Control Engineering Practice 50 (2016) 12–21

Contents lists available at ScienceDirect

Control Engineering Practice

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

High speed laser scanning microscopy by iterative learning control of a galvanometer scanner

Han Woong Yoo*, Shingo Ito, Georg Schitter

Automation and Control Institute (ACIN), Vienna University of Technology, Gusshausstr. 27-29, 1040 Vienna, Austria

ARTICLE INFO

Article history:
Received 3 September 2015
Received in revised form
1 December 2015
Accepted 15 February 2016
Available online 27 February 2016

Keywords:
Iterative learning control
Galvanometer scanner
Non-minimum phase zeros
Scanning laser microscopy
Precision motion control

ABSTRACT

Iterative learning control (ILC) for a galvanometer scanner is proposed to achieve high speed, linear, and accurate bidirectional scanning for scanning laser microscopy. A galvanometer scanner, as a low stiffness actuator, is first stabilized with a feedback control compensating for disturbances and nonlinearities at low frequencies, and ILC is applied for the control of the fast scanning motion. For stable inversion of the non-minimum phase zeros, a time delay approximation and a zero phase approximation are used for design of ILC, and their attainable bandwidths are analyzed. Experimental results verify the benefits of ILC of its wide control bandwidth, enabling a faster, more linear, and more accurate scanning without a phase lag and a gain mismatch. At the scan rate of 4112 lines per second, the root mean square (RMS) error of the ILC can be reduced by a factor of 73 in comparison with the feedback controlled galvanometer scanner of the commercial system.

1. Introduction

Galvanometer based scanning mirrors are the most widely used scanning systems for high-precision in vivo biological imaging systems, such as scanning confocal and two-photon excitation microscopes (Aylward, 2003; Pawley, 2006; Saggau, 2006). In principle, these microscopes record an image by scanning a laser point by point to achieve a high spatial resolution. A high temporal resolution of microscopic images is desirable for capturing rapid biological phenomena such as a cardiac cycle (Baader, Buchler, Bircher-Lehmann, & Kleber, 2002) or tracking the single molecule movements in living organisms (Meijering, Smal, & Danuser, 2006). Fast imaging in scanning laser microscopes, however, is challenging in practice due to dynamics of the scanner, limiting the bandwidth of the controller (Duma, Lee, Meemon, & Rolland, 2011; Ji, Shroff, Zhong, & Betzig, 2008). To minimize the imaging time and increase the temporal resolution, fast and accurate scanning is a crucial requirement for galvanometer scanners.

One approach to increase the imaging speed is bidirectional scanning (Duma, 2010), doubling the scan rate by using both trace and retrace. Fig. 1 shows two ways of scanning: conventional unidirectional scanning based on sawtooth scanning (left) and bidirectional scanning based on triangular scanning (right), respectively. For conventional scanning laser microscopes, sawtooth scanning is commonly used for unidirectional scanning due to the long linear slope for imaging (Duma et al., 2011; Trepte & Liljeborg, 1994). However, sawtooth scanning is inefficient due to the small duty cycle by long and fast retracing, which may cause overheating of the actuator (Podoleanu & Nicolov, 2009; Montagu et al., 2011) and require an additional shutter for preventing unnecessary photobleaching of the specimen (Pawley, 2006). For bidirectional scanning of galvanometer scanners, Duma et al. (2009), Duma and Awrejcewicz (2009), and Duma (2010) intensively studied various types of bidirectional scanning trajectories for a large linear scan area and compared them to optical coherence tomography (Duma et al., 2011). They point out that triangular scanning is desirable comparing to unidirectional scanning, but it is difficult to obtain an accurate scan at a high scanning speed due to high frequencies induced by the sharp turnaround. Chen et al. also point out that fast bidirectional scanning suffers from mismatches between the trace and retrace due to the phase lags and nonlinearities, deteriorating the quality of the images (Chen et al., 2010). A manufacturer of scanning laser microscopes provides a bidirectional scan option with a phase correction control bar for users to compensate for this mismatch manually (Leica Microsystems, 2005). However, the vibrational dynamics of the scanner, which causes positioning errors near the turnaround, is completely ignored so far.

