Control Engineering Practice 71 (2018) 79–95

Contents lists available at ScienceDirect

Control Engineering Practice

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

Robust fulfillment of constraints in robot visual servoing

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ARTICLE INFO

Keywords:
Visual servoing
Sliding mode
Robot control

ABSTRACT

In this work, an approach based on sliding mode ideas is proposed to satisfy constraints in robot visual servoing. In particular, different types of constraints are defined in order to: fulfill the visibility constraints (camera field-of-view and occlusions) for the image features of the detected object; to avoid exceeding the joint range limits and maximum joint speeds; and to avoid forbidden areas in the robot workspace. Moreover, another task with low-priority is considered to track the target object. The main advantages of the proposed approach are low computational cost, robustness and fully utilization of the allowed space for the constraints. The applicability and effectiveness of the proposed approach is demonstrated by simulation results for a simple 2D case and a complex 3D case study. Furthermore, the feasibility and robustness of the proposed approach is substantiated by experimental results using a conventional 6R industrial manipulator.

1. Introduction

Visual servoing (VS) refers to the motion control of a robot system using visual feedback signals from a vision device (Chaumette & Hutchinson, 2008). For this purpose, a computer vision algorithm must be used to obtain the visual *features* of the target object present in the scene and observed by the camera. This information is used to compute the robot control law in order to achieve the desired robot pose. Taking into consideration the workspace in which the control law is computed (Chaumette & Hutchinson, 2008), the following classification can be made: position-based visual servoing (PBVS), in which the control law is carried out in the operational space, the relative 3D pose of the object is reconstructed from visual features with respect to the camera-robot system and the error is defined between the computed current and desired 3D poses; and image-based visual servoing (IBVS), in which the control low is directly computed in the image space and the error is defined between current and desired visual features in the image.

Regardless of the workspace in where VS control laws are computed, the following mechanical constraints can be violated: *joint range limits*; *maximum joint speeds*; and *forbidden areas*, such as the ones defined to avoid kinematic singularity, to avoid collisions (Gracia, Garelli, & Sala, 2013) between the robot manipulator and objects in the environment, etc. Furthermore, since the VS control law depends on the visual feedback, it is convenient to consider the so-called *visibility constraint* in order to keep the image features within the camera field-of-view (FOV) and to avoid occlusions with the obstacles in the environment during all the task.[1]

Due to the fact that the violation of any of the aforementioned mechanical and visual constraints can lead to the VS control task failure, different approaches have been presented to address this issue. For instance, based on the idea of *combining advantages of PBVS and IBVS* while trying to avoid their shortcomings (Kragic & Christensen, 2002): authors in Chesi, Hashimoto, Prattichizzo, and Vicino (2004) presented a switching method between IBVS and PBVS; authors in Gans and Hutchinson (2007) introduced a switching approach which uses the classic PBVS control law and backward motion along the camera optical axis; authors in Kim, Lovelett, Wang, and Behal (2009) proposed a switching approach using hybrid VS control laws and pure translation motions; authors in Deng and Janabi-Sharifi (2005) introduced a path planning and PBVS–IBVS switching method in order to deal with image singularities and local minima; authors in Kermorgant and Chaumette (2011) presented a combination approach which uses 2D and 3D information from IBVS and PBVS to ensure the *visibility constraint*; and authors in Hafez and Jawahar (2007) proposed a combination method

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[1] Some approaches (Cazy, Wieber, Giordano, & Chaumette, 2015; Garcia, Pomares, Torres, & Gil, 2014; Garcia-Aracil, Malis, Aracil-Santonja, & Perez-Vidal, 2005) provide solutions when loss of the image features occur based on the prediction of the feature behavior, although the main problem of these solutions is that robustness and convergence cannot be guaranteed, specially when the target is moving along an unknown or unpredictable trajectory.

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https://doi.org/10.1016/j.conengprac.2017.10.017
Received 16 April 2017; Received in revised form 21 August 2017; Accepted 30 October 2017

based on weighting IBVS and PBVS control strategies with a 5D objective function.

Other proposals rely on *path planning* algorithms: besides of the work of Deng and Janabi-Sharifi (2005) commented above, authors in Kyrki, Kragic, and Christensen (2004) presented a shortest-path method to guarantee both shortest Cartesian trajectory and object visibility; authors in Baumann, Léonard, Croft, and Little (2010) presented a path planning method which uses a probabilistic road map; authors in Chesi and Hung (2007) introduced a global path planning method to take into account visibility, workspace and joint constraints; authors in Chesi (2009) addressed the issue with a path planning approach based on the use of homogeneous forms and linear matrix inequalities; authors in Kazemi, Gupta, and Mehrandezh (2013) proposed a path planning approach using search trees and IBVS trajectory tracking; authors in Garcia, Pomares, and Torres (2009) introduced a time-independent path tracking in the image and 3D space approach for unstructured environments; authors in Huang, Zhang, and Fang (2014) presented a vision-based trajectory planning approach from the point of view of a constrained optimal control problem, solved by using the Gauss pseudo-spectral method.

Furthermore, there are some proposals relying on *online corrective* terms: authors in Corke and Hutchinson (2001) introduced a partitioned approach to IBVS control with the combination of a potential function for giving solution to the *visibility constraint* issue; authors in Mezouar and Chaumette (2002) developed a path-following IBVS controller that utilizes a potential function to incorporate *motion* constraints; and authors in Chen, Dawson, Dixon, and Chitrakaran (2007) and Cowan, Weingarten, and Koditschek (2002) presented an approach that employs a specialized potential function, namely navigation function.

