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PUBLISHED AS

LePage W, Shaw JA, Daly SH. "Optimum Paint Sequence for Speckle Patterns in Digital Image Correlation." Experimental Techniques 41, 557-563 (2017).

https://doi.org/10.1007/s40799-017-0192-3

# Optimum Paint Sequence for Speckle Patterns in Digital Image Correlation

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**Abstract**

This note answers whether it is better to use black-on-white or white-on-black painted speckle patterns, and provides recommendations for optimum painted patterns for digital image correlation (DIC). Although DIC algorithms have no preference between tracking the patterns of either bright features or dark features on contrasting backgrounds, we show that paint sequence can be important due to fundamental differences in paint pigments. If the sample and experiment conditions call for two painting steps (basecoat and speckles), then applying a basecoat of white paint followed by black speckles is better than the converse. Black speckles are preferred because they increase contrast and provide a higher mean intensity gradient, lower correlation confidence interval, and lower displacement error. The primary reason for the increased contrast is the greater hiding power of black paint versus white paint. A secondary effect that also reduces contrast in white speckles is undertone, or a slight blue hue shift from Rayleigh scattering.

*Keywords: speckle pattern; digital image correlation; DIC; optical imaging; paint order*

## 1 Introduction

Optimizing the speckle pattern on a sample is one of the key ways to improve deformation measurements by digital image correlation (DIC). This work shows that, in the case of painted speckle patterns, the order is often important for the pattern's contrasting basecoat and speckles.

DIC is a non-contact surface displacement measurement technique that is popular for characterizing the mechanical properties of solid materials. DIC computes displacements across the

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surface of a material, so it resolves nonuniform deformations from local features such as material heterogeneities and interfaces. The three fundamental steps of DIC are to (1) apply a pattern of contrasting features, or "speckles," on the sample surface, (2) capture a sequence of images during mechanical deformation of the sample, and (3) compute the sample's surface displacements with a DIC algorithm. The quality of each of these three steps determines the overall accuracy and precision of DIC's displacement measurements.

The ideal speckle pattern has a randomly-distributed arrangement of dots (speckles) with high contrast relative to the background, strong adhesion, and negligible stiffness relative to the sample [1]. Since DIC algorithms compute displacements in pixel space, the length scale of DIC is determined by the imaging system. Reported DIC measurements have spanned orders of magnitude in length, with speckle diameters ranging from individual atoms with high-resolution transmission electron microscopy [2], to nanometers and microns with scanning electron and optical microscopes [3, 4], to centimeters for magnetized plates on bridges [5], and to meters for topological features on volcanoes [6]. At the extreme length scales of nanometers and meters, painted speckle patterns generally do not provide properly sized speckles (about 3 x 3 pixels across) [1, 7]. However, most laboratory DIC experiments use speckles with diameters of about 10 to 1,000 microns. At these typical length scales, speckle patterns of sprayed paint are expedient because of paint's relative compliance on many materials and the ease of applying a random arrangement of acceptably-sized dots. For airbrush painted speckle patterns, guidelines have been established for controlling speckle size and consistency. More consistent speckle sizes were found with diluted paint, increased spraying standoff distance, increased pressure, and decreased airflow. Larger speckles can be created with diluted paint, increased airflow, and decreased pressure [8].

Occasionally, samples already have a uniformly dark or bright surface before painting that serves as the contrasting background, but for most samples, a basecoat is required to maximize contrast and reduce sources of glare such as shiny features on the sample surface. These shiny features can create saturated pixels, which prohibit sub-pixel accuracy and increase correlation error [1]. The basecoat should be thin and uniform to maintain good adhesion and compliance with the sample, and should fully cover the sample surface to avoid the glare sources, particularly with metal samples [9, 10].

For painted DIC speckle patterns, black and white paints are predominantly selected in order to maximize grayscale contrast, because higher contrast lowers correlation error by increasing image gradients [9]. Then the question arises: should the speckle pattern have a black basecoat with white speckles, or a white basecoat with black speckles?

In this work we explore why black paint creates superior speckles over white paint. First, we present observations of paints without performing DIC analyses and discuss the relevant properties of common paints for DIC speckles. Next, we show DIC results of false displacements from static images in order to quantify the noise errors from each paint sequence, and then we conclude with recommendations.