As a solution to compensate for these drawbacks of the triangular scanning motion, iterative learning control (ILC) can be applied. ILC is a feed-forward control for tracking a repetitive reference by updating the control signal based on tracking error measurements obtained at previous trials. For fast scanning ILC has been applied to atomic force microscopy (AFM) (Leang &

* Corresponding author.
E-mail address: yoo@acin.tuwien.ac.at (H.W. Yoo).

http://dx.doi.org/10.1016/j.conengprac.2016.02.007
0967-0661/

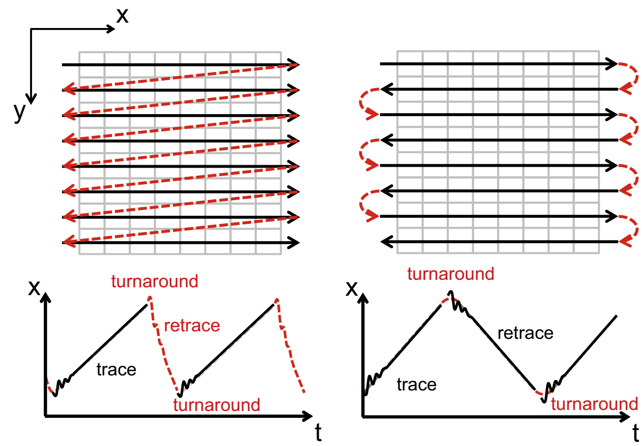

Fig. 1. Unidirectional scanning (left top) based on sawtooth scanning for the fast x-axis over the time t (left bottom) and bidirectional scanning (right top) based on triangular scanning (right bottom) for the fast x-axis. The focused laser beam is moved linearly over the specimen (gray squares) for recording an image along the active scanning region (black solid line). At a high scan rate, both sawtooth and triangular scanning of the fast x-axis may suffer from distortion of trace and retrace scans (black solid line) compared to the desired reference line (gray dotted line).

Devasia, 2006; Schitter, 2009; Tien, Zou, & Devasia, 2006) and an optical scanning system (Yen, Yeh, Peng, & Lee, 2009) to compensate for the dynamics and nonlinearity of the high stiffness piezoelectric actuators. ILC is applied for a galvanometer scanner for a microvia drilling machine to achieve a high tracking and settling performance for integrated circuit correction (Potsaid, Wen, Unrath, Watt, & Alpay, 2007; Wen & Potsaid, 2004). For confocal laser scanning microscopy, an iterative optimization concept, which corresponds to an I type ILC, have been proposed for a 50 Hz unidirectional scan with 85% active linear scan region, reporting a RMS error 0.06% in the linear region (Trepte, 1996). However, compensation of the vibrational modes due to the internal modes of the galvanometer scanner for a fast and accurate scanning over 1 kHz in optical microscopy has not been studied yet.

The goal of this paper is to develop ILC for bidirectional scanning beyond 1 kHz, i.e. 2000 lines per seconds, to be applied to fast and distortion-free laser scanning microscope imaging (Yoo, Ito, Verhaegen, & Schitter, 2012). Section 2 describes the stabilized galvanometer scanner, consisting of the galvanometer scanner and a feedback controller, and its linear model is derived. Based on the model of the stabilized galvanometer scanner, ILC design is investigated in Section 3 and two approaches for deriving a stable inversion of the non-minimum phase scanner dynamics are presented. Experimental results verify the benefits of the proposed ILC approach in Section 4, and conclusions are drawn in Section 5.

