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Citation for published version (APA):
Waterfall, P. W., Read-Jennings, M. C. L., Scenini, F., & McCormick, N. J. (2012). Impact of surface finish and target size for testing and monitoring using cameras. In *9th International Conference on Condition Monitoring and Machinery Failure Prevention Technologies 2012, CM 2012 and MFPT 2012|Int. Conf. Cond. Monit. Mach. Fail. Prev. Technol., CM MFPT* (Vol. 2, pp. 1183-1194). British Institute of Non-Destructive Testing.

Published in:
9th International Conference on Condition Monitoring and Machinery Failure Prevention Technologies 2012, CM 2012 and MFPT 2012|Int. Conf. Cond. Monit. Mach. Fail. Prev. Technol., CM MFPT

Impact of surface finish and target size for testing and monitoring using cameras

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Abstract

Measurement and analysis using camera based techniques is becoming increasingly widespread across a wide range of industries from motion capture to materials analysis, number-plate recognition, surveying and quality control systems. Within the fields of Material Testing, Non Destructive Testing (NDT) and Condition Monitoring (CM), the advantages of camera based systems (notably being non-contact and keeping a visual record) are being recognised and starting to be exploited(1). This is particularly true of the composites industry(2), but includes many materials and structures. The techniques have not been widely adopted at present, in part due to concerns about ease of use, resolution, time taken to generate measurements and the need for patterns on specimens.

This paper seeks to test a system that has been designed to address these concerns(3). In particular, two areas of the technology are looked at which are relevant to adoption within NDT and CM. Firstly, an investigation is carried out to determine whether measurements can be taken without the need for any pattern to be applied to a material or structure. Stainless steel, mild steel, brick, stone, concrete and carbon-fibre composite are all assessed. Secondly, the impact of the size of the 'virtual target' that the software uses for analysis is examined. This has a direct bearing on spatial resolution that can be achieved when trying to analyse an object under test and the imaging locations required. The paper should enable the end user to determine whether for the type of testing they are seeking to undertake, an image based technique would be worth considering.

Results demonstrate that measurements are achievable on a wide variety of surfaces where no target has been applied, to resolutions of over 1/100th pixel. Surface pattern is shown to be key in achieving high resolution, but in all cases considered, suitable resolutions for some applications are achieved. Optimum virtual target sizes vary depending on the nature of the pattern on the material under investigation and the experimental setup, but measurement resolution broadly increases with target size.

1. Introduction

Camera based measurements are now relatively well established within research facilities worldwide(4), and are starting to be used for routine testing applications(5) too. The two techniques normally used for measuring change in size are video extensometry (VE) and digital image correlation (DIC). A further technique, photogrammetry, is used to measure absolute size. This has many useful applications but is not within the scope of this paper as it has a number of fundamental technical differences with VE & DIC.

Video extensometry performs a similar function to an extensometer, measuring to a particular ASTM or BS/EN/ISO standard, whilst avoiding the need for contact with the item under test(6). Usually, a few points within a video are measured in real time. This enables cost savings by speeding up the measurement and preparation process for test specimens, as well as enabling materials to be tested to destruction without the risk of damaging the measurement device. Increased flexibility is added as a video of the test can be recorded for re-analysis using different measurement locations (e.g. if a crack does not propagate where anticipated). It is not used to generate strain maps.

Digital image correlation is primarily concerned with identifying changes in strains or shape across the whole image of the sample under investigation. This method enables differential strains to be highlighted within a specimen, and gives an indication of the strains on a sample. Pressure points can be identified, and areas can be scanned to search for the early onset of cracks. DIC is not usually real time, as the analysis of a complete image takes longer than measuring a few points (as is done in VE).

Both types of system have the potential to be used within NDT and CM, for in-service assessments and laboratory based analysis. The speed of setup and deployment of the best of these systems could lead to an improvement in diagnostic speed for vibrating machinery(7) in certain circumstances. Alternatively, determination of defect location during loading without the need to make contact with the item under investigation would be a safer investigation technique in many cases.

