IMAGE-BASED VERIFICATION: SOME ADVANTAGES, CHALLENGES, AND ALGORITHM-DRIVEN REQUIREMENTS

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ABSTRACT

Imaging technologies may provide particularly useful techniques that support monitoring and verification of deployed and non-deployed nuclear weapons and dismantlement components. However, protecting the sensitive design information requires processing the image behind an information barrier and reporting only non-sensitive attributes related to the image. Reducing images to attributes may destroy some sensitive information, but the challenge remains. For example, reducing the measurement to an attribute such as defined shape and X-ray transmission of an edge might reveal sensitive information relating to shape, size, and material composition. If enough additional information is available to analyze with the attribute, it may still be possible to extract sensitive design information. In spite of these difficulties, the implementation of future treaty requirements may demand image technology as an option. Two fundamental questions are raised: What (minimal) information is needed from imaging to enable verification, and what imaging technologies are appropriate? PNNL is currently developing a suite of image analysis algorithms to define and extract attributes from images for dismantlement and warhead verification and counting scenarios. In this talk, we discuss imaging requirements from the perspective of algorithms operating behind information barriers, and review imaging technologies and their potential advantages for verification. Companion papers will concentrate on the technical aspects of the algorithms.

INTRODUCTION

Future nuclear arms reduction treaties may require precise counting of warheads. How this will be implemented is an open technical and political debate. Imaging technologies, which elucidate both form and function, may be among the best tools for warhead verification. For instance, imaging may be best for discriminating between fissile materials in a weapon form versus rubble. PNNL is developing algorithms that extract attribute information from images behind an information barrier (IB). We are exploring ways to process images so that sensitive data is protected and never stored behind the IB. Imaging for warhead verification has never been implemented because it is so intrusive, but this is also what makes it so useful [1]. New imaging technology may help solve challenging verification problems that might not be solved otherwise without complete, unfettered access to the warhead. We aim to show the utility *and* practicality of imaging with low-intrusion image-processing algorithms operating behind an IB.

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IMAGING IN ARMS CONTROL & DISMANTLEMENT VERIFICATION

The history of imaging in arms control is fairly succinct: flat-out rejection for consideration in warhead counting due to excessive intrusion. Nevertheless, several groups have assessed the possibilities.

Both the Soviet Union and the USA had compelling reasons to forge the Intermediate-Range Nuclear Forces (INF) treaty, which led to unprecedented intrusive inspection measures. Imaging was used in two ways in the verification of the INF Treaty. First, to establish that only SS25 missiles (and not SS20) were leaving the Votkinsk missile facility in Russia, a 9 MeV Linatron x-ray radiography system was used to scan rail cars (with missiles inside) as they left the facility. Warheads were not imaged, but other features of the missiles that were dissimilar (length and width) were determined using imaging [2]. Another feature of the INF treaty was short-notice, on-site inspections, where the neutron flux from a missile was mapped. An inspector used a hand-held neutron counter for measurements along a grid laid on the floor (effectively creating a coarse-resolution image):

> "A launch canister with a missile inside containing a single warhead (SS-25) emitted a different pattern of fast neutrons than did one with a missile having three warheads (SS-20). The American inspection team, using the RDE (radiation detection equipment), compared their measurements against a set of benchmark radiation measurements taken during a special inspection in the summer of 1989. [2]"

While these inspections (and visual inspections of RVs) continued, the U.S. considered technology alternatives and issues for warhead counting [3]. The "Reentry Vehicle On-Site Inspection (RVOSI) Technology Study" aimed to rank available technologies based on confidence, intrusiveness, cost, inspector burden, and operational impact. Most of the technologies surveyed were passive radiation (neutron or gamma-ray) imaging techniques, as they were the most developed. Compton imaging was only just finding applications outside of gamma-ray astronomy, and x- or gamma-ray radiography was considered too intrusive and not included in the study. That left coded apertures, neutron counting systems, collimated detectors, and a few active interrogation methods. Scanning geometries and measurement scenarios were considered. The top pick of the study was the Gamma-Ray Imaging System (GRIS) [4, 5] from LLNL, as it had the most use in field measurements, simpler, end-on-geometry and the highest confidence in correctly counting warheads.

