Towards Determining Relative Densities for Common Unknown Explosives in Improvised Explosive Devices

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***Abstract*— This paper proposes a methodology to obtain a model for estimating relative densities of unknown substances contained in Improvised Explosive Devices (IEDs) using scanning technology and image processing techniques. We assert that this technique can provide teams involved in explosive threat detection relevant information pertaining to a range of possible types of explosive material contained within an IED.**

Keywords — Computed Tomography; Density; Explosives Disposal Unit; Improvised Explosive Devices;

I. Introduction and Background

An improvised explosive device (IED) is a bomb constructed from military or other explosive material and deployed in unconventional ways resulting in a potentially deadly weapon. IEDs, in all their forms, are designed to cause property damage, injury, death and instill fear and uncertainty in a targeted population. IEDs range from extremely rudimentary devices to sophisticated weapon systems containing high-grade explosives.

IEDs consist of several basic components, including an explosive charge and a method of detonation [1]. IEDs comprise of common explosives such as various types of dynamite, homemade explosives, high-grade explosives, and low-grade explosives. When the explosive component of an IED is concealed, such as inside an innocuous container, the type of explosive is impossible to determine through visual inspection. Thus, it becomes important to accurately surmise the type of explosive by other means in order to dispose of the IED safely.

This paper discusses the use of computed tomography (CT) as a means of sensing the physical characteristics of explosives. In our case, we used inert explosive simulants having physical characteristics very similar to their explosive analogs.

Our aim is to provide threat-detection personnel such as explosive disposal units (EDUs), with additional information with regard to the type of the explosive they may be dealing with, accomplished through the analysis of its relative density as determined by the CT scan. Our aim is to make the determination of the type of explosive safer.

II. Related Work

Common explosive and related threat-detection methods include technologies such as walk-through metal detectors (WTMD), handheld metal detector (HHMD), explosive trace detectors (ETD) and stationary and portable x-ray technology [2]. Remote detection systems containing intensified charge-coupled device (ICCD) detectors have also been designed and demonstrated for possibly detecting high explosive materials [3–5] or other chemicals [6].

For the purposes of this study, the focus is on concealed explosives in containers - IEDs, which cannot be safely manipulated without endangering proximate people and property. Typically, EDU employ x-ray technology to determine the nature and location of different IED components and the type of explosive employed in the device in order to determine an effective and safe means of neutralization. Common EDU practices do not use the WTMD or ETD threat-detection technologies when dealing with a suspect IED threat [7], [8], therefore our focus is on x-ray technology.

EDU are trained to operate x-ray screening instruments that rely on the operator's ability to visually identify potential threats by interpreting 2D x-ray images [2], [9–11]. The efficacy of these threat-detection screening systems are highly reliant on the interpretation of the data by the personnel who operate them [12–16]. Despite technological advancements in detection equipment, training and procedures, there are few automated explosive detection systems in place to improve the effectiveness of x-ray screening operators when viewing x-ray scans [17].

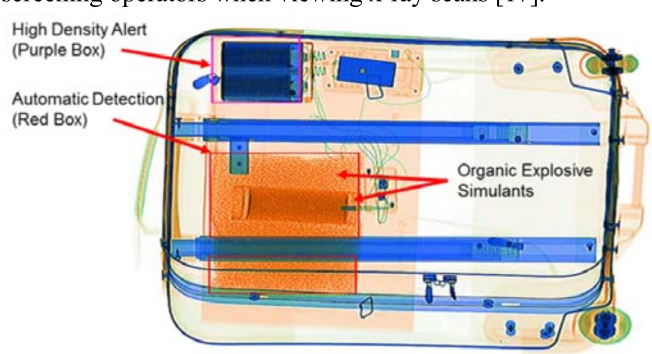

Figure 1 – A threat image projection showing areas of particular interest to an x-ray screener operator [2].

