A Learning-Based Method for Explosives Detection from Multi-Energy X-ray Computed Tomography Measurements

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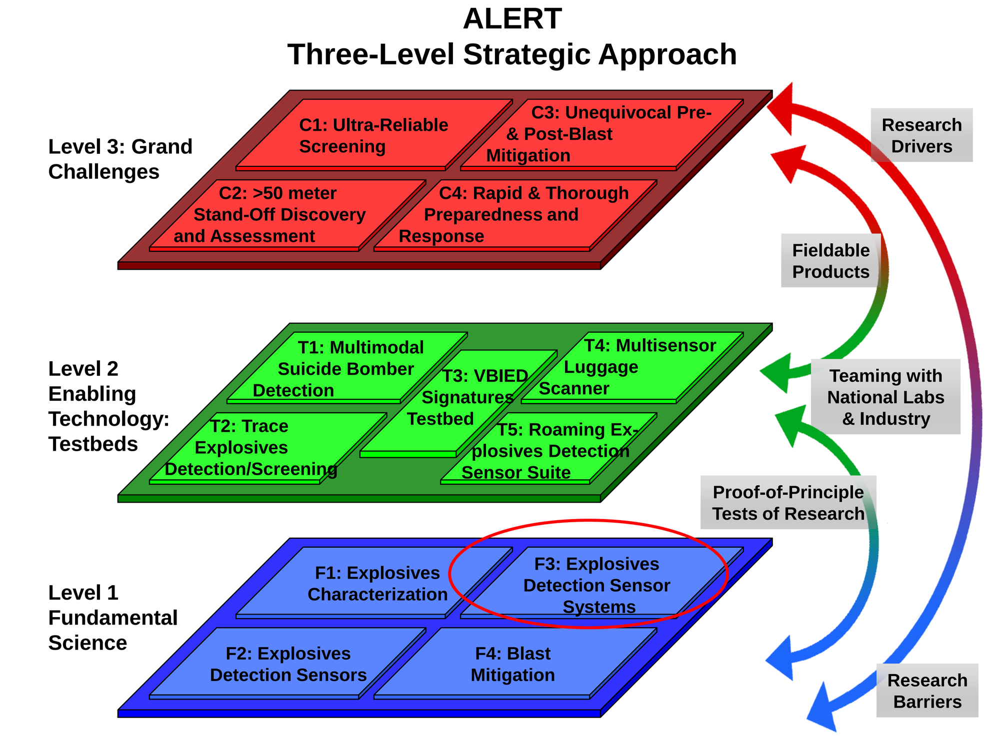


Motivation

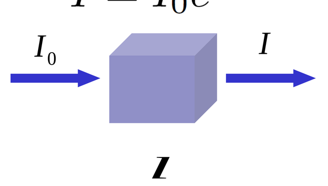
- The **detection of explosives** and illicit material is important for preventing terrorism and smuggling.
- In luggage inspection, **higher detection accuracy** and **lower false alarm rate** are needed.
- **X-ray Computed Tomography (CT)** is a powerful technology, widely used for medical diagnosis and security.
- X-ray attenuation depends on the material being scanned and is also a function of the energy of the incident X-ray photons.
- Conventional CT is not enough to uniquely identify materials since polychromaticity of the X-ray photons is ignored.
- **Multi-energy CT**:
  - achieved by taking multiple measurements with different source spectra or with energy-selective detectors.
  - provides more information about the attenuation at different energies, giving potential to differentiate between materials better.
- We would like to apply a **machine-learning approach** in order to classify between explosives and non-explosives using features related to the attenuation, which can be extracted from multi-energy measurements.

Which features, and how many of them, should we extract from multi-energy measurements, such that the explosives are distinguishable from the non-explosives?

Physical model

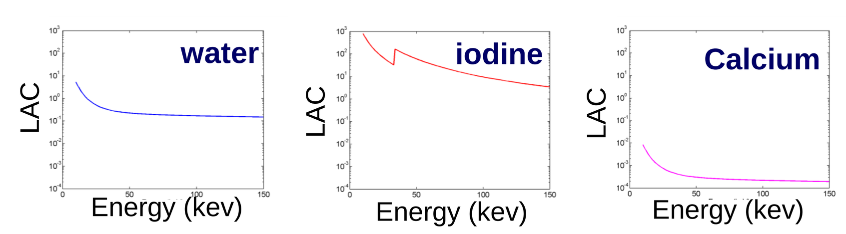
- X-ray measurement is related to the **Linear attenuation Coefficient (LAC)** μ

