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Improved Threat Identification Using Tonemapping of High-Dynamic-Range X-ray Images

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Abstract

Transmission X-ray systems are used to image the contents of suspicious packages, luggage, and cargo. The images can have a dynamic range of 1,000:1 or greater, but are typically displayed on consumer-grade displays with a low-dynamic range of less than 255:1. We show that modern tonemapping algorithms can greatly improve the process of displaying X-ray images on low-dynamic-range displays and compare the performance of some popular algorithms for this purpose.

Keywords

tonemapping; image enhancement; security X-ray imaging; bomb squads; explosives; portable X-ray imaging; high-dynamic-range

Introduction

X-rays are widely used in security applications principally because their ability to penetrate objects allows them to be used to inspect for concealed objects in a fast and non-invasive manner. For example, X-ray imaging is used in airports to scan checked luggage, hand luggage, and sometimes passengers. X-ray imaging of vehicles is employed by the military to find vehicle-borne improvised explosive devices and by customs to help secure borders.

This article is primarily concerned with the X-ray imaging tools used by bomb squads to examine the contents of suspicious packages. To decide whether a suspicious package contains an explosive device, bomb technicians look for components such as detonators, wires, and bulk explosives. To aid in recognizing objects and details, several types of image enhancements are typically employed. In this article, we investigate ways to improve this image enhancement process.

The particular equipment and settings used to display X-ray images can greatly affect how useful they are in their application. Some X-ray imaging systems produce very high-dynamic-range (HDR) images, but if viewed on consumer-grade equipment, the dynamic range of the displayed image is limited to that of the display. In many applications, this

limitation can be improved using image enhancement techniques. There are a specific class of algorithms designed to display HDR images on low-dynamic-range displays called tonemapping algorithms, and we aim to test their effectiveness in security related applications.

Tonemapping is an image-processing technique that maps one set of pixel values to another. A common application of tonemapping is the compression of HDR images into low-dynamic-range images that can be displayed on low-dynamic-range displays or printed to paper. Modern tonemapping algorithms are able to greatly compress the dynamic range of the image while still maintaining local contrast in all areas. The technique has become common in photography for representing scenes that contain both very bright regions and very dark regions. Tonemapping algorithms can be divided into two types: global and local. Global operators apply the same function to every pixel in an image. The resulting pixel value does not depend on surrounding pixels. For local tonemapping operators, pixels are mapped in a way that depends on their value and the value of other pixels in the surrounding area. After a local tonemapping operator is applied, one can no longer be sure whether pixels from different parts the image were originally darker or lighter than one another. Local tonemapping operators are able to greatly compress the dynamic range of an image while still retaining local contrast. The majority of the most popular detail-enhancement tonemapping algorithms utilize local operators [1].

Visible light HDR images can be created using consumer-grade cameras by combining multiple exposures [2]. The creation and tonemapping of HDR images has become extremely popular among photography enthusiasts, and in recent years, “HDR mode” has become an option for many smartphone cameras. There are a wide range of HDR tonemapping algorithms in use, most of which were designed to produce photorealistic images. Many papers have compared the performance of these tonemapping algorithms in various contexts, often by asking human study participants to subjectively judge the desirability of different images (e.g., by asking which image they prefer or which they think looks more real) [3]. HDR video can be collected in an analogous way, by varying the exposure of each frame. This video data can be combined and processed after the fact or even in real time [4,5]. Many of the same tonemapping algorithms are used for video processing, although some include time-dependent effects meant to replicate the response of human vision to changing lighting conditions [6].

Many photodetectors have a response that is not linearly proportional to the amount of light incident onto them. This is not advantageous for many image processing algorithms, such as sharpening, or indeed, combining multiple exposures into an HDR image. One can correct for this non-linearity by determining the response function of the camera, as is common in photography using comparametric methods [7]. At X-ray wavelengths, such techniques could be valuable for energy dispersive detectors, which generally suffer from non-linearities at high count rates due to pulse pile up. In this study, photostimulable phosphor plates were used, which are known to be extremely linear and have been verified to be so for the doses considered in this work [8].

Recent advances in tonemapping algorithms have led to great improvements in displaying HDR images on low-dynamic-range displays. In this article, we aim to show that this research can be extremely useful in the security context. In particular, these algorithms can be used to reveal fine details such as wires and obscured electronic components that would be otherwise invisible when displayed on standard displays. In the present work, we apply several tonemapping algorithms to X-ray images of explosive devices and compare their performance.

