Feasibility of optical detection of landmine tripwires

Stephen K. Babey[a], John E. McFee[b], Clifford D. Anger[a], Avygdor Moise[a] and Stephen B. Achal[a]

[a]Itres Research,
155, 2635 - 37th Avenue N.E., Calgary, AB, Canada T1Y 5Z6

[b]Defence Research Establishment Suffield,
Box 4000, Station Main, Medicine Hat, AB, Canada, T1A 8K6

ABSTRACT

Research to assess the feasibility of developing a standoff active or passive optical tripwire detector is discussed. Reflectivities of typical tripwires and background materials were measured for UV, VNIR and SWIR wavelengths. A breadboard testbed was developed to obtain images of tripwires against various backgrounds for various geometries and a wide range of UV and VNIR wavelengths. Sample images of simulated and real tripwires in uncluttered environments and against typical cluttered backgrounds were acquired and analyzed. Line detection algorithms were applied to the images to detect tripwires. Although detection was not attempted in real-time, analysis showed that available, cost-effective DSPs could potentially execute those algorithms on the images in real-time. The algorithms successfully detected tripwires in a heavily cluttered background and even have the capability to detect partially obscured wires. To complement the measurements, a spreadsheet model was developed to evaluate the merits of different detectors, sources of illumination, wavebands and geometries for different scenarios. Acceptable signal-to-clutter ratios were found for a number of reasonable passive and active illumination scenarios. The study demonstrated that an optical tripwire detector is feasible in principle.

Keywords: Mine detection, tripwire, optical detection

1. INTRODUCTION

1.1. Background

Trip wires are triggering devices that are frequently found on conventional military landmines, particularly antipersonnel mines. One end is attached to the mine and activates it by means of a pulling or bending force inadvertently applied to the wire by the victim. Activation force is typically less than several Newtons (a few pounds), which makes them extremely hazardous to be near. Trip wires can be made of metal filaments, which may be single or multi-strand and either bare or coated with paint or plastic. Nonmetallic fibers, typically bare or coated monofilaments of nylon or other plastics, are also common. Trip wires have lengths which vary from a few tens of centimeters to a few meters and have diameters of 0.5 mm or less. They are typically placed 15 to 20 cm above the ground, although they can be much lower and occasionally are placed at chest or head height in thick foliage. They may be coloured to match the background, with green, olive, yellow, sand and black being common colours. Because of their size, camouflaged colour and closeness to the ground, they are extremely difficult to detect with the naked eye, even on bare ground. Detection in thick foliage is even more difficult.

Present methods of detecting tripwires are very limited. The most common method is visual inspection, which is unreliable and very hazardous. Also common is the use of "feeler rods", which are essentially thin, bent rods similar to coat hangers, suspended by one end from an operator's outstretched fingers. The other end is dangled a few centimeters above the ground. The operator makes the feeler rods sway back and forth with a slow, light motion. If a tripwire is present, the feeler rod bounces off it and vibrates. This slight change in motion can be detected by the operator, who then hopefully stops before activating the trip wire. The method is somewhat reliable, but probability of detection (Pd) and false alarm rates (FAR) are anecdotal and likely poor. Light vegetation impedes the process and even moderate vegetation renders it useless. More importantly, the method puts the operator at great risk due to proximity to the mine and trip wire and is extremely stressful to the operator. Two out of seven organizations

Other author information: (Send correspondence to J.M.)
J.M.: Email: John.McFee@dres.dnd.ca; Telephone: 403-544-4739; Fax: 403-544-4704
S.B., C.A., S.A.: Email: steveb@itres.com; Telephone: 403-250-9944; Fax: 403-250-9916

that employ dogs for mine detection also train the dogs to detect tripwires.[1] The detection mechanism is not well understood, but is thought to include sight, sound and smell. The number of tripwires encountered in the operations involving these agencies is small and no comprehensive trials have been done, so it is difficult to assess Pd and FAR. However, dogs trained to detect tripwires do at times detect other nonexplosive substances which slows their rate of mine clearance. Thus there is reluctance among some of the agencies to employ dogs with this additional capability.

A standoff tripwire detector, if effective, would have significant value as an alternative to visual inspection and feeler rods. The reduction in risk and stress to the operator associated with a tripwire detector that does not directly contact the wire would be advantageous, particularly if the sensor can detect the wire at greater ranges than a feeler rod. The ideal configuration would be to attach the tripwire detector to a conventional low metal mine detector or foliage cutter. The tripwire detector would look ahead of the metal detector or cutter (either in the scan direction of the metal detector or cutter or the forward direction of the operator). The tripwire detector could also operate as a stand alone unit. Such an instrument would be a significant advance over the slow, dangerous mechanical tripwire detection process.

In addition to its usefulness in humanitarian and military de-mining, a reliable, forward-looking tripwire detector would have other uses as well. Trip wires are also found on off-route mines and are a common part of improvised explosive devices (IEDs), such as home-made bombs. At present there are very few technologies for the detection of nonmetallic mines and off-route mines. Trip wire detectors, stand alone or attached to conventional low metal mine detectors, would improve safety for mine detection operations. They would also have application on teleoperated detection vehicles, such as the Improved Land Mine Detection System (ILDS)[2] or the protection vehicle which precedes it, to detect tripwire activated mines that could damage the vehicle. Because of the improvement in safety over conventional methods, a successful tripwire detector would be useful to the military, anti-terrorist squads, police organizations and security companies searching for IEDs.