$$I = I_0 e^{-\mu l}$$

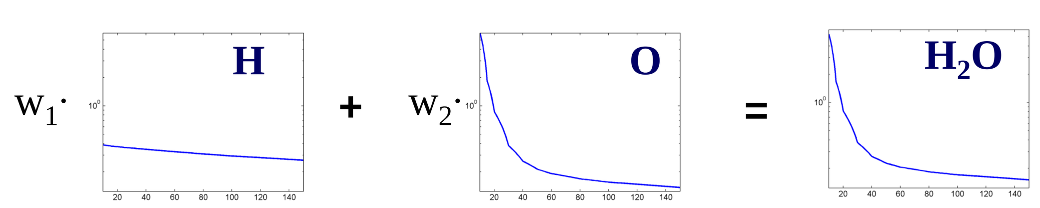


Beer's law

- Different for each material



- For a mixture or compound:



- Assumption: $$\mu(E) = \sum_{i=1}^{N} a_i f_i(E)$$

material-specific coefficients — known energy-dependent basis functions

- A common **physics-based representation** is [1]: $$\mu(E) = \underbrace{a_P f_P(E)}_{\text{Photoelectric effect}} + \underbrace{a_C f_C(E)}_{\text{Compton scatter}}$$

- The problem: **photo-Compton model does not fit all materials**.

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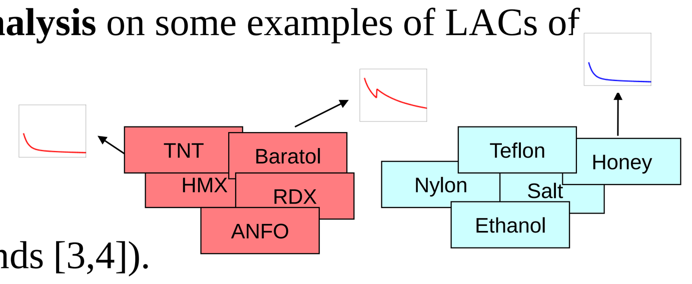
Understanding the space of the linear attenuation coefficients

We performed **Singular Value Decomposition (SVD) analysis** on some examples of LACs of explosive and non-explosive materials (following [2]).

- Collect examples of sampled-LAC-curves of materials (in our case - 84 explosive and 40 non-explosive compounds [3,4]).



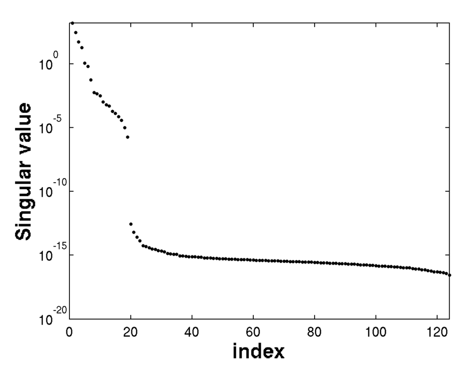
- Put the curves in the columns of a matrix

$$M = \begin{array}{c} \begin{array}{cccc} \text{TNT} & \text{Honey} & & \text{RDX} \end{array} \\ \begin{bmatrix} | & | & & | \\ \mu_1 & \mu_2 & \cdots & \mu_{N_m} \\ | & | & & | \end{bmatrix} \\ \xleftarrow{\quad} \text{material} \xrightarrow{\quad} \end{array} \updownarrow \text{energy}$$

