Hyperspectral Sensor Testbed For Real-Time Algorithm Evaluation

James Jafolla and Mark Dombrowski
Surface Optics Corporation
San Diego, CA 92127

ABSTRACT

Hyperspectral imaging has proved to be a valuable tool for performing material based discrimination of targets in highly cluttered backgrounds. A next step for utilizing this technology is to integrate spectral and spatial discrimination algorithms for Autonomous Target Recognition (ATR) applications. This paper describes a hardware and software testbed system for performing spectral/spatial ATR and presents initial results from a field test in the Anza-Borrego desert.

INTRODUCTION

Recent developments in spectral processing techniques have demonstrated hyperspectral imaging to be a valuable tool for performing material based discrimination of targets in highly cluttered backgrounds. A new challenge is to combine hyperspectral and spatial algorithms in a real-time processor to perform Autonomous Target Recognition (ATR) processing. Our ATR technique is based on sequential spectral-spatial correlation filtering. Traditional pattern recognition algorithms rely on edge enhancement filters or iterative statistical techniques, which suffer from poor reliability, particularly for low contrast/low light level scenes or under adverse weather conditions. The spectral/spatial technique makes use of spectral optical features of materials to produce spectrally correlated images that dramatically reduces the clutter leakage to the spatial correlator. The spatial correlator uses a traditional 2D template-matching algorithm, with templates generated on the fly to account for range/aspect variability.

Figure 1 shows the fundamental spectral/spatial correlation approach. The algorithm first performs a pixel-by-pixel spectral correlation against a known spectral template; the resulting correlation image map is then processed using a two-dimensional spatial correlation filter generated from the spatial template.

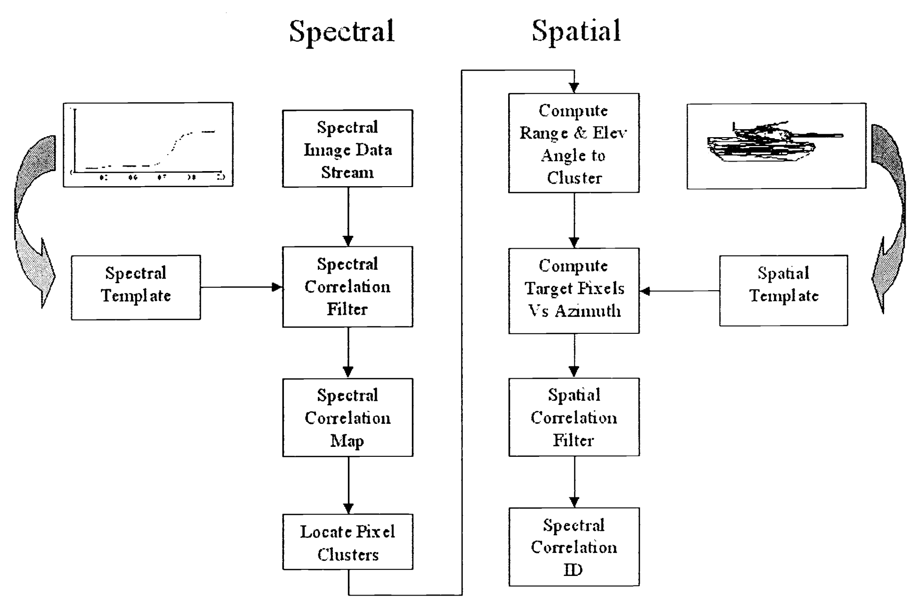

Figure 1. Spectral/Spatial Correlation Algorithm Approach.

The algorithm requires two distinct types of data input – a target spectral template and spatial template, and correlation threshold levels to define detection for both segments of the processing.

Imaging Spectrometry VII, Michael R. Descour, Sylvia S. Shen, Editors,
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The spectral template is based on a spectral reflectance measurement of the coatings on the target surface. *A-priori* correlation against measured paint reflectance also requires that spectral atmospheric absorption and illumination conditions be computed and removed prior to processing. Alternatively, algorithms based on anomaly detection using spectral radiances measured in-flight can be applied, but that is outside the scope of this discussion.

The result of the spectral processing stage is a binary (1/0) correlation image map. Highlighted pixels are those that exceed the correlation threshold value for a given spectral filter. Dark pixels represent materials that do not correlate with the desired material spectral filter. Clusters of correlated pixels are passed to the 2-D spatial correlation algorithm to assess the size and shape of the cluster.