For potential applications, key areas of interest are system resolution, measurement speed, implementation cost and pre-test preparation. This paper takes a VE system which seeks to differentiate itself on the basis of speed and accuracy(8), and assesses its resolution on a number of surfaces that are relevant to CM and NDT. The appearance of a surface under investigation is of particular importance to getting good measurement resolution with image based measurement techniques, and so this assessment is a key enabler – if it is possible to make good measurements on an engineering surface without an artificially applied pattern, many new application areas will be opened up.

2. Image Based Measurement – Fundamental Technologies

Image based measurement of change uses two fundamental technologies – Pattern Recognition and Image Correlation. A camera (video or still) collects information it receives from the lens on a sensor (usually either CCD or CMOS). This sensor has a number of pixels, and each pixel records a level of greyscale (shade). Depending on the sensor type, this would usually be between 8-bit (256 shades) and 16-bit (65,536 shades). Pattern recognition software can keep a spatial record of these shades, which can then be used either to identify predefined objects directly (such as numbers and letters on a registration plate), or stored for use later.

To calculate measurements, a sub-image (say 20 × 20 pixels) is recorded, then searched for again in the following frame (image correlation), as shown in Figure 1. Once the pattern is located, its movement relative to the previous frame can be calculated. At a basic level, this can be done from one pixel to the next, so a measurement resolution of 1/1,000 of the field of view could be achieved for a 1 megapixel camera (1,024 pixels in each direction). This resolution is acceptable for some systems where large amounts of movement are of interest – for example motion capture or crash testing, but it is not precise enough for most test and measurement applications. For this reason, many researchers have investigated how to obtain sub-pixel resolution(9).

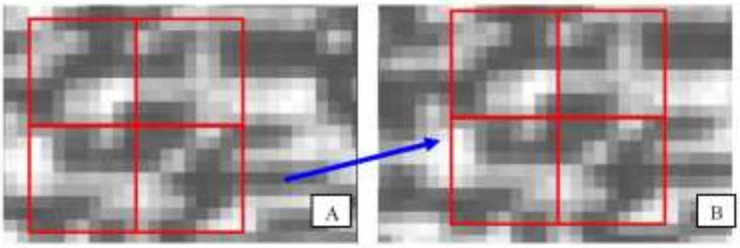

Figure 1 – Image correlation tracks the specified sub image from one frame of the digital video to the next.

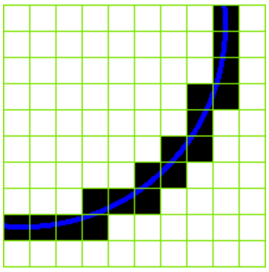

Figure 2 – sub-pixel render of a ¼ circle. (10)

2.1 Sub-Pixel Resolution

Ssub-pixel resolution is achievable because the real world is analogue. This is true of both shape and shade. So, for a camera looking at a bicycle then however the frame is orientated, all the tubes will not line up with the pixel orientation of the sensor. This will lead to steps in the pixel record (Figure 2) where a pixel goes from being mostly background shade to mostly frame shade. Additionally, depending on how much of the frame is in the pixel, the overall shade will vary (e.g. a black frame would show a darker grey if ½ the pixel was frame than if ¼ of the pixel was frame). It is possible from the pixel record to derive an equation that more accurately describes where the edge of the tube is than the pixel record does, using the shade contours. These indicate the most likely extent of any particular shade and hence the shape of an object of that shade.

Published algorithms take the possible resolution of a system such as this (whether VE or DIC) to around 1/50th of a pixel(9), meaning that the resolution for a 1 megapixel camera is pushed up to 1/50,000 of the field of view. At this level, the technique becomes useful for a number of applications as described above.

