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Employing vision-based sensing for long-term monitoring

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Abstract
Despite the crucial role of structural health monitoring (SHM), traditional approaches rely on contact-based sensors which are both costly and lack automation. Vision-based sensing techniques such as Digital Image Correlation (DIC) have recently emerged as a viable substitute, due to their non-contact nature and low cost. To date, however, the long-term performance of DIC has not been evaluated. This study assesses DIC for long-term displacement monitoring. Firstly, the robustness of the monitoring of ambiently excited structures over long periods is examined. This is achieved through the measurement of drift of control points. Then, correlation is examined between the drift measurements and the ambient temperature, to examine the influence of temperature on the robustness of the DIC measurements. After, the effectiveness of employing DIC for monitoring ambiently excited structures is examined. Towards this aim, the displacements of the midspan of the experimental bridge structure are monitored for one month and compared with those of a traditional contact-based sensor, i.e., a Linear Variance Displacement Transducer (LVDT). Finally, to further demonstrate the effectiveness of employing DIC measurements for ambiently excited structures, a correlation is sought between the midspan displacements and the ambient temperature. Concerning the robustness of the long-term DIC measurements, the drift was found to be relatively small (i.e., equal to 0.06 mm) whilst the temperature was found to potentially influence this. With regard to the overall effectiveness of long-term monitoring with DIC, the study found that non-contact sensing has comparable accuracy to the LVDT, with a correlation coefficient equal to 0.996, root mean square error of 0.012 mm, and mean absolute error of 0.010 mm. Moreover, the correlation of DIC measurements with temperature showed its effectiveness in capturing complex structural behaviours (e.g., extremely slow and small movements) typically associated with ambiently excited structures. Whilst this study is only on a small-scale structure, it paves the way for the employment of vision-based on large-scale structures enabling the general use of DIC for SHM.
Keywords: SHM, vision-based monitoring, ML models

1 Introduction

Structural Health Monitoring (SHM) is of the most effective and advanced approaches available for the safety assessment of civil engineering structures. Brownjohn [1] defines SHM as the implementation of a scheme of monitoring a structure, through periodically spaced dynamic response measurements. Moreover, Catbas [2], defines SHM as observing a structure's deviations from *'a sound condition'* due to damage. Consequently, it can be employed to detect deterioration and indicate when a given structure would warrant repair, retrofit or strengthening.

Despite the advances in SHM, it is mostly employed for exotic structures [3]. For instance, short-to-medium span bridges which constitute most of the world's bridge stock do not benefit from SHM. As a result, the failure of such structures is becoming more common, especially due to ageing, the extreme climatic events and the discrepancies between design and actual loads (e.g., increased traffic loads and density)[3]. The main difficulties in deploying SHM for civil structures are the cost of traditional contact-based SHM sensors and the complexity of interpreting SHM data. Additionally, according to Brownjohn, et al. [4], further challenges include: the unwillingness of asset owners and design engineers to take the liability of SHM data (in the case of damage necessitating remediation); the uniqueness of each civil structure (which often warrants a unique SHM system for each structure) and, at the present, there is not a reliable methodology for damage detection and prediction.

This study is primarily aimed at the first difficulty in the application of SHM. Specifically, traditional instrumentation of assets is costly and burdensome, involving the employment of contact-based sensors, such as strain gauges, accelerometers, and Linear Variance Displacement Transducers (LVDTs). Such devices are electrical, and function by converting mechanical movement into an electrical signal at a very high frequency and accuracy. However, such devices suffer from the same limitations: a) they are point-based, meaning their measurement is limited to a single discrete point, b) they have a costly installation (the cost of installation including gaining access to the asset with scaffolding etc. may exceed the sensory costs by various magnitudes)[3]. Nowadays, non-contact sensing techniques have emerged as suitable counterparts to traditional contact-based sensors. An array of such sensing techniques exists, which may be laser tracking, terrestrial laser scanning (TLS), Structure-from-motion (SfM) photogrammetry, laser vibrometers, and Digital Image Correlation (DIC)[3]. Of interest to this study is the DIC, which functions by calculating differences in the pixels of digital imagery over time to infer displacement of the monitored structure. DIC is particularly advantageous in comparison with contact-based sensors due to its low cost both of sensors and installation, and its ability to monitor multiple points simultaneously at an extremely high resolution (which is application-specific).

DIC has a proven effectiveness for short-term measurements, however, it has not been employed for long-term monitoring campaigns exceeding several weeks[5]. This is a major shortcoming in deploying DIC for SHM. This is in part a result of the inherent limitations of the technique, such as the challenges of storing its voluminous data produced over the long-term (since video files are recorded), the security risks associated with leaving the equipment on-site long-term and the sensitivity to environmental parameters[5].

