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AN OBJECTIVE APPROACH TO DETERMINING THE STEEL PENETRATION CAPABILITIES OF X-RAY CARGO INSPECTION SYSTEMS

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ABSTRACT

The ANSI steel penetration test is an important measure of the image performance capability of a cargo x-ray inspection system. Currently, the method for determining the arrow's orientation is completely subjective. An objective method would incorporate the contrast-to-noise ratio (CNR) between the steel plate and the arrow. A series of penetration scans were taken with the thickness of the steel plate ranging from 290-350 mm, and it was found that CNR decreases with increasing steel thickness. There is a point at which the CNR begins to level off – namely the 'limit of determination'. This is where the arrow can be objectively deemed as being no longer visible and, in this experiment, it was found to be at a CNR of around 0.23-0.25. Under-sampling the image data was also tested, and it was found that it did not have a detrimental effect on the CNR, and therefore the image performance. Once tested on more data sets, a definite value of the 'limit of determination' can be found. In future, this method has the capability of replacing the current method as an objective approach to determining the visibility of the arrow, and therefore measuring image performance using the steel penetration test.

INTRODUCTION

In x-ray security inspection, image performance is important and there are many requirements when determining the image performance capabilities of an x-ray cargo inspection system. One of these requirements is the ANSI (American National Standards Institute) penetration test [1]. This test is used in cargo inspection to determine the maximum thickness of steel behind which the orientation of an arrow can be determined, with the thickness of the arrow being 20% of the thickness of the steel plates, visualised in Fig. 1.

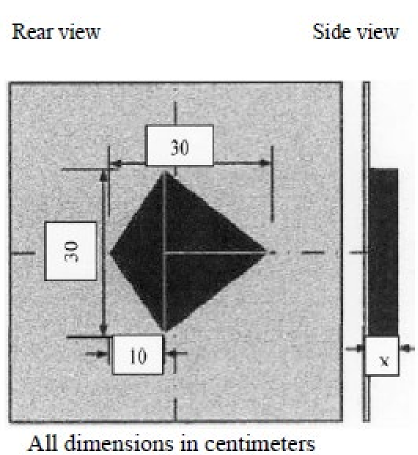

Figure 1: Steel penetration test piece set-up [1]

Currently, this test is very subjective, as it relies on opinion as to whether the arrow's shape and direction are visible. In the security and cargo inspection industry this is a problem, as what we may deem to be 'visible', the customer could disagree with.

A new and objective approach to determining the visibility of the arrow is using the contrast-to-noise ratio (CNR) between the arrow and the steel plate. CNR is the difference between the measured intensity signal of the x-rays having passed through the plates and those having passed through the plates and the diamond, divided by the average of the standard deviation in both signal measurements, and is given by Eq.(1).

$$CNR = \frac{I_P - I_A}{\sqrt{\frac{\sigma_P^2 + \sigma_A^2}{2}}} \quad (1)$$

Where I_P and I_A are the signal intensities of the plate and the arrow respectively and σ_P and σ_A are the standard deviations of the plate and the arrow respectively.

This approach would allow for the visibility of the arrow to have a specific CNR value associated with it, where a certain value, namely the 'limit of determination', would be the point at which the arrow is no longer visible.

Under-sampling is the process of removing lines or pairs of lines in an image to simulate higher speed operation, with the possibility of the ability to operate at lower time-averaged doses.

Previous Work In The Field

Work has been done previously with using the CNR to determine the visibility of the arrow. Bendahan used simulated images of the ANSI penetration test piece and determined the CNR between the steel plate and the arrow, for a range of Linac powers, collimations, and detector array distances. The largest CNR was found when the relative linac power was the highest and the collimator length was largest [2].

Lim et al. also used simulations to calculate CNR, focussing on its change with the x-ray beam angle. It was found that the CNR decreased with increasing x-ray beam angle [3].

RESEARCH AND METHODOLOGY

In this research, steel penetration scans were taken according to the ANSI N42 46-2008 standard (arrow thickness is 20% of plate thickness) for plate thicknesses ranging from 290 up to 350mm, in 5mm increments. A 6/4 MeV pulsed ETM linac and a high-resolution array were used to image the ANSI penetration test piece. To find the CNR between the arrow and plate, a MATLAB code was created in which regions were selected in both the arrow and the diamond. The code allowed for consistent region selection

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across the various images to reduce systematic error. The mean intensity and standard deviation values were computed in these regions and were then averaged separately across the arrow and the diamond. Using multiple regions accounts for identifying and reducing systematic errors. The CNR values were then calculated using Eq. 1. For each steel thickness, four scans were taken (two in each direction) and the CNR was averaged across these four scans, with anomalies removed.

