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Robust visual tracking control system of a mobile robot based on a dual-Jacobian visual interaction model

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ABSTRACT

This paper presents a novel design of a robust visual tracking control system, which consists of a visual tracking controller and a visual state estimator. This system facilitates human–robot interaction of a unicycle-modeled mobile robot equipped with a tilt camera. Based on a novel dual-Jacobian visual interaction model, a robust visual tracking controller is proposed to track a dynamic moving target. The proposed controller not only possesses some degree of robustness against the system model uncertainties, but also tracks the target without its 3D velocity information. The visual state estimator aims to estimate the optimal system state and target image velocity, which is used by the visual tracking controller. To achieve this, a self-tuning Kalman filter is proposed to estimate interesting parameters and to overcome the temporary occlusion problem. Furthermore, because the proposed method is fully working in the image space, the computational complexity and the sensor/camera modeling errors can be reduced. Experimental results validate the effectiveness of the proposed method, in terms of tracking performance, system convergence, and robustness.

1. Introduction

An intelligent robot uses its on-board sensors to collect information from the surroundings and react to the changes of its immediate environment. In recent years, vision systems have been widely used for various intelligent robots, and the research on visual tracking control has gained increasing attention in the area of robotic research [1–25]. In robotics, visual tracking control means vision-based robot motion control to track an interesting target. Based on the motion constraints of the robot, visual tracking control can be classified into two categories: visual servoing for holonomic manipulators and visual tracking for nonholonomic mobile robots. Although visual servoing of holonomic manipulators has been discussed extensively and many results can be found in the literature [1–3], mobile robots are commonly nonholonomic and the visual servoing results for holonomic manipulators are unsuitable for a mobile platform [4].

This paper addresses the problem of visual tracking control of unicycle-modeled or usually termed as wheeled mobile robots equipped with an *on-board* monocular vision system. Due to large number of mobile robot visual tracking control methods, we classify the reported methods into four groups based on the type of the target to be tracked. Many efforts focus on the first group which aims to track a static target, such as a ground line, landmark, or reference image, for the purpose of mobile robot navigation or regulation (so-called homing) [5–17]. For a mobile robot to track a ground line, Ma et al. formulated the visual tracking control problem as controlling the shape of a ground curve in the image plane and proposed a closed-loop vision-guided control system for a nonholonomic mobile robot [5]. Coulaud et al. proposed a simple and stable feedback controller design, which avoids sophisticated image processing and control algorithms, for a mobile robot equipped with a fixed camera to track a line on the ground [6]. In the case of tracking the landmark, the reported controllers usually modify the visual servoing technique to satisfy the nonholonomic constraint for the motion control of the mobile robot [7–10]. In [11], Zhang and Ostrowski utilized an optimal control method to solve the visual motion-planning problem by generating a virtual trajectory in the image plane and the corresponding optimal control signals for the robot to follow. Nierobisch et al. proposed a visual tracking control method for a mobile robot with a pan-tilt camera to track visual reference landmarks in the acquired views during autonomous navigation [12]. Recently, the homography-based [13,14] and epipolar-based [4,15–17] visual tracking control approaches were proposed for a mobile robot equipped with a pinhole or an omni-directional (so-called central catadioptric) camera to track a reference image toward a desired configuration. These two approaches consider the mobile robot visual tracking

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control problem as a visual servoing regulation or visual homing problem. In [13], Chen et al. developed a visual tracking controller based on the Euclidean homography to track a desired time-varying trajectory defined by a prerecorded image sequence of a stationary target viewed by the on-board camera as the mobile robot moves. However, the stability of their result is restricted by the non-zero reference velocity condition of the desired trajectory. To overcome this drawback, Fang et al. exploited Lyapunov-based techniques to construct a homography-based visual servoing regulation controller for proving asymptotic regulation of the mobile robot [14]. In [15], Mariottini et al. exploited the epipolar geometry defined by the current and desired camera views to develop a two-step visual servoing regulation controller. They also extend this design to the visual servoing regulation control of a mobile robot with a central catadioptric camera [16]. In [17], Goedemé et al. developed a vision-only navigation and homing system for mobile robots with an omni-directional camera. Their method divides the visual homing operation into two phases and computes visual homing vector based on epipolar geometry estimation. Although these approaches of the first group provide appropriate solutions for static target visual tracking control problem, they cannot guarantee to solve the moving (non-static) target visual tracking control problem.

