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Vision-based sensing for structural health monitoring: Displacement errors in an outdoor context

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Abstract. Digital Image Correlation (DIC) is a well-established technology in the realm of indoor, small-scale experimental materials testing. Apart from short-term measurements, however, it is yet to be demonstrated outdoors for long-term monitoring of full-scale structures and has not been deployed for Structural Health Monitoring (SHM). This study investigates errors in DIC measurements in an outdoor context through an exploratory experimental campaign. Firstly, the errors in the displacement of various fixed control points were measured. Beyond displacement measurements, camera stability (i.e., camera pitch, roll, and yaw) and environmental parameters (i.e., luminosity, humidity, temperature) are also monitored simultaneously. The study found that: a) the effect of camera stability was of major significance to the displacement errors; b) the temperature parameter was hypothesised to be a potential cause of displacement errors since it has a common periodicity with all the error measurements and physical rotations/movements of the camera; and c) the employment of camera stability and environmental sensors could improve the DIC data robustness. These findings are promising, demonstrating the causes of errors in DIC measurements and potential avenues for improving the overall robustness of DIC for its employment in SHM.

1 INTRODUCTION

Digital Image Correlation (DIC) is commonly employed for short-term measurements however, it has not yet been deployed for long-term monitoring campaigns (i.e., weeks of monitoring) [1-3]. Reasons for this are associated with the inherent limitations of the technique. Practical limitations exist such as that of storing its voluminous data produced over long terms and tackling the security risks associated with leaving the equipment on-site for a long time. Another major limitation is the loss of monitoring robustness due to variations in camera stability and environmental factors, over time.

This study is focused on the camera stability and environmental parameters that affect DIC. The lack of camera stability or change in the camera position can induce errors in the photogrammetric process due to altering the camera position from those of the initial calibration. The variation in lighting and air properties within the monitored specimen and camera leads to the DIC system misinterpreting structural change, leading to measurement errors. Owing to the novelty of the DIC technique and the prohibitive cost of overcoming the above limitations, both a few real-world industrial applications and academic studies can be found involving the long-term employment of DIC.

DIC sources of error can be categorised according to the following components, according to Reu [4]: a) experimental setup (e.g., lens distortion, camera motion, sample motion, air turbulence, image blur and system resolution); b) image acquisition (e.g., noise, contrast, speckle size and aliasing); c) image correlation; 2D position, motion and strain (e.g., filtering, strain and displacement error calculation).

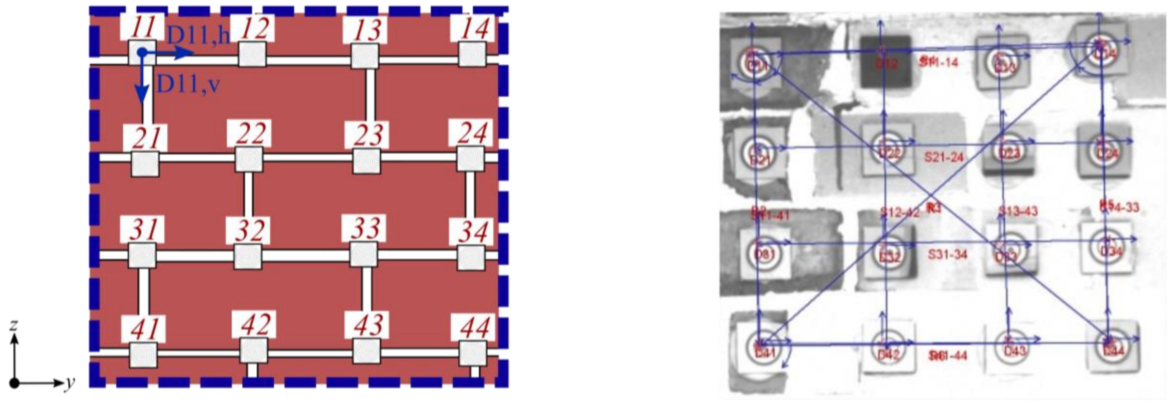
Whilst many studies are on the errors of the correlation and processing phases, not many investigations exist on the actual physical setup and image acquisition. Even then, such studies in the general field of SHM are lacking, and mostly limited to the field of extensometry, within laboratory conditions. For instance, Reu [4] provided an error budget based on empirical and experimental information for the extensometry use of DIC. The author also demonstrated the effect of heat-induced camera distortion for various cameras, demonstrating the effectivity of cooled cameras on reducing this effect. However, little is known about the effect of camera movements and the environment in DIC, especially in an outdoor context (similar to that of an SHM campaign). Based on this, the present study assessed the influence of camera stability and environmental parameters on the accuracy of DIC measurements through an exploratory experiment.

