# HTPX - Fast, automatic, low-cost X-ray bag screening for mass-casualty threats

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## ABSTRACT

We describe a novel fast, automatic and low-cost approach to screening bags for mass casualty threats at sports events, visitor attractions, transport hubs and other publicly accessible locations. This uses simple dual energy X-ray imaging combined with additional microwave radar and optical sensors designed to distinguish benign bags from those containing large explosives or weapon threats. An algorithm based on machine-learning techniques provides automatic detection without the need for an operator to view any image. A prototype has been developed and shown to be able to screen in excess of 1000 bags/hour with high detection and low false alarm rates. Algorithm testing using data from real-life bags taken from a major London visitor attraction and threat bags containing representative firearm and simulated IED threats gave a detection rate of 90% with a corresponding false alarm rate of 2.5% and 95% at 7% false alarms.

**Keywords:** X-ray, High throughput bag screening, Automatic detection, Homeland security, Multi-sensor system, Explosives detection, Weapons detection

## 1. INTRODUCTION

With the increase in terrorist attacks on publicly accessible locations aimed at causing mass casualties, many organisations such as sporting and entertainment venues, visitor attractions, museums and galleries, shopping centres, train stations and transport hubs etc. are introducing or looking to introduce additional screening of visitors' bags. At these sites, screening needs to be carried out quickly, at low cost and with minimal interruption to the normal flow of commerce.

Manual bag searches are slow and intrusive and rely on staff maintaining focus and vigilance in order to be effective. X-ray bag screening is a cornerstone of aviation security but does not currently transfer well to high throughput applications. This is primarily due to low belt speeds; the need for human screeners to interpret complex bag images; the high cost-overhead of providing sufficient staff to operate systems; large bulky machinery and high false alarm rates. As a consequence, there is a need for a low cost, compact, high-throughput X-ray system to automatically screen bags for the larger threat items of interest in our target applications.

Whilst there has been significant progress in the development of advanced X-ray screening technology, this work has virtually always focused on the needs of the aviation security sector where the need is to find relatively small threats in complex, 'busy' bags and where the screening budget can be several dollars per passenger.

In a series of UK Government funded research projects, Iconal has taken a fresh look at this problem. By analysing the detection and operational requirements of what is becoming known as 'high footfall screening' we have identified concepts, developed a prototype and evaluated a high-speed, low-cost, automatic X-ray based bag scanner capable of detecting mass casualty threat items including explosives devices, large firearms and quantities of ammunition, where the budget is just pennies per person screened.

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## 2. APPROACH

Traditional work in automatic threat detection algorithms focusses on using detailed data from a single sensor type (such as a transmitted intensity image) to identify objects within a bag with the characteristics and shape of a threat item such as a gun, knife against a background of other objects. Similarly, X-ray image interpretation by human X-ray screeners combines this approach with one of recognising the objects in the bag as 'normal' and selecting any bags with unrecognised objects for further inspection.

In contrast, our approach identifies features of the bag and its contents *as a whole*, using data from *multiple sensor modalities*, to classify the bag as threat-containing or benign. For example, a bag that is light and/or largely empty is unlikely to contain a threat. Similarly, an IED threat-bag designed to cause mass casualties is likely to be completely filled with explosive for maximum effect, whereas a bag containing many different types of object is more likely to be the benign bag of a commuter or weekend traveller.

A further principle used in this work was to consider carefully the range of bag types that the detection system should aim to screen. Whilst ideally this would be as wide a range as possible, in terms of size, shape and contents, there is a significant advantage in restricting the range to those most commonly found at the sites where the technology would be deployed. Many venues restrict bag sizes as a matter of security policy and it is usually possible to implement a separate screening process for the small number of over-sized bags, allowing the large majority to be screened by a much faster overall process. We used data collected from observations at various high footfall sites together with a scenario-based bag design process to produce sets of typical bags for different types of venue — sporting, visitor attraction, mass transport and others.

Development was carried out by first considering the physical characteristics of threat and benign materials and objects in these bags and selecting a range of sensors to identify these signatures. Signatures from multiple sensors were combined, again using physical principles, to produce a set of features representing the bag, such as its overall mass, density, homogeneity of contents, amount of very dense material such as ferrous metal, and so on. Machine learning was then used to identify the most relevant features and to train a detection algorithm to classify bags as threat or benign.

