Determination of Maximum Accuracy of Concrete Textures as Natural Targets for Movement Tracking Through DIC

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Abstract

The use of natural targets is one of the obstacles to the extensive use of digital image cross-correlation for measuring movements in civil structures. Long distance measurement through image and without access to the structure itself, brings results in an improvement in accessibility, being the procedure cheaper and safer than common methods that require direct access to the measuring point. One of the most used materials in construction is concrete. Therefore, it is important to analyze its performance when using image cross-correlation. In this work, we have made a series of concrete probes with different production characteristics to have a representative variety of concrete surfaces. With them, we have studied their floor error in a cross-correlation procedure using different illumination and blur conditions, to evaluate the influence of those parameters on the results. All results are compared to those obtained using the conventional texture for image cross-correlation techniques, that is a pseudo-speckle target. All experiments are done in laboratory conditions to control all variables involved and to avoid the influence of other variables linked to open air conditions, such as atmospheric disturbances. As a result, we have determined the best conditions to use the natural concrete texture and we have quantified that using this texture leads to a decrease in the accuracy of the results from two to three times the one obtained with a typical pseudo-speckle texture.

Keywords Concrete texture · DIC target · Measurement accuracy · Brightness and blur conditions

1 Introduction

Digital image cross-correlation (DIC) is a well-known tool to measure movement and deformations [1]. In most cases, this tool is used on pseudo-speckle patterns which ensures homogeneity of the response through all image regions [2]. The pseudo-speckle is a unique pattern formed by random dots which is printed, sprayed or attached on a surface [3]. This pattern resembles the typical speckle pattern obtained when a surface is illuminated by a coherent source [4]. This pattern has been shown to be particularly convenient for tracking displacement and deformations through DIC (see

for example [5–7]). The advantages of this texture have led to its adoption in commercial systems such as GOMCorrelate [8] or Ncorr [9], which have adapted their algorithms to this particular image. Additionally, and in order to encourage research on new algorithms and methods, a public image and video database of calibrated movement with several pseudo-speckle configurations is provided by the Society for Experimental Mechanics [10].

This texture can be glued or sprayed to the target surface [11, 12]. Then a sequence is captured and, through digital correlation one can obtain the global or local displacement of the texture, thus obtaining information about shifts or deformation of the material on which the texture is applied. This procedure is simple for small pieces that are easy to manipulate. However, if one is interested in measuring the movements of a real large civil structure, such as a damp or a bridge, the point with the larger expected movement is usually out of simple reach, making it difficult, expensive, and even dangerous to attach or glue an artificial target. The best solution in these cases would be to measure the movements and deformations at a distance (usually long due to the size of

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civil structures) by using the natural texture of the material, thus avoiding direct access to the structure.

Concrete is one of the most used materials to build civil structures. Therefore, being able to measure movements using cross-correlation on concrete surfaces, without reaching the surface itself at any point of the structure seems interesting [13, 14]. Recently, in [15], the authors presented a manuscript to measure displacements on structures without artificial markers, just by using borders or natural elements. Despite the good results obtained, up to our knowledge the presence of such natural markers cannot be given by granted when large structures are analyzed, and an alternative or complementary method may be useful. In our case, we propose to use the natural texture of the concrete surface as a tracking target.

Concrete texture can be considered quite similar to a sparse pseudo-speckle pattern due to its surface small holes (Fig. 1). This similarity leads to the question whether DIC can be applied on natural concrete texture with acceptable results or not. Notice that. while there may be a similarity in the size of the details between concrete textures and pseudo-speckle textures, it is important to note that concrete details are not uniformly distributed throughout the image. This characteristic makes it more challenging to utilize concrete textures as tracking targets compared to uniformly distributed speckle details [16]. If our hypothesis is correct, it would allow displacement or deformation measurements without the need for access to the measurement point, making the procedure much easier, safer, and cheaper than the conventional procedure with artificial pseudo-speckle targets.

There are some previous concrete texture studies under the point of view of displacement measurement. In [17], a concrete probe was used to evaluate a local displacement in its surface using DIC method while applying loading-unloading cycles to the probe. Result was compared to a traditional strain gauge and, although results through DIC were noisier, the obtained accuracy of the method was 0.03 px [18].

However, since only one concrete probe was used, it remains the question whether a different concrete probe would give the same results or not as well as the influence on those results given by variations in light intensity, orientation and image focusing. Influence of light intensity and orientation has been analyzed in the literature indirectly, in the form of different characteristics in the pseudo-speckle pattern [19], so here we have also included this analysis in the concrete texture analysis. Additionally, image blurring has been reported to have an important effect on the accuracy of the DIC method. In the literature [6, 17] it is described that a low pass filter, which in images can be assimilated to a blur, may affect the accuracy of subpixel DIC methods. Therefore, also different blur conditions will be analyzed here to study their influence on the results when using a concrete texture.