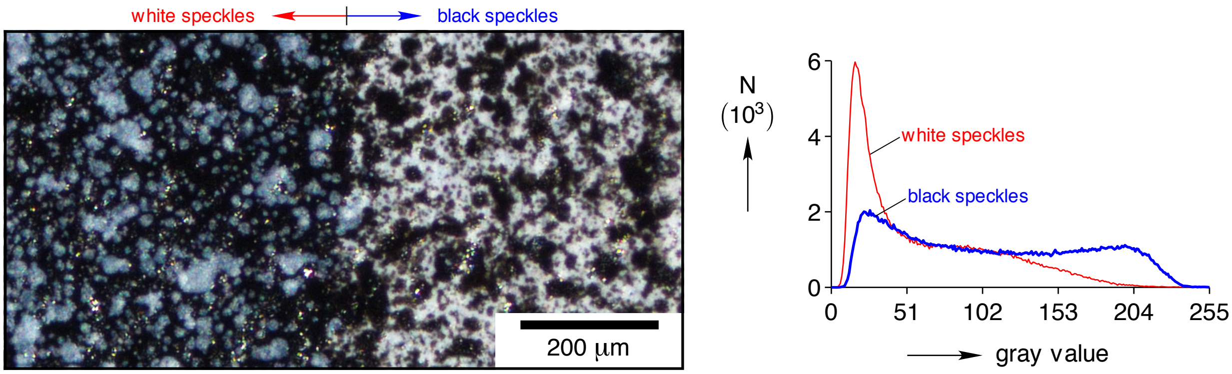
## 2 Observations and properties of paints

On top of the basecoat or sample surface, contrasting dots (speckles) are applied to create a pattern of spatially unique areas of pixels, or "subsets," for correlation. Speckles should consistently be at least 3 x 3 pixels across to avoid aliasing [11], but not much larger than 3 x 3 pixels to maximize spatial precision [7]. Another consideration for painted speckles patterns is the elapsed time between painting and testing. Shorter times are preferred, from hours to a few days, especially for high-strain or high-rate experiments, because the paint becomes more brittle with prolonged drying [1, 10].

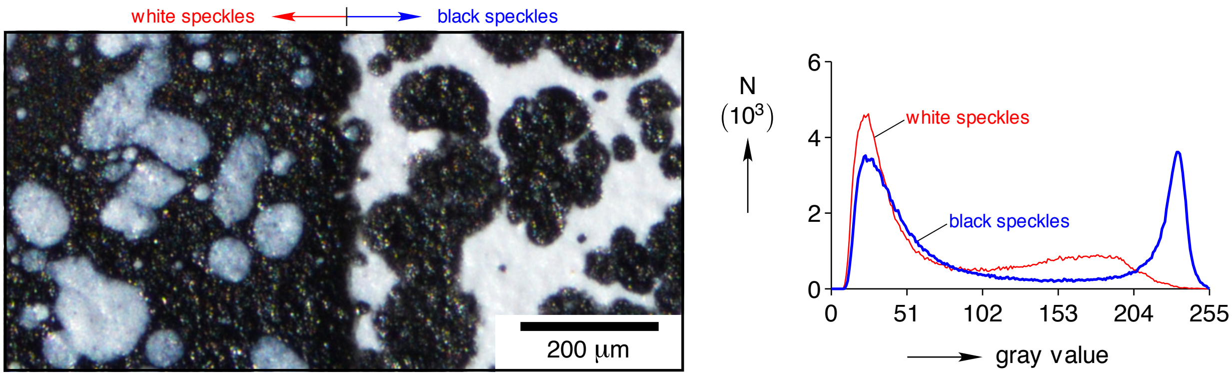
Fundamental differences between black and white paints were probed by examining speckle patterns made by two common paint patterning methods, airbrush and spray can. With both samples, paint sequence was alternated in two adjacent regions by selectively masking with low-adhesion tape (ScotchBlue, 3M). This allowed the two paint sequences (black speckles on white basecoat, and white speckles on black basecoat) to be viewed simultaneously for accurate comparison (Figure 1).

