Hyperspectral monitoring of chemically sensitive plant sentinels

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ABSTRACT

Automated detection of chemical threats is essential for an early warning of a potential attack. Harnessing plants as bio-sensors allows for distributed sensing without a power supply. Monitoring the bio-sensors requires a specifically tailored hyperspectral system. Tobacco plants have been genetically engineered to de-green when a material of interest (e.g. zinc, TNT) is introduced to their immediate vicinity. The reflectance spectra of the bio-sensors must be accurately characterized during the de-greening process for them to play a role in an effective warning system. Hyperspectral data have been collected under laboratory conditions to determine the key regions in the reflectance spectra associated with the degreening phenomenon. Bio-sensor plants and control (non-genetically engineered) plants were exposed to TNT over the course of two days and their spectra were measured every six hours. Rochester Institute of Technologys Digital Imaging and Remote Sensing Image Generation Model (DIRSIG) was used to simulate detection of de-greened plants in the field. The simulated scene contains a brick school building, sidewalks, trees and the bio-sensors placed at the entrances to the buildings. Trade studies of the bio-sensor monitoring system were also conducted using DIRSIG simulations. System performance was studied as a function of field of view, pixel size, illumination conditions, radiometric noise, spectral waveband dependence and spectral resolution. Preliminary results show that the most significant change in reflectance during the degreening period occurs in the near infrared region.

Keywords: Bio-sensors, explosives detection, de-greening

1. INTRODUCTION

Recent global events make it clear that chemical and biological threats against the public are very real. Prevention of these threats from becoming acts is of the utmost importance to national security. There are already steps in place that serve as preventative measures. Limitations on liquids carried by passengers on planes and the presence of explosives trace detectors in airports are two such measures.[1] But these types of measures are impractical and expensive for large public areas such as malls and schools. What is needed is an inexpensive method to distribute many sensors over large open areas.

Biologists have engineered plant based threat detectors in response to this need. These bio-sensors are being designed to have a response that is easily recognizable by the public. The plants discussed in this paper are a variety of tobacco. Altered gene circuitry causes them to cease chlorophyll production and rapidly turn white (a.k.a. de-green) in the presence of an inducer.[2] Sensitivity at 8.6 parts per billion has been demonstrated.[3] Figure 1 shows two arabidopsis plants de-greening over a 48 hr period. On going research is aimed at speeding up this response.

Bio-Sensors are ideal for use in public areas such as transportation centers, malls and schools. They require no more maintenance than the common house plant and are easily distributed. Multiple bio-sensors could be included in the landscaping and design of a public space. Their obvious reaction to a threat would be easily seen by people in the area. Figure 2 shows a scenario where explosives sensitive bio-sensors would be useful. A school is shown with several bio-sensors planted around it and it's walkways. To the side there is a pole supporting a multi-spectral monitoring system that stares at the bio-sensors and images them. Each image is analyzed for the presence of a de-greening bio-sensor. Should the system detect de-greening an alert would be sent to school officials or the police department for further investigation.

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Figure 1. Example of two arabidopsis plants that were exposed to a chemical inducer and de-greened over the course of two days.

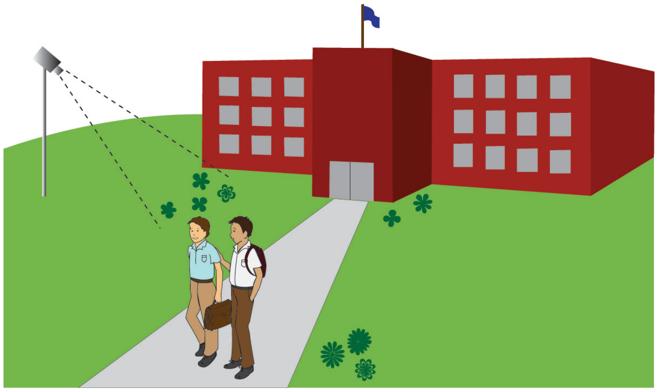

Figure 2. This figure shows an example of a setting for bio-sensors. TNT sensitive bio-sensors are planted outside of a school and a multi-spectral monitoring system mounted on a pole images them.

Quick identification of a chemical attack is vital to the prevention of harm to people or property. While visible change in the plant is apparent after a day, the reaction can be remotely sensed within a couple of hours. A spectral imaging remote sensing system designed specifically for the detection of de-greening biosensors would provide the fastest indication of a threat detected by the plants. A faster response time increases the likelihood of identifying the threat and preventing it from becoming an attack.

