Automated Comparison of X-Ray Images for Cargo Scanning

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***Abstract*—Customs administrations are responsible for the enforcement of fiscal integrity and security of movements of goods across land and sea borders. In order to verify whether the transported goods match the transport declaration, X-ray imaging of containers is used at many customs site worldwide. The main objective of the research and development project "Automated Comparison of X-ray Images for Cargo Scanning (ACXIS)", which is funded by the European 7th Framework Program, is to improve the efficiency and effectiveness of the inspection procedures of cargo at customs using X-ray technology. The current inspection procedures are reviewed to identify risks, catalogue illegal cargo, and prioritize detection scenarios. Based on these results, we propose an integrated solution that provides automation, information exchange between customs administrations, and computer-based training modules for customs officers. Automated target recognition (ATR) functions analyze the X-ray image after a scan is made to detect certain types of goods such as cigarettes, weapons and drugs in the freight or container. Other helpful information can also be provided, such as the load homogeneity, total or partial weight, or the number of similar items. The ATR functions are provided as an option to the user. The X-ray image is transformed into a manufacturer-independent format through geometrical and spectral corrections and stored into a database along with the user feedback and other related data. This information can be exchanged with similar systems at other sites, thus facilitating information exchange between customs administrations. The database is seeded with over 30'000 examples of legitimate and illegal goods. These examples are used by the ATR functions through machine learning techniques, which are further strengthened by the information exchange. In order to improve X-ray image interpretation competency of human operators (customs officers), a computer-based training software is developed that simulates these new inspection procedures. A study is carried out to validate the effectiveness and efficiency of the computer-based training as well as the implemented procedures. Officers from the Dutch and Swiss Customs administrations partake in the study, covering both land and sea borders.**

Keywords*—Customs border control, cargo inspection, security screening, X-ray screening, automated target recognition, X-ray image analysis, image standardization, simulation, computer-based training

I. Introduction

The current age of globalization with its advances in transportation and information technology has increased the trade across the world and the freedom in which we carry out these trades. In 2014, almost 3.8 billion metric tons of maritime cargo were handled in the harbors in the European Union, with over 570 million metric tons passing through Dutch harbors alone [1].

Inland freight transport in the European Union is similarly impressive. Over 2'200 billion metric ton-kilometers (tkm) in freight was transported inland in 2014. Inland transportation took place predominantly by road (75.1%), over four times as much as by rail (18.3%). The remainder of freight was carried along waterways (6.6%) [1]. In Switzerland, a landlocked country, over 25 million tkm in freight was transported.

This volume in cargo traffic calls for efficient inspection procedures, whilst the persistent threat of terrorism and smuggling requires an effective implementation of these procedures.

Customs administrations aim at identifying cargo that is inconsistent with its declaration, contains illegal goods, or that

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pose threats to society. Smuggling of counterfeited and pirated goods cause harm to a nation's wellbeing due to missed taxes that could otherwise be put to service for society. The Organization for Economic Co-operation and Development (OECD) estimates that the global international trade in counterfeits and pirated goods in 2007 may amount to $250 billion USD, which would equate to 1.95% of global trade [2]. Cigarettes lead the chart in the European Union with around 35% among all smuggled goods [3].

Regarding illegal goods, drugs are an important category. For example, a study by the United Nations International Drug Control Programme (UNDCP) estimates the global illicit drug sales to consumers for 1995 at roughly $400 billion [4].

Terrorism has the capacity to threaten the social and economic stability of countries. Although acts of terrorism can be prepared entirely from within a country's territory, they have dramatic effects to the country's economic wellbeing. The immediate impact of the 9/11 attacks, for example, saw the gross domestic product (GDP) in the United States drop by 0.5% and the rate of unemployment increase by 0.11% (equivalent to 156'000 jobs) [5].

National and international legislation constrains the way border security is implemented. In 2007, the United States passed a law requiring 100% container scanning. Such measures impose an enormous burden upon the customs administrations [6]. As a consequence, the United States in 2012 missed its own targets, with only 4.1% of all containers passing border control being scanned [7]. Technological advances and smart policies are required to facilitate the inspection and achieve integrated security. The World Customs Organization (WCO) published in 2005 its non-binding view on supply chain security in its SAFE Framework [8]. In this framework, the WCO proposes technical customs standards to enhance security without impeding the international trade. The European Union focuses on public-private collaborations to enhance its supply chain security [9].