For the airbrush sample, a 3 mm diameter metallic rod was selectively masked and painted with thin basecoats of black and white paint (Golden High Flow Carbon Black, no. 8040-4, lot 345307, made with calcined natural iron oxide containing manganese; Golden High Flow Titanium White, no. 8549-4, lot 366162, containing titanium dioxide rutile [13]) using an Iwata CM-B airbrush with 0.18 mm fluid nozzle and needle, with an Iwata Studio Power Jet air compressor at 210 kPa (30 psi). Then speckles were applied with the same conditions using the opposite paint, again with selective masking to create two adjacent patterns with alternate paint sequence. For the spray can sample, a glass slide was speckled in the same selectively-masked method with Rustoleum Flat Protective Enamel black and Rustoleum Flat Protective Enamel white.

Optical micrographs of the samples created by airbrush and spray can methods reveal differences between black speckles and white speckles (Figure 1). Similar effects are seen for both patterning methods. Black speckles exhibit good *hiding power*, or the ability to obscure the underlying white basecoat, while white speckles have lower hiding power on the black basecoat. This is particularly true when the white paint is applied in a thin layer (shown later in Figure 2). Full opacity to cover the underlying black paint is not achieved because the white paint does not have sufficient hiding power. Later, we show that this incomplete opacity is also manifested by lower




(a) airbrush




(b) spray can

Figure 1: Black speckles maintain high contrast on white basecoats, while white speckles have less contrast because white paint has lower *hiding power*, or the ability to obscure the underlying basecoat. There is also a slight contrast decrease (when viewed in grayscale images for DIC) from undertone, which is the subtle blue hue in the white speckles from Rayleigh scattering. Optical micrographs (in color) of adjacent speckle patterns were created by an airbrush (Figure 1a) and spray can (Figure 1b). The optical micrographs shown do not include cross polarization, so there are numerous bright spots due to glare. Cross polarization was used for the DIC images, however, to attenuate the glare [12]. Each image is a single color micrograph (not stitched together), with accurate white balance to show the blue hue from undertone. The grayscale histograms to the right of each image are computed from the micrograph areas that are shown.

speckle densities (Figure 4). Black paint is known to have superior hiding power versus white paint, especially because of inherent differences between their origins of hiding power. Black paint creates hiding power by absorbing light, while white paint creates hiding power by scattering light. Light scattering is more difficult to achieve with paints because it requires pigment with a high refractive index and uniformly small particles with diameters slightly less than half the wavelength of light to be scattered (about 200 to 300 nm) [14, 15]. Much work since the 1930s has improved the hiding power of white paints, especially with the development of synthetic titanium dioxide pigments and coatings [16] and an ASTM standard to measure the hiding power of paint [17], but it still lags the hiding power of black paint.

In addition to incomplete opacity from lower hiding power, white speckles exhibit a small but noticeable effect called undertone that reduces contrast slightly. This undertone is evidenced by the bluish hue of the white speckles in Figure 1. Undertone arises from Rayleigh scattering, which is the interaction of various wavelengths of light with particles smaller than the wavelength of light. Blue light has a shorter wavelength and higher scattering efficiency, while red light has a longer wavelength and higher absorption, so the reflected light has a bluish hue. Due to a more prominent difference between the scattering of blue wavelengths and absorption of red wavelengths, undertone is more prevalent in white paints than in darker paints [14, 15].

Both the lower hiding power and undertone of the white speckles decrease their contrast against the black basecoat. No bleeding of the black basecoat into the white speckles is suspected because there was no observable difference in optical micrographs of patterns with a ten minute drying time and patterns with a two day drying time.