2.2 Increasing Resolution

Researchers at Imetrum(3) have developed algorithms that are now capable of delivering over 1/500th of a pixel resolution in ideal circumstances, as in the case of the speckle pattern here. This enhanced resolution has led to widespread use within the composites industry where strains are typically lower than a standard system could reliably detect. It also means that for larger structures, it is possible to a relatively wide field of view lens and still get measurements of sufficient resolution at many points on the structure(11).

3. Assessing Measurement Resolution

There are a large number of variables involved in image based measurement (lens, camera, lighting, processing algorithms, software setup, distance from object, field of view, surface finish), making an exhaustive comparison of all of them impractical. For this reason, the investigations here primarily deal with the surface finish of the object under investigation and the target sub image size used by the software for analysis. Camera, lighting and software setup are as consistent as practical, with lenses of similar quality. Different lenses, measurement distances and fields of view were used to reflect likely measurement scenarios for real applications.

3.1 Measurement Principles

The main focus of this paper is to assess the impact of surface finish and target size on resolution. When using a camera to take measurements, a number of factors contribute to the errors in position measurement observed. One of the most significant can be any apparent differential movement between the camera and the object being measured. For this reason, relative measurements have been taken for the purposes of this assessment (the difference between two points), rather than absolute measurements. This nullifies some of the effects of camera movement and some of the effects of variations in the optical path (e.g. heat haze). Those familiar with DIC principles will also know that image sensor noise also has an impact on lowering measurement resolution, and for this reason standard equipment was used to minimise any impact of this effect.

To quantify the resolution, the standard deviation of the measurement when the target is stationary is generally quoted. In videos where the targets being measured are not stationary, the standard deviation from a line of best fit between the measurement points in used. Because measurements are between two points and the errors in position of the measurements typically follow a normal distribution, we can say that for a single point,

$$Resolution\ (pixels) = \frac{1}{2}\frac{\sigma(measured\ strain)}{gauge\ length\ (pixels)} \quad \text{(1)}$$

3.2 Equipment

Standard uncooled machine vision cameras with two different Sony ICX CCD sensors were used to suit the range of applications. Standard tests used a 1388 × 1038 pixel, 6.45 μm pixel size sensor (1mp). Some tests required greater resolution of measurements, and so used a 2452 × 2056 pixel, 3.45 μm pixel size sensor (5mp). Depending on context, either an General Purpose (GP) or Material Testing (MT) lens was used. All tests used a standard Dell laptop running Imetrum's Video Gauge software. Trials were conducted at speeds of 5 Hz and 15 Hz, although the system is capable of running at up to 400 Hz in real time. Whilst using two different sensor sizes and running at two different frame rates will have some impact on ‘shot noise’ from the image sensor, and hence measurement resolution, this effect is small compared to the impact of surface pattern being studied.

3.3 Methodology

Firstly, tests were undertaken using standard 80 × 80 pixel sub images as virtual targets. These virtual targets were set up within the software equidistant from the centre of the image, around ⅔ of the way to the edge of the field of view. These were arranged to form a vertical strain gauge and a horizontal strain gauge in the software, as indicated in Figure 3. For the tests done at NPL, the bullseye target (on site) and the mild steel (on site), two parallel strain gauges were used (e.g. Figure 10). The standard deviations (σ) of both of these were recorded in microstrain (μs), usually for around 1000 frames.

A more detailed investigation of the impact of target size was then done for selected materials. This consisted of re-running the tests using exactly the same video, but changing the sub image size to 160 × 160, 120 × 120, 60 × 60, 40 × 40 and 20 × 20 pixels in order to understand the impact of reducing the amount of digital information the processing algorithms have available for sub-pixel interpolation. This provides insight into maximum measurement resolution available where spatial resolution is less of a concern, such as for vibration analysis. This approach also gives an idea of spatial resolutions achievable where a DIC approach to identify crack locations is required.

