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A reliable, accurate, and inexpensive optical detector for table-top applications is described here. Based on a commercial high resolution office scanner coupled to a projection plate, it enables a large image plate surface, allowing recording of large images without systematic errors associated to coupling optics' aberrations. Several tests on distance-dependent and steady interference patterns will be presented and discussed. The extension to other types of optical measurements by substituting the projection plate is proposed.

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I. Introduction

The detector plays a fundamental role in most experimental setups, especially in optical applications. Photographic films are being replaced by CCD (Charge-Coupled Device) image plates[1], which are revolutionizing many areas of experimental science in both table-top and large facilities applications. Nevertheless, they have some important drawbacks and limitations. One of their major inconveniences is the reduced detection surface. Although image plates can be assembled as large as 36.9x36.9 mm with a pixel size of 9x9 microns[2], these are still state-of-the-art equipment, which turns into a serious budgeting problem for most standard laboratories. This problem can be solved either by reducing the size of the signal down to the dimensions of a less expensive CCD by optical means, or by reducing the sampling distance. In the first case, optical aberrations caused by coupling optics are additional sources of systematic errors, and often involve a rather cumbersome data analysis[3]. On the other hand, reducing the sampling distance has the drawback that it prevents recording images at relatively long distances from the source, which are formed by almost parallel incoming beams. This information is very important, for instance, in optical interference patterns studies, like the example discussed here.

With this in mind, the goal of this paper is to introduce an alternative device to carry out a series of table-top optical measurements, by using a modified commercial high resolution scanner coupled to a projection plate.

II. Setup Description

The essentials of the proposed setup are essentially quite straightforward. Most commercial scanners take an image of the reflecting light coming from their own illumination lamps. These lamps and the detector are fixed onto the same carriage. Therefore, by switching off, unplugging, or simply removing the internal lamps, the scanner is turned into an optical detector attached to a mobile carriage.

Although it would be desirable that the detector and the carriage have the same length, commercial scanners usually have a detector several orders smaller than the carriage length. In these cases, the image is focused by a series of cylindrical lenses. Therefore, in order to have the image at the focus plane of the lenses, the optical signal needs to be projected onto a thin plate attached to the surface of the screen. For optimal results, the material used for the projection plate should show a high scattering efficiency (see Fig. 1).

FIG. 1. Scheme and photograph of a modified commercial scanner converted into an optical detector. In this particular experiment, a Fabry-Pérot interference pattern is recorded. The signal produced is caused by focusing a diode laser through two parallel reflecting plates. The diffuser plate is made of aluminum oxide power.

In applications involving shorter wavelengths, or even ionizing radiation, the plate material should be able to convert the signal into the visible, so a luminescent material or a scintillator is customary. The only prerequisite concerns the stability of the radiation, *i.e.* free from pattern fluctuations during the carriage movement. It does not imply, however, that the signal has to be continuous. In the case of a pulsed signal, the device should work as well, provided that the pulse period is much shorter than the scanning line-step.

III. Sources of distortion analysis

As it is widely known, in order to capture a given image, a scanner measures successive lines as the array detector-carriage is displaced. Afterwards, the measured lines are put together digitally to obtain the full image. If one assumes that the digitalization is an error-free procedure, the image distortion can only be originated from: a) the carriage movement (longitudinal distortion), b) the capture of each line (lateral distortion), or c) the diffuser plate (planar distortion). We shall now analyze these systematic error sources. Some examples are provided on Fig. 2.

III. A. Longitudinal distortion

A longitudinal distortion of the projected image may occur due to imperfections on the carriage displacement, either due to an uneven speed or due to a misaligned movement. In practice, the resulting experimental longitudinal distortion is often a mixture of both effects.

Unpredictable slippages as the carriage displaces at each scan deform randomly the image along the y longitudinal axis. It is shown in the same elapsed-time positions 1 to 2 and 2 to 3 of Fig. 2. However, this type of distortion is expected to occur only in certain few longitudinal positions, and does not affect the dimensions along the lateral axis (x).

Since the carriage movement is usually executed by pulling the carriage from two lateral fixing points, the slippage seldom takes place in both fixing points simultaneously. In general, there exists a slight unparallel movement of the sensor, as shown in positions 4 and 5 of Fig. 2.

FIG. 2. Typical imperfections on carriage's movement. Each label corresponds to different positions of the carriage. The elapsed time between positions 1-2 and 2-3 is assumed to be the same. On position 4 there exists a tilt, while on position 5 the carriage is laterally displaced.