The initial phase of the work consisted of desk research into sensors and signatures, combined with simulation using data collected on a conventional X-ray machine to explore the effect of different X-ray energies, flux and image resolution, as well as potential additional sensors. A proof-of-principle prototype was then constructed using a small single-view, dual-energy X-ray machine modified to increase the belt speed by a factor of four, with additional 3D optical and microwave radar sensors to provide information about the bag and its contents. This was used to collect data from benign and simulated threat bags for detection algorithm development.

Initial results were promising and led to further work to make the prototype more robust and suitable for gathering data in a realistic operational environment that could be used to optimise the algorithm and assess how well the system might perform in real life – both from a detection perspective and one of usability as a practical screening tool.

### 2.1 Sensor selection

**X-ray** systems are well proven as a technology for screening bags of all types. Although X-ray sources and detectors are relatively costly and measures have to be taken to ensure the safe use of ionising radiation, X-rays provide excellent penetration and image contrast on nearly all bags, high resolution imaging is possible and dual-energy X-ray imaging provides valuable information on material characteristics, particularly organic materials. Our initial study found that the x-ray photon flux and resolution provided by typical commercial X-ray systems was more than adequate for this detection task. Belt speeds of 0.15-0.20 $\mathrm{ms}^{-1}$ have become standard to give a human operator time to view each image. By removing this requirement to keep pace with a human operator, we found we could increase the belt speed by four and retain sufficient signal to noise to make effective observations.

Conventional 60 to 100 kV X-ray generators have adequate flux and the usual dual energy detection approach can be used to discriminate between large objects made of different materials.

We therefore chose a typical small single-view, dual-energy conveyor driven baggage X-ray system as the primary sensor. Since speed is important and, as noted above, X-ray photon flux is higher than needed, we changed the conveyor drive motor to increase the belt speed to 0.7 $\mathrm{ms}^{-1}$.

The single view X-ray with its fan-beam geometry provides very little information on the thickness of the bag, making it impossible to distinguish between a thick object of low density and a thin object of much higher density. Normal X-ray practice would be to add an orthogonal, second X-ray source and detector array to provide a side view allowing the height and thus density of objects to be estimated. Unfortunately, this significantly increases the cost and the physical size of the system.

Instead, we turned to alternative sensor types and chose a combination of microwave radar and a 3D imaging camera to provide both height and additional information about the bag contents.

The **3D optical time of flight camera** measures the outer surface of the bag as it passes through the X-ray tunnel. A Microsoft Kinect One Time of Flight camera was used in the prototype. This camera has subsequently been discontinued but a wide range of other commercially mature 3D imaging cameras are available.

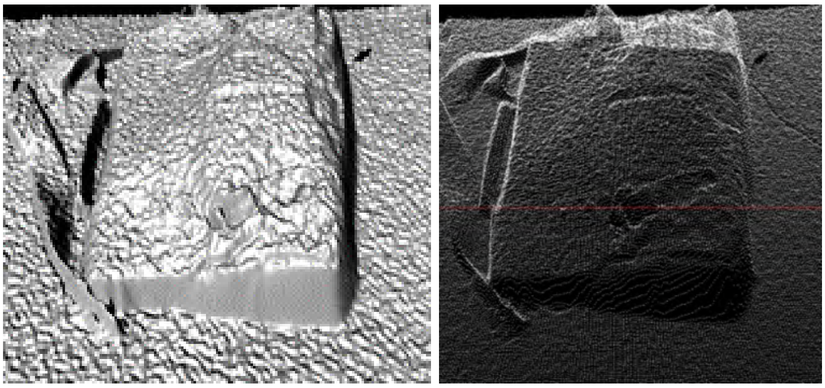

Figure 1. Time-of-flight images of a satchel on a flat surface captured by the Kinect One. The left image shows a single exposure (surface map), while the right image is an average of multiple exposures (point cloud).