In this paper, based on results from the ACXIS project, which is funded by the European 7th Framework Programme, we propose improvements to the existing customs X-ray inspection procedures for container and truck cargo shipments. Automated target recognition (ATR) functions detect suspicious cargo and provide the customs officer with information for further inspection. The scans are stored in a central reference database, which contains X-ray images of legal and illegal cargo in a manufacturer-independent format. The ATR functions are designed to be self-improving, using the reference database as their source.

The data contained in the reference database can be automatically accessed by or shared with other customs administrations, which facilitates information exchange and enables future inspection scenarios, for example by comparing in-transit cargo at border import and export. The reference database is also designed to operate with a computer-based training (CBT) tool specifically developed to train and certify customs screening officers.

We are withheld from publishing details of the risk analysis and performance characteristics of the ATR functions due to their sensitive and confidential nature. Instead, we provide rough indications and quantify results in broad terms.

II. Reference Database

A database containing a large dataset of legitimate and illegitimate cargo is essential for detection algorithms and customs officers to learn and improve themselves. In ACXIS we collected 38'331 X-ray scans of container-and-trailer combinations using HCVS and CAB2000 scanners from Smiths Detection. These primarily contain legitimate cargo. To acquire sufficient samples of illegitimate cargo, we pursued various strategies to simulate images containing illicit items (Fig. 1). 3D models and X-ray scans of contraband for various types of cargo were acquired and converted into a 2D X-ray image standard. Smuggling scenarios were simulated by blending these images into real X-ray images of freight containers and trucks. Altogether we acquired scans of 1'382 objects from different views and angles. Scans were made using the HCVS and CAB2000 scanners from Smiths Detection and laboratory setups from CEA, EMPA and EZRT [10].

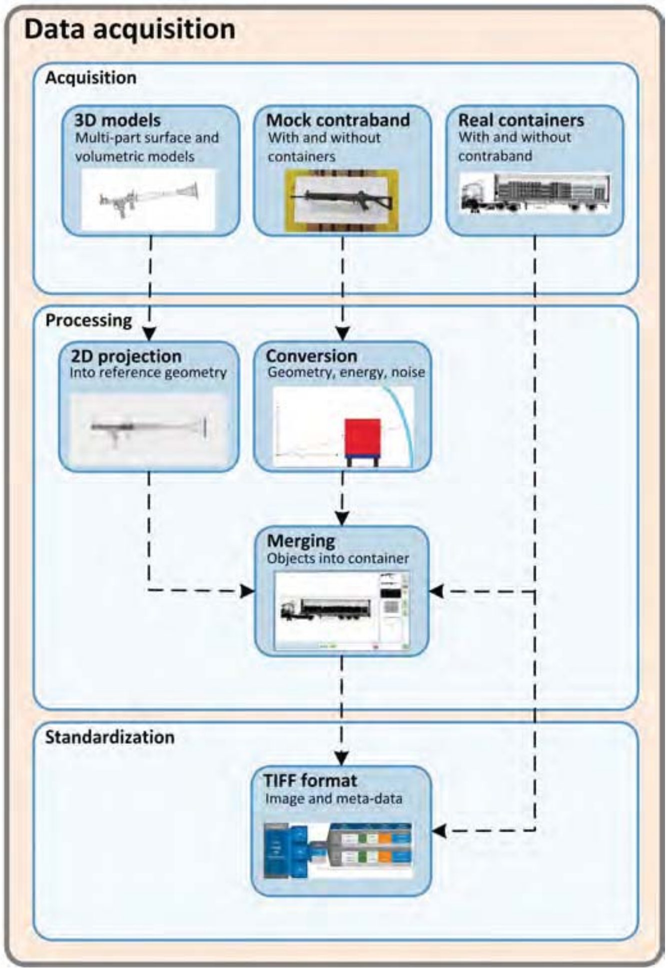


Fig. 1. The image acquisition workflow to construct the reference database with images of historic cargo, and simulated illicit items projected into container images. The data is standardized through conversion and formatting.