Firstly, a dataset was acquired with various sensors. Then, the displacement errors are presented. Then, to understand the effect of camera stability on the measurement errors, the correlation between displacement error and camera stability parameters is investigated. Finally, to effect of environmental stability on the measurement errors, the correlation between displacement error and environmental parameters is investigated. The structure of this paper is as follows: Section 2 details the employed methodology including the employed instrumentation; Section 3 presents the study's results; and Section 4 presents the study's conclusions.

2 METHODOLOGY

This Section presents the methodology for acquiring and quantifying the robustness of the DIC measurements. To quantify the effects of environment and camera stability, various static points on a wall were monitored for in-plane displacements, as illustrated in Figure 1. The displacements of these were monitored according to the y, and z-axis coordinates of the same figure and represent displacement errors across the camera's field of view. Indicatively, the horizontal and vertical displacements of the control point 11 would be $D11_{,\ h}$ and $D11_{,\ v}$ accordingly of Figure 1. It is to be noted that the nomenclature chosen is analogous to the indexing of a 4x4 array. Thus, the field of view is subdivided into 16 regions, with each region having a corresponding erroneous. These are employed to identify whether displacement errors are common (i.e., homogenous) or dissimilar (i.e., localised) across the field of view. This is employed because according to the literature [4], it is well known that camera motion-induced displacements are homogenous, and heat-induced displacements are localised (radial). Little is known about the environment; however, they are assumed to be non-homogeneous. Thus, by checking the homogeneity of the displacements, insight into the source of the displacement error be found.

Then, the basic logic is that any deviation of the control displacement values from zero is a measurement error. This can be solely attributed to the effect of the camera stability and environment since there is no actual movement of the specimen. It is also to be noted here that in addition to the displacement, also roll of the camera was measured (i.e., rotation within the z-y axis), herein termed DIC roll. Finally, at the same time, camera stability and environmental parameters are monitored. After, the data is checked for correlations. Where significant correlations are found, they are inspected, and their potential source is determined.



(a) (b)

Figure 1: View of the specimen and monitored points: (a) schematic; and (b) in VideoGauge.

2.1 Instrumentation

The instrumentation of the experiment consisted of a commercial DIC system in conjunction with environmental and camera stability sensors. These are detailed in the following paragraphs.

The DIC system was a single-camera setup enclosed in a steel container, with a glass observation panel, as demonstrated in Figure 2. The camera was an *Allied Vision Camera 034* [6] whilst the lens was consumer-grade with a focal length of 300 mm. To ensure a stable position, the camera was mounted on a gear-head mount. This was attached to a rigid aluminium frame which was, in turn, bolted to concrete blocks beneath it. The whole assembly of the steel enclosure is herein termed, the primary sensor unit.

