Improved Intruder Detection Using Seismic Sensors and Adaptive Noise Cancellation

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Abstract

Maintenance of a secure perimeter around military camps is a significant problem. Detecting foot-borne intruders is a particularly difficult aspect of this problem. Visual surveillance and electronic imaging currently serve as the primary surveillance modalities. Seismic sensors, however, offer an attractive alternative and several commercial seismic surveillance products are available. These systems usually employ a small seismic sensor (geophone) combined with on-board signal processing algorithms to automatically detect personnel and vehicles. The performance of the existing seismic sensor systems, however, is often limited by local interference sources. Under funding from the U.S. Army ERDC-CRREL, Creare has been developing a seismic monitoring system that employs innovative data processing algorithms to overcome some of the limitations of the existing systems. In particular, we have developed adaptive noise cancellation (ANC) algorithms that have proved effective against certain classes of interference sources. In the work presented here, we performed controlled field tests with interference from a nearby diesel tractor engine and from a nearby gasoline power generator. Despite this interference, our ANC algorithms enabled the automatic detection of walking intruders at a range of more than 100 feet.

1 INTRODUCTION

Traditional methods of visual or electronic surveillance can readily detect approaching vehicles; however, they struggle to detect pedestrians operating undercover. Magnetic sensors are being used in some applications, but can only detect vehicles at relatively close range. In contrast, seismic sensors offer much greater detection ranges (approximately twice that of passive infrared sensors and three- to six-fold greater than magnetic sensors). Unfortunately, the tremendous potential of unattended seismic monitoring has yet to be realized. For example, detection ranges have been shown to fall dramatically during the daytime due to increased seismic noise levels (Peck 2004). An evaluation of two of the leading commercially available systems (REMBASS-II, L-3 Communications and EMIDS, Qual-Tron) revealed that the maximum footstep detection range was only 30 meters with a reliable detection range of only about 10 meters (Peck 2006).

We believe that personnel detection range is limited by the current state of the detection algorithms. We believe that significant improvements in detection range can be achieved
through advanced algorithms that better account for the wide range of conditions—especially background noise and interference—that may be seen in our perimeter surveillance application.

Any intruder detection system must contend with the large variability in both signal amplitude and morphology caused by differences in seismic propagation and variability in the distance between the subject and the nearest sensor. One widely accepted method of intruder detection is based on the computation of kurtosis (Succi 2001), which is a measure of statistical distribution used to detect extreme deviations from the mean (such seismic impulses due to footsteps). Another approach used by some investigators is to detect footsteps in the frequency domain by looking for the regular cadence of a typical human gait (Houston 2003). Both of these methods are block-wise processing algorithms that look for a collection of footsteps prior to issuing an alert.

An alternate approach is to search for individual footsteps as opposed to groups of footsteps. Using some combination of filtering and envelope extraction, this approach has been used by a number of investigators (Richman 2001 and Sabatier 2008). We believe that it is this approach—detection of individual footsteps—that offers the best opportunity for addressing the performance deficiencies seen in current systems such as limited range and limited tolerance to interference.

For the application of perimeter surveillance, seismic interference is an important concern. The performance of existing seismic surveillance systems is severely degraded by noise sources such as cars, generators, and wind, which may preclude their use near many active bases and in urban environments. An Army study (Peck 2006) recommended that the Qual-Tron system be used 130 to 200 feet (40 to 60 meters) from legitimate personnel activity to avoid nuisance alarms. The inability to use existing systems close to military bases or roads may render them impractical in many settings.

In the work presented here, Creare has developed its own intruder detection algorithms to improve the detection range. We have also developed adaptive noise cancelation algorithms that reduce the degradation in performance caused by seismic interference from machinery noise.

2 INTRUDER DETECTION APPROACH

Our approach to improving detection range and for improving the tolerance to seismic interference is to focus on improved algorithms. We use off-the-shelf geophones (single-axis, 4.5 Hz geophones) combined with off-the-shelf signal conditioning, digitization, and processing hardware components. Our algorithm stack has three major elements: adaptive noise cancellation (ANC), the detection of individual footsteps, and the detection of an intruder based on the cadence of the detected footsteps. All processing is automated—there is no need to manually set the processing parameters or detection thresholds.

The performance of the Creare footstep detection algorithms can be seen in Figure 1. This data (from ERDC-CRREL) is from a 4.5 Hz geophone for a single walker crossing a hay field located in rural New Hampshire (a very quiet site). The walking course was a straight line toward the sensor. For the three trials shown, the Creare algorithms successfully detected over 50% of the individual footsteps out to a range of 350 feet (105 m).
Figure 1. Performance of Creare Footstep Detection Algorithms in a Quiet Environment. In these three trials, we are able to detect over 50% of the individual footsteps out to a distance of 350 feet. The raw data was provided by ERDC-CRREL.

