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TEMPERATURE-INDUCED ERROR IN LONG-TERM CONTINUOUS MONITORING OF DISPLACEMENT WITH VIDEOGRAMMETRY

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ABSTRACT

Videogrammetry has demonstrated great potential in structural health monitoring (SHM), and there has been sustained interest towards applying this non-contact technique in SHM. This paper focuses on the effect of temperature variation on the measurement accuracy of videogrammetry to examine its feasibility in deformation/displacement monitoring. A long-term indoor videogrammetric measurement test was conducted, and the performance of the videogrammetric displacement monitoring technique under ambient temperature was examined. The result showed that temperature variation does cause non-negligible errors which contain not only daily fluctuation pattern but also overall trend. In terms of daily fluctuation pattern, the horizontal measurement error and indoor air temperature are in satisfactory consistency, while the vertical measurement error are not. In terms of overall trend, the vertical measurement error is highly correlated with indoor air temperature, having a positive linear relationship between them. However, the horizontal one has a complicated pattern when temperature varies.

1 INTRODUCTION

Over the last few decades, the videogrammetric technique shows great potential in the field of civil engineering and it is being applied to an ever-increasing range of tasks (Baqersad et al. 2017; Dai et al. 2015; Jiang et al. 2008). Thanks to its non-contact nature, it has allowed for opportunities in monitoring displacements of civil structures. However, surrounding environment of this vision system will fluctuate significantly over a long time period, which may induce intolerable errors in the in-suit measurement result (Feng and Feng 2016, 2017; Lee et al. 2007; Park et al. 2015; Dai and Lu 2013). To date, a few studies have been reported in this regard and most of these studies focused on the temperature effect. On one hand, the dark current, which is a noise source intrinsic to the image sensor, is strongly temperature dependent (Widenhorn et al. 2002). On the other hand, temperature variations induce thermal deformation of the vision measurement system, resulting in changes in the intrinsic and extrinsic parameters of a camera and subsequently the virtual drifts of image (Yu et al. 2014; Zhou et al. 2017; Podbreznik and Potočnik 2012). Nevertheless, prior studies on the temperature effect are still very limit. Particularly, the videogrammetric measurement tests were conducted in air conditioned environments and lasted a short period of time only in these previous studies. The performance of the vision measurement system under varying ambient temperature, as is often the case in field monitoring, remains unexplored but critical.

This paper reports a data-driven approach to investigate the temperature effect on the videogrammetric technique under ambient temperature conditions, focusing mainly on the feature extraction of the temperature-induced measurement error. First, a long-term videogrammetric measurement test, which lasted intermittently for more two and a half months, was carried out in indoor environment so as to shield off other environmental factors. Meanwhile, indoor air temperature was

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recorded. Making use of the long-term measurement data, the characteristics of the displacement measurement errors were then examined. The measurement error refers to the difference between the true value of the displacement of a monitoring target and its corresponding value measured from a vision measurement system. Correlation analysis between the displacement measurement errors and indoor air temperature was performed to clarify the relationship between them. Finally, making use of the identified features of the temperature-induced measurement error, the possible means to eliminate the error was discussed in the context of the deformation monitoring of a civil structure.

2 EXPERIMENTAL SETUP

As illustrated in Figure 1, the videogrammetric measurement system comprised an monochrome 1/2″ CDD with a resolution of 1024×1024 pixels, a 12×zoom lens, and a laptop computer. To minimize the uncertainties caused by the tripod from creep deformation, the zoom lens as well as camera was placed on an invariable-alloy optical platform. In order to enable the measurement in both day and night, a total of five LEDs were fixed on a target panel of 500×500 mm^2 which was mounted on a support made of invariable alloy. The measured distance was about 80 m, which was closed to the distance in most in-suit videogrammetric tests. With a thermal expansion coefficient of $1.6\times10^{-6}/^{o}C$, the thermal expansion of the platform and support could be ignored. To determine the measurement error, it is necessary to collect the true value of the displacement of the target. To simplify the test, the target panel was fixed, whose true displacement could be thought of as zero. Correspondingly, its displacement measured by the vision system is namely the displacement measurement error. With help of the digital image processing software of *Metron*, the real-time displacement of targets can be measured. The optical axis was adjusted to be perpendicular to the monitoring plane. Therefore, the camera could be calibrated using the scale factor approach. After the calibration, the digital camera worked uninterruptedly at a frame rate of 1 fps.