The spatial template is a wireframe description of the target geometry. This is simply a file that defines the vertices and facets (panels) that define the target shape. This template is also downloaded to the processor and used to generate shape-matching template chips on the fly for a variety of elevation and azimuth angle combinations. The result of the spatial processing stage is a location list of spectral/spatial correlation clusters, thresholded in both the spectral and spatial domain, and rank ordered in decreasing probability.

SPECTRAL/SPATIAL ALGORITHMS

The power of a hyperspectral system is manifested in spectral correlation. This process highlights target pixels with respect to the background clutter. Spectral correlation achieved by filtering each pixel's spectrum against sought-after spectra, known *a-priori* or identified directly from measured spectral imagery. Several different filtering algorithms with varying degrees of sensitivity can be implemented. The algorithms implemented in the hardware/software testbed system are described below.

Spectral Angle Algorithm

The spectral angle, or dot product, algorithm is a very simple filtering algorithm that treats each spectral radiance as an N-dimensional vector and simply computes the angle between the two vectors by dividing the dot product of the two vectors by each vector's magnitude. Formally, this algorithm is given by

$$C_{DOT} = \frac{\sum L(\lambda_n) \cdot F(\lambda_n)}{\sqrt{\sum L(\lambda_n)^2 \cdot \sum F(\lambda_n)^2}}$$

where $L(\lambda_n)$ is the measured spectral radiance at the n^{th} wavelength, and $F(\lambda_n)$ is the filter spectral radiance at the n^{th} wavelength.

Root Sum Squared Differential Area Algorithms

Another completely different type of matching algorithm can be formed by normalizing both the measured and filter radiances such that each encloses unity area, and subtracting the area "trapped" between the two curves from 1.0, as shown in Figure 2.

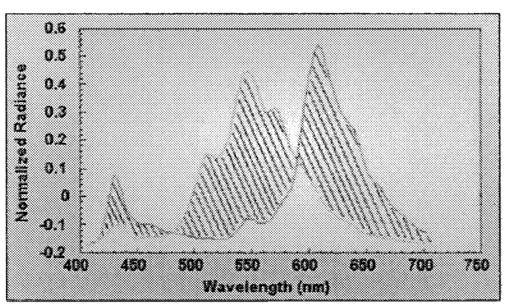

Figure 2. The zero-mean, RSS differential area algorithm.

For two identical spectral radiances, zero area will be "trapped", and the correlation value will be 1. As more and more area lies between the two curves, the correlation value will become smaller and smaller. This algorithm, the RSS differential area correlator, is given formally by

$$C_{RSSDA} = 1 - \sqrt{\sum\left[\frac{L(\lambda_n)}{\sqrt{\sum L(\lambda_n)^2}} - \frac{F(\lambda_n)}{\sqrt{\sum F(\lambda_n)^2}}\right]^2}$$

By subtracting the mean from each spectral radiance value and using the resultant radiance values in the above algorithm yields the zero-mean RSS differential area algorithm, given formally by

$$C_{ZMDA} = 1 - \sqrt{\sum\left[\frac{L(\lambda_n) - \langle L(\lambda_n)\rangle}{\sqrt{\sum\left(L(\lambda_n) - \langle L(\lambda_n)\rangle\right)^2}} - \frac{F(\lambda_n) - \langle F(\lambda_n)\rangle}{\sqrt{\sum\left(F(\lambda_n) - \langle F(\lambda_n)\rangle\right)^2}}\right]^2}$$

where the spectral radiance mean is given by

$$< L(\lambda) > = \frac{1}{N} \cdot \sum_{1}^{N} L(\lambda_n)$$

and similarly for $<F(\lambda)>$.

Spatial Filtering Algorithms

Spatial filtering is the final stage in the target detection process. The spatial algorithms exploit shape information to identify potential targets from pixel clusters in the spectrally filtered image scene. Spectral filtering produces a binary image scene where pixels are set "on" to represent areas whose reflectances match any of a set of known target spectra, and "off" for pixels that represent non-target image areas. Potential targets appear in the spectrally filtered scene as clusters of connected pixels. The goal of spatial filtering is to identify those targets whose shapes most closely match the desired target type as it would appear in the image plane when viewed in any possible ground orientation.