Limited work has been done on standoff detection of tripwires. A few companies have sold metal wire detectors which are primarily aimed at detection of command detonation wires found in many IEDs and a few mines (e.g., Claymore). These are electromagnetic induction detectors or radiofrequency detectors that have been optimized for wire detection. Since they detect radiofrequency emissions or electrical conductivity changes, they are incapable of detecting nonmetallic wires. In fact, such instruments are not very sensitive to inactive metallic wires either. In a limited test at the Defence Research Establishment Suffield (DRES), metallic wires could not be reliably detected using a wire detector manufactured by a UK company (the unit is apparently discontinued). Like feeler rods, the operator is required to be in close proximity to the mine. The US Night Vision Laboratory, Ft. Belvoir, VA, employed under contract a forward looking ultraviolet imager for tripwire detection as a component of one version of a vehicle mounted mine detector system, under their GSTAMIDS program. The vehicle mounted mine detector development program continues but the wire detector appears to have been dropped from subsequent versions. No information is available regarding the technical details of the detector or the reason for the decision. The Countermine Technologies for Humanitarian Demining Program of the US Night Vision Laboratory carried out research on a handheld tripwire detector system, which consisted of a 3-5 micron handheld infrared imager with a 256 x 256 platinum silicide focal plane array and 50mm focal length fore-optics. Illumination was provided by a 200 W light bulb in an aluminum reflector and a 500 W generator. The system, mounted on a tripod or cart with a television monitor and videotape recorder, was intended to aid a deminer on foot by providing visual cues, presumably by specular reflection from the wires. Performance tests were planned for December 1995, but no record of results or follow-on work has been found.

1.2. Preliminary investigations

In 1995 DRES noted the lack of a reliable tripwire detector and recognized that this was a significant deficiency both for military mine clearance and humanitarian demining. Discussions with Itres Research Limited suggested potential solutions to the problem. A preliminary study, carried out from October 1996 to April 1997, investigated the feasibility of standoff solar blind wire detection.

The optical characteristics of tripwires, various backgrounds, and illumination conditions were estimated and a preliminary model was developed to evaluate the feasibility of optically detecting tripwires. Initial results were favourable, with moderate to high signal-to-noise ratios being obtained for the difference between the tripwire signal and the background signal for a number of passive and active illumination scenarios. Sample images of simulated tripwires were also acquired and analyzed. The Hough Transform, one particular line detection algorithm, was applied to the imagery and found to be successful at detection of tripwires, even in a heavily cluttered background. Further, it had the capability to detect partially hidden wires.

The preliminary study was mainly based on estimated characteristics of backgrounds and wires, with a number of assumptions, a simple model and few experimental measurements. For example, the highest signal to noise ratios were obtained in the model for the UV solar blind region, due to the absence of background daylight signal. However, little knowledge exists about scene and tripwire characteristics in that spectral region (below 290 nm wavelength), where sunlight does not reach the Earth's surface due to ozone absorption.

A follow-on study was thus initated to confirm or modify the previous assumptions, confirm feasibility of developing an optical tripwire detector and determine an optimal configuration for the detector. The research plan included assembling laboratory equipment to measure images of real trip wires against neutral and realistic backgrounds, as well as measuring reflectance spectra of tripwires and typical backgrounds. These realistic values would provide input to an improved detection model to estimate detectability for different scenarios. If detectability suggested that a practical system could be developed, a conceptual design for a field-portable tripwire detector prototype would be created.

2. EXPERIMENTAL MEASUREMENTS

2.1. Spectral reflectance measurements

At the start of the project, little information was available regarding the reflectivity, as a function of wavelength, of tripwires compared with that of typical background materials. However at that time, another project was using a portable spectrometer to measure the reflectance spectra in the 350 nm - 2500 nm waveband, in 1 nm steps, of a large number of types of mines and background materials. Tripwire samples were added to the list of targets.

For each spectral measurement, a sample was positioned about 25 cm directly below the input optical fiber of an Analytical Spectral Devices FieldSpec spectrometer and a 500 W quartz halogen lamp was positioned close to the sample. The spectral radiance of the sample was first measured. Next the sample was replaced by a calibrated reflectance panel and its spectral radiance was measured. Lastly, dark current data were obtained. Reflectance could then be straightforwardly calculated.

Fig. 1 shows the ultraviolet (UV), visible/near infrared (VNIR) and short wave infrared (SWIR) reflectance spectra of yellow and green military tripwires, together with representative soils and vegetation. For most of the spectrum, there are substantial differences between the tripwire reflectivities and those of the soils and vegetation. These differences are largest in portions of the SWIR spectrum, although they are also significant in the UV/VNIR region. Spectral regions exist where the tripwire and background reflectivities are equal, but these are few and narrow. Tripwire reflectivities are fairly low, being less than 0.4 for yellow and less than 0.1 for green. The reflectance of the yellow trip wire varies substantially across the UV/VNIR (from about 0.07 to 0.37) and has a peak reflectance in the NIR (about 0.37 near 750 nm). The green tripwire has a much lower reflectivity and, on an absolute scale, varies more slowly in the UV/VNIR (from about 0.04 to 0.09). In general, as was found for the landmines, the spectra of military and improvised tripwires were significantly different from background materials in the UV/VNIR/SWIR waveband and the two classes could be readily distinguished by straightforward pattern clustering and classification techniques.

2.2. Breadboard testbed

The previous experiment provided UV/VNIR/SWIR spectra, but did not extend into the UV solar blind region (<300nm wavelength) and provided no imaging information. It was essential to obtain images of tripwires against natural backgrounds across a broad UV/VNIR spectral band in order to examine the effects of background variations on detectability and to allow development and testing of line detection algorithms. Extensive survey of the literature and the Internet revealed that there was very limited availability of commercial off-the-shelf (COTS) technology that could image in the UV solar blind region. One camera was identified which claimed to offer true solar blind operation, but actually showed some small transmission in the 400-500 nm region. Because the visible ambient daylight radiation flux density is extremely large compared to that in the UV region, even slight leakage of visible light through a filter obstructs solar blind function.

