Effect of imaging distance on image texture of sand in PIV analysis

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ABSTRACT
This paper presents the results of an investigation into the impact of distance between the camera and the target on the image texture and the measurement accuracy of a particle image velocimetry (PIV) analysis for two types of sand. To obtain an optimal result from the PIV technique the results indicate that a certain level of image texture, quantified by the mean intensity gradient (MIG), is required. It was found that on a global scale, the optimal texture occurred at a similar working distance for the two sands, owing to the similarity in the grain size; however, the MIG was larger for the synthetic olivine due to its colour variation. Results show that decreasing texture of individual subsets was more likely to lead to errors in the analysis. Furthermore, subsets with adequate MIG values can still produce significant errors in one direction versus the other suggesting the need for a better texture descriptor. It is shown that correct placement of the camera will help to reduce the likelihood of measurement errors.

RÉSUMÉ
Cet article présente les résultats d'une enquête sur l'influence que la distance entre la camera et la cible a sur la texture de l'image et sur la précision d'une analyse de deux types de sable basé sur la vélocimétrie d'image de particules (PIV). Pour obtenir un résultat idéal en utilisant la technique PIV les résultats dans ce papier indique qu'il est nécessaire que la texture de l'image, quantifiée par le gradient d'intensité moyenne (MIG), doit être à un certain niveau. Il a été constaté que sur une échelle mondiale, la texture idéale a été produite avec une distance similaire pour les deux types de sable grâces aux similarités entres la taille des grains. Mais il faut noter que le MIG était plus grand pour l'olivine synthétique à cause des variations de ses couleurs. Les résultats démontrent qu'en réduisant la texture des sous-ensembles individuels l'analyse est plus susceptible aux erreurs. En outre, les sous-ensembles avec des valeurs de MIG adéquates peuvent comme même produire des erreurs significatives dans un sens par rapport à l'autre suggérant une nécessité pour un meilleur descripteur de texture. Il a été démontré que le placement correct de l'appareil contribuera à réduire la probabilité des erreurs de mesures.

1 INTRODUCTION

Recent advances in digital image analysis have enabled measurements of soil deformations in laboratory and field experiments to be made with a precision and measurement density previously unattainable (White et al., 2003). This analysis method, often called Particle Image Velocimetry (PIV) or Digital Image Correlation (DIC), is a digital image-based surface displacement measurement technique which compares a reference image to a series of deformed images. The technique divides the reference image into a grid of square subsets, which can later be identified using their pixel intensity variations as a signature. The PIV algorithm then searches the deformed images within a specified search zone for the subset whose intensity pattern is of maximum similarity to the same subset in the reference image. The difference between the target subset and the reference subset is the displacement vector of the subset's center. To achieve accurate correlation, the subset must contain sufficient intensity variations to be distinguished from the surrounding search zone. This intensity variation is dependent on the image contrast variation (image texture) of the object being observed.

The technique of image comparison using PIV has been used previously in geotechnical research as a non-invasive indirect displacement measurement technique in both materials with natural image texture such as sands (e.g. White et al., 2003; Rechenmacher, 2006; Slominski et al., 2007) and fine grained materials in which image texture had to be artificially generated (e.g. Take and Bolton, 2004; Thushyanthan et al., 2007).

PIV has been implemented in geotechnical research to measure full-field vector displacements of small-scale landslides (Take, 2004) and to observe the failure mechanism of sand foundations. As seen in Figure 1, which shows PIV results capturing the compression behaviour of loose sands under a shallow foundation, a uniformly coloured quartz sand was prone to erroneous results while a colourful synthetic olivine was not. The reason for this difference is image texture, which is the topic of this paper.

It has been found that to obtain optimal results from the PIV technique a certain level of image contrast variation (image texture) is required to accurately determine the displacements (e.g. White et al., 2001; Take, 2003; Pan et al., 2009). With sands, the image texture is related to the shape, colour, and grainsize of the soil particles. At small camera distances, digital images of sands will contain a high degree of texture as the ratio of grainsize to pixel size is large, resulting in individual grains to be resolved. As the camera distance is increased, the ability of resolving individual grains will be lost, lowering the level of texture in a digital image. In using this technique, therefore, it is likely that there will be an optimal camera distance that maximises the field of

view but does not impact measurement accuracy due to poor texture. The objective of this paper is to investigate the relationship between image texture and measurement accuracy by conducting a series of experiments in which the distance between a sand target and the camera is varied. A background of the image texture is presented in Section 2. The experimental setup is described in Section 3. The results from the experiments are presented in Section 4 with further considerations in Section 5.