3 INTERFERENCE REJECTION

Because of the importance of interference rejection for systems that may be used close to human activity, we investigated the impact of machinery noise on the ability to detect walkers. Specifically, we focused on stationary diesel and gasoline motors to simulate the presence of electric generators or heating and cooling units that often accompany military camps or installations.

One example of such interference is shown in Figure 2. In this footstep detection test, Creare laid out a serpentine walking range to generate many footsteps at many different ranges. We recorded the walker using a 4.5 Hz geophone driven into the frozen, January ground. To generate interference, a farm tractor was parked 16.5 feet (5 m) to the side of the geophone. As can be seen in the top spectrogram, the individual footsteps at a range of 100 feet (30 m) are relatively clear with no interference present. Once the tractor engine is running, however, a large amount of interference is generated, as seen by the numerous lines in the lower-right spectrogram. The footsteps are still present, but their energy is much smaller than the interference from the tractor engine.
Figure 2. Walking Test with Interference From a Stationary Diesel Engine on a Farm Tractor. (Left) Serpentine walking course illustrating location of the tractor. (Right Top) Spectrogram of seismic signal from 4.5 Hz geophone with the walker at 100 ft and no interference. (Right Bottom) Spectrogram of the seismic signal with the tractor engine running. Note the significant number of narrowband interference lines.

To reduce the degradation in footstep detection performance that might occur due to such strong interference, Creare developed proprietary ANC algorithms that automatically minimize the signal energy associated with this type of interference. Without ANC, Figure 3 shows that the footstep detection algorithms do not perform well because the signal power of the interference is so much larger than the signal power of each footstep. With ANC enabled, however, the signal power from the interference is greatly reduced and nearly full footstep sensitivity is restored out to a range of nearly 150 ft (45 m).
Figure 3. Footstep Detection Performance Despite Interference From a Diesel Tractor Engine. The tractor is 16.5 feet (5 m) from the geophone. With the baseline Creare footstep detection algorithms (red line), the detection performance is highly degraded by the presence of the interference. With Creare’s ANC algorithms, however, detection performance is restored out to a range of about 150 ft (45 m).

To more fully demonstrate their performance against time-varying interference, Creare performed another series of walking tests, this time with a nearby gasoline-powered electric generator instead of the diesel tractor engine. In this new test series (Figure 4), the walker completed several circles around the geophone at a range of 40 feet (12 m). The generator was placed 20 feet (6 m) from the geophone. Tests were performed while the generator was held at its “high” speed, while it was held at its “low speed”, and while it was toggled between its “high” and “low” speeds every 8 seconds. A spectrogram of the raw seismic signal during this latter time-varying test is shown on the right plot of Figure 4. The variation in engine speed is clearly seen. Also note that there are footsteps present (look to the pulsing energy below 20 Hz) and that they are barely visible beneath the strong interference from the generator.

Figure 5 shows the performance of the Creare footstep detection algorithms in the presence of this interference. As before, the baseline footstep detector is highly degraded by the presence of the noise. Enabling the ANC algorithms, however, restores nearly all of the detection performance (91%). Even in the very difficult case of the time-varying motor speed, the ANC adapted well and excellent detection rates were achieved (81%).
Figure 4. Test to Explore Effect of Time-Varying Seismic Interference. In this test, a single walker completed several circles around the 4.5 Hz geophone at a radius of 40 feet (12 m). A gasoline-powered generator was 20 feet (6 m) from the geophone. Some raw seismic data during the varying-speed generator test is shown as a spectrogram on the right. Note that the individual footsteps are barely visible through the interference.

Figure 5. Footstep Detection Performance Despite Varying Interference From a Gasoline-Powered Generator. The generator is 20 feet (6 m) from the geophone. The walker is completes several circles around the geophone at a range of 40 feet (12 m). Note that ANC is very effective at minimizing the degradation due to the interference. In particular, the ANC enabled good performance despite the varying speed generator.
4 COMPARISON WITH COMMERCIAL SYSTEMS

4.1 SYSTEMS TESTED

A number of seismic surveillance systems are commercially available that advertise some degree of personnel detection capability. For comparison testing with its own processing, Creare was able to borrow a REMBASS II Seismic and Acoustic (SA) sensor as well as a two Qual-Tron Mini Seismic Sensors (MSSH). These units combine a seismic sensor with on-board processing to detect the presence of vehicles or personnel. The two systems issue any alerts via an attached wireless transmitter, which is then received via a corresponding held-held receiver.

