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Characterizing X-ray Attenuation of Containerized Cargo

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Characterizing X-ray Attenuation of Containerized Cargo

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Abstract. X-ray inspection systems can be used to detect radiological and nuclear threats in imported cargo. In order to better understand performance of these systems, the attenuation characteristics of imported cargo need to be determined. This project focused on developing image processing algorithms for segmenting cargo and using x-ray attenuation to quantify equivalent steel thickness to determine cargo density. These algorithms were applied to over 450 cargo radiographs. The results are summarized in this report.

This research was performed under an appointment to the U.S. Department of Homeland Security (DHS) HS-STEM Summer Internship Program, administered by the Oak Ridge Institute for Science and Education (ORISE) through an interagency agreement between the U.S. Department of Energy (DOE) and DHS at the Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. ORISE is managed by Oak Ridge Associated Universities (ORAU) under DOE contract number DE-AC05-06OR23100. This work has been supported by the US Department of Homeland Security, Domestic Nuclear Detection Office, under competitively awarded contract/IAA HSHQDC-12-X-00341. This support does not constitute an express or implied endorsement on the part of the Government. All opinions expressed in this paper are the author's and do not necessarily reflect the policies and views of DHS, DOE, or ORAU/ORISE.

1. Project Introduction

Approximately 20 million cargo containers are imported to the United States every year. The Domestic Nuclear Detection Office (DNDO) of the Department of Homeland Security (DHS) aims to characterize new and emerging inspection technologies to ensure that imported cargo does not contain radiological or nuclear (Rad/Nuc) threats. Previous DNDO studies have shown that high-energy (several MeV) x-ray inspection systems can be used to detect Rad/Nuc materials in cargo, and that detection performance varies with cargo density and complexity.

The purpose of this project was to gain a better understanding of the x-ray attenuation characteristics and bulk density of U.S. imported cargo. To this end, algorithms were developed to process cargo container radiographs to isolate cargo-containing regions of the images. Attenuation statistics were calculated for these cargo-containing regions. Attenuation was analyzed for a set of DNDO engineered representative cargos with well-defined physical characteristics. It was found that attenuation within the cargo-containing regions correlated well with physical bulk density. Attenuation characteristics were then computed for a set of 483 stream-of-commerce (SOC) cargo radiographs.

2. Project Methods

Data and Apparatus: The radiographs used in this analysis were created by a Smiths Detection HCVM mobile, single-energy, 3.5-MeV x-ray system (Figs. 1, 2). The first stage of the analysis used a set of 18 DNDO engineered representative cargos designed to span the characteristics of U.S. imports. These included diverse cargos such as furniture, toys, paper, cement, and auto parts. Later analysis was performed on a set of 483 cargos. All cargos were packed in ISO standard intermodal cargo containers either 20 or 40 feet long. 40 foot containers were scanned individually while 20 foot containers were often scanned in pairs on a single truck chassis.

The raw x-ray images included the container(s), cargo, transportation chassis, and often the towing truck, as shown in Fig. 3. These items presented a challenge to obtaining cargo attenuation characteristics. In order to segment the cargo-containing regions of the images, the edges of the containers needed to be found. An edge-finding algorithm was developed to do this. Once container edges were located, the cargo within could be found by thresholding methods. Python scripts were written to run both algorithms on the image sets.

Figure 1. The Smiths Detection HCVM mobile system with boom stowed.

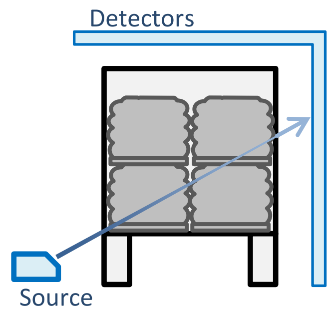

Figure 2. Rear view diagram of the HCVM system scanning cargo.