Therefore, in this manuscript we explore the viability of using concrete natural texture as a target for DIC. In our study, the measurements were conducted in a controlled laboratory setting with controlled lighting conditions and static sample positioning. We captured a total of 60 images per sample and per experiment, providing us with a substantial dataset for analysis. The standard deviation of the movement measured through the sequence of 60 images recorded will be the absolute accuracy obtained for the texture recorded. This accuracy will be compared to results obtained using a pseudo-speckle texture obtained from the DIC challenge database [10] and the same laboratory procedure.

To account for any potential variability, we performed a thorough analysis of the correlation function for each sequence. This allowed us to establish a noise band that characterizes the expected variation in the measured displacements. Any displacement falling within this noise band is considered within the margin of error and is not registered as a significant shift.

2 Materials and Methods

As we said above, the variability of the tracking method has been checked by acquiring a static sequence of images of different concrete textures. The experimental setup has been depicted in Fig. 2. The concrete probe has been situated in front of the camera, at a distance of 475 mm. The camera used

Fig. 1 Texture generated by spray painting to be used for DIC measurement (left) [20] and the peculiar concrete texture obtained by in-site formwork (right)
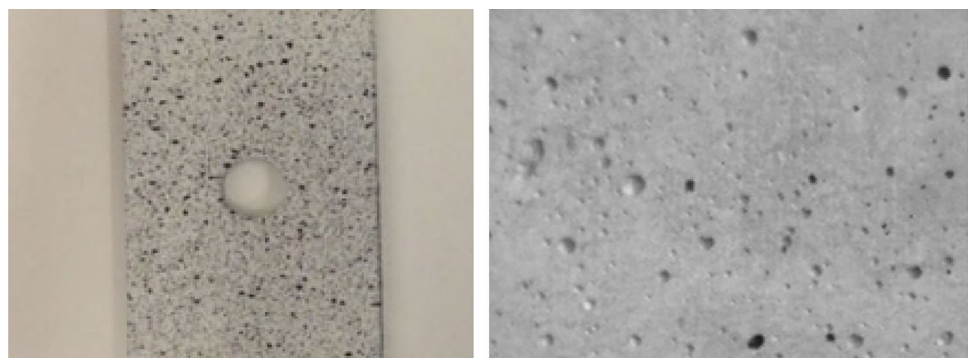
Fig. 2 Setup for the experiments. In the image, a concrete texture is being recorded

was a BASLER acA4600-10uc together with a PENTAX TV LENS f/1.4, giving a scale ratio of 18.28 px/mm. Both the camera and the target were attached to an antivibration table and remained fixed through all the acquisition process. Illumination was done using 2 led lamps with selectable light intensity, ranging from 50 to 600 lumens. Those lamps were located laterally, in a symmetrical position with respect to the sample so that one can have planar illumination, which is achieved by switching on both lamps at the same intensity or lateral illumination by switching only one lamp.

Before the experiment itself, the camera was properly calibrated. A test image with a dotted pattern was used and a thermal drift was observed. In order to stabilize the sensor, a heat sink was attached to the camera and all the sequences were acquired after two hours of pre-heating.

After that, the procedure stablished for all sequences was the same: after two hours of preheating, one image per minute was recorded for 60 min. Individual frames obtained were processed selecting a single channel from the RGB image. Usually, the green channel is selected since it has better quality, and it is the channel with less interpolation. Then, a region of interest (ROI) is selected in the image so that all the concrete surface lays within the ROI while the background is excluded. The absolute accuracy related to each concrete texture is obtained through the standard deviation of the movement measured. This accuracy is then compared to the accuracy obtained using a pseudo-speckle target with the same laboratory setup and image processing.

The experiment was repeated for different concrete samples and with different conditions. First, we checked the influence of defocus: three different sequences for each sample were registered with focused, slightly blurred, and moderate blurred images.

In order to measure the two blurring levels used, we analyze the number of pixels needed in the transition from printed black to white (see Fig. 3). Ideally, with a real black (0) and a focused image, the transition would accomplish in only one pixel. As the image is blurred, the slope of the transition gets lower. In real experiments, achieving a perfect focus is difficult due to noise and aberrations so, in our experiment, the printed black and white target was focused with a jump of 8 pixels to pass from black to white. The first blurring level selected has a jump of 18 and the second one a jump of 28 pixels.

Other factor that has been evaluated is light intensity. It has a strong influence on image contrast, thus may affect to the final accuracy of the method. Therefore, three different intensities have been used to illuminate the focused sample, ranging from poorly illuminated to a bit over illuminated. This was accomplished by using two lamps located laterally to the probe (Fig. 2) and varying their intensity from 5% (low) to 25% (high). Percentages refer to the maximum light intensity provided by the lamp (50 to 600 lumens). In Fig. 4 an example of these illumination differences is shown.

Finally, we also tested the influence of light direction. In addition to the sequences already described, we also recorded all the probes using only a lateral light and high light intensity with focused image. Results from these experiments will be compared to those obtained using centered light and high intensity. To compensate differences in light intensity due to the use of only one lamp or two lamps, we needed to raise the light intensity to 30%. In Fig. 5, lateral and central illumination can be compared for the same probe. The difference can be seen in the contrast obtained in all the small irregularities that typically appears in the concrete surface.