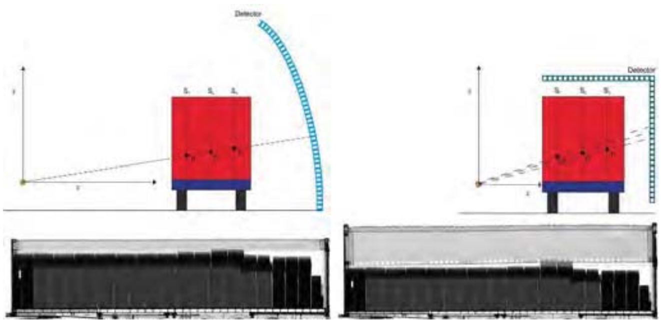
A. *Image Selection by Risk Analysis*

A risk analysis was conducted to identify the types of goods that are a priority to customs administrations. The analysis takes into account the quantity and value of goods, and the mode of smuggling. Among the prioritized goods, twelve categories of illicit items were defined, each divided into three levels of quantity. In addition, seven different cargo categories were defined, e.g. textiles and scrap metal. The analysis focused on two modes of transport: curtain-sided trailers and ISO containers on trailers. Based on the experience of the customs administrations, five smuggling scenarios (e.g. hiding illicit items in between manifested cargo) with up to eleven smuggling locations were identified. The smuggling scenarios and associated illicit items that are expected to provide most meaningful improvements were selected from the resulting 1341 variations. These form the base requirements for the ATR functions described in this paper.

B. *X-ray Image Standardization*

Given the large variety of X-ray scanners deployed by the customs administrations and the different scanners used for the image acquisition in ACXIS, establishing a uniform standard for X-ray images is important. With such a standard, the ATR functions can benefit from the full dataset available in the reference database, future acquisition can be easily integrated, and customs administrations can exchange data and integrate it with their installations. The data resulting from the conversions is stored in a custom TIFF format to allow easy data exchange. The following paragraphs explain the challenges and solutions regarding image acquisition and a uniform image standard.

The acquisition geometry can differ greatly between scanners with variations in the position of the source, detector and container, as well as the detector shape and resolution [11]. The geometries of the scanners were modelled to define the image transformation from one geometry to another. However, a complete transformation of the 2D image data between two scanners with significantly different geometries is impossible. It can be limited only to some properties as the horizontal and vertical sampling, and partially the geometrical distortion (Fig. 2).

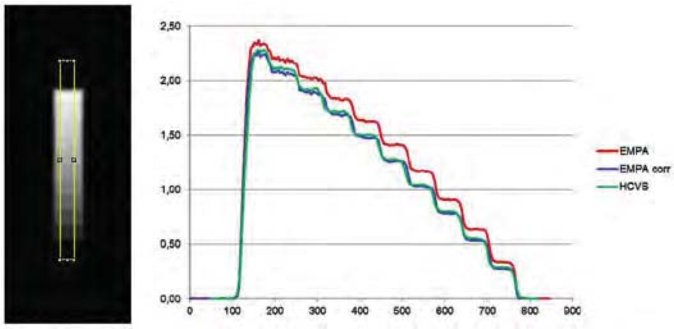


(a) (b)

Fig. 2. Difference in geometry between the HCVS (a) and the CAB2000 (b) scanner. Top row: Representation of the scanner geometry; bottom row: the effect of geometrical distortion for the given scanner.

Contrast adaption is necessary to account for differences in source spectra. Several source spectra were simulated, and the detector response was evaluated for different scanners using step wedges made out of different materials (steel, carbon, aluminum, etc.), each giving a different response curve for a particular scanner.

From these images, for a given thickness of material we express the attenuation value of one system as a function of another. The equation of this curve corresponds then to the contrast conversion function, which is applied after the geometric conversion to adapt the contrast from the source to the target scanner (Fig. 3).



(a) (b)

Fig. 3. Image of a step wedge (a) and comparison between intensity profiles (b) along the image of the step wedge for the HCVS scanner (green), the EMPA scanner (red), and the EMPA scanner adapted to the HCVS spectrum (blue).

Another aspect of conversion is the simulation of noise. The signal-to-noise ratio (SNR) of X-ray images varies between scanners and needs to be modelled [12]. Lastly, the images need to be corrected for scatter in highly attenuated regions as it decreases the effective dynamic range [13]. Preliminary results show that a misalignment of the shielding by 1mm can contribute to scatter with up to 10% of the original signal.

The algorithms have been tested on images from Smiths Detection's HCVS and CAB2000 scanners, which have significantly different configurations. The geometry difference between these two scanners is enormous, whilst a spectral quality of the CAB2000 does not provide sufficient detail for the ATRs to reliably detect items. We therefore propose to define categories of X-ray scanners, each with their own reference standard. The specification of these categories is currently under construction.