2 IMAGE TEXTURE

The word texture in image analysis can be defined as a pattern to characterize objects (Jähne, 2004). Knowing what is a good or bad texture is intuitive (e.g. images that are composed largely of one colour have poor texture), but ranking one image compared to another is challenging. Bad texture leads to poor outcomes; for example, trying to locate a subset in a uniformly coloured image leads to a non-unique and erroneous result (a wild or noticeably wrong displacement measurement). Good textures, on the other hand, are harder to quantify as they can appear to be fairly similar to one another.

Over the past several years, researchers have investigated image texture and the associated relationship with PIV precision and measurement accuracy (e.g. Pan et al., 2009). Artificially generated patterns applied to the surface of an object have been used to both numerically and experimentally study the impact on accuracy and precision of the PIV technique. It has been found that the size of the dots in the artificial patterns and the size of the subset influence the displacement accuracy (Lecompte et al., 2005). The use of a larger subset decreases the error; however, if there are steep gradients in the displacement or strain field, a large subset will smooth the real behaviour leading to a reduction in accuracy.

These artificial textures, often called speckle patterns, are created by spraying white and/or black paints to create randomly sized and shaped high contrast dots. The speckle pattern deforms together with the specimen's surface and enhances the correlation process during the subset tracking stage. As the speckle pattern can be made by various techniques or by different practitioners, the resulting pattern may show different characteristics. Features such as the histogram distribution, image contrast and other parameters may be entirely different between patterns. It has been observed that displacement errors using the PIV technique are related to the quality of the specimen's texture (Yaofeng and Pang, 2007; Fazzini et al., 2009).

The ability to quantify and assess this image texture is important for the sample's surface preparation in order to optimize the use of the PIV technique. In laboratory experiments, it has been found that multiple sources of error are created. These sources include but are not limited to optical lens distortion, target lighting, out-of-plane displacement, and the camera's sensor (Haddadi and Belhabib, 2007). The use of good texture is thus critical to minimize these errors.

The texture of an image can be examined on a global or local scale. The global parameter encompasses how the entire image looks whereas the local descriptor presents how one subset compares with the remainder. This paper will use a global texture descriptor proposed by Pan (2010) called the mean intensity gradient (MIG). This parameter is defined as follows (Pan et al., 2010):

$$\mathrm{MIG}=\sum_{i=1}^{W}\sum_{j=1}^{H}\left|\nabla f(x_{ij})\right| \Big/ (W\times H) \qquad [1]$$

$$\left|\nabla f(x_{ij})\right|=\sqrt{f_x(x_{ij})^2+f_y(x_{ij})^2}$$

where W and H (in pixels) are image width and height, is the modulus of the local intensity gradient vector where f_x and f_y are the first-order intensity derivatives at pixel x_{ij}.

Pan (2010) found that the displacement measurement accuracy and the precision of the analysis are inversely proportional to the product of the subset size and the MIG of the speckle pattern. In other words, a specimen with a larger MIG is predicted to have smaller measurement errors and standard deviation of error. This global value is a good indicator of the required artificial texture and can be used during the preparation of a specimen's surface when the subset size is already selected. However, it is not clear what the relationship between MIG and texture