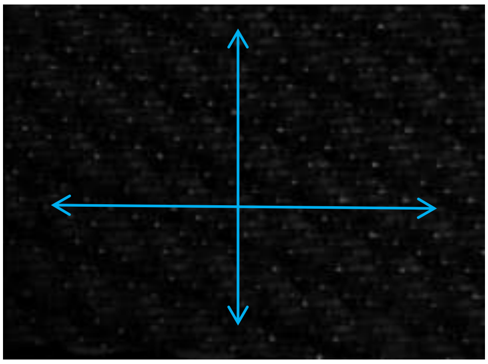

Figure 3 – Rough carbon composite

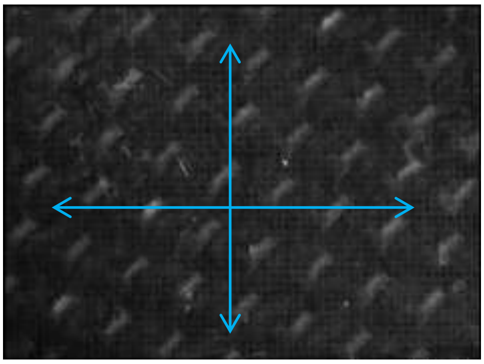

Figure 4 – Smooth composite

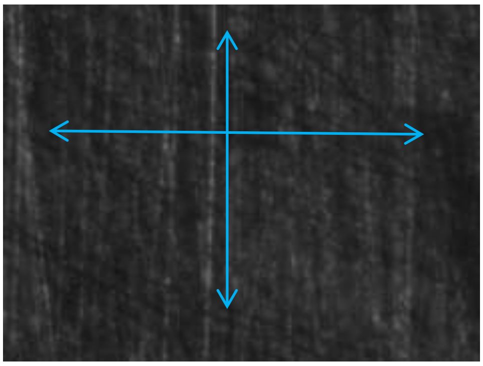

Figure 5 – 1200 grit polished stainless steel (0.6 × 0.4mm FoV)

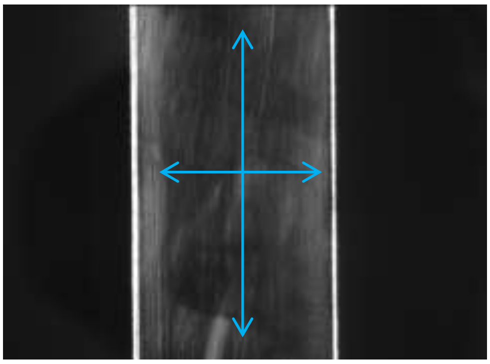

Figure 6 – 1200 grit polished stainless steel (24 × 18mm FoV)

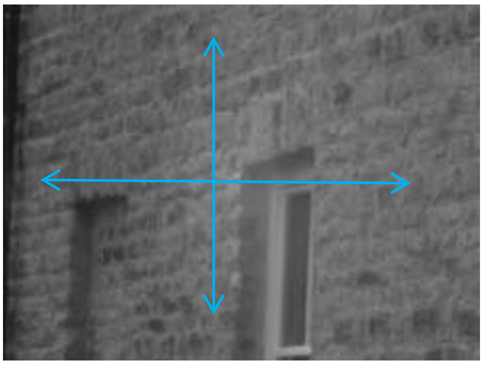

Figure 7 – Stone (under bridge)

Figure 8 – Mild steel

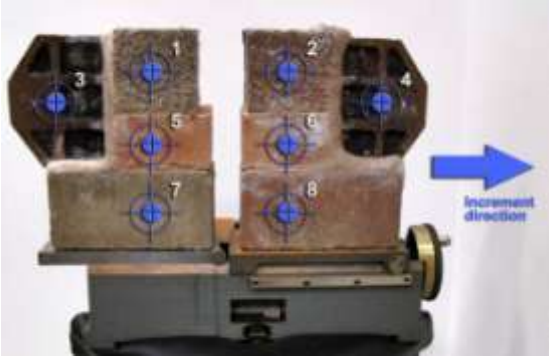

Figure 9 – NPL test setup (calibration rig)