Of particular interest to this study are the latter environmental parameters, such as temperature and lighting which have been shown to negatively influence the robustness of the DIC measurements [6]. This happens due to the camera's position changing the image scene (e.g., movements due to the tripod heating up) as well as the properties of the air which affect the light reaching the camera itself. This in turn leads to the DIC system misinterpreting actual structural change when in fact only the camera's calibration or perception of the structure has changed. Owing to these limitations, both few real-world industrial applications and academic studies can be found involving the long-term employment of DIC.

Whilst some pioneering studies have employed DIC over long periods for monitoring [5,7-10], none have investigated the robustness of the method. Given this necessity, this study assesses DIC for long-term displacement monitoring. Firstly, the robustness of the monitoring of ambiently excited structures over long periods is examined. This is achieved through the measurement of drift levels of control points. Then, correlation is examined between the drift measurements and the ambient temperature, to examine the influence of temperature on the robustness of the DIC measurements. After, the effectiveness of employing DIC for monitoring ambiently excited structures is examined. Towards this aim, the displacements of the midspan of the experimental bridge structure are monitored for one month and compared with those of a traditional contact-based sensor, i.e., an LVDT. Finally, to further demonstrate the effectiveness of employing DIC measurements for ambiently excited structures, a correlation is sought between the midspan displacements and the ambient temperature.

The structure of this paper is as follows: Section 2 presents the experimental structure subject to monitoring; Sections 3 and 4 detail the instrumentation and methodology employed respectively; Section 5 presents the study's results; and Section 6 summarises the study's conclusions.

2 Experimental structure: "*Copper bridge*"

This study considered a simple bridge composed of a copper beam resting on supports resembling pinned supports as shown in Figure 1. All the properties of the bridge are found in Table 1.

Figure 1: Experimental structure: "*Copper bridge*".

Table 1: Characteristics of "*Copper bridge*".

Material	Modulus of elasticity [GPa]	Density [kg/m^3]	Span [mm]	Width [mm]	Thickness [mm]
Copper	117	8960	880	20	4

The choice of this specific structure was based on the literature regarding experimental SHM studies with physical models [11-13]. Furthermore, the structure's simplicity and resemblance to a simply supported bridge, commonly found on the UK rail and highway network were considered advantageous, since it resembles are real-world data acquisition campaign.

3 Instrumentation

The core instrumentation comprised of the DIC-based displacement measurements employing *Imetrum VideoGauge*. This included a dual-camera system mounted on a tripod with the addition of an LED light (as shown in Figure 2a). The dual camera was selected, as it is a pre-calibrated system that is capable of capturing three-dimensional motion. To reduce the influence of external lighting, a cloth was placed to cover the bridge, whilst an LED light was employed to provide constant diurnal and nocturnal lighting (as shown in Figure 2b). Additionally, an LVDT was employed to control the reliability of the DIC displacement measurements (as shown in Figure 2c). This consisted of a *Vishay HS10* [14], with a nominal stroke equal to 11.2 mm, a volt sensitivity equal to 5.3 mV/mm and a non-linearity equal to 0.5% of the nominal stroke. Also, to understand the influence of temperature, a thermal logger was, mounted on the structure. As such, during all the monitoring campaigns, the temperature of the beam was logged employing an *Arduino Uno* micro-computer in conjunction with a *DS18B20* [15] digital thermal logger. Finally, a *National Instruments BNC2010* data logger was employed to convert the analogue data and fuse it with that of the DIC software. It is important to note that the rig, LVDT and the beam were all aligned with the use of a spirit-level to ensure vertical measurements (as shown in Figure 2d-f).

Regarding the monitored points, the midspan of the bridge was monitored for in-plane displacements, as illustrated in Figure 3. Also, a further two fixed points were monitored on the walls to evaluate potential drift in the DIC-based measurements, not related to movement. Regarding the selection of DIC measurements, DIC_{actial_LVDT} is employed to monitor the actual midspan displacement. The logic is to measure the displacement of the same point from the LVDT and DIC and then, examine the difference in the values for a good agreement. $DICcont._{x}$, $DICcont._{y}$, $DICcont._{diag.}$ are control measurements (between static points) to monitor the influence of environmental parameters (in this case temperature) on the robustness of the DIC measurements. Here the logic is that any displacement observed of $DICcont._{x}$, $DICcont._{y}$, $DICcont._{d.}$ will be solely attributed to drift since there is no actual movement. It is important to note that here that within the context of this study, drift is defined as anomalous deviation of the DIC measurement, associated with three factors: a) movement of the camera (e.g., change of its position due to thermal expansion of tripod); b) air humidity changing according to temperature; and c) changes in the lighting of the image scene (e.g., the appearance of direct sunlight).