Image tracking was achieved using the DIC (Digital Image Correlation) technique, employing the normalized cross-correlation algorithm *norxcorr2* implemented in Matlab. Each image in the sequence was compared to the initial image. Since cross-correlation provides a tracking resolution of 1 pixel, subpixel corrections were applied to enhance accuracy. Among the methods described in the literature [21],[22] The approach used in this study was described by Tomas et al. [7]. In summary, it involved refining the search around the correlation peak by fitting an analytical function to a local neighborhood surrounding the maximum. Specifically, an 11 × 11 subarray centered on the peak was considered, and the values were adjusted to a two-dimensional Gaussian function. The refined position of the template was determined based on the peak of the fitted function.

The results are presented as they arise from the calculation described; no more manipulations are done on them, including smooths or detrends. The complete flow chart of the process is shown in Fig. 6. The same image processing was done for concrete and pseudo-speckle textures.

The mean value and standard deviation of a measured hypothetical shift were calculated. Since the target remained static throughout the experiment, the mean value is expected
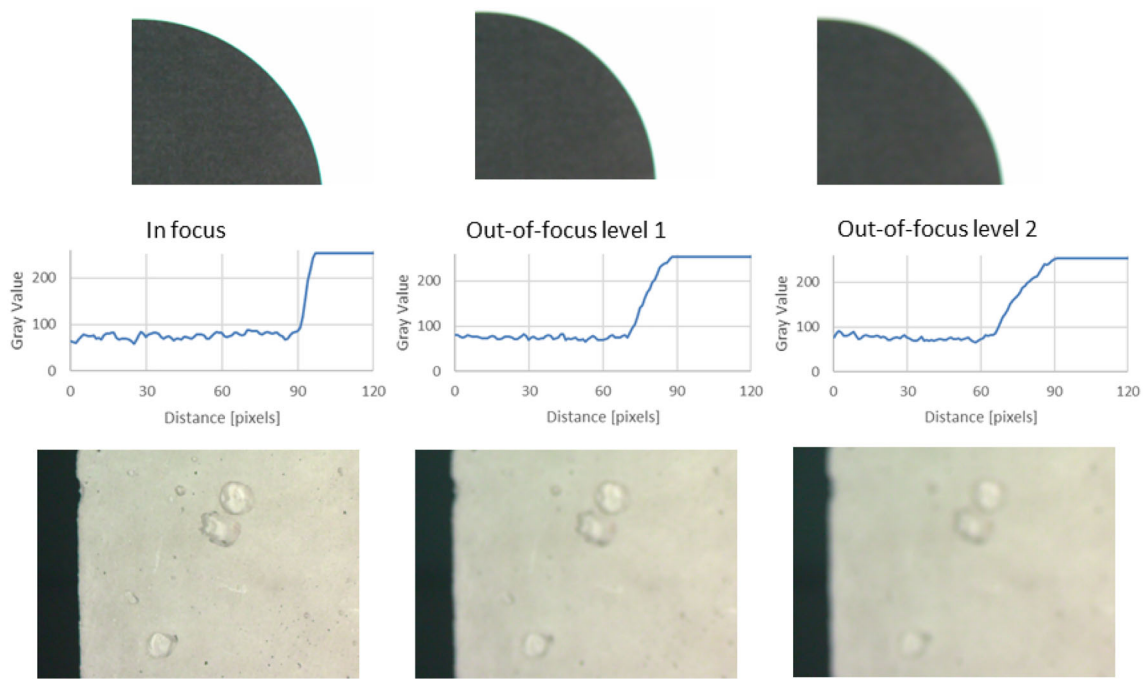
Fig. 3 Out-of-focus levels determination for this work, applied to a printed black and white circular target (upper row) and to a particular concrete texture (lower row). In the middle row, the graphs show the gray value intensities in the black and white boundary of the black and white target. The number of pixels to change from printed black to white are 8, 18, and 28 for in-focus, out-of-focus level 1, and out-of-focus level 2, respectively
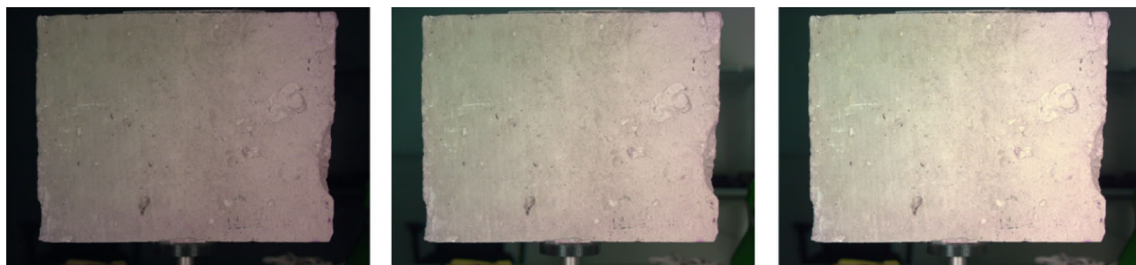