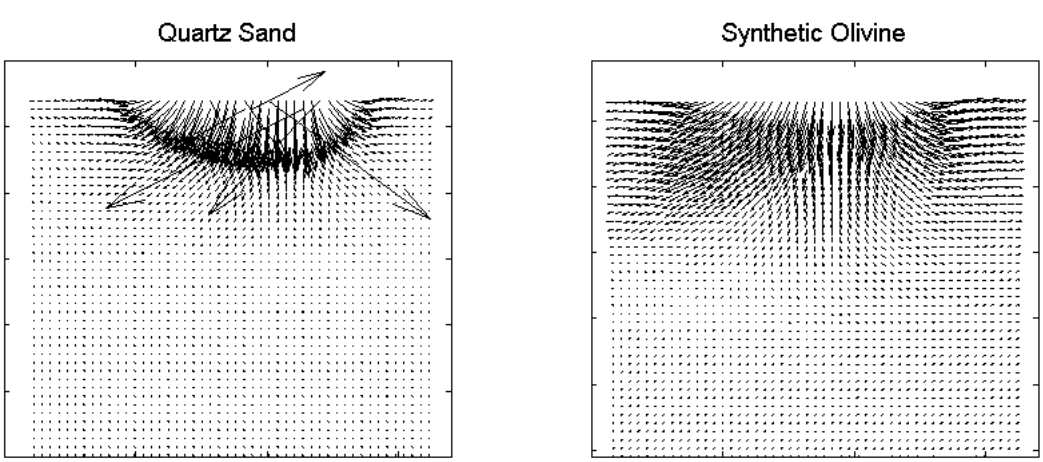

Figure 1. Vector displacement plot of compression beneath a shallow footing on a loose quartz sand (left) and synthetic olivine (right)

for commonly used sands are and so this is the subject of further investigation presented in this paper.

A common question when setting-up an experiment is where to place the camera to obtain the best possible results? The distance between the lens and the target will dictate the maximum field of view that can be achieved. Placing the camera too close limits this field of view and so the camera is usually placed further away. But as the camera is moved further away, the grain size to pixel ratio increases, with a subsequent reduction in accuracy. This paper's objective is to investigate what happens to the specimen's texture as the distance is increased. The apparent change in the texture will then impact the accuracy and precision of the PIV analysis results.

3 MATERIALS AND METHODS

Most engineering materials, including many types of clay, have a poor level of image texture associated with them; however, sand and gravel have a natural texture pattern generated by their varied grain size distribution and colour. In this paper, a quartz sand and a synthetic olivine sand are compared. The materials, as shown in Figure 2, are commonly used in geotechnical experiments.

A sieve analysis of the two sands, given in Figure 3, was performed to determine what the average grain size was and how the two sands compared. The distribution curves show that the sands are poorly graded with an average particle size of 0.81 mm and 0.73 mm for the quartz and artificial sand respectively. The material properties are given in Table 1. The similarity in size means that the colour of the grains rather than their size will be the most critical variable in the texture analysis.

In order to create the images, the sand was placed inside of a Plexiglas box. Pictures were then taken with the camera at varying distances away from the Plexiglass box. The camera used in the experiments was a Canon EOS XTi with a Canon EF 100 mm macro lens. To reduce camera movement and vibration, the body was placed on a tripod and the shutter was remotely activated with a trigger. The working distance, the length between the target and the front of the lens, was used for distance measurements.

The use of the Plexiglas box created a problem with reflection on the surface of the Plexiglas. In images that were taken sufficiently far away from the box, the legs of the tripod could be seen. However during the image analysis, the reflection was not an issue as the photographs were cropped down to a 1000 pixel square and the area in question was removed.

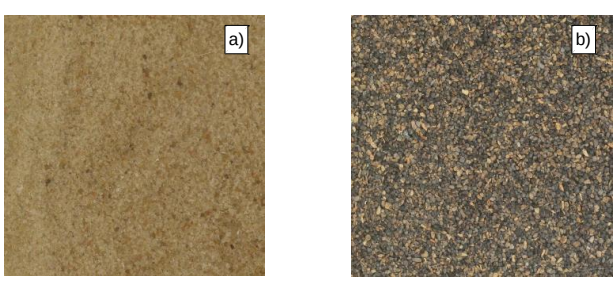

Figure 2. Photograph from one meter away of a) quartz sand and b) synthetic olivine

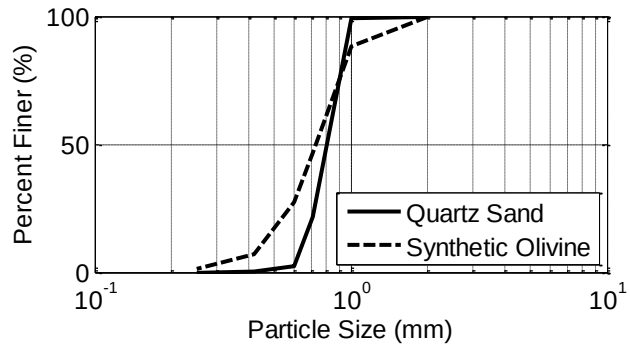

Figure 3. Grain size distribution of the quartz sand (solid) and the synthetic olivine sand (dashed)

Table 1. Material properties.