This document presents an approach for designing an effective bio-sensor monitoring system. We begin by collecting hyperspectral data of de-greening bio-sensors in a laboratory environment. From this data we determine the necessary sensitivity of the detector in the bio-sensor monitoring system. DIRSIG is used to simulate imagery captured using system of the monitoring system. The resulting imagery is then evaluated to determine if green bio-sensors are distinguishable from de-greened bio-sensors.

2. APPROACH

The following approach was used to design a monitoring system for de-greening bio-sensors. First, hyperspectral data were collected to understand the changes that the spectra undergo during de-greening. Next, the most significant spectral features are identified using a band selection algorithm. Finally, a system is designed based on the necessary sensitivity for the detector. Other system parameters are selected based on the results of a trade study.

2.1 Data Collection

Hyperspectral data of de-greening bio-sensors were collected in a laboratory environment in early August 2008. The data used for this analysis was collected by two imaging spectrometers. The SOC 700 collectes between 390 nm to 900 nm with approximately 4 nm resolution. The SOC 720 collects in the region from 900 nm to 1700 nm at approximately 9 nm resolution. Both instruments generate images 640 px by 640 px in size. Figure 3 is an image captured by the SOC 700. Measurements were made every six hours for two days with the exception that no late night measurements were made.

Figure 3. An RGB image created from bands 73, 37 and 27 of a SOC 700 image cube.

There were two types of bio-sensors measured. Vapor sensitive bio-sensors were exposed to TNT particulates in the air of an enclosed tank. The other type responded to exposure via their root system which was placed in an agar tainted with TNT. Figure 4 shows the tank that housed the vapor plants and Figure 5 shows the petri-dishes that the root exposure plants were in.

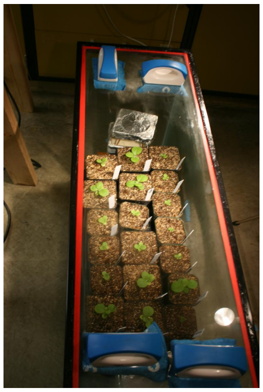

Figure 4. Vapor sensitive plants were exposed via TNT particulates in the air of an enclosed glass tank.

Three bio-sensors from this experiment were found to display a reaction to TNT exposure. Spectra from these plants were used for the remaining steps of our approach.

2.2 Band Selection

Characterizing the spectral changes that occur over the course of de-greening is imperative to the successful design of a system for monitoring bio-sensors. Knowing what spectral regions show the most change as the plant de-greens will indicate where our monitoring system's detector should be the most sensitive. A feature selection method has been chosen to determine the locations of such regions.

The method chosen is a spectral angle mapper (SAM) optimization algorithm.[4] The technique iteratively adds bands that create a maximum increase in spectral angle until additions begin to decrease the angle. In other words, it adds bands until additions are no longer able to increase the spectral angle.

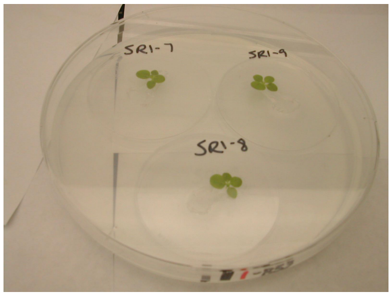

Figure 5. Bio-sensors designed to sense TNT through their root system were planted in petri dishes and exposed via the agar they were rooted in.

Spectral angle mapper quantifies the angular separation of two spectral vectors. For two spectral vectors x and y of length m, it is defined as

$$\theta(x,y) = \arccos\left(\frac{< x, y >}{\|x\|\|y\|}\right) \tag{1}$$

The analysis begins by calculating the spectral angle between every band pair combination. The band pair corresponding to either the minimum or the maximum spectral angle can be used as the starting point for the iterative band add-on (BAO) technique.