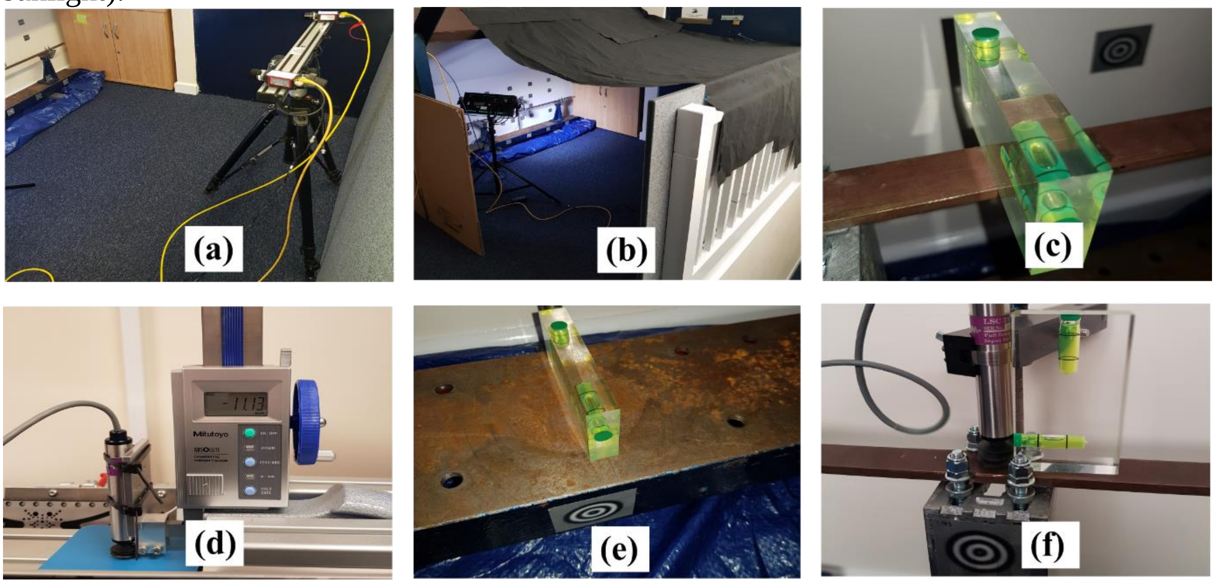

Figure 2: Instrumentation and experimental setup: (a) PDT camera system; (b) artificial lighting and direct sunlight masking; (c) alignment of the copper beam; (d) calibration of LVDT within calibration rig; (e) alignment of the experimental rig; and (f) alignment of LVDT.

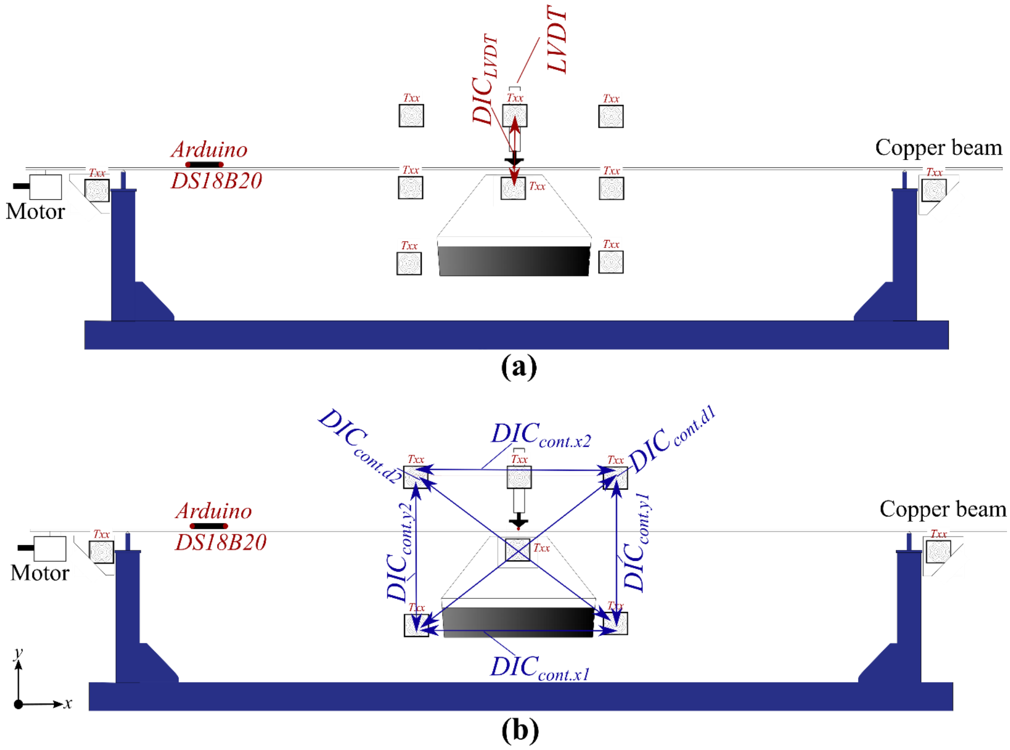

Figure 3: Instrumentation and monitored points: (a) Thermal logger, LVDT and DIC measurements' location; and (b) DIC control measurement locations.

