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Brief paper

Non-vector space approach for nanoscale motion control ☆

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ABSTRACT

As the advancement of nanotechnology, it is possible to manipulate structures at nanoscale with various nanomanipulation tools such as scanning probe microscopes. To achieve successful manipulations, precise motion control is required, especially for objects with sizes from subnanometer to several nanometers. To address this issue, this paper presents an image based non-vector space control approach. Considering images obtained from the microscopes as sets, the dynamics of the system can be formulated in the space of sets. Since the linear structure of the vector space is not available in this space, this method is called the non-vector space control. With the dynamics in the non-vector space, we formulate the stabilization problem and design the controller. The stabilization controller is tested with images obtained by atomic force microscopes, and the results verify the proposed theory. The method presented in this paper does not rely on external sensors for position feedback. Moreover, unlike the traditional image based control method, we do not need to extract features from images and track them during the control process. Finally, the control precision can be as good as the imaging resolution. The approach presented in this paper can also be extended to other systems where the states can be represented as sets.

1. Introduction

Scanning probe microscope (SPM) such as atomic force microscope (AFM) or scanning tunneling microscope (STM) are powerful imaging tools at nanoscale. Recently, SPMs, especially AFMs, have been widely utilized for nanomanipulations to mechanically push, pull, or cut structures by using a sharp tip at the end of a probe as a nanoscale robotic manipulator (Requicha, 2003). With the help of an augmented reality system (Song, Xi, Yang, Lai, & Qu, 2010), AFM has been employed for quantitative cell analysis (Fung et al., 2008), automated nanomanufacturing (Lai et al., 2009), and nanosensor fabrication (Chen, Xi, Lai, Fung, & Yang, 2010).

The accurate point-to-point position control or motion control at nanoscale is a critical requirement for SPM based nanomanipulations because they rely on precisely moving the probe's tip from one position to a desired position. For example, in AFM based nanosensor fabrication, carbon nanotubes were pushed to a desired position by a nano-manipulator to form photodetectors, and the position accuracy of the manipulation should be within 10 nanometers to facilitate the integration to a nano-antenna that has a gap of 30 nm (Chen et al., 2012). The SPM based manipulator was utilized to modify DNA molecules with nanoscale resolution because their diameters are smaller than five nanometers (Zhang et al., 2008).

Although the imaging resolution for SPMs can be up to subnanometer (Requicha, 2003), it is challenging, if not impossible, to achieve such a precision for nanoscale motion control due to the spatial uncertainty of the probe's tip. The main reason for such a deficiency is the piezoelectric actuation method for SPM systems. The inherent nonlinearities of piezo actuators such as hysteresis, creep, vibration, and thermal drift make position control within one nanometer extremely difficult (Croft, Shed, & Devasia, 2001). Additionally, the modeling errors include parameter variation, unmodeled dynamics, and coupling effects also exert extra difficulties for precise position control (Devasia, Eleftheriouand, & Reza Moheimani, 2007).

Generally, researchers address the nanoscale motion control problem using closed-loop control with position feedback from external sensors, which can achieve a high feedback rate (Devasia et al., 2007). There are two potential issues with such approaches. The first issue is the inaccurate feedback from position sensors, which cannot provide the tip's true position because the

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sensors can only be added to the piezo actuators instead of the tip. The second issue is the control methods. Most control methods try to eliminate all the adverse effects by a feedforward compensation based on model inversion (Clayton, Tien, Leang, Zou, & Devasia, 2009). This method, however, requires model identifications and the model may also be time varying. Recent efforts include the combined feedback and feedforward control method with advanced control techniques such as robust or adaptive control (Abramovitch, Andersson, Pao, & Schitter, 2007). Nevertheless, the performance of such controllers is limited by the feedback sensor as well.

Different from the traditional approaches, we propose an image based closed-loop control method, which eliminates external position sensors. In fact, the tip can be considered as a single pixel camera with two translational degrees of freedom. By moving the tip locally in a small area, a local scan image can be obtained (Liu et al., 2008). Since the image is obtained from the local scan, it accurately reflects the tip's true position. If a desired local scan image around a desired tip position is given, then a controller can be designed to steer the tip position to the desired position based on the image feedback.

The image based control method belongs to the literature of visual servoing, which utilizes vision to control the motion of a mechanical system. For traditional image based visual servoing methods, prominent features are first extracted from the image, and then a controller is designed to make the vector of feature positions converge to a desired value (Chaumette & Hutchinson, 2006). Two possible issues exist for this feature based vector control method. On the one hand, robust feature extraction and tracking are difficult in natural environments (Marchand & Chaumette, 2005). On the other hand, feature extraction suffers from information loss because only the feature information is used for control.