To achieve the above aims, a laboratory breadboard imaging system was assembled. An imaging chamber used in the Itres **casi** hyperspectral imager[3] was modified to provide an acceptable response at wavelengths as short as 200 nm and to enable static images to be obtained. Hardware and software were produced to allow full frame images to be acquired and stored. Two UV grade fused silica singlet lenses, 50 mm and 100 mm $f/1$, were obtained and

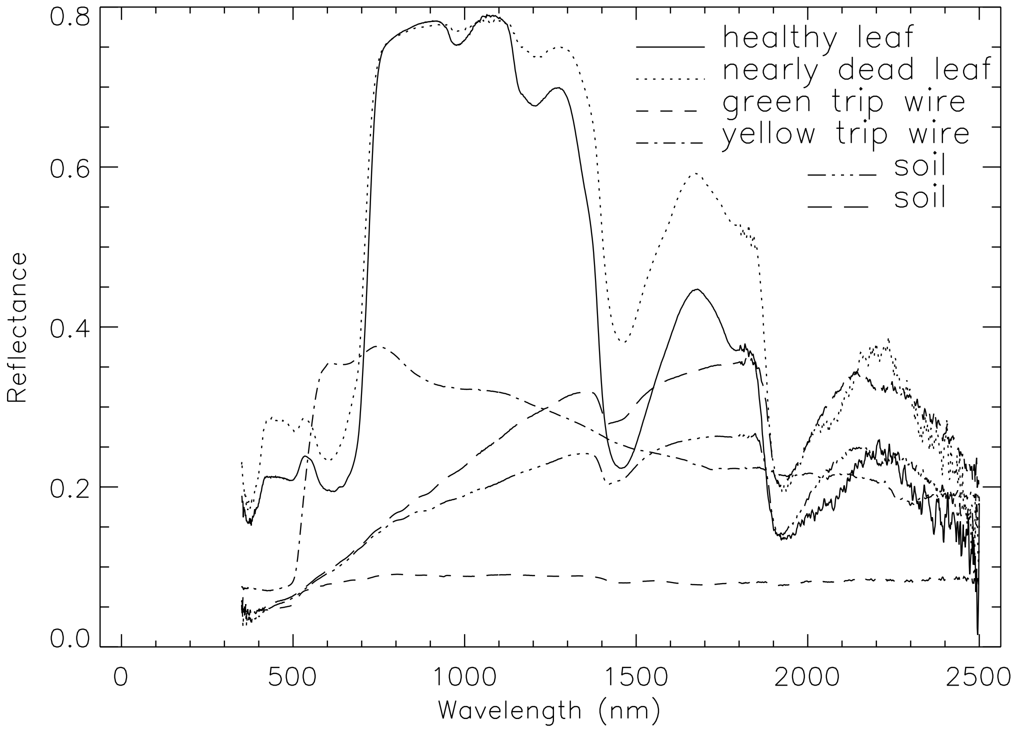

Figure 1. UV, VNIR and SWIR reflectance spectra of tripwires, soils and vegetation.

adjustable focus lens barrels were constructed. A Schneider 75 mm $f/1$ adjustable aperture lens was used for the VNIR measurements. Sources of illumination included a low pressure Mercury spectral line source (253 nm), quartz-halogen and tungsten incandescent sources for the visible range, and a 670 nm diode laser. A 253 nm interference filter, a 700 nm center frequency bandpass filter and a broad band optical filter were also used in the tests. The breadboard imaging system is shown in Fig. 2.

2.3. UV solar blind and VNIR imaging experiments

Calibration experiments against targets of known size and contrast were first performed to determine the optical magnification and to assess camera performance under controlled, benign conditions. Grey scale charts of straight lines with positive and negative contrasts from 1 to 100% and diameters from 0.1 mm to 2 mm were printed. Images of these lines were acquired at various exposure levels and camera-to-target distances. Natural light (ambient light from windows and fluorescent overhead lighting) was used in these experiments. This information was then used in the spreadsheet model described later to determine reasonable camera parameters and to allow estimation of the number of pixels occupied by a specific diameter wire at a specific distance.

Nine military and improvised tripwire samples, made of various materials and colours, with diameters ranging from roughly 0.5 to 1.5 mm, were imaged (Table 1). They were stretched taut and mounted horizontally in a metal frame (Fig. 3) which was placed in front of various backgrounds.

One set of images were obtained in an optical dark room with various sources and optics, where conditions could be tightly controlled. These experiments were performed with the target and sensor head at approximately the same height and a horizontal camera line of sight. Fluorescent lighting was provided by overhead ceiling lights. A 60 W tungsten bulb was placed at about 45° to the camera line of sight at a distance of 1 m. The same geometry was used for the laser diode and the UV source, except that the source-target distance was 10 cm for the UV source.

Another set of images were obtained in an atrium which provided a cluttered background of tropical vegetation. The target and sensor head were at approximately the same height, with a horizontal camera line of sight. Natural lighting consisted of ambient light through windows plus tungsten ceiling lamps. The laser diode was placed at 10° to the camera line of sight and 20 cm closer to the target than the camera. A diffuser lens and a 700 nm interference filter, tilted to maximize 670 nm transmission of the laser diode, were also used for some images.