Fig. 4 The three different centered illumination intensities used for one of the concrete probes used in this work

Fig. 5 Lateral illumination (left) and centered illumination (right), The probe is the same as the one shown in Fig. 5
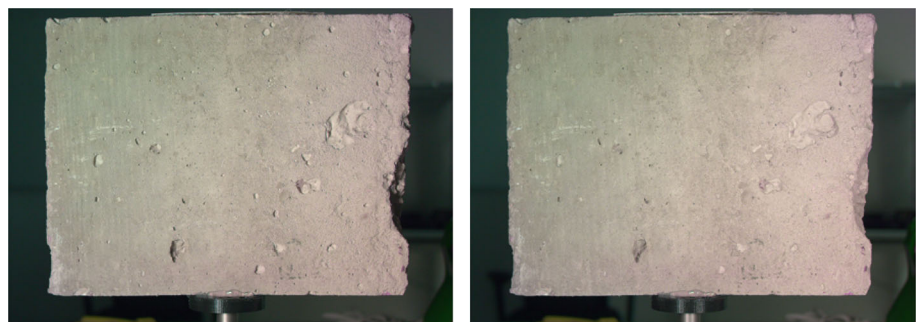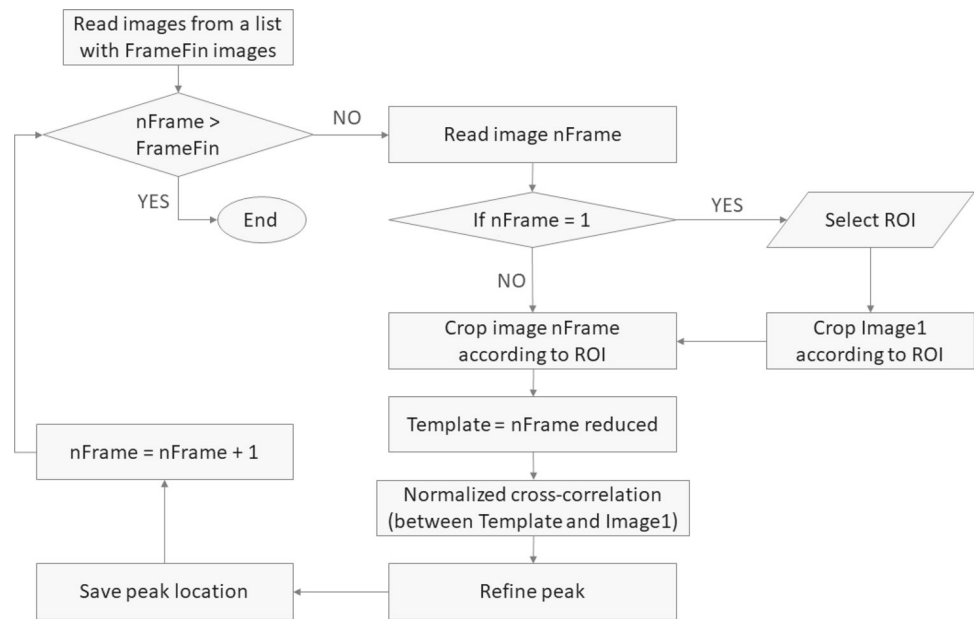
Fig. 6 Flow chart for the image processing used in this work

to be zero. The standard deviation of the calculated position takes into account both experimental and numerical errors. This value defines a range within which any detected movement may be difficult to distinguish from the inherent noise. Consequently, the standard deviation serves as a measure of the absolute accuracy of the method.

It is worth noting that when the texture details are more dispersed and less contrasting, the correlation peak becomes wider, resulting in larger localization errors and a broader error range. Pseudo-speckle textures have been designed in order to provide very narrow peaks in the correlation plane thus being more robust in presence of noise. The more different the concrete texture is from a pseudo-speckle pattern the wider noise band will be obtained. Thus, the standard deviation indirectly indicates the suitability of specific textures for tracking through DIC.

To evaluate the performance of concrete textures, we compared the results from concrete to those obtained using a printed pseudo-speckle texture from the DIC challenge database [10]. We followed the same laboratory procedures for both cases. By comparing results from the concrete texture with those with pseudo-speckle under the same conditions, we establish a clear reference point for assessing the acceptable level of accuracy loss when using concrete textures for measurement purposes through DIC. The pseudo-speckle image was taken from the Sample 8 of the 2-D DIC Challenge 1.0 [10] (see Fig. 3). The selected texture has the adequate detail to be printed, with the point big enough to be seen in the image but small enough to have a representative speckle texture. The image printed in a conventional printer at 1200 ppp and attached toa screen just in front of the camera. The target was illuminated by both
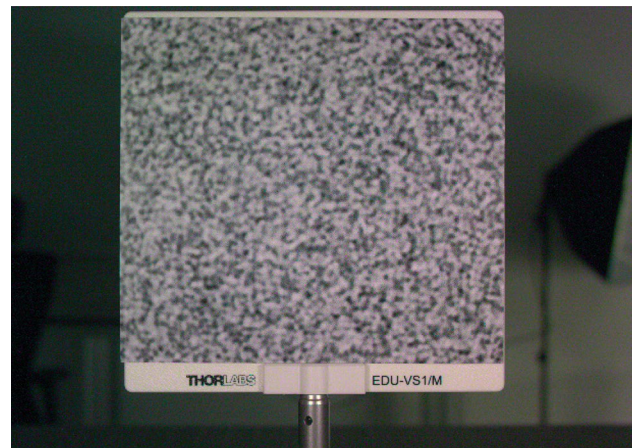