The first stage in the process is target chip generation. Target chips are the templates used to match clusters in the spectrally filtered image to potential targets. They are binary images whose set pixels show the projected area of a 3-D target model onto the image plane, taking into account the range to target and look-down angle to match the scale and elevation of the target as viewed by the sensor. Multiple chips are produced to allow for many possible orientations of the target on the ground. Figure 3 shows a set of target chips generated for a M60A3 model at 12 different ground orientations and a sensor look-down angle of 5.5 degrees.

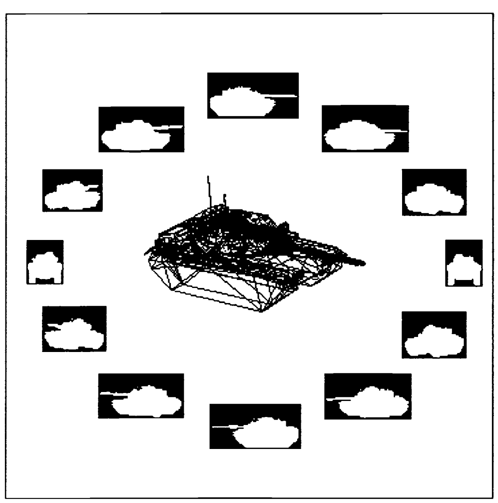

Figure 3 Wire frame model of M60A3 and typical target templates.

Targets are detected by a template matching procedure, in which the target chips are scanned pixel-by-pixel across the spectral output image. At each scan position, a metric, MSE, which is similar to mean square error, but optimized for processing speed, is calculated to measure the similarity between the target chip and the spectral output in the neighborhood of the scan position.

Derivation of the template matching algorithm begins with the definition of the MSE image. Let $g(i,j)$ be the spectral filter output image, $t(i,j)$ be the target chip, and D be the domain of definition of the target chip. The MSE image at scan position (m,n) is

$$E^2(m,n) = \frac{1}{N}\sum\sum[g(i,j) - t(i-m, j-n)]^2$$

where the double sum is over all i,j such that $(i\text{-}m,j\text{-}n)$ is in D, and N is the number of terms in the sum.

Expanding the square term gives

$$E^2(m,n) = \frac{1}{N}\sum\sum\left[g^2(i,j) - 2g(i,j)t(i-m,j-n) + t^2(i-m,j-n)\right].$$

Note that the second term in the sum is constant at all scan positions, since the sum is over the domain of t. Furthermore, we can make the g^2 term constant if we adopt the convention for binary images that reset pixels have the value –1 and set pixels have the value +1. Then minimizing the E^2 metric is equivalent to maximizing the new metric

$$N(g,t) = \frac{1}{N}\sum\sum g(i,j)t(i-m,j-n)$$

Since the (–1)/(+1) convention for binary images is inconvenient to implement in hardware, we rewrite the metric using logic operations as follows:

$$N(g,t) = \frac{1}{N}\sum\sum\left\{\overline{XOR[g(i,j),t(i-m,j-n)]} - XOR[g(i,j),t(i-m,j-n)]\right\},$$

where g and t are now assumed to use the standard (0/1) binary convention. This equation defines the spatial matched filter output image.

SOFTWARE ATR TESTBED

The ATR Test Bed code is a PC software package that provides a set of tools kit for performing spectral and spatial correlation analysis on hyperspectral image cubes. The code is also written in Java will run on any computer or workstation that has the Java Virtual Machine (JVM) 1.3 installed. Figure 4 shows the User Interface (UI) for the ATR Test Bed code, which is arranged as a series of tab selected work panels for defining various aspects of the spectral/spatial analysis problem.

The Image tab panel, shown in Figure 4 provides tools and functions for performing the spectral correlation analysis. This panel displays individual wavelength images in gray scale or integrated RGB images as well as correlation image maps and correlation map overlayed images.

