Mechatronics 21 (2011) 1170–1182

Contents lists available at SciVerse ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Design and implementation of robust visual servoing control of an inverted pendulum with an FPGA-based image co-processor

Yi-Wei Tu, Ming-Tzu Ho *

Engineering Science Department, National Cheng Kung University, No. 1, University Road, Tainan 701, Taiwan

ARTICLE INFO

Article history:
Received 12 November 2009
Accepted 14 July 2011
Available online 1 September 2011

Keywords:
Visual servoing
Inverted pendulum system
Mixed H_2/H_∞ control
Field programmable gate array (FPGA)

ABSTRACT

This paper presents the design and implementation of robust real-time visual servoing control with an FPGA-based image co-processor for a rotary inverted pendulum. The position of the pendulum is measured with a machine vision system. The pendulum used in the proposed system is much shorter than those used in published vision-based pendulum control system studies, which makes the system more difficult to control. The image processing algorithms of the machine vision system are pipelined and implemented on a field programmable gate array (FPGA) device to meet real-time constraints. To enhance robustness to model uncertainty and to attenuate disturbance and sensor noise, the design of the stabilizing controller is formulated as a problem of the mixed H_2/H_∞ control, which is then solved using the linear matrix inequality (LMI) approach. The designed control law is implemented on a digital signal processor (DSP). The effectiveness of the controller and the FPGA-based image co-processor is verified through simulation and experimental studies. The experimental results show that the designed system can robustly control an inverted pendulum in real-time.

1. Introduction

Visual servoing [1] is a control framework that incorporates visual information in feedback control loops. It is applied in many fields, such as robotics [2,3], industrial automation [4], and automated vehicle guidance [5]. Vision-based control involves results from many areas, including image processing, kinematics, dynamics, control theory, and real-time computation. Real-time image data acquisition and processing is a critical issue in visual servoing applications. A high frame rate and low processing latency are essential since the visual servoing system must make quick decisions based on the information extracted from a scene. To meet real-time constraints, visual servoing systems usually require high-cost specialized hardware and software, which presents serious obstacles to their design. Real-time image processing requires a high pixel processing rate, massive and parallel computation, and efficient hardware utilization. General-purpose processors cannot always provide enough computational power to fulfill real-time requirements due to their sequential nature. Due to their inherent architectural parallelism and configurable flexibility, field programmable gate arrays (FPGAs) have become increasingly popular implementation platforms for a wide variety of applications [6–8]. Real-time image processing benefits greatly from the real-time processing capabilities and flexibility of FPGAs. In [9], an FPGA/DSP (digital signal processor) architecture was proposed for real-time image processing. This architecture was designed to deal with parallel/pipelined procedures to handle multiple input images. A flexible FPGA-based systolic architecture for real-time window-based image processing was proposed in [10]. The computational core was based on a configurable two-dimensional systolic array of processing elements. In [11,12], FPGAs with a pipelined architecture were used to implement optical flow estimation from image sequences in real-time.

There are a number of non-contact sensors such as radars, ultrasonic sensors, infrared sensors, or vision sensors which may be used for position sensing of a target. However, vision sensors offer many advantages compared to other non-contact sensors. Vision sensors are able to identify and track targets within the scene with ease and provide more information about the relationship between targets and environment. Measurements made from images are noisy in nature due to modeling uncertainty of the image sensor and changes in the environment, background, and illumination, which deteriorates the performance of visual servoing systems. To mitigate noise, a filter is commonly used to smooth noisy data before it is fed to the controller. Various filtering approaches have been proposed in the literature for visual servoing, such as Kalman filters [13,14], fuzzy filters [15], and particle filters [16].

Combining the merits of H_2 optimal control and H_∞ robust control, the mixed H_2/H_∞ control design allows one to minimize a nominal performance measurement subject to robust stability constraints. In [17], the state-feedback and output-feedback problems

* Corresponding author. Tel.: +886 6 275 7575x63349; fax: +886 6 276 6549.
E-mail address: bruceho@mail.ncku.edu.tw (M.-T. Ho).

0957-4158/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.mechatronics.2011.07.011