Fig. 7 Pseudo-speckle target used as reference value

lamps simultaneously with an intensity of 5%, low enough to avoid white saturation. The image was focused using the letters under the pattern (see Fig. 7).

The error obtained using a pseudo-speckle target is shown in Table 1. The mean values observed are due to small drifts probably due to thermal noise. Accuracy of the measurement should be taken from the STD value since any measurement within the standard deviation band may be due to noise. Note also that there is a difference between horizontal and vertical error. This error may be due to the geometrical shape of the camera and image, being larger in the horizontal dimension. However, these values are calculated to be reference values to compare them with the results of the concrete texture. Therefore, we will consider the smallest error obtained to be on the best scenario; with this, the reference value to determine the relative accuracy of using concrete texture is 0.003 px.

Table 1 Reference values obtained using a pseudo-speckle target

Target texture	Horizontal error (px)		Vertical error (px)	
	Mean	STD	Mean	STD
Pseudo-speckle	− 0.0087	**0.0063**	− 0.0048	**0.0030**

Bold values indicate the best result for each case

Regarding concrete textures, let us recall that there is not a single concrete appearance, but it highly depends on the way in which the concrete is poured into its formwork and compacted as well as on its slump. To have a large variety of concrete textures, a series of laboratory probes were made combining these characteristics:

- Concrete slump: four different slump ranges were used: [0–25], [25–50], [50–90], [90–150] mm.
- Type of surface for the formwork: steel and wood surfaces were used.
- Way of concrete compaction: three types of compactions were used: ramming with a steel bar, tapping with a rubber mallet, and using an electric vibrator.

Combining these factors, a total of 21 cubical concrete probes were made with a size of 20 cm of side. As each lateral side has slight differences in texture, for each concrete probe, the four lateral sides were vertically cut to a thickness of 2 cm (slim probes) to have four different versions of each combination. Therefore, a total of 84 concrete slim probes were made. A visual analysis of the obtained textures allowed for selecting those with singular differences in them, resulting in a total set of 11 slim probes to make the image experiments (Fig. 8).

In Table 2, we present a summary of all experiments done for each of the 11 slim concrete probes, with the combinations of factors between light intensity, blurring, and location of light. Percentage refers to the maximum intensity (600 lm) provided by the lamps. A total of 6 sequences have been captured for each sample, four focused with different illumination conditions and two more with different blurring levels.

3 Results

As both the camera and target remain static during all the acquisition time all measured movements may be considered as errors and thus may determine the accuracy of the method on natural concrete textures. In this section, we will compare the results obtained using a pseudo-speckle target with those obtained using concrete textures.

As we did with the pseudo-speckle sequences all results have tested for both vertical and horizontal movements. As
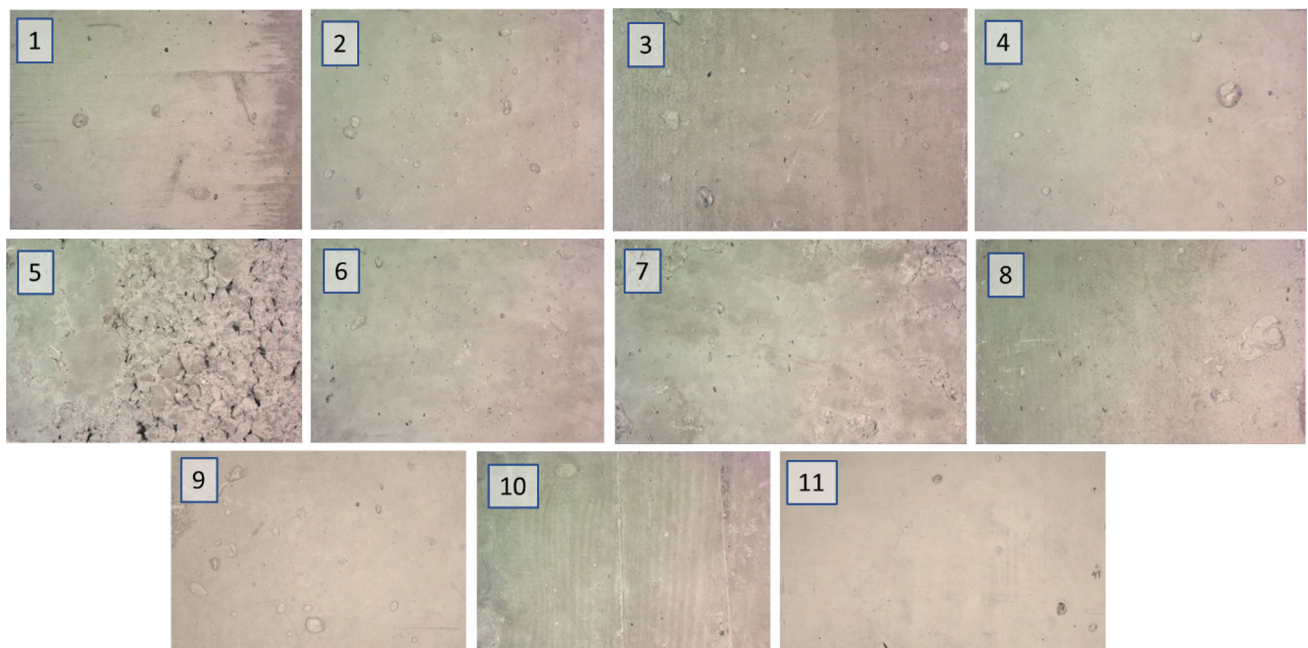