Recently, direct or featureless visual servoing methods are proposed to address the above two issues. Such methods design the controllers directly based on all the image intensities instead of some features extracted from the image. Examples include the kernel based method (Kallem, Dewan, Swensen, Hager, & Cowan, 2007), the sum-of-squared-difference method (Collewet & Marchand, 2011), and the mutual information method (Dame & Marchand, 2011).

Different from the above direct visual servoing methods, we present a non-vector space control method in this paper. The general idea is to form a set from an image and formulate the image dynamics in the space of sets. This space is called the non-vector space due to the lack of linear structure that exists in the vector space. Based on the image dynamics, a controller can be designed directly on the image sets. Initial results for the non-vector space controller have been reported in Zhao, Song, Xi, and Lai (2011), Zhao et al. (2012).

The non-vector space control comes from a general framework called mutation analysis for set evolutions (Aubin, 1998). Mutation analysis provides a natural way to describe various physical phenomena because some objects such as shapes and images are basically sets. Since the introduction of mutation analysis, it has been applied to image segmentation (Lorenz, 2001), visual servoing (Doyen, 1995), and surveillance networks (Goradia, Xi, Cen, & Mutka, 2005).

The visual servoing using mutational analysis is proposed in Doyen (1995). Nevertheless, possibly due to its abstract nature, no further extension is performed afterwards. In this paper, we extend the results and apply the method to nanoscale motion control. Three major extensions are carried out. First, we establish the general framework for the non-vector space control in this paper. Second, the original formulation only deals with binary images, while gray scale images are considered in this paper. Third, we apply the theory to nanoscale motion control.

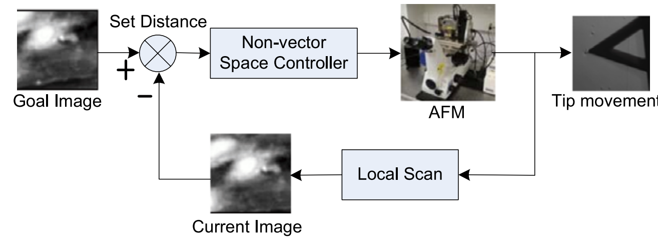

Fig. 1. Schematic for non-vector space control with the AFM as an example.

Fig. 1 shows the schematic for the image based nanoscale motion control in the non-vector space with the AFM as an example. A desired image set corresponding to the desired tip position is first given. Based on the current image feedback, the non-vector space controller generates a control signal to drive the tip to a new position. An updated current image is obtained at the new position, and the same process is repeated until the tip reaches the desired position.

Since images are used for the nanoscale motion control in this paper, we also briefly review image based methods for applications in micro/nano environments. Clayton and Devasia have conducted extensive research to enable high speed SPMs using images with standard calibration samples to compensate the dynamic effects (Clayton & Devasia, 2005, 2007, 2009). Nevertheless, they focus on the accurate and fast imaging applications, while we emphasize the precise position control for nanomanipulations. Another close research uses the direct visual servoing method for automated microassembly with an optical microscope (Tamadazte, Le-Fort Piat, & Marchand, 2012). Nevertheless, the non-vector space approach is different from the vector space ones, and the characteristics of optical microscopes are different from SPMs.

The major contributions of this paper can be summarized in three aspects. First, the image based motion control is proposed for SPM systems to improve the precision. This approach excludes the use of external position sensors, which reduces the cost for the system and mitigates the noise from measurements. Second, the general framework for the stabilization problem in the non-vector space is presented. The framework can also be employed to stabilize other systems if the state can be represented as a set. Third, we apply the non-vector space control method to nanoscale motion control, which, unlike traditional image based control methods, does not require the feature extraction and tracking.

The rest of this paper is organized as follows. First of all, the dynamics in the non-vector space is introduced with tools from mutation analysis in Section 2. After that, the stabilization problem in the non-vector space is introduced in Section 3, where the stabilizing controller is designed. Finally, the testing results using AFM images are given in Section 4 to validate the theory.

2. Dynamics in the non-vector space

Before examining the motion control problem with the non-vector space approach, we should first formulate the dynamics. For SPM systems, the governing equation for the probe's tip motion can be modeled as a differential equation in the vector space. If the local scan image is considered as a set, then this set evolves with the tip's movement. In other words, the differential equation for tip motion induces the set evolution, which can be considered as the dynamics in the space of image sets. In this section, we discuss the dynamics equation in the non-vector space induced from a differential equation.

The challenge for the dynamics formulation in the non-vector space is the time derivative of set evolutions. As will be shown later, the time derivative is the differential equation inducing the