Technical Seminar

The Long Island Chapters of the IEEE AESS, APS and SPS

Target Detection Using Optical Joint Transform Correlation

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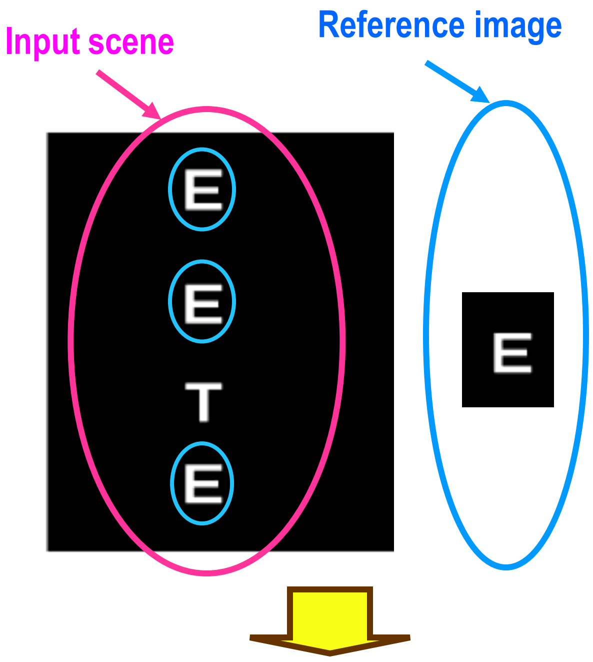
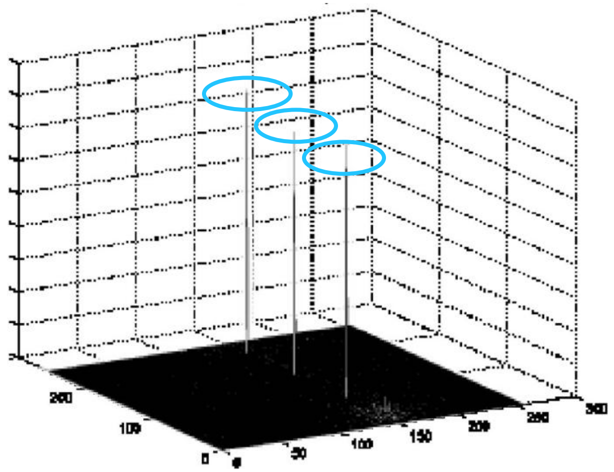
Outline of Presentation

- Target detection/Pattern recognition
- Optical pattern recognition technique
- Optical joint transform correlation (JTC) techniques
- Modified and efficient JTC technique
- Color pattern recognition
- Hyperspectral pattern recognition
- Conclusions

Pattern recognition

- Identification of prescribed targets/ objects from an arbitrary input scene
- Primary information used as reference: spatial features (shape) of the desired object
- Basic technique employed: correlation
- Recognition result is provided as correlation peaks





Correlation output

Pattern recognition

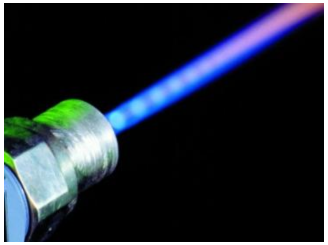
- Applications
  - Target identification
  - Target tracking and motion analysis
  - Machine parts recognition in industry
  - Character recognition
  - Face detection
  - Finger print detection
  - Medical imaging
  - Meteorology
  - Robotics
  - Security systems

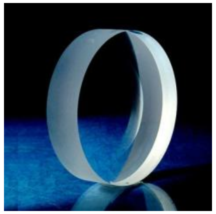
Pattern recognition

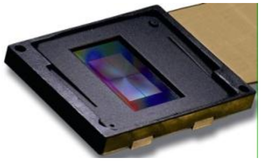
- Requirements
  - No false positive (reject any non-target objects in the input scene)
  - No false negative (don't miss any target object in the input scene)
  - Sharp discrimination between target and non-target objects
  - Fast operation for real-time applications
- Real-time pattern recognition
  - Optical joint transform correlation (JTC)

Optical image processing

- Optoelectronic implementation can enhance the speed and efficiency of pattern recognition performance significantly
- Optoelectronic equipment
  - Laser
    - Light source (carrier signal)
  - Lens
    - Focusing
    - Fourier transformation
  - Spatial light modulator (SLM)
    - Light modulation
  - CCD camera
  - Computer

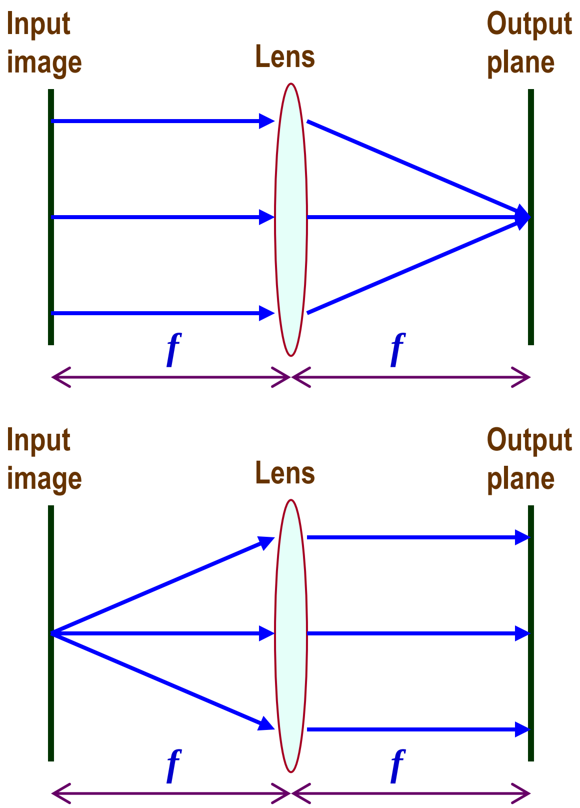


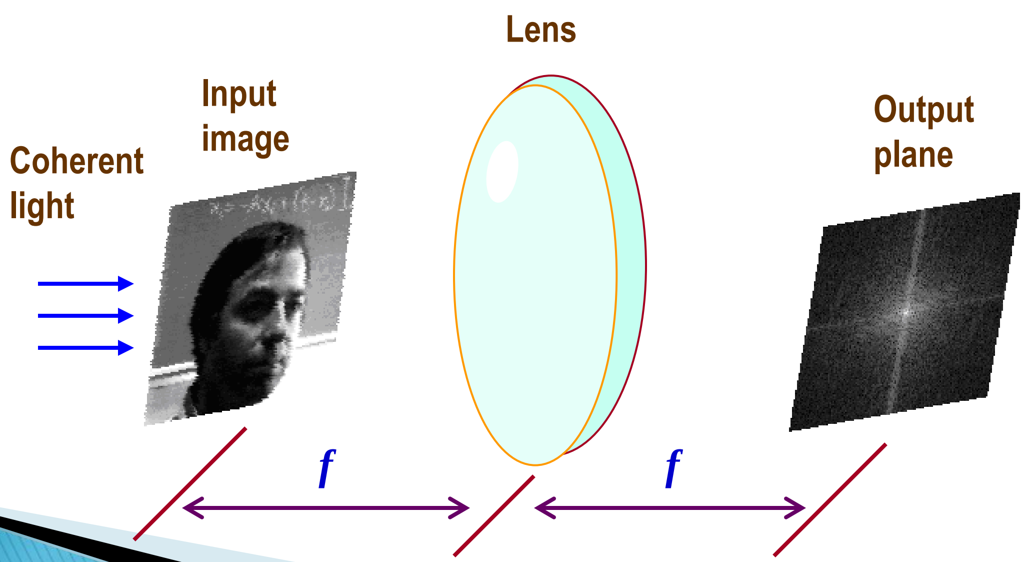




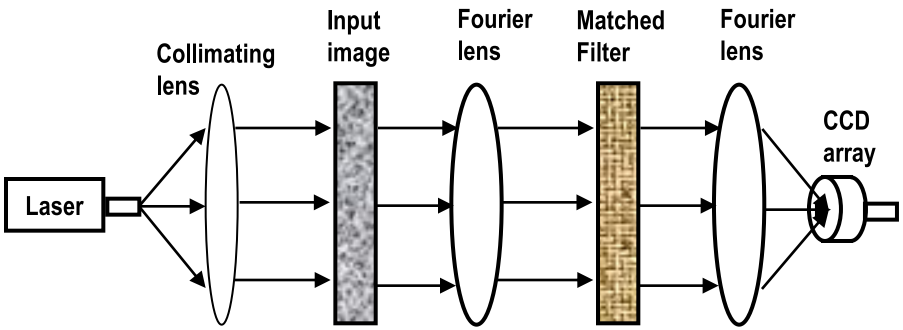
Optical lens

- Fourier transformation by lens
  - Input image placed at the focal plane
  - Transformed image displayed at the other focal plane
- Features
  - Operation at light speed
  - Parallel transformation
  - Bi-directional operation





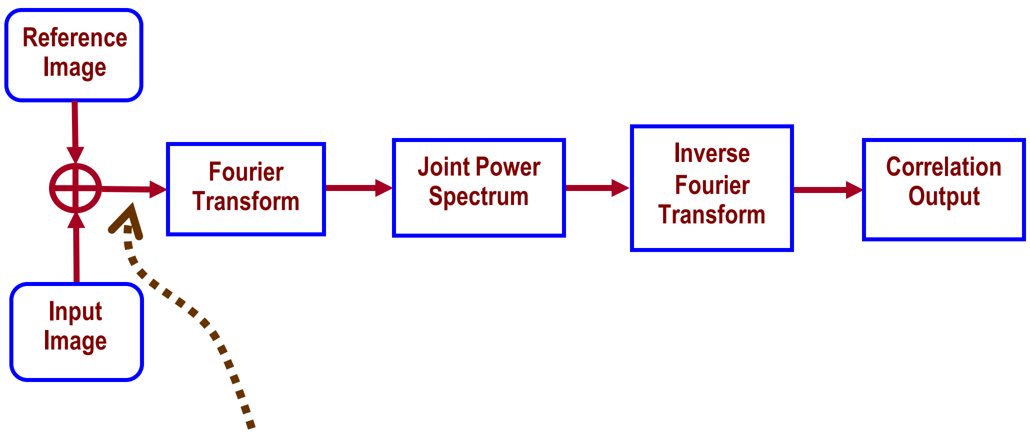
Vanderlugt correlator



- First optical correlation technique
  - A linear space-invariant filter needs be matched to reference image
  - Real-valued signal is resulted at the center for a matching
- Limitations
  - Filter be matched
  - Filter be aligned accurately in optical axis
  - Accurate positioning of the filter

Optical joint transform correlation

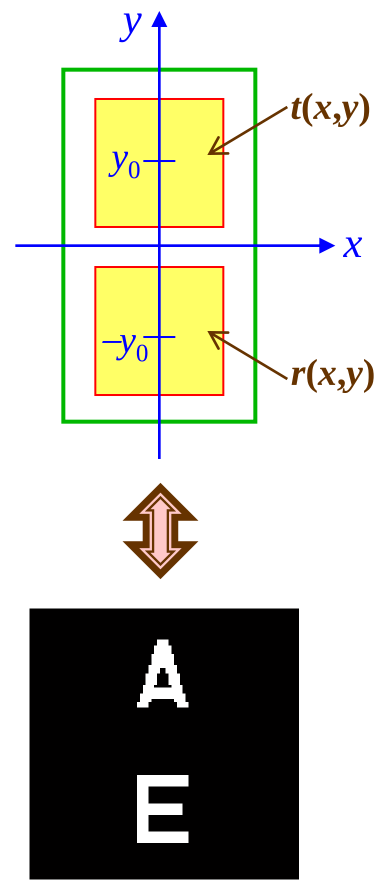
- Input and reference images are placed side-by-side and illuminated using an SLM



Joint image: input image and reference image

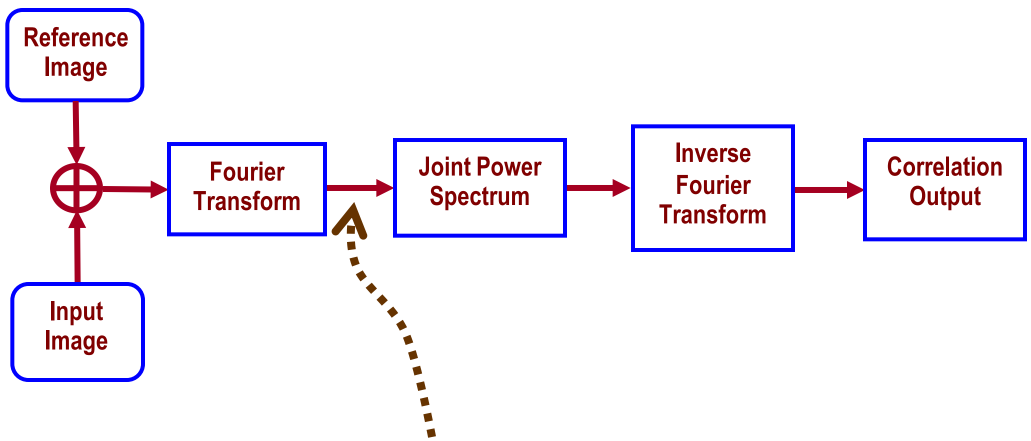
$$f(x, y) = r(x, y + y_0) + t(x, y - y_0)$$

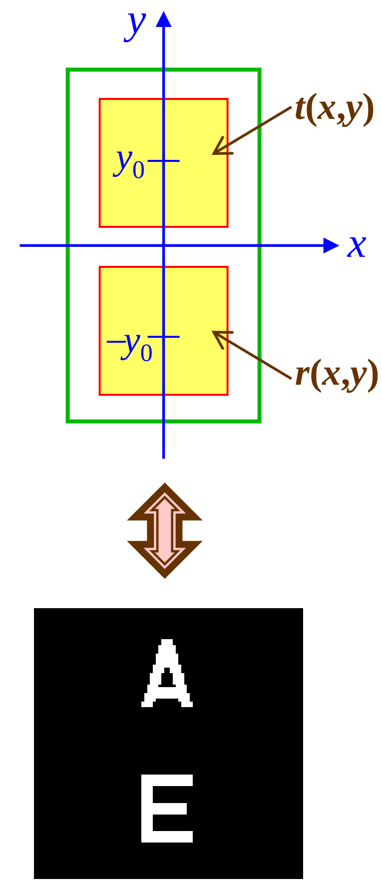
r(x,y): reference image, ***t(x,y)***: input image



Optical joint transform correlation

- Lens performs Fourier transformation of the joint image





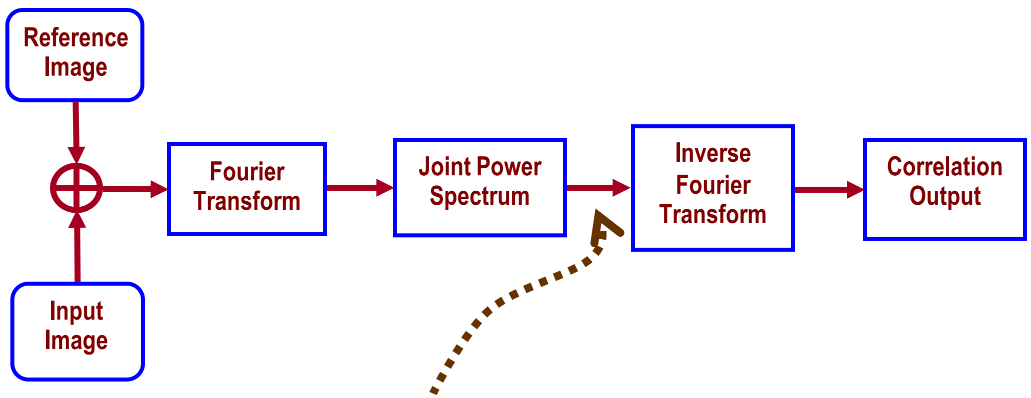
Fourier transform:

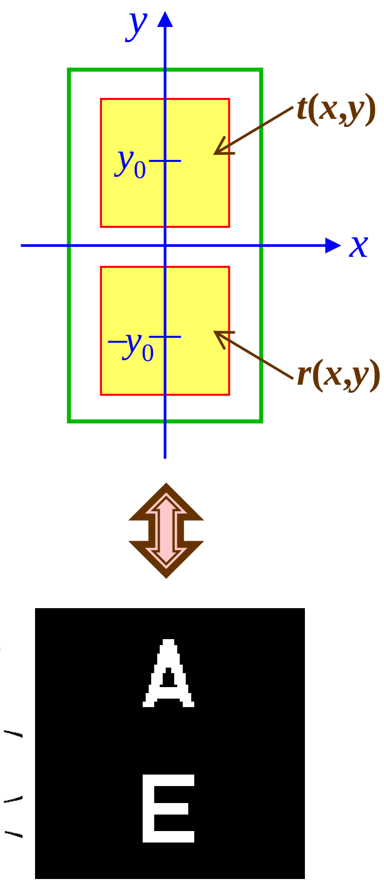
$$F(u,v) = |R(u,v)| \exp[i\phi_r(u,v)] \exp(-jy_0 v) + |T(u,v)| \exp[i\phi_t(u,v)] \exp(+jy_0 v)$$