Fig. 8 Concrete textures selected to make the study

Table 2 Combination of factors for the experiments done on each concrete sample

Focus	Illumination	Intensity (% of maximum)
Focused	Lateral	High (30%)
	Bilateral (centered)	High (25%)
		Medium (15%)
		Low (5%)
Out-of-focus level 1	Bilateral (centered)	High (25%)
Out-of-focus level 2		

the results from concrete are bulkier, it is worth to consider whether both dimension measurements (horizontal and vertical) are statistically equivalent or not. To analyze that, we have performed an independent two-sample, two-tailed t-test with a statistical significance of 0.05 and unequal variances. This analysis has been done for all sets of x and y measurements obtained for the 6 experiment types done for each one of the 11 studied samples (66 x and y sets). The result in all cases does not reject the null hypothesis at the 5% significance level, which means that both data (measurements in x and y) are statistically equal and the difference between both axes can be ignored. Therefore, in what follows, only measurements in x will be shown, described, and analyzed, since the same conclusions can be extended for the y direction.

For each experiment type, we have calculated and represented the mean and the standard deviation of the results for every concrete probe (see Figs. 9, 10 and 11). To every graph we have added in a black continuous line the reference values of mean and STD obtained for the pseudo-speckle target. In dotted lines, the mean of all means and STDs are also represented following the color selected for each case. Additionally, we include in the graphs the particular concrete probe linked to each result (using the number code shown in Fig. 8), to search for common characteristics for each probe and to analyze the influence of the studied parameter in the result for every probe. Therefore, in all cases, the results will be discussed under two points of view: general influence of the studied parameter for all concrete texture studied and the influence of that parameter on every probe, if there is something remarkable under this point of view.

3.1 Influence of Light Intensity

Light intensity influence is analyzed by comparing the errors obtained through central illumination with three different light intensities and no blurring in the images.

Results for low, medium, and high light intensities are shown in Fig. 9 for the 11 slim concrete probes tested. On one hand, sequences with lower light intensity present higher
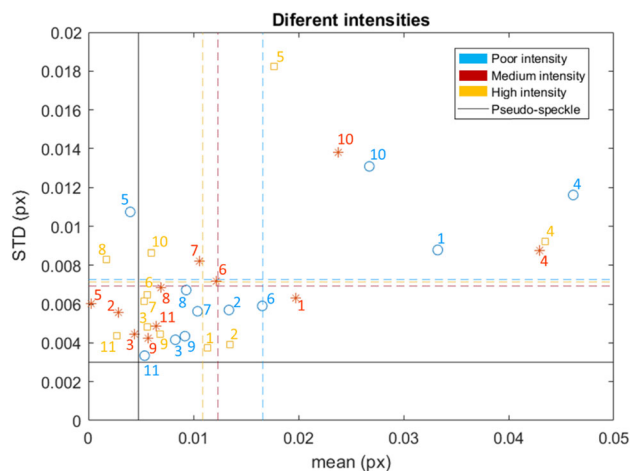

Fig. 9 Mean and STD values for concrete under different light intensity experiments. In continuous line, pseudo-speckle values are shown, and dotted lines indicate the mean of all means and the mean of all STD for each intensity illumination. Numbers refer to probes in Fig. 8
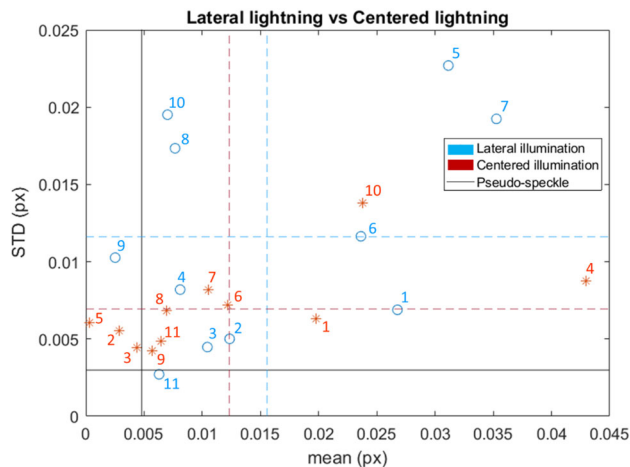