Both the REMBASS and Qual-Tron units have a user programmable “gain” or “sensitivity” that is used for their seismic processing. For the REMBASS II SA sensor, the sensitivity was set to “high” for all tests. For the Qual-Tron MSSH units, a gain of “8” was used on one sensor for all tests. For the other Qual-Tron sensor, the gain was varied between “4” and “9” (“9” being maximum) depending upon the particular test conditions.

Note that the REMBASS and Qual-Tron units are fully-packaged, fieldable products. The Creare “system”, by contrast, is composed of a 4.5 Hz geophone attached to a 16-bit data acquisition system whose data is then post-processed on general-purpose computers at a later time. Creare did have a soft real-time prototype software build of its algorithms running on a laptop computer while in the field, but the results reported here are from the post-processed data.

4.2 TEST SETUP

The goal of the comparison testing was to evaluate the range at which the Creare processing was able to detect a walking intruder compared to the range at which the REMBASS and Qual-Tron units detected the intruder and issued an alert.

Creare used two test sites in rural Vermont to compare the three systems. Test Site 1 (Figure 6) was a former horse riding arena. It has ledge base covered with fill and topped with gravel and sand. Due to its disuse for many years, the field had a sparse grass covering. Test Site 2 (Figure 7) was a former pasture that is gently sloping and that has a natural drainage (swale) passing through. The pasture has relatively deep soil (for Vermont) and, at the time of the test, was topped with thick grass (though still less than 1 ft tall).
Figure 6. A Former Riding Arena (Test Site 1) Used for Comparison Testing of Creare Algorithms to Two Commercial Seismic Surveillance Systems.

At both sites, the sensors were arranged in a line. Each sensor was buried about 6 inches into the soil, seated securely, and covered with soil. Two Qual-Tron MSSH units were used, one

Figure 7. A Former Pasture (Test Site 2) Used for Comparison Testing of Creare Algorithms to Two Commercial Seismic Surveillance Systems.
REMBASS II SA unit was used, and two 4.5 Hz geophones (the Creare system) were used. The sensors were evenly spaced over a line that was approximately 13 feet wide. The position of each sensor relative to the others is shown in the inset of Figure 6. The same arrangement was used at the second test site, though the “right” Creare geophone was unavailable at Test Site 2 due to problems with the data acquisition system.

At both sites, each test was performed by having a single walker proceed in-bound along a straight line toward the center of the line of sensors. Cones marked every 50 feet of distance and a voice log was used to note the location of the walker every time he passed a cone. The voice log was also used to note time of each alert generated by the commercial systems. At both sites, the walker started from a distance of 250 feet from the sensor line. Three different walkers were used during the overall test series. The walkers proceeded at a natural cadence of around 2 Hz. No attempt was made to make the cadence especially regular or irregular.

4.3 DATA PROCESSING

For the Creare system, the raw seismic data was recorded by computer. The data was then post-processed using the ANC and footstep detection algorithms as described earlier. ANC was active for all tests. For both the ANC and for the footstep detector, the same processing parameters were used for all tests—the algorithms are fully-automated and require no analyst intervention.

Once the individual footsteps were detected, Creare then applied a proprietary “intruder detection” algorithm that evaluates the properties of the detected footsteps to determine if an intruder is present. The “time” at which the Creare intruder alert is issued corresponds to the time of the individual footstep that finally triggered the intruder detection algorithm. Since this was done in post-processing, no processing latency nor radio transmission latency is part of the Creare alert time.

The processing performed by the REMBASS and Qual-Tron systems is unknown. During the testing, each sensor would issue an alert when it detected the presence of an intruder or vehicle. The alert would be transmitted over the system’s wireless link to a handheld receiver being monitored by the test engineer. The alert tone generated by the receiver would be audible in the voice log. Being in the voice log, the time of each alert tone could be accurately measured after the test. The test engineer would also verbally note which sensor had issued the alert. Unfortunately, the processing and transmission latency of these two systems is not known and could not be accounted for in the results. Therefore, we present the time at which the alert tone was produced by the receiver.

The range to the walker at the time of each alert was estimated by knowing the time when he passed each 50 foot marker. Using these markers, the time of the alert was converted to range through simple linear interpolation.

4.4 TEST RESULTS

The results for all of the tests are shown in Table 1. The results are described in detail in the sub-sections that follow.
Table 1. Detection Range of a Single Walking Intruder at Two Sites in Rural Vermont With and Without Additional Interference Noise. The red color coding indicates a detection range of less than 50 feet. Yellow indicates a detection range of 50-100 feet. Green indicates a detection range greater than 100 feet.