$|R(u,v)|$, $|T(u,v)|$: magnitudes; $\phi_i(u,v)$, $\phi_t(u,v)$: phases

Optical joint transform correlation

- Joint power spectra is recorded by a CCD camera



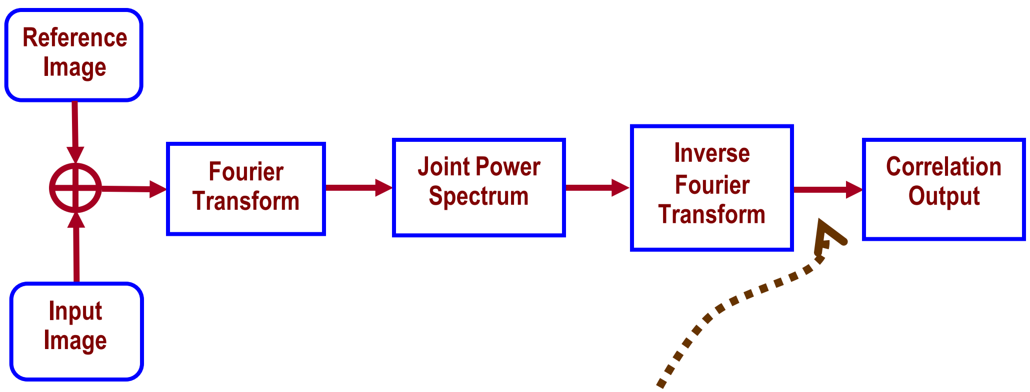


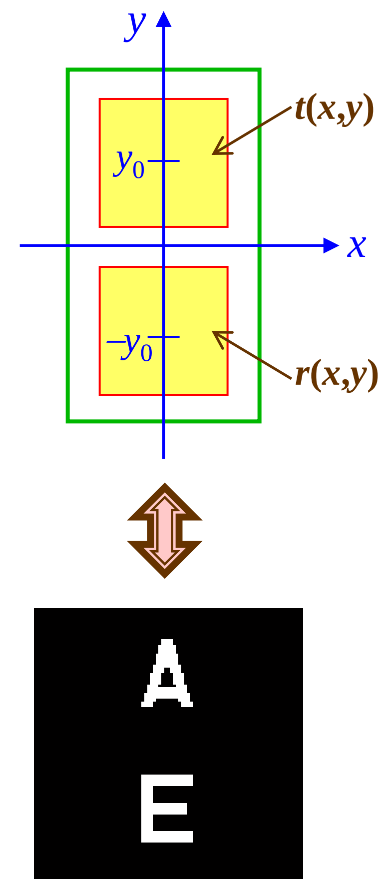
Joint power spectrum (JPS): magnitude of Fourier transform

$$J(u,v) = |F(u,v)|^2 = F(u,v)F^*(u,v) = |R(u,v)|^2 + |T(u,v)|^2$$
$$+|R(u,v)||T(u,v)|\exp[j\phi_r(u,v) - j\phi_t(u,v)]\exp(-2jy_{0}v)$$
$$+|R(u,v)||T(u,v)|\exp[-j\phi_r(u,v) + j\phi_t(u,v)]\exp(2jy_{0}v)$$

Optical joint transform correlation

- Lens performs inverse Fourier transformation





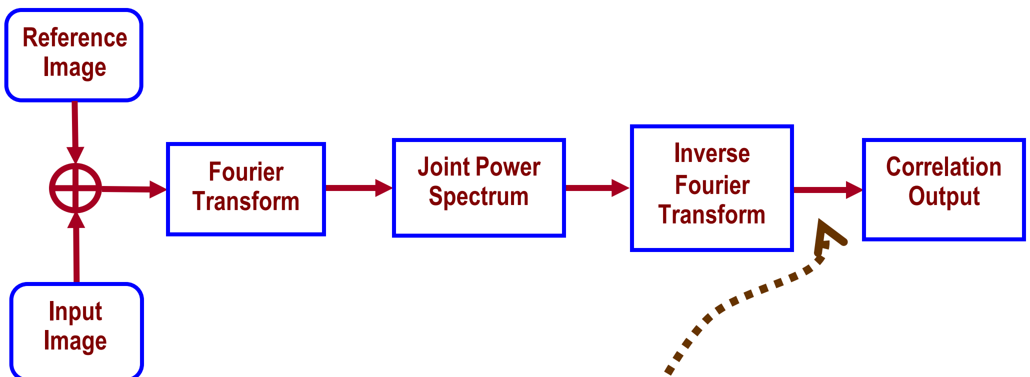
Inverse Fourier transform of JPS: correlation signal

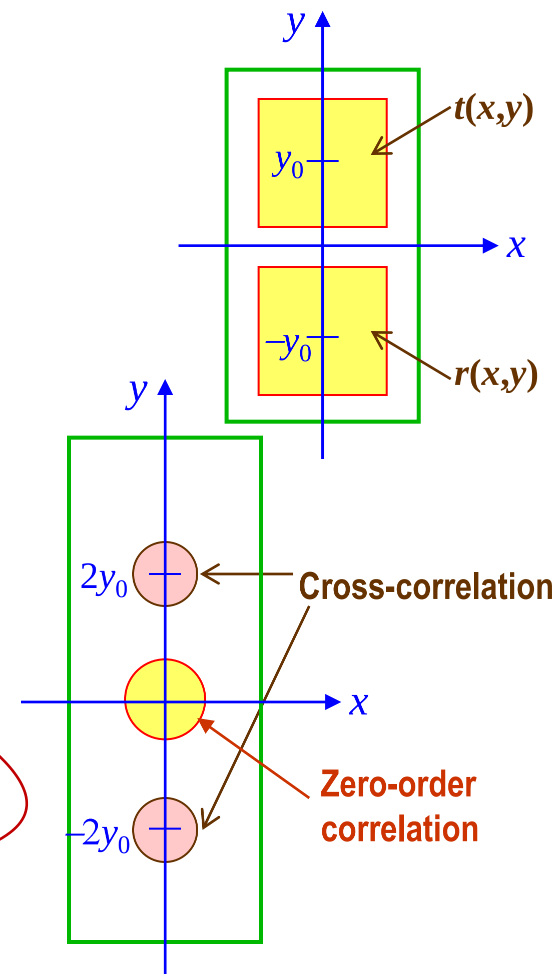
$$
\begin{aligned}
j(x,y) &= r(x,y) \oplus r(x,y) + t(x,y) \oplus t(x,y) \\
&\quad + r(x,y+2y_0) \oplus t(x,y+2y_0) \\
&\quad + r(x,y-2y_0) \oplus t(x,y-2y_0)
\end{aligned}
$$

$\oplus$: correlation

Optical joint transform correlation

- Lens performs inverse Fourier transformation





Inverse Fourier transform of JPS: correlation signal

$$
\begin{aligned}
j(x,y) &= r(x,y) \oplus r(x,y) + t(x,y) \oplus t(x,y) \\
&+ r(x,y+2y_0) \oplus t(x,y+2y_0) \\
&+ r(x,y-2y_0) \oplus t(x,y-2y_0)
\end{aligned}
$$

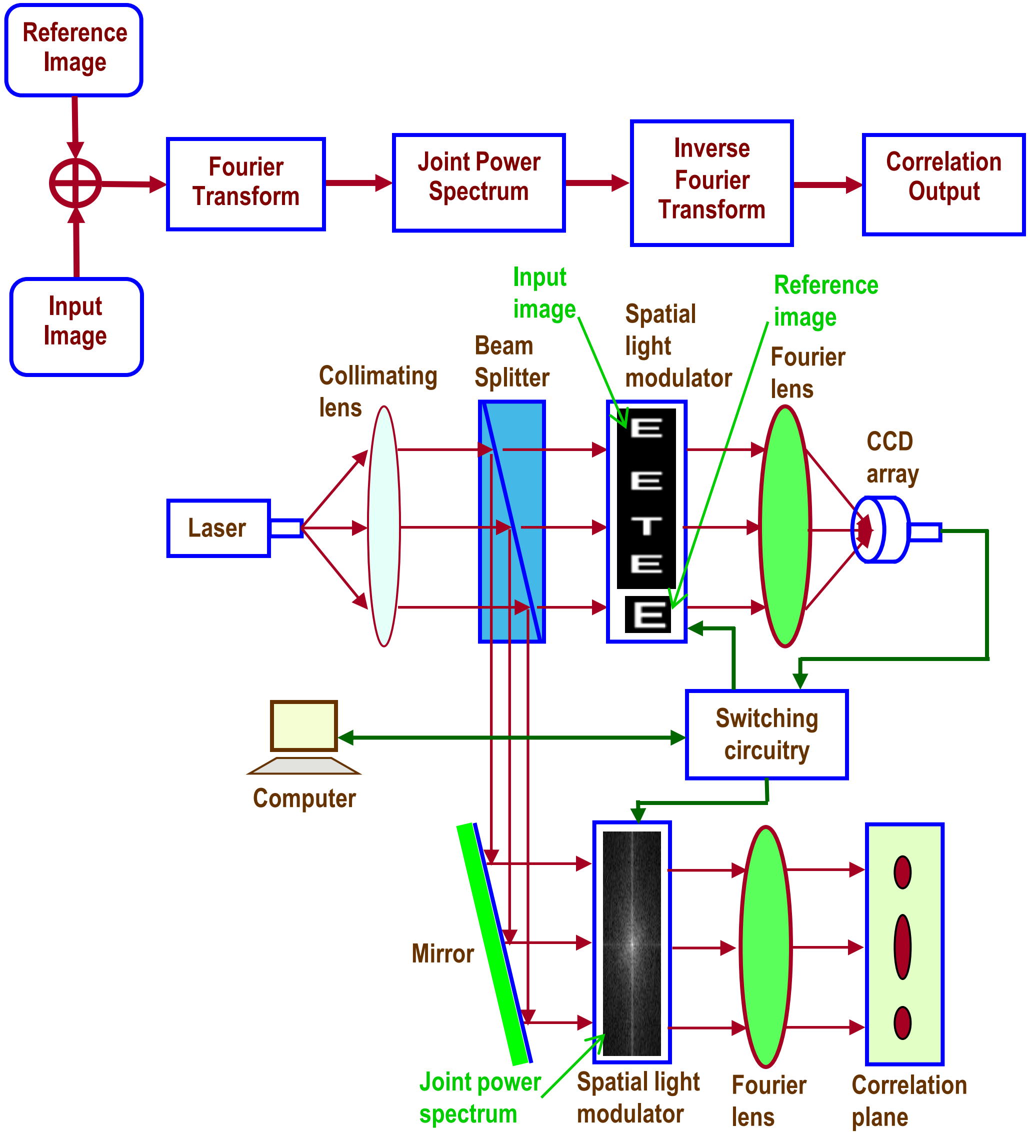
Correlation output:

(a) zero-order correlation

(b) cross-correlation

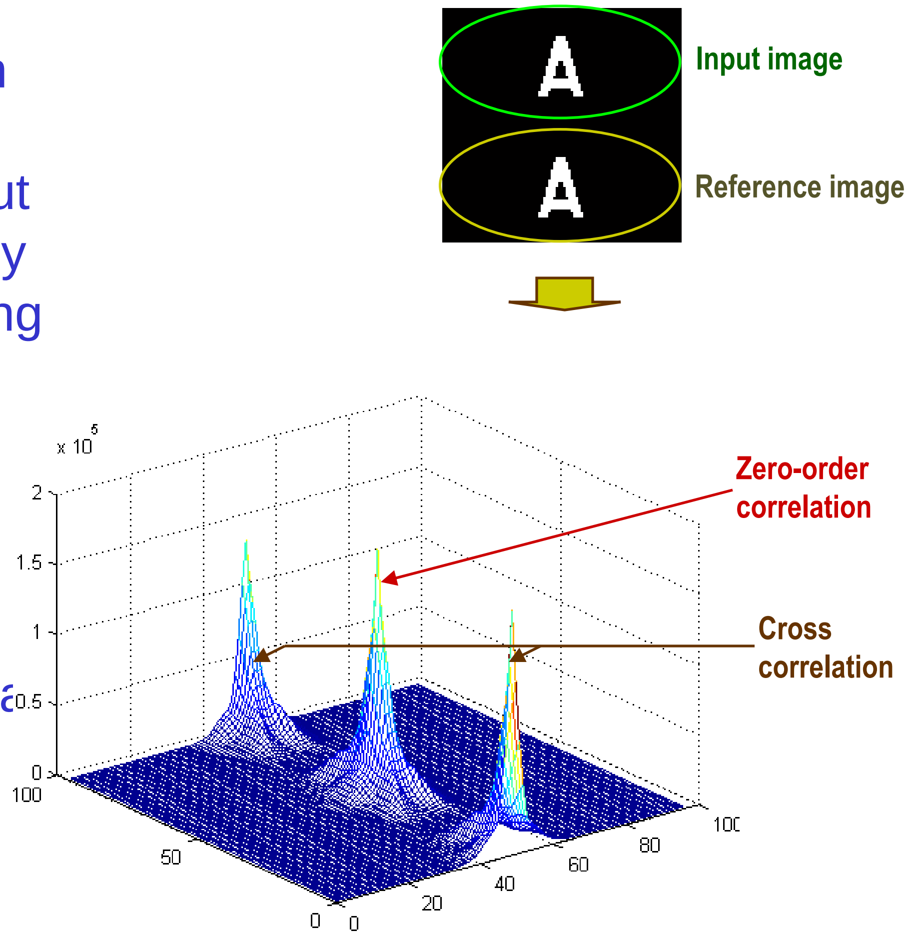
Optical jtc Architecture

- Collimating lens yields coherent and parallel light
- Reference and input images are fed to spatial light modulator (SLM) which modulates the incoming light accordingly
- Fourier lens performs Fourier transformation
- CCD camera records the magnitude spectrum
- JPS signal is fed to SLM
- Inverse Fourier transformation of JPS produces the correlation output



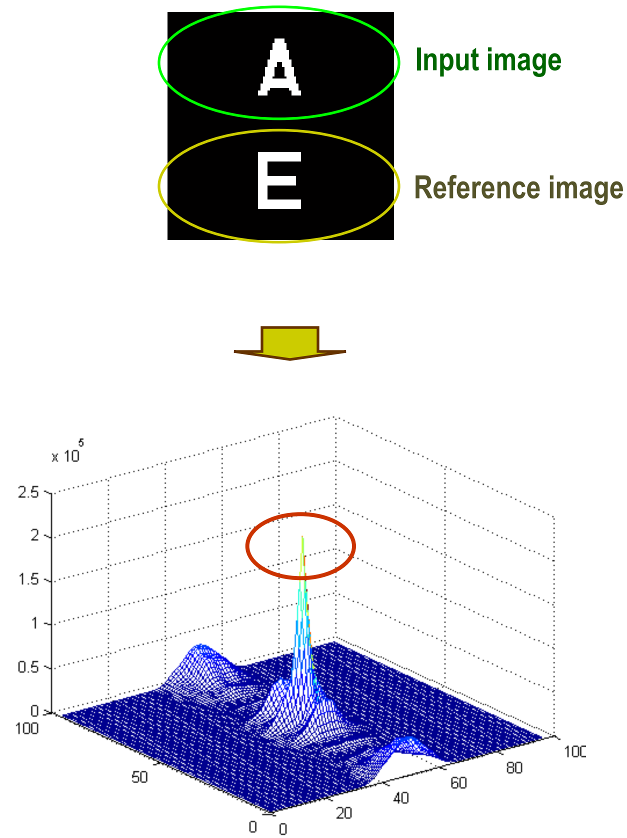
Optical jtc features

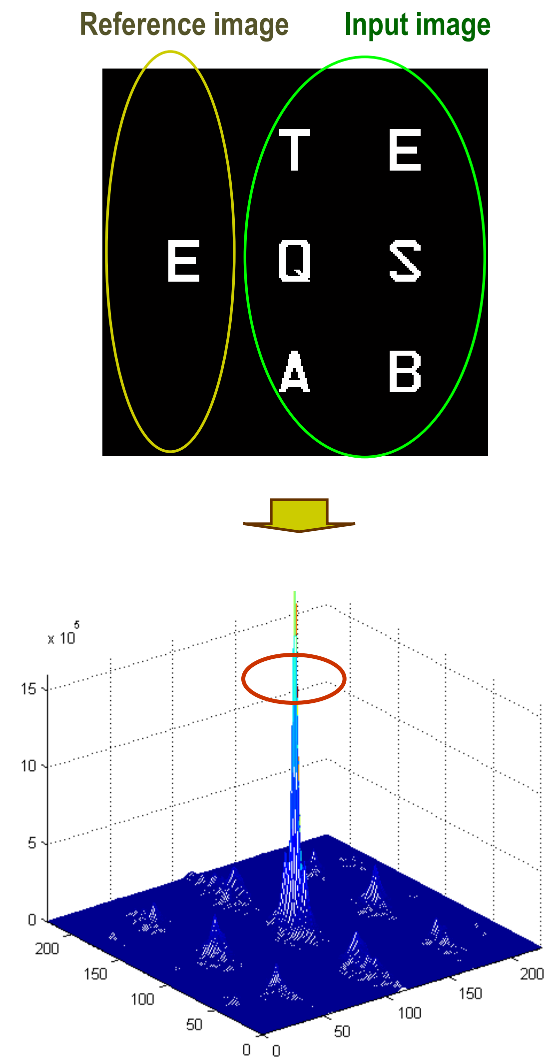
- Advantages
  - Does not require complex filter fabrication
  - Reference image can be updated in real time
  - Reference image and unknown input image are processed simultaneously
  - No requirement of precise positioning
- Problems/limitations
  - Zero-order correlation
  - Pair of correlation signals for each object
  - Wide side lobes
  - Poor discrimination between target a[nd] non-target objects
  - Spatial inefficiency



Optical jtc performance

- Strong zero-order correlation term even in case of mismatching
- Zero-order term overshadows desired correlation terms



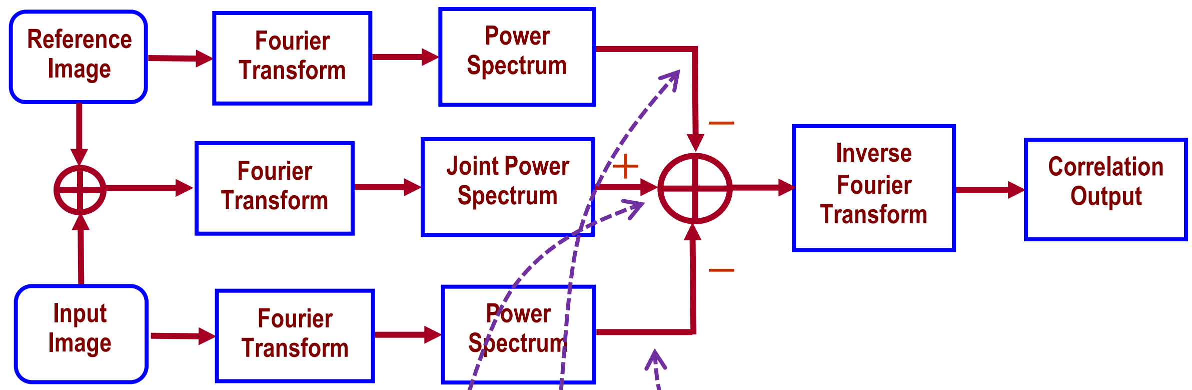


Optical jtc modifications

- JTC with power spectra subtraction
- Phase-encoded JTC
- Phase-encoded and phase-shifted fringe-adjusted JTC