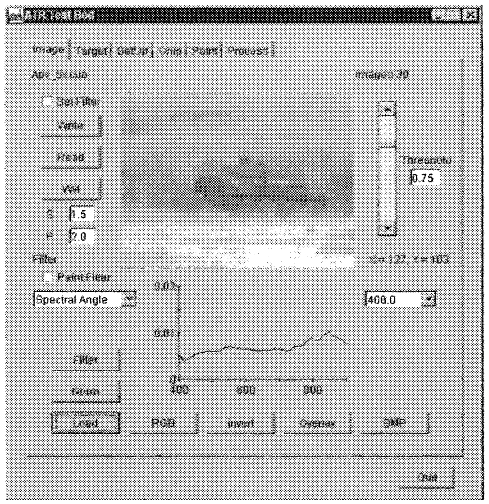

Figure 4. ATR tool kit for spectral/spatial image processing

The Target definition tab panel is shown in Figure 5. This is used for specifying the target wireframe geometry, which is used to generate the target template chips for the spatial correlation analysis. Wireframe models are input in Wavefront (.obj) format. The .obj format is simply an ordered list of x-, y-, z-coordinates of vehicle verticies (or nodes), followed by a list of vertex connectivity to define the facets (or panels) with facet normals specified by the right hand rule. Facets can be defined as triangles or arbitray n-sided polygons. There are no limitations on the number of model facets or verticies used in the model. However, run times for generating target chips at multiple aspect angles can get quite long for very high resolution models. Moderate resolution models, with 2-3 thousand verticies and facets are recommended for the spatial analysis.

The Chip tab panel, shown in Figure 6, generates and displays the binary target chip templates used in the spatial correlation analysis. The SetUp tab panel is used to define the sensor parameters used to calculate the target chip. The target chip resolution is determined by the sensor parameters: altitude, lookdown angle, IFOV.

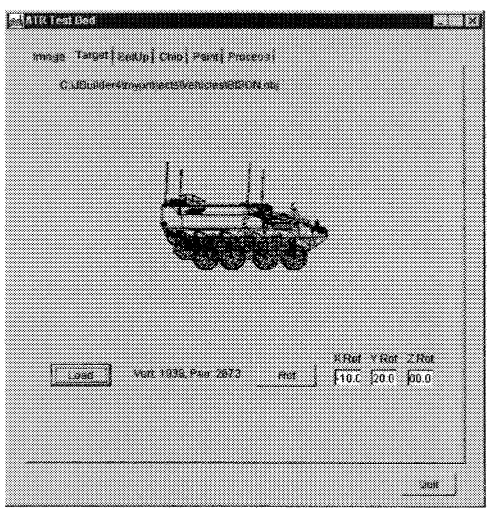

Figure 5. ATR target template window.

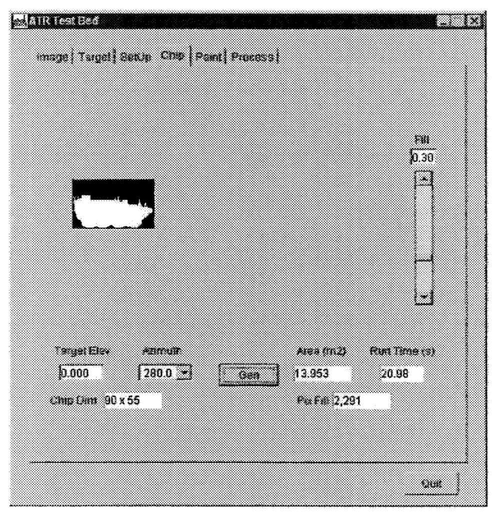

Figure 6. ATR image chip generation.

The Process tab panel, shown in Figure 7, provides the tools and displays the results of the 2-D spatial correlation analysis. The bottom image window displays the spectral correlation pixel clusters identified from the processing performed in the Image tab panel. The red highlighted pixels denote a contiguous cluster group that is considered by the spatial processor. The initial spatial processing eliminates clusters that are not within 20% of the filled target chip pixels that were generated based on the geometry and sensor parameters.

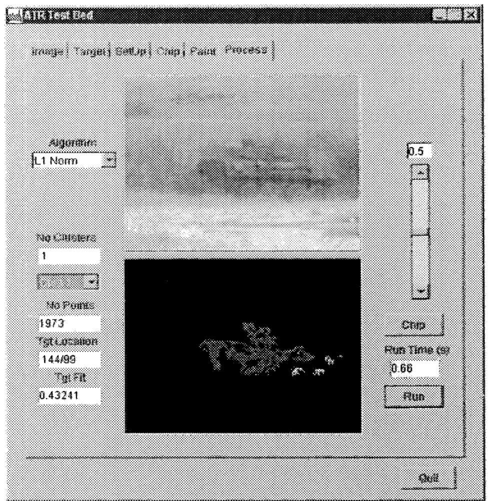

Figure 7. ATR spatial correlation and detection.