Many photographic tonemapping algorithms seek to mimic aspects of the human vision system [3]. They aim to compress the dynamic range while still retaining local contrast without making the image look unnatural. This constraint of realism is not relevant for X-ray images since an X-ray image never appears “natural” to human eyes. Therefore, a tonemapping algorithm for X-ray images need only achieve two goals: dynamic range compression and detail enhancement.

There has been much research into HDR techniques beyond conventional visible light photography. The breadth of this work will not be surveyed here, but we point the interested reader to examples where HDR processing techniques have also been advantageously applied to sonar [9], radar [10], and audio processing [11,12]. At X-ray wavelengths, Park and Montag investigated the performance of nine tonemapping algorithms for rendering scientific HDR images, including medical radiographs [13]. They tested the performance of these algorithms on laymen and radiologists using medical images and concluded that different types of images were more effectively rendered by different algorithms and called for more research “to evaluate the effectiveness of these algorithms for the specific tasks.”

In recent years, tonemapping options have been included in the software packages of some commercially available portable X-ray systems. A basic histogram equalization function was included in the widely-used X-ray Toolkit, the X-ray acquisition and processing program developed by Sandia National Laboratories (Albuquerque, New Mexico) for bomb technicians.³ The particular algorithms underlying these tools are generally proprietary and not described in any detail. In this article, we test a number of the most advanced and popular tonemapping algorithms that have been described in the scientific literature.

Tonemapping Algorithms

In the present work, we investigate the performance of several tonemapping algorithms by comparing how well they enhance details within a cluttered security image. The performances of eight tonemapping algorithms were examined. We compare the performances of four of these algorithms in detail in the following section. The remaining four algorithms were found to perform poorly in this application and were therefore excluded from the comparisons in the subsequent sections of this article. The algorithms were: Ashikhmin [14]; Drago et al. [15]; Durand and Dorsey [6]; and Pattanaik et al. [16].

³More details about the Sandia-developed X-ray Toolkit can be found at www.xraytoolkit.com

One of the most highly-cited tonemapping algorithms was published by Reinhard et al. in 2002 in the paper “Photographic Tone Reproduction for Digital Images” [17]. The algorithm was designed to tonemap photographic images but has also been found to be very effective at tonemapping medical X-ray images [13].

Fattal, Lischinski, and Werman proposed a tonemapping algorithm that compressed the dynamic range of an HDR image “while preserving fine details” [18]. This is achieved by “attenuating the magnitude of large gradients.”

Inspired by the gradient-domain methods of Fattal, Lischinski, and Werman, Mantiuk, Myszkowski, and Seidel published the 2006 paper “A Perceptual Framework for Contrast Processing of High Dynamic Range Images” [19]. The tonemapping algorithm of Mantiuk, Myszkowski, and Seidel incorporated research on human visual perception and attempted to process images in “perceptually linearized visual response space.”

A commonly used software package used by bomb squads is the Logos Imaging Application (Logos Imaging LLC, Loveland Colorado)⁴. The application provides some basic tonemapping functionality. While the exact algorithms being implemented are not stated, they are referred to as “histogram equalization” and “adaptive histogram.” We found that the best results were achieved by applying the histogram equalization function once, then applying the adaptive histogram function one to three times. This process can lead to considerably improved results compared with previous versions of the software. However, the process requires the operator to make judgments about which image-enhancement functions to apply and how many times to apply them. This means that the resultant images will vary from operator to operator, and equivalent components (e.g., detonators) will appear subtly different.

Comparison of Performance

A test image was devised to reflect some tasks in security screening. The unprocessed image is shown in Fig. 1a. The image contained four key objects that are highlighted in Fig. 1b: a plastic knife highlighted in orange; a round stopwatch is highlighted in green; a 9V battery (highlighted in blue) was placed behind a sheet of steel and a steel line-pair gauge; a large aluminum step wedge is located toward the center of the image and its boundary is highlighted in yellow. The X-ray image was generated using a Logos Imaging System (phosphor image plate) that utilized a Golden Engineering XR200 (Golden Engineering Inc., Centerville, Indiana) using 26 pulses from the 150-kV tungsten X-ray source with a source to detector distance was 100 cm.

The tonemapping algorithm was judged on how well it displays each of these objects and especially its ability to allow the operator to:

- identify the path of a wire

⁴Certain commercial equipment, instruments, or materials are identified in this article in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the U.S. government, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

- identify electrical components (e.g., a 9V battery)
- identify the shape of a piece of low atomic number material in a cluttered environment (e.g., a plastic knife)
- identify the shape of a metallic material (e.g., a stopwatch) behind shielding, and
- identify all of these objects in a single image.