Figure 1 is a threat image projection (TIP) taken from an x-ray screener which shows automated bounding boxes around areas of the image which correspond to high density clusters, assisting the operator by highlighting areas of particular interest [2], [18].

The information provided in Figure 1 is limited to showing bounding boxes for high density areas, and does not provide additional automated information that can aid the operator in identifying the type of explosive that may be present.

CT scanning technology is a commonly used form of medical imaging for viewing cross sectional images of internal body structures, and can aid in determining the location, size, and relative densities of unknown masses. With the use of CT scanning--a modified form of x-ray technology that takes multiple cross-sectional (tomographic) scans of the entire container--an operator can see a container's contents in 3 dimensions without physically interacting with it [19], [20].

CT scanning technology provides the benefit of creating 3-dimensional reconstructions and multi-planar views that allow the detection of unknown masses including allowing the determination of their locations, sizes and relative densities with respect to surrounding materials.

However, CT scanning technology is not without challenges. CT scanners tend to be large, expensive and not easily transported to the site of an incident. There is considerably more expertise required of the operator in addition to the challenges of recalibration of parameters, and there are the challenges of positioning the CT scanner in order to image the target IED without disturbing it.

The size and density of the target are increasingly problematic. For instance, a larger and denser target would require more x-rays and larger field of view, whereas a smaller and less denser target would require less x-rays and a smaller field of view [21]. In order to obtain relevant information from CT scans, it is essential for operators to have thorough knowledge and practical experience with CT scanning technical parameters, standard procedures and protocols—none of which are current practice in EDU units.

It is important to note that results obtained from scanner to scanner vary significantly, even when the same brand and model of scanner is used. Other variables that may affect the internally generated raw data values may be scanner parameters, reconstruction artifacts or the use of different scan geometries [22]. Levi et al. describes that internally generated raw data values from CT scanners are unreliable as absolute values and caution must be advised in the use of these values for diagnostic and therapeutic purposes [22]. However, the methodology presented in this paper is able to obtain values that can be associated with specific parameters and a particular scanner, enabling a high fidelity relative density measurement. This will be true as long as the same scanner and parameters are used to scan subsequent targets. For any new scanner, technical parameter, procedure or protocol, one must first calibrate their base values with the methodology presented in this paper.

III. Methodology and Experiments

When threat-detection personnel are tasked to identify and neutralize the threat associated with an IED, one method of evaluation is to focus on the arrangement of the IED's components, the quantity of materials, their position and the size and density of those materials.

We aim to augment this process by utilizing CT scanning as another non-invasive technology used to obtain relevant information concerning concealed unknown materials. Our CT scanning protocol follows the head and neck standard protocol outlined in [23] designed by board-certified medical physicists of the American Association of Physicists in Medicine (AAPM). This protocol is optimized for obtaining CT scans on targets that are relatively smaller, therefore requiring smaller slice thicknesses, higher resolutions and a smaller field of view (FOV) as parameters.

Our proposed methodology is comprised of seven steps, and assumes calibration is performed before estimating relative densities of concealed unknown materials.

A. Set CT parameters

We begin by adjusting the CT scanner according to the parameters in the head and neck protocol [23]. In our teats, we employed the Philips Big Bore CT [24] with Pinnacle3 [25] as the treatment planning system. The use of alternate CT scanners are also possible but should follow the AAPM CT lexicon translation chart to discern important CT terminology and parameters of different manufacturers' systems [26].

The technical parameters [27] that are often adjusted are:

- **Tube current-time product (mAs)** - The product of tube current and exposure time per rotation, expressed in units of milliampere * seconds (mAs).
- **Slice thickness (in millimeters)** - Nominal width of reconstructed image along the z axis.
- **Resolution - T**he ability of the imaging modality to differentiate two objects. Low spatial resolution standards will be unable to differentiate between two objects that are relatively close together.
- **Field of measurement (or calibrated field of view FOV)** - The diameter of the circular region within the scan plane over which projection data are collected.