The top image window shows the RGB (or gray scale spectral) image overlayed with a red cross-hair denoting the center of the pixel cluster selected as a result of the spatial correlation. Different correlation algorithms are selected using the combo box on the upper left side of the panel, and the statistics of the potential target clusters can be view using the combo box on the middle-left side of the panel. The Chip button generates the series of target template chips for the run, and the Run button starts the spatial correlation analysis. The spatial correlation threshold is set using the slide bar on the right side of the panel.

HARDWARE TESTBED

The hardware testbed system, shown in Figure 8, includes an active and passive imaging head, electronics rack, a laptop control computer and support equipment.

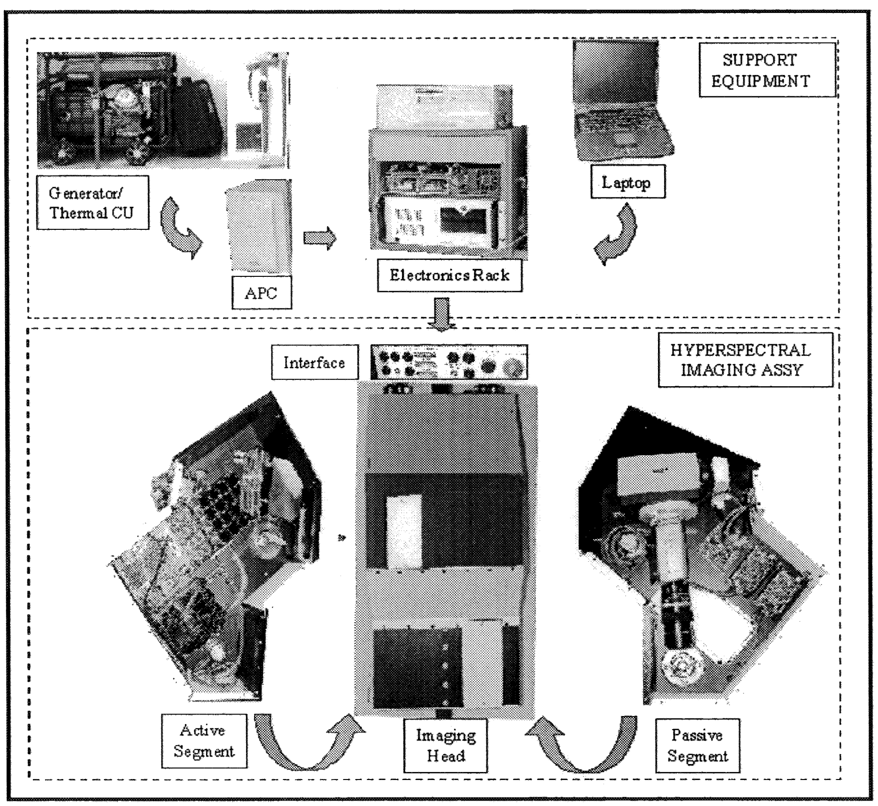

Figure 8. Hyperspectral testbed imaging system.

The passive imager assembly, shown in Figure 9, has a F/2.8 grating based spectrometer using a Thompson-CSF, TH7998, array with 14 micron pixels and custom FPA electronics. Fixed focal length lenses provide both wide (10 degree) and narrow (4 degree) fields of view. A scan mirror is used to provide line scanned images, or can be fixed to operate in a push-broom mode. The hypercube format is nominally 632 pixels wide by 384 lines by 96 bands. The spectral band is 500 to 900 nm, with 4 nm resolution.

The hyperspectral imaging head also includes an active illumination assembly, with 3 diode lasers (780, 830 and 860 nm) that is bore sighted to the passive imager. This provides "flashlight" strip illumination nighttime operation with NIR multispectral capability. The FPA electronics implements range gating by charge shifting on the array to eliminate atmospheric backscatter.