Researchers at the Atomic Weapons Establishment in the UK considered imaging techniques for a dismantlement verification project, including thermal imaging, radiography, and neutron counting [6]. Because of the invasiveness of these methods, it was concluded that "national security and proliferation concerns will probably mean that such 'unfiltered' techniques will be of limited use in a verification regime without information security barriers [6]." Issues with verifying an operational weapon versus a dismantlement component are noted as well:

> "The challenge associated with authenticating a fully assembled thermonuclear warhead, of unknown design complexity and potentially mated to a carrier or reentry vehicle, is far greater than authenticating a warhead's fissile pit or material in a transport or storage container [2]."

Inspector confidence and technology intrusiveness have suffered an inversely proportional relationship for consideration in warhead counting. If the intrusiveness of imaging is sufficiently mitigated by operating behind an IB, then its use in a verification regime may be more easily accepted. A key aspect of the success may be jointly developed imaging hardware and imaging algorithms [7] . With low-intrusion algorithms we aim to enable imaging as a highly useful tool in challenging verification scenarios.

LOW-INTRUSION ALGORITHMS

In 2010 we presented three low-intrusion algorithms [1, 8] which showed promise for simple objects. This year we are developing techniques in two broad areas, which are described in more detail in companion papers [9, 10]. In short, we examined the concept of using a 'perceptual hash' to protect image data (Fig. 1) and multi-energy methods for material discrimination (Fig. 2).

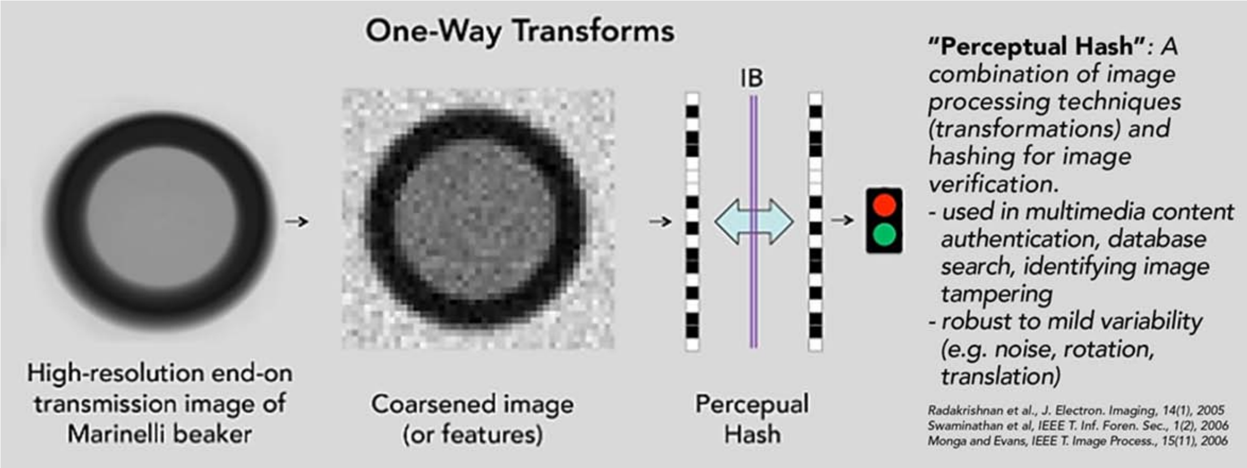

Figure 1: Overview of perceptual hash concept. More details are in a companion paper [9].

One-way transforms (such as hashes) are a way to protect sensitive information and transfer it out of the IB [11, 12]. However, no two images will ever be exactly the same, thus standard hashes of those images will differ. The perceptual hash might be a way to compare several images of the same item taken under slightly different conditions (e.g., viewing angle) and give the same hash output. It could thus be used on image data from any source for verifying attributes within a certain range or comparing against a measured template (in which only the hash result would be stored).