4 Methodology

The test herein described consisted in monitoring the bridge's displacement subject to ambient changes. Specifically, the effect of the change of mass on the midspan of the bridge was monitored (e.g., evaporated water from a container placed at the midspan). To achieve this, the container was filled with half a litre of water and then the movement of observed for one month. One-minute recordings were carried out per quarter-hour resulting in 96 minutes of monitoring data per day. Regarding loading, the experiment is considered quasi-static, since the evolution of load is in a very slow fashion (as demonstrated in the forthcoming paragraphs, circa 0.10 to 0.20 mm per week). Thus, each time series was averaged into a singular one-dimensional vector, representing the displacement of the according quarter-hour time-step and plotted. It is also to be noted that for all the measurements, an outlier detection scheme was also employed (using the DBSCAN [16] clustering algorithm) to distinguish anomalous monitoring values from normal ones. Thus, all measurements are separated into two classes: a) normal, termed "All points"; and b) abnormal, termed "Class -1"

5 Results

5.1 Drift measurements

To understand the robustness of the DIC measurements, the drift in the horizontal, vertical and diagonal control displacements are presented in Figure 4 respectively. From Figure 4, the following can be understood: a) all the control measurements appear to have a periodicity, similar to that of the temperature variation; and b) there were common non-periodic outliers present in all the measurements, with a maximum magnitude equal to 0.10 mm; and c) the overall value of drift was relatively small, and with the range of -0.05 to 0.05 mm.

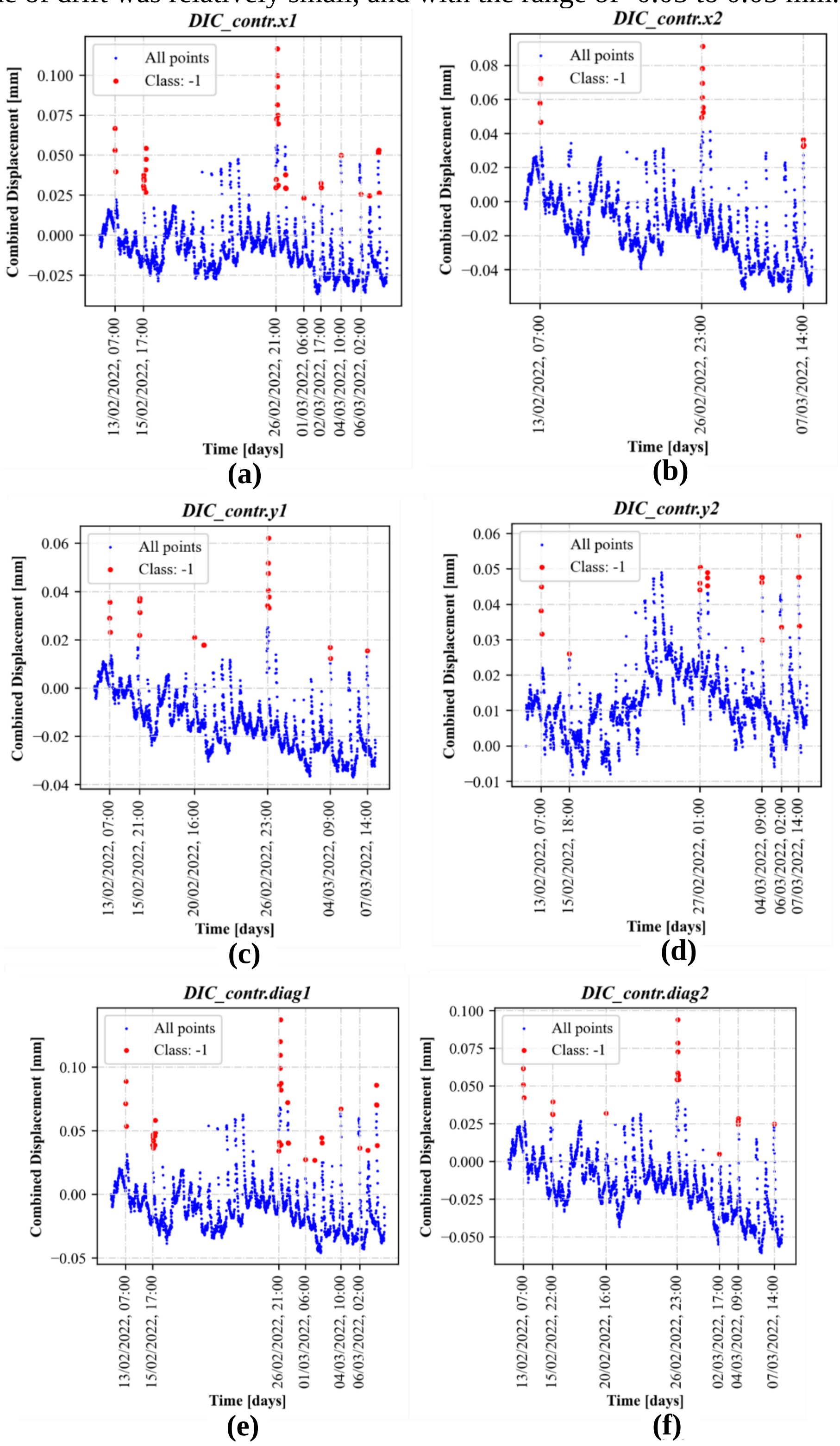

Figure 4: Control measurements: (a) $DICcont._{x1}$ with outliers marked; (b) $DICcont._{x2}$ with outliers marked; (c) $DICcont._{y1}$ with outliers marked; (d) $DICcont._{y2}$ with outliers marked; (e) $DICcont._{diag1}$ with outliers marked; (f) $DICcont._{diag2}$ with outliers marked.

