ISA Transactions 68 (2017) 402–411

Contents lists available at ScienceDirect

ISA Transactions

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

Research article

Global finite-time adaptive control for uncalibrated robot manipulator based on visual servoing

Tao Li [a], Hui Zhao [b,*]

[a] School of Electrical Engineering and Automation, Tianjin University, Tianjin 300072, PR China
[b] Tianjin Agricultural University, No.22, Jinjing Rd. Xiqing District, Tianjin 300384, PR China

ARTICLE INFO

Article history:
Received 11 July 2016
Received in revised form
23 September 2016
Accepted 12 October 2016
Available online 11 March 2017

Keywords:
Visual servoing
Adaptive control
Finite-time stability
Lyapunov stability

ABSTRACT

The paper addresses the finite-time convergence problem of a uncalibrated camera-robot system with uncertainties. These uncertainties include camera extrinsic and intrinsic parameters, robot dynamics and feature depth parameters, which are all considered as time-varying uncertainties. In order to achieve a better dynamic stability performance of the camera-robot system, a novel FTS adaptive controller is presented to cope with rapid convergence problem. Meanwhile, FTS adaptive laws are proposed to handle these uncertainties which exist both in robot and in camera model. The finite-time stability analysis is discussed in accordance with homogeneous theory and Lyapunov function formalism. The control method we proposed extends the asymptotic stability results of visual servoing control to a finite-time stability. Simulation has been conducted to demonstrate the performance of the trajectory tracking errors convergence under control of the proposed method.

1. Introduction

A visual servo system, generally speaking, can be divided into three key processes [1,2]. Developing kinematic models of the system will be the initial step. Once having established the kinematic models, deriving the image Jacobian matrix with kinematic models and camera parameters will be the second stage and that play a vital role in the development of visual servo system. After obtaining the Jacobian matrix, the process can finally move on to the last step which is mapping errors in image-space onto joint-space to close the feedback loop by using inverse or transpose Jacobian matrix schemes. It is well-known that image jacobian depends on the camera intrinsic and extrinsic parameters. The obtaining of the intrinsic and extrinsic parameters of camera are well known as off-line calibration. However, the calibration is an error prone process, even the calibrated parameters themselves may change their value over time. Besides, it is well known that robot kinematics are nonlinear and including many uncertainties, and the uncertainties in robot kinematics also make the obtaining of image Jacobian more complex. Up to now, how to estimate Jacobian matrix accurately has been an active research topic.

To overcome the problem of lacking analytic Jacobian matrix, some vision-based controllers were designed based on online-estimated Jacobian to accomplish control task without calibration [3–5]. Moreover, many papers [6,7] developed uncalibrated visual servoing methods using estimation of nonlinear visual mapping modes to avoid camera calibrations.

In order to solve the time-varying issue of camera parameters, adaptive control techniques are employed due to its well-known performance in coping with measurement variation adaptively. In [8,9], adaptive visual servoing controllers were proposed to handle unknown camera parameters through designing adaptive laws.

The uncalibrated visual servoing approaches afore-mentioned are all based on robot kinematics and visual mapping. However, the robot dynamics is also highly nonlinear [10,11]. Taking the importance of nonlinear force into account of control error and system stability, dynamic-based visual servoing strategies had also attracted more and more attention. Dynamics uncertainties in the Jacobian matrix were considered in [12–14]. Jacobian-fixed-approximation approach which considered dynamics was proposed by [13] to set-point control manipulators in task-space. Jacobian-fixed-approximation controllers do not require the exact physical parameters of Jacobian matrix but substituted them with approximate ones. Although the methods proposed by afore solved the design problem of Jacobian matrix and the off-line estimation of approximated Jacobian matrix is neglected, the constraints on the bound of approximating Jacobian matrix can not be ignored. In order to remove these constraints, more attention has been paid to the adaptive Jacobian matrix estimation control schemes, which estimate the Jacobian matrix online in contrast with off-line estimation in Approximate-Jacobian scheme. Some tracking methods based on Jacobian-Adaptive-estimation are proposed in [15,16] and [17]. These controllers accomplish control tasks with adaptive image Jacobian matrix.

* Corresponding author.
E-mail address: Zhaohui3379@126.com (H. Zhao).

http://dx.doi.org/10.1016/j.isatra.2016.10.006
0019-0578/

It is noteworthy that depth parameter in the Jacobian matrix is also uncertain. [18–21] proposed non-linear observer which is able to estimate depth parameters online, and Euclidean homography needs to be calculated and decoupled in these controllers. Being different from observer methods, [22] proposed a uncalibrated visual servoing control scheme with a depth-independent interaction matrix. The proposed depth-independent interaction matrix allowed the depth parameters to be linearly parameterized so that adaptive laws can be designed to estimate these parameters. Therefore the most distinguishing feature of [22] is that it can cope with the unknown time-varying depth information and the scheme is known as depth-independent-Jacobian-matrix-based visual servoing scheme.

On the other hand, however, apart from the stability and asymptotic stability, there is another important research issue called fast convergence in practice control systems, i.e., finite-time stability. The finite time stable system is firstly asymptotically stable and its convergence speed should be faster than asymptotic stability. Apparently, FTS is of significant value in robotic control field on either theoretical level or practical level. Many works have been done in the past years [23–30] and [31].

