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# Design and implementation of a sliding-mode controller and a high-gain observer for output tracking of a three-axis pickup

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**Abstract**

A novel decoupling actuation scheme applied to a new three-axis four-wire optical pickup is synthesized in this study based on theories of sliding-mode control and high-gain observer. The three-axis pickup owns the capability to move the lens holder in three directions of focusing, tracking and tilting. This capability is required particularly for higher data-density optical disks to annihilate the non-zero lens tilting. To achieve control design, Lagrange's equations are first employed to derive equations of motion for the lens holder. A sliding-mode controller is then designed to perform dynamic decoupling and nonlinearity cancellation with the aims of precision tracking, focusing and no tilting. A full-order high-gain observer is next forged to estimate the velocities of the moving lens holder in order to provide low-noised feedback velocity signals for the designed sliding-mode controller. Simulations are carried out to choose appropriate parameter values of the designed controller and observer. Finally, experiments are conducted to validate the effectiveness of the controller for annihilating lens tilting and the capability of the observer for reducing the effects of digital noises on pickup positionings.


*Keywords:* Three-axis optical pickup; Sliding-mode controller; High-gain observer

## 1. Introduction

Optical disk drives (ODDs) serve as data-reading platforms for various applications such as CD-ROM, DVD, CDP, LDP, etc. One of key components in optical disk drives is the pickup, which performs data-reading via a well-designed optical system installed inside the pickup. Fig. 1 shows a photo of a three-axis four-wire type pickup actuator, which is designed and manufactured by the Industrial Technology and Research Institute, Taiwan (ITRI). This pickup consists mainly of an objective lens, a lens holder (often called "bobbin"), wire springs, sets of wound coils and permanent magnets. Thanks to flexibility of wire springs, the bobbin could easily be in motion as the forces acting on the bobbin are generated by the electromagnetic interactions between the magnetic fields induced by permanent magnets and the currents conducted in sets of coils. A conventional pickup actuator (not the three-axis one shown in Fig. 1) often owns only two sets of wound coils—the focusing and tracking coils. In this way, two independent actuating forces are generated in the directions of focusing (vertical) and tracking (horizontal to the disk) to perform precision positioning of the lens. This type of actuator is therefore named as "a two-axis actuator".

Large numerical apertures (NA) and/or short wavelength lasers are recently employed for objective lens design in pickups in order to produce a smaller optical detecting spot on an optical disk for better data-reading resolution. This aims at increasing data density of an optical disk via decreasing the circular radius of the aberration region of the optical spot, the main factor limiting resolution of data storage for disks. As the size of the optical spot is decreased, some original electro-mechanical designs of the pickup structure might become obsolete. One of critical challenges arises from the unavoidable tilting of the bobbin during its motion [1]. This tilting is caused by an uneven magnetic field and/or by the fact that the net electromagnetic force in the directions of focusing and tracking do not act through the mass center of the bobbin while the bobbin moves from its static position to

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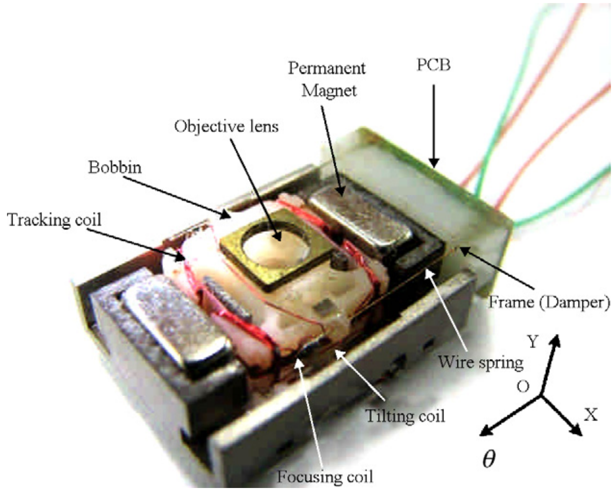


Fig. 1. Structure of the three-axis four-wire type optical pickup by ITRI.

desired vertical and radial positions, resulting in a tilting moment on the bobbin and then a non-zero tilt angle of the bobbin. This non-zero tilting of the bobbin inevitably results in larger levels of distortion on the supposedly circular detecting spot. The spot distortion was originally tolerable for a lower data-resolution design; however, as higher data density of discs is in demand, the level of the spot distortion needs to be restrained for a more accurate, faster data-reading. To this end, the tilting control of the bobbin provides an effective means to minimize the level of the spot distortion. Some three-axis pickups with an additional pair of coils, including the one by ITRI as shown in Fig. 1, were designed recently by researchers to create the servo capability of the bobbin in the tilting direction [2–6]. These actuator structures own the capability of suppressing the unavoidable tiltings of the bobbin in the pickup.