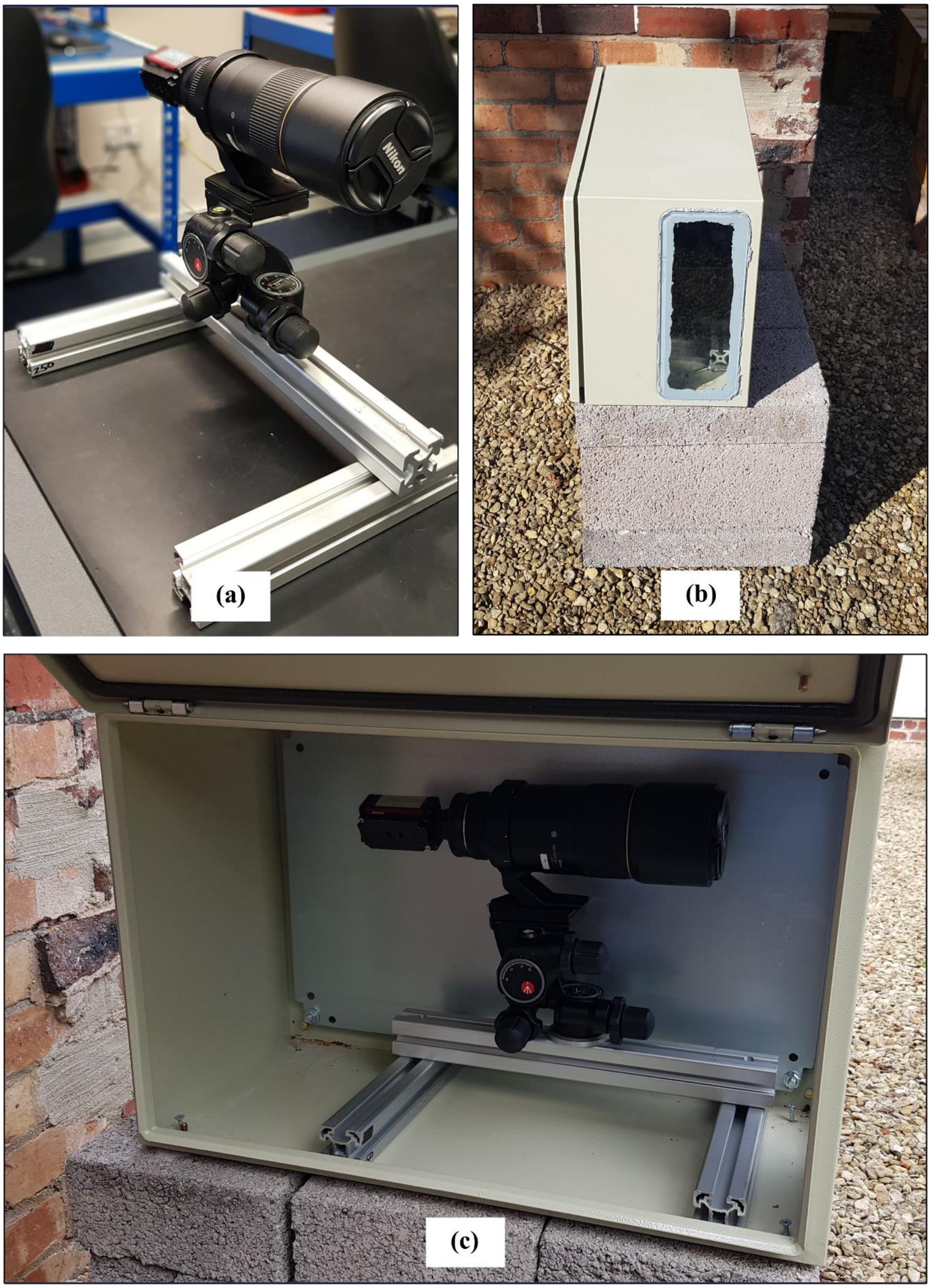

Nikon
(a)
(b)
(c)

Figure 2: Setup of primary sensory unit: (a) camera mounted on the stable rig; (b) steel enclosure with observation window; and (c) camera rig mounted inside steel enclosure.

To monitor the environmental and camera stability parameters, two types of sensors were employed in conjunction with an *Arduino Nano 33* [7] microcontroller. The environmental parameters were acquired with two *Fermion environmental sensors* [8] whilst the camera stability/ vibration parameters were obtained via two *Murata SCL3300-D01-PCB* MEMS inclinometers [9] and *ADXL 355* MEMS accelerometers [10].

3 RESULTS

Firstly, the displacement errors are presented. Then, to understand the effect of camera stability on the measurement errors, the correlation between displacement error and camera stability parameters is investigated. Finally, to the effect of environmental stability on the measurement errors, the correlation between displacement error and environmental parameters is investigated.

3.1 Displacement errors

Figure 3a-b displays the long-time series of horizontal and vertical displacements for the monitored period. From Figure 3a-b it can be observed that both the horizontal and vertical displacement errors are of a similar magnitude and periodicity across the image field. This homogeneity between the displacement errors leads to the hypothesis that they have a common source and are potentially due to camera movement.

