Target Detection Using Optical Joint Transform Correlation

Mohammed Nazrul Islam
Senior Member, IEEE
State University of New York
Farmingdale, New York 11735
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

Input scene
Reference image
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)
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**
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
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
Input and reference images are placed side-by-side and illuminated using an SLM.

Joint image: input image and reference image

\[ f(x, y) = r(x, y + y_0) + t(x, y - y_0) \]

\( t(x, y) \): reference image, \( t(x, y) \): input image
Optical joint transform correlation

- Lens performs Fourier transformation of the joint image

Fourier transform:

\[
F(u,v) = |R(u,v)| \exp \left( j \phi_r(u,v) \right) \exp \left( j y_0 v \right) + |T(u,v)| \exp \left( j \phi_t(u,v) \right) \exp \left( j y_0 v \right)
\]

\(|R(u,v)|, |T(u,v)|\): magnitudes; \(\phi(u,v), \phi(u,v)\): phases

Reference Image

Fourier Transform

Joint Power Spectrum

Inverse Fourier Transform

Correlation Output

Input Image

Target Detection/M.N.Islam  December 7, 2011
Joint power spectra is recorded by a CCD camera.

Joint power spectrum (JPS): magnitude of Fourier transform

$$J(\xi, \nu) = |F(\xi, \nu)|^2 = F(\xi, \nu) \overline{F^*(\xi, \nu)} = |R(\xi, \nu)|^2 + |T(\xi, \nu)|^2$$

$$+ |R(\xi, \nu) \overline{T(\xi, \nu)} \exp \{-j \phi_r(\xi, \nu) - j \phi_t(\xi, \nu) \exp \{-2 j \gamma_0 \nu \}}$$

$$+ |R(\xi, \nu) \overline{T(\xi, \nu)} \exp \{j \phi_r(\xi, \nu) + j \phi_t(\xi, \nu) \exp \{j \gamma_0 \nu \}}$$
Lens performs inverse Fourier transformation

Inverse Fourier transform of JPS: correlation signal

\[ j(x, y) = r(x, y) \oplus r(x, y + t) \oplus r(x, y - t) \]

\[ + r(x, y + 2y_0) \oplus r(x, y + 2y_0 - t) \oplus r(x, y + 2y_0 + t) \]

\[ + r(x, y - 2y_0) \oplus r(x, y - 2y_0 + t) \oplus r(x, y - 2y_0 - t) \]

\(\oplus\): correlation
Lens performs inverse Fourier transformation

Inverse Fourier transform of JPS: correlation signal

\[ j(x, y) = r(x, y) + r(x, y + t) + r(x, y - t) + r(x + 2y_0, y) + r(x + 2y_0, y + t) + r(x + 2y_0, y - t) + r(x - 2y_0, y) + r(x - 2y_0, y + t) + r(x - 2y_0, y - t) \]

Correlation output:
(a) zero-order correlation
(b) cross-correlation

Target Detection/M.N.Islam  December 7, 2011
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 and 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

Target Detection/M.N.Islam December 7, 2011
Optical JTC modifications

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

\[
J_s(u, v) = |F(u, v)|^2 - |R(u, v)|^2 - |T(u, v)|^2
= |R(u, v)|^2 T(u, v) \exp(i \phi(u, v) - j \phi_t(u, v)) \exp(-2 j y_0 v) + |R(u, v)|^2 T(u, v) \exp(-j \phi(u, v) + j \phi_t(u, v)) \exp(j y_0 v)
\]
Problems
- Slow operation
- Duplicate correlation
- Wide side lobes
Input scene is phase-encoded:

\[ t(x, y) = t(x, y) \odot \phi(x, y) \]

Correlation output:

\[ e(x, y) = r(x, y) \odot r(x, y) + t(x, y) \odot t(x, y) \odot \phi(x, y) + r(x, y-y_0-y_i) \odot t(x, y-y_0-y_i) + r(x, y+y_0+y_i) \odot t(x, y+y_0+y_i) \odot \phi(x, y) \]

Target Detection/M.N.Islam  December 7, 2011
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
Reference image is phase-encoded using a random phase mask.

\[ s(\xi, y) = r(\xi, y) \otimes \phi(\xi, y) \]

\( \phi(x, y) \): 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

$$f_1(x, y) = s(x, y) + t(x, y) + r(x, y \phi(x, y) + t(x, y))$$
$$f_2(x, y) = -s(x, y) + t(x, y) - r(x, y \phi(x, y) + t(x, y))$$
Phase-encoded & shifted fringe-adjusted jtc

JPS signals:

\[
J_1(u, v) = |R(u, v)|^2 + |T(u, v)|^2 + R(u, v) \overline{T^*(u, v)} + \overline{R^*(u, v) T(u, v)}
\]

\[
J_2(u, v) = |R(u, v)|^2 + |T(u, v)|^2 - R(u, v) \overline{T^*(u, v)} - \overline{R^*(u, v) T(u, v)}
\]
Phase-encoded & shifted fringe-adjusted jtc

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

\[ P(u, v) = \sum_{l} J_1(u, v) \Phi(u, v) \]
\[ = R(u, v) T^* (u, v) \Phi^2 (u, v) \]

Desired cross-correlation term
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
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
Psftc Performance

- **Gray image:**
  - Intensity varying gradually from black to white

- **Gray target detection:**
  - Successful recognition of all targets
  - Rejection of any non-target objects
Psfstc 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
Class-associative target detection in noisy environment:

- Noisy environment
  - Illumination variation
  - Foggy weather
- Efficient and successful target detection
PsfTc 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:**
  \[ \text{SDF} = \sum_i a_i r_i(x,y) \]
  - \( r_i(x,y) \): training images, \( a_i \): coefficients

- **Correlation between SDF and each training image:**
  \[ \text{corl}_i = \text{SDF} \oplus r_i(x,y) \]

- **Error:**
  \[ \text{err} = \frac{\text{corl}_{\text{max}} - \text{corl}_{\text{min}}}{\text{corl}_{\text{max}}} \]

- **Updated coefficients:**
  \[ a_i = a_i + \delta (\text{corl}_{\text{max}} - \text{corl}_i) \]
  - \( \delta \): 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
Multiple target faces with pose and mood variations can efficiently be recognized.
Face Recognition in Noisy Environment

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

Reference faces
Noisy input image
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 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.
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.
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 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.

Hyperspectral Image Processing
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.
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 imaging produces a three-dimensional data structure, referred to as image/data 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** : \(0.4 - 2.5 \ \mu m\) (visible through middle infrared)
- **Typical wavelength spacing** : \(0.01 \ \mu m\)
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
- The spectral signature can also be viewed as a vector in the $n$-dimensional space, where $n$ is the number of spectral bands

Ref: “Introduction to Hyperspectral Imaging”, TNTmips®
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
The whole image is scanned and the correlation output gives the detection results.
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

Reference Signature → FT → IFT → 180° → FT → JPS  
Phase Mask  
Input Signature → FT → JPS  
Correlation Output → IFT → FAF

Target Detection/M.N.Islam  
December 7, 2011
1-D PSFJT C 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 PSFJT 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
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
1-D PSFSTC 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.
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**

- “Pattern recognition in hyperspectral imagery using one-dimensional shifted phase encoded joint transform correlation,” *Optics Communications*, 2008.
Thanks
For your attention

Contact:
islamn@farmingdale.edu