C. *Projecting 3D Models*

Image acquisition using physical scanners is a time-consuming task. To enlarge the quantity and variety of images, simulation tools were used to create images of 3D models of illicit items (Fig. 4).

(a) (b)

Fig. 4. 3D CAD model (a) and the simulated 2D X-ray projection (b).

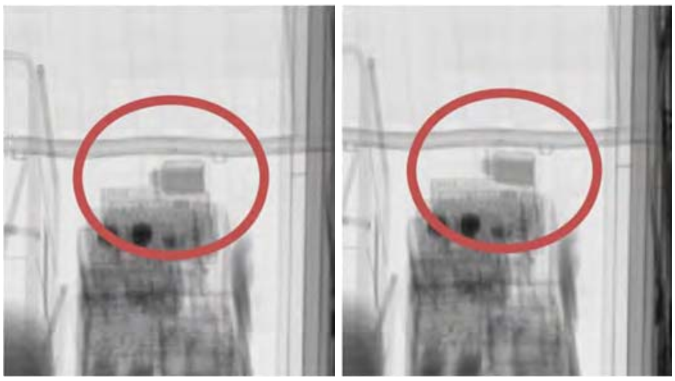
In the CIVA software [14], we defined the acquisition geometry identical to the one of the reference scanner, together with the associated source and detector parameters. 3D models of illicit items were inserted in the virtual setup, allowing to create multiple realistic X-ray projections at any position and any incidence angle. The noise level was set to be similar to the one of the reference system.

D. Blending Images of Illicit Items into Containers

Realistic images of illegitimate cargo are produced by blending the simulated or mock-up X-ray images into real X-ray images of containers. Image blending follows the principle of the attenuation of photons when traversing matter, described by the Beer-Lambert law. As described in [10], the blending of one image into another can be described by

$$I_{det} = I_{bg} \cdot \frac{I_{ii}}{I_0} \quad (1)$$

where I_{det} and I_0 are respectively the intensity of the X-ray beam at the detector and source points, I_{bg} is the intensity image of the background (i.e. the container image with its cargo) and I_{ii} is the intensity image of the illicit item (i.e. the simulated or mock-up image). According to expert judgement by customs officers and X-ray imaging experts, the pixel-for-pixel application of (1) produces realistic results. An example is shown in Fig. 5, where the left image has been constructed using (1) from an image of a mock-up representing an improvised explosive device (IED) acquired in air (I_{ii}) and an image of a container without this mock-up (I_{bg}). The image on the right shows a real scan with the illicit item physically placed inside the container between other items in the load.



(a) (b)

Fig. 5. Comparison between an illicit item blended into a container image (a) and the object as part of the scanned cargo (b).

III. AUTOMATED TARGET RECOGNITION

One of the goals of ACXIS is the development of specific automated target recognition (ATR) functions to ease and enhance the detection of both legitimate and illegitimate cargo in ISO containers and trucks. Due to the sheer trade volume, such algorithms are indispensable to achieve 100% container scanning (see introduction).

A. Image Denoising

Noise is an inherent part of X-ray images and dependent on the particular type of X-ray machine. In order for the ATR to optimally benefit from the signal in the image, this noise needs to be removed. Six denoising methods were tested on X-ray images from X-ray machines of different make: Gaussian smoothing [15], bilateral filtering [16], guided filtering [17], anisotropic filtering [18], non-local means (NLM) [19] and block matching 3D (BM3D) [20]. Among these, preliminary results show that BM3D yields the best overall performance.

B. Cigarettes Detection

Cigarettes are among the most commonly smuggled goods. They are typically transported in large quantities and appear in X-ray scans as homogeneous regions with specific textures due to the common way of packaging layers of cartons into boxes (Fig. 6). A learning database was calculated from X-ray images of a 9 MeV HCVS system. Cross validation on this dataset resulted in a high probability of detection (POD). The probability of false alarms (PFA) is very low tested on thousands of images (9 MeV HCVS system) without cigarettes, corresponding closely with the expectations of the customs administrations.

Fig. 6. Boxes of cigarettes stacked in the back of an ISO container.

C. Detection of Illicit Items

Illicit items, and particularly narcotics, are frequently trafficked and difficult for customs officers to identify due to their relatively small size. Furthermore, narcotics are often moldable and lack specific texture and shape, making them more difficult to identify by feature-based detection algorithms. In this paper, we focus on the rip-off scenario, in particular where narcotics are hidden in the container structure.