III. B. Lateral distortion

It is caused by imperfections on the internal cylindrical lenses of the scanner. Both Seidel and chromatic aberrations might be experimentally checked and delimited on each specific scanner before operation. As almost every lateral line scan is equally deformed, Seidel aberrations can be easily delimited, for instance, by scanning a calibrated graph paper.

When different signals at separate wavelengths are expected to be measured at the same time, chromatic aberrations can be delimited too. It can be done by taking a sequence of several images of the same calibrated graph paper with different chromatic filters.

III. C. Planar distortion

The planar distortion depends on the size and density of the scatters or luminescent particles on the projection plate. It must be taken into account that the scanned image is a mosaic of the points where the incident light has effectively been scattered. Therefore, the denser and thinner is the plate, and the smaller is the particle, the finer is the image measured.

Special care has to be taken to attach the plate on the surface of the scanner image screen, avoiding possible tilts or wrinkles. An alternative consist on painting or depositing the scanner surface with the diffuser substance, but maintenance is more critic this way.

IV. Experimental delimitation of the total distortion

Since each commercial scanner has its own peculiarities, it is necessary to establish a general procedure to experimentally delimit the total image distortion. Such procedure should be always performed before the first use, and occasionally during the instrument lifetime.

Let us first consider that the image is equally distorted on the lateral axis along most of its longitudinal positions. According to the previous analysis, only a lateral displacement of the carriage contradicts this statement (positions 4 and 5 in Fig. 2), because the optical aberrations of the internal lenses are constant.

It can also be considered that the slippage of the carriage supports never happen along the whole displacement, but only at certain random points. Therefore, there will always be areas where the image is not deformed at all, at least along the longitudinal dimension.

Thus, the most straightforward procedure to delimit the possible distortions of the scanner consists of comparing several pictures of a planar caliper (such as a calibrated graph paper or a ruler) recorded at different positions. The optimum caliper length to perform this test is around one third of the longitudinal axis. The length of the object is scanned parallel to the lateral axis at multiple positions through the longitudinal axis (see Fig. 3A) with a monochromatic light source. Since the measured value should kept constant, the observed distortion can only be attributed to Seidel aberrations of the internal lenses.

The same procedure can also be performed along the longitudinal axis. As the scanner internal lenses are cylindrical, the observed deformation is only related to an uneven movement of the carriage (see Fig. 3B).

FIG. 3. Different steps to delimit accuracy of the scanner. A) Estimation of Seidel aberrations (of the scanner internal lenses). B) Estimation of uneven speed of the carriage. C) Estimation of the precision value of the detector. The lower picture shows the different caliper distances measured from each of the images. The standard deviation is in this case 0.449 mm on around 160 mm, that is, the 0.28%.

An additional correction is needed in those scanners that mount non-square detection pixels, *i.e.* have not the same distance on different dimensions. It can then be known by performing a series of calibration measurements in both axis, and checking the proportions of the pixel.

In order to obtain the precision value of a 2D image plate scanner, pictures of the caliper at different angles must be taken. In general, the extension of the caliper will vary depending on which picture is measured, because of the scanner deformations. The maximum difference measured can be considered as an upper limit to both the precision and the accuracy of the detector. In practice, this error is typically less than 0.3% in current high resolution scanners.

There exists, however, a finer correction. It has been recently applied to digitalize the Carte du Ciel plates in Astrometry[4]. It consists on finding the residuals, adjusting the resulting graph, and subtracting a parameterized equation to each scanned image. Errors lower than $1.7 \cdot 10^{-3}$ % can be easily obtained afterwards. Most optical experiments do not require such high precisions, and the estimation of the error described above is usually satisfactory for many purposes.

V. Test on an interference pattern

The use of a modified office commercial scanner is especially worthwhile to analyze very fine optical images. A good working example is the analysis of the interference patterns observed by focusing a monochromatic light through a generalized Fizeau interferometer. Even in the simplest case of Fabry-Pérot fringes this detector is quite helpful, because it allows a large signal optical aperture. Having a large detection area is also very interesting when the image has numerous fringes of varying intensities. If the same digital image has to be taken with a small square shaped CCD, the required additional optics not only would substantially increase the budget for the setup, but they would introduce further aberrations.

In Fig. 4 we show slightly different patterns resulting from focusing a monochromatic light into a generalized Fizeau interferometer at different angles of the refractive plates. The light source employed for these measurements was a 660 nm diode laser (Thorlab's diode laser ML101J27, 660 nm, 130 mwatt). As a diffuser plate, we used an ultra-fine aluminum oxide grindstone sheet (0.1 Micron Aluminum Oxide Abrasive Film Disc, 8" diameter, from Southbaytech). As it is shown in Fig. 4, the fringe patterns increase their complexity as the distance between the detector and the interferometer decreases.
This is a very stringent test for any detector. In order to guarantee that the fringes do not overlap, a divergent exit light beam with a very large numerical aperture must be formed,

so a large and accurate image plate is required. As demonstrated in Fig. 4, such type of complex measurements can be easily performed with an adapted commercial office scanner like the one described here[5].