From the chosen starting point the following decomposition of SAM is used for the BAO technique. Again, x and y are two spectral vectors of length M that have been partitioned such that $\mathbf{x} = [\mathbf{x_a}\ \mathbf{x_b}]$ and $\mathbf{y} = [\mathbf{y_a}\ \mathbf{y_b}]$ where $m = a + b$.

$$\begin{aligned} \cos\theta(x,y) &= \left(\frac{< x, y >}{\|x\|\|y\|}\right) && (2) \\ &= \cos\left(\frac{1 + \frac{<x_b, y_b>}{<x_a, y_a>}}{\sqrt{1 + \frac{\|x_b\|^2}{\|x_a\|^2}}\sqrt{1 + \frac{\|y_b\|^2}{\|y_a\|^2}}}\right) && (3) \\ &= \cos\theta_a\beta && (4) \end{aligned}$$

Using Equation 4, β is calculated for all remaining bands based on the initial pair of bands. The procedure is repeated until no bands satisfy $\beta \geq 1$. The user now has a set of bands that create a maximum spectral angle. The BAO technique will provide an idea of the key regions in the spectrum to which the bio-sensor monitoring system should be sensitive.

2.3 Scene Modeling and System Design

This project will employ the synthetic image generation tool called Digital Imaging and Remote Sensing Image Generation (DIRSIG) developed at RIT.[5] First, a scene will be created to represent field deployment of bio-sensors. Different system designs will be tested to determine the best type of imager needed to monitor the biosensors. Presented here is a brief overview of DIRSIG and its many uses.

DIRSIG is a collection of first principles based radiation propagation sub models.[6] It produces simulated imagery in the visible through thermal regions of the electromagnetic spectrum. DIRSIG as a whole incorporates several models that consider things such as surface BRDF characteristics, transmission and atmospheric conditions (i.e. MODTRAN). These models allow the software to fully recreate the imaging chain from source to scene to sensor and produce radiance information in the final imagery.

This project took advantage of an existing DIRSIG scene. MegaScene1 covers a portion of the Greater Rochester area of New York State.[7] Within this scene we modified the region around Dake Middle School to meet our needs. Our focus is around the entrance to the school where bio-sensors would be the most useful for detecting explosives threats before they entered the school. Extra trees and shrubbery were removed from the scene resulting in Figure 6. Models of the bio-sensors were created, attributed and placed in the scene. Figure 7 shows the scene in ENVI complete with the tobacco placed at the entrance of the school.

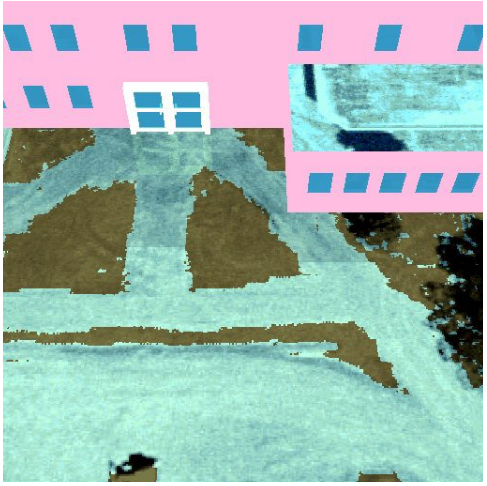

Figure 6. Dake Middle School entrance in MegaScene1 with trees and shrubs removed.

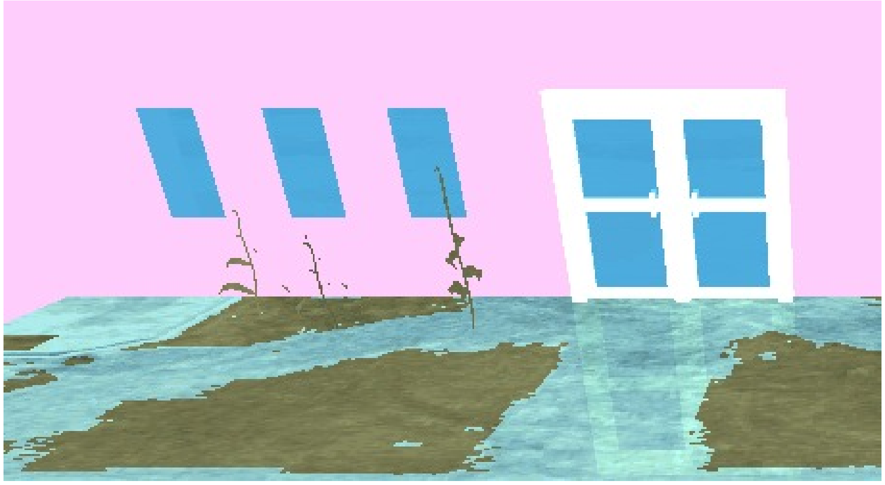

Figure 7. Bio-sensors added to DIRSIG scene.