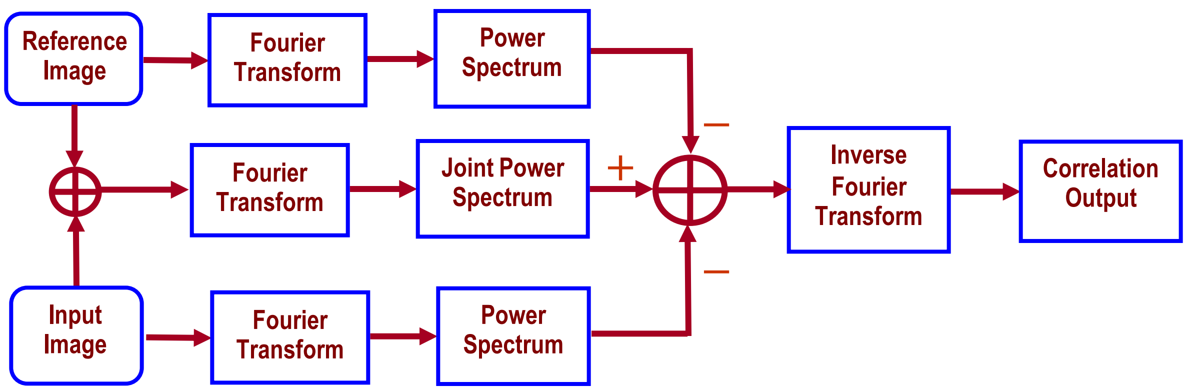
jtc with Power spectra subtraction

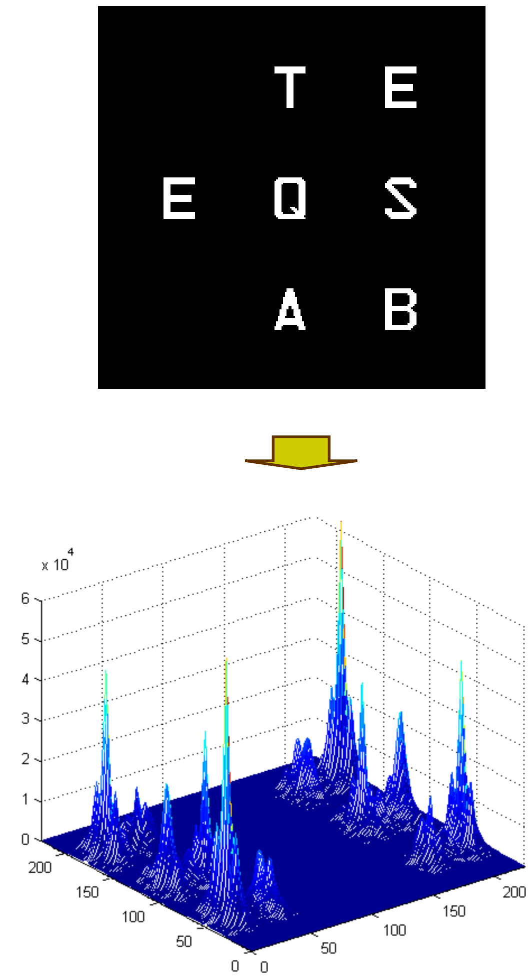
- Power spectrum of reference-only image and that of input-only image are measured and then subtracted from the JPS signal
- Zero-order correlation term is removed



$$
\begin{aligned}
J_s(u,v) &= |F(u,v)|^2 - |R(u,v)|^2 - |T(u,v)|^2 \\
&= |R(u,v)||T(u,v)| \exp[j\phi_r(u,v) - j\phi_t(u,v)] \exp(-2jy_{0v}) \\
&+ |R(u,v)||T(u,v)| \exp[-j\phi_r(u,v) + j\phi_t(u,v)] \exp(2jy_{0v})
\end{aligned}
$$

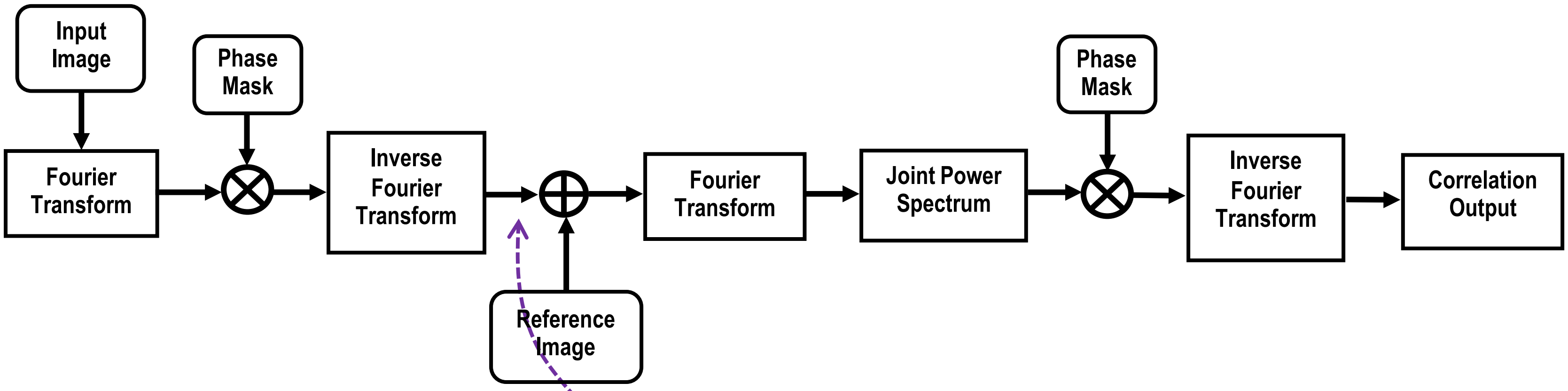
jtc with Power spectra subtraction





- Problems
  - Slow operation
  - Duplicate correlation
  - Wide side lobes

Phase-encoded jtc



- Input scene is phase-encoded:

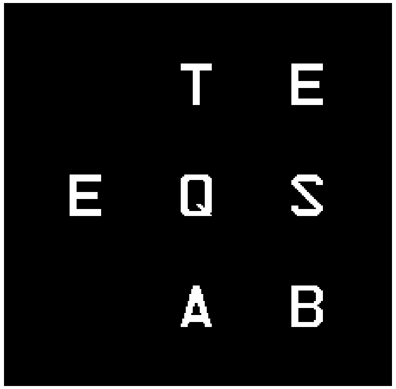
$$t_i(x,y) = t(x,y) \otimes \phi(x,y)$$

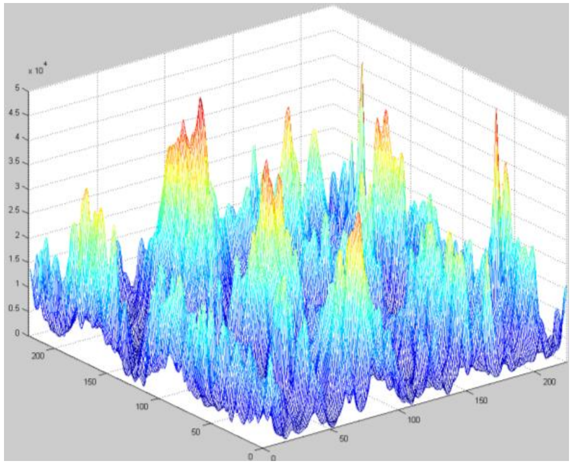
- Correlation output:

$$\begin{aligned} e(x,y) &= r(x,y) \otimes r(x,y) + t_i(x,y) \otimes t_i(x,y) \otimes \phi(x,y) \\ &\quad + r(x, y - y_0 - y_i) \otimes t_i(x, y - y_0 - y_i) + r(x, y + y_0 + y_i) \otimes t_i(x, y + y_0 + y_i) \otimes \phi(x,y) \end{aligned}$$

Phase-encoded jtc

- Slow operation
  - Phase-encoding of input scene
- Wide side lobes
- Sensitive to noise
- Worse performance for input scene having large number of objects



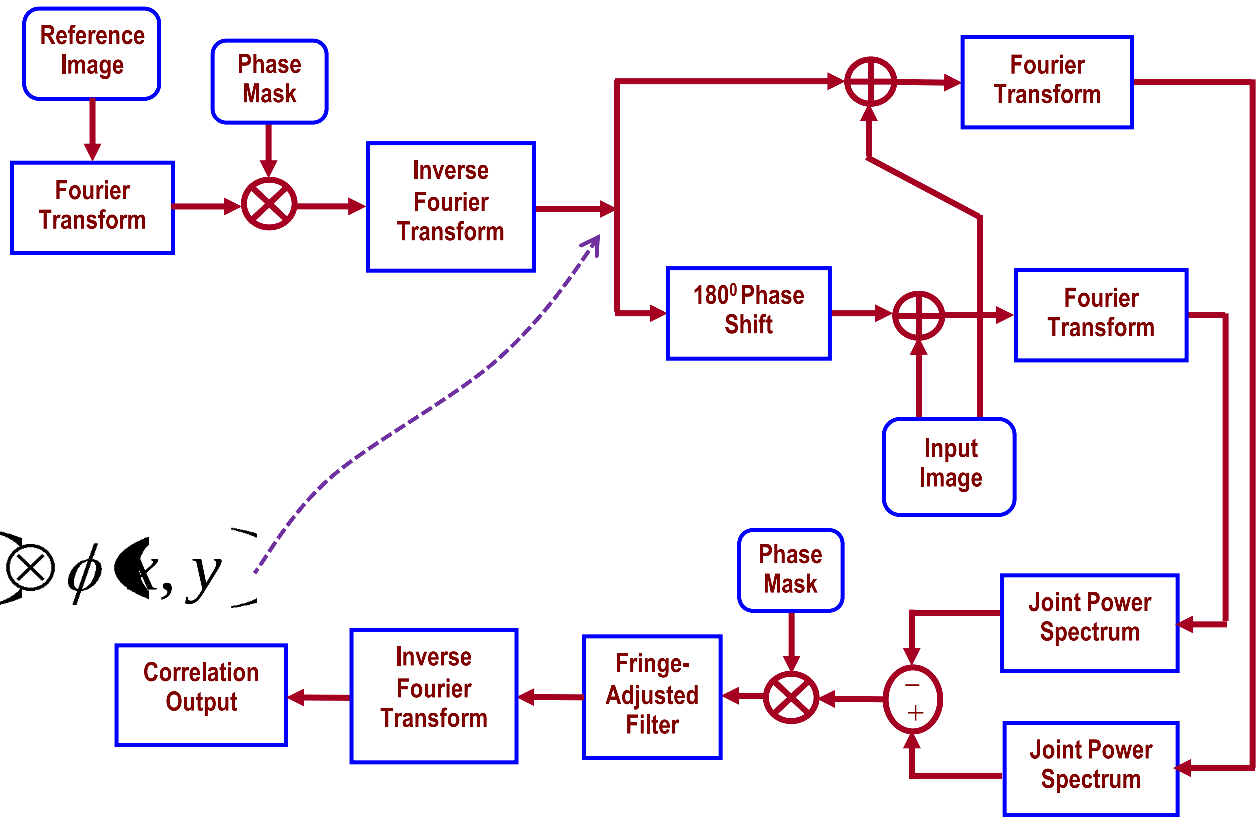


Phase-encoded & shifted fringe-adjusted jtc

- Reference image is phase-encoded using a random phase mask

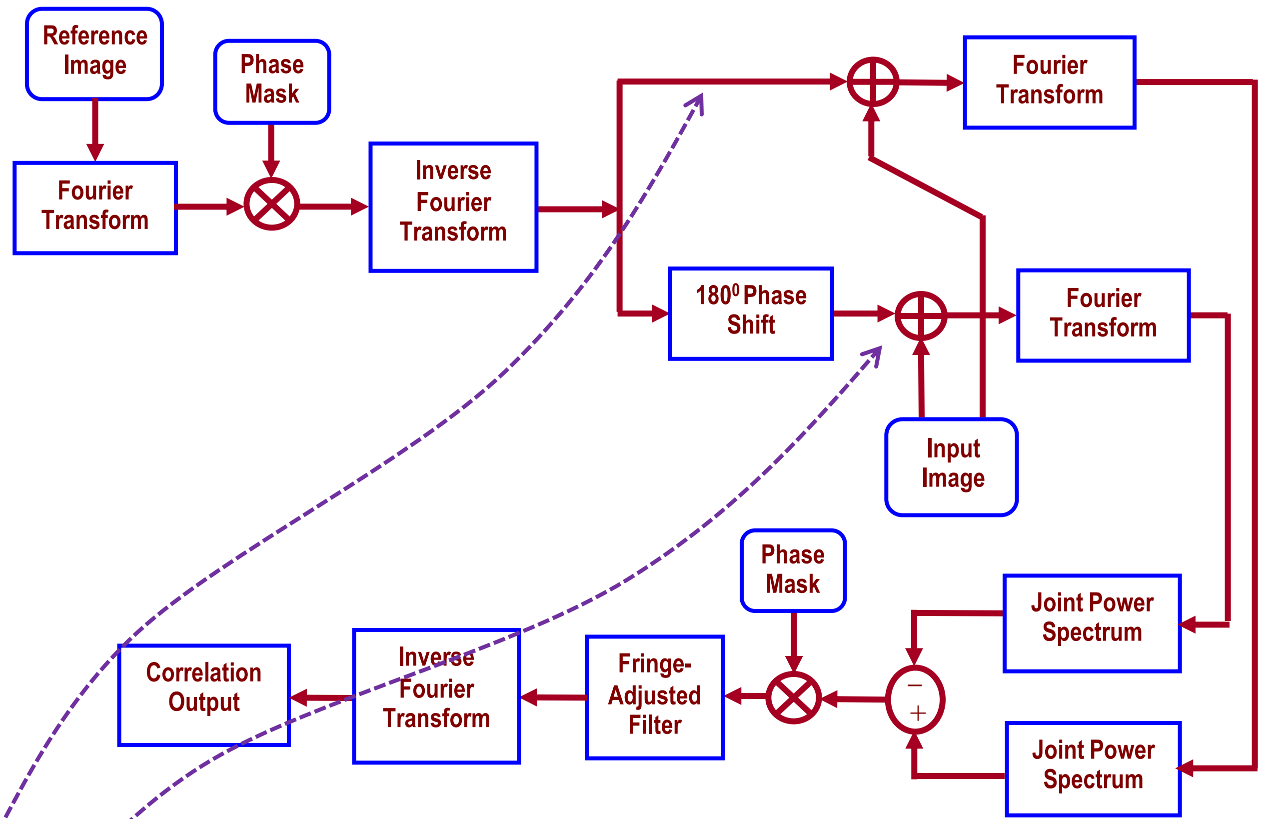
$$s(x,y) = r(x,y) \otimes \phi(x,y)$$

$\phi(x,y)$: phase mask



Phase-encoded & shifted fringe-adjusted jtc

- Phase-encoded reference image is processed in two channels
  - 0^0 phase shift
  - 180^0 phase shift
- Input image is introduced to both channels



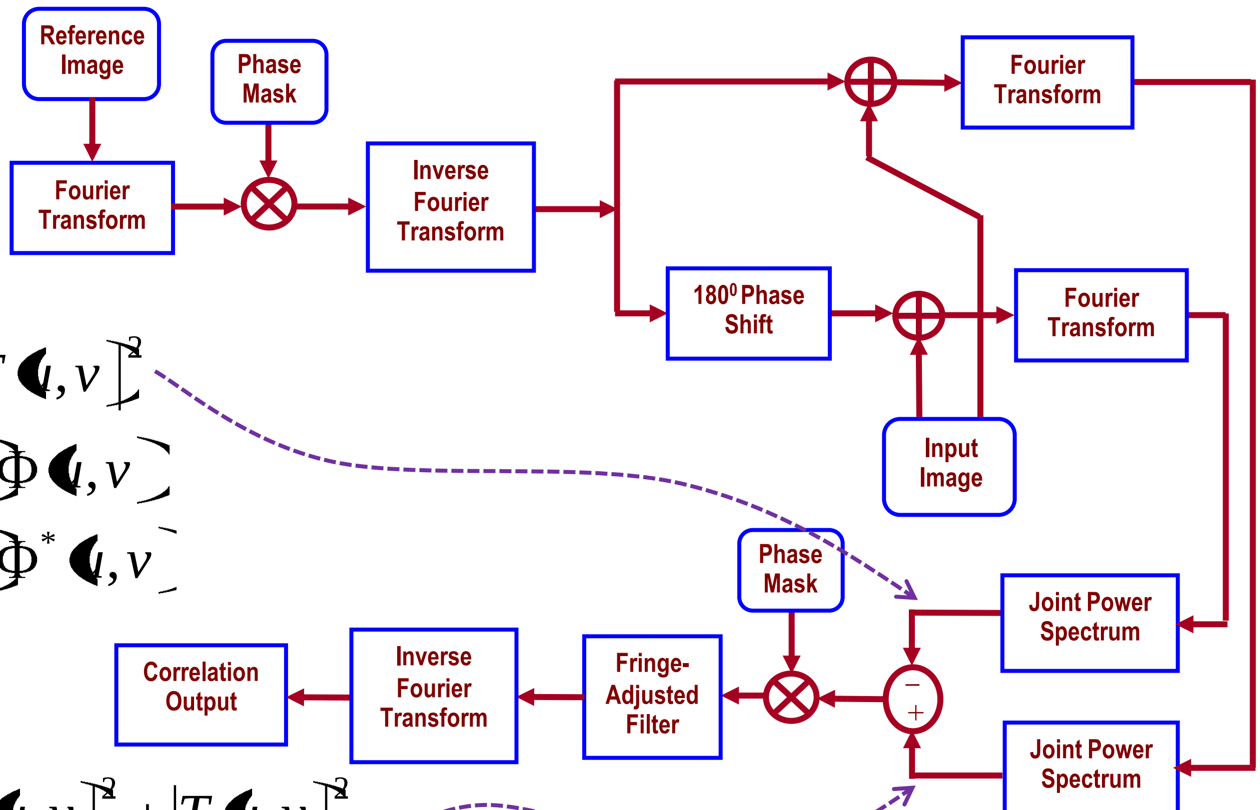
$$f_1(x,y) = s(x,y) + t(x,y) = r(x,y) \otimes \phi(x,y) + t(x,y)$$

$$f_2(x,y) = -s(x,y) + t(x,y) = -r(x,y) \otimes \phi(x,y) + t(x,y)$$

Phase-encoded & shifted fringe-adjusted jtc

- JPS signals:

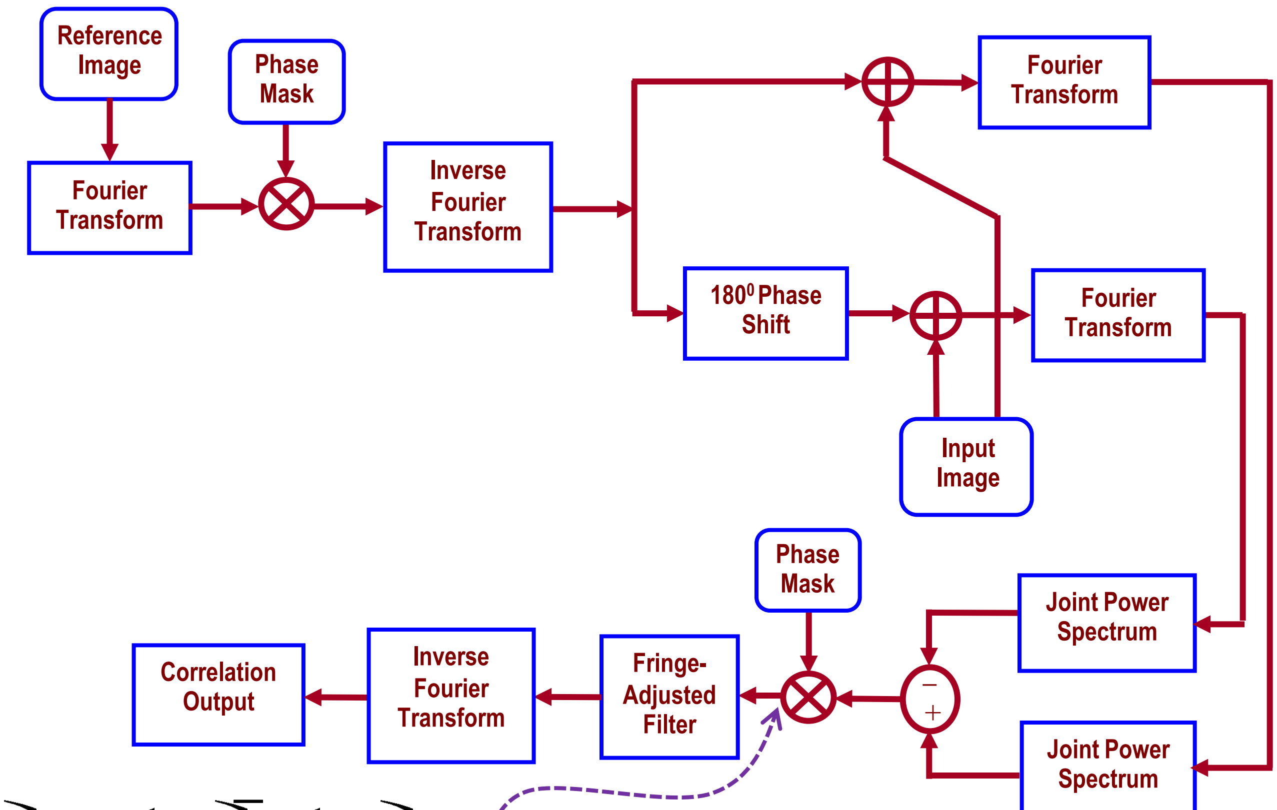
$$J_1(u,v) = |R(u,v)|^2 + |T(u,v)|^2 + R(u,v)T^*(u,v)\Phi(u,v) + R^*(u,v)T(u,v)\Phi^*(u,v)$$



$$J_2(u,v) = |R(u,v)|^2 + |T(u,v)|^2 - R(u,v)T^*(u,v)\Phi(u,v) - R^*(u,v)T(u,v)\Phi^*(u,v)$$

Phase-encoded & shifted fringe-adjusted jtc

- JPS signals are subtracted one from another
- Modified JPS is multiplied by the same phase mask



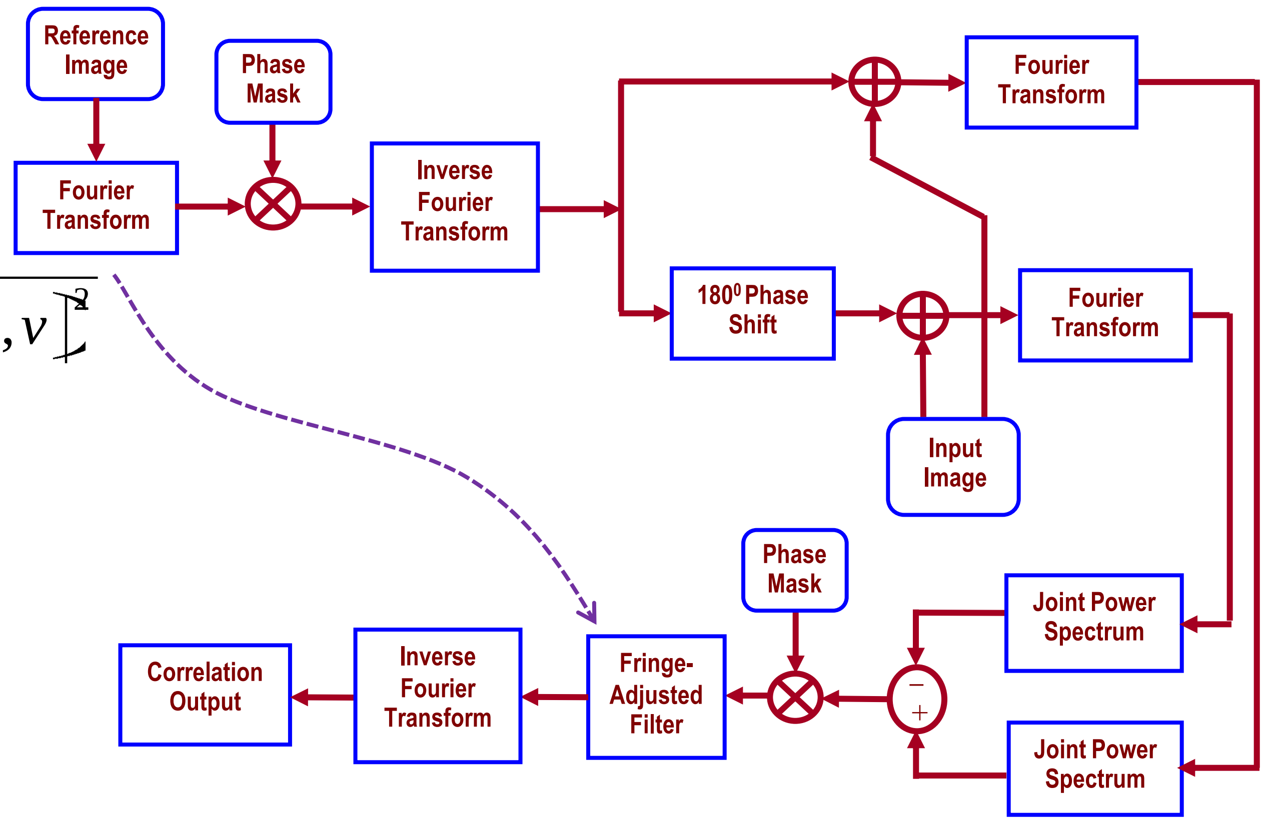
$$P(u,v) = [J_1(u,v) - J_2(u,v)]\Phi(u,v)$$
$$= R(u,v)T^*(u,v)\Phi^2(u,v) + R^*(u,v)T(u,v)$$

Desired cross-correlation term

Phase-encoded & shifted fringe-adjusted jtc

- Fringe-adjusted filter (FAF):

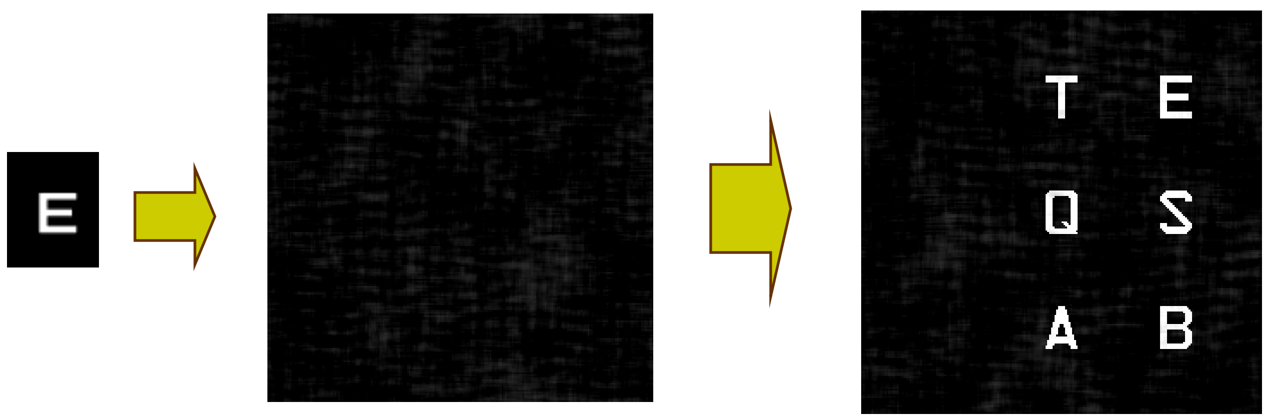
$$H(u,v) = \frac{C(u,v)}{D(u,v) + |R(u,v)|^2}$$



- Modified JPS is filtered and then inverse Fourier transformed to yield the correlation signal

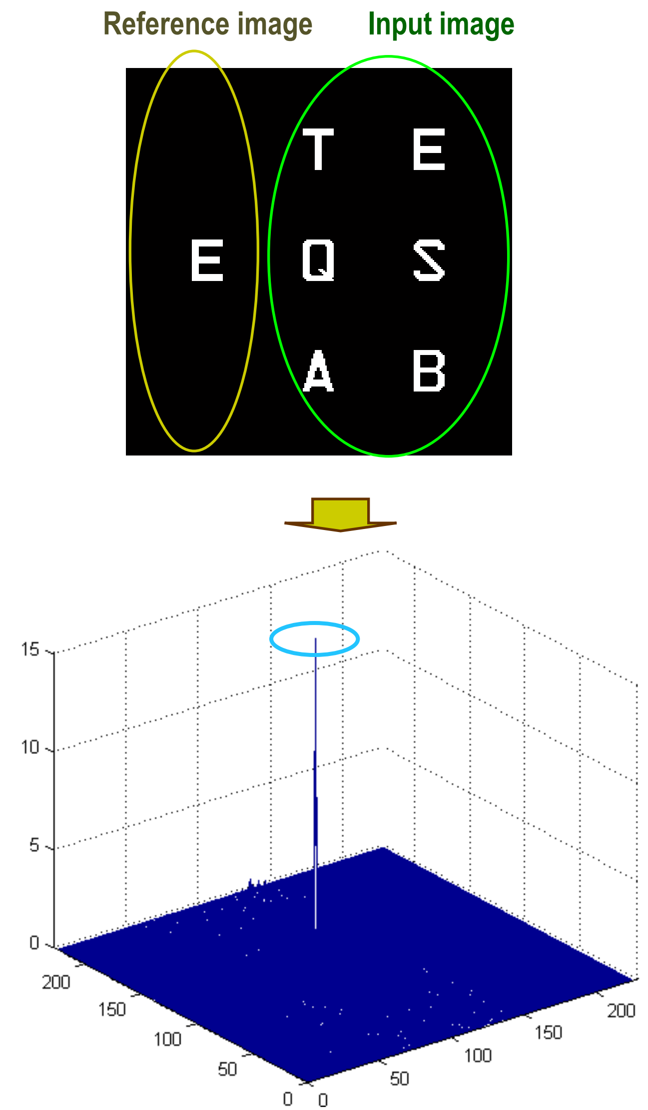
Psfftc Performance

- Reference image – phase-encoded
  - Distributed all over the image plane
  - Does not require the reference image be separated from the input scene
  - Location of target can easily be identified



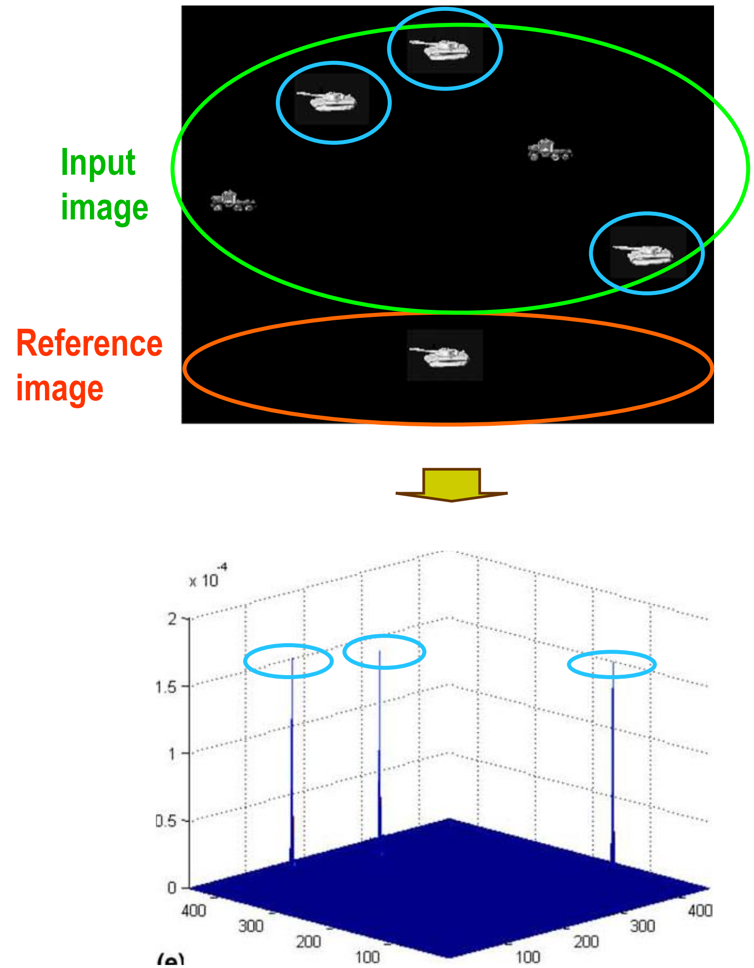
Psfftc Performance

- Features:
  - Single correlation peak for each target
  - Delta-like correlation peak
  - Negligible correlation for non-target objects
  - Simultaneous detection of multiple target objects
  - Class-associative detection
    - Multiple reference classes of targets
  - Parallel processing – fast operation
  - Spatially efficient
  - Optoelectronic implementation
    - Real-time system



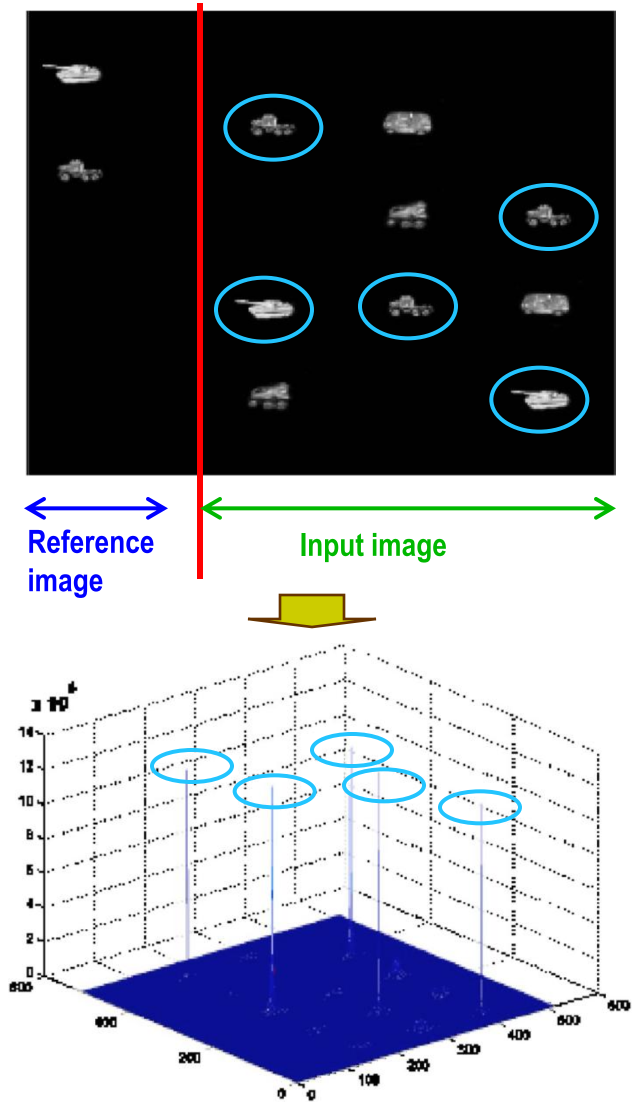
Psfftc Performance

- Gray image:
  - Intensity varying gradually from black to white
- Gray target detection:
  - Successful recognition of all targets
  - Rejection of any non-target objects



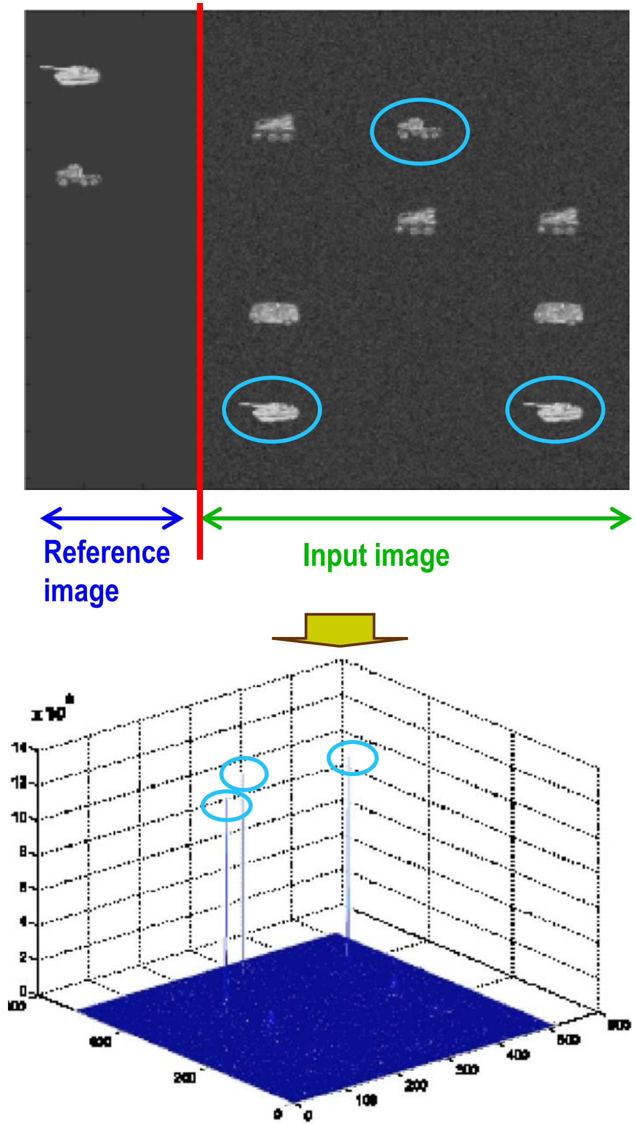
Psfftc Performance

- Class-associative target detection:
  - Multiple reference class objects
  - Detection of all targets corresponding to every reference class at the same time
  - No false alarm
    - No target is missed
    - No non-target is detected