Generally, FTS methods are divided into three classes: terminal sliding mode control (TSM), homogeneous system theory and finite-time Lyapunov method. In the matter of TSM, [28] proposed a TSM controller to achieve finite-time trajectory tracking control of nonlinear robot manipulator and other related works see [29,32,27]. In the matter of homogeneous system theory, Hong et al. [33] formulated PD plus gravity compensation scheme using homogenous theory to achieve global finite-time stability with measurement of joint position and velocity and achieve local FTS stability with only measurement of position by using velocity observer. [30] and [34] simplify the velocity observer by introducing quasi-differential technique and non-smooth continuous function, and achieve global FTS tracking control for robot manipulators. As for Lyapunov method, [23] and [35] set up the Lyapunov stability criterion for finite-time control system. Meanwhile, due to the characters of robotic system researching on robot system using Lyapunov stability methods to achieve finite-time stability is still very few.

Since finite-time control is an important control method due to its faster convergence than asymptotic stability control and some FTS control schemes achieved in different ways [23,34] and [36], FTS realization on robot system is still rare, especially on visual servoing robot system. As far as we know, not much articles have discussed this problem.

Motivated by the visual servo control, we now investigate the finite-time stability control in uncalibrated visual servoing scheme. The effectiveness of the control scheme proposed lies in three aspects: kinematic uncertainty handling, free of image-velocity and finite-time convergence. Comparing with [15] and [17], which are fail to cope with time-vary depth parameter, we propose a depth-independent-Jacobian-matrix-based control scheme for visual tracking control through separating estimation of kinematics, dynamics and depth uncertainties (time-varying) into three adaptive laws. Moreover, another notable uncertainty is position of selected feature point with respect to robot base. Be distinguishing from [37], the scheme proposed in this paper also allows unknown of feature points' position. It is well-known that the image-space velocity is commonly obtained by the standard numerical differentiation of the images-pace position information. Due to effects of camera quantization and low sampling, image-space velocity is undesirable to use image-space velocity in our control design. Therefore, the proposed control method in this paper is free of image-velocity in adaptive law and controller design. Besides, one possible drawback of the above results which deal with visual tracking problem is that they are asymptotically convergence. It is well-known that asymptotic convergence means system trajectories converge to equilibrium as time goes to infinity, and meanwhile, finite-time stabilization of dynamical systems may give rise to better robustness and high-precision performances besides finite-time convergence [23]. Hence it is meaningful to apply finite-time convergence into visual servoing control. Despite lots of works [30,31] and [34] address finite-time tracking of robot manipulator, most of them focus on joint-space feedback control. The most challengeable difficulty is that FTS-based controller is commonly non-smooth, which makes it difficult to be analyzed theoretically. A creativity work on FTS-based control scheme is proposed by in [33]. The controller proposed in [33] consists of part of model information's PD term and gravity-compensation term (or inverse-dynamics term). Furthermore [34] consider actuator constraint situation in finite-time tracking controller design. Controller proposed in [34] replace the linear error in the commonly used PD+ with saturated non-smooth exponential-like ones. All of FTS-based control schemes afore-mentioned use joint state as feedback terms. However the visual servoing system means that the feedback states are image-space states, meanwhile it contains more uncertainties and more difficulties, hence FTS-based control method remains a lot of challenging problems. To overcome these problems, control scheme proposed in this paper exploits homogeneous system theory, quasi-differential technique and non-smooth continuous function to achieve finite-time trajectory tracking control. In order to involve visual errors into design, we propose a controller with visual position term, which is non-smooth continuous function and can be seen as proportion term. Besides, for avoiding to use image velocity, we define a new vector which consists by joint-space velocity and reference joint velocity. The new vector feedback term is also non-smooth continuous function and can be regarded as quasi-differential term. With the addition of inverse dynamics estimation, which is estimated by adaptive law, we propose the FTS-based control scheme. Comparing to [33,38], our work extends application of FTS-scheme to a time-vary nonlinear system with multiple uncertainties which is more complicated.

The main contributions of this paper can be summarized as: (a) a new adaptive FTS controller with commonly used Non-linear Proportion Differentiation plus (NPD+) scheme is first proposed under unknown of dynamics, kinematics and the depth parameters of feature points. Comparing to [34], the new FTS controller is based on visual servoing and it considers more unknown parameters of visual-robot system. Another notable difference from [39] is that the proposed controller possesses a rapid convergence; (b) by considering the nonlinear dynamics, we present a new Lyapunov-type positive definite function to rigorously prove asymptotical convergence of image tracking errors, furthermore, we achieve global FTS of image tracking errors through homogeneous theory.

The rest of this paper is organized as follow. Some definitions and lammas are given in Section 2. Section 3 reviews unified kinematic model and dynamics of manipulator-vision system. Section 4 present the primary works of the paper. The finite-time uncalibrated controller and adaptive laws for unknown parameters are proposed, and the global finite-time convergence of the system is proven. Section 5 presents simulation results. Finally, we concluded the work in Section 6.

2. Preliminaries

To facilitate following analysis, some important definitions are given in this section. Consider the system

$$\dot{x} = f(x), \tag{1}$$

where $f(0) = 0$, $x(0) = x_0$, $x \in \mathbb{R}^n$, with $f: U_0 \to \mathbb{R}^n$ continuous on