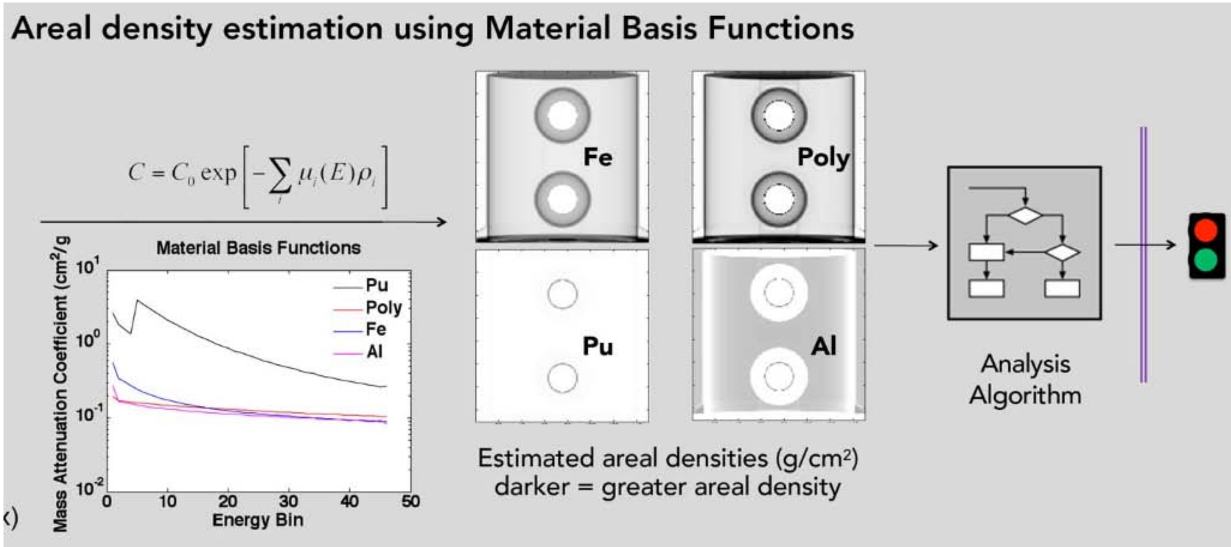

Figure 2: Overview of areal density estimation from material basis functions and a simulated AT-400R container. By using a Bremsstrahlung source and a photon-counting detector, materials in a radiograph may be distinguished. More details are given in [10].

Spectral methods may permit material discrimination and enhance previous attempts to discern materials within active and passive radiography images. Some material discrimination approaches easily show the presence of nuclear materials, allowing for a simple detection metric for SNM presence to be developed. These methods may prove useful for the verification of objects in both warhead counting and dismantlement regimes.

REVIEW OF IMAGING TECHNOLOGIES

We surveyed the open literature on imaging technologies that had been developed or proposed for arms control verification. Nuclear and radiological systems were of primary consideration, and within this broad category we focused almost entirely on systems that rely on direct emissions or transmissions. Several recent reports summarize the state of the art in image formation methods (e.g., [13, 14]), thus, only the salient features of individual imaging systems are described. A host of mature and emerging technologies could be applicable to warhead counting, including some non-radiological methods (e.g., thermal imaging). A limited, neutral survey of the field is given in Table I.

PASSIVE IMAGING

Any signal emanating from a warhead can be used to help identify the source materials. However, there may be very little signal coming out of the object depending on the shielding. Passive technologies may be summarized in terms of the following five groups.

Fast-neutron scatter cameras: [15, 16]. SNL's camera detects and distinguishes fast neutron interactions and gamma-rays with two planes of liquid scintillator detectors. Pulse shape analysis permits discriminating between gamma-rays and neutron interactions. Based on the interaction position of the scatter in the front and back plane and the time between the events, the direction of the neutron can be confined to a conical shell. Images are created by processing (using backprojection or iterative reconstruction algorithms) the list-mode data which contains timing and energy information.

Coded Apertures (Gamma-ray): These consist of a patterned mask of attenuating material (many pinholes), a position-sensitive detector, and a deconvolution scheme [17]. They are generally most efficient for imaging sources with energy below 500 keV, above which it becomes challenging to create sufficiently attenuating masks. These systems have a long history in astronomy (imaging point sources in the sky) and a mixed history in medical imaging (where sources are often distributed and in the near-field). Their demonstrated performance in arms control verification tests is noteworthy (e.g., OSL Coded aperture (PNNL) [18, 19] and GRIS (LLNL) [4, 5]). Instead of a coded aperture, a simple pinhole or parallel-hole collimator can be used. These have lower efficiency, but do not require a deconvolution scheme since the object projections from each hole do not overlap. Such a gamma-camera (Anger camera) with a honeycomb collimator was jointly developed by Russian and US scientists in the late 1990s to determine a shape attribute of fissile material [20].

