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Planar feature-based motion control for near-repetitive structures

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ABSTRACT

This paper focuses on the motion control for machines used for the production of products that inherently consist of equal features placed in a repetitive pattern. In many cases the repetitiveness of these structures is prone to imperfections, for example due to thermal expansion, such that the distance between successive features deviates. As a consequence the metric positions of the features of such near-repetitive structures are unknown a priori such that setpoints cannot be created a priori. The considered motion task in this paper is to position a tool relative to the features of a near-repetitive structure with an accuracy of $< 10\ \mu m$. Instead of metric positions novel two-dimensional feature-based positions will be used that are obtained from a camera capturing images at 1 kHz for feedback, resulting in a direct visual servoing control approach. The robustness with respect to imperfections in the repetitiveness is investigated and the design is validated on an experimental setup.

1. Introduction

Many production processes take place on repetitive structures. In each of these processes one or more consecutive steps are carried out on the particular features of the repetitive structure to create the final product. Such production machines often consist of a tool and a stage or carrier on which the repetitive structure is to be processed. The considered control task is therefore to position the tool relative to the features of the repetitive structure. In current industrial practice, local position sensors such as motor encoders are used to measure the position of the tool and the stage separately. Often the absolute reference points of these measurements do not coincide, such that the final accuracy of the alignment of the tool directly relies on properties such as thermal stability, mechanical stiffness and assumptions on the pitch between successive features of the repetitive structure. Any falsification of these assumptions results in a poor alignment.

Possible solutions for the posed problem can be found in the field of visual servoing (Hill & Park, 1979) or visual servo control (Chaumette & Hutchinson, 2006; Hutchinson, Hager, & Corke, 1996), in which machine vision data is used in the servo loop to control the motion of a system. Extensive overviews on the topic of visual servoing can be found in Kragic and Christensen (2002), Malis (2002), Hutchinson et al. (1996), Corke (2001), and Hashimoto (2003). Many classifications are known within visual servoing. We will now briefly discuss these and position our work in the field of visual servo control. The first classification makes a distinction between *indirect* and *direct* visual servoing (Sanderson & Weiss, 1980). Indirect visual servoing has a hierarchical or cascaded control architecture in which the vision system provides (velocity) setpoints to low level joint controllers. Indirect visual servoing is often split up into static look-and-move and dynamic look-and-move approaches. In static look-and-move three steps are taken consecutively: (1) the system "looks" at the scene and measures the relative position between the tool and the feature, (2) based on the difference between the current position and the desired position a trajectory is planned and (3) the system "moves" to the desired position. In the dynamic look-and-move approach the above steps are executed in parallel. By far, most literature adopt the dynamic look-and-move approach (Chaumette & Hutchinson, 2006, 2007; Corke & Hutchinson, 2001; Crétual & Chaumette, 1997; Espiau, Chaumette, & Rives, 1992). In *direct* visual servo control the visual controller computes the input (typically torques and/or forces) to the plant directly (Ishii, Nakabo, & Ishikawa, 1996; Ishikawa, Morita, & Takayanagi, 1992; Nakabo, Ishikawa, Toyoda, & Mizuno, 2000). The second classification is the *eye-in-hand* versus the *eye-to-hand* visual servoing. The first configuration has the camera mounted to the tool. In this case it is often assumed that there is a known kinematic relation between the tool and the camera in order to position the tool relative to the feature. The second configuration has the camera mounted in the workspace. The eye-in-hand configuration has a precise sight of the scene relative to the camera, whereas the eye-to-hand configuration often has a more global sight which might be less precise. Blocking of the field of view is more likely to happen in the latter configuration. *Position based* or

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PBVS versus *image based*visual servoing or IBVS is the third classification. In both concepts features are extracted from the image. However, in PBVS a cartesian position is estimated from these features and the control law is executed in the cartesian domain (Martinet & Gallice, 1999; Thuilot, Martinet, Cordesses, & Gallice, 2002; Wilson, Williams Hulls, & Bell, 1996). On the other hand, in IBVS the control law is computed directly on the basis of the image coordinates of the features (Espiau et al., 1992; Weiss et al., 1987). The last classification is concerned with *endpoint open-loop* or EOL versus *endpoint closed-loop* visual servoing or ECL. In EOL only the target feature is within the field of view, whereas in ECL both the tool and the target feature are within the field of view. In the latter the relative position between the target feature and the tool can be computed, whereas in the first this relies on how well the relation between tool position and camera position is known (see also eye-in-hand versus eye-to-hand). Note that EOL is often less computational expensive since only the target feature is to be detected and not the tool as is the case in ECL.