Sand	D_{50} (mm)	C_u	C_c
Quartz	0.81	1.33	1.01
Synthetic Olivine	0.73	1.82	1.09

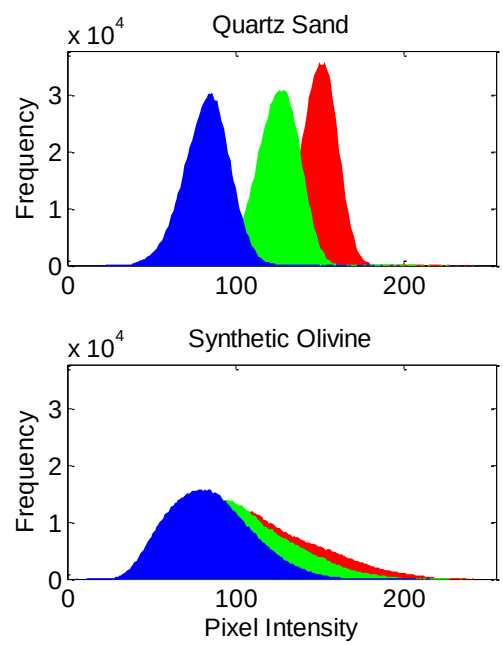

Figure 4. Pixel intensity histogram of the quartz sand (top) and the synthetic olivine (bottom)

4 EXPERIMENTAL RESULTS

4.1 Global Scale Texture

To determine the impact of distance between the camera and the target on the texture of sand, the camera was incrementally moved from 150 mm to 2750 mm as images were captured. An increment of 250 mm was used during the experiment. At the closest distance, few grain particles filled the images whereas the further away the camera moved; the grains began to blend together. Figure 5 illustrates the relationship between distance and the image texture as described using the MIG.

The mean intensity gradient focuses on the relative change in brightness between pixels. A higher MIG corresponds to larger gradients and a higher contrast image. The experiments showed that placing the camera too close to the specimen not only limits the field of view, but also results in poor texture. This low texture score is due to multiple pixels falling within a single grain. Looking at the pixel intensities along a line over a grain will show fairly similar values as the grain is typically uniform in colour. Once at the edge of a grain, the colour or brightness changes and the gradient increases rapidly. Moving the camera further away from the specimen increases the grain size to pixel ratio. This results in the MIG increasing. However, beyond a certain distance, it is observed that the global texture diminishes. The grain size to pixel ratio continues to increase but pixels now begin to span between two or more grains. The impact is to blur the image and the MIG decreases.

In these experiments, it was found that the maximum MIG occurred for each target at the same distance of 1750mm. Since both materials have similar mean grain sizes, it is believed that the shared maximum location is due to the similar grain size. In addition, the value of the maximum texture is noticeably different between the two sands. The quartz sand was found to have a maximum MIG of 4.3 whereas the synthetic olivine's maximum MIG was 12.8. This large difference is caused by the colour variation between the two sands as predicted previously by the histogram.

The variation in colour has been seen to play an important role in increasing the MIG and texture of an image. Once again looking at the pixel intensities along a line over a single grain now shows a changing gradient as the colour is not uniform from pixel to pixel across the grain. Furthermore, having different colours between adjacent grains will continue to enhance the gradients. This result matches well with earlier research into speckle patterns and how they have been found to have good texture (Pan, 2010). These patterns, which are primarily black and white, are not uniform in colour and tend to cover the full range in pixel intensities which in turn results in large intensity gradients.

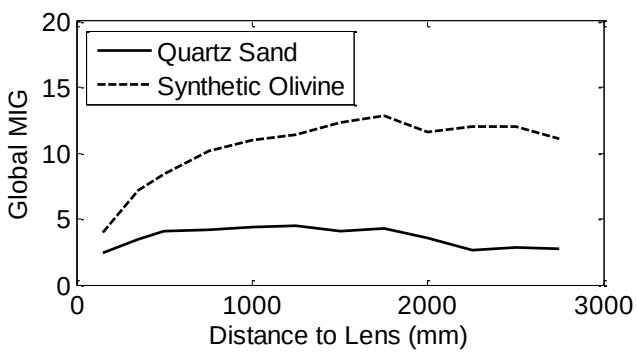

Figure 5. Impact of distance from lens to target sand on the global mean intensity gradient

