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Technical note

Characterization of instrument drift using a spherical artifact

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ABSTRACT

Drift is a common and inevitable error source in measurements. Currently there are two main approaches to address instrument drift in image or area-based measurements, drift calibration with target tracking and active feedback correction. We propose an alternative approach to drift calibration for profilometers, particularly high speed instruments such as confocal microscopes or scanning white light interferometers. The method is based on sequential measurements of a spherical artifact whose diameter is larger than the field of view. A best fit sphere algorithm is used to determine the movement of the spherical artifact's center over time. This reduces drift measurement uncertainty because it uses height data over the full field of view, compared to target tracking strategies that involve tracking small features. Simulation results show that under practical conditions, e.g. with typical noise levels and typical drift rates, this method is quite effective and can yield measurements with low uncertainty. The measurement is demonstrated on a commercial confocal microscope to determine drift rate magnitude and direction.

1. Introduction

Surface topography impacts functionality of the workpiece [1–3], consequently surface metrology is becoming more and more important. Optical profilers are popular for micro and nano-scale surface measurements such as the scanning white light interferometers (SWLI), whose vertical resolution can be sub-nm [4]. Another example is the scanning confocal microscope which offers the advantage of a larger measurable slope range, reportedly as large as 85° [5]. Stage drift during the measurement causes errors in the height and x y mapping of the height data. Stage drift has long been a limiting factor in tracking micro features of surfaces during a scanning process [6]. For sequential frame data acquisition, drift will lead to a mismatch between subsequent measurements. Thus, drift rate considerations are important and often need to be reduced through environmental, procedural, and/or instrument modifications. Whether the goal is to fully characterize instrument performance or to ultimately improve a measurement, instrument drift should be characterized and repeated often and over a range of time scales, as each instrument in its own environment has its own unique drift characteristics.

Several methods can be used to address instrument drift, and they can be roughly grouped into two categories: drift calibration with target tracking and active feedback systems. Tracking with a fiduciary marker on top of the sample is a good example of target tracking. Resolution on the order of 1 nm in the horizontal X–Y plane and 5 nm in Z direction has been demonstrated in certain limits [7]. There are several approaches in the target tracking category [8–10] and this category has a long history, particularly for imaging in biology. The preparation of the marker and the setup are often complex, and this method is not always practical for surface metrology needs in precision engineering, especially when stage drift changes from day to day. In addition, tracking the target's position is not an easy task as measurement noise can easily affect data processing and the identification of the target's location. Further, when tracking methods are based on intensities, drift in the intensity itself will negatively impact the measurement. Active feedback systems are another way to stabilize the stage. By using this method, Carter et al. demonstrated a system that can maintain the stability of 0.1 nm in three dimensions for 1 s [11]. In their setup, a marker was used to track displacement and a piezoelectric stage was used to correct drift. Setups are complicated in this category and usually costly. In many applications, a convenient and robust method for simply calibrating drift rates is sufficient.

In this paper, we discuss the combination of a spherical artifact and a robust ball fitting algorithm to estimate drift rates. Instead of tracking a visible spot (a fiducial) in the field of view (FOV) directly, we take subsequent height profile measurements of a cap on a spherical artifact whose diameter is larger than the field of view. We use a robust fitting algorithm to find the center of the best-fit sphere to the data and the center location provides the information on the drift properties, such as drift direction and drift rate. The

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method is simple and inexpensive, and the measurement uncertainty can be relatively small since height data over the entire field of view is used for the analysis. Choosing the best diameter for the spherical artifact is important. If the diameter is too large, a spherical fit becomes ill defined as the height profile becomes too flat over the FOV. If the diameter is too small, steep slopes at the edge of the FOV can lead to noisy data and/or data dropout. Best calibration occurs when the ball is as small as possible with minimal data dropout. We validate the method through both simulation and experiment. A grade 3 steel ball is used in the experiment to characterize the drift rate in a laser scanning confocal microscope [12]. The ball has a radius of ~0.6 mm with an RMS surface error of 100 nm. Measurements showed a typical X drift of 75 nm/min with an estimated uncertainty of 4 nm/min, and a Y drift of −54 nm/min with an uncertainty of 8 nm/min.