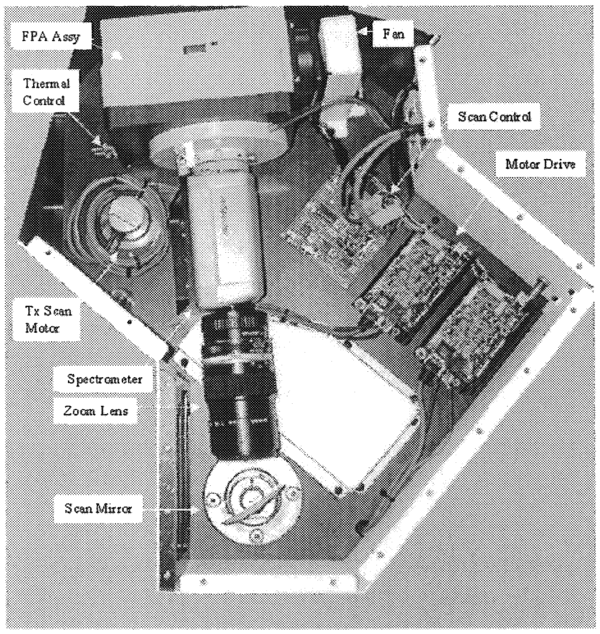

Figure 9. Passive hyperspectral imager assembly.

The heart of the ATR testbed system is the real-time spectral/spatial processing electronics shown in Figure 10. The processing is implemented in a two board set, with a standard PCI interface. One board performs radiometric calibration (spatial uniformity, spectral and radiometric), atmospheric correction and spectral correlation. The spectral processor can simultaneously perform three integrator channels to provide RGB images and six separate spectral correlation filters, which are combined and passed through to the spatial processor.

The second board implements the spatial algorithms. Both boards utilize Field Programmable Gate Array (FPGA) devices so that multiple algorithms can be easily implemented and tested. Instead of using standard DSP devices or general purpose processors, the algorithms are implemented directly in the FPGA, providing a moderately parallel and highly pipelined architecture which provides processing rates up to 160 megapixels per second throughput.

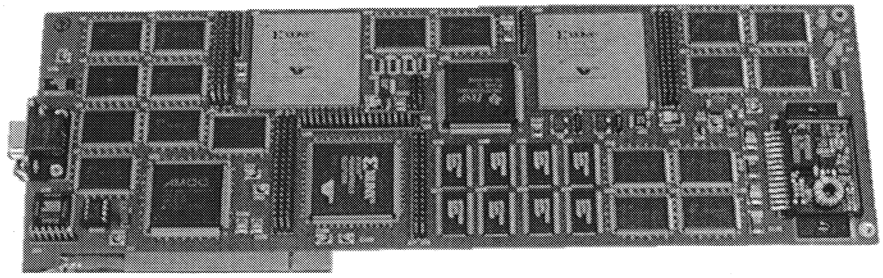

Figure 10. Real-time spectral/spatial processing board.

ANZA-BORREGO FIELD TEST

A series of field tests were performed to test the hardware functionality and provide a data set for algorithm development and validation. In order to simulate a typical airborne ATR scenario, a test site was chosen in the Agua Tibia Mountains overlooking the Anza-Borrego desert. Figure 11 shows a typical view from a mountain overlook to the desert floor.

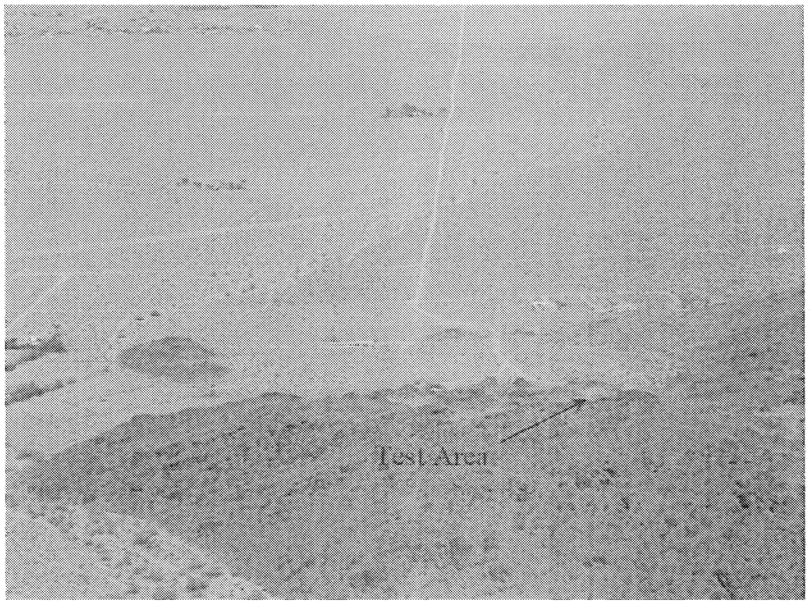

Figure 11. Anza-Borrego test site to simulate airborne ATR

This long desert road provided a number of sensor-target geometries, with ranges from 1.8 to 4 km and an altitude of approximately 300 meters. Figure 12 shows the target configuration, at a range of 1.8 km, at the test site designated in Figure 11. A civilian vehicle is parked next to a humvee, which was covered with a Barracuda Saudi 2D camouflage net. The object of this test was to discriminate the camouflaged target from the nearby non-target.