In addition, these parameters must be calibrated according to the size and density of the target in order to produce reasonable output. Failure to calibrate according to the target would cause the output images to suffer from excessive noise which can hamper the detection process.

The parameters we used are shown in Table 1, other parameters are normally not adjusted for in the head and neck protocol.

Head & Neck	Values
FOV	500 mm
View Angle	Multi Surview
kV	120
Tube current	30
Thickness	3 mm
Increment	3
mAs/slice	300
Resolution	standard
Filter	standard (B)

Table 1 – Head and neck parameters taken from the standard AAPM head and neck protocol, optimized for dense objects.

The parameters in Table 1 are defined as follows [26]:

- Field of measurement or field of view (FOV) is the diameter of the circular region within the scan plane over which projection data are collected.
- Multi surview is the scanned projection radiograph, often acquired by the CT system to allow the user to prescribe the start and end locations of the scan range.
- Tube potential (kV) is the electric potential applied across an x-ray tube to accelerate electrons towards a target material, expressed in units of kilovolts (kV).
- Tube current is the number of electrons accelerated across an x-ray tube per unit time, expressed in units of milliampere (mA).
- Thickness is the nominal width of reconstructed image along the z axis.
- Increment is the distance between two consecutive reconstructed images.
- Tube current-time product (mAs/slice) is the product of tube current and exposure time per rotation, expressed in units of milliampere seconds (mAs). In axial scan mode, this is equal to tube current × (scan angle ÷ 360) × rotation time. In helical scan mode, this is equal to tube current × rotation time.
- Resolution is the pre-defined standard dimensions of the images before 3D reconstruction.
- Filter is the pre-defined standard image modifications to alter sharpness or smoothness (done in image space without reconstructing images)

B. Scan rudimentary common substances of varying densities to obtain range of relative brightness

We define baseline outputs from CT scans of 7 different common substances with varying densities defined Table 2.

Substance	Density (g/cm^3 or g/mL)
Honey	1.42
Corn Syrup	1.33
Detergent	1.06
Water	1.00
Vegetable Oil	0.92
Lamp Oil	0.81
Rubbing Alcohol	0.79

Table 2 - The substances used in our preliminary experiment and their densities.

Figure 2 shows the actual substances and a 2D image slice from a CT scan with the standard head and neck protocol parameters. We consider water at 1.00 g/mL as our baseline (center bottle).

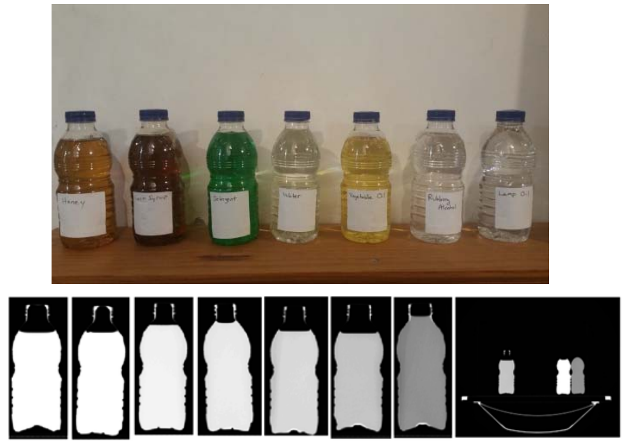

Figure 2 - From left to right, the liquids shown are honey, corn syrup, detergent, water, vegetable oil, lamp oil and rubbing alcohol, each showing up on the scan as different light intensities as a result of their different densities.

C. Relate relative brightness to densities of common substances

In order to gauge photometric brightness, we utilize the hue, saturation and value (HSV) colour space - most commonly used in computer vision techniques to separate 'luma', or the image intensity, from the color information.

Since we are only concerned with brightness dimension, we extract the luma component V, which is given as a real number between 0 to 1 – or in other words, it seems to appear as black at 0 and white at 1. In this paper we refer to the value component as brightness.