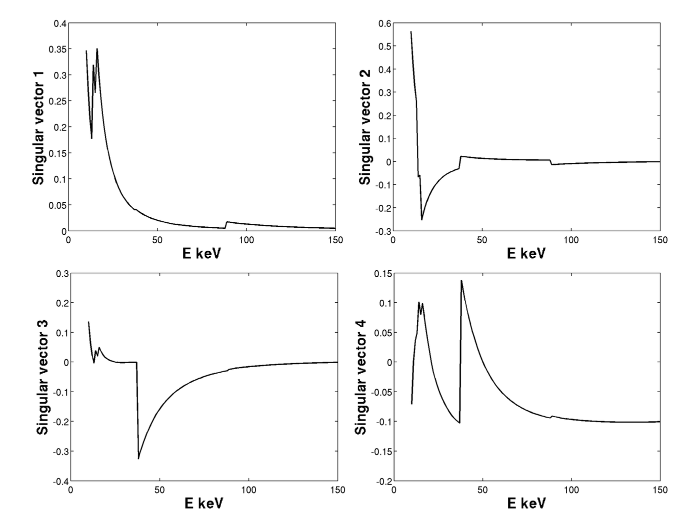
- Compute the SVD of the matrix

$$M = USV^T = \begin{bmatrix} | & | & \\ \mathbf{u}_1 & \mathbf{u}_2 & \cdots \\ | & | & \end{bmatrix} \begin{bmatrix} s_1 & 0 & \cdots & 0 \\ 0 & s_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \end{bmatrix} \begin{bmatrix} - & \mathbf{v}_1 & - \\ - & \mathbf{v}_2 & - \\ & \vdots & \end{bmatrix}$$

The results:



Singular values of the example materials LAC curves



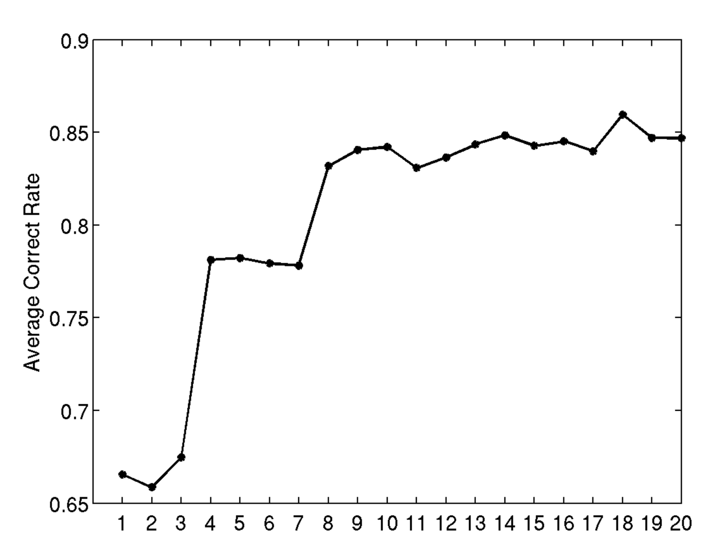
First four singular vectors of the example materials LAC curves

- **Singular values show: dimensionality of the LAC space > 2.**
- **Singular vectors: new basis functions.**

Effect of feature dimensionality on classification performance

- Project LAC-curves onto singular vectors $\quad \boxed{\mathbf{c}_i = \boldsymbol{\mu}_i^T U}$
- Projection coefficients = features
- We take a subset of the coefficients. We train a **Support Vector Machine (SVM)** classifier on 80% of the labeled examples, test it on the remaining 20% of examples, repeat 1000 times and calculate the average correct rate.

The results:



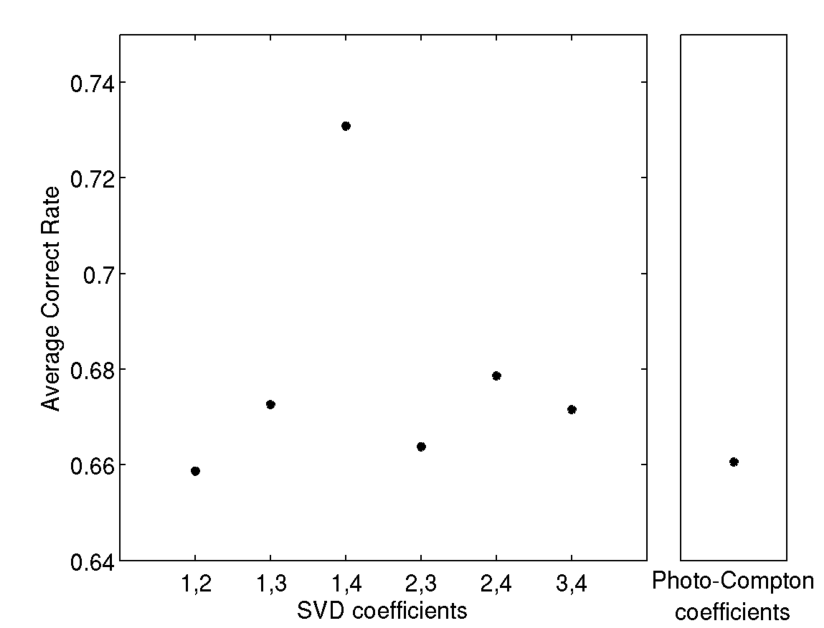
Classification performance when using different numbers of SVD coefficients as features