In this way, we seek to determine the most effective tonemapping algorithm(s) for the types of images relevant to the security application.

In the unenhanced X-ray image, the aluminum step wedge is dark, but each level of the wedge is visible and distinct. Based on the brightness of each step, one can see that the lowest step is thickest and that each higher step is thinner. The plastic knife is visible, but there is weak contrast between the knife and the background. The stopwatch is visible as a silhouette, but the internal details are difficult to see. The region of the stopwatch that was obscured by the step wedge is also difficult to see. The lengths of wire that are behind the step wedge are difficult to see. The 9V battery is not identifiable.

Fig. 1c was enhanced using the Logos Imaging Application. This algorithm did a good job of enhancing small details, especially in the dark areas of the image. For example, the internal cell structure and terminals of the battery are now clearly visible. This detail enhancement was achieved by brightening the darker areas. As a result, it is very difficult to judge the relative thickness of objects or even discern which part of the step wedge is thickest. The enhancement algorithm also produced significant artifacts, especially at the boundaries between light and dark areas. These halo artifacts seem to exist out to a constant radius and greatly distort the brightness values on and around the step wedge.

The image shown in Fig. 1d was enhanced using the tonemapping algorithm of Fattal, Lischinski, and Werman. This algorithm was the best at enhancing small details, as can be seen by how well it displays the 9V battery and the stopwatch. One consequence of this is that the noise has also been amplified. There are some halo artifacts around the outside of the step wedge, although they are not as bad as the Logos-enhanced image. The relative thicknesses of the steps is almost impossible to determine from this image. Overall, this algorithm sacrifices information about relative thickness in order to provide excellent enhancement of fine details.

The tonemapping algorithm of Mantiuk, Myszkowski, and Seidel was used to produce the image shown in Fig. 1e. This algorithm did a very good job of enhancing the fine details within the 9V battery and stopwatch. The path of the wire is also very easy to follow. Unlike the algorithm of Fattal, Lischinski, and Werman, this enhancement was achieved without producing excessive noise. There are no obvious halo artifacts and the thicknesses of the step wedge are clearly discernable. This algorithm provides very good detail enhancement, while still preserving some information about relative thickness.

The image in Fig. 1f was enhanced with the widely-used tonemapping algorithm of Reinhard et al. This algorithm does a poor job of enhancing details, but preserves relative thickness information.

The two algorithms that did the best job of detail enhancement were Fattal, Lischinski, and Werman and Mantiuk, Myszkowski, and Seidel. They acted in a manner that improved the visibility of all objects in the image, particularly in very dark areas (e.g., the 9V battery and the stopwatch) without introducing strong artifacts. Hence, the best performance was found among the more recent “gradient-domain” algorithms (e.g., Fattal, Lischinski, and Werman) and the related algorithms they inspired (e.g., Mantiuk, Myszkowski, and Seidel).

To make these observations more quantitative, a set of features were developed (see Table 1) to quantify the effect of the different algorithms on the visibility of certain elements of the image. Broadly speaking, Features 1 and 3 measure the algorithms effect on areas of the image with low X-ray attenuation, which is important for the detection of objects found in some explosive devices (e.g., sheet explosives). Features 2 and 4 relate to areas with high X-ray attenuation (i.e., dark areas), which become important when detecting objects behind shielding. Feature 1 measures the visibility of the plastic knife, as quantified by the change in grayscale value, while Feature 3 measures the magnitude of the background noise in the top right corner of the image, as measured by the standard deviation of the pixel values over a 1 in. $\times$ 1 in. (25.4 mm $\times$ 25.4 mm) region. We will consider an algorithm to have done well if it increased the visibility of Feature 1 without increasing the background variation (Feature 3) too much. If we consider the ratio of these two features to be a kind of signal-to-noise ratio, we can get an indication of the overall effect of each algorithm on the visibility of the thin plastic knife. By this measure, the best algorithms were the Logos App and Mantiuk, Myszkowski, and Seidel, which improved the ratio of Features 1 and 3 from a value of 2.5 up to 6.9 and 5.3, respectively. The performance of the algorithms in enhancing objects behind shielding can be estimated in a similar way, that is, by dividing Feature 2 by a quantity proportional to Feature 4 (converted to grayscale units by calculating the equivalent variance that would occur in a region with a mean brightness of 100). By this measure, the best algorithms for enhancing shielded areas of the image were Fattal, Lischinski, and Werman, with a value of 5.8, and Mantiuk, Myszkowski, and Seidel, with a value of 5.0. The overall best algorithm, performing well for both high and low X-ray attenuation, is that of Mantiuk, Myszkowski, and Seidel, in agreement with the earlier subjective assessment.