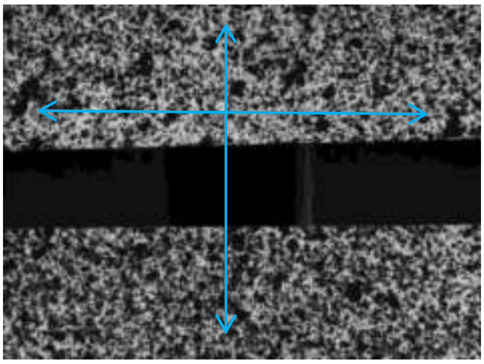

Figure 10 – Speckle pattern

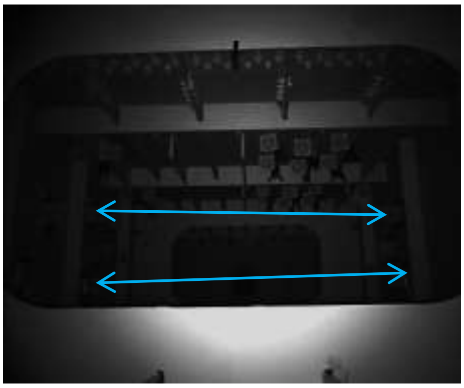

Figure 11 – Bullseye (on site)

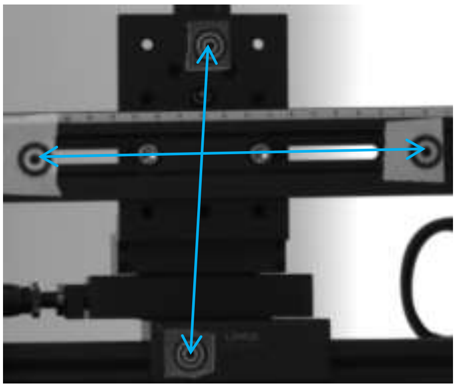

Figure 12 – Bullseye (in lab)

4. Results

4.1 Surface Pattern

The resolution achieved for various surface finishes on different configurations are shown in Table 1. The results are both for unmarked sample materials (Figures 3-9) and for ‘ideal’ setups (Figures 10-12) The data were taken from running the measurement software in post-process mode, following the methodology outlined above. The locations of each test are also indicated since testing was undertaken in different locations: at NPL, University of Manchester (UoM), Imetrum and on site.

Table 1. Resolutions for various surface finishes (refer to Figures 3-12 above)

Location (sample image)	Material	Dist (m)	Field of view (mm)	σ 1 (μs)	σ 2 (μs)	Resolution (pixels)	Approx no. of frames	Camera & lens type
Imetrum (Fig. 3)	Comp. (rough)	0.07	26 × 19	10.9	15.7	1/137	1000	1mp MT
Imetrum (Fig. 4)	Comp. (smooth)	0.07	26 × 19	10.9	11.8	1/156	1000	1mp MT
UoM (Fig. 5)	S. Steel 1200 grit	0.05	0.6 × 0.4	55	32	1/46	500	5mp MT
UoM (Fig. 6)	S. Steel 1200 grit	0.54	24 × 18	166	173	1/17	500	5mp MT
On Site (Fig. 7)	Stone	15.7	1870 × 1400	137	100	1/12	1000	1mp GP
On Site (Fig. 8)	Mild Steel	6	3000 × 2200	47	57	1/34	600	1mp GP
NPL (Fig. 9)	Smooth Concrete	7.8	640 × 480	109	115	1/53	900	1mp GP
NPL (Fig. 9)	Rough Concrete	7.8	640 × 480	64	48	1/84	900	1mp GP
NPL (Fig.9)	Brick	7.8	640 × 480	78	89	1/71	900	1mp GP
NPL (Fig. 9)	Mild Steel	16	640 × 480	167	253	1/12	900	1mp GP
Imetrum (Fig. 10)	Speckle Pattern	0.3	32 × 24	4.95	3.47	1/433	500	1mp MT
On Site (Fig. 11)	Bullseye	4	4200 × 3500	8.13	11.7	1/90	250	5mp GP
Imetrum (Fig. 12)	Bullseye	1.8	210 × 160	7.69	6.73	1/207	1000	1mp GP

MT = Material testing lens; GP = General purpose lens.