Fig 1 shows two images of a satchel taken using the Kinect One, which demonstrate that the bag surface is clearly mapped, with features such as handles, straps and buttons visible. A single exposure from the camera (left image) is quite noisy, with of the order of 2 cm noise on each pixel, however integrating over several exposures (right image) produces a relatively clean image.

A **microwave 3D imaging radar** is used to create a low-resolution 3D radar map of the bag. The radar module is based around a commercially available Walabot Developer device, which uses a single chip radar developed by Vayyar and an array of 18 antennas. The measurements from multiple transmit–receive antenna pairs are analysed to reconstruct a three-dimensional "image" of the environment. It is an ultra-wideband (UWB) system and operates between 3 and 10 GHz to provide depth resolution of a few cm.

The radar identifies where objects are located in the bag and the degree to which they reflect radar energy. Due to its limited depth and spatial resolution, the radar tends to measure the average properties of a region of the bag (Fig 2), rather than resolving all the discrete layers within the area under inspection.

Alternative sensors providing higher and lower resolution, such as higher frequency millimetre-wave radar and simple light-gates for height measurement were considered, but we found that the above approach provided sufficient information to supplement the X-ray image, as well as being low-cost, robust and relatively straightforward to implement.

## 2.2 Detection Algorithm

The detection approach is built around the extraction and combination of a number of features from the raw sensor data that represent some characteristic of bags containing threat objects or of benign bags and their contents. Typical features include the dimensions and volume of the bags; magnitudes of different sensor responses; homogeneity and image complexity measures; and X-ray and radar characteristics of very dense or homogenous organic regions. Overall, some 50–100 features have been defined, based on the physics of the interaction between the various types of sensing used to interrogate the bag.

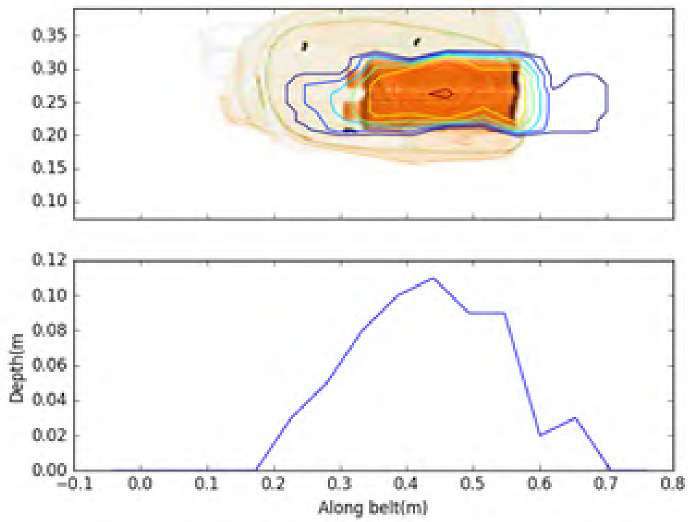


Figure 2. Radar image of a bag containing two 1 litre bottles of water. The top image shows reflected radar energy overlaid on the X-ray image. The bottom graph shows the corresponding radar measurement of average depth along the length of the bag.

This differs from the approach used in many 'deep learning' applications where, typically, a deep neural network is fed the raw sensor data. This data is used without much filtering in order to directly infer the features themselves from the unprocessed information. We believe that our feature engineering approach, with its ability to incorporate prior knowledge of the application task and sensor physics into our model, adds significant additional power to the detection algorithm.

The informed choice of these features is therefore a way of 'feeding' knowledge into the algorithms and helping increase the effective 'signal-to-noise ratio' of the data used to make the detection decisions. We do not expect that all the features will be relevant (indeed, many will be highly correlated), however the process of classifier fitting automatically selects useful features over weaker, less significant features which have no discrimination capability.

Several machine-learning approaches to the classification of the feature vectors were explored, alongside more traditional statistical clustering techniques. Experiments showed that ensemble classifiers such as random forests [1] gave good overall performance, with advantages including good resilience to overfitting, the ability to produce understandable outcomes and the limited need to fine tune a large number of model parameters to achieve good results. One potential disadvantage is that the technique may be computationally slow in some cases in producing a verdict, but this has not prevented real-time performance. Neural networks were trialled in parallel, and performed better in some cases, but were much less consistent and lacked the ability to probe into the reasoning of detection verdicts.