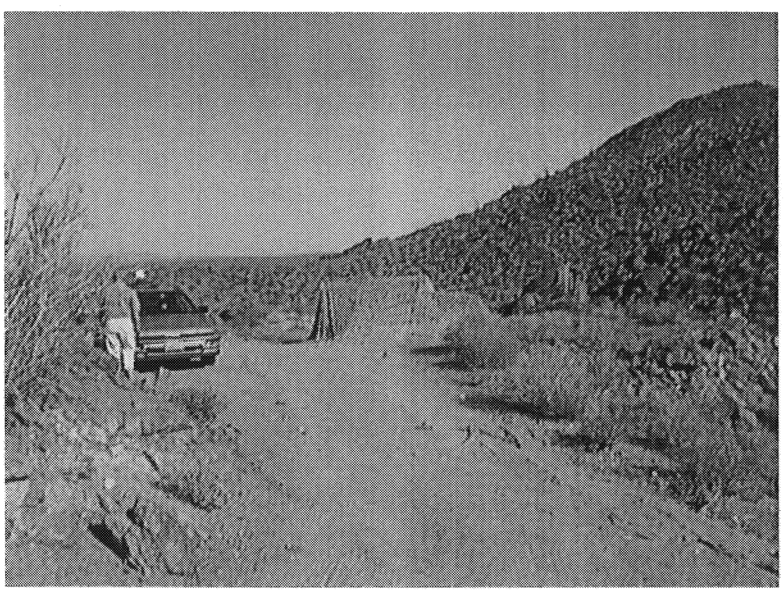

Figure 12. Target configuration at test site

PRELIMINARY RESULTS

A NFOV image of the camouflaged target at 1.8 km range is shown in Figure 13. This image shows one of the gray scale spectral image planes in the NIR, at 700nm. The civilian vehicle is seen parked off to the left.

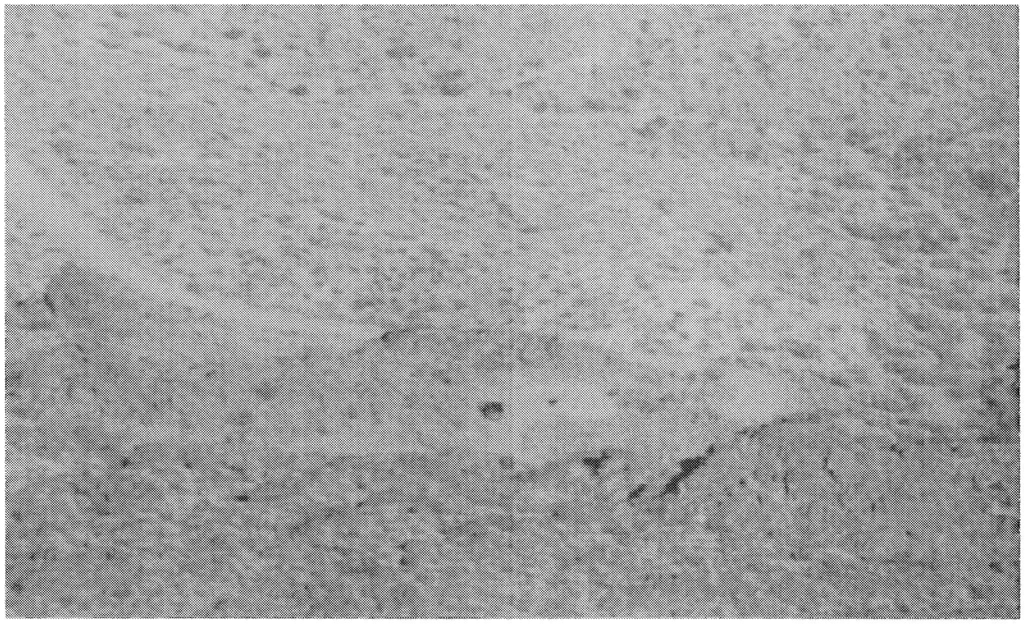

Figure 13. NFOV image in NIR of camouflaged target next to civilian vehicle

Figure 14 shows the results of spectral correlation performed on the image cube and overlayed on the original image. The filter was selected from pixels on the target net and the Spectral Ratio filter was used with a threshold of 0.6. The target readily stands out in the overlay image, however there is still a significant amount of spectral clutter leakage from the soil background for this threshold level.