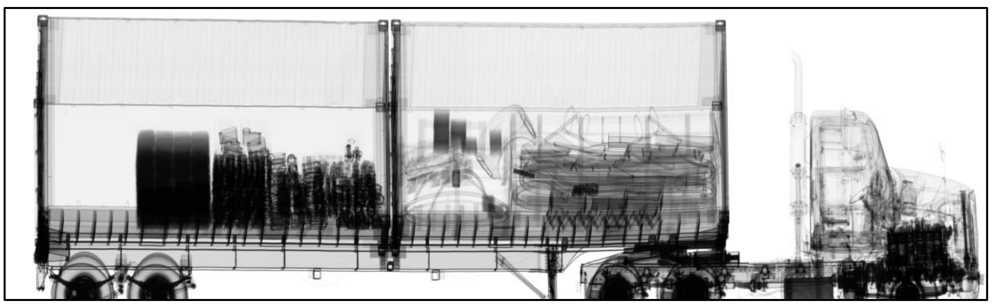

Figure 3. Raw image from HCVM system showing two 20-foot containers on a chassis towed by a truck. The cab is visible on the right. The front container contains playground equipment and the rear has electrical devices.

Container Edge Location: Locating the edges of the cargo container in a raw radiographic image was done using a one-dimensional Hough transform. For the front and back vertical walls, a region of interest (ROI) was selected over the upper part of the image (Fig. 4). This eliminated effects from the cab and all but the highest-stacked cargo. Columns were then summed, providing a profile of the ROI (Fig. 5). Thresholding was applied to this profile and the threshold crossings nearest the front and back of the image were selected as the locations of the front and back container walls. The top of the container was found using a similar method by summing rows and selecting the peak nearest the top of the image. The bottom was found to be a fixed number of pixels from the top edge because the limited clearance of the detector boom forced trucks to be approximately the same distance from the detector in every scan. For images containing two 20 foot containers the center edges were located using a modified version of the same algorithm. An example of the resulting container edges is shown in Fig. 6. The edge values found by this process were written to a data file for use in other analysis scripts.

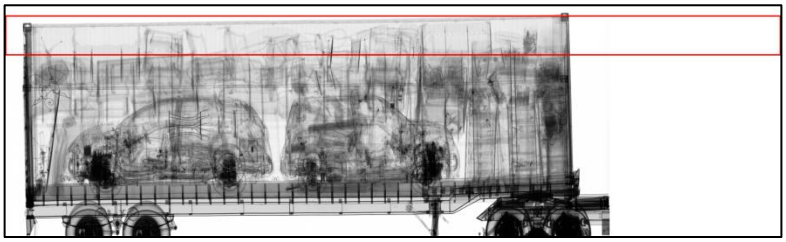

Figure 4. Image showing the ROI used for edge finding.

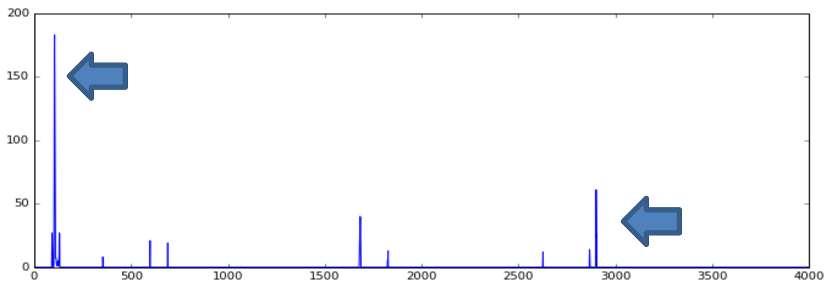

Figure 5. The summed columns within the ROI in Fig. 4, after an applied threshold. Front and back edge threshold crossings can be clearly seen.

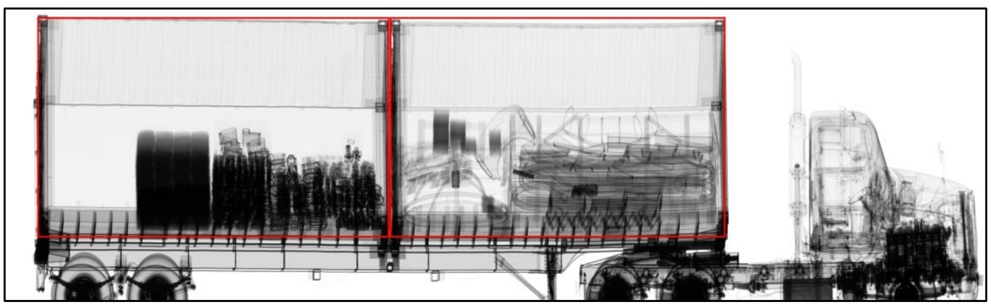

Figure 6. Container edges found by container edge location algorithm.