In addition, some authors have focused his research on proposing more complex VS controllers to address the commented constraints. For instance, authors in Allibert, Courtial, and Chaumette (2010), Hajiloo, Keshmiri, Xie, and Wang (2016) and Heshmati-alamdari, Karavas, Eqtami, Drossakis, and Kyriakopoulos (2014) introduced control laws based on model predictive control frameworks, whilst authors in Song and Miaomiao (2017) on control Lyapunov functions. Moreover, authors in Chaumette and Marchand (2001) and Nelson and Khosla (1995) developed several control laws in order to deal with joint limits and space singularities.

On the other hand, other authors have focused on providing more feasible trajectories in other to avoid visibility and mechanical constraints. Thus, in Zhong, Zhong, and Peng (2015), authors dealt with the visibility constraint problem using a neural network approach which assists a Kalman filter, whilst in Chesi and Vicino (2004), circular-like trajectories are designed to ensure shorter displacements and visibility.

Finally, some authors relay their proposals on new VS control tasks. For instance, in Garcia-Aracil et al. (2005), the camera invariant VS approach is redefined to take into account the changes of visibility in image features, and in Mansard and Chaumette (2007), a global full-constraining task is divided into several subtasks that can be applied or inactivated to take into account potential constraints of the environment.

This paper addresses the problem of mechanical and visual constraints in VS with an alternative solution to all mentioned above. The proposed method can be interpreted as a limit case of *artificial potential fields* (Rimon & Koditschek, 1992). The basic idea is to define a *discontinuous* control law inspired by the fact that, in the limit case, as the repulsion region decreases, a potential field could be characterized as a discontinuous force: zero away from the constraint limits, and a large value when touching them. One of the advantages of this approach is that the allowed space is fully utilized, although some corrective speed-related terms are needed to avoid approaching the limits at high speed.

Discontinuous control laws have been deeply studied in the context of sliding mode control (SMC) (Edwards & Spurgeon, 1998; Gracia et al., 2013). Concretely, in VS field of research SMC has been used mainly to increase the robustness against errors while executing the main robot control task (Becerra, López-Nicolás, & Sagüés, 2011; Becerra & Sagüés, 2011; Burger, Dean-Leon, & Cheng, 2015; Kim, Kim, Choi, & Won, 2006; Li & Xie, 2010; Oliveira, Leite, Peixoto, & Hsu, 2014; Oliveira, Peixoto, Leite, & Hsu, 2009; Parra-Vega, Arimoto, Liu, Hirzinger, & Akella, 2003; Parsapour, RayatDoost, & Taghirad, 2015; Parsapour & Taghirad, 2015; Xin, Ran, & Ma, 2016; Yu, 2013; Zanne, Morel, & Piestan, 2000). However, to the best of the authors knowledge, SMC techniques have not yet been used in VS to fulfill constraints.

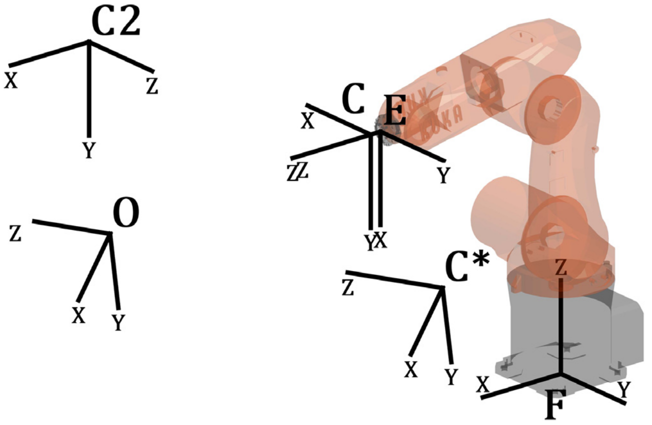

Fig. 1. Frames involved in visual servoing.

It may perhaps be observed that the algorithm solution proposed in this work cannot be seen as a conventional SMC, since the algorithm is only activated when the VS system is about to violate any constraint, whilst a pure SMC would always be active to keep the system on the sliding surface. Besides the SMC algorithm to fulfill the visibility constraints, another task with low-priority (Nakamura, Hanafusa, & Yoshikawa, 1987) is considered to track the target object.

The paper is organized as follows: next section introduces some preliminaries and objectives, while Section 3 presents the basic theory used in this work. The proposed method is developed in Section 4, while some important remarks about the method are given in Section 5. The main advantages and disadvantages of the proposed approach are discussed in Section 6. Subsequently, Section 7 presents the conditions considered for the simulations and experiments. The proposed approach is applied in Section 8 and Section 9 to a simple 2D case and a complex 3D case study, respectively, in order to show its applicability and effectiveness. The feasibility and robustness of the proposed approach is substantiated by experimental results in Section 10 using a conventional 6R industrial manipulator: the Kuka KR6 R900 sixx (Agilus). Finally, some concluding remarks are given.

2. Preliminaries and objective

Coordinate frames.

Fig. 1 shows the coordinate frames involved in the VS problem: F robot base frame; E robot end-effector frame; C current camera frame; C^* desired camera frame; O object frame; $C2$ camera frame for eye-to-hand configuration (in this case the camera does not move with the robot).

Kinematics.

The VS application is characterized by the so-called visual *feature vector* $\mathbf{s}$, which is computed from image measurements (Chaumette & Hutchinson, 2008). In general, this vector depends on the robot