# 3 DIC experiments and results

Eighteen speckle patterns were prepared on glass slides with the airbrush method outlined in Section 2 with varied speckle density (or coverage). A range of sparse to dense speckles were created by manually airbrushing a gradient of paint onto 9 glass slides for each paint sequence. The speckle patterns are presented in Figure 2, with increasing speckle density $\rho_s$ going down the page. The 18 patterned slides were imaged with a 3-D DIC system comprised of two cameras (Point Grey GRAS 50S5MC with Nikon Micro Nikkor 200 mm f/4-30 lenses at f/11) and two LED light panels (LitePanels no. 935-1003), as shown in Figure 3. The patterned slides were held stationary, so any measured displacements are false (see Figure 5). These repeated measurements access the “type A” errors that define the measurement noise floor [18]. For DIC, type A errors include image noise, contrast, speckle quality, and air turbulence [19]. Cross polarization, or the use of orthogonal linear polarizing filters on the cameras and lights, was deployed to improve DIC quality. Cross polarization increases contrast and attenuates saturated pixels to decrease DIC error and enable smaller subsets [12]. Also, a fan mounted on a tripod separately from the DIC setup maintained turbulent airflow to avoid error from heat waves [20]. The LED light panels operated at full power, and the exposure times $t_{exp}$ of the cameras were increased in 0.5 ms intervals just until no saturated pixels were observed with either camera. The exposure times were all relatively short, ranging from 11.5 to 17.5 ms. In general, more white paint in the speckle pattern (whether as the basecoat or as the speckles) reduced the exposure time for which no saturated pixels were observed (Figure 4).

DIC analysis was performed with Vic3D 7 software. The correlation threshold values are listed in Table 1. Correlation step size (the spacing among DIC data points) was 7 px for all cases, and the central 25 % of the area (7.5 mm$\times$9 mm) was chosen as the area of interest. This yielded about 25,000 3-D DIC data points for each speckle pattern. Vic3D software includes a "suggested subset size" feature that computes the subset size that yields a mean correlation confidence interval ($\overline{\text{CCI}}$) closest to 0.01 px. All of the suggested subset sizes ($S_{sugg}$) are relatively large, ranging from 53 to 121 px (Figure 4), because most of the speckles are also relatively large (about 100 $\mu m$) compared to the pixel size (7 $\mu m/px$). For a fair comparison among speckle patterns of DIC metrics, such as correlation confidence intervals and false displacements, the suggested subset size was not chosen, but rather a subset size of 53 px was used for all of the DIC analyses. The correlation confidence interval (CCI) is a statistical measure of the correlation's accuracy for a subset's displacements from the reference configuration, so a smaller CCI indicates a better correlation. The smallest CCIs are observed for the patterns with black speckles ( Figure 4).

Speckle patterns with the highest (best) mean intensity gradients (Figure 4) had the broadest grayscale intensity distributions (Figure 2). The mean intensity gradient (denoted here as $\overline{\nabla G}$, but also commonly written as MIG) has been suggested as a good metric to evaluate the quality of DIC speckle patterns and images, because higher values of $\overline{\nabla G}$ indicate higher contrast spatially [21]. The mean intensity gradient is an image-wide parameter based on the local parameter of sum of square of subset intensity gradients (SSSIG). Recently a speckle pattern quality metric was developed based on SSSIG and the secondary auto-correlation peak height. SSSIG was demonstrated to be the best measure of speckle pattern quality, and was the primary component in the new speckle pattern quality metric. The new quality metric also included the secondary auto-correlation peak height because SSSIG alone provides high (favorable) values for repeated patterns such as checkerboards [22]. Repeated patterns can be problematic because spatially unique features are required for subset uniqueness. For random patterns such as the painted patterns assessed here, though, the contrast measurements locally from SSSIG and thus globally from $\overline{\nabla G}$ are sufficient. For each of the 18 speckle patterns, the mean intensity gradient ($\overline{\nabla G}$) was computed with the Prewitt numerical