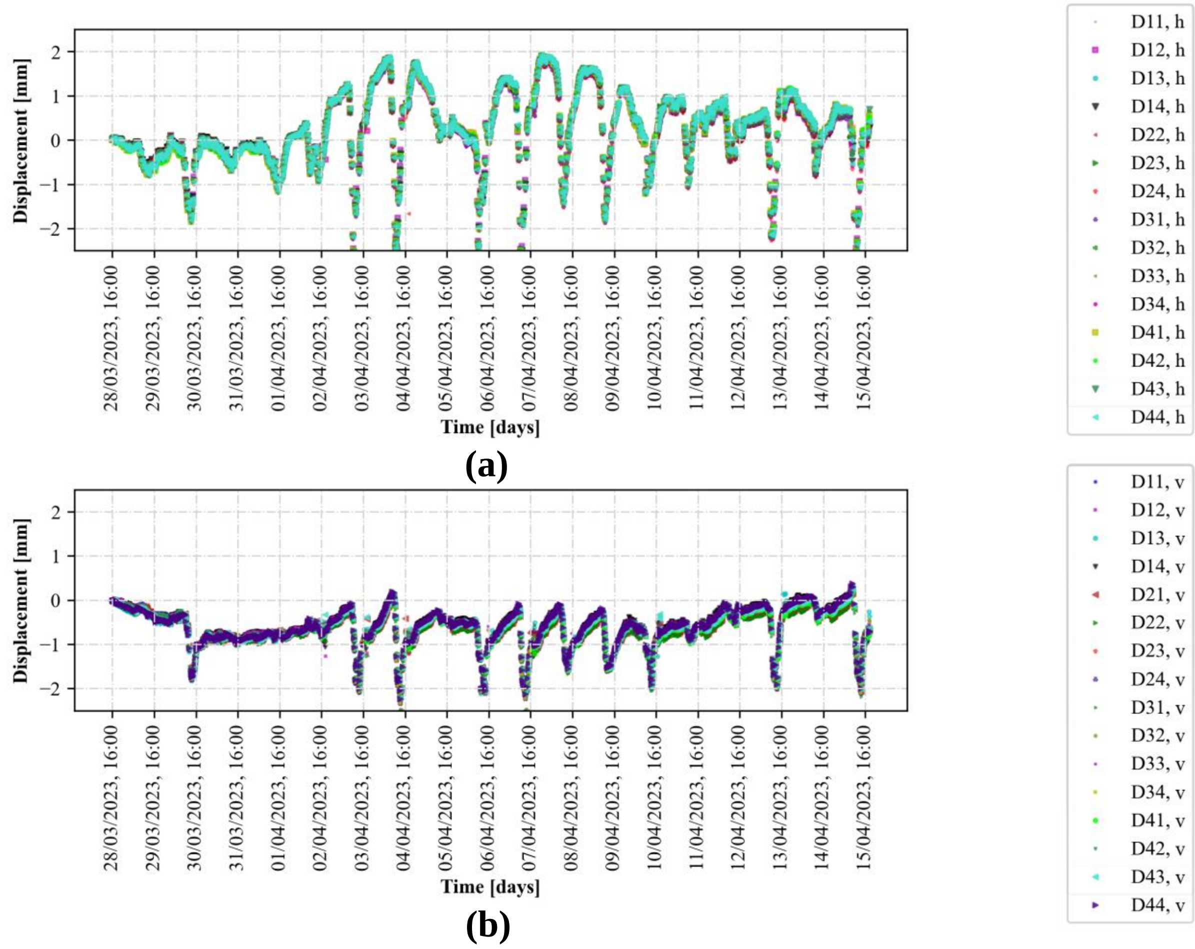


Figure 3: Displacement errors: (a) horizontal; and (b) vertical

3.2 Correlation between camera stability and displacement errors

From the previous Section, it was found that the displacements were potentially due to camera motion owing to their homogeneity. To investigate this, various camera stability parameters were correlated with the measurement errors. One strong correlation was found, with a coefficient of correlation equal to 0.94. Namely, of all the camera stability parameters, the rotations of DIC (DIC roll) were found to be in good agreement with the contact-based sensor (MEMS roll). This leads to the hypothesis that an important source of the displacement error was camera movement (i.e., camera yaw and then pitch). This finding reinforces previous studies' findings that the effect of camera stability is potentially of major significance to displacement errors [4].