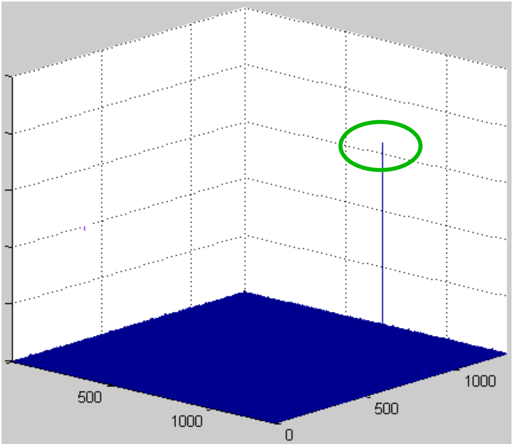
Psfftc Performance

- Class-associative target detection in noisy environment:
  - Noisy environment
    - Illumination variation
    - Foggy weather
  - Efficient and successful target detection



Psfftc Performance

- Real-life image:
  - Boat in water background
    - Trees and other background objects
  - Sharp correlation peak with almost zero false signals



Synthetic discriminant function

- SDF image is formed from training images:

$$\mathrm{SDF} = \sum_i a_i r_i(x, y)$$

  - $r_i(x,y)$: training images, a_i: coefficients

- Correlation between SDF and each training image:

$$\mathrm{corl}_i = \mathrm{SDF} \oplus r_i(x, y)$$

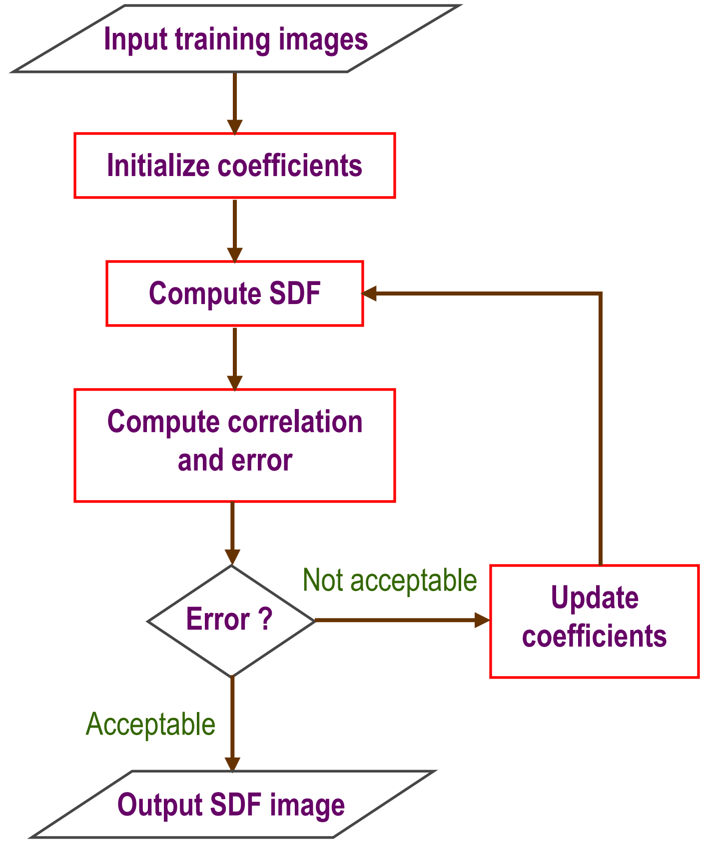
- Error:

$$\mathrm{err} = \frac{\mathrm{corl}_{\max} - \mathrm{corl}_{\min}}{\mathrm{corl}_{\max}}$$

- Updated coefficients:

$$a_i = a_i + (\mathrm{corl}_{\max} - \mathrm{corl}_i)\delta$$

  - δ: relaxation factor



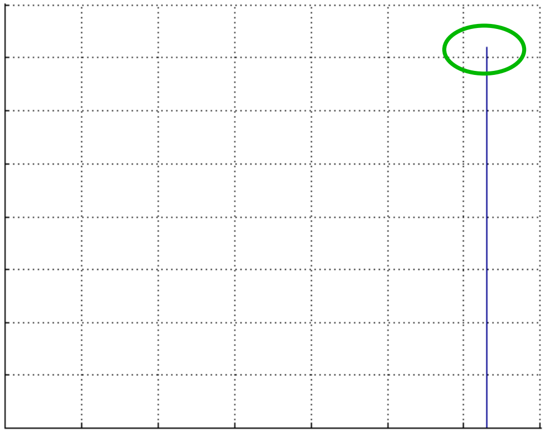
Sdf formation

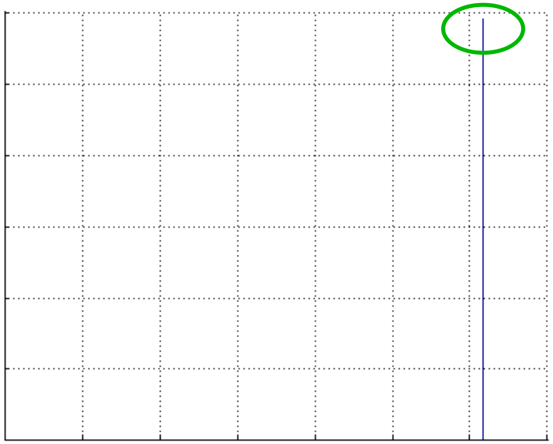
Training images

SDF image

Boat detection

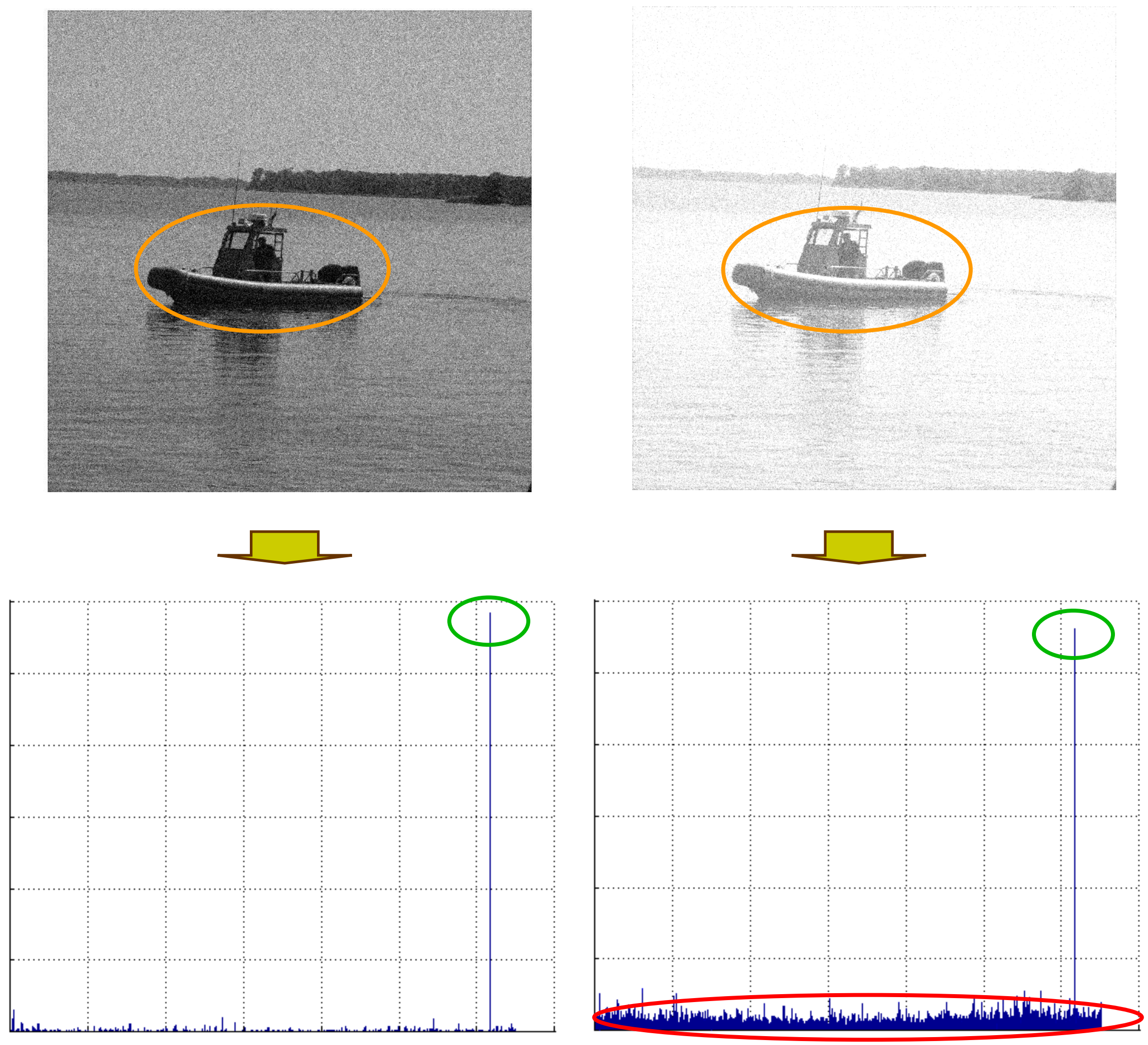
- Out-of-plane rotation:
  - Boat appears in different orientations
  - Successful detection of target boat in any orientation





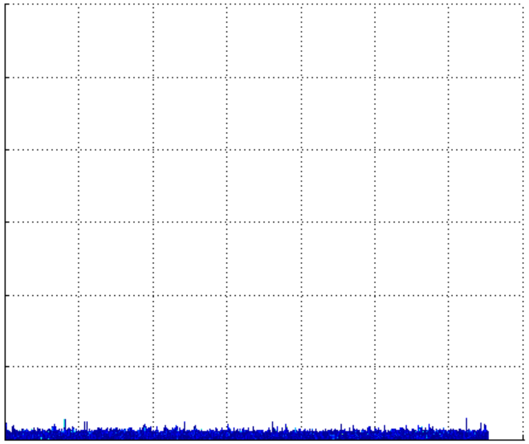
Boat detection

- Noisy input scene:
  - Foggy weather
  - Successful detection performance
  - Very low noisy signal in the correlation plane
  - Very high discrimination between target and non-target objects



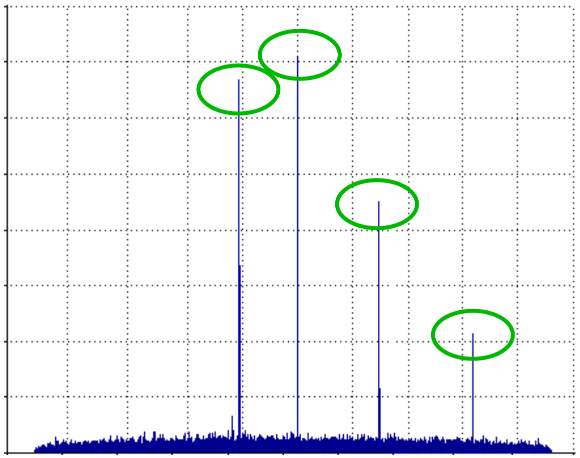
Boat detection

- Non-target boat:
  - Negligible correlation signal
    - Successful rejection of non-target objects



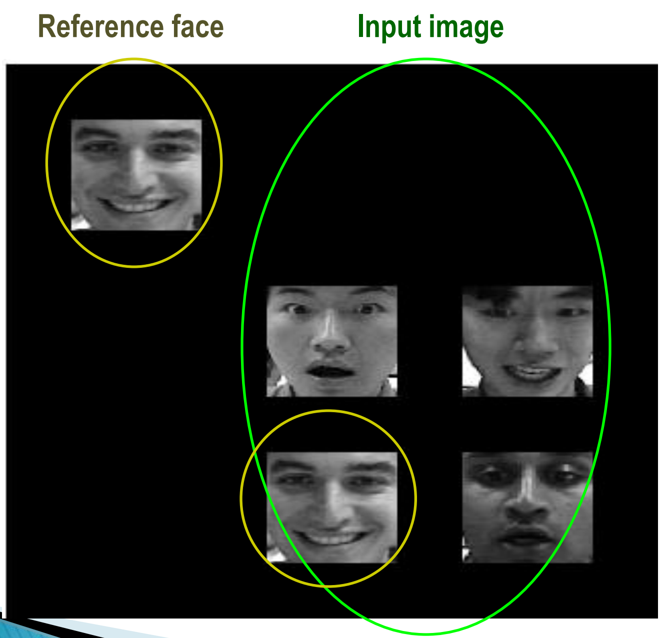
Boat detection

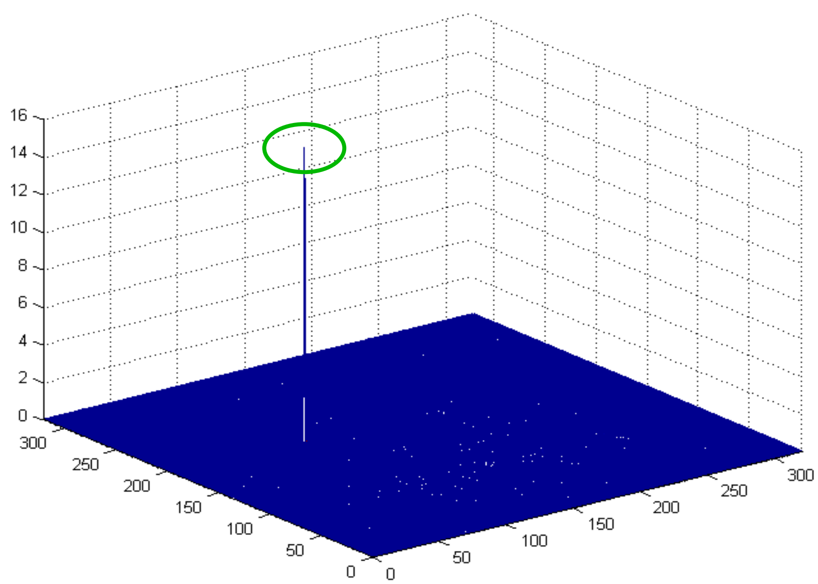
- Complex scenario:
  - Multiple target as well as non-target boats
  - Successful detection of all target boats
  - Rejection of all non-target boats



Face Recognition

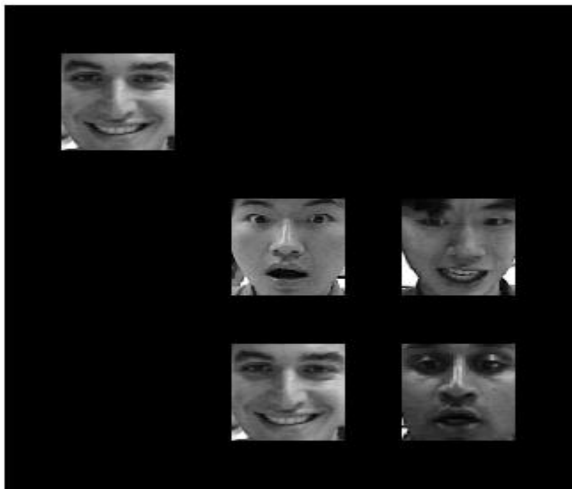
- Target face is recognized with a sharp correlation peak
- Non-target faces are rejected with negligible peaks
- High discrimination between target and non-target faces