The core idea of the technique is to extract specific regions of interest (ROIs) and compare these to a corresponding reference image. The first step consists of the classification of the ROI combined with a search across our reference database for the closest match in terms of structure and intensity features. Next, a set of descriptors is computed for both the reference and the current image using SURF [21] (Speeded-Up Robust Features). Matching pairs of corresponding keypoints are calculated using a nearest-neighbor approach (Fig. 7).

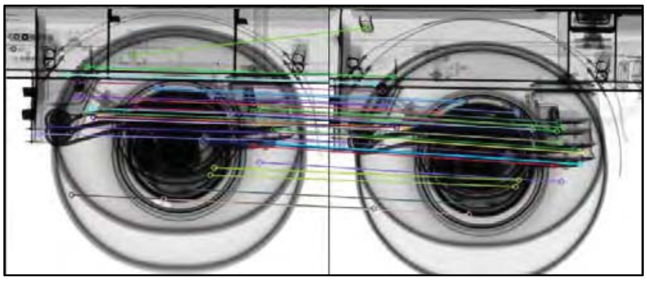


Fig. 7. Example of illicit items detection for the “wheels” region of interest. Keypoint in the current and reference images are shown along with the maching lines.

When plane objects are projected onto a sensor, images acquired from different viewpoints can be linked by a projective transform, also called homography [22]. To transform the current image, these coefficients can be estimated using at least four points in the image and their corresponding position in the reference image [23]. Given a set of points, the RANSAC filtering algorithm [24] iteratively selects a small subset of points to compute the corresponding transform and measures the number of points that are correctly mapped by the transform (inliers). After N iterations, the largest set of inliers is selected to estimate the affine or homographic transformation from one image to the next (Fig. 8).

Fig. 8. RANSAC filtering and transform computation.

The transform extraction enables to register the current and reference images such that a difference map can be computed. An adaptive thresholding technique is used, along with the application of morphological operators to yield a binary map of the most relevant differences. This way, the illicit item can be detected and localized in the ROI (Fig. 9 and Fig. 10).

(a) (b) (c)

Fig. 9. Map of differences between current image and registered reference (a), the binary map displaying most relevant differences (b), and the illicit item detection (cocaine) and localization (c).

(a) (b)

Fig. 10. Another example of smuggled cocaine in a container (a) and its corresponding binary map of differences after registration (b).

D. Additional Tooling

The declaration of goods on the waybill often contains information on the weight or the number of items of the cargo. These goods are typically subject to taxation, and it is important for the customs administration to know if the amount declared matches the actual cargo.

The weight of an image region is determined by subtracting the known container weight from the weight associated to a pixel. The pixel weight is calculated by comparing the pixel intensity to the calibrated pixel intensity for a volume of steel. The type of container is identified by extracting key features and comparing these against a catalogue of reference containers.

Another tool counts the number of similar objects, based on a ROI selected by the officer. This ROI serves as a template against which other regions are matched. In Fig. 10, a region with crates filled with fruits has been selected manually, based on which the algorithm automatically detects and highlights 24 similar patterns.

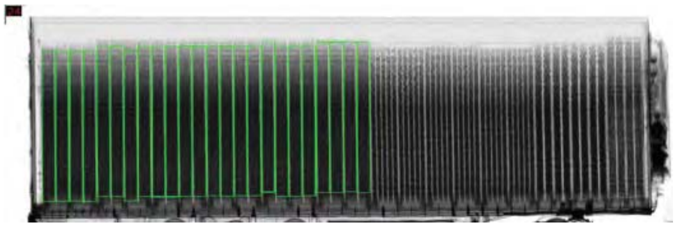


Fig. 11. Counting the recurrence of a manually selected ROI in semi-homogeneous cargo.

IV. Inspection Procedures

The inspection procedures currently in place at customs administrations were identified to determine how the ATRs could best be integrated. Customs administrations expressed a strong preference for opt-in functions.

The ATR functions were integrated into the X-ray screening software of Smiths Detection. The X-ray image is automatically analyzed by the ATRs when a scan is made, and the detection results can be called upon at the officer’s volition. A learning database backs the ATRs and is regularly updated from the reference database, which is available either centrally or on premise. The reference database stores the officer’s inspection results, the standardized X-ray data and the results of the ATRs (Fig. 12).