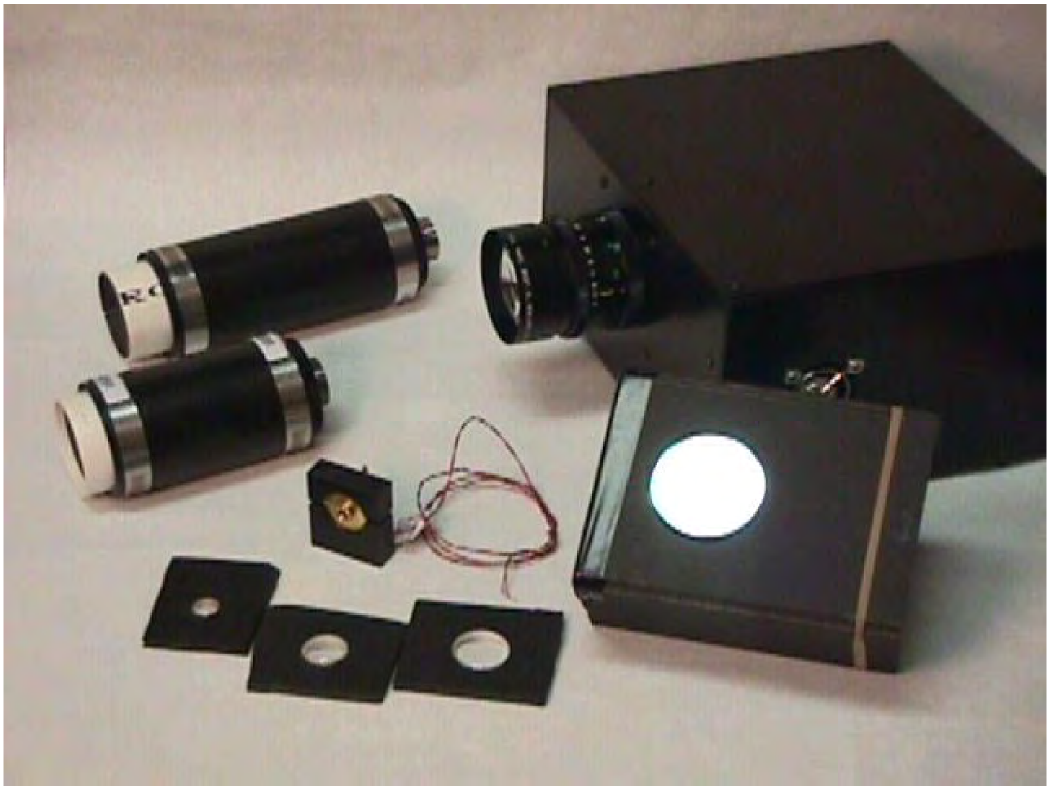

Figure 2. The breadboard imaging system. Shown are the camera unit, some of the lenses, filters and sources.

Sample Number	Wire Type	Nominal Colour	Diameter (mm)	Comments
1	military	yellow	0.51	painted metal
2	military	yellow	0.51	rusted painted metal
3	military	green	0.49	painted metal
4	military	green	0.49	rusted painted metal
5	jute string	green	1.05	biodegradable
6	fishing line	clear	0.24	6 lb test
7	steel wire	black	1.00	19 gauge, oiled
8	galvanized wire	metallic	0.90	20 gauge
9	nylon cord	white	1.50	

Table 1. Tripwire samples used in imaging experiments. Sample numbers increase from left to right in tripwire images (Figs 4, 5, 6).

2.4. UV solar blind and VNIR imaging results

UV illuminated images had very poor contrast and required very long (few second) integration times (Fig. 4). Comparison to a $BaSO_4$ reflectance standard confirmed that this was caused by the tripwire and background having very low reflectances in the UV. Specular reflection in the UV was not apparent in the data collected, although such reflections might occur with other configurations or sources.

After contrast optimization, all wires in images which were illuminated by daylight, fluorescent or tungsten light could be readily distinguished from background (although not necessarily in the raw images), regardless of diameter, colour or material. Images taken with the fluorescent lights required an order of magnitude less integration time and had much better contrast than the UV (Fig. 5). Wire/background contrast with tungsten light, although better

Figure 3. The metal frame with military and improvised tripwires installed.

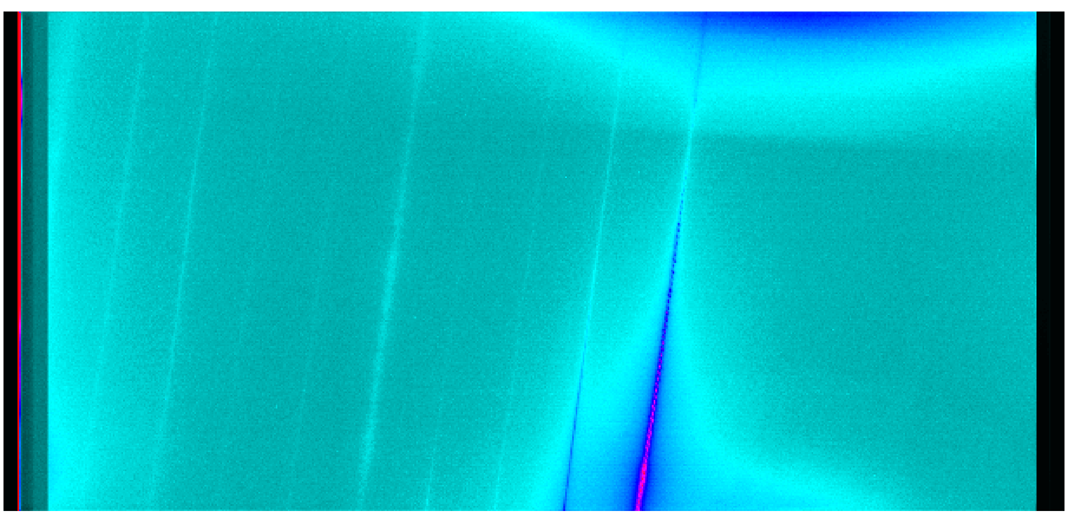

Figure 4. Image of tripwires in darkroom, illuminated by UV light.

