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A Robust Approach Toward Kernel-Based Visual Servoing

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***Abstract*— We introduce a robust controller for kernel-based visual servoing systems. In such systems, visual features are sum of weighted-image intensities via smooth kernel functions. This information along with its derivative are input to the controller in which we have developed a sliding mode approach to generate system commands. In vision-based systems, image uncertainties affect the tracking performance and stability, and the target object may get out of the field of view. Unless considerable image uncertainties appear, such systems are able to track the object within desired precision. Hence, we have investigated the effect of the image noise as the main source of uncertainty, and encapsulated its characteristics in a proper representation. In order to fulfill the sliding condition, some bounds over image uncertainty and tracking errors are considered, and the controller gains are tuned online to keep the tracking error bounded. An application of the proposed method is experimentally tested on an industrial robot.**

I. Introduction

Tracking performance of visual servoing (VS) systems is extensively affected by uncertainties. Uncertainties are mainly originated from issues related to *vision systems* (e.g., quality of sensing elements, camera parameters, and calibration error) [1], *environmental conditions* (e.g., image noise, movement irregularities) [2], and *image blur* [2], [3]. Considerable image uncertainties cause larger tracking errors and consequently larger control commands, where the target object might leave the camera field of view. As a result, such an issue challenges the robustness of VS controllers to guarantee tracking stability and consequently keep the target in the field of view.

Our VS method here is kernel-based visual servoing (KBVS). KBVS deals with tracking featureless objects through the kernel-measurement concept which is sum of weighted-image intensities via smooth kernel functions. Kallem *et al*. [4], [5] introduced KBVS for four degrees of freedom (DOF) motion (i.e., x, y, and z directions, and orientation about z axis), in which the controller was designed based on the derivative of kernel-measurements.

In order to enhance the tracking performance of the conventional KBVS, we designed the sliding mode control (SMC) approach in [6], where no uncertainty was considered. In this work, we propose a procedure of designing a robust controller for the kernel-based approach in the presence of uncertainties. Our proposed method is an introduction to the robustness of featureless-based VS approaches and can be applied to other forms of VS problems in which direct information is derived from images. Hence, we have adapted and redesigned our previous approach in [6] to the image noise which is the main source of the uncertainty. The image noise is mainly related to the environmental light levels and the light reflection, and affects the kernel-measurement calculation.

In the controller design process, we consider some constraints through the *sliding condition*. These constraints are an upper bound on the image uncertainty and tracking errors. The sliding condition tunes the controller gains online in the feedback loop. A major advantage of online tuning of the controller gains is that the gains may remain in a specific range while keeping the tracking errors bounded. This formulation is similar to the ones used in the standard multi-input multi-output (MIMO) sliding mode control [7], [8]. Given some bounds over uncertainties and tracking errors, our controller is able to produce commands which are able to keep the target object in the workspace. As we have employed the same kernel functions as [5], our method can control the visual servoing system in 4 DOF; however, it can easily get extended to 6 DOF by defining new kernel functions for orientation about the x and y axes.

The rest of the paper continues with Section II which defines basic definitions of the kernel-measurement, and sliding mode control. Section III encapsulates the image noise uncertainty in spatial and frequency domains. Section IV presents the controller design to bound tracking errors, and it is tested on an industrial robot in section V.

II. Basic Definitions

A. Kernel-Measurement Definition

The first step in kernel-based VS is the definition of visual information. Consider the image signal $\boldsymbol{I}(\boldsymbol{\omega}, t)$, as pixel intensities. Image intensities are weighted through a continuous and differentiable function known as a kernel function, $\boldsymbol{K} \in \mathbb{R}^n$. The kernel-projected value of image intensities is called kernel-measurement, $\boldsymbol{\xi} : \nu \to \mathbb{R}^n$ which is defined as follows

$$\boldsymbol{\xi}_i = \int_{\nu} \boldsymbol{K}_i(\boldsymbol{\omega}) I(\boldsymbol{\omega}, t) d\boldsymbol{\omega} \tag{1}$$

where $\boldsymbol{\omega} \in \nu = \mathbb{R}^2$ is the image spatial indexing variable for perspective cameras, and i denotes the direction at which the kernel-measurement and kernel function are calculated. The type of kernel functions is Gaussian and was proposed in [5].

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