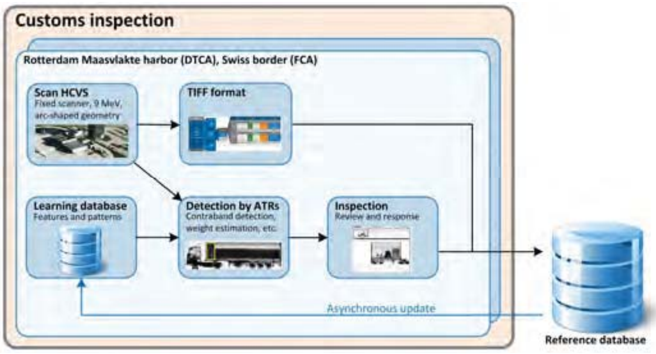


Fig. 12. The customs officer can benefit from the detection of the self-learning ATRs. The officer's response and X-ray data are persisted in the reference database. The learning database for the ATRs regularly updates itself from the reference database.

A graphical user interface allows customs administrations to access the reference database to view, annotate and modify its content. In a decentralized environment, with multiple sites or customs administrations having their own installation of the reference database, direct data exchange is possible.

V. Validation and Training

To evaluate the impact of the new inspection procedures and its ATRs, a validation study has been designed to measure the detection performance of customs officers under different training conditions and compare their results (Fig. 13).

Fig. 13. Study design for the validation of ATRs and training for customs screening officers.

The participants are selected from the customs administration of The Netherlands and Switzerland. An Ishihara color perception test [25] is carried out first to ensure that the participants are able to identify the colored frames that highlight the ATR detection results. At the beginning (T1), an object recognition test (ORT) [26] is conducted to create three groups that are equivalent regarding visual abilities which are needed to cope with effects of viewpoint, superposition and visual complexity in X-ray images [27]. The three groups are balanced by average ORT performance, years of experience, and gender.

The groups are put through a test-training-test methodology [28] [29] to determine the compounded improvements between training with ATRs, training without ATRs, and no training at all. At T2, the first test is conducted to determine the baseline detection performance for each group prior to training. Next, groups A and B train twice a week 20 minutes for three months. At the end of the validation study (T3), the three groups are tested again to determine their performance improvement.

Group A carries out the tests and training with the opt-in ATR detection results enabled. Group B does not receive X-ray images with ATR support. Group C serves as control group without ATR support and no training. This way, the difference between group B and C at T3 provides a measure of the improvements in detection performance with and without training. The difference between group A and B at T1 and T3 measures the improvement that can be attributed to the ATRs before and after training. A similar study with customs officers as participants has been carried out in [30] to measure the effect of pseudo-colors on X-ray image interpretation.

The validation study is currently running and expected to be completed by late 2016. The training and T2 and T3 tests are implemented with a computer-based training tool that has been specifically developed for the study (Fig. 14). The software has been designed with the latest web-based technologies (HTML5, AngularJS). It provides functionality from X-ray image interpretation training software that was originally developed for airport security X-ray screeners (X-Ray Tutor) [31] which was proven to be very effective and efficient [28] [29] [32] [33]. In addition, it simulates the results of the opt-in ATR functions through frames that highlight the suspect area.

Fig. 14. The *Customs Simulator* is a computer-based training and testing tool that is capable of simulating ATR functions.

VI. Summary and Conclusion

To improve the efficiency and effectiveness of border checkpoints, enhancements of inspection procedures are proposed. Automated target recognition functions have been defined and developed that provide customs officers with optional assistance during X-ray image analysis. We focused on the most relevant illicit items and scenarios. The preliminary results in the detection of cigarettes and the detection of anomalies in the container structure prove promising. However, the current datasets limit the successfulness of some of these functions. For example, further development and validation experiments are necessary to increase the probability of detection for firearms. We intend to investigate incremental support vector machines (SVM), convolutional networks, and entropy pursuit.

We investigated the possibility of creating a single X-ray image standard. Due to the inherent differences between X-ray scanners it is impossible to define a single standard from which conversions to all existing models is possible. We propose to categorize the X-ray scanners and define a reference standard for each of these categories. More work is necessary to define the exact categorization.

A large dataset of legitimate and illegitimate cargo was created from historic container scans to which simulated illicit items were added. We showed how 3D models and 2D image acquisitions of illicit items can be blended into container scans to easily and quickly produce a large, high quality dataset.