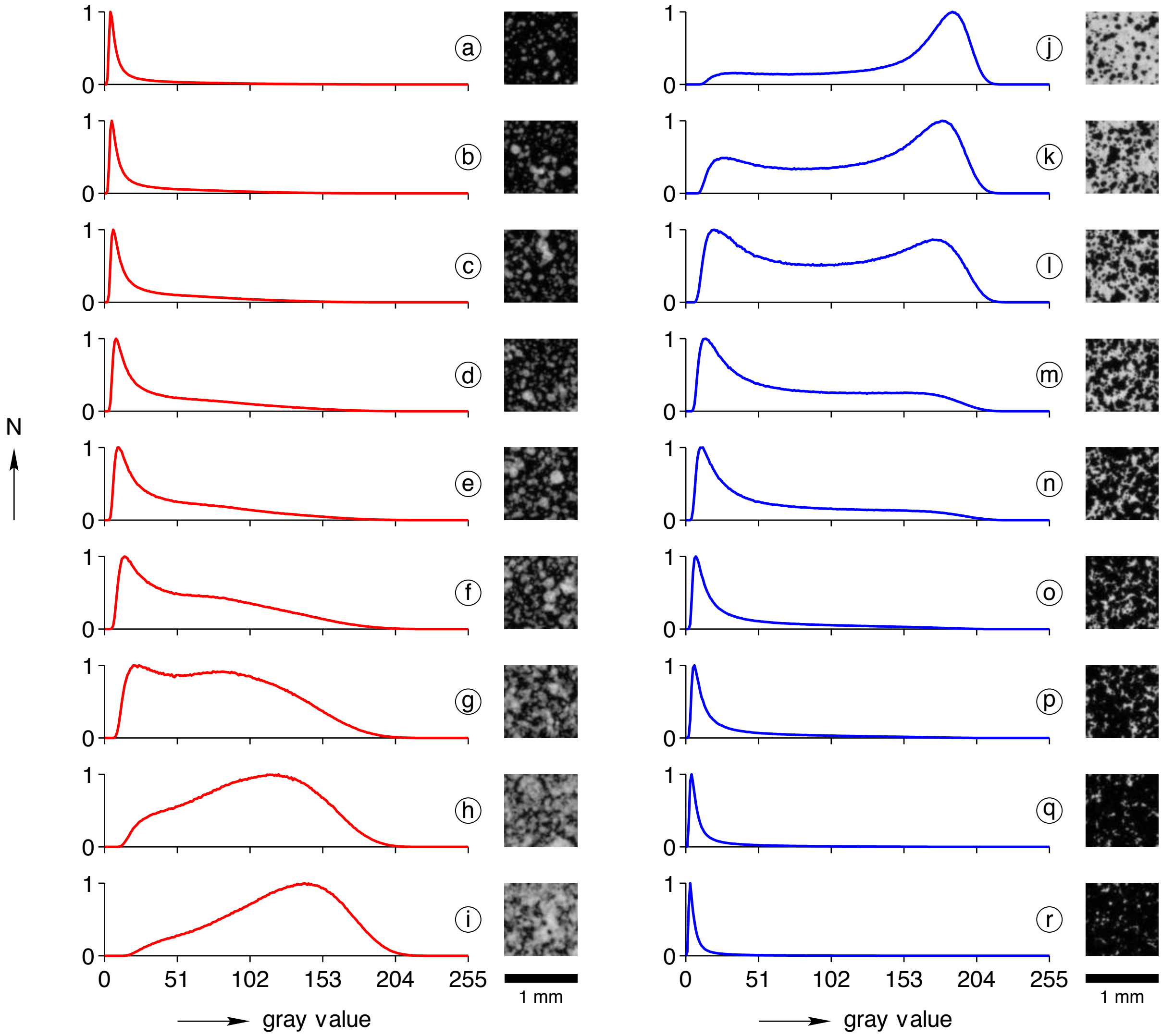
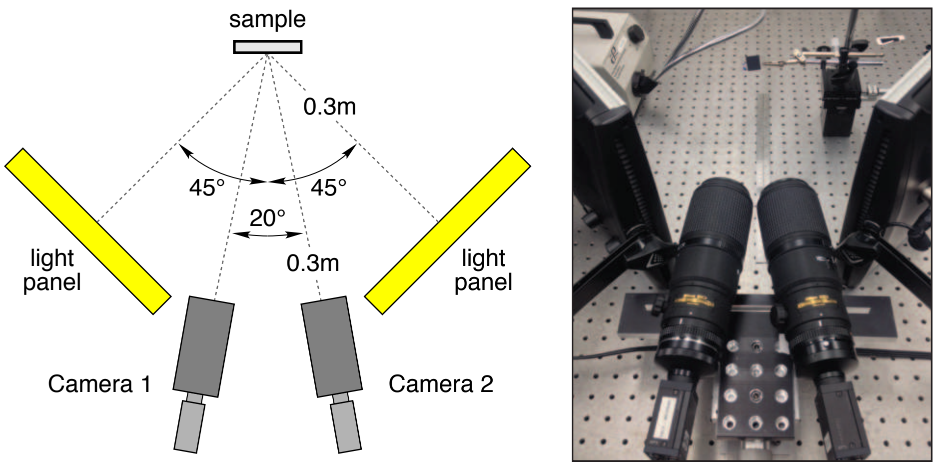