5.2 The influence of temperature on the drift

To investigate the influence of temperature on the drift, the control measurements are plotted together with the temperature, in Figure 5 for the first week of monitoring. The four local maxima (i.e., peaks) in the temperature graphs, represent the hottest time of the four working days respectively (of a laboratory in which heating was turned on). The first two local minima (i.e., troughs) represent the weekend (without heating). From Figure 5, it is evident that there is no correlation in the graphs, however, a common periodicity. Effectively, it is evident that the local maxima of both the displacement and temperature graphs appear to coincide, however with a time lag. Though other causes of uncertainty cannot be ruled out, this suggests that temperature has a potentially important role in the robustness of DIC measurements. The aforementioned time lag is hypothesised to be caused by the conjunction of temperature with other environmental parameters, such as humidity and lighting. A future study monitoring all these parameters would be beneficial to investigating this hypothesis.

5.3 Midspan displacement measurements

To demonstrate the effectiveness of employing DIC measurements for monitoring ambiently excited structures (e.g., extremely slow-moving phenomena such as the evaporation of the water of the experimental bridge), they are compared with measurements from an LVDT. As such, Figure 6 displays the midspan displacement measurements from the LVDT and DIC respectively. From Figure 6, the following can be understood: a) the LVDT and DIC were in good agreement (with a correlation of 0.996, root mean square error of 0.012 mm, and mean absolute error of 0.010 mm); and b) there were no outliers present in the midspan displacement measurements; c) for the given equipment and range of measurement (0.5 mm), the displacement resolution of the DIC was equal to 0.001 mm; and d) since the water was evaporating, the displacement is predominantly positive, except for local minima, occurring on weekends, and days in absence of laboratory heating. Since this negative displacement is present in both LVDT and DIC, it was attributed to actual movement and not drift. In particular, it is hypothesised to be attributed to the beam’s stiffening caused by temperature decrease (in agreement with the temperature dependence of the bridge’s copper material [17]). Whilst a future study monitoring all other environmental parameters, such as humidity and lighting would be beneficial to investigate this hypothesis, the above findings are promising, demonstrating the effectiveness of DIC for long-term monitoring of an ambiently excited structure.