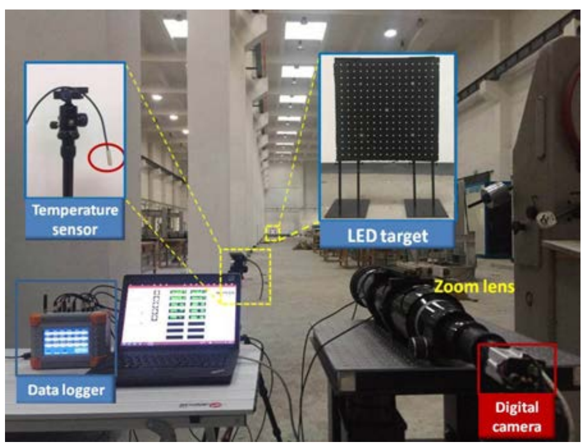
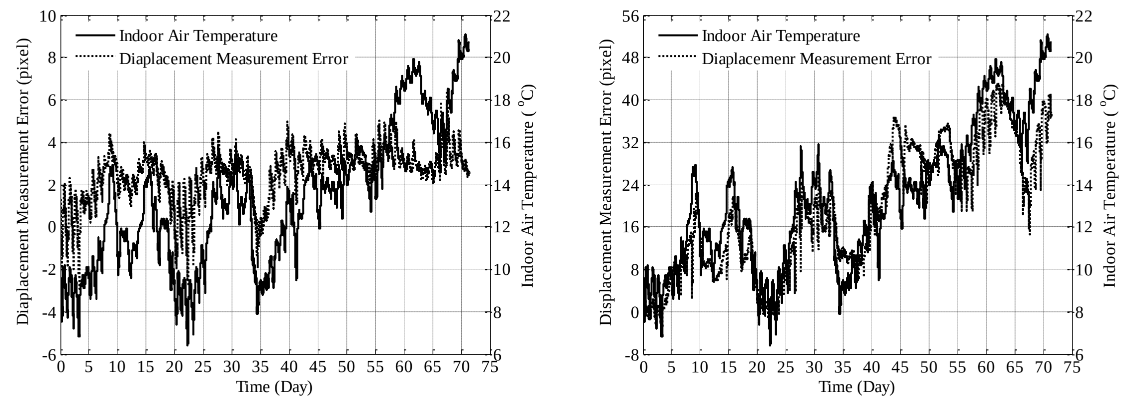


Figure 1: Experimental setup.

3 EXPERIMENTAL RESULTS

A total of 1,713-hour continuous measurement data were obtained. No notable differences were observed between the displacements of the five targets. With reference to the displacement of the central target, the maximum difference in average is 0.09 and 0.18 pixels in the horizontal and vertical directions. Figure 2 shows the indoor air temperature, displacement of central target in the horizontal and vertical directions measured by the vision measurement system respectively, which was averaged every 1 min and was deducted by the mean displacement at 0 o'clock sharp on the first day of test (zero reference). Time lag between the indoor air temperature and measurement displacement was eliminated according to the maximum correlation coefficient after time shifting. The air temperature fluctuated on the range of 6.4~21.1 ^{o}C, and the ranges of the horizontal and vertical measurement errors were 8.64 pixels (-