Coded Aperture Cameras (Neutron): For thermal neutrons the mask is made of cadmium [21]; for fast neutrons the coded aperture is poly [22]. Both of these could be useful in warhead counting for verification of different attributes.

Compton cameras: These have better performance for gamma-rays with energy above 300 keV. Two detector planes are generally required (ideally the photon scatters in the first plane and the scattered photon is absorbed in the second plane). The interaction positions and the energy depositions make it possible to define a cone of angles from which the photon originated. An example high-resolution system was made by Burks at LLNL [23].

Hybrid (Coded aperture + Compton): These systems extend the energy range for imaging efficiency. A combined system better utilizes the expected range of photon energies emitted from special nuclear materials. The High Efficiency Multimode Imager (HEMI) uses an active mask coded aperture, which doubles as the scattering plane in a Compton camera and as an attenuating mask for a coded aperture system [24].

ACTIVE IMAGING (TRANSMISSION, REFLECTION, OR INDUCED)

Active imaging systems require that a radiation source (x-ray tube, Co-60 source, DT head, etc.) irradiates the object of interest and that a detector records the resulting signals. These systems may be broken into categories by source type.

X- or gamma-ray radiography: The CoLOSSIS system is an accelerator-based x-ray computed tomography (CT) system for high-resolution inspection in stockpile stewardship activities [25]. This machine produces a 9 MeV Bremsstrahlung beam and includes a lens-coupled CCD detector that offers higher spatial resolution than would probably ever be needed for arms control verification. Systems using lower-energy x-rays and off-the-shelf components (e.g., 450 kVp industrial x-ray tube with a flat panel integrating detector) may be sufficient to determine a symmetry attribute. For highly shielded objects, high-resolution MeV imagers that are being developed for cargo scanning (e.g. [26]) may find use in arms control. Such imaging systems may be similar to the INF scanner, but perhaps with energy-resolved detectors.

Neutron radiography: Associated particle sealed-tube neutron generators can be used to scan a missile on its circumference and gain isotopic information about the contents from fission gamma rays or density/material information from neutron attenuation [27]**.** The Nuclear Materials Identification System (NMIS) and the Advanced Portable Neutron Imaging System (APNIS), both tomographic imagers, can produce several types of images (transmission, induced fission, and induced neutron pairs [22, 28-31]). These systems have the ability to create density maps with the neutron transmission data and overlay them with estimates of SNM-containing regions from the induced fission data.

Table I: Neutral survey of imaging technologies and example systems.

Mode	Imaging Technique	Example Imaging System
Passive	Compton imaging	LLNL, M Burks, Si + HPGe planes [23]
	Gamma-ray coded aperture	LLNL, K Ziock, GRIS [5]; PNNL, S Miller, OSL [19]
	Thermal neutron coded aperture	BNL, PE Vanier, Cd aperture [21]
	Fast neutron coded aperture	ORNL, Blackston & Hausladen [22]
	Fast neutron double-scatter camera	SNL, N Mascarenhas [16]
	Thermal imaging	ORNL & others, [32]
	Hybrid Compton/coded aperture	LBNL-UC Berkeley, PN Luke, HEMI [24]
	Time projection chamber	LLNL, N Bowden [33]
Active (transmission)	X- or gamma-ray radiography	LLNL, Colossis [25]; ANL, Gamma hodoscope [34]
	Associate particle neutron radiography	ANL, Hodoscope [35]
Active (induced)	Induced Fission Mapping	ORNL, JT Mihalczo, NMIS [28]
Multi-modal	Emission/transmission CT (photon)	Waste drum scanners: LLNL, WIT [35]; LANL, TGS [36-38]
	Passive/active neutron imaging	ORNL, Blackston & Hausladen [22]
	Neutron-photon radiography	CSIRO, B Sowerby, FNGR [39]
	Coded aperture + LIDAR	ORNL, K Ziock [40]

MULTI-MODALITY IMAGING SYSTEMS

Fast neutron and gamma-ray radiography (FNGR): FNGR measures the ratio of fast neutron and gamma-ray mass attenuation coefficients, which gives the average material composition in the beam independent of the mass of the material [39]. A commercial system is being tested at Brisbane International Airport [41].