Tonemapped images should not be presented to security personnel in isolation, since the relative brightness of objects isn’t always meaningful after a local-tonemapping algorithm is applied. This is not the case for images that have been enhanced using global tonemapping operators, and that means that one can determine information about density, thickness, and material composition based on how dark each object appears in the image. Therefore, we recommend that security personnel be presented with a globally tonemapped image first, so that they can see which objects are attenuating the most X-rays. They should then have the option of viewing a locally tonemapped image to enhance the fine details in the image and identify any threat objects that are present.

Tonemapped images could prove extremely useful in security application, where threat objects must be accurately identified based on their shape and internal details. In particular, these algorithms could improve performance in situations where threat objects are located in cluttered environments or behind thick pieces of metal. While several of the tonemapping algorithms surveyed here performed very well, further research would likely yield

improvements. Development of a tonemapping algorithm specifically for security X-ray images may yield improvements over current algorithms that were designed for other applications (e.g., visible light photography). The results described here suggest that a modification of a gradient-domain method might be a fruitful research direction.

Conclusions

Tonemapping is a very useful tool for enhancing HDR security X-ray images. Tonemapping algorithms can help improve the visibility of threat objects, especially in a cluttered environment or when obscured by metal shielding. We tested the performance of eight algorithms for tonemapping of images containing objects that are commonly encountered by security screeners. The gradient-domain algorithms of Fattal, Lischinski, and Werman and of Mantiuk, Myszkowski, and Seidel were the best at improving the visibility of the objects. Overall, we found that the algorithm of Mantiuk, Myszkowski, and Seidel was best, since it produced excellent detail enhancement without completely discarding information about local relative thickness. Development of application-specific tonemapping algorithms for security X-ray imaging that builds upon the most successful current methods would likely lead to even better results.

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References

- [1]. Devlin K, Chalmers A, Wilkie A and Purgathofer W, "Tone Reproduction and Physically Based Spectral Rendering," Eurographics 2002: State of the Art Reports, The Eurographics Association, Geneva, Switzerland, 2002, pp. 101–123.
- [2]. Mann S, "Compositing Multiple Pictures of the Same Scene," presented at the The 46th Annual IS&T Conference, Cambridge, Massachusetts, May 9–14 1993, Society for Imaging Science and Technology, Springfield, VA, pp. 319–325.
- [3]. Ashikhmin M and Goyal J, "A Reality Check for ToneMapping Operators," ACM Trans. Appl. Percept, Vol. 3, No. 4, 2006, pp. 399–411, <https://doi.org/10.1145/n90036.1190040>
- [4]. Mann S, Lo RCH, Ovtcharov K, Gu S, Dai D, Ngan C, and Ai T, "Realtime HDR (High Dynamic Range) Video for Eyetap Wearable Computers, FPGA-Based Seeing Aids, and Glasseyes (Eyetaps)," presented at the 25th IEEE Canadian Conference on Electrical & Computer Engineering, Montreal, Canada, April 29–May 2, 2012, Institute of Electrical and Electronics Engineers, Piscataway, NJ.
- [5]. Kang SB, Uyttendaele M, Winder S, and Szeliski R, "High Dynamic Range Video," ACM Trans. Graphics, Vol. 22, No. 3, 2003, pp. 319–325, 10.1145/882262.882270
- [6]. Durand F and Dorsey J, "Interactive Tone Mapping," presented at the Eurographics Workshop on Rendering, Brno, Czech Republic, June 26–28, 2000, Springer, New York, NY, pp. 219–230.
- [7]. Mann S, "Comparametric Equations with Practical Applications in Quantigraphic Image Processing," IEEE Trans. Image Process, Vol. 9, No. 8, 2000, pp. 1389–1406, 10.1109/83.855434 [PubMed: 18262976]
- [8]. Miyahara J, Takahashi K, Amemiya Y, Kamiya N, and Satow Y, "A New Type of X-ray Area Detector Utilizing Laser Stimulated Luminescence," Nucl. Instrum. Methods Phys. Res. Sect. A, Vol. 246, Nos. 1–3, 1986, pp. 572–578, 10.1016/0168-9002(86)90156-7

