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# FPGA-based visual control system using dynamic perceptibility

Javier Pérez *, Aiman Alabdo, Jorge Pomares, Gabriel J. García, Fernando Torres

*Department of Physics, System Engineering and Signal Theory, University of Alicante, San Vicente del Raspeig, POBox 99, 03080 Alicante, Spain*

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ABSTRACT

This paper presents an embedded architecture based on field programmable gate arrays technology to implement direct visual controllers. These controllers directly generate the joint torques to perform visual servoing tasks taking into account the robot dynamics. Additionally, the concept of dynamic perceptibility, which provides information about the system capability to track objects using direct visual servoing, is defined. This concept is integrated in the proposed controllers and implemented in the embedded architecture for robot and image singularity avoidance. To do this, the paper presents an optimal control framework for direct visual servoing robots which integrates the concept of dynamic perceptibility. This paper presents the formulation of the optimal framework and details the implementation of one of the derived controllers in the FPGA-based architecture. In order to evaluate the proposed architecture, the FPGA architecture is applied to two different robots. The first one is the industrial robot Mitsubishi PA10 with 7 degrees of freedom and the second one is a 4 degrees of freedom robot designed by the authors. Additionally, different experiments are described to show the system behavior when a trajectory close to a singularity is obtained.



## 1. Introduction

The cost reduction of the Field Programmable Gate Arrays (FPGAs), their increasing capabilities, and the possibility to improve the performance of sensor processing tasks with specific hardware technologies, have increased their use in new fields of application related with control. The current capabilities of FPGAs provide a specific hardware technology, which can be employed to implement embedded control systems [1]. FPGAs have already been used with success in different systems as the development of a higher degree polynomial profile generator for CNC and robotics applications [2], control of robotic arms [3], neural networks based controllers [4], mechatronic systems [5], etc. FPGAs and their partial re-configurability provide additional properties to control systems (e.g. processing, interface, testing, configuration capabilities, etc.). In this paper, an FPGA based visual servoing system is proposed to perform the guidance of robots using an eye-in-hand camera system.

Visual servoing aims at controlling robotic systems by the information provided by one or more cameras [6]. In image-based visual servo the robot motions are controlled by canceling errors on visual features defined in the image. This type of visual servoing consists of using feedback information defined directly in the images provided by a vision sensor to control the motion of a robotic system. Classical image-based visual servoing systems generate Cartesian or joint velocities. However, when a direct visual servoing approach is considered the controller directly generates the joint torques to perform the visual servoing task taking into account the robot dynamics. For the implementation of these kind of systems, the FPGA allows to obtain a dedicated parallel architecture that can be adapted in runtime to the system needs. As it is described throughout the text, the hardware implementation of a visual control system can improve the speed performance. Within the ambit of visual servoing systems, there are just a few previous implementations that integrate FPGAs in some element of the visual servoing system. The majority of the delays in these systems are due to the image processing tasks. This is why there are some works as [7] that optimize the image capture process through the hardware implementation allowed by an FPGA. Additionally, it is possible to find embedded indirect visual servoing systems that integrate the image processing as well as the control [8]. However, it is not possible to find architectures for the direct visual control of robot manipulators with various degrees of freedom (dof) as described in this paper. Furthermore, in order to evaluate the proposed architecture, the FPGA visual control system is applied to two different robots. The first one is the industrial robot Mitsubishi PA10 with 7 dof and the second one is a 4 dof robot designed by the authors whose main kinematic and dynamic properties are described in [9].

* Corresponding author.
*E-mail addresses:* jpalepuz@ua.es (J. Pérez), aalabdo@ua.es (A. Alabdo), jpomares@ua.es (J. Pomares), gjgg@ua.es (G.J. García), Fernando.torres@ua.es (F. Torres).

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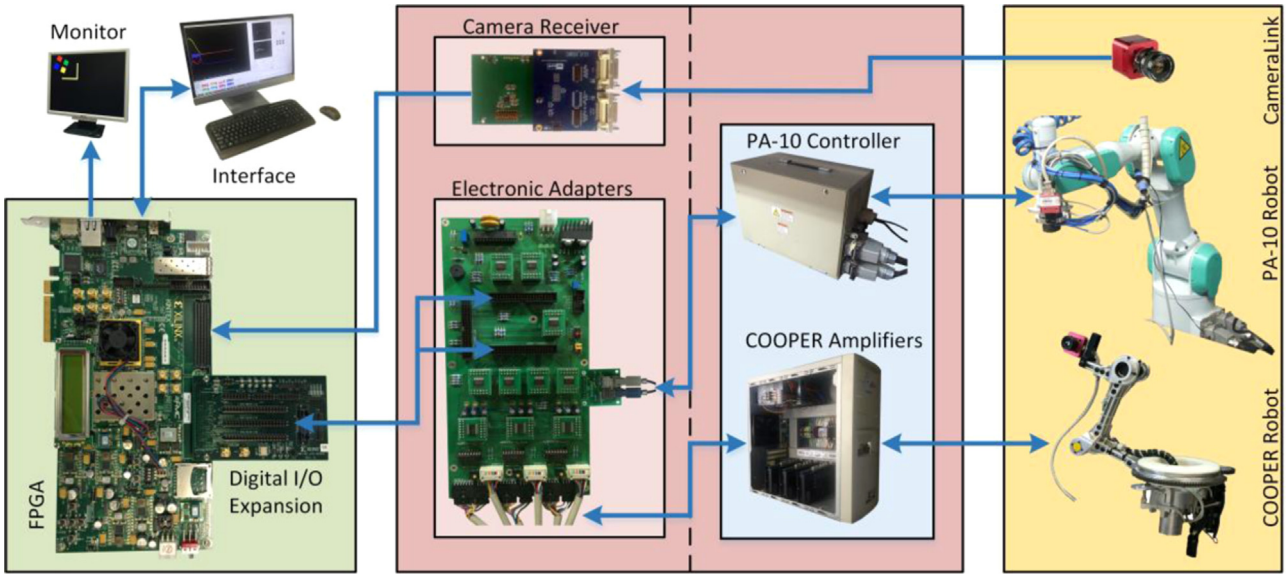