FIG. 4. Fizeau interference patterns at different angles of the refractive plates (α), recorded on a modified commercial office scanner. A 660 nm diode laser was used. The images recorded (left) are compared to the theoretical profiles (right) along a diameter. A perfect match between both patterns is observed.

Finally, let us discuss the capabilities of a modified commercial scanner compared to other large-surface detection techniques, like photographic films. Although this solution is apparently easier and more direct than modifying a scanner, it has nevertheless two important drawbacks. The first one is related to the manipulation of the film to avoid wrinkles while it is exposed to the incoming radiation. Commercial photographic films are typically thin, and they are covered with comparatively thick protective sheets, which are removed just before being exposed inside a black box. Independently of the tightness of the lateral fixing springs over the film, it is virtually impossible to avoid the appearance of small wrinkles on it, which are a primary source of systematic errors. The second drawback is that the resulting image must be digitally processed by means of a commercial scanner. Therefore, most of the distortions analyzed above are directly transferred to the analysis of the photographic film measurement.

VI. Conclusion

In this paper we suggest that a standard high resolution commercial scanner is an appealing alternative to perform some table-top optical measurements. As an example, a study of the complex interference patterns resulting from focusing a monochromatic laser light into a generalized Fizeau interferometer have been shown and analyzed here.

The scanner-based detector only requires a simple modification on the commercial office scanner, and a projection plate attached to its screen. The only essential requirement concerns the stability of the optical signal during each line-scan. By choosing a proper material for the plate (diffuser or luminescent), this detector can be used for a series of experiments covering a wide range of electromagnetic frequencies.

Three main distortions of the image have been identified. The first one is related to the mechanical performance of the scanner (uneven and non-parallel carriage movement). The second one concerns the optical aberrations of its internal optics. And the third one is due to the characteristics of the diffuser plate. Although such distortions are specific for each particular scanner, a general procedure is suggested here to estimate the total distortion of the resulting image.

The main advantages of the device described here are simplicity and affordability. It does not require special training or skills, and acquisition and analysis software packages are easily available from different sources, including those provided by scanners' manufacturers. The use of a conventional scanner still provides further advantages in comparison to other standard detectors, perhaps the major advantage is the possibility of having a large acquisition area. The straightforward delimitation of systematic distortions is also a convenient point. Finally, no coupling optics is required, which allows direct optical measurements, free from cumbersome aberration corrections.