- [9]. Giassi D, Liu B, and Long MB, "Use of High Dynamic Range Imaging for Quantitative Combustion Diagnostics," *Appl. Opt.*, Vol. 54, No. 14, 2015, pp. 4580–4588, 10.1364/AO.54.004580 [PubMed: 25967519]
- [10]. Lambers M, Nies H, and Kolb A, "Interactive Dynamic Range Reduction for SAR Images," *IEEE Geosci. Remote Sens. Lett.*, Vol. 5, No. 3, 2008, pp. 507–511, 10.1109/LGRS.2008.922732
- [11]. Blesser B, "Audio Dynamic Range Compression for Minimum Perceived Distortion," *IEEE Trans. Audio Electroacoust.*, Vol. 17, No. 1, 1969, pp. 22–32, 10.1109/TAU.1969.1162021
- [12]. Janzen R and Mann S, "High Dynamic Range Simultaneous Signal Compositing, Applied to Audio," presented at the 25th IEEE Canadian Conference on Electrical & Computer Engineering, Montreal, Canada, April 29–May 2, 2012, Institute of Electrical and Electronics Engineers, Piscataway, NJ.
- [13]. Park SH and Montag ED, "Evaluating Tone Mapping Algorithms for Rendering Non-Pictorial (Scientific) High-Dynamic-Range Images," *J. Visual Comm. Image Represent.*, Vol. 18, No. 5, 2007, pp. 415–428, 10.1016/j.jvcir.2007.06.008
- [14]. Ashikhmin M, "A Tone Mapping Algorithm for High Contrast Images," presented at the 13th Eurographics Workshop on Rendering, Pisa, Italy, June 26–28, 2002, The Eurographics Association, Geneva, Switzerland, pp. 145–156.
- [15]. Drago F, Myszkowski K, Annen T, and Chiba N, "Adaptive Logarithmic Mapping for Displaying High Contrast Scenes," *Comput. Graphics Forum*, Vol. 22, No. 3, 2003, pp. 419–426, 10.1111/1467-8659.00689
- [16]. Pattanaik SN, Tumblin J, Yee H, and Greenberg DP, "Time-Dependent Visual Adaptation for Fast Realistic Image Display," presented at the 27th Annual Conference on Computer Graphics and Interactive Techniques, New Orleans, LA, July 23–28, 2000, ACM Press/Addison-Wesley Publishing Co., New York, NY, pp. 47–54.
- [17]. Reinhard E, Stark M, Shirley P, and Ferwerda J, "Photographic Tone Reproduction for Digital Images," *ACM Trans. Graphics*, Vol. 21, No. 3, 2002, pp. 267–276, 10.1145/566654.566575
- [18]. Fattal R, Lischinski D, and Werman M, "Gradient Domain High Dynamic Range Compression," *ACM Trans. Graphics*, Vol. 21, No. 3, 2002, pp. 249–256, 10.1145/566654.566573
- [19]. Mantiuk R, Myszkowski K, and Seidel H, "A Perceptual Framework for Contrast Processing of High Dynamic Range Images," *ACM Trans. Appl. Percept.*, Vol. 3, No. 3, 2006, pp. 286–308, 10.1145/1166087.1166095

FIG. 1.

The performance of a number of tonemapping techniques is compared to the original image shown in (a). In (b), the location of several key objects is indicated: a plastic knife is shown in orange; a section of wire is highlighted in red; a stopwatch is shown in green; an aluminum step wedge is outlined in yellow; and a 9V battery is highlighted in blue. Image (c) shows a typical LIA enhanced image. Image (d) was enhanced using the tonemapping algorithm of Fattal, Lischinski, and Werman. Image (e) used the algorithm of Mantiuk, Myszkowski, and Seidel. Image (f) used the algorithm of Reinhard et al.

TABLE 1

The visibility and variability of various features and regions in the images shown in Fig. 1

	Feature 1: plastic knife edge	Feature 2: watch edge	Feature 3: background variation	Feature 4: variation in 2nd top step
Original image	9	6	4	2 %
Logos App	62	57	9	21 %
Fattal, Lischinski, and Werman	24	70	9	12 %
Mantiuk, Myszkowski, and Seidel	21	30	4	6%
Reinhard et al.	3	11	2	4%

Note: Feature 1 measures the visibility of the edge of the plastic knife, as measured by the change in grayscale value of the top edge. Feature 2 measures the visibility of the right edge of the watch, based on the change in grayscale value at the edge. Feature 3 reflects the level of the variation in the background region, as measured by the standard deviation of the pixels in a 1 in. $\times$ 1 in. (25.4 mm $\times$ 25.4 mm) region in the center of the empty area in the top right of the image. Feature 4 measures the variation in pixel values over the span of the second top step of the step wedge, as measured by the standard deviation of the pixels in a region spanning 90 % of the width of the step and 80 % of the height (represented as a percentage of the average over the same region).