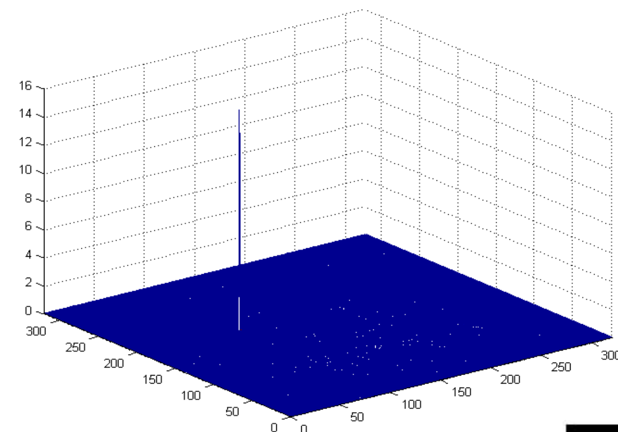


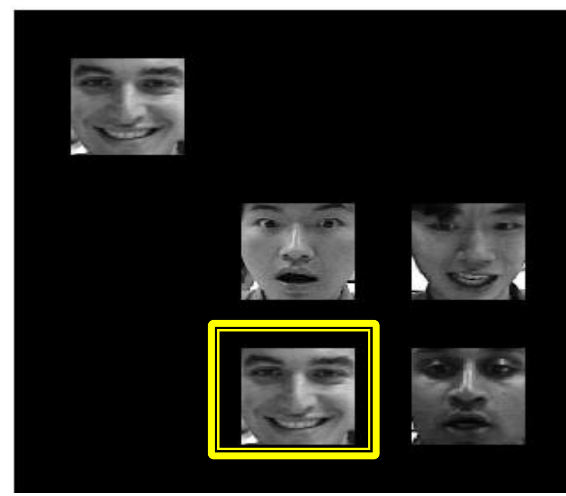


Face Recognition

- Location of target face can also be determined

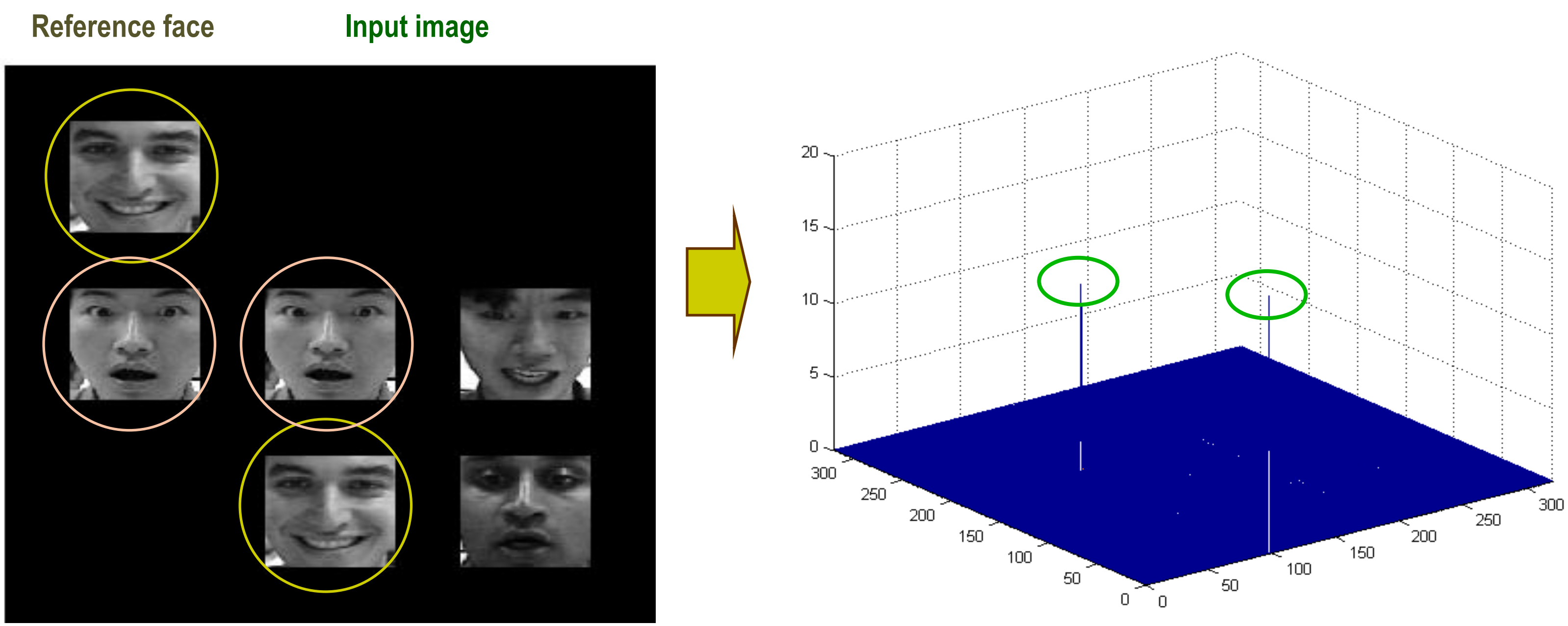






Face Recognition

- Multiple reference faces can be recognized simultaneously
- High discrimination between target and non-target faces



Distortion-Invariant Face Recognition

Training face images

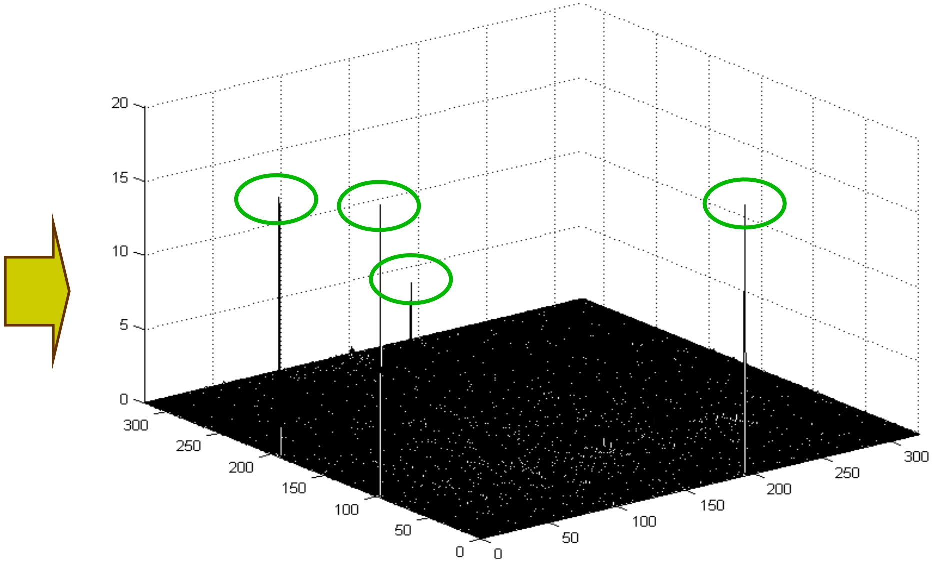
SDF image

Distortion-Invariant Face Recognition

- Multiple target faces with pose and mood variations can efficiently be recognized

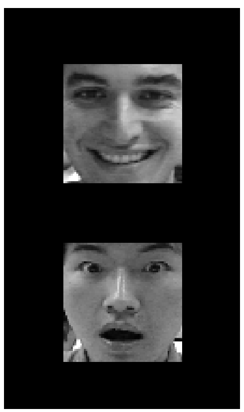
Reference SDF face

Joint Input image

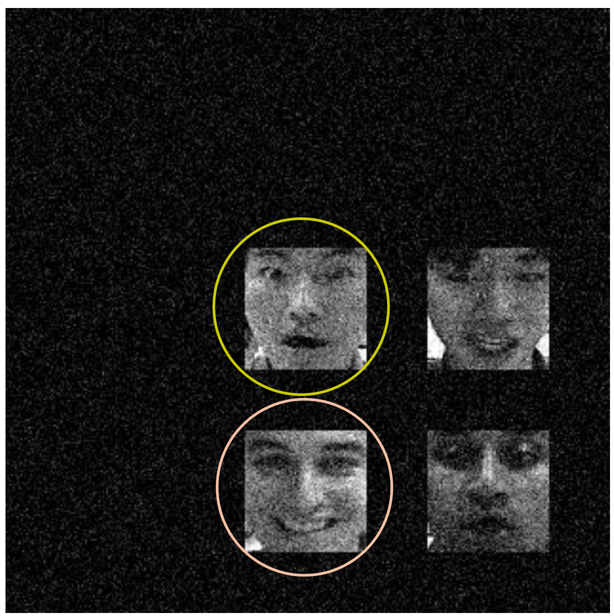


Face Recognition in Noisy Environment

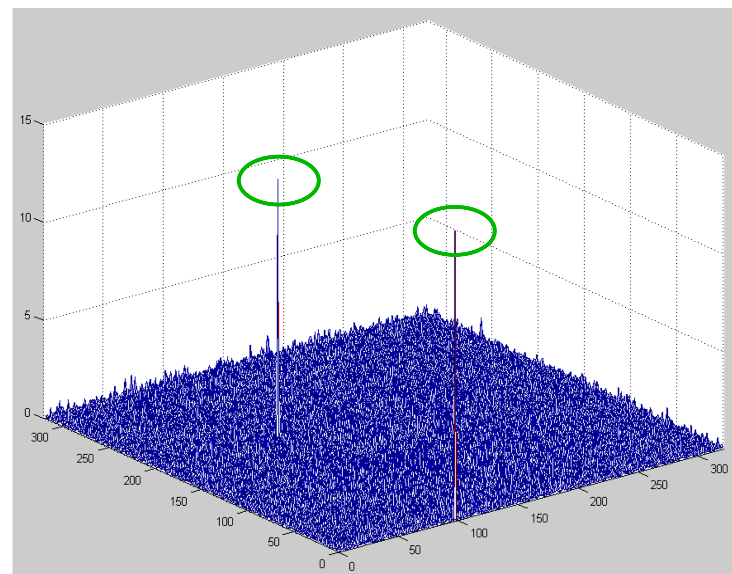
- Noisy input scene simulates practical recording conditions
- Target faces are still distinguishable from others



Reference faces

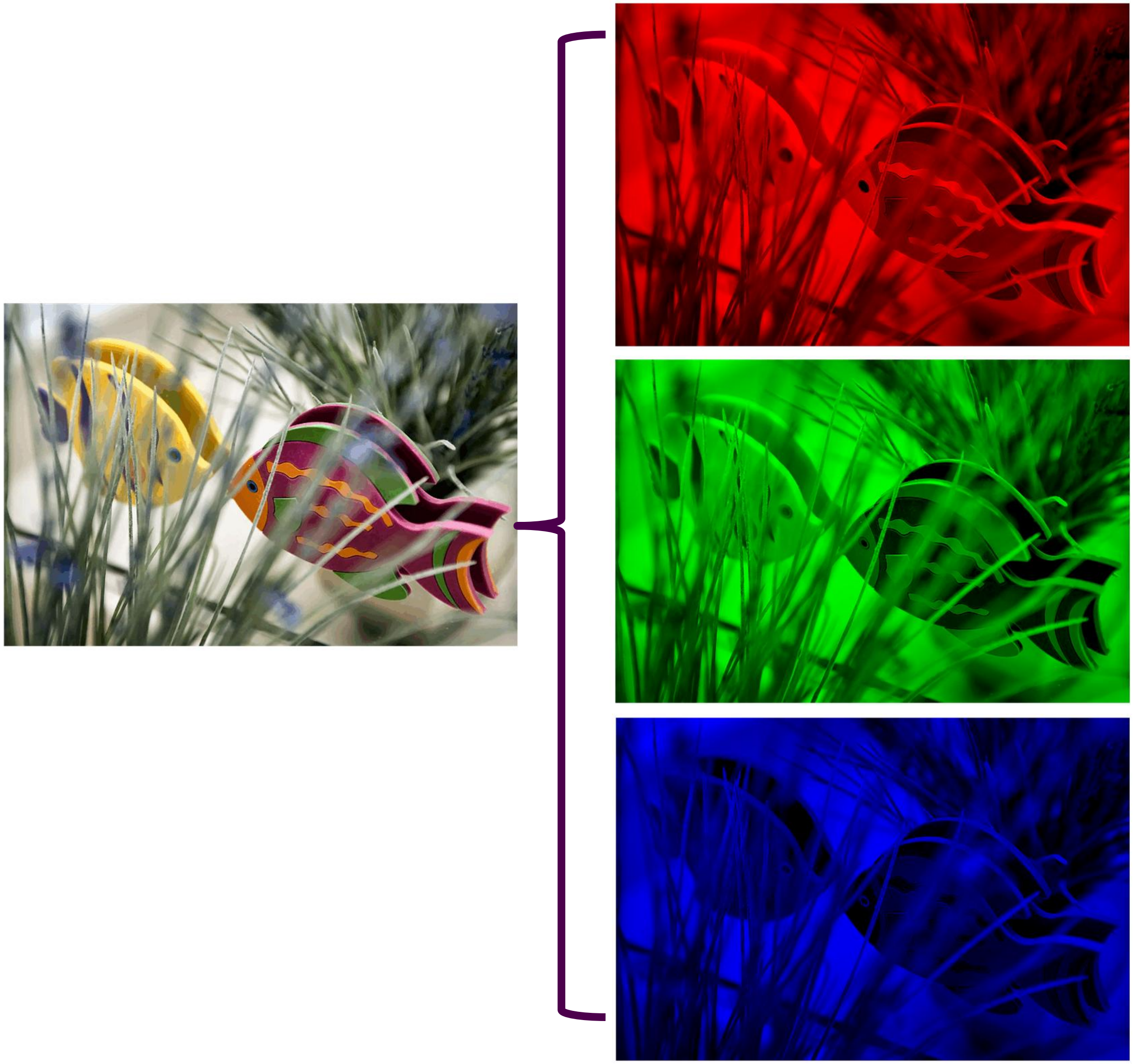


Noisy input image



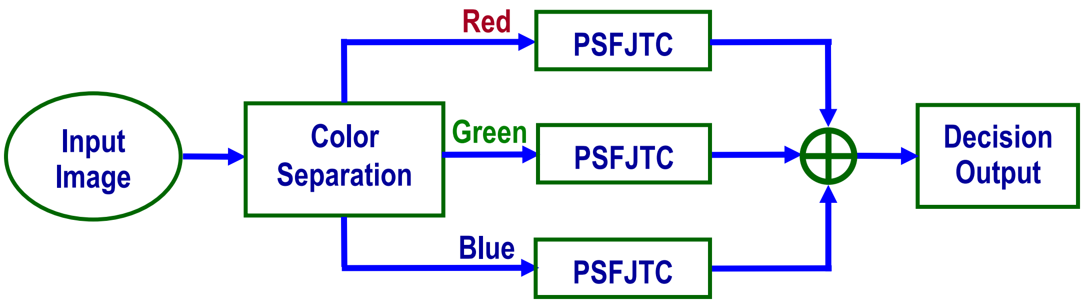
Color pattern recognition

- Pattern recognition performance can be enhanced by including color information in addition to spatial properties of the targets
- Color information basically includes three components, red, green and blue



Color pattern recognition

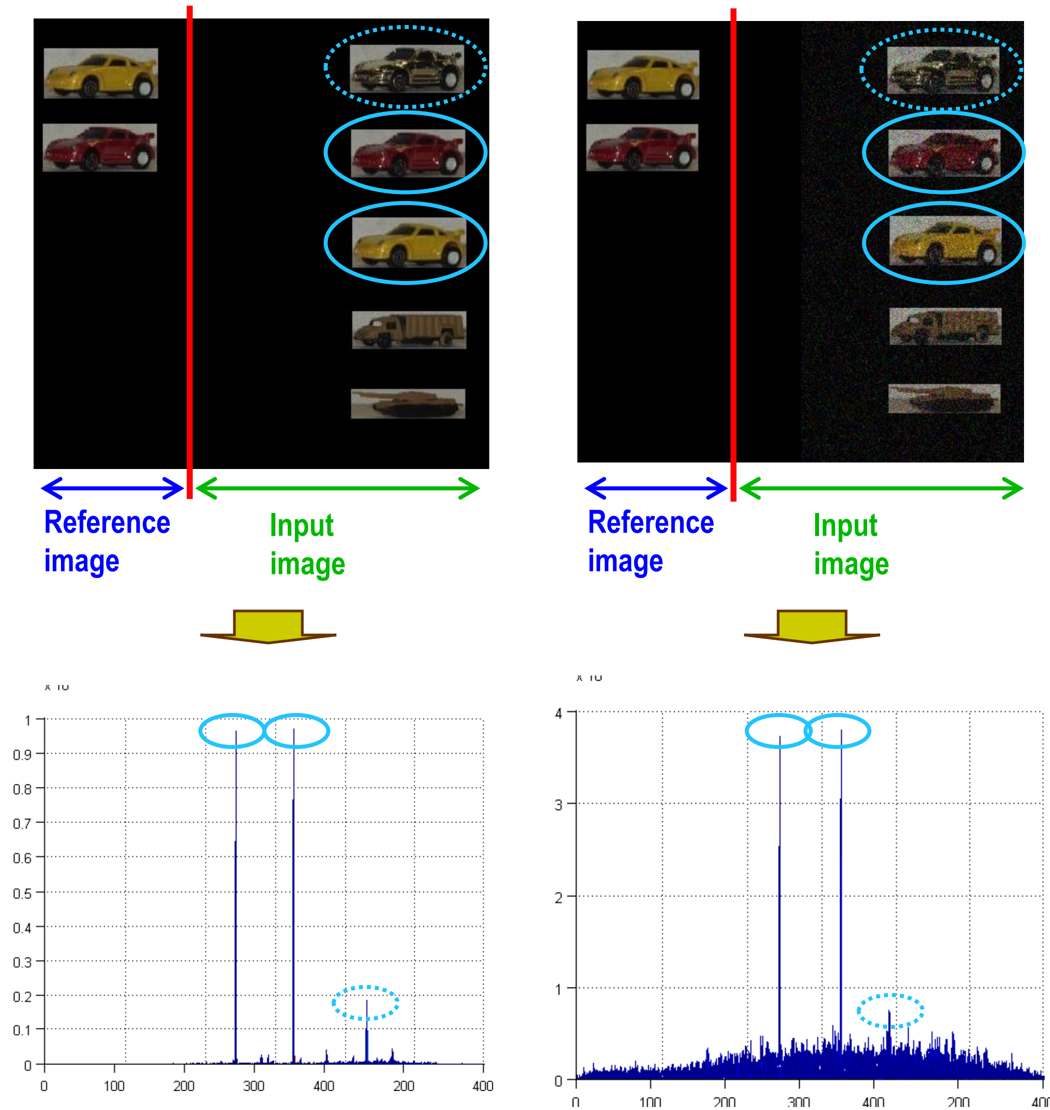
- Color pattern recognition techniques involve separation of the red, green and blue components



- Three individual and parallel correlation processing are carried out on the three color components
- Individual pattern recognition decisions are fused together to obtain the final correlation decision about the presence of any target

Color pattern recognition

- Target detection performance is sensitive to shape as well as color
- Top car on right hand side produces very small peak though it has the same spatial shape
- The noisy input simulates real life picture where also the pattern recognition technique works efficiently



Multispectral pattern recognition

- Color processing introduces three components of the same spatial information to enhance the correlation decision
- To further enhance the pattern recognition performance, it can be extended to multiple spectral components
- Multispectral remote sensors have been developed to record the image at different frequency bands
- Multispectral imagery yields spectral information in addition to the spatial information for pattern recognition purpose

Multispectral pattern recognition

- Multispectral pattern recognition may also fail for images having very little spatial information, especially when recorded from a long distance using satellite or unmanned air vehicle
- It is necessary to derive a continuous spectral characteristics about the targets for such applications