From the results above, it is notable that surface pattern has a significant impact on system resolution. There is a factor of 35 difference between the best resolution (speckle pattern), and the worst (stone). The patterns offering the highest resolution are indoors where an artificial pattern has been applied. The measurements on the two pieces of unmarked carbon fibre have resolutions greater than 1/100th pixel, illustrating that the weave in these particular cases is good for the software to track. The tests on concrete and brick both indicate a resolution of greater than 1/50th pixel (around 10 μm in this case), which would be sufficient for a range of measurement requirements.

Lower resolutions are measured on the 1200 grit polished stainless steel, stone and mild steel. All offered some pattern that allowed the system to measure movement to around 1/20th pixel. For the stone (as an example), the system provided an overall resolution of approximately 0.1 mm, which is acceptable for most Civil Engineering applications. For the polished stainless steel, 1/17th pixel translates to around 1 μm resolution over the 24 × 18 mm field of view being examined, which is again adequate for many applications.

In broad terms, measurements taken outside give a lower resolution. This confirms that optical noise needs to be considered carefully for any particular setup.

4.2 Virtual Target Size

The impact of target size on measurement resolution for stainless steel, mild steel, stone, a bullseye target (both in the lab and on site) and a speckle pattern is examined here. The physical setup of the experiment is as before (all using same 1mp camera except ‘bullseye on site’ which uses 5mp), however the size of the virtual targets used by the software is varied. For each test, the target is centred on an object likely to provide a reasonable lock in both directions. Average standard deviations in microstrain (μs) are shown in Table 2 below and resolutions indicated graphically in Figures 13 and 14.

Table 2. Resolutions for reducing target size

Target size	S. steel 1200 grit 0.6 × 0.4	Mild steel	Stone	Carbon composite (rough)	Bullseye target (lab)	Bullseye target (site)	Speckle pattern
	Average standard deviations (μs)						
160×160	15.3	56.0	108	5.06	6.45	30.5	2.34
120×120	17.6	57.8	113	8.01	6.67	11.7	2.79
80 × 80	29.1	52.1	118	9.40	7.21	9.92	3.50
60 × 60	29.1	54.0	125	12.30	9.74	11.7	3.54
40 × 40	48.8	56.7	128	14.0	9.78	14.0	4.59
20 × 20	56.7	92.2	152	17.8	21.1	24.4	9.33

Resolution broadly increases with target size, as there is more information on which the software can lock the precise location of the target. There appear to be 3 exceptions to this general principle:

1. The bullseye-target on site shows a reduction in resolution above 80 × 80 pixels. This is because the bullseyes were designed for an 80 × 80 target, and were fixed to the location with brackets of a similar size. When the target size increases beyond this, then the software starts incorporating information from a different part of the structure which is moving differently, and therefore generating more variation.

2. The bullseye target in the lab has very little increase in resolution above 80 × 80 pixels for a similar reason (but the surround area is not moving differently).

3. For trials carried out where the object being measured is fully outside (mild steel and stone), there appears to be no change in resolution above 40 × 40 pixels. This suggests that the governing factor of the resolution is not the quality of the virtual target being assessed, but the effects of the variations in optical

path associated with the setup. The other alternative would be that the increased size of virtual target does not add significant extra information to determine location (as in the case of the bullseye targets). However, from looking at the image files, this does not appear to be the case.