Cargo Region Segmentation: The next step in the cargo segmentation process was the elimination of empty areas within the containers. Thresholding was the primary method used for this purpose, but one specific issue complicated the process. The source/detector geometry caused vertical distortion of the images, especially on the upper parts of the container and cargo. The effect can be seen in Fig. 7, where the strong horizontal line appearing near the center of the container is in fact the top edge of the container opposite the x-ray source. This edge precluded attempts to apply a single threshold to the image to segment the cargo.

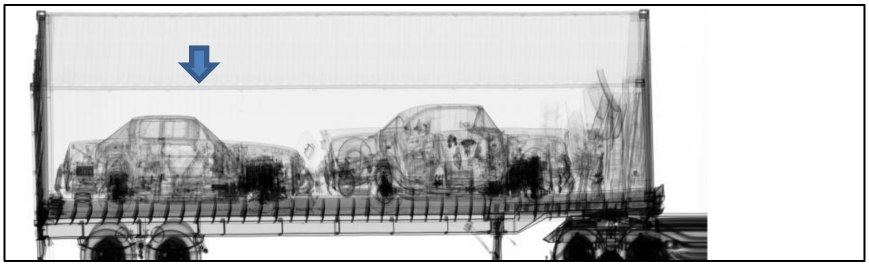

Figure 7. SOC image showing 40-foot container with prominent back wall edge highlighted by the arrow.

The back wall edge problem was addressed using two complementary techniques. The first, which completely solved the issue in most cases, involved removing the edge from the images. The edge's approximate vertical location was found using a fixed ratio between the top and bottom of the container. Around this location a narrow ROI was created. A row sum was applied as in the previous algorithm and the peak was located. The back wall edge in the majority of images presented a strong peak. With the exact location identified, a 35 pixel strip along the edge was replaced with values interpolated from above and below the edge (Fig. 8). In a few cases, this approach failed to eliminate the back wall edge problem. Notably, when the image had slope, making the edge off-horizontal, this technique either failed completely or left parts of the edge intact. To deal with these cases, a multi-value thresholding approach was used. The image was split into three horizontal regions: a top region extending from the top to the vicinity of the edge, a wide strip around the edge location, and a region extending to the bottom. The thresholds in the top and bottom regions were based on the local background values, being slightly higher on the top. The center threshold was raised to eliminate remaining edge effects after the removal process. This successfully reduced residual edge effects but in some cases eliminated low-attenuation cargo near the edge (Fig. 9). The cargo regions obtained from this process were saved as image masks for use in further analysis. Fig. 10 shows a typical example of the final cargo-containing region found.

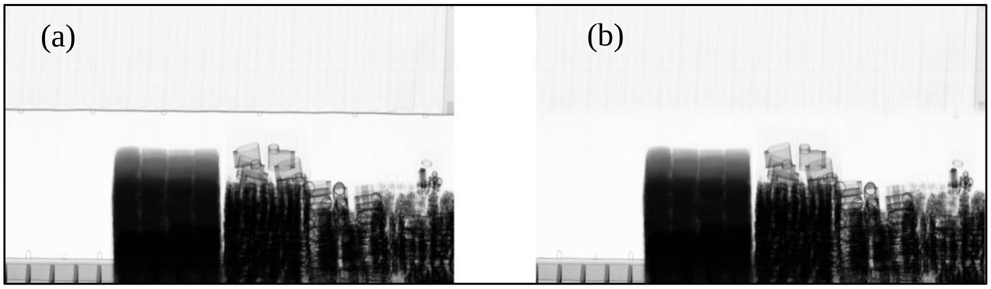

Figure 8. Interior of a 20-foot container showing removal of the back wall edge. (a) shows the original image with strong edge, and (b) shows the image with edge removed.