- **Classification improves as feature dimensionality increases.**
- **It is possible to do better than with just 2 coefficients.**

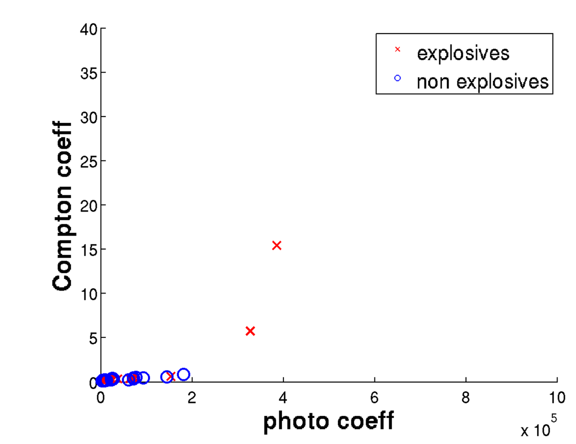
Effect of feature choice on classification performance

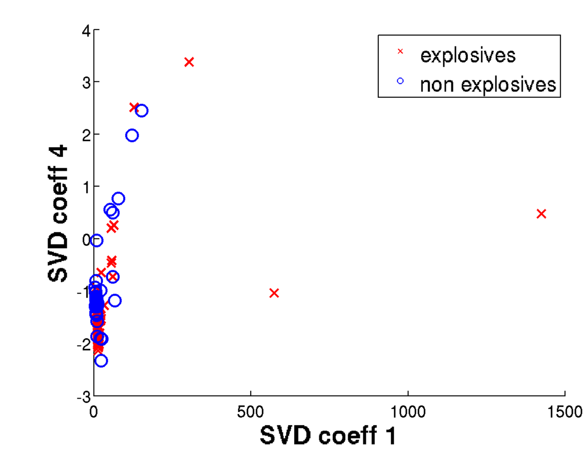
- We examine how well **different combinations of 2 SVD coefficients** perform as features.
- We find the **photoelectric and Compton coefficients** of the LACs and test those coefficients as features.
- Same experiment setup as in previous section.

The results:



Classification performance when using different combinations of two SVD coefficients and the photoelectric and Compton coefficients as features

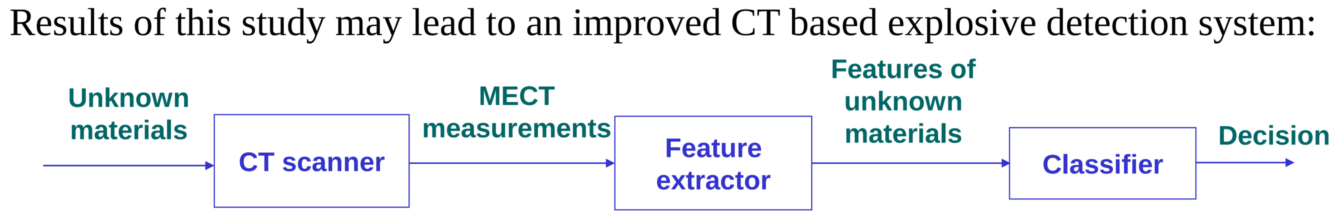




- **The choice of features is not trivial.**
- **An "unexpected" combination of two SVD coefficients provides highest performance.**
- **It is possible to do better than with the photoelectric and Compton decomposition.**

Research to Reality

Results of this study may lead to an improved CT based explosive detection system:



Future work will include:

- building a larger training set by finding more examples of materials
- finding better choices for basis functions and features
- incorporating the choice of optimal feature set into the complete MECT problem

References:

[1] R. E. Alvarez and A. Macovski, "Energy-selective reconstructions in X-ray computerized tomography," Physics in medicine and biology 21 (5), pp. 733-744, 1976.

[2] L. A. Lehmann and R. E. Alvarez, "Energy selective radiography: a review," in Digital Radiography: Selected Topics (S. T. J. Kareiakes and C. Orton, eds.), pp. 145–188, New York: Plenum, 1986.

[3] M.J. Berger, J.H. Hubbell, S.M. Seltzer, J. Chang, J.S. Coursey, R. Sukumar, and D.S Zucker, "XCOM: Photon Cross Section Database," National Institute of Standards and Technology, http://physics.nist.gov/xcom.

[4] B. Dobratz and P. Crawford, LLNL Explosives Handbook. Properties of Chemical Explosives and Explosive Simulants. 1985.