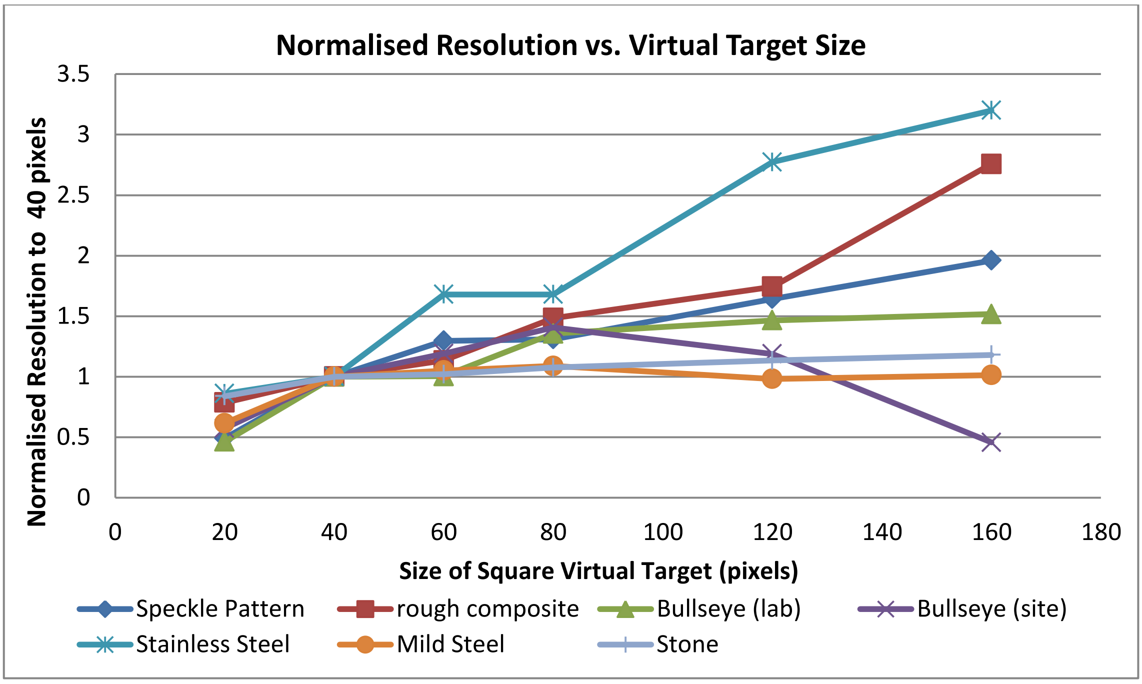

Figure 13 – Normalised resoltion vs. target size (resolution at 40 × 40 pixels = 1)

These 3 effects are drawn out clearly in the graph of normalised resolution in Figure 13 where it can be seen that there is no increase in resolution above 40 pixels for Stone and Mild Steel, or 80 pixels for the bullseye targets. Resolution of the other materials broadly continues to increase with target size, although there are some instances where the effect is minimal, such as between 60 and 80 pixels for the stainless steel.

The importance of surface pattern to the overall resolution of measurements can be seen clearly from a plot of the results tabulated above. The maximum resolution achieved here for a surface with speckle pattern of close to 1/800th of a pixel is well beyond any resolution levels previously published for Digital Image Correlation or Video Extensometry using commercially available cameras(12,13). The resolutions of 1/300th pixel for unmarked carbon composite and 1/100th pixel for Stainless Steel polished with 1200 grit emery paper are also well beyond what has been published previously. They indicate the viability of using this particular image based measurement system for a wide range of NDT and CM applications, provided appropriate testing procedures can be developed to conform to international standards (as has been the case with video extensometers and BS/EN/ISO 9513(14)).

The wide range of measurement resolutions (plotted in figure 14) show that for any particular test or monitoring requirement, it will be important to assess whether a suitable pattern is available on the surface of the material to get measurements to sufficient resolution. If this pattern is not available, then a suitable means of applying one needs to be considered.

