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Multiple parameter-dependent robust control of miniaturized optical image stabilizers[☆]

Pan Zhao [*], Ryozo Nagamune, Mu Chiao

Department of Mechanical Engineering, The University of British Columbia, Vancouver, BC, V6T 1Z4, Canada

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ABSTRACT

This paper presents the design of multiple parameter-dependent robust controllers for mass-produced miniaturized optical image stabilizers (OIS's), which are used to minimize the image blur in mobile devices caused by hand-induced camera shake. The dynamics of batch-fabricated OIS's with inevitable product variations is represented by a set of linear models, parameterized by two product-dependent natural frequencies and one uncertain gain. It turns out that the natural frequencies for each OIS product are difficult to determine accurately, and thus assumed to be estimated with errors. The controller is designed to be parameter-dependent on estimated natural frequencies, as well as to be robust against both estimation errors of the natural frequencies and the gain uncertainty. Experimental results on large-scale prototypes demonstrate that the proposed controller outperforms a conventional parameter-independent robust controller as well as a single parameter-dependent robust controller. Specifically, the proposed controller yields more than 27% improvement over the conventional robust controller in terms of lens-tilting tracking performance.

1. Introduction

Nowadays high-quality digital cameras have become one of the main attractions for smart phones and tablets. Although the image quality has been dramatically improved by increasing pixels, image blur due to involuntary hand-shake while taking photos is still an issue.

Technologies in cameras to alleviate the hand-shake induced image blur are called *image stabilization*. The two categories of image stabilization techniques are *electronic image stabilization (EIS)* and *optical image stabilization*. EIS is cost-effective and easy to implement as it only relies on digital image processing (Kim, Byun, & Ko, 2010; Morimoto & Chellappa, 1996); however, EIS often leads to degraded image quality due to image scaling and image processing artifacts (ROHM, 2013). Cameras with the optical image stabilization, on the other hand, are more expensive as they need hardware components, named as the *optical image stabilizer* (OIS), to stabilize the image projected on the image sensor before the sensor converts the image into digital information. Despite the higher cost, OIS can provide superior performance compared to EIS, and therefore it is popular among single-lens reflex (SLR) and point-and-shoot cameras (ROHM, 2013).

As of December 2017, there has been an increasing tendency to popularize OIS's in mobile platforms, such as Apple iPhone 8 and Samsung Galaxy S8. There are mainly four mechanisms for OIS, i.e. CCD-shifting (Chiu, Chao, & Wu, 2007; Yeom, 2009), lens-shifting (Cardani, 2006), module-tilting (ROHM, 2013) and lens-tilting (HTC, 2013). Among these four mechanisms, lens-shifting and lens-tilting are most appropriate for mobile applications because of their easiness for miniaturization. In Pournazari, Nagamune, and Chiao (2014), a concept of miniaturized magnetically-actuated lens-tilting OIS based on micro-electro-mechanical-system (MEMS) technology was proposed, and the concept was validated with large-scale prototypes in Zhao, Alizadegan, Nagamune, and Chiao (2015). The device uses four folded beams to support a lens platform (LP) and four moving-magnet actuators that can actuate the LP in three degrees of freedom (DOFs). The proposed OIS employs a feedback control structure, where the LP is tilted to track reference angles under an OIS controller in order to mitigate the image blur. The lens-tilting tracking performance yielded by the feedback controller directly determines the image quality.

A number of controllers have been proposed to control OIS systems, such as lead–lag compensator (Yeom, Park, & Jung, 2007), fuzzy proportional–integral–derivative (PID) controller (Chang, Kim, Song, & Choi, 2009), adaptive PID controller (Yu & Liu, 2008a), gain-scheduling lead–lag compensator (Yeom, 2009), and sliding mode controller (Yu

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* Corresponding author.
E-mail addresses: panzhao@mech.ubc.ca (P. Zhao), nagamune@mech.ubc.ca (R. Nagamune), muchiao@mech.ubc.ca (M. Chiao).

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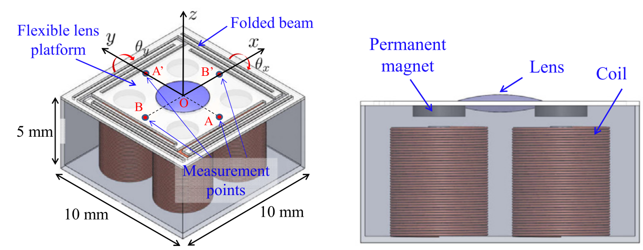
& Liu, 2008b). All the OIS systems controlled by those controllers employed voice coil motor (VCM) actuators, and most of the controllers were mainly for dealing with the nonlinearity associated with the VCM actuators such as hysteresis and friction. In contrast, the OIS system proposed in Pournazari et al. (2014) that is targeted in this paper employs a moving-magnet actuator instead of a VCM actuator, and the nonlinearity can be approximately canceled using the estimated relation between air gap and magnetic force. Thus, the aforementioned work is not suitable for controlling the OIS system presented in this paper. In addition, none of the above methods consider dynamics variation among different products due to product variations, and thus cannot provide stability guarantee for all the OIS products.