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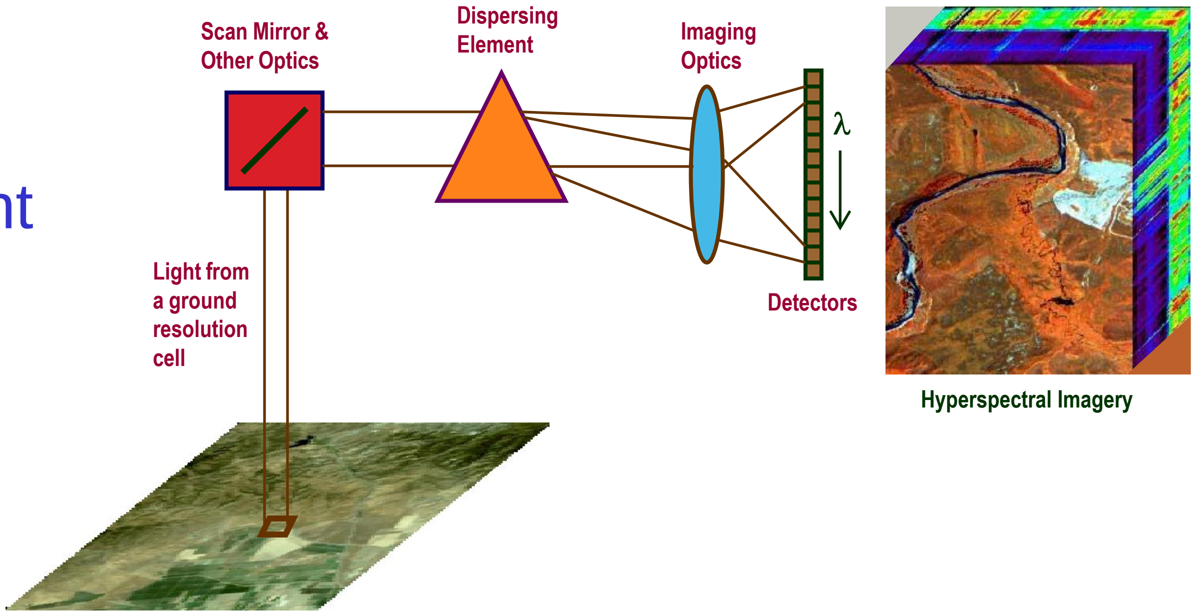
Hyperspectral Image Processing

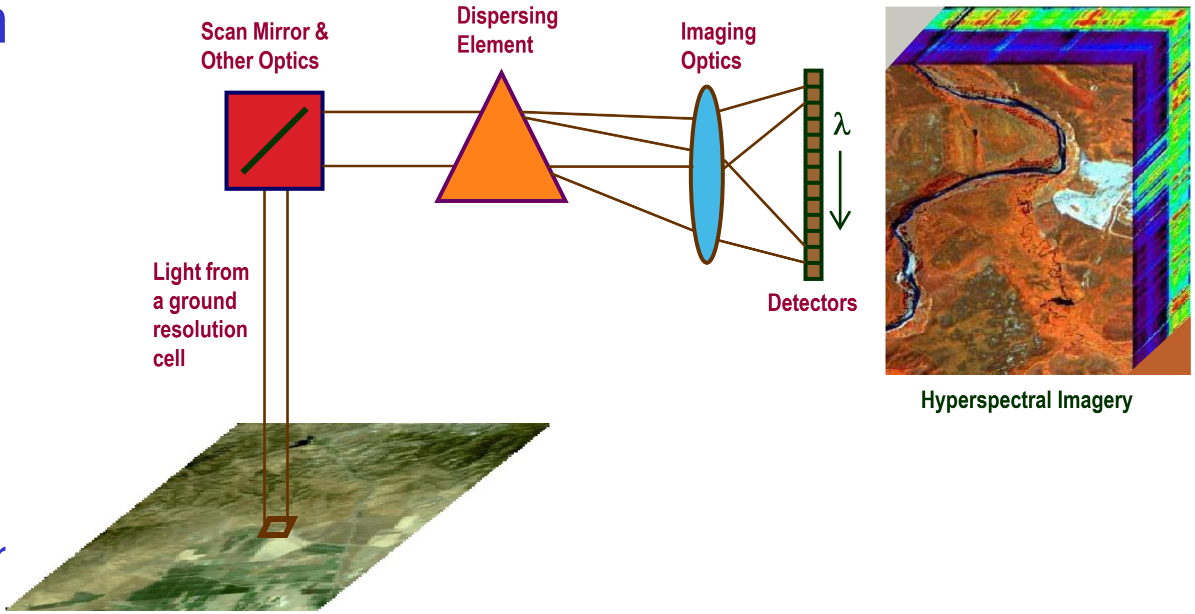
Hyperspectral sensors

- Hyperspectral sensors record the spectrum of sunlight that is diffusively reflected by test materials
- An optical dispersing element splits the reflected light into many narrow, adjacent wavelength bands

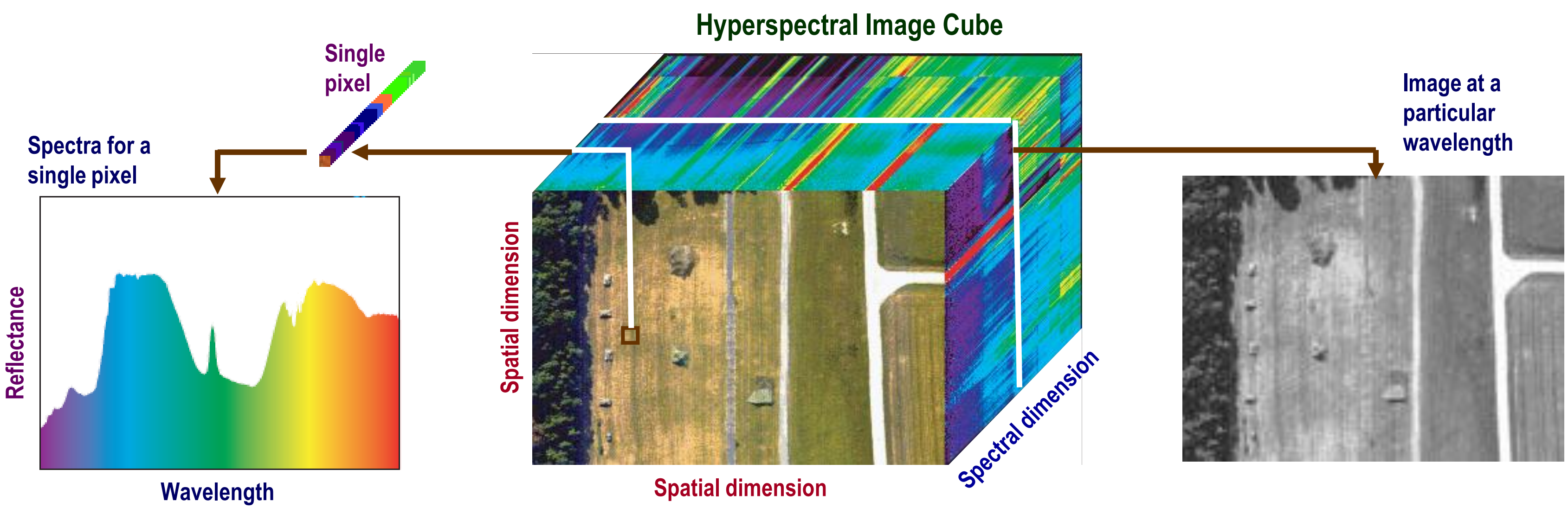


Hyperspectral sensors

- The energy in each band is measured by a separate detector
- Therefore, hyperspectral imagery contains images derived from the reflected light from a test area in hundreds or even thousands of narrow and adjacent spectral bands

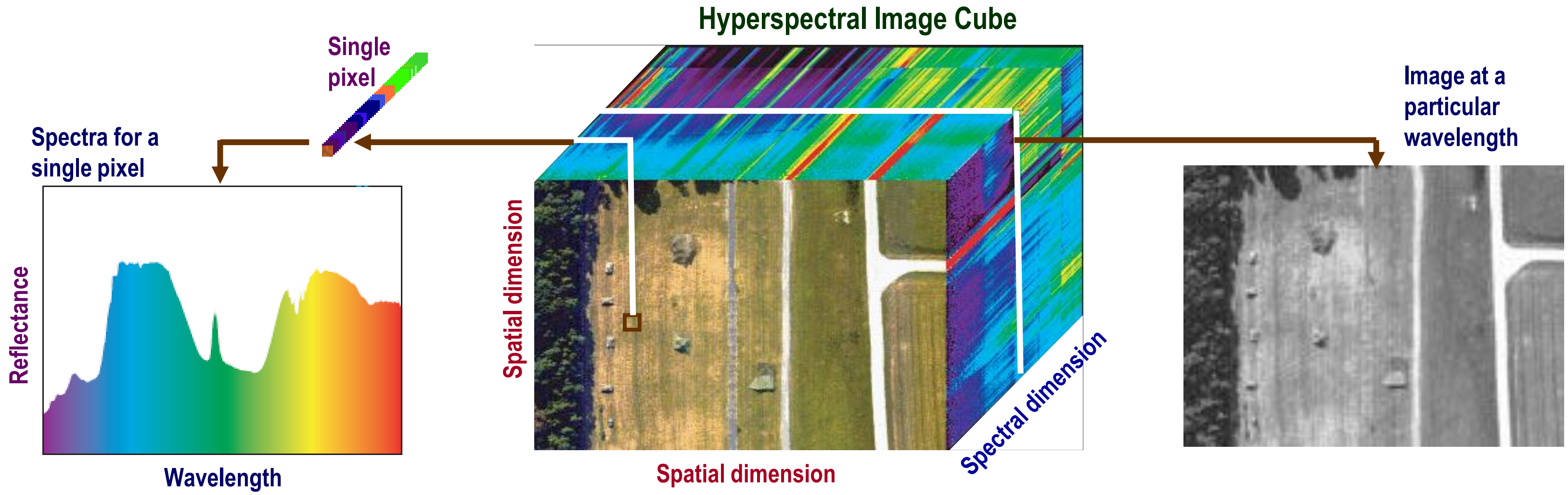


Hyperspectral image cube



- Hyperspectral imaging produces a three-dimensional data structure, referred to as image/data cube

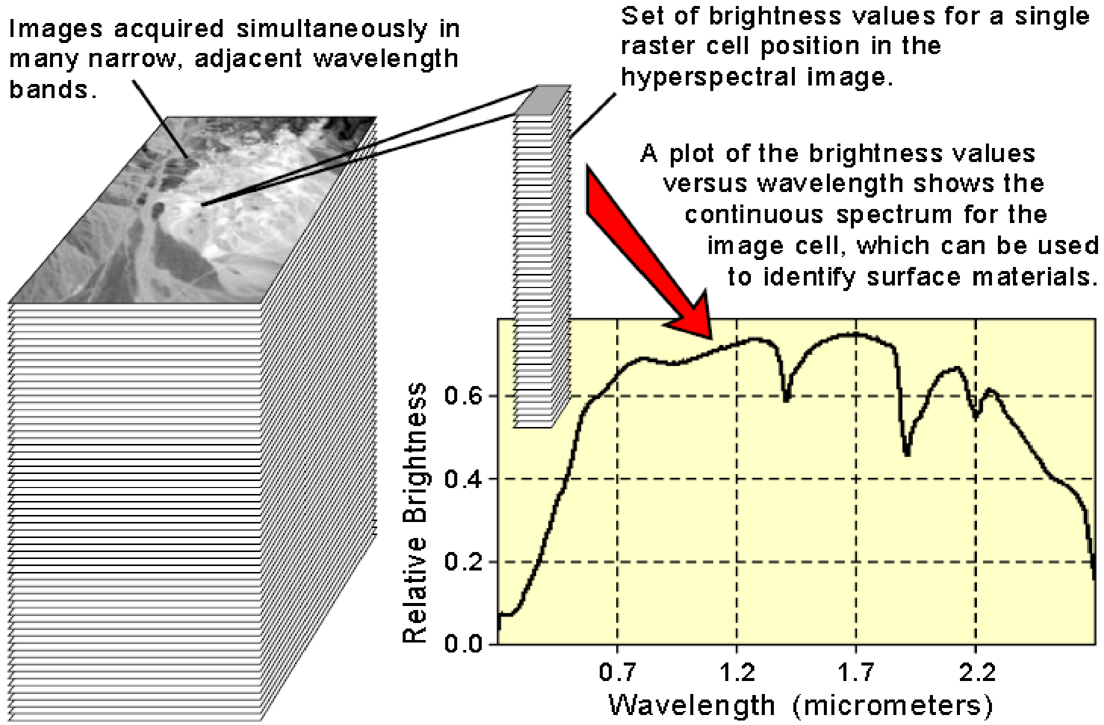
Hyperspectral image cube



- Image size= $x \;\; y \;\; z$
  - x, y : spatial dimensions (corresponding to aperture size of sensor/camera)
  - z : spectral dimension (corresponding to bandwidth of the sensor/camera)
- Typical wavelength range: **0.4 – 2.5 μm** (visible through middle infrared)
- Typical wavelength spacing: **0.01 μm**

Hyperspectral imagery

- Hyperspectral imaging:
  - continuous spectrum for each image pixel
  - high resolution in both the spatial and spectral domain
  - Each pixel is represented by its reflectance characteristics over different wavelength bands, called the spectral signature

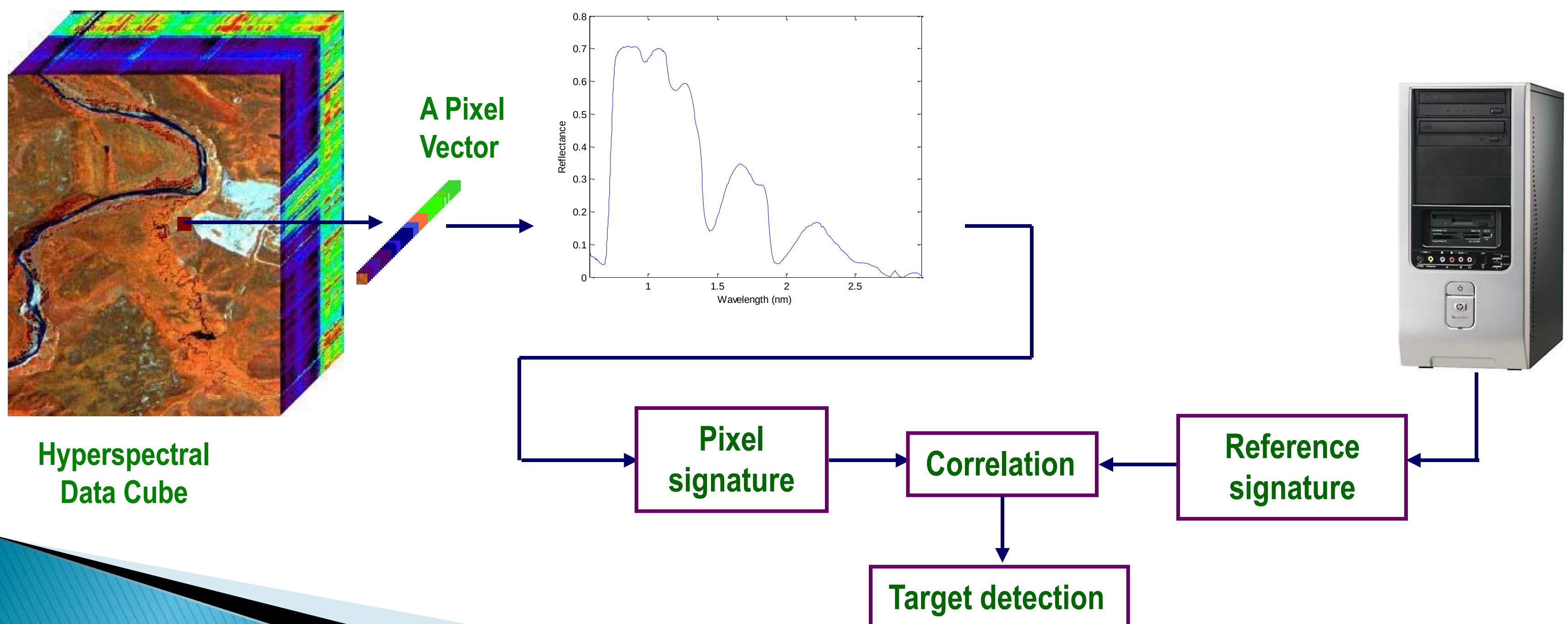


Ref: "Introduction to Hyperspectral Imaging", TNTmips®

  - The spectral signature can also be viewed as a vector in the *n*-dimensional space, where *n* is the number of spectral bands

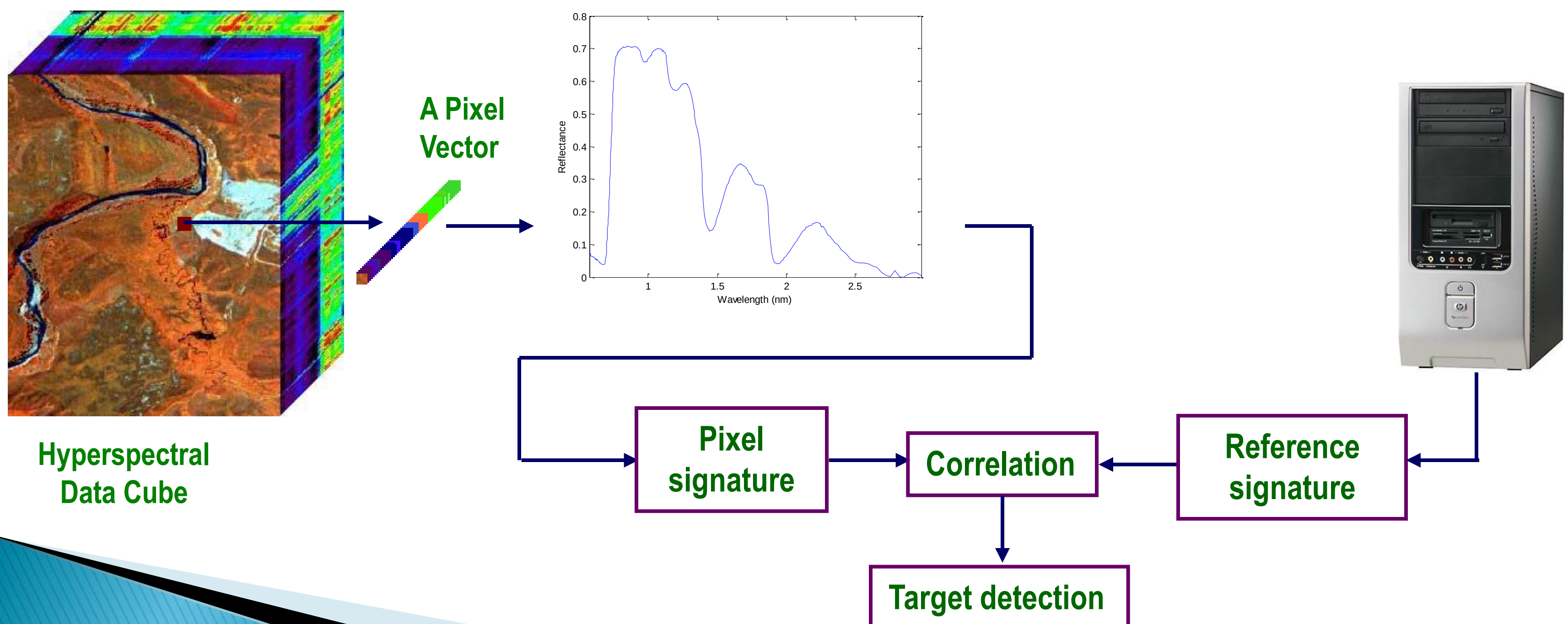
Hyperspectral image processing

- A pixel vector is formed from the spectral information of each pixel
- Each pixel vector is correlated with the field or laboratory reflectance spectra of the material of interest