For each region of each substance, we calculate the average brightness and associate it with the density of the substance.

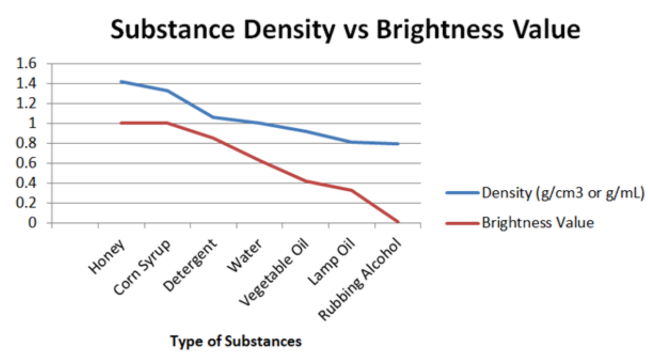

Figure 4 – This graph shows the density values vs values in the HSV color space)

The data values for Figure 4 are shown in Table 3, we use these points to create a line of best fit to normalize our model, which will be explained in part G of this section. The brightness value for water acts as our baseline substance. As a heuristic, the CT scanning parameters are calibrated such that the brightness value is near 0.5 - a median brightness value in the HSV color space.

This heuristic could ensure that the variety of substances more dense or less dense than water can be represented in the HSV color space. If the brightness value for water is near 1, then the parameters should be adjusted accordingly to obtain a lower baseline value for water.

Substance	Brightness Value (in HSV color space)
Honey	0.9998
Corn Syrup	0.9993
Detergent	0.8519
Water	0.6298
Vegetable Oil	0.4214
Lamp Oil	0.3239
Rubbing Alcohol	0.0062

Table 3 – The value obtained from the average of HSV pixel segment of the substance.

D. Determine linear trends for both density and brightness values.

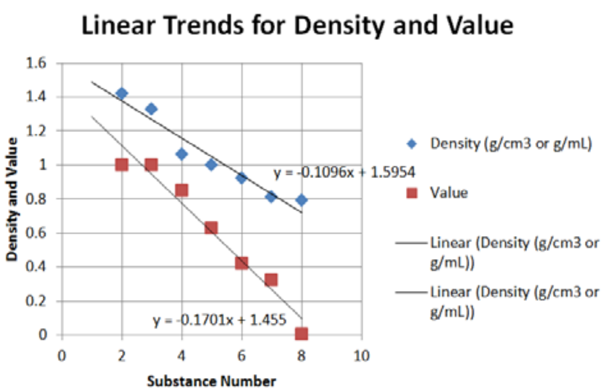

Figure 5 – This graph shows the calculated linear trend for density and value.

The linear trend line acts as our baseline formula, we can use this information to evaluate whether our calibration of the CT scanner is optimized for reasoning about densities of unknown masses. If the line of best fit closely fits the data points, then the CT scanning parameters are acceptable and calibration is complete.

E. Testing phase - Scan explosive simulants to obtain range of relative brightness

After obtaining base values and calculating the linear trends, we undertook scanning 6 high-grade inert explosives designed as high fidelity physical replicas of real explosives [28]. These inert explosives closely match the critical features, density, effective atomic number (Z_{eff}), colour and texture of the real explosive. We show the inert explosives in Figure 6, and we perform CT scans of the following inert simulants; smokeless black powder, nitro dynamite, TNT cast booster, M112 block (C-4) Assembly, pentaerythritol tetranitrate (PETN) and Semtex 10 Assembly—all available through DSA Detection [28].