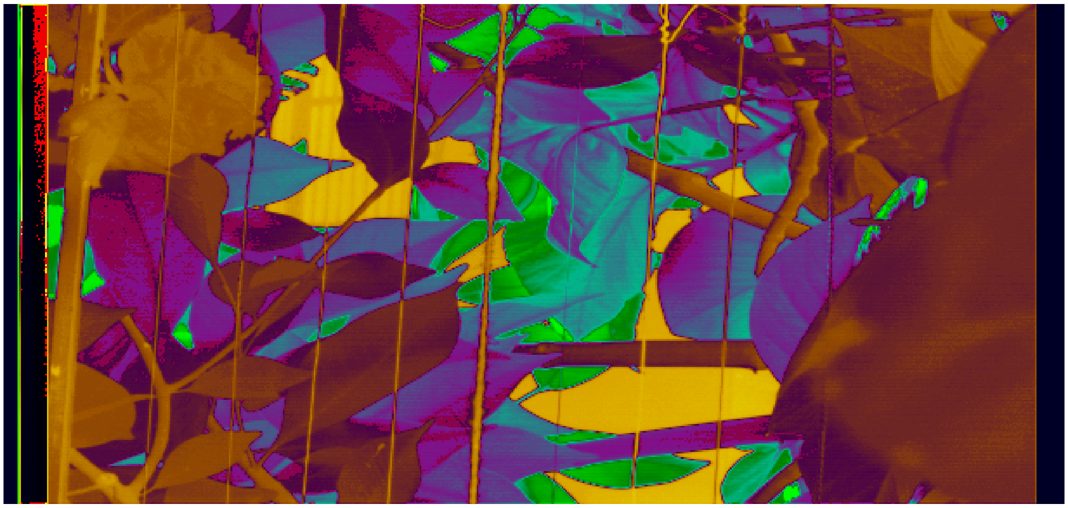

Figure 5. Image of tripwires against cluttered tropical vegetation under natural lighting (fluorescent + daylight).

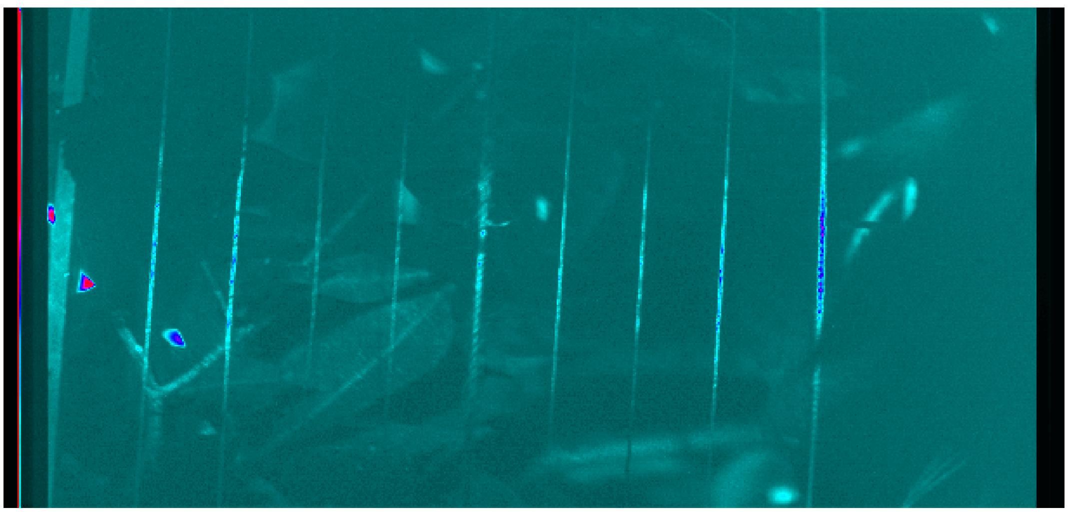

Figure 6. Image of tripwires against cluttered tropical vegetation, illuminated by 670 nm laser diode. The camera has a 700 nm angled bandpass filter.

than the UV, was poorer than the fluorescent/visible light, particularly for certain wires.

Images taken with the 670 nm laser diode and angled 700 nm bandpass filter gave reasonable results but required integration times of 0.5 to 2 seconds (Fig. 6). These long integration times are possibly due to the low intensity of the 5 mW diode laser, combined with attentuation of the 700nm filter, which was not optimal for 670 nm. (A filter centered at 670 nm was not available.)

3. TRIP WIRE REFLECTANCE MODEL

3.1. Model description

The ability to detect a tripwire can vary dramatically with the scenario. A wire which appears dark against a background in one situation, may appear light against the same background if illumination conditions change. This phenomenon is commonly seen when observing overhead power lines. Detectability is ultimately dictated by the signal-to-clutter ratio. Because a variety of different detection geometries, illumination methods, targets and backgrounds had to be evaluated, it would have been extremely expensive and time consuming to conduct enough experiments to select the best configuration. An Excel spreadsheet model, using data from experimental measurements and the literature, was thus developed to aid in the selection process. The model allowed a choice of various illumination parameters, background and tripwire characteristics, and detector characteristics. Both artificial and natural illumination were modelled, as were the two chief expected types of background, the sky and nearby soil or vegetation.

The principal elements of the model are a source of artificial illumination, a tripwire, a background scene and a camera system which looks at both the illuminated tripwire and surrounding background. The tripwire is modelled as both a cylindrical specular reflector and cylindrical Lambertian diffuser. The background can be the sky with a specified radiance or a diffuse terrestrial scene composed of soil or vegetation at a specified distance from the light source and camera system. The reflectance of the background is assumed to have some variability across the region viewed by the camera, characterized by a standard deviation which is a specified fraction of the average background reflectance. The tripwire and terrestrial background are assumed to be illuminated by both the light source and the sky. The model accounts for absorption of light by the atmosphere between the source and tripwire and between the source and background. If the tripwire subtends less than a pixel, it is assumed that the remainder is comprised of background.

Probability of detection is heavily influenced by camera characteristics through its effect on signal-to-noise ratio (SNR) and number of pixels subtended by the wire. The camera model includes all parameters that effect sensitivity, such as aperture, angular field of view of a pixel, transmission of the optics, dark current, detector area and quantum efficiency. Shot noise as well as quantization noise from digitizing the signal are taken into account in the calculation of SNR. Camera angular resolution, wire diameter and the distance between the tripwire and the camera determine the number of pixels subtended by the tripwire.

Two quantities are calculated by the model. The first is the contrast ratio or the ratio between the signal from a pixel where the tripwire is present and a pixel where only background is present. Contrast ratios are calculated for four combinations of wire reflectance and background (specular or diffuse reflection, sky or terrestrial background). The second is SNR, where signal is defined as the difference between tripwire and background signals.