Fig. 10 Mean and STD values for concrete with centered and lateral illumination experiments. In continuous line, pseudo-speckle values are shown, and dotted lines indicate the mean of all means and the mean of all STD for each illumination type. Numbers refer to probes in Fig. 8

location error (mean value); this trend can be clearly seen in the mean value of all means for each intensity type (dotted lines). This could be linked to a slight difference in the details that makes the correlation peak softer thus increasing the error in determining the location of the maximum. Notice that the probe with large error in all situations is nr. 4 which shows a more uniform appearance.

On the other hand, standard deviation for the three illumination intensities is similar in the three situations. This again may be due to the poor dynamic range of the samples, so a change in the illumination does not change very much the visibility of the different details. In fact, sample 10, which seems to have more details, is very much affected by this

Fig. 11 Mean and STD values for concrete defocus experiments. In the red square there are a magnification of the small values. In continuous line, pseudo-speckle values are shown, and dotted lines indicate the mean of all means and the mean of all STD for each illumination type. Numbers refer to probes in Fig. 8
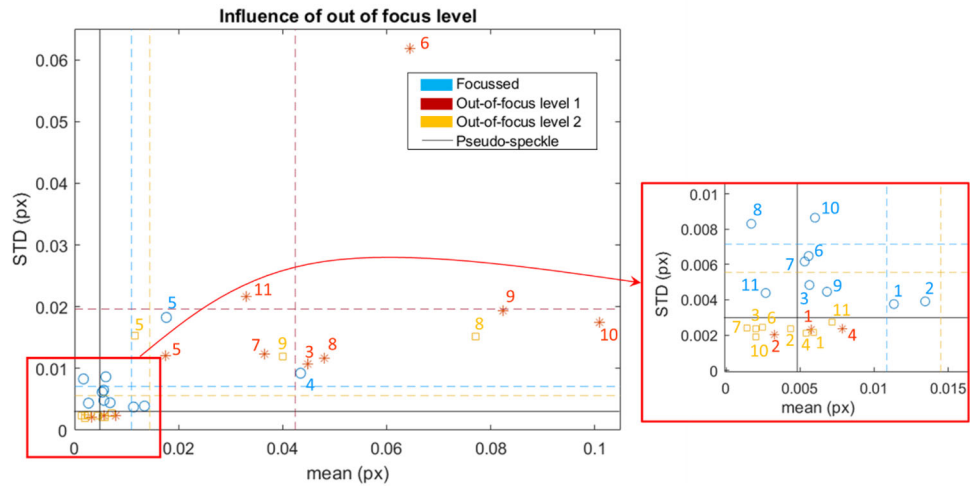

Table 3 Ratio between the average tacking results obtained from natural textures and from the artificial pseudo-speckle target for different light intensities

	Natural to pseudo-speckle textures ratio	
Lighting	MEAN	STD
Poor	3.46	2.4
Medium	2.56	2.3
High	**2.27**	**2.4**

Bold values indicate the best result for each case

Table 4 Ratio between the average tacking results obtained from natural textures and from the artificial pseudo-speckle target for different light locations

	Natural to pseudo-speckle textures ratio	
Lighting	Mean	STD
Lateral	3.24	3.9
Centered	**2.27**	**2.4**

Bold values indicate the best result for each case

illumination change. On the other side, sample 5 has a contrary behavior having the highest error with the highest light intensity. The texture of this probe is the one with the highest irregularities, having the left side quite different texture than right side; also, the right side has a unique texture with many hollows and no planar surface. Our hypothesis is that a high light intensity enhances this texture differences between both image sides, so the error may increase.

However, with these data, we can conclude that, in average, high light intensity provides the best conditions for using natural concrete texture. Caution should be taken when a high heterogeneity appears, as higher intensity can lead to the worst conditions. In order to better compare the concrete texture results with those from the pseudo-speckle texture we have calculated the ratio (see Table 3) between them, obtaining that, with intense light, the performance of tracking through concrete texture is only two times worse than tracking through pseudo-speckle artificial targets.