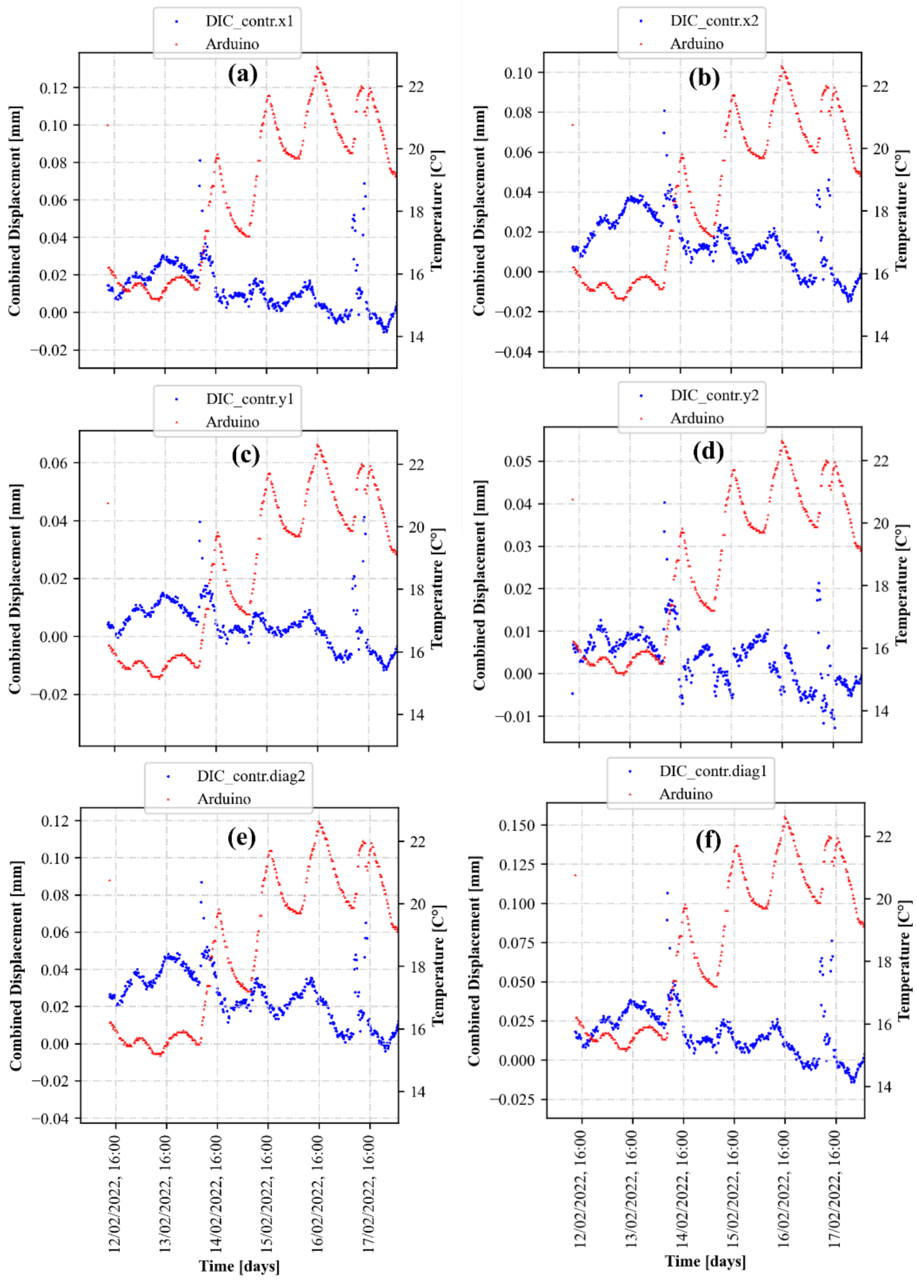

Figure 5: The influence of temperature on drift, for week #1 of monitoring. Superimposition of normalised measurements of thermal logger with: (a) DICcont.$_{x1}$.; (b) DICcont.$_{x2}$.; (c) DICcont.$_{y1}$.; (d) DICcont.$_{y2}$.; € DICcont.$_{diag1}$.; and (f) DICcont.$_{diag2}$.

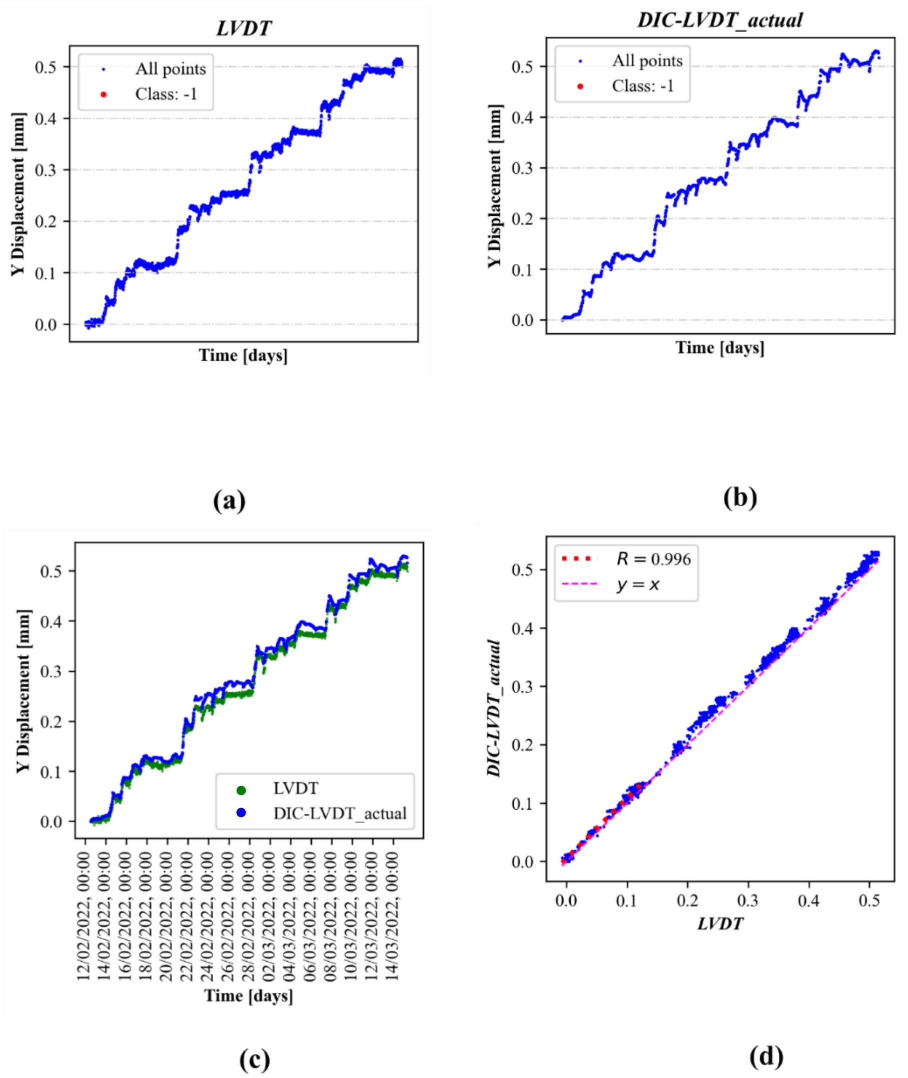

Figure 6: Midspan displacement measurements: (a) LVDT with outliers marked; (d) DIC-LVDT with outliers marked; (c) superimposed; and (d) correlated.