VII. Acknowledgement

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FIGURE 1

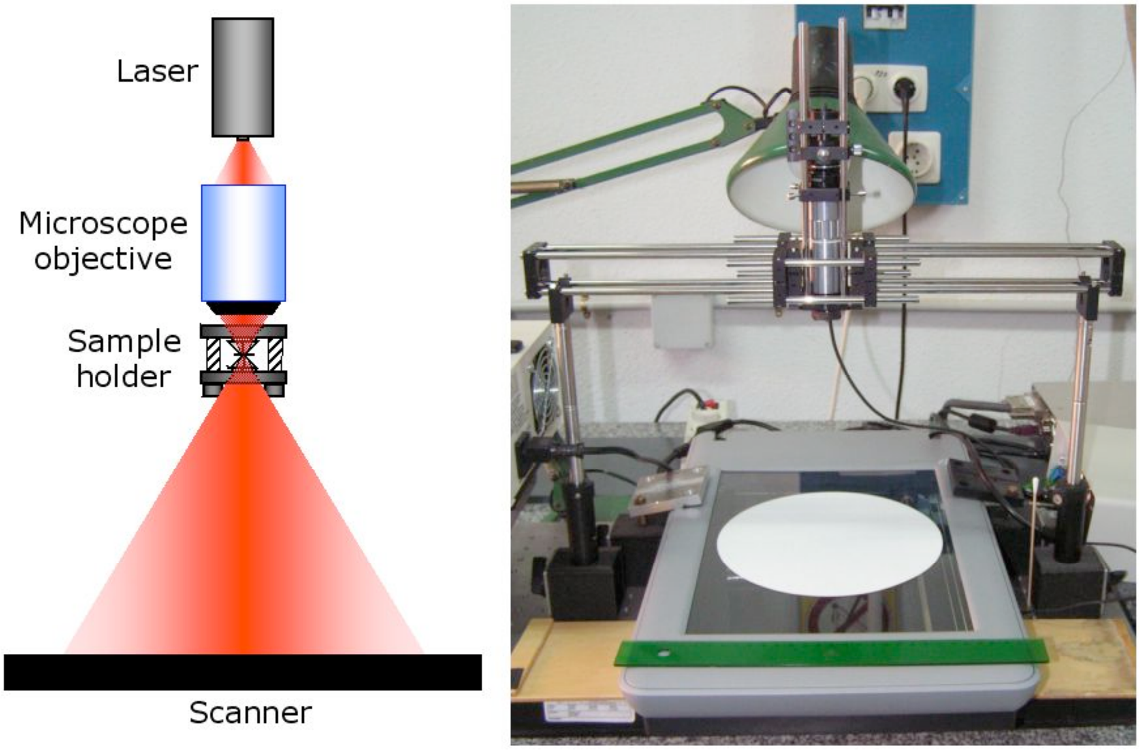

FIGURE 2

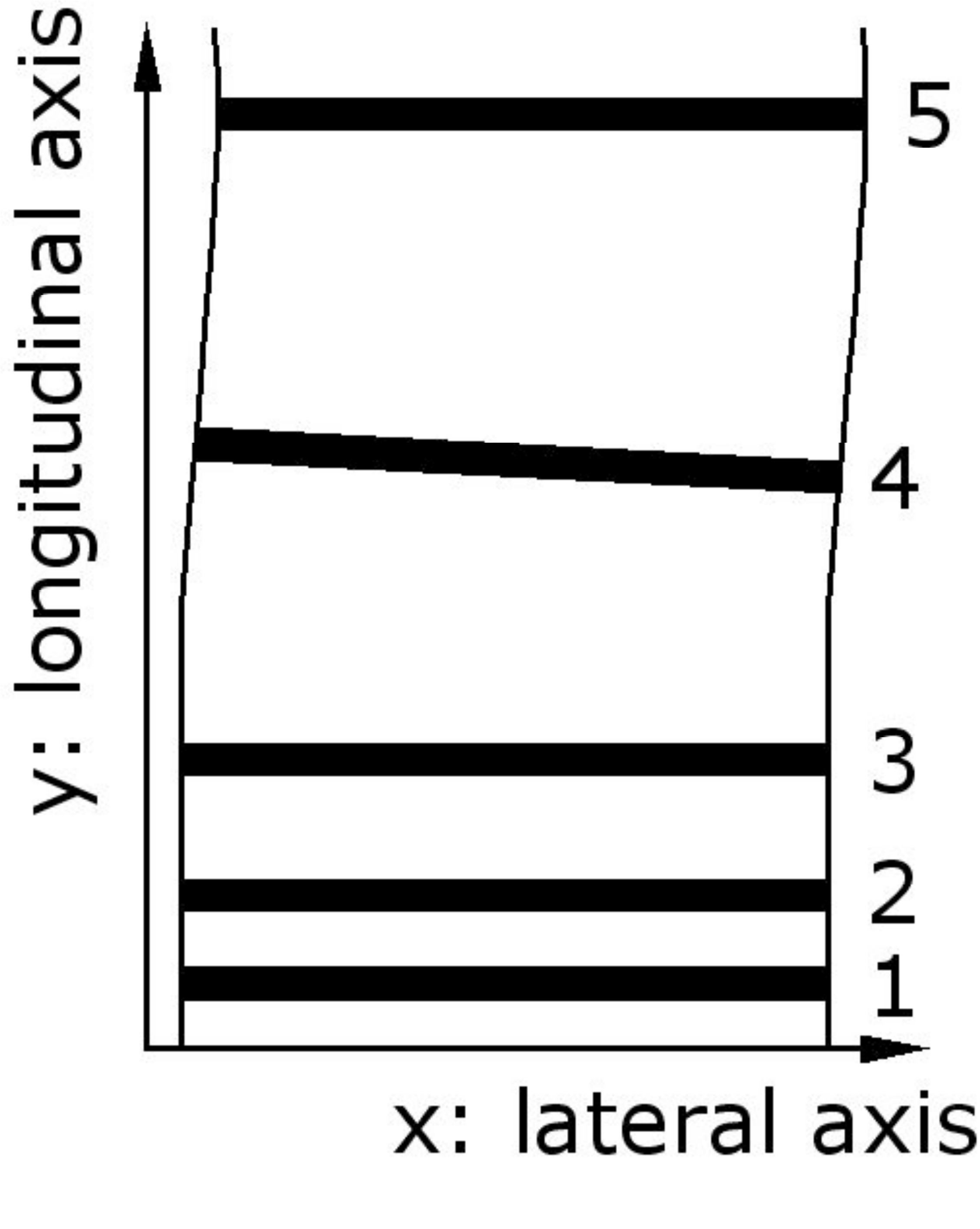

FIGURE 3

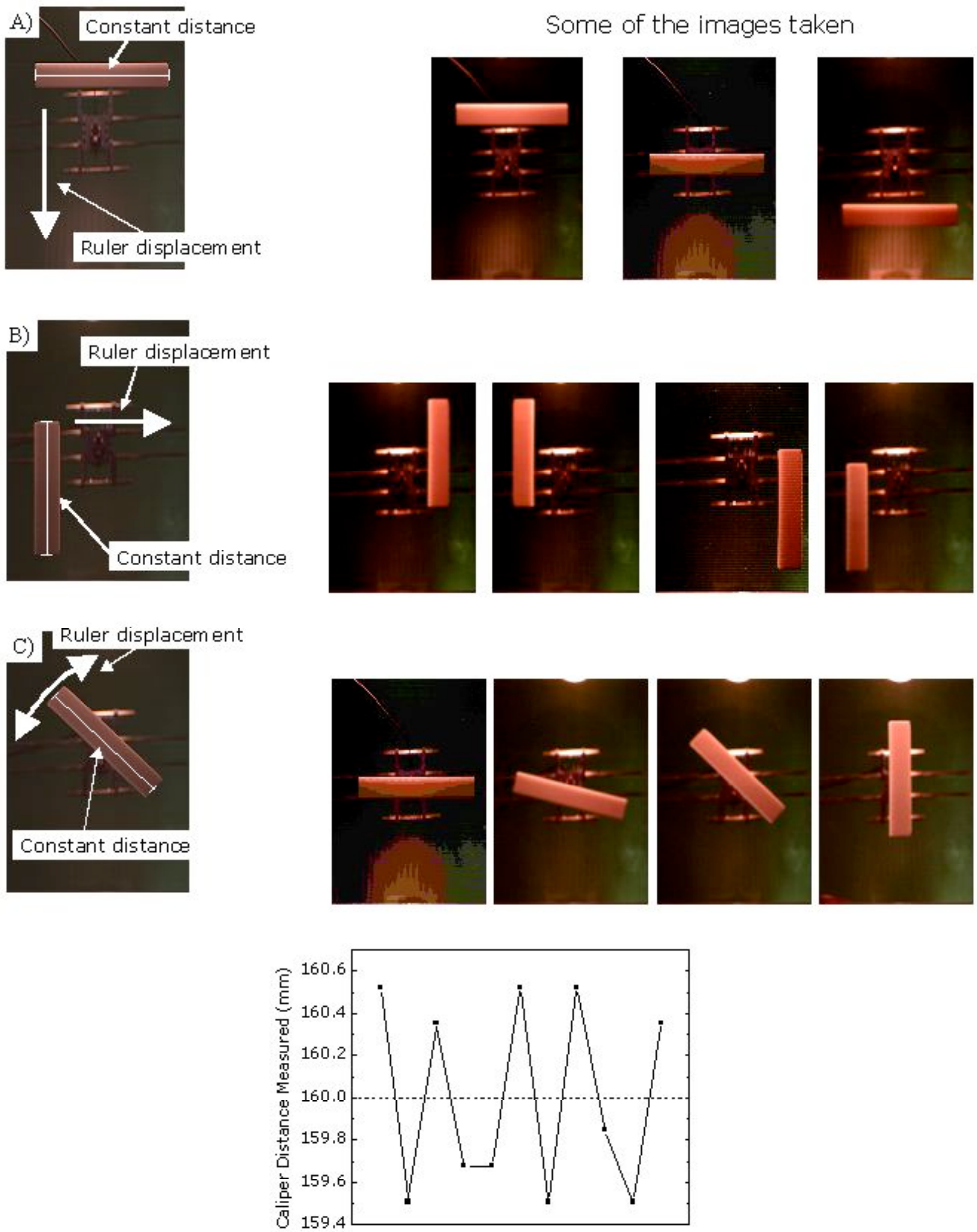
A)
Constant distance
Ruler displacem ent
Some of the images taken
B)
Ruler displacem ent
Constant distance
C)
Ruler displacem ent
Constant distance
Caliper Distance Measured (mm)
160.6
160.4
160.2
160.0
159.8
159.6
159.4

FIGURE 4