On-line linear guideway monitoring using laser mouse sensor

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Abstract. A low-cost, on-line linear guideway straightness monitoring system for machine tools is presented. The monitoring system which includes an embedded optical sensor from the optical mouse, an image display module, a displacement calculation module, an image enhancement module and a data visualization module are integrated into an edge computer. This proposed sensing system can measure the displacement in two orthogonal directions simultaneously, i.e. a two-dimensional displacement sensor based on digital image correlation, DIC. With image enhancement technique and a custom-made speckle patterns printed using a standard low-cost monochrome laser printer, results show that this two-dimensional displacement sensing system has a displacement resolution less than 5 µm in both orthogonal directions. The measuring range is 1mm for static measurement but is effectively infinite while moving at a low speed less than 0.05m/s. However, the accumulation error increases with the measuring range. A novel application of utilizing this displacement sensing system upon on-line monitoring the linear guideway healthy status, i.e. linear guideway straightness, of machine tools is presented. The performance and the associated advantages and disadvantages of this proposed sensor as well as the on-line monitoring system is assessed experimentally.

1. Introduction
Optical sensors used in displacement measurements have already proved to be reliable and accurate. However, the high cost limits their applications. A cost-effective optical displacement sensor with an acceptable accuracy which can be embedded in machines theoretically is invaluable in numerous applications. The optical mouse sensor which has a coefficient of determination of $R^2 = 0.9998$ in a linear displacement measurement is a candidate to fulfill this requirement [1]. In fact, the optical mouse sensor has been proposed in various applications, such as a displacement sensor [1-5], a rotary encoder [6, 7] and even a two-Euro counterfeit coin detector [8]. However, several drawbacks limit its industrial applications, such as very sensitive to the measurement surface [3], out of focus easily due to focus distance changes [2, 3], and poor performance while in circular trajectories [1, 5]. Most of all, both the accuracy and precision are not good enough for industrial applications. Nevertheless, with the advance both in hardware and software in recent years, the optical mouse has a great potential as a built-in sensor for machines in industrial applications.

In this study, the image from CMOS of the optical mouse is employed as an inexpensive image acquisition device. Two ways to improve the accuracy and precision in measuring the displacement. The first is to increase the resolution of the image captured by the CMOS through the image processing. The second is to optimize the non-repetitive speckles pattern in order to maximize image discrimination as well as the resulting displacement.
A custom-made speckle patterns printed using a standard low-cost monochrome laser printer was pasted on the measurement surface, which remedies the problem caused by varying sensitivity due to measurement surface. Moreover, the CMOS is mounted on a jig which not only maintains the focus distance but also shields out the noise due to environmental lights, which takes advantage of the short focal distance featured by the optical sensor. An application of utilizing optical sensor upon on-line monitoring the linear guideway healthy status, i.e. linear guideway straightness, parallelism, of machine tools is presented. The performance and the associated advantage and disadvantage of this proposed sensing system and the on-line monitoring system as well is assessed experimentally.

The remainder of this paper is structured as follows. Section 2 and 3 introduce the hardware and working principle for optical sensor measuring system, respectively. Section 4 presents the image processing techniques adopted to improve the image quality acquired from the CMOS.

The speckle pattern that enhances the resolution in displacement measurement is also illustrated. In Section 5, the performance of this displacement sensor system based on optical mouse is assessed experimentally. A novel application of utilizing this optical sensor upon on-line monitoring the linear guideway straightness of machine tools is presented. Section 6 summarized the results and contributions of this study.

2. Sensing principle of optical mouse
The optical mouse has a laser diode (LD) and CMOS sensor. The CMOS sensor consists of an array of pixels with a size of $30 \times 30$. Each pixel has a physical size around 30 $\mu$m. The black and white CMOS sensor has intensity value ranging from 0 (black) to 255 (white). When the optical mouse is moving on a surface, the lens capture images of the surface texture onto the CMOS sensor continuously. Then the mouse displacement along two orthogonal directions, i.e. x and y axes, is calculated according to the correlation between the present image of the surface texture with previous one, i.e. the digital imaging correlation (DIC) [9, 10].

To assess the performance of a typical mouse sensor in measuring the displacement, figure 1 compares the positioning accuracy from an off the shelf mouse sensor installed on the worktable of a feed drive system with the motor encoder. The mouse sensor used in this study has a resolution up to 8200 CPI (Count per inch) which is approximately 0.6 mm in terms of displacement resolution. However, figure 1 shows that the deviation in positioning accuracy as compared to that calculated from motor encoder is close to 5 mm when the work table is traveling at a speed of 2 m/min. Nevertheless, it is still far from an acceptable positioning accuracy, i.e. less than 10 $\mu$m, roughly requested by the machine tool industry.

There are two aspects to improve the resolution in measuring displacement of the optical sensor. The first is to utilize the image processing technique such as image interpolation, edge detection, etc. to improve the image quality and thus the resulting sensitivity in calculating the displacement using DIC. The second is to utilize a custom-made information patterns for DIC instead of the surface texture on the targeted object. Note that the DIC is originally adopted in measuring the strain of a deformed specimen after it is subjected to an external force. The information pattern conventionally is a speckle pattern created by paint sprayed on it, which ensures the speckle pattern is random and is strongly bonded on the specimen. The objective is to measure the speckle pattern displacement before and after the specimen is deformed based on DIC. On the contrary, the objective in this study is to measure the displacement of the optical sensor not the deformation of the targeted specimen.