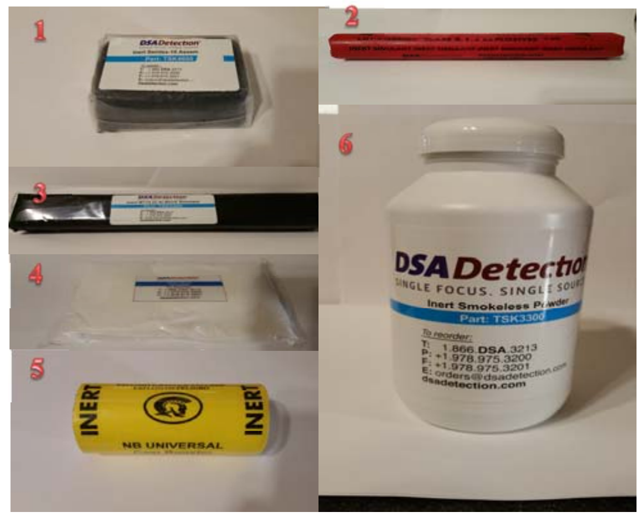

Figure 6 – 1. Semtex 10 Assembly 2. Nitro dynamite 3. M112 block (C-4) Assembly 4. PETN 5. TNT cast booster 6. Smokeless black powder

Figure 7 shows the multi-planar reconstruction of scans from 3 planes; sagittal, axial and coronal views of the inert explosives. We segment parts of image slice that correspond to the inert explosive and then extract the average brightness value from the HSV colour space of that segment.

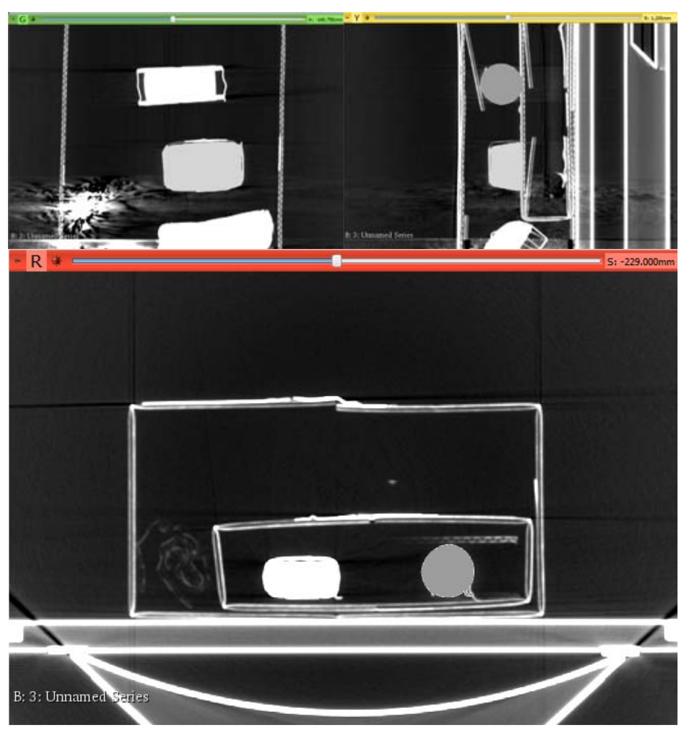

Figure 7 – A slice from the result of a CT scan of 6 different types of inert explosives in 3 planes.

F. Correspond relative brightness to densities of explosive simulants

Figure 8 shows the relative brightness of the inert explosives with their corresponding densities.

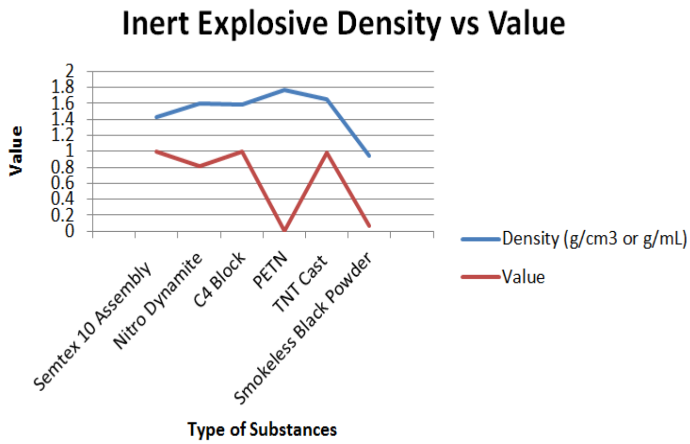

Figure 8 – A graph depicting the densities of inert explosives to their corresponding CT scanned value from the HSV color space.