Gamma-ray + LIDAR: HPGe strip detectors and a coded aperture with laser scanning (LIDAR) were combined in [40]. LIDAR gives 3D (surface) scene information. The advantage of the LIDAR data is clear in holdup scenarios with varied backgrounds, but probably has limited utility in a warhead counting or dismantlement scenario, where everything is behind a shroud or other purposeful concealment.

Combined Emission/Transmission Computed Tomography: Tomographic Gamma Scanning (TGS), developed by at LANL and commercialized by Canberra, uses a radioisotope source to perform a transmission scan of a waste drum, which is then used to perform attenuation-correction on passive gamma-ray images [42-44]. Waste Inspection Tomography (WIT), developed by LLNL & Bio-Imaging Labs, LLC, uses active and passive computed tomography (emission images are attenuated-corrected by transmission data as in the TGS system) [36-38]. WIT is implemented on a semi-truck and uses a Linac to perform transmission scans. Both show the utility of combining active and passive data.

Photon transmission imaging allows access to attenuation coefficients (Z and density), and possibly elemental ID if we consider the K-edges; neutron transmission radiography might allow material ID, but in general has no better material ID capability than photon radiography, although the cross-section info may be complementary [39]. In comparison, photon/neutron-induced signatures identify material. Passive emission signatures (photon/neutron) identify material but are dependent on inherent shielding properties. Thermal imaging may indicate presence of radioactive material. Choice of signature will have to consider the other material in the object that may have confusing or obfuscating properties.

IMAGER REQUIREMENTS

What imager requirements are needed to ensure top algorithm performance? This is a broad question that is highly dependent upon the object type and geometry of the measurement. We can, however, make the following general statements:

- Multi-modal systems can provide complementary information which theoretically increases confidence in warhead counting scenarios (more attributes, better spoof detection)
- Induced signals may be acquired from more flexible geometries (require access to only one side of object), but require longer acquisition times ($1/r^4$ instead of $1/r^2$ geometric efficiency).
- Task-based performance is the best metric: e.g., how well does the imager count warheads?
- Imaging algorithms and the IB should be jointly developed [7].

For a specific scenario, we can search for the technologies that provide acceptable tradeoffs between the competing demands of (in a proposed descending order of importance) [45]:

- Confidence in the result (transparency and verification), including spoofing detection;
- Protection of classified information (inherent imaging system obfuscation, e.g. to produce poorer resolution than is possible, may not be needed with the right algorithms);
- Time of measurement;
- Cost; and
- Operational robustness.

In the past, efforts have been made to mechanically limit the intrusiveness of the monitoring/verification system by purposefully reducing the spatial or energy resolution of the system (e.g., [46]). Another idea is to keep the coded aperture obscured, making the image-unfolding process nearly impossible [19]. On the other hand, if there is great confidence in the IB, more resolution likely means increased algorithm performance. From the perspectives of algorithms developed in this project the imager would need:

- Sufficient Spatial/Angular resolution for edge-finding algorithms.

- Photon-counting detectors with sufficient count-rate capability for multi-energy radiography and materials discrimination algorithm.

CONCLUSIONS & FUTURE WORK

We are developing image-processing algorithms for attribute verification behind an IB to mitigate potential intrusion concerns and enable imaging technologies for arms control. The perceptual hash represents promising route to this end, and the material basis algorithm should enhance the utility of transmission radiography. The algorithms are intended to be nominally independent of specific imaging systems. Recognizing the breadth of technologies outlined here and many more not included in this outline, it is of interest to combine the algorithms with imaging technology developers to benchmark results with measured data and determine imager requirements in terms of algorithm performance. Combinations of algorithms and multi-modal systems may prove especially fruitful, and further study on what can be achieved by combining nuclear and non-nuclear (e.g., resonant ultrasound [47] and induced eddy current [48]) techniques in terms of attribute verification is needed [45, 49]. Additionally, we currently consider only radiography. Reconstructing 3D images behind an IB involves more processing and analysis, but the potential benefit may be high verification confidence.

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