2. Theory

In this method, a collection of ball surface measurements are taken by a profilometer without intentionally moving the ball. Drift causes the ball to move over the field of view so tracking the position of the ball center provides the drift information. For short periods of time, drift is usually linear [13]. Let x and y represent the coordinates in the plane of the part and z represent the orthogonal height axis. The drift model will be

$$x_c(t) = x_{co} + \mu_x t \quad (1)$$

and

$$y_c(t) = y_{co} + \mu_y t \quad (2)$$

where x_c and y_c are the center coordinates of the best-fit sphere and x_{co} and y_{co} are the coordinates at the start of the drift test (approximately the middle of the field of view). The linear drift rate can also be evaluated as

$$\mu_l = \sqrt{\mu_x^2 + \mu_y^2} \quad (3)$$

and the center coordinate tracked along a line as

$$l = \mu_l t \quad (4)$$

The drift rates are determined by taking a series of measurements of the surface of the spherical artifact, fitting each measurement to a sphere to determine the center coordinates, and plotting the center coordinates as a function of time. A linear fit to the data is then used to extract the slopes μ_x and μ_y for Eqs. (1) and (2).

Since the method relies on determining the center position of the ball from measurements of a spherical cap on the ball, several factors must be considered such as the algorithm used to determine the best-fit sphere to the spherical cap data, the realistic geometry of the ball, the size of the ball, and random noise in each measurement.

2.1. Ball size and best fit algorithm

The technique uses height profile data from a cap on the surface of a ball to estimate the center of the best-fit sphere for the entire ball. Given geometric errors on a ball and noise in each measurement, the best estimate of the ball's center occurs when the size of the cap is large. All profilometers have a maximum measurable slope. The slope is large at the edge of the FOV, so if the cap is too large, the instrument will not be able to measure these regions, as shown Fig. 2. Thus, the smallest diameter ball should be used that allows a surface measurement over the entire FOV. Since measurable slopes are usually quite limited, this typically leads to a ball diameter choice that is larger than the field of view, as shown Fig. 1.

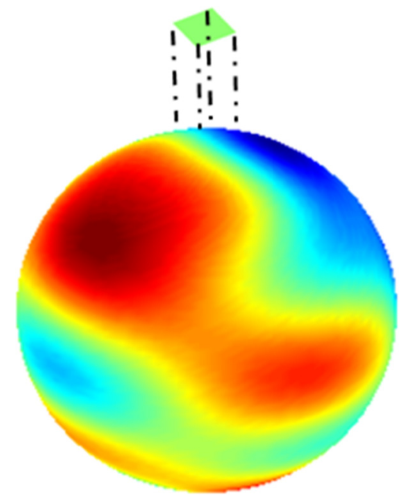

Fig. 1. Example of size scales involved in the drift rate measurement. These size scales shown are representative of a measurement with a confocal microscope with a field of view of 0.256 mm × 0.256 mm and a ball with a radius of 0.595 mm and ball error with an RMS of 100 nm.

Least-square fitting to a cap on a sphere to determine the best fit center must be done with care and a robust best-fit algorithm is needed. We use a method proposed by Forbs [14] (Fig. 2).

The basic idea for the spherical cap fit is to constrain the number of parameters of the best-fit sphere model [15,16]. In essence, a general equation of a spherical cap in Cartesian coordinates can be written as

$$A(x^2 + y^2 + z^2) + Bx + Cy + Dz + E = 0 \quad (5)$$

where (x, y, z) is the point on a sphere, and A, B, C, D, E are the coefficients of an equation for a sphere. A plane can be fit to the height profile of the cap and rotated so the normal to the best-fit plane points along the positive Z axis, this ensures $D = 1$ in the equation. Then a least square fit is carried out to determine the best fit radius and coordinates of the sphere center.

2.2. Geometric errors on the ball

Geometric errors on the ball will impact the center coordinates of the best-fit sphere when fitting over a finite area. The goal of the drift measurement is to track the ball center coordinate *change* over time, so an error in the best-fit center coordinates is only a problem if the error changes over time. This is a concern only if the ball geometry over the field of view changes significantly over time. This is best explored through simulation and is described in the simulation

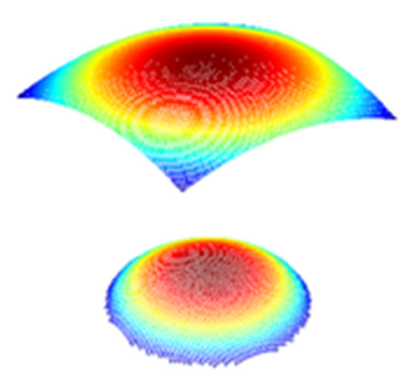

Fig. 2. Schematic of a nearly flat ball profile when a very large radius artifact is used (top) and a highly curved profilewhen a very small radius artifact is used (below), showing data drop out at the edge due to slope limitations of the instrument.