The values of the CT scan slice and respective densities are as follows:

Inert Explosive	Density (g/cm^3 or g/mL)	Value (in HSV color space)
Semtex 10 Assembly	1.43	0.9998
Nitro Dynamite	1.6	0.9993
C4 Block	1.58	0.8519
PETN	1.77	0.6298
TNT Cast	1.654	0.4214
Smokeless Black Powder	0.95	0.3239

G. Evaluate relevant relative brightness

In this section, we eliminate obvious outliers from the results. As PETN and smokeless black powder are both forms of powder, pockets of air around the powder may have been captured and included in the segmentation process--leading to errors.

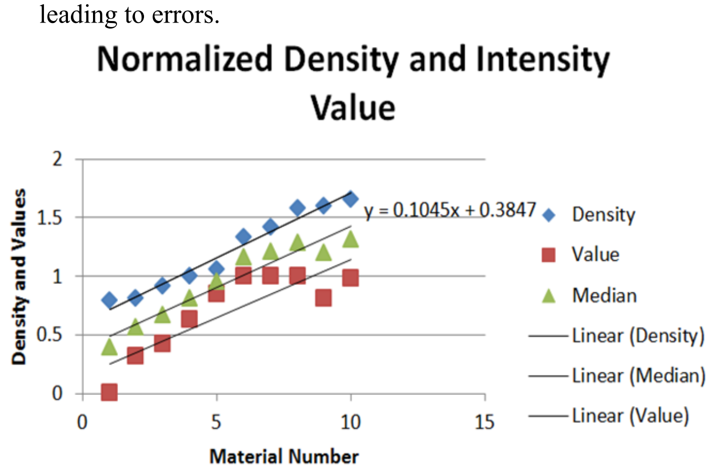

Figure 9 – A normalized linear equation as our model for estimating future unknown materials using the same parameters and scanner.

We then compare the inert explosives' brightness to baseline brightness and normalize against the brightness values of the baseline. As shown in Figure 9, we output a median line as our model to estimate unknown masses.

IV. Results

The resulting normalized linear equation is employed as the model to calculate a relative density of an unknown mass, using the same parameters and scanner, with a brightness value obtained from the segment of pixels of the slice of the target.

Based on our model, an example evaluation would be a relative brightness value of 0.9 correspond to an approximate relative density of 1.1162 g/cm^3 which falls under the material number most associated with densities that are associated with detergent or corn syrup, but not in the range of an inert TNT cast or nitro dynamite which should yield an brightness value of 0.9993 or 0.9998.

V. Conclusion and Future Work

We have proposed a methodology to calibrate a CT scanner and obtain a model to calculate relative densities as a form of additional information for threat-detection personnel. We argue that this methodology can be used to arrive at a reasoned estimate of the type of explosive being scanned as long as subsequent scans use the same pre-defined parameters, procedure and protocol and scanning machine.

Many techniques and approaches have been implemented in the medical field that use CT scanning to evaluate unknown masses in the human body. However, within threat-detection related fields, to our knowledge, no such methodology has been defined to determining relative densities of unknown substances in IEDs. By using inert explosives, the methodology we have presented is a theoretical baseline approach towards aiding EDU and other threat-detection personnel. This methodology may be quite useful if wide-scale adoption of portable CT scanners becomes more commonplace in the threat-detection fields.

Our future work includes adding additional features to augment the analysis of the study of the unknown mass(es) to better determine the type of explosive in the IED. One such method can involve using 3D reconstruction to implement other factors such as size, shape, location and arrangement of the type of unknown material. Knowledge of these characteristics can significantly aid EDU processes when direct interaction with IEDs is never a good idea.

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