The FOV, GSD, sensor size and focal length will be determined by the desired spatial resolution of the bio-sensor leaves. We begin with a mounted system that has an FOV encompassing the entire entrance to the middle school. From there we can determine the GSD and focal length necessary to resolve bio-sensor leaves from one another. It is necessary to have at least this level of spatial resolution because some plants in the scene will be showing a reaction, while others will not. In order to distinguish one plant from another it will be necessary for the leaves to be resolvable by the monitoring system.

A starting point for the sensor sensitivity and spectral resolution will be provided by the band-selection algorithm results. The number of bands and the location in the spectrum will suggest where the sensor needs to be the most sensitive to changes. The range that the sensor covers will depend on the range of the selected bands.

3. RESULTS & DISCUSSION

Initial results using the BAO technique described in Section 2.2 found the bands located at the wavelengths listed in Table 1 to maximize the spectral angle between the two classes. Figure 8 shows the input spectra to the algorithm (with the exception that the last 4 bands of the SOC 700 and the first 9 bands of the SOC 720 data were removed due to noise). These results indicate where the detector must be sensitive in order to pickup on de-greening in the bio-sensors.

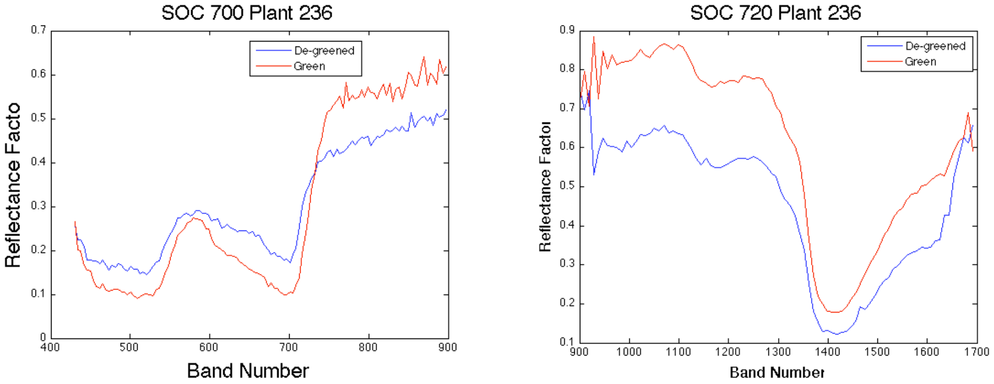

Figure 8. Input green and de-greened spectra to band add on algorithm a) SOC 700 b) SOC 720

SOC 700	SOC 720
555 nm	1098 nm
563 nm	1107 nm
700 nm	1117 nm
763 nm	1475 nm
767 nm	

Table 1. List of wavelengths found to maximize the spectral angle between the green and de-greened spectra of plant 236

Figure 9 is an output image from DIRSIG. This image is a result of an early stage model of a sensing system that has been used as a starting point to move forward in our trade studies with. The system model used to generate this image consisted of four bands centered at 400 mm, 500 nm, 600 nm, and 700 nm. While not the wavelength found by the band study, this image is a useful initial attempt to demonstrate the process. The sensor was 130 feet above ground level. The image is 1024 pixels by 1024 pixels generated by a framing array of detectors. Also, a lens with an $f/15$ aperture was used. Figure 7 shows a close up of the bio-sensor plants. The leftmost bio-sensor is a green bio-sensor and the rightmost plant is a de-greened bio-sensor that should signal a detection.

SAM and the Mahalanobis distance will be used to detect de-greened pixels in the image. A review of SAM was provided in Section 2.2. The Mahalanobis distance of the vector $\mathbf{x}$ from the mean vector $\mathbf{m}$ of a class i is defined as[8]

$$d_i = \sqrt{(\mathbf{x} - \mathbf{m_i})^T S_i^{-1} (\mathbf{x} - \mathbf{m_i})} \tag{5}$$

Where $\mathbf{S_i}$ is the covariance matrix of the class.