2. Stabilized galvanometer scanner

2.1. Galvanometer scanner

For the experiments, a high performance galvanometer scanner (6210 H, Cambridge Technology Inc., Lexington, MA, USA) is used, which is widely installed in commercial laser confocal microscopes (Aylward, 2003; Pawley, 2006). The galvanometer scanner is a moving-magnet type as shown in Fig. 2, i.e. magnets along the shaft are rotated by the Lorentz force created by the current i_c through the fixed coils. A scanning mirror is attached at one end of the shaft for directing a laser beam. At the other end of the shaft an encoder is attached for the precise angle measurement of the mirror by the passed light through the blocking butterfly (Aylward,

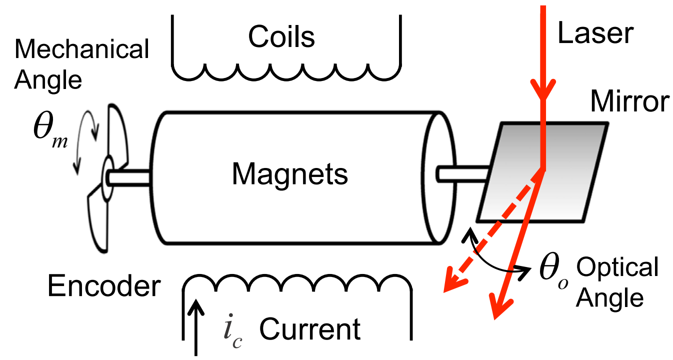

Fig. 2. Structure of a moving-magnet galvanometer scanner. The rotor of a galvanometer scanner consists of magnets, a mirror and an encoder connected by a steel shaft, and coils surrounding the magnets. The Lorentz force induced by the coil current i_c with magnets rotates the mirror at one end and the encoder at the other end measures the mirror angle, mechanical angle θ_m. The deflected mirror angle change the angle of the laser, i.e. optical angle $\theta_o = 2\theta_m$.

2003). The mechanical actuation range θ_m of the galvanometer scanner is $\pm 10°$, corresponding to $\pm 20°$ in optical angle θ_o. The servo driver (MicroMax 671, Cambridge Technology Inc.) consists of a current driver for the coil of the galvanometer scanner, the decoder for the encoder signal, and a closed loop control. The system input and the system output are given by the input to the current driver and the encoder signal through the decoder, respectively. The closed loop control of the servo driver is only used as a benchmark for comparison with the ILC in Section 4, but is disabled for all other experiments.

The galvanometer scanner is marginally stable since the rotor of the galvanometer can be regarded as a floating mass with a weak stiffness and friction at low frequency. Fig. 3 shows the frequency response of the galvanometer $G(s)$ from the control input to the encoder output measured by a Dynamic Signal Analyzer (HP3562, Agilent Technologies, Santa Clara, CA, USA). The frequency response shows the dynamics between 300 Hz and 30 kHz dominated by the inertia of the rotor, providing a -40 dB/dec line in Fig. 3. At low frequencies, however, the magnitude does not show a slope of -40 dB/dec due to the friction, stiction, and weak suspension springs. To counteract the marginal stability and drift of low frequencies, a feedback controller is designed and

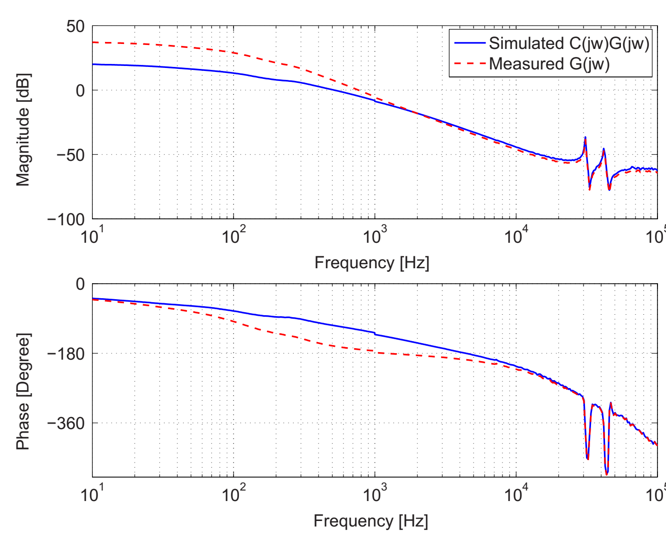

Fig. 3. Measured Bode plot of the galvanometer scanner from the system input to the system output (red dash line) and the simulated frequency response of open-loop transfer function with a tamed PD controller $C(jw)P(jw)$ (blue solid line). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)