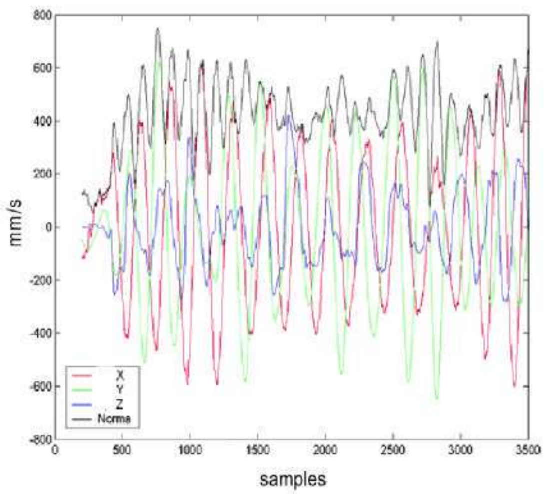

Fig. 11. Predictive Control Law: estimated velocity of the ball

the ball when (13) is applied. For proportional control law, the maximum tracking error is 34.50 mm and maximum velocity of the ball is 779.97 mm/s. For the predictive control law, the maximum tracking error is 14.10 mm and the maximum velocity of the ball is 748.16 mm/s. The error is bounded and the tracking error is reduced by introducing an estimation of the moving object velocity.

These results are no more than preliminary. Next, it will be necessary to evaluate the robustness of the control law with regard to noise in position and velocity estimation, modelling error, and particularly to the eye-in-hand calibration error.

4 Conclusion

This paper describes a position-based visual servoing system for tracking a hanging ball with a robot equipped with an attached camera. A parallel robot is used for this purpose. The ball is tracked as a single point. The control law considers a prediction of the position and velocity of the ball in order to improve the performance of the movement of the robot. The presented experiments have been performed considering both predictions and the position prediction only. These results are no more than preliminary. As future work, is necessary to evaluate the robustness of the system with respect to modeling errors, and to design new visual control strategies that allow to the system tracking velocities of up to 2 m/s.

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