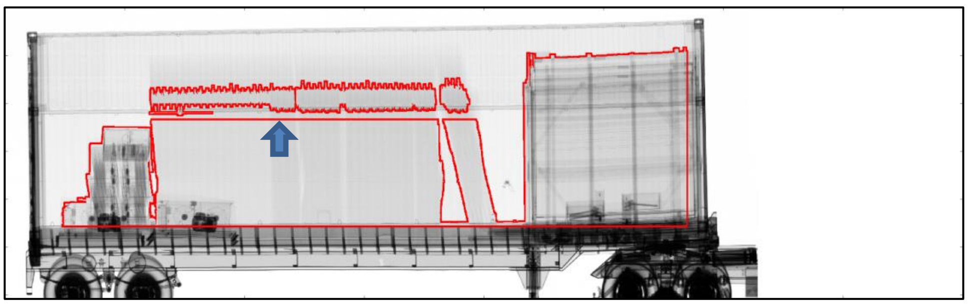

Figure 9. Example loss of a portion of low-density cargo around the back wall edge.

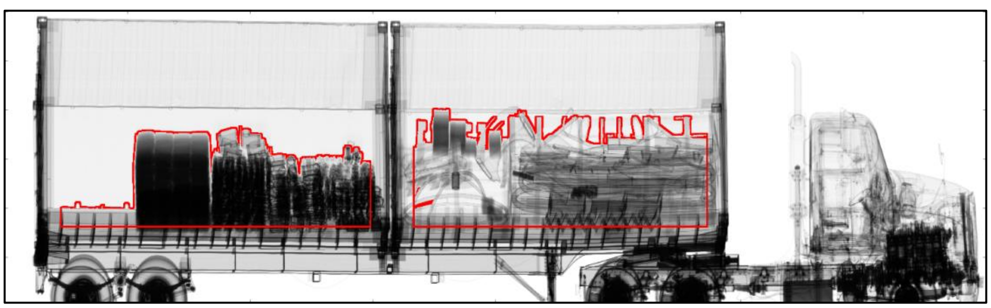

Figure 10. Cargo-containing regions found by the cargo region segmentation algorithm.

Unit Conversion: Before gathering statistics on the cargo it was necessary to convert the images to attenuation space. The raw images recorded the intensity of x-rays hitting the detector. The relation between intensity (I) and attenuation (μx), is given by Beer's law:

$$\mathrm{I} = \mathrm{I}_0 e^{-\mu x}, \tag{1}$$

where μ is the linear attenuation coefficient and *x* is the path length. Once in attenuation space, the images were further converted to equivalent thickness of steel. This was done using a lookup table created from measurements of steel plates of varying thicknesses. This provided a quantitative measure of x-ray cargo properties independent of the scanning technology used. Fig. 11 shows an image that has been converted to equivalent steel thickness.

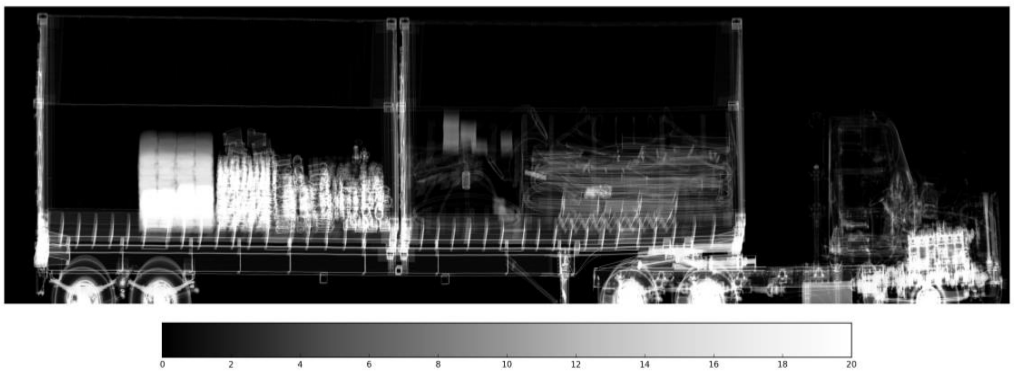

Figure 11. Image converted to equivalent steel thickness.

3. Project Results

With cargo-containing regions isolated, analyses could be performed without noise from irrelevant image features. Analysis of the DNDO engineered cargos revealed a correlation between mean equivalent steel thickness and physical bulk density (calculated from measured net weight and volume of the cargo) (Fig. 12). This was expected and suggests that mean attenuation could be used as an approximate measure of physical density for SOC cargos.