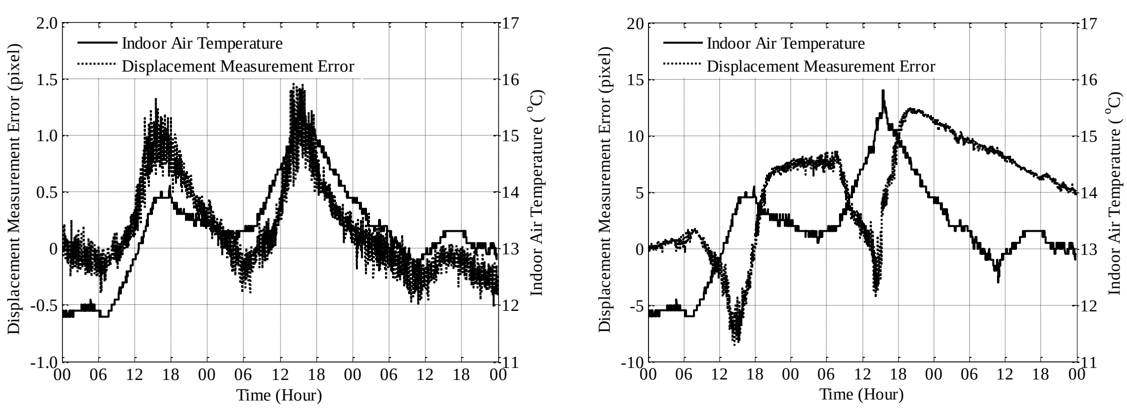
2.93~5.71 pixels) and 46.20 pixels (-3.05~43.15 pixels), respectively. Significant differences in the magnitudes of the measurement errors in the horizontal and vertical directions have also been observed in prior studies (Yu et al. 2014; Adamczyk et al 2018; Daakir et al. 2019). Nevertheless, the reason behind is not known yet. The difference in the magnitudes of the vertical and horizontal measurement errors might be ascribed to the difference of the movements of the CCD chip along the two directions as a result of the non-uniform thermal deformation of the support of the CCD chip. Future work is still needed to reveal the interior effects of the camera.



(a) horizontal (b) vertical

Figure 2: Indoor air temperature and displacement of central target.

As seen in Figure 2, the vertical measurement error coincided well with the indoor air temperature in terms of the overall trend. It therefore substantiated that the vertical measurement error is an outcome mainly attributed to the thermal actions of the vision measurement system. In the first 42 days, in which the trend component of the indoor air temperature maintained almost stationary, the variation of horizontal measurement error similarly coincided well with the change in indoor air temperature thanks to the perfect consistency in their daily fluctuation patterns. After Day 42, the trend component of the indoor air temperature presented an overall ascending trend. Nevertheless, the horizontal measurement error in this period showed no obvious trend except for the daily fluctuation pattern. As a result, the horizontal measurement error commenced to deviate far from the indoor air temperature after Day 42.

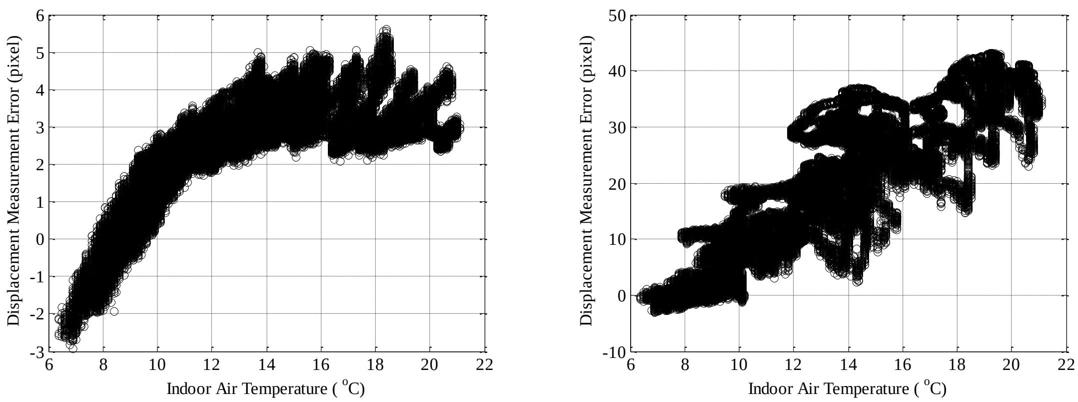


(a) horizontal (b) vertical

Figure 3: Measurement errors and indoor air temperature from Day 26 to Day 29.

In addition to the trend component, it was also observed that the displacement measurement errors present daily fluctuation patterns. In terms of a long time scale, the daily fluctuation pattern is detectable in the horizontal measurement error, while it is unapparent in the vertical measurement error. Figure 3 zooms in the displacement measurement errors and indoor air temperature from Day 26 to Day 29. Obvious daily fluctuation patterns are detected in both horizontal and vertical measurement errors. In terms of the horizontal measurement error, it varies almost in step with the indoor air temperature. Namely, it increases as the temperature rises and decreases as the temperature drops. As a result, its daily fluctuation pattern is nearly the same as that of the indoor air temperature. As mentioned earlier, not only the support of the target panel but also the support of the vision measurement system has negligible thermal expansion. It is therefore concluded that the horizontal measurement error is an outcome mainly attributed to the thermal actions of the vision measurement system.