### 2.3 Prototype System

A prototype system was developed using a Smiths Detection 5030si X-ray machine with modified conveyor mechanism as described earlier. The UWB microwave radar and 3-D imaging sensors were mounted inside a hood on the exit side of the system (figure 3). In a production system, the additional sensors could be mounted inside the tunnel to save space.

A separate computer was added, with an interface to extract the raw image data from the X-ray system, align and process all the sensor data, together with 'stop-go' lights to indicate whether the system is ready to accept bags and another red/green light to signal alarms. Note that the system is completely automatic in operations and does not need or provide any X-ray image display to the operator, whose role is simply to ensure that bags are put on and taken off the conveyor in an orderly fashion and to remove bags which alarm for further inspection.

Figure 3. The HTPX proof-of-concept prototype showing X-ray machine with a hood containing the additional sensors.

## 3. EVALUATION

The prototype was initially evaluated in house using a set of threat bags containing either weapons or simulated IEDs. A set of benign bags was also developed with different types of content such that different subsets of the set could be used to simulate those used at different types of site.

The target threat set included bags containing:

- Simulated IEDs both small and large, with and without metallic/non-metallic shrapnel;
- Firearms – large pistols and automatic weapons, with and without additional ammunition;
- Bladed weapons – long-bladed knives and other large-bladed weapons.

Benign bags were designed using a series of 'scenarios' or 'vignettes' of different types of visitor (age, gender, alone or in group etc) at different types of site (visitor attraction, football match, music, theme park). In decreasing proportions, they included a mixture of rucksacks, shoulder bags, handbags, trolley cases, briefcases, holdalls and laptop bags. The bag contents included varying quantities of clothing, books, food, personal electronics and cameras as appropriate to the vignette.

This test set was used to train the detection algorithm and then to evaluate its performance using different 'hold-out' sets, where the algorithm was trained on a proportion of the test data and then evaluated on a separate subset of the data. Initial results were promising with detection rates for different algorithms of approximately 95% at false alarm rates of 5% averaged across all the threat types used.

In parallel, a dummy X-ray system was constructed with a variable speed conveyor belt and adjustable length input and take-off belt areas. This was used to investigate the optimal speed for patrons to place bags on the conveyor, walk past the X-ray tunnel and collect their bag at the other side.

Varying (false) alarm rates were also simulated in order to explore different alarm resolution processes including stopping the belt on alarm and holding the queue while the bag was searched, and keeping the belt running and removing bags which alarm for resolution in a separate lane. In the first configuration, two operators were employed, one to supervise overall operation and support patrons as necessary, and one to remove and search bags which alarmed. In the second, a single operator would remove bags which alarm for search and restart the belt but could pause the system if a second bag caused an alarm whilst the first was still being checked.

We found that even with a relatively pessimistic false alarm rate of 10%, a throughput of 1600 patrons/hour could be achieved with two operators and 1400 with a single operator. The limited number (approximately 20) of volunteers used in the experiments meant that users rapidly became familiar and compliant with the system. In a more realistic situation, throughput would be somewhat less, but we estimate that 1000-1200 bags/hour should be achievable.

Table 1. Summary of detection performance on the visitor attraction data.

| **Model** | **FPR (TPR=90%)** | **FPR (TPR=95%)** |
|---|---|---|
| Original model trained on in-house data | 15% | 20% |
| Original model retrained on in-house data and 1,500 visitor attraction bag images | 7% | 12% |
| Revised model with water and texture features | 2.5% | 7% |

In order to get a more realistic measure of detection performance and to understand how it would be received by security staff and the general public, we arranged a week-long data collection trial of the working system at one of the major London visitor attractions.

The prototype HTPX system was set up at the exit from the standard entry and security screening process which consisted of manual people screening and checks on a proportion of visitors' bags. After this process, visitors were requested to offer their bags for screening by the HTPX system. In this exercise, bags were placed on the conveyor by an operator and collected at the exit of the system by the visitor. The prototype ran the normal detection algorithm, but alarms were not displayed, and the data was saved for subsequent evaluation.

