Passive Infrared Hyperspectral Imaging for Standoff Detection of Tetryl Explosive Residue on a Steel Surface Using GLS and ELS-GLS

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Anomaly and Target Detection

• Anomaly detection (e.g., PCA, MAF, MDF) finds pixels that are unusual wrt the general trends in an image
  • but, it doesn’t tell the cause of the difference

• Target detection (e.g., LDA, GLS) finds pixels that have an unusual contribution of a specific target direction (e.g., spectrum)
  • detection and classification
Target Detection

- The objective is to detect target in the presence of a cluttered background.
- Clutter includes signal not related to the target and includes:
  - Interferences (variable background) and noise.
- For this example, the boundary between classes might be represented by a non-linear surface between the clutter and target classes.
Fisher’s Linear Discriminant

- The clutter and targets are treated as two classes with means $\bar{x}_c$ and $\bar{x}_t$, and covariances $\Sigma_c$ and $\Sigma_t$ where $\Sigma_c = \Sigma_t$

- The discriminant function is defined as the distance between classes to variance within classes

$$w^2_{cal} = (\bar{x}_t - \bar{x}_c)\Sigma_c^{-1}(\bar{x}_t - \bar{x}_c)^T$$
Mixed Pixels

• Mixed pixels lie on the line between the mean responses
  \[ \mathbf{x} = (1 - c_t) \bar{\mathbf{x}}_c + c_t \bar{\mathbf{x}}_t + \mathbf{e} \]
  where \( c_t \) is the contribution of target and \( c_c = (1 - c_t) \) is the contribution of clutter

• Implicitly assumes closure
Inverse Clutter Covariance $\rightarrow$ Whitening

\[ \mathbf{x} = (1 - c_t) \tilde{\mathbf{x}}_c + c_t \mathbf{x}_t + \mathbf{e} \]

\[ w^2 = (\mathbf{x} - \tilde{\mathbf{x}}_c) \Sigma_c^{-1} (\tilde{\mathbf{x}}_t - \tilde{\mathbf{x}}_c)^T \]

\[ w^2 = (\tilde{\mathbf{x}} - \tilde{\mathbf{x}}_c)(\tilde{\mathbf{x}}_t - \tilde{\mathbf{x}}_c)^T \]

\[ w > w_d \quad \text{new measurements with distances greater than a threshold are considered detections} \]
Closure for Tetryl on Steel

MCR contribution image for Tetryl on Steel at 14 m
Only NNLS used for constraints
Red: Tetryl Target
Blue: Steel Plate

• Closure for Tetryl on a Steel Plate is a good assumption
**LD Analysis for target detection**

- LDA classes are represented by their means
  - stationary spectral shape and magnitude

  \[ x = \bar{x}_c + e \quad \text{off-target pixel} \]
  \[ x = \bar{x}_t + e \quad \text{on-target pixel} \]

- the model of the sensor response is

  \[
  w^2 = (x - \bar{x}_c)^T \Sigma_c^{-1} (\bar{x}_t - \bar{x}_c) \\
  \Sigma_c = \frac{1}{M_c} (X_c - \bar{x}_c^T)^T (X_c - \bar{x}_c^T)
  \]

- how is \( \bar{x}_t \) obtained a priori?
  - it’s likely a scalar multiple of the pure component spectrum \( c_t s_t \)
Generalized Least Squares (GLS)

• Generalized least squares (GLS) is a weighted / whitened version of the CLS model

\[ \hat{c}_i = \left(s_t^T \Sigma_c^{-1} s_t \right)^{-1} s_t^T \Sigma_c^{-1} (x - \bar{x}_c) \]

\[ \hat{c}_i = \left(\tilde{s}_i^T \tilde{s}_i \right)^{-1} \tilde{s}_i^T \left(\tilde{x} - \tilde{x}_c \right) \]

• Aitken Estimator, Matched Filter, Adaptive Matched Filter, et. al

• GLS allows the use of \( s_t \) as the target
  • don’t need to define mean of target class
  • assumes the target shape doesn’t vary but the magnitude can
GLS References

GLS Centered to Clutter Mean

- Centering the signal to the clutter mean $x - \bar{x}_c$ implicitly assumes that $x = \bar{x}_c + c_t s_t$
GLS Projected onto “Mean”

- Use first PC of clutter as a “target”
  - model center is zero
  - extended least squares

\[
\begin{bmatrix}
\hat{c}_t \\
\hat{c}_c \\
\end{bmatrix} = \left( S^T \Sigma_c^{-1} S \right)^{-1} S^T \Sigma_c^{-1} \mathbf{x}
\]

\[ S = [s_t \quad p_c] \]

Applying non-negativity

→ signal anywhere in the triangle (hyper-pyramid) is a detection
GLS For Target Detection

- The GLS model form
  - allows the target and clutter magnitude to vary
  - can easily impose non-negativity
    - physics suggests this constraint
  - can easily impose closure
    - but, what if the signal changes due to lighting or shading?
    - even if closure is appropriate shading suggests relaxing the strict equality
    - $c_t + c_c = 1 \Rightarrow c_t + c_c < 1$
Lighting Changes

- lighting changes can change the magnitude of the clutter
Compare GLSs

- Contributions for the mean-centered model tend to be lower and show less contrast w/ the null than for the extended mixture model (ELS)
- Additionally, contributions on the background (steel plate) are available for the ELS model and provide an additional piece of information in target detection
GLS-ELS Conclusions

• The GLS-ELS version of the target detection algorithm shows distinct promise over the traditional approach to mean-centering of the signal
  • it is more of a ‘chemistry / physics’ view of the signal
• However, …
Simple Radiance Model for Standoff Detection

measured radiance

\[ L(v) = L_u + \left[ \varepsilon(v)B(v, T) + (1 - \varepsilon(v))L_d(v) \right] \tau_a(v) \]

\[ L - L_u - B\tau_a = (1 - \varepsilon)(L_d - B)\tau_a \]

spectrometer

internal noise \( L_{\text{inst}}(v) \)

atmospheric transmission \( \tau_a(v) \)

atmospheric up-welling

\( L_u(v) \)

\( L_d(v) \)

black body radiance \( \varepsilon(v)B(v, T) \)

reflected down-welling \( (1 - \varepsilon(v))L_d(v) \)