Figure 14. Results of spectral correlation filter overlaid on the NIR image.

The spectral clutter is addressed using the spatial correlation analysis. This separates small and irregular clusters of spectrally correlated pixels from the target on the basis of size and shape. Figure 15 shows the results of the analysis of this image using the ATR testbed software tool. Based on the range (1.8 km) and resolution (IFOV 0.3 mr) of the sensor, a humvee sized object at that aspect subtends on the order of 250 pixels (pixel dimension ~0.5 m). The results of a simple 2D spatial correlation filter are shown in Figure 15. The red highlighted pixel cluster, which corresponds to the size, shape and orientation of a humvee target at that range, is correctly identified as the target.

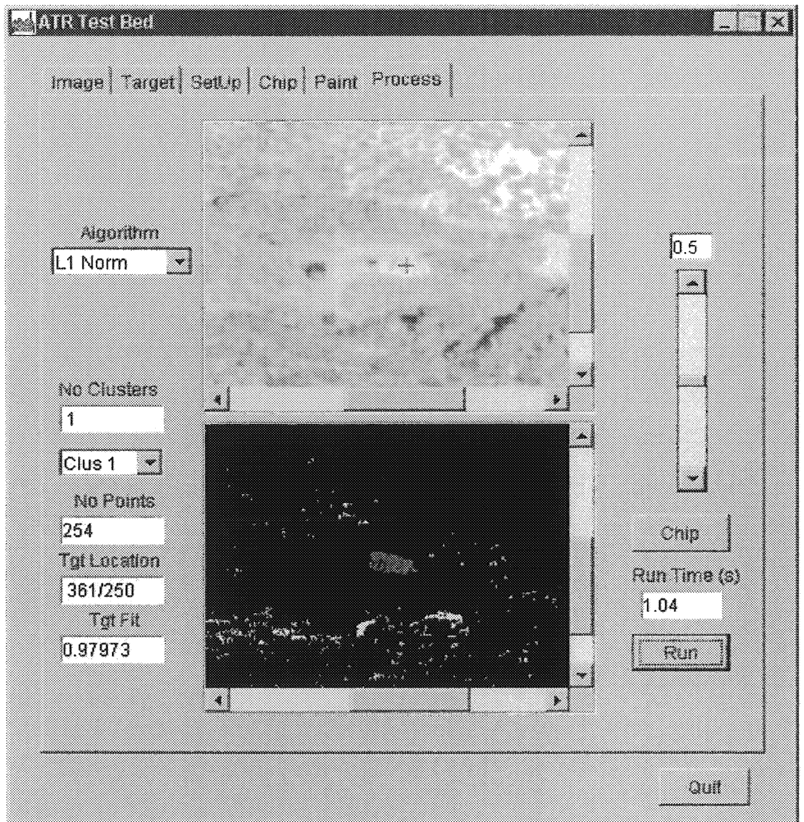

Figure 15. Results of spectral/spatial ATR process showing target detection.

CONCLUSIONS

This paper described a hardware/software testbed system for performing spectral/spatial ATR using hyperspectral imagery. The preliminary results appear promising. Spectral filters applied to the image cube provide a binary correlation map that includes the target along with residual, spectrally correlated, clutter. A simple 2D spatial correlation filter applied to the correlation map identifies the target based on the subtended size and shape for the range/resolution of the image. Two thresholds are associated with the detection process; a spectral correlation threshold that defines the degree of spectral correlation required to define the binary correlation map, and a spatial correlation threshold which defines the tightness of the spatial fit required to obtain a target recognition.

Much work still needs to be done to fully characterize this spectral/spatial ATR approach, including generating detection versus false alarm rate curves for different target types, camouflage techniques, clutter backgrounds and illumination conditions. Also, work needs to be performed to investigate the robustness of using *a-priori* filters versus anomaly detection algorithms. However, the flexibility of this hardware/software testbed system makes it an ideal platform for algorithm development and evaluation.