4.2 Local Scale Texture

In order to analysis texture on a local scale, a PIV analysis was performed using the images of the synthetic olivine using the software geoPIV (White et al., 2003) with a modified B-spline sub-pixel interpolation scheme. Identical images were compared (i.e. the reference image and the deformed image were the same image) to see what effect local subset texture had on the measurement error. A square subset size of 16 pixels was used. Ideally every patch would be found to have zero displacement as the image did not change; however, as seen in Figure 6, there is a scatter in the measurement error. Using the mean intensity gradient to quantify the subset's texture, the impact of local texture on the measurement accuracy and how it varies with distance is illustrated. The errors for most subsets fall within the range of ±0.02 pixels; however, other subsets with similar MIGs produce higher errors. These wild or poorly tracked subsets are a result of the PIV technique being unable to accurately locate their intensity variations against the surrounding pixels in the search zone. Figure 6 shows that the PIV technique can track subsets with a variety of MIGs yet as their MIG decreases, the likelihood of a poorly tracked subset increases.

Marked in Figure 6 are two outliers with comparable MIGs that were selected to be examined and compared in greater detail. Point of interest 1 (POI 1) has been tracked poorly in the x-direction but adequately in the y-direction; the opposite is seen for POI 2, where PIV performs better in the x-direction instead of the y-direction. An enlargement of the two subsets is seen in Figure 7. The MIG suggests that both subsets have similar textures; 11.76 and 11.45 for POI 1 and 2 respectively. This would suggest that both should perform with similar accuracy yet there is a bias in the measurement accuracy in either the x or y-direction.

An accurate result using the PIV technique is dependent on locating the subset's unique pixel intensity variations from the surrounding neighbours. This subset correlation is improved, by contrast differences or gradients along the subsets rows and columns. Overlain on the subsets in Figure 7 are four cross-section lines which are illustrated in Figure 8. Looking at the pixel intensities along X1-X1, there is a single highpoint but then a generally uniform brightness. This is similar to line Y2-Y2, with a single high brightness then a uniform colour after it. Different intensity curves are seen along lines Y1-Y1 and X2-X2, which have peaks away from the subset's edge. Having the peaks located inside the subset creates

two steep intensity gradients; one on either side of the extreme. This added gradient improves the uniqueness of the subset and enhances PIV's ability to track it.

Using this as a possible explanation for why the PIV technique produces varying degrees of displacement accuracy with different subsets suggests that the MIG may not be the ideal descriptor. Originally designed as a parameter to average the global texture of speckle patterns, the use of the MIG on a local scale could be misleading. For POI 1 and POI 2, the intensity gradient in one direction is seen to be adequate while the other is poor. A texture descriptor which can describe the texture in both the x and y-direction is thus required to accurately relate the correlation accuracy with the target's texture.

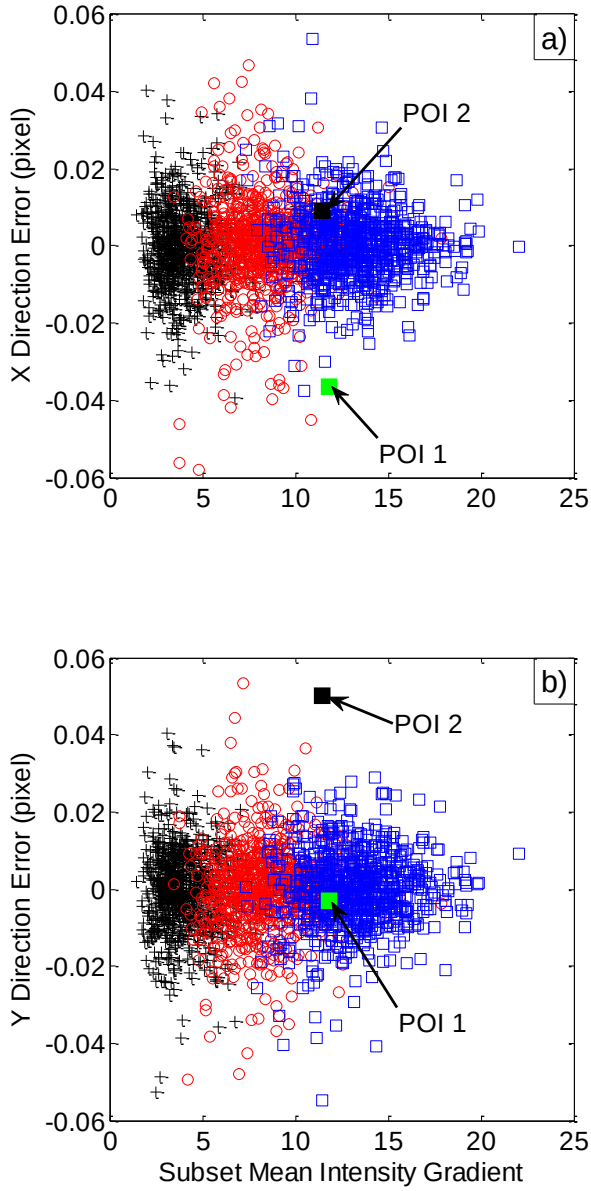

Figure 6. Comparison of subset mean intensity gradient with subset error for synthetic olivine at varying distances; + 150mm, ○ 500mm and □ 1750mm