Figure 10 is the result of applying SAM to the image and thresholding the results. A white pixel in the image corresponds to a 0.00 radian spectral angle between the pixel and the de-greened bio-sensor class. The de-greened (rightmost) bio-sensor in the image is the lightest of the three plants. The thresholded image ignores the sidewalk, building and window materials, but has some trouble distinguishing the de-greened bio-sensor for grass. There are also some false alarms on the green bio-sensors.

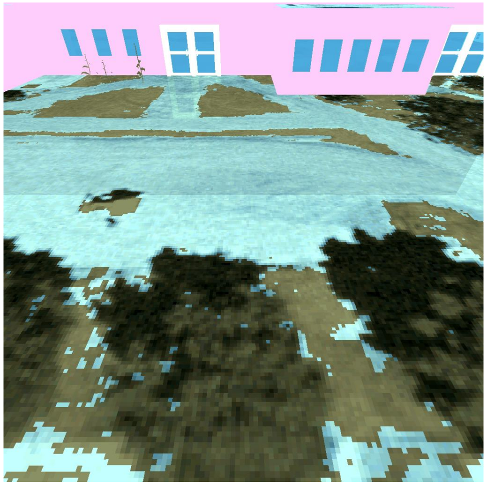

Figure 9. Simulated image capture from DIRSIG.

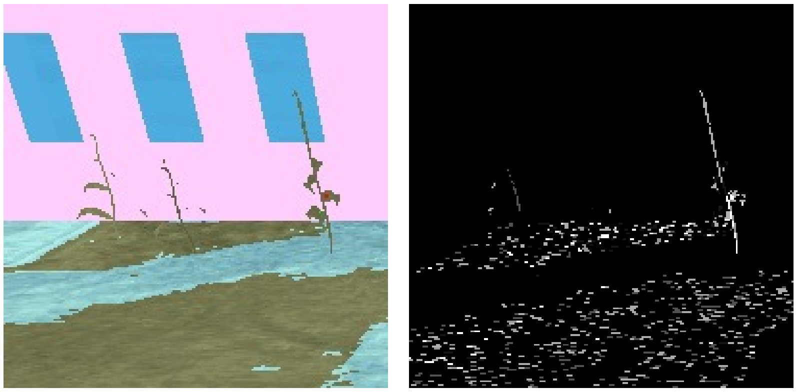

Figure 10. a) A region in the DIRSIG simulated scene b) A thresholded SAM image. White pixels indicate a small spectral angle between the pixel and a de-greened endmember.

4. SUMMARY

At this point we have demonstrated an approach to modeling a bio-sensor monitoring system. Initial results provide a proof of concept that this approach is feasible. Future studies will reflect the results from the band selection algorithm. Further trade studies investigating GSD, FOV, illumination and noise will be conducted.

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REFERENCES

1. "Transportation security administration: How to get through the line faster." http://www.tsa.gov/travelers/airtravel/screening_experience.shtm, June 06, 2009.
2. M. S. Antunes, S.-B. Ha, N. Tewari-Singh, K. J. Morey, A. M. Trofka, P. Kugrens, M. Deyholos, and J. I. Medford, "A synthetic de-greening gene circuit provides a reporting system that is remotely detectable and has a re-set capacity," *Plant Biotechnology Journal* **4**, pp. 605–622, 2006.

3. J. I. Medford, “Some questions relating to plant sentinels project.” email, June 2009.
4. N. Keshava, “Angle-based band selection for material identification in hyperspectral processing,” in *Proceedings of SPIE*, S. S. Shen and P. E. Lewis, eds., *Proceedings of SPIE* **5093**, SPIE, 2003.
5. J. R. Schott, S. D. Brown, R. V. Raqueno, H. N. Gross, and G. Robinson, “Advanced synthetic image generation models and its application to multi/hyperspectral algorithm development,” *Canadian Journal of Remote Sensing* **15**, pp. 99–111, 1999.
6. S. D. Brown and N. Sanders, *The DIRSIG User's Manual*. Chester F. Carlson Center for Imaging Science at Rochester Institute of Technology, 54 Lomb Memorial Drive, Rochester, NY 14623-5604, 2007.
7. E. J. Ientilucci and S. D. Brown, “Advances in wide-area hyperspectral image simulation,” in *Proceedings of SPIE*, W. R. Watkins, D. Clement, and W. R. Reynolds, eds., **5075**, pp. 110–121, SPIE, 2003.
8. J. R. Schott, *Remote Sensing: The Image Chain Approach*, Oxford University Press, New York, second ed., 2007.