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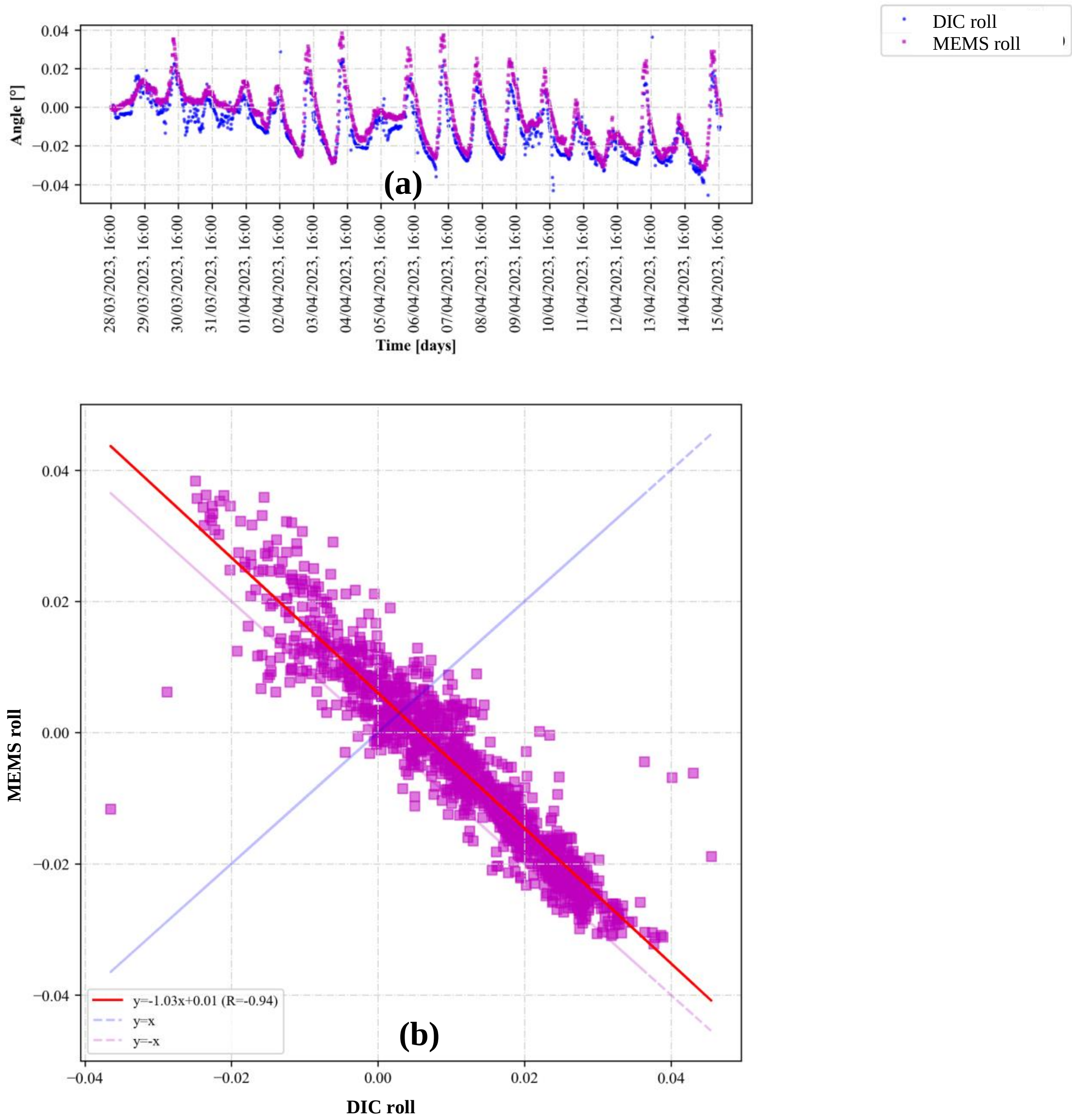

Figure 4: DIC-based roll vs. contact-based roll values: (a) time-series superimposed; and (b) correlation.

3.3 Correlation between environmental parameters and displacement errors

Investigating the various environmental parameters, only one, however not very strong correlation was found, with a coefficient of correlation equal to 0.70. Figure 5a-b displays characteristic horizontal and vertical displacement errors alongside reversed temperature, plotted on a twinned axis. From Figure 5, it can be observed the periodicity in both curves is very similar, leading to the hypothesis that temperature is another potential source of erroneous measurement. Without further investigation, temperature was hypothesised to be a potential indirect cause of displacement errors since it has a common diurnal periodicity with all the error measurements. It is furthermore considered to indirectly cause measurement errors due to being associated with three items: a) camera stability (e.g., the temperature-induced motion of the camera's gear-head mount); b) environmental change (e.g., humidity), and c) camera lens heat-induced deformation, according to [4]. This is also in agreement with a previous study by the Authors of this study [11].

