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Modeling of two-plate capacitive position sensing systems for high precision planar three DOF measurement

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ABSTRACT

This paper investigates the issues associated with the use of two-plate capacitive sensors for the measurement of coupled linear and angular motions, particularly those of three planar degrees of freedom (DOF) micro/nano positioners. Commonly, such sensors are employed for the measurement of linear motions, and angular motion could introduce non-linearities in the capacitance response. An analytic model of a general three sensor system is developed, together with its linearization, which transform the position and orientation (pose) of the end effector of a planar positioner to the capacitance of each sensor. The sensitivities of pose estimations to capacitance non-linearity and parameter variation are analyzed, which further leads to the identification of optimized sensor positioning strategies. The response of a single sensor to tilt is investigated, and experimentation is performed to determine the magnitude of non-linear effects, and its subsequent impact on the three DOF position estimation.

1. Introduction

Many recent developments in science and engineering have been driven by the ability to perform highly precise motion at the micro- and nano- scales. Prominent beneficiaries include the various forms of Scanning Probe Microscopy (SPM), micro-manufacturing and assembly, cell manipulation, optical alignment and the grasping of miniature objects [1–4]. Within such applications, positioning must be performed with high accuracy and repeatability, with a high bandwidth. Careful consideration of the multiple interdependent components which comprise such a system is required to satisfy such constraints.

Within recent research efforts, compliant flexure-based stages have been prevalent as the underlying mechanisms to deliver ultra-precise motion. Many different approaches have been utilized to drive these mechanisms, including the use of piezoelectric stack actuators (PEAs), voice-coil motors and magnetic actuation, with PEAs being the most common. Despite providing nano-scale input displacement, such actuators suffer from varying degrees of hysteresis and other forms of non-linear response. As a consequence, whilst model-based feedforward strategies are often employed [5,6], feedback control is typically mandated. Various control schemes have been devised for these positioning systems, including sliding mode control, H_∞ control, neutral-network based adaptive control, model predictive control and PID control [7–11].

Importantly, the introduction of a feedback control scheme requires accurate measurements of the mechanism's position to be available, which either meet or exceed the precision required for the final positioning. To this end, laser-interferometer, capacitive and eddy-current based sensing and measurement techniques have been utilized to provide position data at a high bandwidth within feedback control systems [12–15]. Recent research efforts have focused on ultra-precise positioning for the production of linear motions, and the above sensing strategies have been shown to be effective for this purpose.

Conversely, other recent studies have led to the development of mechanisms which are capable of providing coupled linear and angular motions [16–19]. This presents difficulties as most sensing techniques are vulnerable to geometric errors, such as Abbe and cosine errors, when a misalignment is coupled to the motion. In extreme cases, such as within laser-interferometry systems, a large rotation can cause the measurement signal to be lost completely.

In this paper, the use of two-plate capacitive position sensors for the measurement of three degree of freedom (DOF) position and orientation (pose) is investigated. Such sensors can achieve sub-nanometer resolution for linear measurement when the two plates are kept parallel. However, plate tilt will cause a non-linear deviation from the ideal behavior. Specifically, this paper seeks to estimate the contributions of multiple error sources, including the capacitance non-linearity, toward the overall three DOF pose

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measurement error. This is of particular importance as a number of recent studies have employed capacitive sensors for the measurement of mechanisms possessing angular motion axes [20–25]. In all these studies, the pose was determined through a linear transformation of the sensor output, without consideration of sensor non-linearity.

This paper is organized as follows. A transformation which maps the end-effector pose to the capacitance of each individual sensor is developed in Section 2. The sensitivity of pose estimation to non-linearity and parameter variation is presented in Section 3, leading to sensor arrangement strategies to minimize their impact, and an estimation of the effects of geometric setup error on the estimation. In Section 4, the non-linearity in the response of a single sensor is studied, together with its impact on the final pose estimation, using an analytic model and experimentation to observe the non-linear behavior.

2. Sensor system modeling

This paper considers the use of two-plate capacitive sensors. These sensors are conventionally used to measure motion along the orthogonal linear axes of a positioning system. With suitable sensor design, such as the use of guard rings, fringing of the electric field can be minimized [26]. A schematic of this situation is shown in Fig. 1a. The relationship between the separation of the plates and the output capacitance under these conditions is then expressed as [12]:

$$C_{\mathrm{ideal}} = \frac{\varepsilon A}{d} \tag{1}$$

where d is the ideal plate separation, A is the cross sectional area of the plate, and ε is the permittivity of the medium between the plates.

2.1. Non-linear capacitance response

The introduction of tilt between the plates, illustrated in Fig. 1b, causes the capacitance to deviate from this relationship. Tilt will be introduced either through misalignment of the experimental setup, or rotation during actuated motion. The range of rotations produced by compliant positioners with angular axes is commonly less than 1–5 mrad [17,23–25]. In addition, as the range of capacitive sensors with nanometre-scale resolution is typically of the order of 100 μm, the angular measurement range is similarly limited. This range is dependent upon the geometry of the sensor apparatus, but will in general be limited to within approximately 5 mrad, as discussed later in Section 3.1.