As far as the vertical measurement error is concerned, it does present a daily fluctuation pattern as well. Nevertheless, its daily fluctuation pattern is much more complicated. Roughly speaking, it decreases as the temperature rises around 7 to 15 o'clock. Then, it rebounds rapidly, usually in no more than 4 hours. After that, it decreases again as the temperature drops till 7 o'clock the second day. In other words, the rise in temperature may lead to either the decrease or the increase in the vertical measurement error and vice versa. Though the daily fluctuation pattern of the vertical measurement error differs significantly from that of the indoor air temperature, it may also be attributed to an outcome of the thermal actions of the vision measurement system as both of them have the same period of 24 hours. In this sense, it seems that the effects of temperature variation on the vertical measurement error are complicated. As it was stated in previous studies (Handel 2009; Yu et al. 2014), not only the thermal expansion of the mechanical components of a digital camera but also the temperature-induced change in the refractive index of the lens optical material contributes to the image drift, which possibly makes the effects of temperature variation on the vertical measurement error complex and intricate.



(a) horizontal (b) vertical

Figure 4: Displacement measurement error vs. indoor air temperature.

To gain an intuitive understanding of the relationship between measurement error and temperature, Figure 4 shows the displacement measurement error vs. the indoor air temperature. As illustrated in Figure 4(a), the curve can be divided into three segments with two turning points ($11\,^{o}$C and $15\,^{o}$C) . In the first segment, there is satisfactory relationship between horizontal displacement measurement error and indoor air temperature. Namely, the horizontal measurement error increases proportionally to the indoor air temperature, which is mainly attributed to the perfect consistency in their periodic pattern as shown in Figure 2(a). In the second segment, it begin to deviate slightly from the first segment accompanied by a reduction in the inclination. Roughly, the slope of first segment is about two times to the counterpart in second segment. When the temperature exceeds around $15\,^{o}$C (second point), the inclination of the curve approaches to zero. After that, the horizontal measurement error fluctuates in a small range only regardless of the significant increase in the indoor air temperature. In this segment, the fluctuation of horizontal measurement error is dominated by the periodic component rather than the trend component in the indoor air temperature.

In contrast, the vertical measurement error and indoor air temperature generally conforms to a favorable linear relationship in the whole temperature range. Recalling the satisfactory consistency in the overall trends between the vertical measurement error and indoor air temperature, it is therefore concluded that the trend component of the temperature variation dominates the variation of the vertical measurement error. Meanwhile, the complicated daily fluctuation pattern of the vertical measurement error increases the discreteness. The correlation coefficients between indoor air temperature and vertical measurement error reaches about 0.9, which demonstrates again the great relationship between the vertical measurement error and indoor air temperature.

4 DISCUSSION AND CONCLUSION

In the long-term deformation monitoring of civil engineering structures, the relationship between measurement errors and indoor air temperature can be used to eliminate the temperature-induced measurement error. In terms of monitoring high-rise buildings, we mainly focus on the horizontal displacement. As shown in Figure 4(a), the horizontal measurement error could be defined in an acceptable range (1.97–5.71 pixel), provided that the air temperature exceeds a certain value (about 15 ^{o}C). In this case, assuming a field of view of 1000×1000 mm^2 parallel to the image plane, the horizontal measurement error in the absolute sense is 3.65 mm, which is an acceptable error for displacement monitoring of high-rise buildings. Furthermore, the field of view is usually smaller in the field monitoring. Thereby, the horizontal measurement error may be further decreased. Therefore, it is more suitable for inspectors to conduct in-situ horizontal displacement monitoring tests when surrounding air temperature can be maintained beyond 15 ^{o}C.

In terms of long-span bridges, its vertical displacement would be concerned. Formulating linear correlation model may be used to predict and subtract the vertical measurement error, given the satisfactory linear relationship between the air temperature and vertical measurement error. However, it is also noted that the rise in temperature may lead to either the decrease or the increase in the vertical measurement error and vice versa. As a result, the linear correlation model has only the possibility to subtract the trend measurement error, but leaving periodic component which also has a non-negligible value. In order to achieve a higher precision, more feasible methods should be considered in future works, such as time-frequency domain approach and time series analysis, to compensate for the temperature-induced vertical measurement error.

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