It must be emphasized that the model is a nonimaging one, which compares the signal strengths in pixels containing a tripwire segment with those which do not. The presence of patterns of similar pixels, such as groups of colinear line segments, is not exploited in the model, but is discussed in Section 4.

3.2. Model results

Three sets of simulations were initially performed to look at regions of the spectrum with reduced solar incidence. The first set assumed a tripwire 1-2 m from the source, illuminated by a laser diode in the narrow O_2 absorption window centered at 762 nm. The wire was viewed by a typical CCD camera with a 1 mr angular resolution. Night and daytime conditions were simulated, with the source on and off in the daytime. Different values of the diffuse and specular reflectivity, within realistic limits, were tried and values of the background reflectance variability between 3 and 10% were used. The second set, based on a handheld detector scenario, was similar to the first except that only natural light was used and the wire-to-source distance was 1 m. A broad wavelength band was used and the camera aperture was reduced to provide relatively high signal levels from the sky and background. The third set, which would be amenable to a vehicle mounted scenario, used an operating wavelength of 290 nm, which is in the UV solar blind region, but was otherwise similar to the first set. For the UV solar blind set, the camera was assumed to have no response to wavelengths longer than 290 nm, which is a serious practical challenge. The wire-to-source distance was 1.5 m and illumination was, of course, purely artificial. Tripwire and background reflectances were assumed to be equal and between 1 and 6% range.

In the VNIR, even when reflectance levels were very low, pure specular reflectance was easily detected in the model at reasonable illumination levels, either by an artificial source or sunlight. Taking advantage of pure specular reflection can be difficult, since the acceptance angles are precise and very narrow, being dictated by Snell's law. However, surface roughness of the tripwire may spread out the reflecting region without necessarily reducing detectability. Painted tripwires may show this effect, since the reflectances of painted surfaces usually have a small quasi-specular component spread over a narrow range of angles, as well as a diffuse, Lambertian component. (Neither specular reflection of sunlight nor surface roughness were taken into account in the model, but an analogous effect is seen in reflection of sunlight off power lines.) For specular reflection, the light source beam and field of view must be wide enough to include the specular region on the tripwire, recognizing that the needed field of view will increase as the angle between the wire axis and the line of sight deviates from the perpendicular.

Diffuse reflection behaved quite differently. For a low reflectance tripwire, which appeared dark against any reasonable background level, artificial illumination of the tripwire decreased the contrast with the background. Best results occurred when background illumination was maximized, which meant that operating in the reduced solar illumination band at 762 nm actually gave slightly poorer results than in adjacent regions. If possible, directing the light source at the background rather than the wire could improve detectability. For handheld detection, where source-to-tripwire distances are less than 1 m, the sky provides an excellent background against which to detect the dark tripwire. Since a broad spectral band pass can be used, the requirements for the camera and optics are less demanding. When the background was darker and more irregular, detection of a diffuse tripwire with no artificial illumination was still promising. Detection might be enhanced, in this case, by reducing illumination from the detector, such as by painting it flat black.

In the UV solar blind region, specular detection of tripwires was readily achieved against sky, vegetation or soil backgrounds. For diffuse reflection, detection of tripwires against a sky background was readily achieved, provided that illumination intensity was adequate. However when the background was vegetation or soil, the ability to detect the wire could not be clearly determined, since the SNR was strongly dependent on relative reflectances of wire and backgrounds. Since there is little information about reflectance of tripwires or backgrounds in that spectral region, the chosen values were a best guess based on typical values around 350 nm in the near UV (Fig. 1). The best illumination method will ultimately depend on the relative reflectances of wire and background. If the background reflectance is much greater than that of the wire, the background and not the wire should be illuminated. If the wire reflectance is much greater than that of the background, if the reflectances are comparable or if specular reflection dominates, both background and wire should be illuminated, relying on the inverse square law to provide the contrast in pixel intensity.

Since a single illumination strategy may not be optimum in all situations, building multiple capabilities into one detection system should be investigated. This multimode or multisensor approach, when combined with appropriate data fusion, is widely recognized as having a much higher likelihood of success for mine or minefield detection than single sensors alone.[2] For example, passive and active illumination can be accommodated by pulsing the source and polarizers can be inserted or removed. Illumination wavelengths should be chosen to maximize the contrast between tripwires and backgrounds.

One important conclusion of the initial modelling studies was that, in daytime, natural illumination might give better detection results than artificial illumination, provided that tripwires were purely diffuse reflectors. The improved detectability, combined with the potentially simplified broadband imaging system, makes such a configuration desirable. (In the previously described CCD tripwire imaging experiments, some tripwire reflectivities did exhibit a specular component, which should be further investigated.) To assess detection in the general visible band, data extracted from the CCD imaging experiments were inserted into the model. Additional cases were then run at specific wavelengths in the visible waveband where it was thought that contrast might be optimal.

Cases were modelled using yellow and green military tripwires with no artificial illumination. The specular component of reflection was assumed to be zero. Three different levels of background reflectivity variability ($\sim 2-11\%$) were tried for each wire colour. The largest variability was typical of the overall scene background variation found in the measured images. Tripwire detectability is more dependent on local variations in reflectivity in the vicinity of the wire, since detection algorithms start with some form of edge detection in which averages of nearby pixels are subtracted from each pixel being tested. The smaller variations used in the model were more typical of those local variations. It was found that SNR was primarily affected by background variability. The SNR decreased from 21 to 3 for the green wire and from 10 to 1.6 for the yellow wire, as the background variability changed from 2 to 11%. Tripwires were detectable in all cases, and detection would be even more enhanced if line detection techniques were employed.

4. LINE DETECTION ALGORITHMS

From the above discussion, it is observed that in most cases in practical geometries there is sufficient contrast between tripwires and background to make detection of individual tripwire pixels possible. To make a reliable and practical tripwire detector, however, automated techniques are required to detect lines of such contrasting pixels in real-time.