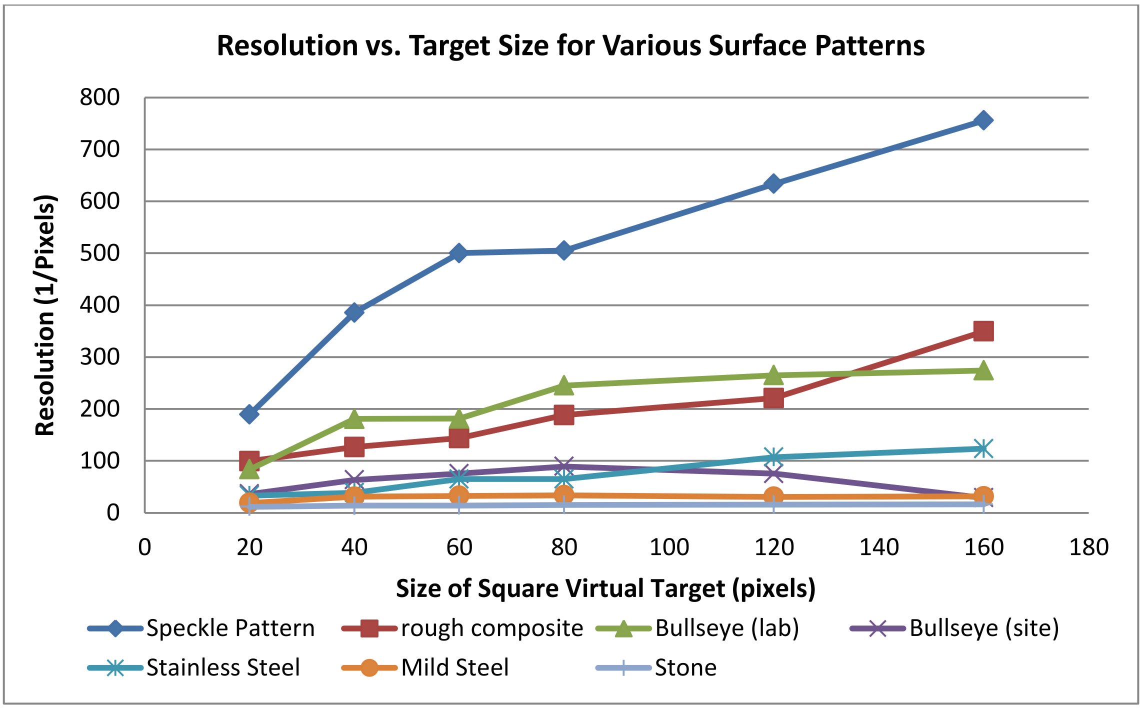

Figure 14 – Resolution vs. target size for various surface patterns

5. Conclusions

The system under test in this paper has been shown to address many of the concerns about using image based measurements within CM and NDT. System resolution has been investigated on 13 different cases, and shown to be acceptable for a wide range of applications. In the best circumstances resolution has been measured at close to 1/800th pixel, and for unmarked carbon composite has been over 1/300th pixel. For unmarked stainless steel, concrete and brick, resolutions of over 1/50th pixel have been achieved, whereas for stone and mild steel, resolutions have been closer to 1/20th pixel. Depending on the field of view used, these resolutions are from 10 nm to 1/10th of a mm.

Resolution has been shown to broadly increase with increasing virtual target size, provided that a) more information is encapsulated in the larger target and b) the effects of variation of the optical path does not have a significant detrimental impact.

The system tested can measure in real time at up to 400 Hz, and has been found by the authors to be relatively straightforward to use on a wide range of structures. Experimental results have highlighted the importance of getting a good setup to generating accurate results, and that surface finish and optical environment are two of the key factors in this process.

Acknowledgements

Much of this work was funded through Bristol University's EPSRC funded Industrial Doctorate Centre in Systems (Grant EP/G037353/1). Some was carried out as part of a UK Government National Measurement Office project investigating optical techniques for civil engineering applications. Further work was done as part of the Technology Strategy Board's Nuclear Feasibility Studies. We also acknowledge the support given by Imetrum, Network Rail, Rolls Royce and Atkins.

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