Stability Analysis of Invariant Visual Servoing and Robustness to Parametric Uncertainties

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Abstract. This paper concerns the stability analysis of a new visual servoing approach which is invariant on camera intrinsic parameters. Contrarily to standard methods, the invariant visual servoing approach can be used with a zooming camera or when the reference image is learned with a camera different from that used for servoing. Even if the error computed in an invariant space does not depend on the camera intrinsic parameters, they are needed to estimate the interaction matrix which links the camera velocity to the displacements of the features in the invariant space. Thus, calibration errors can affect the stability of the control law. For this reason, it is important to study the robustness of the proposed vision-based control with respect to uncertainties on the parameters of the system.

1 Introduction

Visual servoing is a very flexible method for the control of uncalibrated dynamic systems evolving in an unknown environment. Typical applications of visual servoing are the positioning of a robot and the tracking of objects using the information provided by an in-hand camera. The visual servoing approaches proposed in the literature [16,18] can be classified depending on the a priori knowledge available on the parameters of the system and on the observed object. If a 3D model of the object is available we can use a "*model-based*" approach [35,28], while if the 3D model of the object is unknown we must use a "*model-free*" approach [12,24]. Model-free methods, needs a preliminary learning step during which a reference image of the object is stored (teaching-by-showing). After the camera and/or the object have been moved, several vision-based control methods [2,12,25] have been proposed in order to drive the robot back to the reference position. When the current image observed by the camera is identical to the reference image the robot is back to the desired position. The model-free approach has the advantage of avoiding the knowledge of the model but it cannot be used with a zooming camera. If the camera *intrinsic* parameters (e.g. the focal length) change during the servoing, then the reference image must be learned again. Both model-based and model-free approaches are useful but, depending on the "a priori" knowledge we have of the scene, we must switch between them. In order to solve this problem, I propose in this paper a unified approach to vision-based control which can be used whether the model of the object is known or not [22]. The key idea of the unified approach, which

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is an extension of the work presented in [21], is to build a reference in a projective space which can be computed if the model is known or if an image of the object is available. Thus, only one low level visual servoing technique must be implemented at once. The new unified approach is called *invariant* visual servoing since we work in a projective space which is invariant to camera intrinsic parameters [21] and at the same time invariant to the knowledge of the 3D model of the object [22]. Contrarily to standard model-free approaches, this allows us to use the invariant visual servoing approach with a zooming camera or to learn the reference image with a camera different from that used for servoing [20]. There are various ways in which invariance to camera parameters can be obtained [14,34,21]. In [21] invariance to all the camera intrinsic parameters has been obtained by selecting three interest points to build a projective transformation. Consequently, the selection of the three points raised the problem of the best choice. The problem has been solved in [22] by building the projective transformation from all points available in the image. The control in the invariant space can be carried-out within the task-function framework [29] and its structure is very similar to standard image-based approaches [12,16,18]. Even if the task function of the invariant visual servoing does not depend on the camera intrinsic parameters, they are needed to estimate the interaction matrix which links the camera velocity to the displacements of the features in the invariant space [23]. Thus, calibration errors can affect the stability of the control law. In the recent past, research on the stability of image-based visual servoing has been concentrated on the solution of convergence problems [5]. Indeed, the image-based approach is a local method which, even in the absence of calibration errors, can fail if the initial camera displacement is too large [5]. In order to avoid these potential convergence problems several possible solutions have been proposed: hybrid, partitioned and interpolation approaches. In hybrid approaches, some global information is introduced by estimating the camera displacement between the current and reference views [25,27,8]. The rotation of the camera is thus controlled directly in the Cartesian space while some image-based information is used to control the translation. More recently, a partitioned approach [7] has been proposed in order to avoid the camera displacement reconstruction. Another solution to potential stability problem of the image-based approach is provided by interpolation approaches. These methods define a path in the image by interpolating initial and reference image features [17,26,23]. Thus, the error in the image is maintained small at each iteration of the control law. Interpolation approaches are an elegant solution to potential convergence problems of local approaches. In the case of the invariant visual servoing it is even possible to define a path in the projective space such that the robot follows a straight line in the Cartesian space [23]. Even using interpolation approaches, the problem of finding the local robustness domain of the vision-based control law has not been yet solved. Due to the complexity of the problem, only few theoretical results