Therefore, the resolution in displacement measured by the optical sensor can be increased by using a well-controlled speckle patterns pasted on the targeted object. The speckle patterns in this study are optimized aiming to increase the displacement discrimination and printed using a standard low-cost monochrome laser printer to ensure a more consistent sensing sensitivity for the optical sensor.
3. Digital image correlation
For a typical optical mouse, the displacement is calculated from the image correlation between two consecutive surface texture images. In other words, two consecutive images captured at different locations are compared by a subset from the first image and convolute it with the second image. The similarity between two images is quantified using image correlation calculated using the summation of squared differences of the intensity value of each pixel between two images. Then the maximal similarity and then the corresponding displacement of the second image relative to the first one can be determined. The subset size is chosen to be large enough for noise reduction. In this study, a subset size of 30 x 30 pixels has been fixed in conducting the DIC. However, the pattern of the surface texture where the captured image should be non-repetitive in order to have a unique displacement of the second image relative to the first one. The accuracy of displacement measured in such a way depends not only on the pixel size of the image but also on the non-repetitive pattern of the surface texture where the image is captured by the CMOS. The pixel size from a commercial optical mouse from the market so far is more than 30 µm. Subsequently, the resulting displacement resolution is more than 60 µm, which greatly limits its applications in the machine tools.

On the other hand, a non-repetitive speckle pattern is required to cover the area of the targeted flat surface for maximizing the sensitivity in displacement measurement based on DIC algorithm. The size of the speckle as compared to that of the pixel and the associated speckle distribution as well all clearly influence the accuracy of the measured displacements. How to increase the displacement resolution through the optimal design of the non-repetitive speckles pattern is described in the next section.

4. Image processing and speckle pattern
In addition to the lens and the light-sensitive CMOS, the lightning condition has a great influence on the image captured by a CCD-camera. The intensity values of the monochrome image represented by the 30 x 30 pixels have a much smaller range as compared to the theoretical one ranging from 0 (black) to 255 (white). Image blurring is inevitable due to uneven lightness, the targeted speckle pattern unflatness and/or loss of focus to a certain level. Therefore, several image processing methods were adopted to improve the image quality.

The image acquired by the CMOS was resampled from 30 x 30 to 90 x 90 pixels using bicubic interpolation, i.e. upsampling, for adjusting the resolution. The intensity value for each pixel of totally
90 × 90 pixels of the resulting image is an average from 50 images captured within a second to reduce the influence caused by the time drifting or uneven lightness. The speckle pattern is designed to be chess-like and either in black or white, so an image with good contrast which has sharp differences between black and white will certainly increases the image discrimination as well as the resulting displacement calculated by the DIC. To increase the image contrast, the values of the input image intensity were manipulated pixel by pixel in order not only to saturate them at low and high intensities but also to reduce the intensity uncertainty due to the diffraction. The contrast is adjusted using multiple stages to ensure the resulting histogram to be bi-polarizing. Edge detection was also adopted to identify points in an image at which the image has discontinuities based on the abrupt changes in brightness. After through image interpolation, contrast bi-polarization and edge detection, the resulting image has higher sharpness which increases the sensitivity in calculating the displacement based on DIC.

In addition to the image processing, the second way to increase the precision in displacement calculated using DIC is to optimize the speckle pattern specially designed for the optical sensor. The numerically generated speckle pattern is characterized by the size of the speckle and its coverage over an image area with a size of 1mm×1mm occupied by the 30 × 30 pixels. Each speckle is identical throughout an entire pattern; however, needs to be distributed randomly, which is essential for a unique and correct displacement calculation based on correlation. The coverage is defined as the ratio of white/black pixels for per pattern. Different speckle size ranging from 1 pixel to 3 pixels and speckle patterns with a coverage between 10% and 70% as illustrated in figure 2 were examined and compared to assess the associated performance in optimal sensor displacement measurement. For a CMOS optical sensor with an array of 30 × 30, preliminary results show that the optimal speckle size is 1 pixel with a coverage ranging from 60% to 70%.

![Figure 2](image.png)

**Figure 2.** Different speckle size ranging from 1 pixel to 3 pixels and speckle patterns per pattern with a coverage between 10% and 70%.

5. **Performance assessments and applications**

The optical sensor was installed on the work table of a five-axis CNC machine which has a positioning accuracy less than 3 µm in both x and y axes. Figure 3 shows the work table with the optical sensor moves diagonally and stops at every 10 µm projected onto the x and y axes to measure the displacement in both x and y directions. The measurement repeats 10 times and the results are illustrated in figure 4. It shows that the accuracy in displacement and precision in percent error is less than 10 µm and 5%, respectively, along x-direction; but has accuracy and precision less than 20 µm and 10%, respectively along y-direction.
Figure 3. Displacement measurement setup: (a) Five-axis CNC machine; and (b) optical sensor and planed displacement measurement.