**Fig. 1.** System components.

The manipulability is currently a well-known concept that measures the distance between the current configuration of a robot and the closest singular pose [10]. A high manipulability is required to assure the ability of the robot to move in arbitrary directions. Additionally, the concept of dynamic perceptibility has been defined in order to take into account the robot dynamics [11]. However, when a direct visual servoing controller is defined, the control is carried out in the image space and additional considerations must be taken into account to perform the robot guidance. The image-based visual servoing systems employ the concept of interaction matrix which relates the time variation of the extracted visual features to the relative camera-object kinematics screw. The interaction matrix is singular if it contains the image measurements of three feature points that are collinear [3], or belong to a cylinder containing the camera optical center [12], or belong to a plane perpendicular to the camera optical axis and at least one set of image measurements satisfy [13]. At image singularities, certain camera (end-effector) motions cannot be perceived by using the extracted image feature. The perceptibility is a scalar function that provides information about the possibility of the vision system to perceive the motion within its field of view only using kinematics information [14]. The concept of perceptibility has been previously proposed as a measure of closeness to image singularities. In this paper, the dynamic perceptibility concept is proposed in order to take into account the manipulator kinematics and dynamics. This new concept provides information about the system ability to track objects using a direct visual control system and it has suitable properties for high-speed and high-precision motion control avoiding image singularities. The use of this parameter is a useful criterion to determine situations where the robot is close to a singularity (in the image or in the joint space). The dynamic perceptibility is integrated in the proposed controllers for robot and image singularity avoidance. Additionally, an optimal implementation of the dynamic perceptibility concept is carried out by using the proposed FPGA-based architecture.

This paper presents an optimal control framework for direct visual servoing robots which integrates the concept of dynamic perceptibility. The presented approach is based on an optimal control framework and is employed to control robots during the tracking of image trajectories taking into account the robot dynamics. Thus, this control approach considers the optimization of the motor signals or torques sent to the mechanical system during visual control tasks. The dynamic perceptibility concept is integrated in the framework to avoid singularities. Using this framework, several new direct visual controllers can be derived. This paper presents the formulation of the optimal framework and details the implementation of one of the derived controllers in the FPGA-based architecture. The correct behavior of both the controller and the FPGA-based architecture are evaluated with the two previous indicated robots (the 7 dof Mitsubishi PA10 and the 4 dof robot).

This paper is organized as follows. Section 2 described the main components of the proposed FPGA-based architecture. Section 3 presents the main notation and the concept of dynamic perceptibility. Section 4 describes the optimal framework that integrates the dynamic perceptibility concept. This strategy is used to guide the robot avoiding singularities. The FPGA-based implementation of the proposed controller is described in Section 5. Section 6 shows several experiments to illustrate the performance of the FPGA based visual servoing architecture. The final section elaborates the conclusions reached by this paper and possible future works.

## 2. FPGA-based architecture

This section describes the main components of the proposed FPGA-based architecture (see Fig. 1). This architecture will be evaluated for visual servoing two different robots. The first one is the industrial robot Mitsubishi PA10 with 7 dof and the second one is a 4 dof robot (COOPER robot). To visual servoing both robots a PHOTONFOCUS MV-D752-160-CL-8 camera is installed at its end-effector. The camera is able to acquire and process 200 frames/sec using an image resolution of $752 \times 582$ pixels.

The FPGA board used is the KC705 evaluation board from Xilinx. This board is based on the Kintex-7 XC7K325T-2FFG900C FPGA. In order to read images from the camera, a commercial CameraLink receiver CLR-HSMC made by Terasic is employed. It uses the High Speed Mezzanine Card (HSMC) to interface with another motherboard hosting an HSMC/HSTC carrier such Altera's FPGA boards. An adapter board, KY-FMC2HSMC from KAYA INSTRUMENTS is used to enable connection of CLR-HSMC to the Xilinx FPGA board via LPC FMC expansion connector.

In order to test the proposed controller, the system was embedded in an FPGA. As shown in Fig. 2, the embedded system