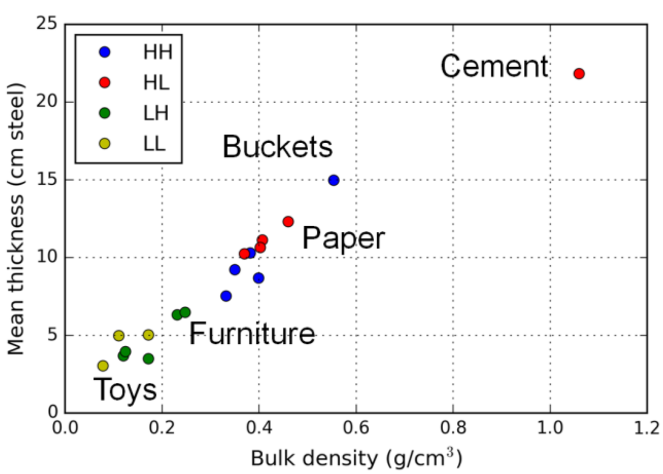

Figure 12. Mean equivalent steel thickness vs. physical bulk density for DNDO cargos. Cargos were manually categorized as high (H) or low (L) density and complexity. (e.g. "LH" is low density, high complexity).

The distribution of mean equivalent steel thickness of the SOC cargos is shown in Fig. 13. It provides an idea of the density characteristics of the 483 SOC cargos, which could be used to make decisions regarding appropriate inspection methods.

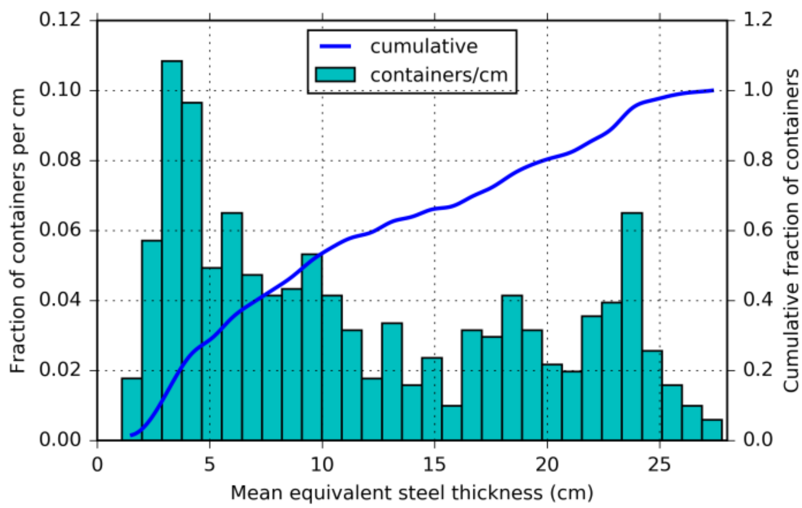

Figure 13. Mean equivalent steel thickness distribution of SOC cargos.

4. Impact of Internship on My Career

This internship provided a valuable opportunity for me to work in an interesting new field, experience the work environment at a national laboratory, and learn about careers in applied physics and engineering. The lectures and tours hosted for interns were superb and provided accessible introductions to many science, technology, and national security topics. Most importantly, the work was rewarding and gave me ideas for a future career direction.

My education and previous research experience are in experimental and computational physics. This position in computational engineering was balanced between familiar and new topics. It was particularly valuable in aiding my graduate school decision-making. I am now considering working towards a PhD in applied physics or imaging science. After graduation I would like to take a position at a government lab or a supporting contractor. The overarching purpose and sense of national pride that I saw at Lawrence Livermore are things I would like to find and contribute to in my future career.

One of the highlights of my time at the lab was the profusion of events, such as lectures and tours, which were offered for interns. A weekly series of DHS lectures on topics ranging from nuclear security to biological modeling and high performance computing provided constant learning opportunities. The lab also hosted several outside speakers on relevant topics in science and technology. Tours of various lab facilities gave a glimpse of the many functions performed there. Social meetups both on and off the lab offered chances to network with other interns and employees. All of these events gave new perspectives on science and engineering jobs that guided my career goals.

Finally, my experience at the lab would not have been nearly as successful without the support of all the employees I worked with, both on my project and on the administrative staff. My research mentors were extremely supportive and provided guidance throughout the project, as well as general advice on education and careers. I emerged from this internship with a new set of skills, experience in a unique working environment, and a much clearer understanding of my career options going forward.