5 FURTHER CONSIDERATIONS

In geotechnical processes, a strain range of 0.01% to 1% is seen to encompass serviceability and pre-failure displacements (White et al., 2001). Depending on the field of view selected and so the image distance to pixel ratio, the required movement accuracy is typically in the order of 0.1 mm. The PIV technique is within this resolution and so knowing the percentage of subsets that are wild is more beneficial. It has been observed that as the MIG decreases, the likelihood of a subset returning a bad result increases.

Another problem that arises as the camera moves back is image focus. During these experiments, it was noticed that after the peak MIG was reached, the camera started to experience autofocus issues. This required multiple exposures being needed and out of focus shots being discarded afterwards. The appearance of this problem is likely linked to texture and distance. A camera's autofocus relies on determining maximum contrast which would indicate a sharp infocus image. As has been observed, increasing the camera distance results in sand grains blending together (i.e. the grain size to pixel ratio increases). This can then result in a poorly focused image with inadequate texture.

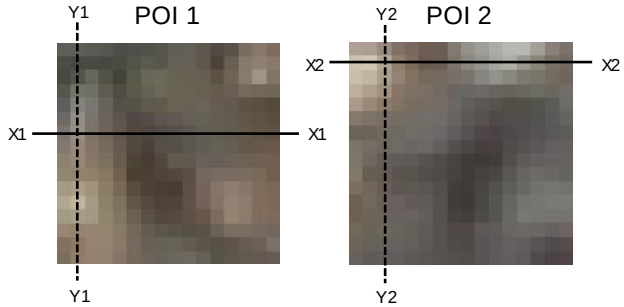

Figure 7. Enlargement of subset showing poor accuracy in the x-direction, POI 1, and in the y-direction POI 2

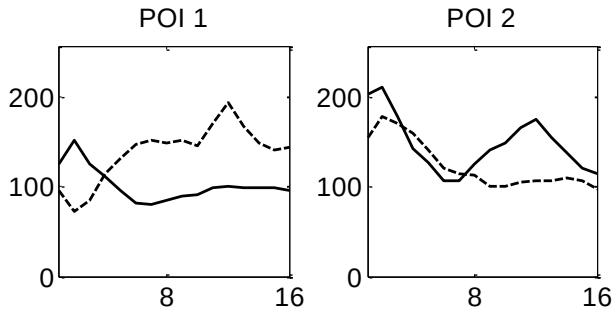

Figure 8. Pixel intensities along the x-direction (solid) and y-direction (dashed) for POI 1 and POI 2.

6 CONCLUSION

A relationship between global texture and the distance between a target specimen and the camera has been presented in this paper. The mean intensity gradient of a target image has been used to assess the texture on a global and local scale. It has been shown that for a given sand, there will be a range of camera locations that result in good texture. The acceptable distance is dependent on the grain size of the sand while the texture parameter is dependent on the colour variations of the target.

In addition, the mean intensity gradient was used to assess the texture on a local scale. The experiments conducted showed that with decreasing local texture, a subset was more likely to be tracked incorrectly. It was also noticed that subsets with similar mean intensity gradients could perform poorly in one direction but adequately in the other. Having a texture parameter, such as the MIG, which is designed as an averaging parameter could lead to an incorrect assumption about an image's texture and the associated accuracy.

The use of the MIG as a texture parameter on sand has been seen to be suitable as a global descriptor but issues arise around its use to quantify local texture. The placement of the camera in an experiment is not just controlled by the desired field of view, but also on the resulting texture of an image. Maximizing the field of view can lead to a decrease in the mean intensity gradient and an increase in the likelihood of a poorly tracked subset. The correct placement of the camera will help reduce these subsets errors by improving the natural texture of the sand.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Natural Science and Engineering Research Council (NSERC) of Canada for their financial support.

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