A couple of efforts have been made to control the lens-tilting OIS proposed in Pournazari et al. (2014). A state-feedback controller was designed and validated on a 1-DOF large-scale prototype in Pournazari et al. (2014). However, without consideration of unavoidable product variations (Shavezipur, Ponnambalam, Khajepour, & Hashemi, 2008; Sun, Fowkes, Gindy, & Leach, 2010) in micro-scale devices, the performance or even the stability of the feedback system cannot be guaranteed for all the mass-produced OIS products. It was validated in Alizadegan, Zhao, Nagamune, and Chiao (2016) and Zhao et al. (2015) on multiple 3-DOF prototypes that lead–lag compensator, LQR and H_∞ controllers were unable to guarantee robust stability due to ignorance of product variabilities, while robust controllers such as the μ controller (Balas, Chiang, Packard, & Safonov, 2007; Packard & Doyle, 1993) and the robust H_∞ controller (Zhou, Doyle, & Glover, 1996) have an ability to offer consistent and satisfactory results for all the prototypes. Despite the successful application of robust control to OIS, there is still a room for reducing the conservatism inherent to robust controllers. This is because some of the parameters regarded as uncertain in robust controller design can actually be identified after the manufacturing, and then employed for controller adaptation.

The contribution of this paper is to propose a method to design multiple parameter-dependent robust (MPDR) controllers for the mass-produced OIS's, which can reduce the conservatism of the robust controllers previously presented in Zhao et al. (2015). The designed controllers are parameterized by the natural frequencies of the LP that represent the most crucial product variabilities in fabrication of the LPs. Considering the difficulty in accurately estimating the natural frequencies due to the extremely low damping of the devices, the natural frequencies are assumed to be estimated with uncertainties. In addition, to characterize the unbalanced forces as a result of unavoidable errors in actuator fabrication and installation, an uncertain gain parameter is introduced in modeling of the OIS's. The controllers are designed to be robust in the sense that both estimation uncertainties of the natural frequencies and the uncertain gain parameter for the unbalanced forces are explicitly taken into account in controller design. To design the MPDR controllers, the approach to the switching linear parameter-varying (LPV) controller design under uncertain scheduling parameters proposed in Zhao and Nagamune (2017) is adopted. The advantages of the MPDR controllers over an existing μ-synthesis robust controller and a classical controller consisting of a lead–lag compensator and multiple notch filters are experimentally verified on large-scale 3-DOF OIS prototypes.

This paper is organized as follows: Section 2 gives a brief introduction of the conceptual miniaturized OIS and large-scale prototypes, as well as the control objectives and challenges. Section 3 presents the feedback control structure employed in the OIS. Mathematical modeling of the OIS's is presented in Section 4. Section 5 explains the implementation and design of the MPDR controllers. The designed controllers are experimentally validated on large-scale prototypes in Section 6. Details of the controller design are given in the Appendix.



(a) Isometric view. (b) Front view.

Fig. 1. Mechanical layout of a miniaturized OIS.

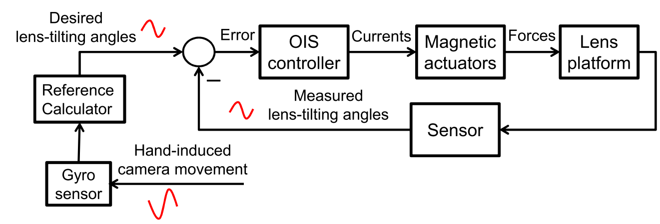


Fig. 2. Block diagram of the OIS system.

2. Conceptual miniaturized OIS and large-scale prototypes

2.1. Miniaturized lens-tilting OIS

The mechanical layout of the miniaturized lens-tilting OIS proposed in Pournazari et al. (2014) is shown in Fig. 1. The device consists of a flexible lens platform (LP) and four moving magnet actuators. The LP includes a plate supported by four folded beams, a lens installed at the center of the plate, and four permanent magnets attached to the plate underneath. The magnets and four air-core electromagnetic coils below them constitute the actuators that can provide 3-DOF actuation of the LP, which are translation along z-axis, pitch (i.e. rotation about x-axis) and yaw (i.e. rotation about y-axis).[1] Among the three DOFs, pitch and yaw are utilized for image stabilization while the translational DOF is for autofocus.

Like most other OIS's, the proposed OIS employs a feedback control mechanism illustrated in Fig. 2. A gyro-sensor is used to detect the hand-induced movement of the camera body while taking photos, which will be used to calculate desired lens-tilting angles in order to restore the optical path to the image sensor. The OIS controller, utilizing the error between the desired and measured tilting angles, determines the currents applied to the magnetic actuators, which actuate the LP to track the reference angles. This paper assumes that the desired lens-tilting angles are pre-specified, while the generation of these angles needs the knowledge of optical imaging theory and is beyond the scope of this paper.

For feedback control, the rotation angle of the LP needs to be measured in real time. Due to the flexibility of the LP, angle sensors may not be applicable to directly measure the rotation angle. A feasible sensing mechanism is to measure the z-direction displacements of two points on the LP for each rotational DOF, and convert them to the rotation angles of the LP. For instance, the displacements of points A and A' (B and B') in Fig. 1(a) can be measured for reconstruction of the pitch (yaw) angle. One type of the potential sensors for measuring the displacement is hall effect sensor, which has actually been widely used in OIS systems (see La Rosa, Celvisia Virz, Bonaccorso, & Branciforte, 2011; ROHM, 2013 for example). Note that in the ideal case when there

[1] For cameras, *yaw*, *pitch* and *roll* are conventionally defined as presented here. See, e.g., ROHM (2013).