When computing the CNR, both the raw and the calibrated data were used. Raw data is the image data output from the system, whereas the calibrated data has been scaled to 16-bit based upon a measure of the light, unattenuated signal and the dark, unilluminated response for each pixel. The raw data required a number of pre-processing steps prior to region selection and analysis. These included the subtraction of dark signal (electronic noise) as well as the re-ordering of channels so as to produce a correctly rendered 2D image of the test piece.

Under-sampling was also performed on the data, to see if there was any impact on the CNR values and therefore the image performance. To under-sample the data, columns were removed in the following ways: even columns (ECR), odd columns (OCR), even pairs of columns (EPCR) and odd pairs of columns (OPCR).

RESULTS AND ANALYSIS

It was found that the raw and the calibrated data give different values for the CNR at each thickness of the steel plate, with the values for the raw data consistently being smaller. The results collected in this experiment can be seen in Table 1.

Table 1: CNR Values for Calibrated and Raw Data

Steel thickness (mm)	Calibrated CNR	Raw CNR
290	1.0554 ± 0.0098	0.4767 ± 0.006
295	0.9862 ± 0.0075	0.4089 ± 0.0045
300	0.9412 ± 0.013	0.3610 ± 0.0018
305	0.9263 ± 0.0066	0.3691 ± 0.0049
310	0.8804 ± 0.0138	0.3348 ± 0.0103
315	0.8572 ± 0.0189	0.2999 ± 0.0223
320	0.7986 ± 0.0172	0.2718 ± 0.0186
325	0.7716 ± 0.0144	0.2334 ± 0.0139
330	0.7634 ± 0.0314	0.2350 ± 0.019
335	0.7476 ± 0.0042	0.2448 ± 0.0077
340	0.7505 ± 0.0129	0.2172 ± 0.0177
345	0.6600 ± 0.0149	0.2100 ± 0.0032
350	0.6597 ± 0.0054	0.1783 ± 0.0033

These results are visualised in Fig. 2.

A similar trend can be seen in both the calibrated and raw sets of data. The general trend seems to be a decrease of CNR with increasing steel plate thickness, before a 'levelling off' occurs at around 325mm, before decreasing again
after 340mm. In Figure 2, the error bars represent the scan-to-scan variation that occurred when the average CNR was taken over four scans, showing there is some systematic error.

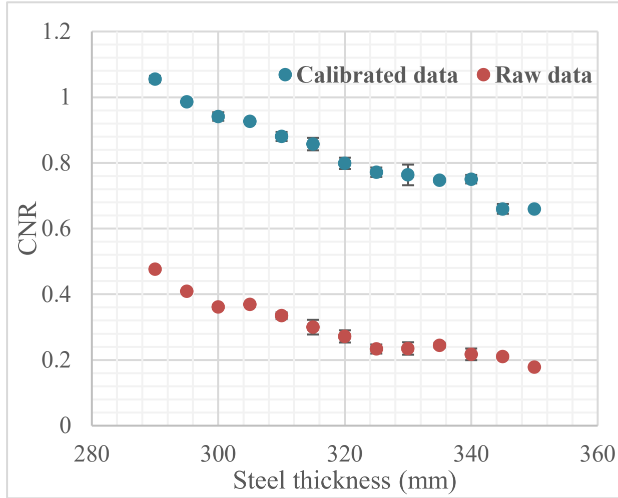

Figure 2: Graph showing the CNR relationship with steel plate thickness for raw and calibrated data

When calculating the CNR, it is preferable to use the raw data, as when the calibrated data was used there was a more significant amount of scan-to-scan variation, and multiple anomalies had to be discounted before an average CNR value could be taken at each thickness of steel. As both sets of data follow a similar trend, and the 'levelling off' occurs at the same point, there is no disadvantage to using the raw data over the calibrated data. The use of raw data should always be consistent, to build up a library of CNR values that can be used for comparison in future.

The 'levelling off' point occurring at a steel plate thickness of 325mm may be defined as the 'limit of determination', i.e., the point at which the arrow stops being visible. For the raw data, this limit occurs at a CNR of around 0.22-0.25, meaning that below this value the arrow's direction can no longer be determined. For the calibrated data, this limit occurs at a CNR of around 0.75.