Automatic target detection methods can free the operator from the burden of making split second decisions, and can increase the Pd and reduce the FAR.

Even though the SNR of the difference between tripwire and background signals may be low for a single pixel, algorithms which exploit the existence of a linear string of similar pixels, as is likely to occur with a taut wire, may substantially enhance the probability of detection of the tripwire. To this end, a number of line detection algorithms were investigated. Most line detection techniques are based on edge detection methods that have been investigated for decades.[4] These methods generally detect edge fragments in isolation and do not consider them as as a set of parts of larger linear or curvilinear features. Random edge pixels due to noise or clutter can further obscure the disconnected edge elements, making the interpretation of them as a connected linear structure difficult.

A few line detection methods exist that use the context of a line to interpret colinear sets of edge elements and link them into lines. Two of the more popular, which have been used for almost 30 years, are the Hough and Radon transforms. Both map two dimensional images with lines into a parameter space where each line in the image produces a peak positioned at its corresponding line parameter coordinates. The computationally intensive segmentation process, which is required in other methods, is replaced by a peak finding strategy to detect the lines and determine their positions and angles. Both transforms are good at extracting lines from noisy data. Furthermore, they can detect lines with obscured or missing segments, such as one would typically find in a tripwire scenario. A complete discussion of the two algorithms is beyond the scope of this paper, but the reader is referred to Refs. 5 and 6 for more details.

The Hough and Radon transforms were coded and optimized for the tripwire detection geometry and conditions. A number of tripwire images with plain and cluttered vegetation backgrounds were tested. The lower image in Fig. 7, taken in the optical darkroom with fluorescent lighting, shows a set of tripwires against a black background. The upper image is a smoothed, equalized, edge-enhanced Radon transform image of the left hand portion of the raw image. Note that the four tripwires and a portion of the frame edge, which appears as a parallel line in the lower image, are detected (five compact, high intensity features near $\phi = 176°$ on the Radon transform image). This agrees well with the angle of roughly 4.5° between the wire direction and vertical (in the analysis, the vertical direction is 0° or 180°). The features corresponding to the tripwires are equally spaced on the displacement axis, as they should be. Also seen are two close bright features at $\phi = 0°$, which correspond to the two vertical frame edges and possibly the vertical image boundary. A less intense compact feature is also seen at $\phi = 90°$ and near maximum negative displacement which may be an artifact due to a horizontal image boundary. Similar results were obtained for specular reflection cases and for tripwires against cluttered vegetation, except that in the latter case, a few more false alarms were observed, presumably due to horizontal linear features in the vegetation.

The complete tripwire detection algorithm used to create Fig. 7 is parallelizable and can be implemented on simple, inexpensive real-time digital signal processors (DSPs). To show this, the algorithm was analysed as a state machine, assuming a geometry and imager similar to what has been described, and the required number of computations per image was determined. A search was made for processors, capable of parallel processing, that could execute the required number of operations fast enough to allow real-time analysis (> 10 images per second, using two processors in parallel). Three families of commercially available digital signal processors were identified that were suitable.

5. DISCUSSION

From the experimental measurements and the modelling studies, a number of points should be mentioned.

In the limited experiments and modelling that was done , it appears that it is generally possible to detect tripwires in a realistically cluttered environment. The tripwire is most detectable when the camera looks upward and the wire is viewed against the sky as background. A down looking geometry with the wire viewed against dirt might be better than viewing against vegetation, since the former may be less cluttered. However, experimentation and modelling using a dirt background were very limited and more research is needed. Specular reflection SNRs were much higher than those for diffuse reflection, but the specular component of wires must be better characterized to see if it is significant for realistic geometries. A high SNR may be achievable in natural light, but more tests are needed for various conditions.

SNRs are a function of the changing geometry, target and background materials, but it may be possible to adjust the instrument to maximize the SNR. The SNR for active illumination may be better or worse than that for passive illumination, depending on the situation. A way around this is to obtain active and passive images essentially

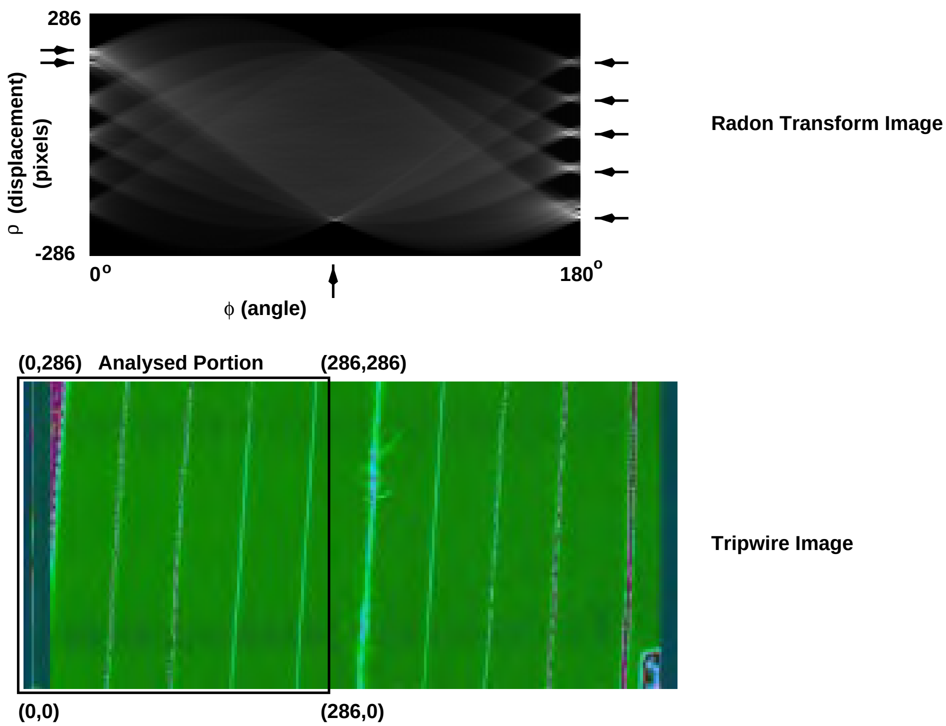

Figure 7. Image of tripwires against a black background (bottom) and corresoponding Radon transform of smoothed, equalized, edge-enhanced image (top).

simultaneously by employing a pulsed source and gated detector. Illumination conditions can also conspire to yield a SNR of 0, that is, no contrast between wire and background. Modelling studies and observations of power lines verify this. Fortunately, this will likely occur in only one part of the spectrum. If a field measurable parameter or an initial test can indicate this condition prior to the start of mine clearing operations, it may be possible to switch to another portion of the spectrum.