This work uses a direct eye-in-hand endpoint open-loop visual servo control approach. Regarding the PBVS versus IBVS classification the authors introduced a new control design paradigm in de Best, van de Molengraft, and Steinbuch (2009, 2012) in which feature-based position measurements on the basis of camera images in combination with non-collocated visual feedback is used leading to feature based visual servoing or FBVS. As such, motion setpoints can be defined from feature to feature without knowing the exact absolute metric position of the features beforehand, while still achieving a high positioning accuracy. The proposed method was restricted to the one-dimensional case. In practical applications the repetitive structure in general will contain a two-dimensional grid pattern, like for example the repetitive structure depicted in Fig. 1(a), which shows diodes on a wafer. Therefore, in this paper the feature domain is extended towards two dimensions. Furthermore, in de Best et al. (2012) the feature-based position is constructed by piecewise linear interpolation between successive features. When passing a feature, a different pitch between the current features is considered. Due to the piecewise linear interpolation the feature-based position is continuous when passing a feature but the feature-based velocity is not and switches instantaneously. As a result, undesired transient responses are observed. In this paper, higher order interpolation will be implemented to reduce these undesired transient responses. The introduction of feature-based positions results in a straightforward setpoint creation from one feature to another target feature, referred to as *feature-to-feature movements*, without having to know the absolute metric position of the target feature. However, besides these feature-to-feature movements, many production processes require metric movements of the tool *with respect to* the feature, like for example engraving text on each feature. These movements are referred to as *relative feature movements*. Typical movements in such applications are therefore constructed by repeatedly alternating between (1) *feature-to-feature movements* from the current feature to the target feature and (2) *metric relative feature movements* with respect to the target feature. These relative feature movements will be implemented in the feature-based control approach, so the contributions of this paper are fourfold: (1) the feature-based position measurement is extended towards two dimensions, (2) the piecewise linear interpolation is extended to higher order interpolation to reduce the transient responses when passing features, (3) next to feature-to-feature movements, relative feature movements are implemented, to increase the versatility of programmable movements and (4) a stability analysis is presented to prove robust stability of the closed-loop system.

The rest of the paper is organized as follows. In Section 2 the notation with respect to the repetitive structure and the different coordinate representations will be presented. Section 3 will first introduce two-dimensional feature-based positions, followed by higher order feature interpolation. At the end of Section 3 the implementation of relative feature movements will be discussed. The experimental setup that will be used for validation will be given in Section 5. The control design and stability analysis will be given in Section 6. Finally, conclusions will be given.

2. Notation

Throughout this paper a repetitive structure will be used that consists of equal features ordered in a near-rectangular repetitive pattern. A practical example is depicted in Fig. 1(a) which shows diodes on a wafer. A schematic representation of such a repetitive structure is given in Fig. 1(b) where the features are circular black dots on a white background.

The image captured by the camera, denoted as I, has a height I_h and width I_w pixels and captures only a part of the repetitive structure. The features have a diameter of D pixels and are placed in a rectangular repetitive pattern. The nominal pitch between features is $\overline{P}$ pixels in both horizontal and vertical directions. In this work pitch imperfections will be considered, which can occur for example due to inaccurate preceding process steps, local stretching of the structure when flexible plastic or metal foil is used as product carrier or thermal expansion of the structure.

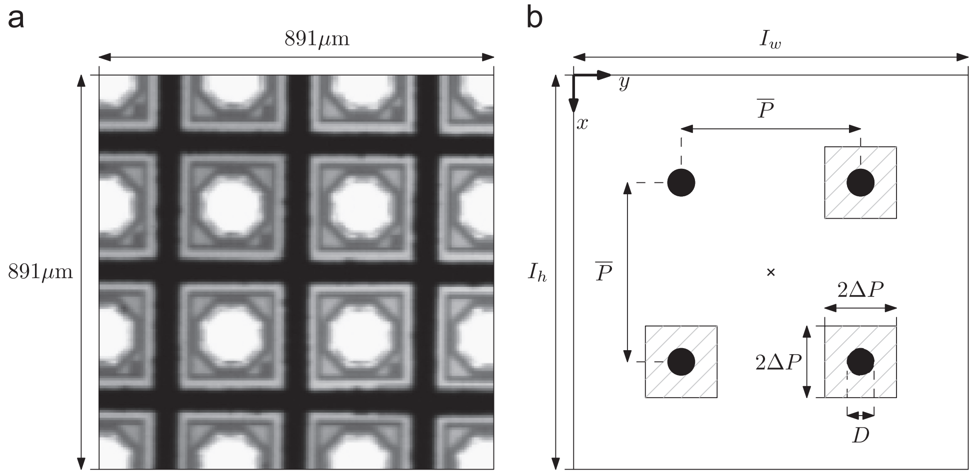

Fig. 1. A part of a two-dimensional repetitive structure. (a) Diodes on a wafer. (b) Schematic representation of a repetitive structure.