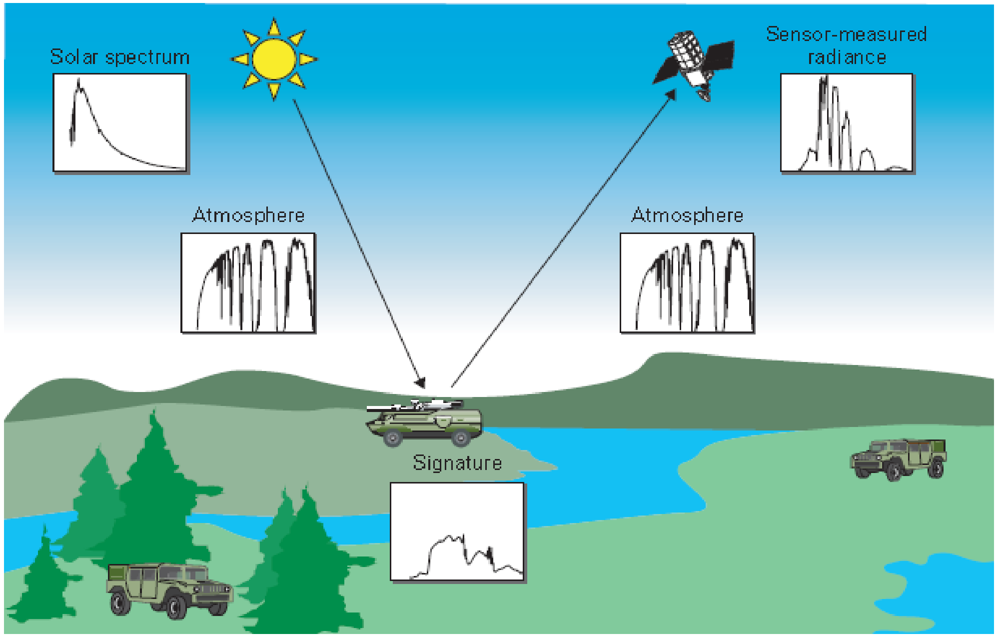
Hyperspectral image processing

- The whole image is scanned and the correlation output gives the detection results

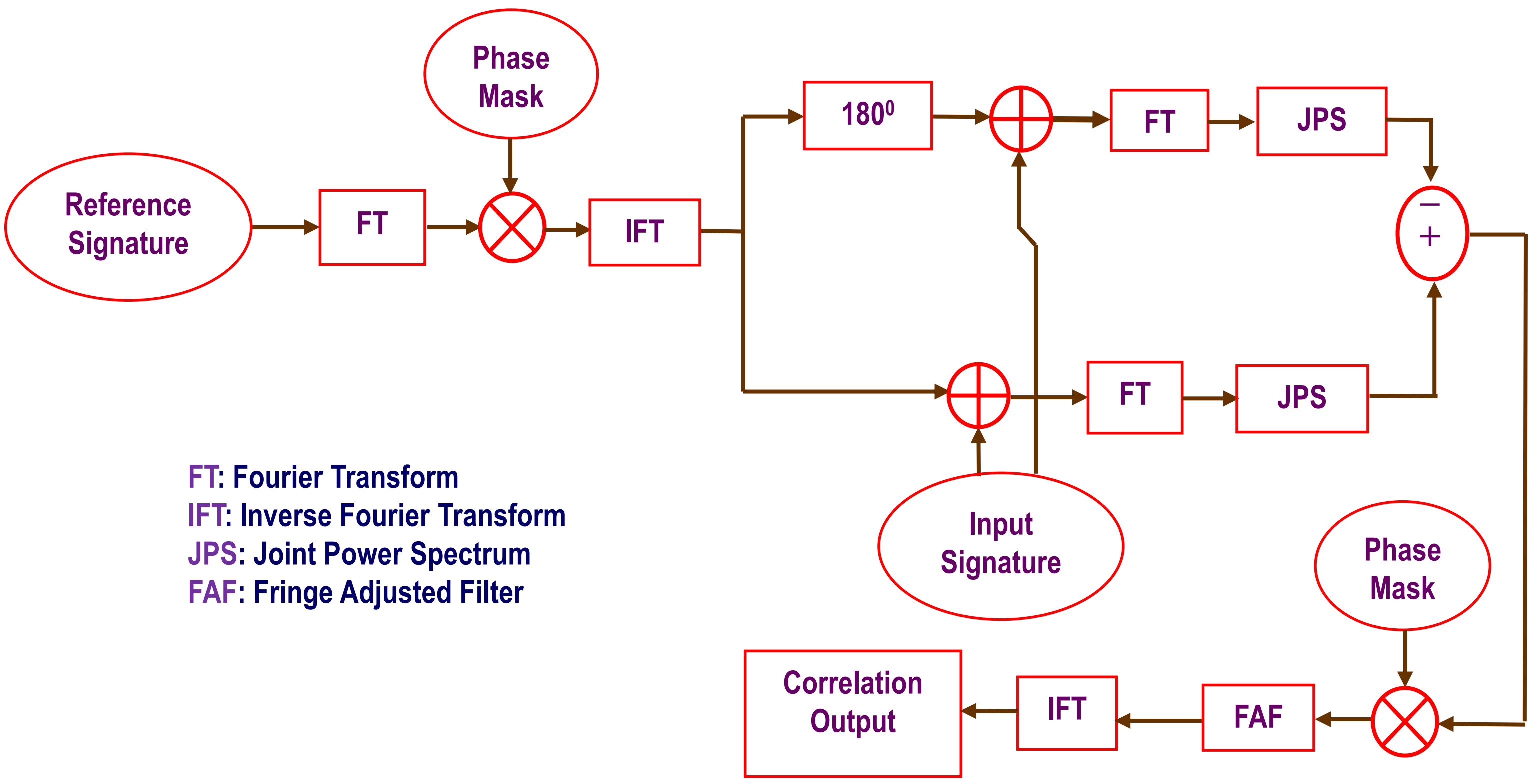


Hyperspectral image processing

- Challenges:
  - Very few pixels of target
  - Huge data size
  - Uniqueness of signature
  - Mixed pixel
- Spectral signature of the same material varies due to
  - variation of material surface
  - variation of atmospheric conditions
  - addition of noise



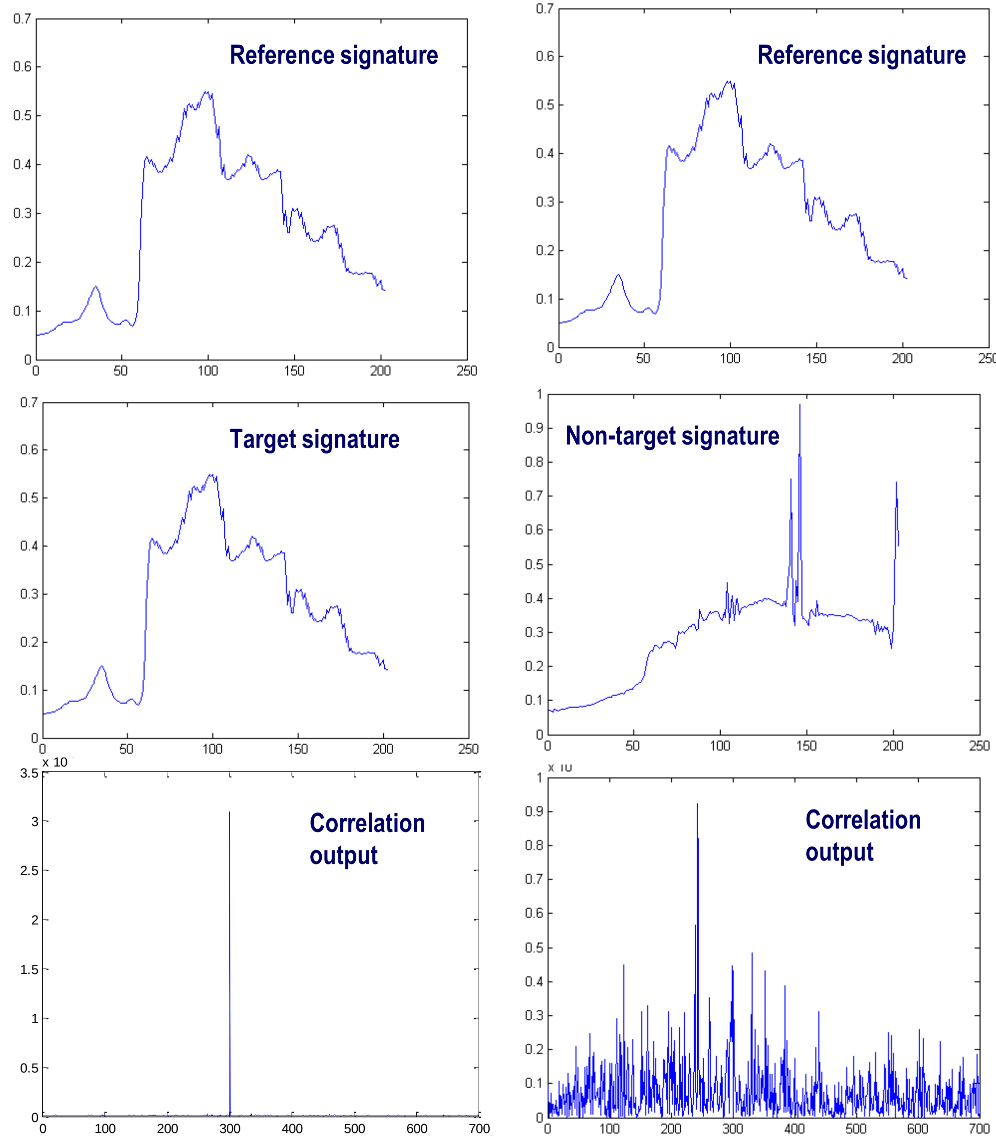
1-D PSFJTC technique



FT: Fourier Transform
IFT: Inverse Fourier Transform
JPS: Joint Power Spectrum
FAF: Fringe Adjusted Filter

1-D PSFJTC technique

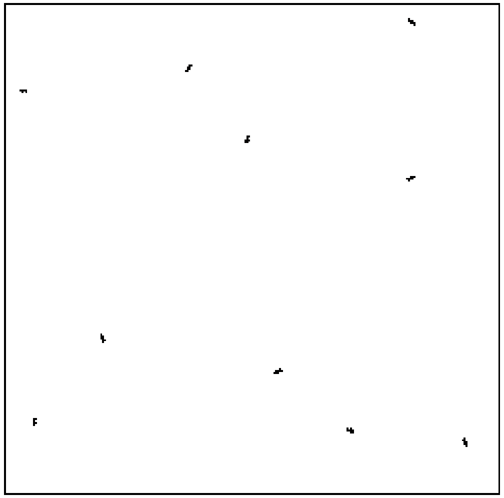
- Target signature produces sharp and single peak
- Non-target signature produces noisy signals
- Targets can easily be distinguished from non-targets and background



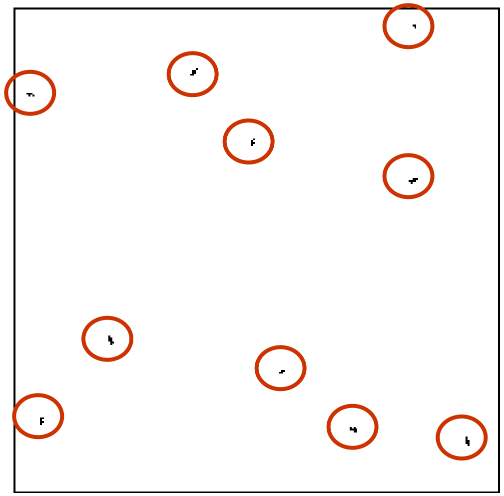
1-D PSFJTC technique

- Input scene of the first hyperspectral dataset is shown
- Truth mask: shows the location and number of pixels of targets in the input image
- Ten targets were placed at different locations
- All the targets are detected successfully
- No false alarm
- Discrimination between the target and the background is excellent

Input scene



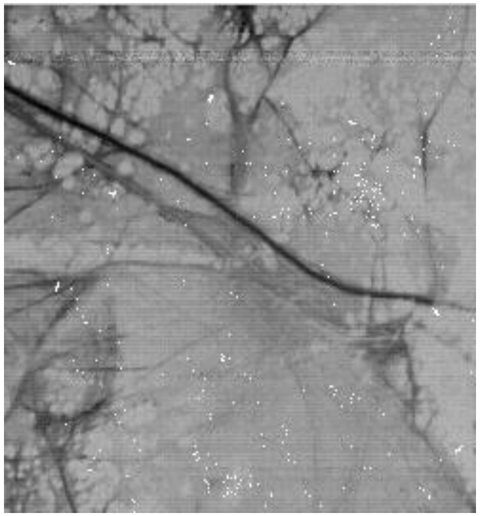
Truthmask



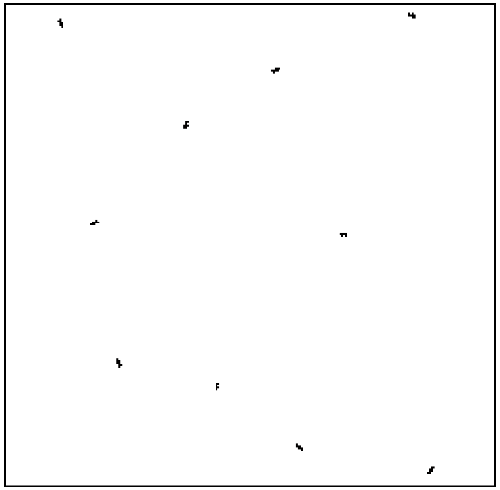
Detection result

1-D PSFJTC technique

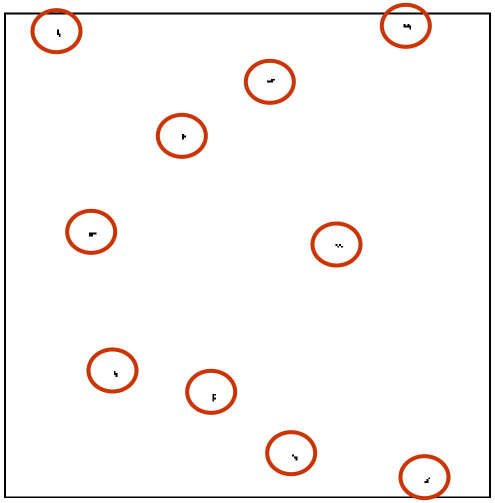
- Input scene of the second hyperspectral dataset is shown
- Ten targets were placed at different locations
- All the targets are detected successfully
- No false alarm
- Discrimination between the target and the background is excellent



Input scene



Truthmask



Detection result

1-D PSFJTC technique

- In applications to agriculture and other fields, there is no specific target, rather it is to detect specific material substance
- Example: detection of green area

conclusions

- Optical pattern recognition is based on joint transform correlation
- Phase-encoded and phase-shifted fringe-adjusted joint transform correlation offers the following excellent features:
  - parallel processing of reference and input scene images
  - single delta-like correlation peak for each potential target
  - almost zero correlation for any non-target objects
  - high discrimination between targets and non-targets
  - simultaneous detection of multiple targets of multiple reference classes
  - fast operation suitable for real-time applications
  - efficient use of space-bandwidth resources
  - position of target can also be determined
  - multiple targets of multiple reference classes can be recognized simultaneously

conclusions

- Hyperspectral imagery provides with additional dimension for pattern recognition
- PSFJTC technique is equally successful for hyperspectral pattern recognition purposes

Selected Journal Publications

- “Optical cryptographic system employing multiple reference-based joint transform correlation technique,” Optical Engineering, 2011.
- “Distortion-invariant pattern recognition using synthetic discriminant function based multiple phase-shifted reference fringe-adjusted joint transform correlation,” Optics Communications, 2011.
- “Automatic fingerprint recognition employing optical phase-modulated joint transform correlation,” Applied Security Research, 2010.
- “Distortion-invariant boat detection using synthetic discriminant function based shifted phase-encoded joint transform correlator,” Optical Engineering, 2008.
- “Target detection using adaptive progressive thresholding based shifted phase-encoded fringe-adjusted joint transform correlator,” International Journal of Electrical, Computer and Systems Engineering, 2008.
- “Hyperspectral target detection using Gaussian filter and post-processing scheme,” Optics and Lasers in Engineering, 2008.
- “Pattern recognition in hyperspectral imagery using one-dimensional shifted phase encoded joint transform correlation,” Optics Communications, 2008.
- “Optical security system using shifted phase-encoded joint transform correlation,” Optics Communications, 2008.
- “Invariant Bangla character recognition using a projection-slice synthetic-discriminant-function-based algorithm,” Istanbul University Journal of Electrical and Electronics Engineering, 2006.
- “Class-associative color pattern recognition using shifted phase-encoded joint transform correlation,” Optical Engineering, 2006.
- “Enhanced class associative generalized fringe-adjusted joint transform correlation for multiple target detection,” Optical Engineering, 2006.
- “Shifted phase-encoded fringe-adjusted joint transform correlation for multiple target detection,” Optics Communications, 2005.
- “Distortion-invariant multiple target detection using class-associative joint transform correlation,” Optical Engineering, 2005.
- “Design of a gain-adjustable filter based joint transform correlator,” Journal of Information and Communication Technology, 2004.

Thanks

For your attention

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