Figure 4. The displacement measured by optical sensors: (a) x-direction; (b) y-direction.
Monitoring the guideway straightness of a feed drive system is demonstrated as an application of the embedded optical sensor system. A custom made feed drive system which features its subsidiary guideway can be adjusted to simulate the guideway misalignment is used in this demonstration. The guideway straightness calculated by the proposed optical sensor sensing system is compared with that measured directly by the Renishaw XL-80 laser interferometer. Several speckle patterns were pasted near the guideway with a distance of 20cm between each other as illustrated in figure 5. The guideway straightness was measured while the work table with the embedded optical sensor was traveling on the guideway and stop at each speckle pattern for 1 second to capture the image of speckle patterns. The first image captured by the optical sensor at each speckle pattern is used as a reference in positioning, and the second image at the same position next time is used to determine the displacement relative to the first one according to DIC. Note that the measured displacement is two-dimensional, i.e. the displacement along y-direction is longitudinal whereas the x-direction is transverse as indicated in figure 5. The longitudinal displacement indicates the deviation in positioning, whereas the transverse one represents a sample in quantifying the rail way straightness. With several speckle patterns pasted along the y-direction, the rail way straightness can be determined with the transverse displacements, i.e. the x-direction, measured by the optical sensor at different positions of railway. The whole procedure in measuring the railway straightness is conducted automatically using a program in the CNC controller.

![Figure 5](image)

**Figure 5.** The guideway strightness monitoring system with embedded optical sensors.

To simulate the guideway misalignment, one end of the adjustable guideway of the custom-made feed drive system is pushed by a screw by 40 µm away from the bearing support away from the motor along the x- direction as shown in figure 5. The first captured image of each speckle pattern was used as reference when the work table is traveling away from the motor. Then the guideway was adjusted to deviate from 40 µm further to 80 µm and the second image of each speckle pattern was captured. Table 1 lists the linear guideway deviation along the x-direction measured respectively by the laser interferometer and the embedded optical sensor after the guideway is adjusted from 40 µm to 80 µm. Table 1 lists two measurement results for checking repeatability. It shows that the differences in both displacement measurements between the embedded optical sensor and those from laser interferometer were less than 5 µm. It is worthy of note that the carriage fixed under the work table forces the misaligned guideway back to its original position when the work table was moving. The original misalignment of 80 µm at the end of the bearing support of the guideway is forced to reduce to 4.8 µm. The experiment repeated again but the guideway is adjusted furthermore to 100 µm from 80 µm at the end of the bearing support. The displacement measured by the proposed sensing system and the laser interferometer is listed in table 2. It indicates that the differences in displacement measurements between the embedded optical sensor and those from laser interferometer were also less than 5 µm. It concludes that guideway misalignment can be monitored successfully by the proposed optical sensing system if the misalignment is larger than 5 µm.
Table 1. Linear guideway deviation measurements when subsidiary guideway is adjusted from 40 µm to 80 µm.

| Positioning (mm) | Laser interferometer (µm) | Optical sensor (µm) | Laser interferometer (µm) | Optical sensor (µm) |
|------------------|---------------------------|---------------------|---------------------------|---------------------|
| 100              | -1.6                      | 0                   | +0.5                      | +1                  |
| 200              | +1.4                      | 0                   | +3.0                      | 0                   |
| 300              | +0.9                      | +1                  | +2.9                      | +1                  |
| 400              | +3.0                      | +4                  | +6.7                      | +4                  |
| 500              | +4.8                      | +6                  | +6.5                      | +5                  |

Table 2. Linear guideway deviation measurements when subsidiary guideway is adjusted from 40 µm to 100 µm.

| Positioning (mm) | Laser interferometer (µm) | Optical sensor (µm) | Laser interferometer (µm) | Optical sensor (µm) |
|------------------|---------------------------|---------------------|---------------------------|---------------------|
| 100              | +1.7                      | +1                  | +1.9                      | 0                   |
| 200              | -0.3                      | 0                   | +3.0                      | 0                   |
| 300              | +1.2                      | +1                  | +4.0                      | +1                  |
| 400              | +8.6                      | +6                  | +4.9                      | +5                  |
| 500              | +7.4                      | +9                  | +8.3                      | +8                  |

6. Conclusions
A low-cost embedded optical sensor system based on optical mouse was proposed to monitor the linear guideway healthy status, i.e. linear guideway straightness. This proposed sensor system can measure the displacement in two orthogonal directions simultaneously, i.e. a two-dimensional displacement sensor based on digital image correlation. With the image enhancement technique and a custom-made speckle patterns printed using a standard low-cost monochrome laser printer, results show that this two-dimensional displacement sensor has a displacement resolution less than 5 µm. The linear guideway straightness can be on-line monitored with an accuracy within 5 µm as compared to that measured by the Renishaw XL-80 laser interferometer. With an accuracy within 5µm of this proposed embedded displacement sensing system, more industrial applications are under development.

Acknowledgments
This study was supported by the Ministry of Science and Technology, Taiwan, ROC (under Contract No. MOST 107-2634-F-194-001).

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