Assuming a planar geometry, with an infinite out-of-plane dimension, and utilizing multiple conformal transformations of the geometry, the capacitance per unit length can be shown to be given by [27]:

$$C = \varepsilon\left(\frac{K(k_{\mathrm{in}})}{K'(k_{\mathrm{in}})} + \frac{K(k_{\mathrm{out}})}{K'(k_{\mathrm{out}})}\right) \tag{2}$$

where

$$k_{\mathrm{in}} = \sqrt{\frac{\left(r_1^{\frac{\pi}{\phi}} + r_2^{\frac{\pi}{\phi}}\right)\left((r_1+L)^{\frac{\pi}{\phi}} + (r_2+L)^{\frac{\pi}{\phi}}\right)}{\left(r_1^{\frac{\pi}{\phi}} + (r_2+L)^{\frac{\pi}{\phi}}\right)\left((r_1+L)^{\frac{\pi}{\phi}} + r_2^{\frac{\pi}{\phi}}\right)}}$$

$$k_{\mathrm{out}} = \sqrt{\frac{\left(r_1^{\frac{\pi}{2\pi-\phi}} + r_2^{\frac{\pi}{2\pi-\phi}}\right)\left((r_1+L)^{\frac{\pi}{2\pi-\phi}} + (r_2+L)^{\frac{\pi}{2\pi-\phi}}\right)}{\left(r_1^{\frac{\pi}{2\pi-\phi}} + (r_2+L)^{\frac{\pi}{2\pi-\phi}}\right)\left((r_1+L)^{\frac{\pi}{2\pi-\phi}} + r_2^{\frac{\pi}{2\pi-\phi}}\right)}}$$

and $K(k)$ and $K'(k)$ are the complete elliptic integrals of the first kind of k and its complementary modulus k', respectively. However, for the milliradian-scale operating range considered, the computation of the capacitance from this model is infeasible. In particular, large numerical errors are incurred as the terms $r^{\pi/\phi}$ in k_{in} are too large to be computed accurately, and $k_{\mathrm{in}} \approx 1$, where $K(k)$ possesses a singularity.

An approximation has been produced for use with small angles, avoiding the difficulties in evaluating (2). This approximation, which neglects the terms higher than second order, including those of fringe effects, is given by [28]:

$$C = \frac{\varepsilon L}{q} + \frac{\varepsilon}{\pi}\left[\left(1 + \frac{L}{4q}\right)|\phi| + \frac{1}{2}\phi^2\right] \tag{3}$$

where q, and ϕ, together with an added parameter p, which will be referred to as the *separation parameters*, are the plate perpendicular separation, tilt, and shear, respectively, as shown in Fig. 1b. It can be seen that if L is considered an analog for the cross-sectional area A, the model (3) reduces to (1) when there is no tilt. Hence, it is assumed that the small-angle approximation is appropriate, despite the plates having finite out-of-plane length.

2.2. Three DOF sensor modeling

The capacitance of each sensor, given by (3), depends on the separation parameters q and ϕ. Hence, this section develops a transformation from a planar mechanism pose to the local separation of each sensor. Whilst the model presented in this section is general and can be easily extended for systems with differing numbers of motion axes, positioners with three planar DOFs have been focused on within this paper.

A schematic of this transformation is shown in Fig. 2. It is assumed that the motion of the positioner is in the X–Y plane with

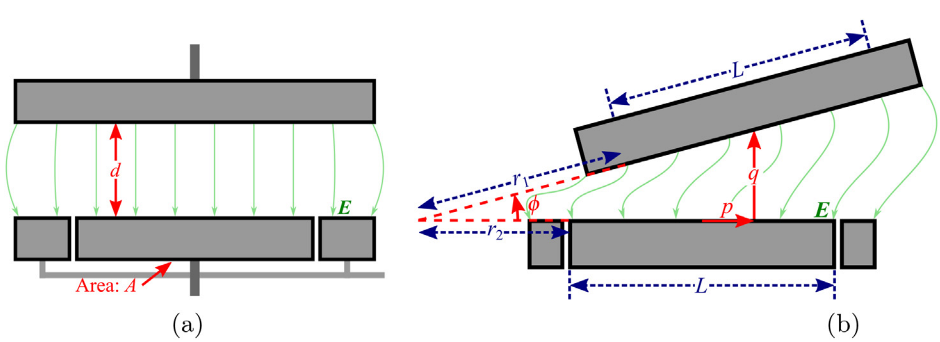

Fig. 1. Schematic of two-plate capacitive plate sensor with guard rings: (a) ideal configuration and (b) tilted configuration.