Most of the trip wires were successfully detected in the images that were acquired. Nevertheless, the probability of detection and false alarm rates for general wavebands and a wide variety of scenarios could not be determined, since information for many cases came only from the spreadsheet model. Pd and FAR are a function of the signal-to-noise ratio in the vicinity of the wire along its length and the number of pixels subtended by the tripwire and must be determined following application of line detection or other image processing algorithms to a realistically cluttered image. In addition to Pd and FAR, optical requirements of the instrument and maximum standoff distance for detection are critically dependent on the number of pixels subtended by the tripwire. Extensive experiments will thus be required to quantify Pd and FAR and the minimum and optimum number of pixels that a tripwire can subtend.

As a complement to experiments to determine Pd and FAR, it might be possible to integrate the spreadsheet model with an image model. This would reduce the number of experiments needed by allowing estimation of Pd and FAR for a complete end to end system employing different line detection and other image processing methods, a wide range of wavebands, geometries, and illuminations. The model could be also be refined to determine in field operations confidence parameters, such as the Pd and FAR, based on real-time evaluation of background and illumination. Realtime confidence parameters could also be used to tune the detection algorithm or the instrument or to determine a safe sweep speed.

6. CONCLUSIONS

Research to assess the feasibility of developing a standoff active or passive optical tripwire detector has been described. Reflectivities of typical tripwires and background materials were measured for UV, VNIR and SWIR wavelengths. A breadboard testbed was developed to obtain images of tripwires against various backgrounds for various geometries and a wide range of UV and VNIR wavelengths. Sample images of simulated and real tripwires in uncluttered environments and against typical cluttered backgrounds were acquired and analyzed. Line detection algorithms were applied to the images to detect tripwires. Although detection was not attempted in real-time, analysis showed that available, cost-effective digital signal processors could potentially execute those algorithms on the images in real-time. The algorithms successfully detected tripwires in a heavily cluttered background and even have the capability to detect partially obscured wires. To complement the measurements, a spreadsheet model was developed to evaluate the merits of different detectors, sources of illumination, wavebands and geometries for different scenarios. Acceptable signal-to-clutter ratios were found for a number of reasonable passive and active illumination scenarios.

The study demonstrated that an optical tripwire detector is feasible in principle, but additional information is needed before building a prototype. This is the subject of ongoing research. Further research is required on VNIR imaging, including active and natural sources, active specular reflection, dirt as a background and colour imaging at high resolution. High resolution imaging will allow investigation of texture analysis to compare with techniques which are intended for wires with widths of a few pixels or less than a pixel. High resolution imaging will also allow determination of the optimum number of pixels that a wire should subtend. Optimum wavebands must be selected, based on expected SNR and ease of implementation. The performance limits of the line detection algorithms must be explored and real-time implementation must be demonstrated. Probabilities of detection and false alarm rates of the complete detection system need to be estimated for practical scenarios. With this information, the configuration can be optimized and the likelihood of success of a practical tripwire detector can be determined.

After the above issues are resolved, a conceptual design for a practical prototype hand-held or vehicle-mounted tripwire detector prototype, already being formulated, will be completed. The tripwire detector will then be developed in two stages. First, a real-time vehicle-mounted prototype will be constructed, thoroughly tested, and evaluated. A vehicle mounted configuration will allow flexibility in developing the detector without the tight space, power and weight constraints of the person-portable role. If successful, the size, weight and power reduction of the vehicle-mounted unit would lead to a person-portable field prototype unit.

ACKNOWLEDGMENTS

Preliminary research leading up to the work described was sponsored by the Canadian Space Agency under the STEAR program, the Defence Research and Development Branch (DRDB) of the Department of National Defence, Canada and Itres Research. The present work was supported by DRDB, under Project 2mb20, and the Canadian Center for Mine Action Technologies (CCMAT).

REFERENCES

1. C.Horwood, B.Howell, R.Keeley, and J.-B. Richardier, "The use of dogs for operations related to humanitarian mine clearance," Technical Report ISBN 2-909064-33-6, Handicap International, 1998.
2. J.McFee, V.Aitken, R.Chesney, Y.Das, and K.Russell, "A multisensor, vehicle-mounted, teleoperated mine detector with data fusion," in *Detection and Remediation Technologies for Mines and Mine-like Targets III*, A.C.Dubey, J.F.Harvey, and J.T.Broach, eds., *Proc. SPIE* **3392**, pp. 1082–1093, 1998.
3. S.K.Babey, C.D.Anger, S.B.Achal, A.Moise, P.R.Costella, and J.DeBliek, "Development of the next-generation Compact Airborne Spectrographic Imager: **casi-2**," in *Fourth International Airborne Remote Sensing Conference/ 21st Canadian Symposium on Remote Sensing*, (Ottawa, ON, Canada), June 1999.
4. B.K.P.Horn, *Robot Vision*, ch. 8, pp. 161–184. MIT Press, 1986.
5. R.O.Duda and P.E.Hart, "Use of the Hough transform to detect lines and curves in pictures," *Communications of the ACM* **15**, pp. 11–15, 1972.
6. S.Helgason, *The Radon Transform*, Birkhauser, 1980.