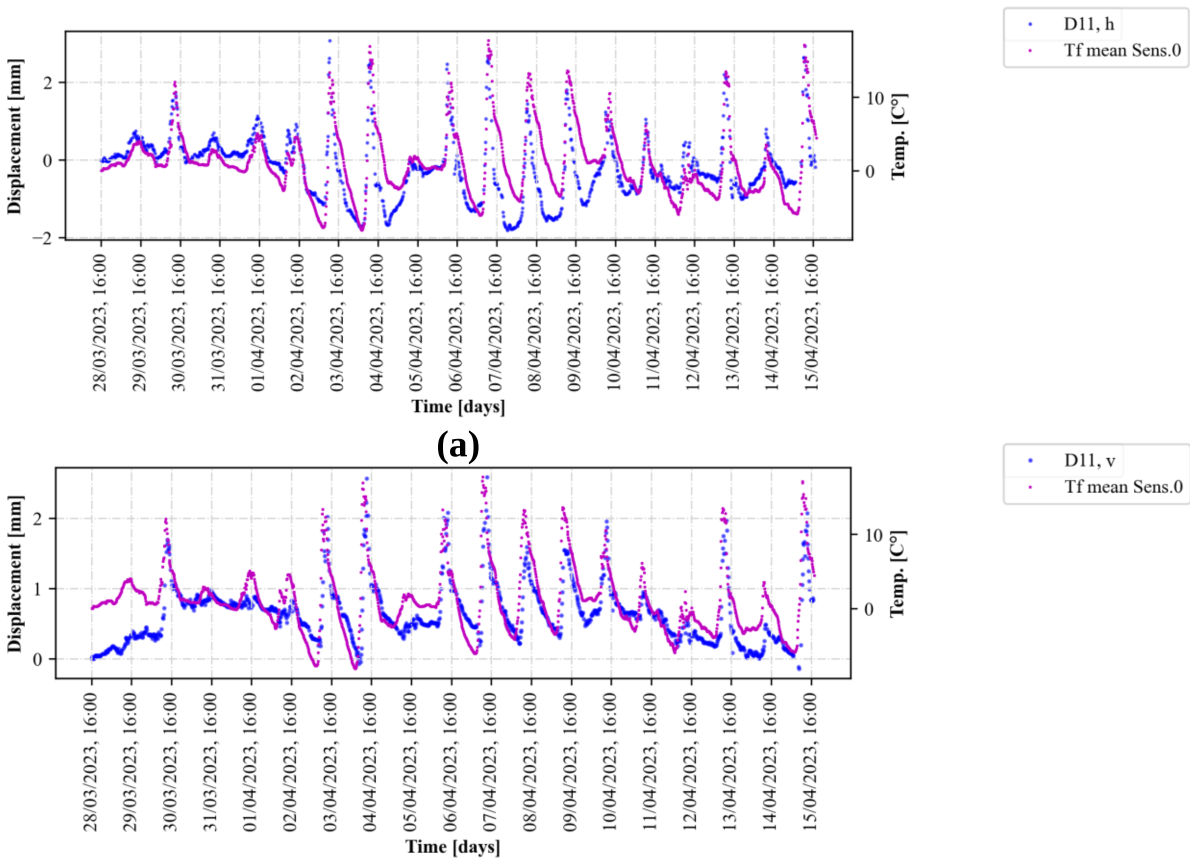

Figure 5: Displacement errors vs. temperature: (a) horizontal; (b) vertical

4 CONCLUSIONS

This study investigated displacement errors of DIC in an outdoor context through an exploratory experimental campaign. Firstly, the displacements of various fixed control points were measured, termed displacement error since they should be equal to zero. Apart from displacement errors, an array of camera stability (i.e., camera pitch, roll, and yaw) and environmental parameters (i.e., luminosity, humidity, temperature) were monitored simultaneously. From the study, the following were found:

- Both the horizontal and vertical displacement errors were of a similar magnitude and periodicity across the image field. This homogeneity between the displacement errors led to the idea that they have a common source;

- Owing to the homogeneity between the displacement errors, camera stability was hypothesised to be the main source of the displacement errors (i.e., camera yaw and then pitch);
- Temperature was hypothesised to also be a potential indirect cause of displacement errors since it had a common diurnal periodicity with all the error measurements;
- Temperature was furthermore considered to indirectly cause measurement errors via the following three items: a) camera stability (e.g., the temperature-induced motion of the camera's gear-head mount); b) environmental change (e.g., humidity), and c) camera lens heat-induced deformation, according to [4];
- Owing to the above, it is considered that the employment of camera stability and environmental sensors could significantly improve the DIC data robustness.

These findings are promising, demonstrating potential causes of errors in DIC measurements and avenues for improving the overall robustness of DIC. This could pave the way for its employment in SHM, such as bridge monitoring applications. A future study will be carried out employing higher accuracy third-party sensors to not only investigate the effect of stability on displacement errors in DIC but to also counteract for it.

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