A validation study has been designed to evaluate the impact of the novel ATR functions on the detection performance in X-ray screening in the customs domain. An investigation among the customs administrations in the European Union has shown that educational programs in X-ray screening are not standardized, if implemented at all. We expect a significant improvement in detection performance for X-ray screening of cargo if computer-based training is consistently implemented by customs administrations.

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Threat Image Projection (TIP) into X-ray images of cargo containers for training humans and machines

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***Abstract*—We propose a framework for Threat Image Projection (TIP) in cargo transmission X-ray imagery. The method exploits the approximately multiplicative nature of X-ray imagery to extract a library of threat items. These items can then be projected into real cargo. We show using experimental data that there is no significant qualitative or quantitative difference between real threat images and TIP images. We also describe methods for adding realistic variation to TIP images in order to robustify Machine Learning (ML) based algorithms trained on TIP. These variations are derived from cargo X-ray image formation, and include: (i) translations; (ii) magnification; (iii) rotations; (iv) noise; (v) illumination; (vi) volume and density; and (vii) obscuration. These methods are particularly relevant for representation learning, since it allows the system to learn features that are invariant to these variations. The framework also allows efficient addition of new or emerging threats to a detection system, which is important if time is critical.**

We have applied the framework to training ML-based cargo algorithms for (i) detection of loads (empty verification), (ii) detection of concealed cars (ii) detection of Small Metallic Threats (SMTs). TIP also enables algorithm testing under controlled conditions, allowing one to gain a deeper understanding of performance. Whilst we have focused on robustifying ML-based threat detectors, our TIP method can also be used to train and robustify human threat detectors as is done in cabin baggage screening.

I. Introduction

A major challenge for obtaining high human performance at visual screening tasks, such as detecting Small Metallic Threats (SMTs) in X-ray baggage scans, is the rarity of real threats. Studies have shown that humans perform much better in terms of detection and false alarm rates if threat items have high prevalence [1]. This prompted research into Threat Image Projection (TIP) techniques, mostly in Cabin Baggage Screening (CBS), whereby threat items are realistically projected into baggage imagery to increase threat prevalence during live screening operations. TIP is also used in Computer Based Training (CBT) [2, 3], and for evaluating operator performance and vigilance [4].

Most TIP methods insert Fictional Threat Items (FTI) from a threat database into the image [5]. Researchers have focused on determining realistic placement locations (voids) in baggage and generating threat noise and artefacts that are consistent with the rest of the baggage [6–8], so as to reduce visual cues for operators. To our knowledge there have been no academic publications on TIP methods for cargo. Authors have commented on possible cues caused by superposition-based TIP methods for single-view X-ray baggage [8]. We follow a similar superposition approach, but demonstrate, experimentally, that it does not lead to any obvious visual cues.

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Researchers also face a similar threat prevalence issue when training Machine Learning (ML) based Automated Threat Detection (ATD) algorithms. There is often a large imbalance between the *innocuous* and *threat* classes. This often leads to learning algorithms that are biased towards the *innocuous* class and therefore detection performance on the *threat* class suffers. This observation is similar, and possibly analogous, to the one found in humans. Class imbalance can also affect performance evaluation, particularly accuracy measures, in what is known as the "accuracy paradox" [9].

To remedy the class imbalance problem, researchers often consider: (i) dataset re-sampling [10, 11]; (ii) reformulating the problem as one-class [12]; (iii) adjusting the algorithm cost function [13]; or (iv) generating or collecting more data. Recently, with the development of end-to-end ML methods such as Convolutional Neural Networks (CNNs), which require very large amounts of training data, dataset augmentation [14, 15] has become increasingly the focus of attention. In dataset augmentation, class-preserving transformations are made to existing training data to expose the ML algorithm to natural variation, which reduces overfitting and improves generalisation to unseen examples. Such transformations often include rotations, translations, reflections, and changes in illumination and noise.

In cargo screening, we are faced with a major class imbalance problem since threats are extremely rare in the wild. It is also expensive and time consuming to collect large numbers of realistic *staged* threat examples. To this end, we have developed a TIP framework for cargo. The framework allows generation of realistic synthetic threat images and the injection of realistic variation derived from the characteristics of X-ray cargo image formation. These variations include: (i) translations; (ii) rotations; (iii) pixel noise; (iv) magnification; (v) illumination; (vi) volume and density; and (vii) obscuration. Whilst TIP is beneficial in training ML-based algorithms, it is also useful for gaining a deeper understanding of algorithm performance by controlling particular aspects