From a usability perspective, the system was readily accepted by visitors. Many visitors expressed surprise at how fast and straightforward it was. There were very few negative comments received and no one refused to participate. Security staff feedback was also very positive.

Over the week some 4,000 bags were screened and the data was used to retrain the algorithms and further evaluate the detection performance. Using the original algorithm trained on the in-house developed benign bag set, the false alarm rate was 3-4 times higher than on the in-house data. However, when the algorithm was retrained using approximately half of the live data and then tested on the other unseen half, the false alarm rate reduced significantly, though not quite to the original levels.

On investigation, it was found that false alarms were often caused by bottles of water and large quantities of food, which was present in many of the bags (the data collection trial was carried out during a school half-term holiday week when many visitors were family groups on a day-out with children). Additional water identification and texture features were added to the algorithm to help recognise bags with these types of contents. This reduced the false alarm rate considerably and the final algorithm achieved 2.5% false alarm rate at 90% detection and 7.5% at 95% detection rate (table 1).

Receiver operating characteristic (ROC) curves for the final algorithm, calculated for different subsets of the data are shown in figure 4. The amount of training data used in the training set is still very low in terms of machine learning best practice and additional training data and feature tuning should further improve performance.

Subsequent to the data collection trial, a further evaluation was carried out on behalf of UK Government using live explosives and a larger range of firearms and other weapons.

## 4. CONCLUSIONS AND DISCUSSION

Whilst considerable progress has been made in the last 20 years in solutions for screening people for both metallic and non-metallic threats concealed on the body[2], work in screening for threat items carried in bags has been mainly focused on aviation security where either human image interpretation or relatively complex and costly techniques such as X-ray computed tomography have been employed.

In our work, we have explored the challenge of identifying a low-cost, fast and automatic solution for screening bags for mass casualty threats at publicly accessible locations such as sports venues, concerts, visitor attractions, transportation hubs and other sites where the risk and people flux precludes the use of aviation-style techniques.

We found that a combination of simple single view dual energy X-ray imaging combined with additional microwave radar and optical sensors to provide additional 3-D information about the bag size, shape and contents, could be used to distinguish benign bags from those containing large explosives or weapon threats. An algorithm based on machine-learning techniques provides automatic detection without the need for an operator to view