The second group aims to track other robot teammates in a robot team for the formation control purpose [18,19]. The proposed approaches in this group usually are based on a central catadioptric camera model in order to detect all robot teammates at the same instant. The subject of the third group is to track a predictable moving target, such as a projectile or straight moving ball, for mobile robot interception purpose [20,21]. In [20], Borgstadt et al. utilized a human vision-based strategy to guide a mobile robot to intercept a projectile ball. Similarly, Capparella et al. extended the concept of human-like strategy to develop a vision-based two-level interception approach, which contains a lower level controller to control the on-board pan-tilt camera and a higher lever controller to operate the mobile robot platform, for intercepting a straight moving ball [21]. A common point of the second and third group is that the motion of the interesting target is known and predictable. However, in many robotic applications, a mobile robot requires to track a dynamic and unpredictable motion target, such as a human's face, for the purpose of pursuit or interaction. Thus, the existent methods of the aforementioned two groups are not suitable to solve the dynamic moving target visual tracking control problem.

The purpose of the fourth group is to solve the problem of tracking a dynamic moving target [22–25]. In [22], Wang et al. proposed an adaptive backstepping control law based on an image-based camera-target visual interaction model to track a dynamic moving target with unknown height parameter. Although the approach in [22] guarantees the asymptotic stability of a closed-loop visual tracking control system in tracking a dynamic moving target, the case of tracking a static target cannot be guaranteed due to the non-zero restrictions on the reference velocity of the mobile robot. In [23], Malis et al. integrated template-based visual tracking algorithms and model-free vision-based control techniques to build a flexible and robust visual tracking control system for various robotic applications. Because their visual tracking result is based on the homography estimation, which requires two images of the target pattern to estimate the optimal homography, the reported system only overcomes the partial occlusion problem but fails in the fully occlusion problem. In [24], Han et al. proposed an image-based visual tracking control scheme for a mobile robot to estimate the position of the target in the next image and track the target to the central area of the image. Since their method utilized the differential approximation method to estimate the velocity of the target in the image plane, the estimation result is very sensitive to image noise. Recently, a visual interaction controller had been proposed for a unicycle-modeled mobile robot to track a dynamic moving target such as a human's face [25]. The drawback of this method is that the controller requires the target's 3D motion velocity, which is difficult to estimate when only a monocular camera is used.

From the literature survey, we note that challenges in the mobile robot visual tracking control design is to develop a robust tracking control system to estimate the motion of the moving target and to track the target based on a stability criterion. This problem motivates us to derive a new model for developing a robust visual tracking control system to solve the tracking problem of dynamic moving target in the image plane directly and efficiently. To do so, the visual interaction model described in [25] is extended to derive a novel dual-Jacobian visual interaction model for designing a robust mobile robot visual tracking control system, which encompasses a visual state estimator and a visual tracking controller. The visual state estimator is constructed by a real-time self-tuning Kalman filter and aims to estimate the optimal system state and target motion in the image plane directly for later use by the visual tracking controller. The visual tracking controller then calculates the robot's control velocities in the image plane directly. The main differences between the proposed method and other existent approaches are summarized as follows:

(1) The proposed dual-Jacobian visual interaction model considers not only the effect of mobile robot motion, but also the effect of target motion. Thus, based on the proposed model, the visual tracking control problem of a unicycle-modeled mobile robot for tracking a dynamic moving target can be solved with asymptotic convergence using a single controller. Moreover, the proposed model also considers the kinematics of a tilt camera platform mounted on the mobile robot. Therefore, the applicability of the proposed method is greatly increased.
(2) The proposed visual tracking control system not only possesses some degree of robustness against the system model uncertainties, but also overcomes the unmodeled quantization effect in the velocity commands and the occlusion effect during visual tracking process. This advantage enhances the reliability of the proposed method in practical applications.
(3) The proposed visual tracking control system works fully in the image space. Therefore, compared with position-based [23], homography-based [13,14], and epipole-based [4, 15–17] visual tracking control approaches, the computational complexity and the sensor/camera modeling errors can be much reduced due to the advantages of image-based visual servo control [2].
(4) The proposed self-tuning Kalman filter can automatically choose a suitable observation covariance matrix in varying environmental conditions. This helps to improve the estimation performance when there is noise in the system observation.

To validate the performance and robustness of the proposed control system, computer simulation and experimental studies of tracking a moving target have been conducted. Simulation and experimental results will be presented and discussed to verify the effectiveness of the proposed control system, in terms of tracking performance, system convergence, and robustness. Note that a brief version of the research results has been published in [26]. This paper will present the complete design of the proposed tracking control system, including robustness analysis, computer simulation and experimental validation.

The rest of this paper is organized as follows. Section 2 describes the proposed dual-Jacobian visual interaction model. Section 3 presents the results of visual tracking controller design. Section 4 develops the visual state estimator using Kalman filter with self-tuning algorithm. Simulation and experimental results are reported in Section 5. Extended discussion of several interesting observations will be presented. Section 6 concludes the contributions of this paper.