With the hardware of the three-axis pickup well developed, a three degree-of-freedom (DOF) nonlinear controller based on the exact nonlinear dynamic model of the moving bobbin is designed in this study to forge the actuating forces and moment required to perform precision positionings in focusing, tacking and tilting simultaneously. To this end, Lagrange's equations are first applied to system kinetic and potential energies for deriving nonlinear system equations of motion, which is followed by designing a robust sliding-mode control (SMC) [7,8] with considerations of parameter uncertainties and external vibratory disturbances satisfying the input matching condition [8,9]. Note that thanks to the capabilities of first counteracting the known system nonlinearity and then augmenting an artificial tunable switching part in the controller to approach the desired states, the general advantages brought by the SMC over other control designs (such as well-known $H^{\infty}$ control), are the abilities to directly tackle system nonlinearity, control convergence speed and offer a less complicated design procedure. Along with the SMC is a high-gain observer [10–16] synthesized in this study for the pickup to estimate the feedback moving velocities of the bobbin in the directions of focusing, tracking and tilting. The employment of the high-gain observer is aimed to avoid the high differentiation noises caused by the computer discretizations in practical implementations. Note that most of the high-gain observers were originally designed to estimate the velocities of the robots [12,14–16], since joint velocities are usually measured by noise-contaminated tachometers. With the controller and observer designed theoretically, experiments are conducted to verify the effectiveness of the designed SMC for annihilating bobbin tilting and the capability of the observer for reducing the effects of digital noises on pickup positionings.

This paper is organized as follows. Section 2 presents the mathematical modeling of the three-axis four-wire-type lens actuator. Section 3 presents the design of the sliding-mode controller, while Section 4 does the synthesis of the full-order high-gain observer. The numerical and experimental results are presented in Sections 5 and 6, respectively, to predict and verify the effectiveness of the proposed controller/observer scheme. Finally, conclusions are given in Section 7.

## 2. Mathematical modeling

A typical three-axis pickup actuator designed ad fabricated by ITRI as shown in Fig. 1 is considered in this study. This pickup mainly consists of a lens holder—bobbin, inner/outer yokes, four wire springs, coils for actuations in directions of tracking/focusing/tilting, four permanent magnets and a PCB holder. To actuate the pickup, three external voltages are applied independently across the respective spring wires to generate the wire-carried currents through the magnetic fields posed by surrounding magnets. This would induce electromagnetic forces and moment on the bobbin for generating necessary motions for precision positioning in the directions of tracking, focusing and tilting. The resulted motion of the objective lens on the bobbin up to expectations makes possible fast, correct data-reading.

### 2.1. Dynamic modeling of the bobbin

The conventional bobbin, due to its specially designed supporting structure of four parallel wires, exhibits motions mainly in the directions of tracking (*X-axis*) and focusing (*Y-axis*). In addition to the motions in $X$ and $Y$ directions, small tilting often occurs about ($\theta$*-axis*), which is caused by manufacturing tolerance, uneven magnetic fields and/or geometric mis-passes of the electro-magnetic forces acting line on the bobbin mass center. The objective of this study is to design a controller that owns three independent actuating forces and moment in $X$, $Y$ and $\theta$ directions in order to perform precision focusing/tracking and to simultaneously achieve zero tilting to avoid any errors in optical reading signals. The design of such controller starts with an establishment of the system dynamic model. It is first assumed that the pickup assembly can be simply modeled as a lumped mass-spring-damper system due to bobbin's high material rigidity compared to the flexibility of the suspending wires. Fig. 2 shows the schematic bobbin from planar view and accompanying coordinates/notations defined for capturing the bobbin motion from the viewpoint toward the $X$–$Y$ plane. As seen in this figure are coordinates $xyz$ defined as the body-fixed ones to the moving bobbin, while coordinates $XYZ$ are global, ground coordinates. $X$ also serves as a dynamic variable, capturing the horizontal, tracking motion; $Y$ does the vertical, focusing