3.2 Influence of Light Location

Results obtained for all concrete probes analyzed under centered (bilateral) and lateral illumination are shown in Fig. 10, together with the reference value (pseudo-speckle

with frontal illumination). For both illuminations type we have selected a high intensity, as it was shown in the previous section that it gives the best results. Dotted lines shows that centered light resulted in slightly better results than lateral light. Lateral illumination usually provides high contrasted image and tends to enhance borders and details, similarly to a high-pass filter. However, it is shown in the bibliography [6] that a low-pass filter may enhance the tracking results, so it is reasonable to pose that a high-pass filter may have the contrary effect. Note also that results from lateral illumination are much more disperse than those with frontal light. This may happen because of the lateral light, that may enhance small differences between textures in the same probe, making the comparison more heterogeneous. Results for sample number 5 match very well with the general rule, while samples number 4 and 11 show the contrary tendency. Those two samples are the ones with most smooth surfaces, having big surface areas without any detail in them. In Table 4, the ratios for each case are given, showing that with the centered illumination, the tracking has better accuracy than with lateral light.

3.3 Influence of Image Blurring

The results (Fig. 11) show that slightly defocused tests (level 1) have worse results in both mean and STD than the sharp

Table 5 Comparison between the values obtained from concrete and from pseudo-speckle in terms of the multipliers needed to obtain the first one from the second one

	Natural to pseudo-speckle textures ratio	
	Mean	STD
Focussed	**2.27**	**2.4**
Out-of-focus level 1	6.54	8.8
Out-of-focus level 2	**3.02**	**1.8**

Bold values indicate the best result for each case

and higher defocused tests (level 2). It is known that blurring produces widening and smoothing of the correlation peak, thus decreasing the noise in the sequence. Additionally, high frequency details in the texture may disappear. Because of this, it is expected that the bias error increases while decreasing the variability in the location (STD) [17]. Here we can observe this effect with the focused and the highly blurred tests, while the sequences with small defocus seem to have an anomalous behavior with an increment of the error in almost all probes. Only probes 8 and 9 have shown worse error being defocused at level 2 than being focused, especially in the mean value, but also observable in the STD. As any special particularity have been found on those probes by comparison to the rest of them (samples 9 and 2 have quite similar texture, for example, but they have different tendency when increase the out-of-focus level) we cannot lead to conclusions regarding a particular probe and therefore we will include all results as a results for a general concrete texture.

In [6] the authors show that the effect of a low pass filter on the accuracy of the DIC method depends on the texture size. While a particular low-pass filter may decrease the accuracy when applied on a small size speckle pattern, the same filter can decrease the location error when used on speckle textures with large spots. Concrete texture shows a mixture of details sizes. If the image is on focus, all details contribute to the correlation, while when the image is out of focus, only the large spots do. In an intermediate situation, there may be middle sized spots that are not clearly defined and thus contribute to increase the error.

Results of the tracking are quantified in Table 5. As we said above, tracking with focused images provides better mean value but worse STD than with a defocus of level 2. The highest error is found for the mean value of out-of-focus level 2, but we may consider that the high values obtained for samples 8 and 9 have risen the global mean value for a slight blurring. It is also shown that having a slight defocus is worst situation in both mean and STD parameters. Note that in open air, with large distances and other factors such as dust or atmospheric disturbances, having the image perfectly focused all the time can be tricky and thus it could be interesting to have an intentional blur in order to avoid an intermediate situation with larger errors.

4 Conclusions

In this work, we have evaluated the use of the texture of concrete surfaces as a target to measure displacements using digital image cross-correlation. This is especially important when a civil structure is involved, as many times the areas with higher displacements (therefore the most important to measure under a structural point of view) are in the higher and most inaccessible places, making it difficult and even dangerous to stick or print a pseudo-speckle target there.

To analyze the concrete surface texture, we have analyzed 11 concrete probes, covering a wide variety of textures, similar to those that can be observed in real constructions. The accuracy of the methods has been set by acquiring image sequences of a static targets under different conditions: different light intensity, illumination orientation and blurring. Since the object is not moving, all variability observed can be linked to a error of the method for detecting a real movement. Results obtained have been compared to tracking errors obtained with a typical pseudo-speckle texture.

Results show that, the best conditions for using concrete textures as tracking target are high light intensity, with planar incidence and a perfect focus. In this case, the accuracy of the method decreases in a factor of 2.3 with respect to the results obtained with the typical pseudo-speckle texture. Note that, since the concrete texture is not homogeneous, a slight defocus degrades the accuracy very much, while a noticeable blurring provides again similar results to the focused cases, with a larger bias error but lower variability. In any case, some of the obtained error trends could be linked to some characteristics of the concrete textures, but not all of them. Therefore, further work is needed in order to fully characterize the textures and expand the present study to all applications where pseudo-speckle is used.

In summary, we found that the accuracy of using concrete natural textures is two to three times worse than the accuracy that can be obtained with a pseudo-speckle texture; even though the accuracy for tracking concrete textures is of the order of hundredths of a pixel. Of course, the maximum possible accuracy is advisable in all circumstances, but in some cases, a compromise between resolution and security is needed and, in such cases, the loss of accuracy may be worth.

Declarations

Competing Interests The authors declares that there are no conflicts of interest regarding the publication of this article.

Ethical Approval Not applicable.

Consent for Publication All authors whose names appear on the submission agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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