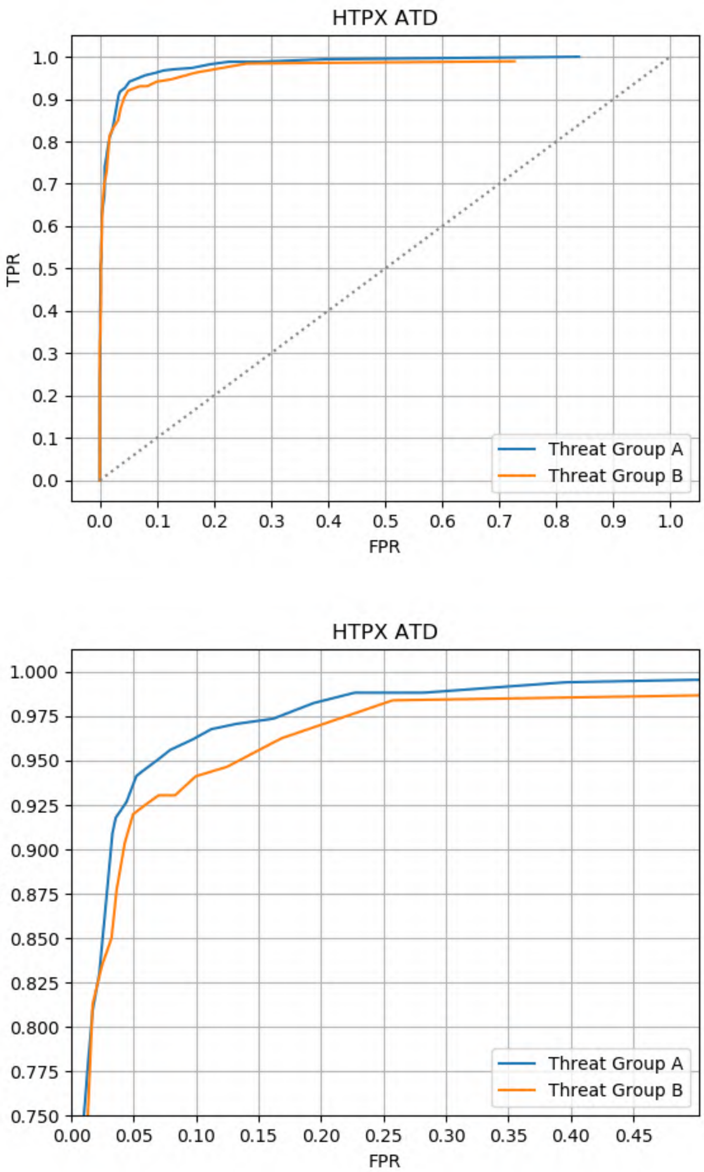


Figure 4. ROC curves using the final algorithm for different subsets of threat item on a random sample of 1,500 bags screened during a data collection trial at a London visitor attraction. Threat group A consists of the larger firearms and IEDs, group B includes medium-sized threats. Bottom image shows a close-up of the top left-hand region.

any image. A prototype has been developed and shown to be able to screen in excess of 1000 bags/hour with high detection and low false alarm rates[3].

The additional sensors are estimated to cost less than $1,000 and are relatively straightforward to integrate into a conventional conveyor X-ray system design. Data processing needs are also modest, with the sensor interface, low level data processing, control software and detection algorithm all able to run on a standard PC. It is likely that a lower voltage, lower flux X-ray source could be used, possibly reducing the footprint and amount of shielding needed. The number of detectors could probably also be decreased, potentially reducing cost. Whilst further development work could certainly be carried out to improve its self-service capability, the current prototype has been trialled successfully with a single operator to supervise its use.

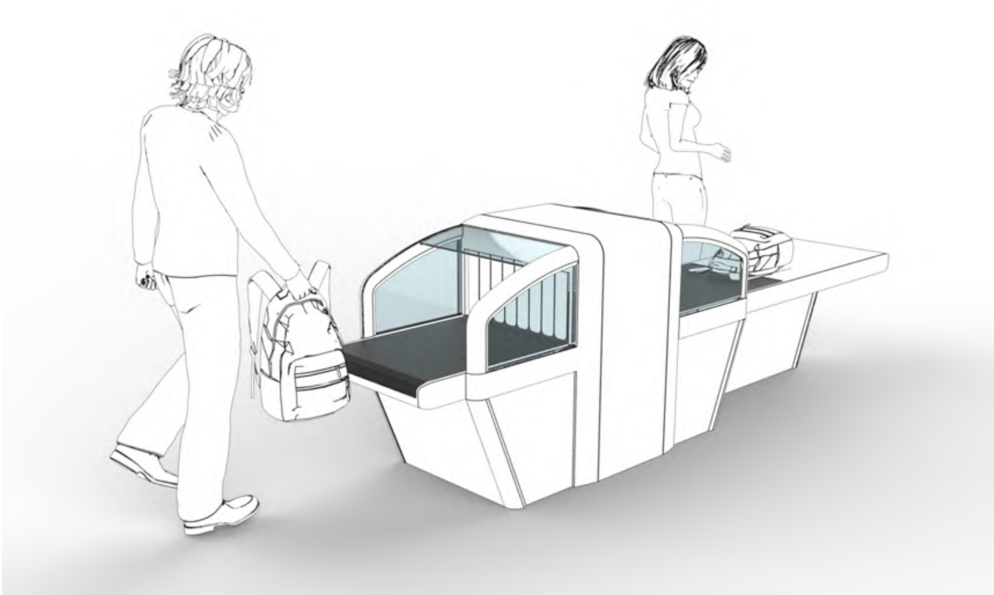

Figure 5. Concept image of a 'drop and go' high throughput x-ray system.

Overall, we believe that the approach developed, which we have called HTPX (High Throughput X-ray) could form the basis for an effective new form of security screening capability.

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