Under-Sampling

The effect of under-sampling on the CNR values was investigated for the raw data and the results can be seen in Fig. 3.

The data points for the under-sampled data follow a similar trend to the original image data, with the 'levelling off' occurring at similar CNR values and beginning at a steel plate thickness of 325mm. It can be seen that under-sampling the dataset does not have a detrimental effect on the CNR values at each steel thickness, and in most cases, it even slightly increases, which could be due to a number of factors such as misalignment and shadowing. This leads to the conclusion that under-sampling the data does not reduce the image performance for the ANSI penetration test.

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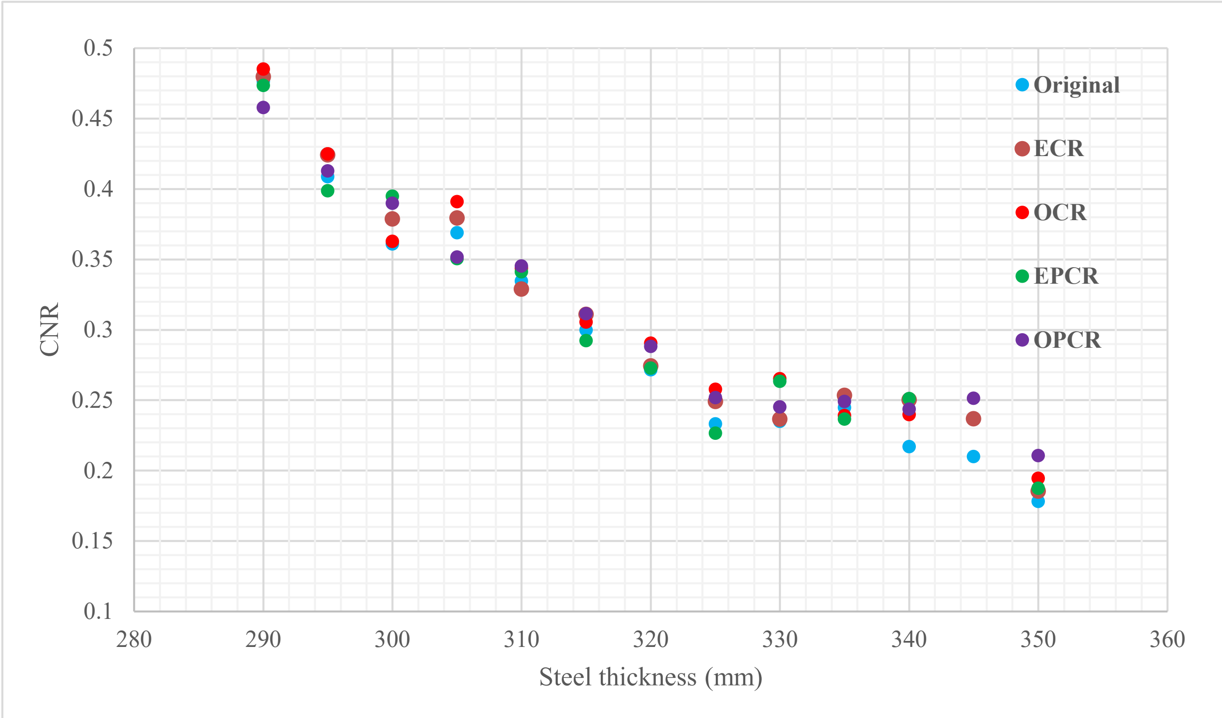

Figure 3: Graph showing the effect of under-sampling on CNR

CONCLUSION

The current method of analysing the steel penetration capabilities of cargo inspection systems is subjective, however using the CNR between the arrow and the plate is an objective approach to determining the visibility of the arrow. This new method allows for a certain value to be associated with the visibility of the arrow and its direction, removing some of the subjectivity. When using the raw data, it was found that the 'limit of determination' is around 0.22-0.25, occurring at a steel thickness of 325mm.

It was also found that under-sampling, i.e., removing columns of data, does not have a detrimental effect on the CNR and therefore the image performance. This is the first set of data that this method has been tested on, to confirm the 'limit of determination' found in this experiment, this method would need testing on multiple other data sets, including at different arrow orientations. Once a library of data has been built up, a single 'limit of determination' can be confirmed, and this can be applied to new systems as an objective approach to determining the visibility of the arrow, according to the ANSI penetration test.

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