<table>
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<tr>
<th>Test Conditions</th>
<th>Creare</th>
<th>REMBASS</th>
<th>Qual-Tron</th>
</tr>
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<tbody>
<tr>
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<td>Site</td>
<td>Walker</td>
<td>Noise</td>
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<td>1</td>
<td>B</td>
<td>Quiet</td>
</tr>
<tr>
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<td>1</td>
<td>B</td>
<td>Quiet</td>
</tr>
<tr>
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<td>D</td>
<td>Quiet</td>
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<tr>
<td>13.1</td>
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<td>Generator</td>
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</table>

4.4.1 Results in Quiet

At both sites, walking tests were performed with no added background noise. The results are summarized in Figure 8 and in the top half of Table 1. Note that the Creare detection range exceeded 150 feet in all but one case and was greater than 200 feet in two cases. By comparison, the performance of the Qual-Tron units was good at its maximum setting ("Gain 9") but dropped off rapidly as its gain setting was decreased. The REMBASS system was at its "high" sensitivity but did not perform well against personnel walking at these two sites.
Figure 8. Detection of a Walking Intruder Using the Creare Algorithms Versus Two Commercial Systems—the Qual-Tron MSSH and the REMBASS II Seismic and Acoustic Sensor. Each test was performed with a single in-bound walker under quiet conditions with no additional interference sources.

4.4.2 Results with Interference from a Diesel Tractor Engine

At Test Site 1, we performed tests with added interference. We used a stationary diesel tractor (this was a different tractor than used for tests discussed in Section 3) that was located 40 feet behind the line of sensors. With the tractor running, we found that both Qual-Tron units began continually issuing false personnel alerts. As a result, we unburied the Qual-Tron unit that had been set to “9” and dialed it back to “6”. It was still issuing false alerts, so we turned it down to “4”. At this setting, no false alerts were generated. We re-buried the sensor and proceeded with our walking tests. The unit that had been set to “8” was left undisturbed.

The detection ranges that we achieved despite the interference from the diesel tractor engine are shown in Figure 9 and the bottom half of Table 1. This test was performed only at Test Site 1 and it used a different walker than the tests in quiet. Note that the performance of the Creare system was still excellent with all detections in excess of 150 feet and with three of the detections past 200 feet. The commercial systems, by comparison, did not perform well in the presence of this interference.
Figure 9. Detection of a Walking Intruder With Interference From a Stationary Diesel Tractor Engine. The tractor was 40 feet behind the sensors. Each test was performed with a single in-bound walker at Test Site 1.

### 4.4.3 Results with Interference from a Gasoline-Powered Electric Generator

At Test Site 2, we added interference by using a gasoline-powered electric generator (this was the same generator as used in Section 3). The generator was placed about 40 feet behind the line of sensors. The speed of the generator was not controlled, but left to equilibrate naturally based on the power being drawn from it by the laptop computers and data acquisition system. The speed was generally constant and it was generally closer to its “high” setting than its “low” setting.

As before, the interference caused continuous false alerts from the Qual-Tron systems with high gain values. Again, we un-buried the sensor that had been set to “9”, dialed it back to “4”, and re-buried it. We left the sensor set to “8” undisturbed.

The results of these tests are shown in Figure 10 and in the bottom half of Table 1. Note that the performance of the Creare system in this test was substantially lower (56–68 feet) compared to the interference-free cases for this site (130–179 feet). It appears that the ANC algorithms were not as effective on the generator noise as there were on the tractor engine noise. Still, the results for the Creare system substantially exceeded the results from the commercial systems. The commercial systems did not perform well in the presence of this interference.
4.5 TEST CONCLUSION

In all tests, the Creare system appears to show better detection range than the commercial systems. In the tests in quiet, the Qual-Tron systems showed good results at high sensitivity, but that high sensitivity made the units unusable in the presence of interference. As a result, good performance requires user intervention to tune the system to the expected operating conditions. The Creare algorithms, by contrast, use entirely automated processing that learn from and adapt to the changing conditions. As a result, the Creare algorithms achieve their maximum performance both in quiet and in interference without user intervention.

5 SUMMARY

Creare has been developing a seismic surveillance system for improving the detection of walking intruders. Creare has focused on advanced algorithms to increase the detection range against walkers and to improve the tolerance to interference sources. Creare has demonstrated the effectiveness of its approach through field experiments in quiet environments and against interference from stationary diesel engines and gasoline generators. Our detection ranges exceed those of two commercial systems in quiet and especially in the presence of the interference.

6 REFERENCES