5.4 The influence of temperature on the midspan measurements

To further demonstrate the effectiveness of employing the DIC in capturing the complex structural behaviours associated with ambiently excited structures, the influence of temperature on the midspan measurements was investigated. As such, a correlation of both the DIC and LVDT with the temperature was sought. For this, the one month of monitored data is plotted in four separate weeks together with the respective temperature, in Figure 7. From Figure 7, it is evident that all graphs present a common periodicity. Specifically, the local maxima of the displacement graphs correspond to those of the respective temperature graphs, especially near the warmest time of the days (16:00). To further demonstrate this, the gradients of the vertical displacements (of the DIC) and temperature are plotted together in Figure 8, for the first week of monitoring. This is effectively to assess where the local maxima are occurring (i.e., where the gradients are equal to zero). From Figure 8, it can be observed that, especially near the warmest time of the days (marked with vertical grey dark lines), the gradients of both the temperature and vertical displacement are passing from the value of zero (as highlighted with magenta points).

This coincidence of maximum displacement with maximum temperature is hypothesized to be attributed to the elevated temperatures causing an increase in the evaporation rate of the air surrounding the experimental bridge and leading to a larger rate of displacement. Then, when the ambient temperature drops, the displacement graphs stabilise. This is attributed to the maximum evaporation rate of the surrounding air having been reached leading to no further evaporation and consequent displacement. The aforementioned time lag is hypothesised to be caused by the conjunction of temperature with other environmental parameters, such as humidity and lighting. A future study monitoring all these parameters would be beneficial to investigating this hypothesis.