Figure 2: Black speckles on white paint (right column, lettered “j” through “r”) achieved generally higher contrast, as indicated by wider histograms, than white speckles on black paint (left column, lettered “a” through “i”). The samples are arranged down the page with increasing speckle density ($\rho_s$), and each image tile shown is the center 1 x 1 mm region of the full 15 x 18 mm image from the left DIC camera. The histograms are computed from the full images. The histogram bins are one grayscale unit, and the frequencies (N) are normalized for each pattern.

| | |
|---|---|
| step size | 7 px |
| subset size | 53 px |
| consistency threshold | 0.02 px |
| maximum confidence interval | 0.05 px |
| matchability threshold | 0.1 px |

Table 1: Correlation thresholds and settings.




(a) (b)

Figure 3: 3-D DIC measurements used two cameras at a 20$^o$ stereo angle with two LED light panels, shown in the schematic on the left (not to scale), and in the photo on the right. Cross polarization, or the orthogonal placement of linear polarizing filters on the cameras and lights, was deployed to improve DIC quality [12]. Also, a fan (not shown; on a tripod out of view) maintained turbulent air flow across the setup to avoid errors from heat waves [20].

differentiation filter [23], following Pan, Lu and Xie [21]. The patterns with the highest mean intensity gradients also had speckle densities $\rho_s$ ranging between about 30 % and 70 %. The speckle densities $\rho_s$ were computed with a grayscale thresholding filter, following Reu [7] and Lecompte, et al. [24]. An important consideration is that speckle density is coupled with speckle size: patterns with either too low or too high $\rho_s$ will include both undersized and oversized speckles [25].

The median normalized false displacement for the four black-speckled patterns with the highest $\overline{\nabla G}$ (patterns e, f, g, and h) was 0.87 $\mu m$, 24 % lower than the 1.14 $\mu m$ median normalized false displacement for the four white-speckled patterns with the highest $\overline{\nabla G}$ (patterns k, l, m, and n), shown in the top half of Section 3. The same data can also be visualized as an empirical cumulative distribution function, again indicating the lower false displacements for the patterns with black speckles, shown in the bottom half of Section 3. The false displacement magnitudes are $|\boldsymbol{u}|$ =

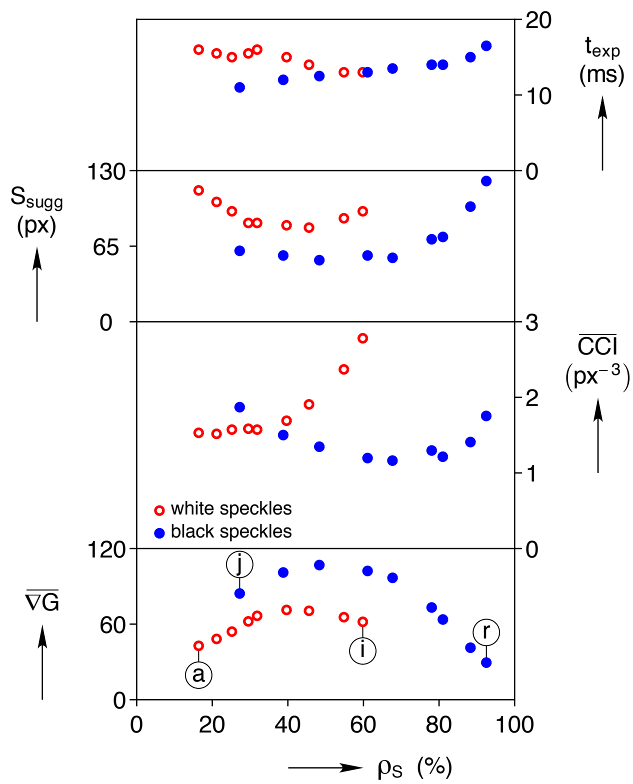



Figure 4: Exposure times ($t_{exp}$) were relatively short, and more white paint in the speckle pattern (either as speckles or the basecoat) generally decreased the exposure time. The patterns with black speckles were superior in three different metrics: smaller suggested subset sizes ($S_{sugg}$), smaller mean correlation confidence intervals ($\overline{CCI}$), and higher mean intensity gradients ($\overline{\nabla G}$). The patterns with the highest mean intensity gradients also had the broadest histograms (Figure 2). The increasing speckle density ($\rho_s$) in the positive horizontal direction of this figure corresponds to the patterns progressing down the page in Figure 2.

$\sqrt{u^2 + v^2 + w^2}$, where $u$, $v$, and $w$ are the horizontal, vertical, and out-of-plane components of displacement. Each speckle pattern was fixed in place while a series of 20 images were captured in one second intervals. Since each sample was stationary, any nonzero displacements are false and indicate the effective noise floor.

# 4 Conclusions

The optimum paint sequence for painted DIC speckle patterns is a basecoat of white paint covered by speckles of black paint. Fundamental differences between black and white paints, especially the higher hiding power of black paint and the undertone of white paint from Rayleigh

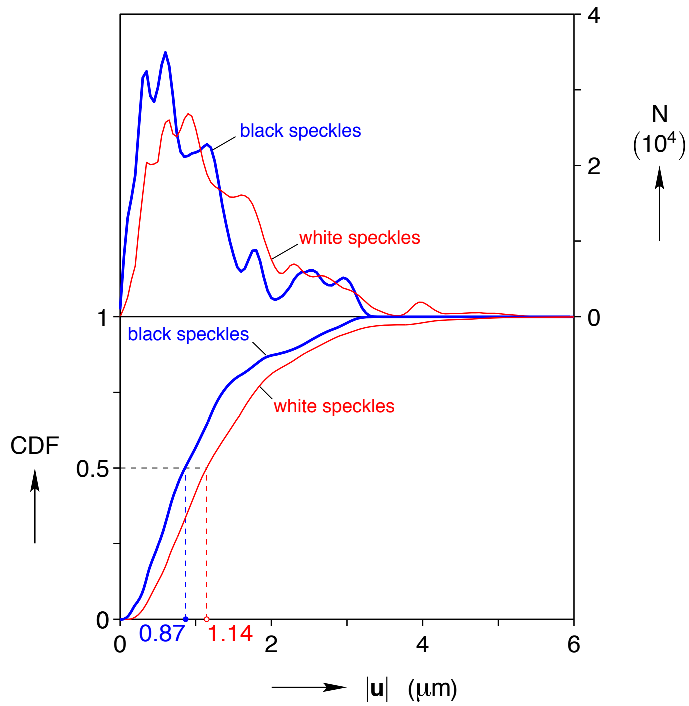



Figure 5: The patterns with black speckles had a 24 % lower median normalized false displacement (0.87 $\mu m$) than the patterns with white speckles (1.14 $\mu m$). False displacement magnitudes ($|\boldsymbol{u}|$) were binned in 0.05 $\mu m$ intervals from the four patterns from each paint sequence with the highest mean intensity gradients (patterns e, f, g, and h with white speckles, and patterns k, l, m, and n for black speckles). The same false displacement data are replotted as an empirical cumulative distribution function (CDF), also indicating the lower false displacements for black speckles.

scattering, enables black paint to maintain higher contrast in a thin layer as speckles. The improved contrast of patterns with black speckles is manifested as smaller suggested subset sizes, smaller correlation confidence intervals, higher mean intensity gradients, and ultimately more accurate displacements (24 % lower median normalized false displacement). In summary, the ideal painted speckle pattern has:

1. a thin basecoat of white paint, applied just thick enough to make complete coverage over the sample surface (especially for reflective samples such as shiny metals),

2. approximately equal amounts of coverage for the basecoat and speckles (speckle density $\rho_s \approx 50$ %), and

3. speckles of black paint with uniform size of at least 3 x 3 pixels to avoid aliasing, and random spatial positions for subset uniqueness.

*Acknowledgments*

We are grateful to the National Science Foundation (CAREER Award, CMMI-1251891) and the Department of Defense (NDSEG Fellowship) for financial support, to Prof. Neil Dasgupta at the University of Michigan for providing the optical microscope used in Figure 1, as well as Mr. Richard Goldman (Chicago Airbrush Supply), Ulysses Jackson (Golden Artist Colors, Inc.), Ms. Preena Lake (General Motors Corporation), and Ms. Laura Shea (retired from Ford Motor Company) for insightful discussions.

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