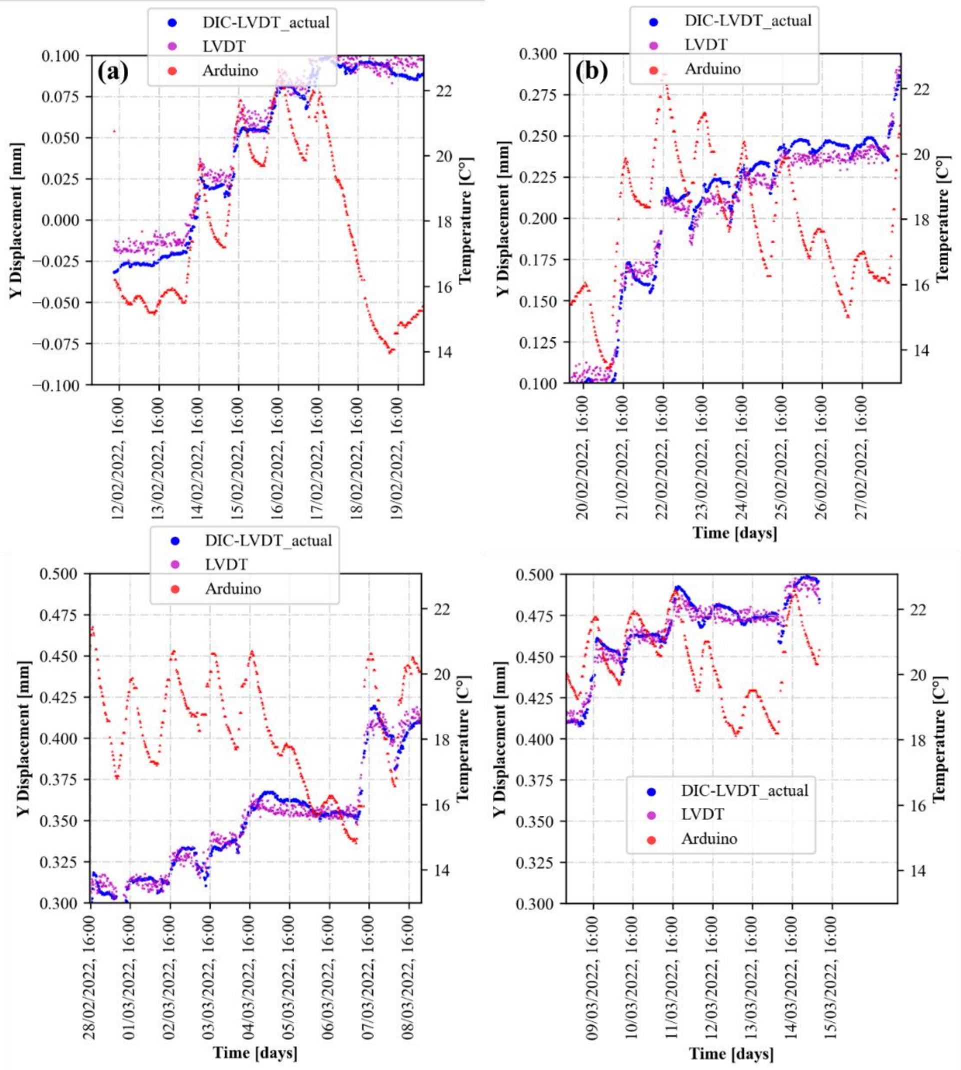

Figure 7: The influence of temperature on midspan displacements. DIC-LVDT, LVDT with superimposed temperature for various weeks of monitoring: (a) week #1; (b) week #1; (c) week #3; and (d) week #4.

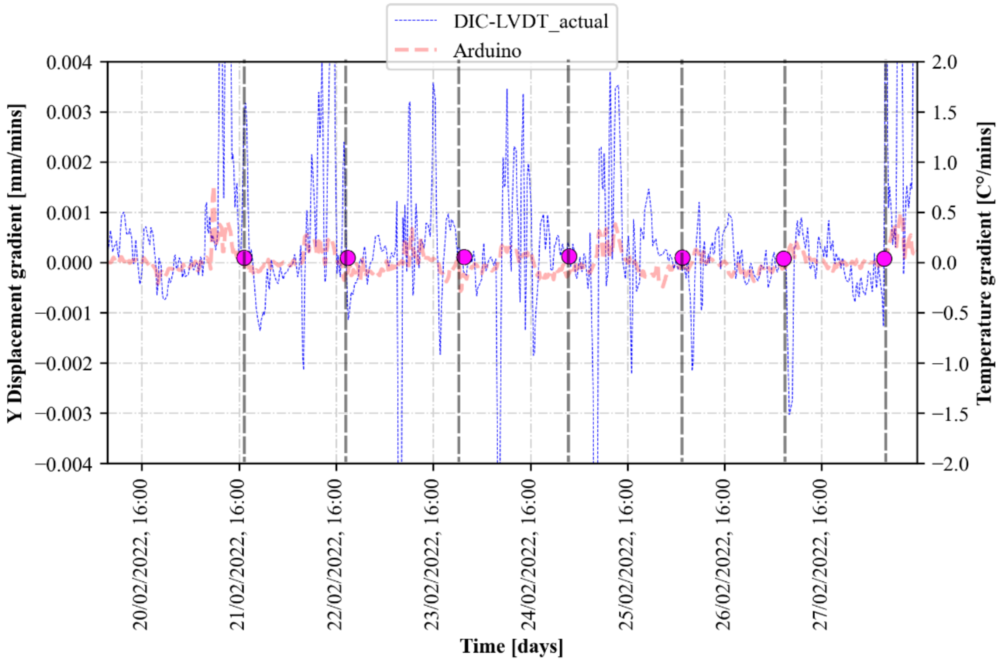

Figure 8: The influence of temperature on midspan displacements. The gradient of vertical displacements (DIC-LVDT) with the superimposed gradient of temperature for the first week of monitoring.

6 Conclusions

This study assessed DIC for long-term displacement monitoring. Firstly, the robustness of the monitoring of ambiently excited structures over long periods was examined. This was achieved through the measurement of the drift of control points. Then, a correlation was examined between the drift measurements and the ambient temperature, to examine the influence of temperature on the robustness of the DIC measurements. After, the effectiveness of employing DIC for monitoring ambiently excited structures was examined. For this, the displacements of the midspan of the experimental bridge structure were monitored for one month and compared with those of traditional contact-based sensors, i.e., an LVDT. Finally, to further demonstrate the effectiveness of employing DIC measurements for ambiently excited structures, a correlation was sought between the midspan displacements and the ambient temperature.

Concerning the robustness of long-term monitoring, the study found the values of drift within the range of 0.06 mm, which is considered relatively small. Concerning drift's periodicity, it was found to be common with the temperature, suggesting the important role of temperature in the robustness of DIC measurements. Regarding the effectiveness of DIC for long-term measurements, a comparable accuracy was found with traditional contact-based sensors. As such, the DIC measurements were found to be in good agreement with the LVDT, with a correlation coefficient equal to 0.996, root mean square error of 0.012 mm, and mean absolute error of 0.010 mm. This is a promising result, demonstrating the potential of DIC to be employed on real-world assets for SHM. Finally, the investigation of the correlation between temperature and the midspan displacements further demonstrated the effectiveness of DIC to capture extremely small and slow-small movements, typical of ambiently excited structures.

Whilst this study is only on a small-scale structure, the potential of DIC for long-term monitoring of full-scale structures was demonstrated. Future research is planned to investigate the influence of other environmental parameters (e.g., lighting and humidity) on the robustness of the DIC measurements. Also, an external monitoring campaign is scheduled for both small and large-scale structures.

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