Footstep Detection and Tracking

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Abstract

Persons or vehicles moving over ground generate a succession of impacts; these soil disturbances propagate away from the source as seismic waves. These seismic waves are especially useful in detecting footsteps which cannot be detected acoustically. Footstep signals can be distinguished from other seismic sources, such as vehicles or wind noise, by their impulsive nature. Even in noisy environments, statistical measures of the seismic amplitude distribution, such as kurtosis, can be used to identify a footstep. These detection methods can be used even with single component geophones. Moreover, the seismic signal is a vector wave that can be used to track the source bearing. To do such tracking a three-component measurement is needed. If multiple sources are separated in angle, we can use this bearing information to estimate the number of walkers.

Keywords: detection, tracking, seismic, passive sensing

1. Introduction

The task here is to use a seismic sensor to detect people walking nearby the sensor. In a previous paper[1] we discussed the use of a 3-component sensor to detect and track personnel. The virtue of a 3-component sensor is that it can be used to determine the bearing of the signal (exploiting the vector properties of the Rayleigh surface wave). DARPA has asked us to consider a sensor that can be launched from a 40 mm grenade launcher. In designing the sensor we found there is simply not enough room to include the 3 geophones necessary for a measurement for the vector wave. We considered the problem of personnel detection using a single geophone. Here we discuss a method to distinguish between footsteps and other seismically induced signatures using the single component sensor

A footstep signature is caused by the impact on the ground. The ground is an elastic half space that supports waves that travel away form the point of impact. Each footstep has a characteristic shape that can be used to distinguish it from other noise. One way to detect footsteps is to look for the periodic impact. The interval between impacts depends on the walker's (~2 Hz)

The most striking feature of the footstep when comparing time series data for footsteps to other seismic signatures is the series of sharp "spikes" generated by each impact (figure 1). This differs from the random noise induced by the winds over the ground and from vehicle noise. Vehicle noise is composed of two parts: a periodic signature at the track impact rate and a broadband signature due to interaction with the random surface features on the ground. The problem is how to quantitatively distinguish the shape of a footstep signature from other seismic signatures.

We make this distinction by considering a statistical measure of the amplitude of the signature, the *kurtosis.* Kurtosis is ratio of the 4^{th} to 2^{nd} moment of the amplitude distribution of the signature. The kurtosis value compared for a sample sequence is much higher in the presence of impulsive events than it is in the presence of Gaussian or sinusoidal signatures.

The technique is a common in the detection of machine faults in roller bearings. In roller bearing wear faults form as surface imperfections in the bearing races. As each ball rolls past the race, it excites as structural wave that is carried throughout the machine. A transducer (usually and accelerometer) on the machine housing can detect the imperfection by monitoring the kurtosis.

Note that the method depends only on the shape of the signature and not the amplitude. This is an important aspect of the technique. The problem is that the absolute amplitude detected by the transducer varies from site to site. The variation is caused by both the type of ground and the transfer function between ground and transducer.

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2 Sample signatures

Figure 1 depicts a footstep signature. The data was taken at Ft. Irwin with a Geospace type GS-20 vertical transducer. Data is acquired at a rate of 1 kHz. Most of the energy is in the band from 10 to 100 Hz. A four second record is presented. During this time there are 8 footsteps. The raw signature is illustrated in the top of the figure, and the envelope of the signature in the bottom. The envelope is computed by taking the amplitude of the analytic signal

For each chunk of N samples of data, the kurtosis is calculated:

$$Kur = \frac{\dfrac{\sum_i (x_i - \mu)^4}{N-1}}{\left(\dfrac{\sum_i (x_i - \mu)^2}{N-1}\right)^2}$$

where μ is the computed mean over N samples;

The kurtosis can be calculated for either the raw signature or its envelope. The qualitative results are similar for both calculations. The magnitude of kurtosis tends to be higher for the raw signature, and we will use it herein. In this particular record the kurtosis is ~13. Kurtosis values computed for sinusoids are less than 2 and for Gaussian noise are approximately 3.

Our technique is analyze the signal in overlapping 4 second increments, and compute the statistics of the signal in that sample. In figure 2 we present the data for a single walker moving in a circle of 30 m radius. Figure 2a gives the bearing computed with the 3 axis geophone, Figure 2b gives the kurtosis of the signal, and figure 2c the signal level (in arbitrary units) . The kurtosis varies with time but is always above the threshold value (5).

In Figure 3 we present data taken at Ft Irwin. During this test the sensor was located approximately 50 m from a dirt road. Also there is a group of people monitoring the sensors ~70 m from the road and 30 m from the sensor. The purpose of the test was to monitor the acoustic and seismic signature of a large wheeled armored personnel carrier as it traveled along the road. In figure 3a we present the seismic level (solid line) and in figure 3b the distance from the sensor to the APC. Notice that the signal level goes up as the distance decreases (the expected result)

We also plot the kurtosis of the seismic signal (crosses) in Figure 3a. Notice that when the vehicle is close to the sensor, the vehicle signature dominates, and the kurtosis is ~3. As the vehicle moves away the kurtosis increases. This signature is from the test personnel located nearby

3.0 Kurtosis statistics for background noise and vehicles

The kurtosis itself varies with target, time and distance. Here we will look at the distribution and demonstrate that for vehicles and background noise the kurtosis is low. Our technique is to break the data sample into 4 second increments, and then to compute the kurtosis of the signature in each increment.

In figure 4 we present the distribution for ambient noise. The mean of the kurtosis is 3 and the variance 0.4. In figure 5 we present the distribution for a light passenger car. The mean of the kurtosis is about 3, and the variance approximately 0.6 In figure 6 we present the signature for the APC (for those times in which the APC was close) Here the kurtosis is again 3, and the variance a larger 1.9. In all three cases, background noise, light passenger vehicle, heavy armored personnel carrier, the mean value of kurtosis is approximately 3. The data is summarized in tables 1, and 2.

Table 1. Ambient noise (Ft Devens)

	Sensor 1		Sensor 2	
Run	μ_{kur}	σ_{kur}	μ_{kur}	σ_{kur}
fde001	3.02	0.46	3.17	0.89

Table 2. Toyota Camry runs N/S (Ft Devens)

	Sensor 1		Sensor 1	
Run	μ_{kur}	σ_{kur}	μ_{kur}	σ_{kur}
fde010	2.92	0.30	2.66	0.40
fde011	3.01	0.41	2.92	0.38
fde012	2.94	0.56	2.86	0.28
fde013	2.90	0.33	2.89	0.25
fde014	3.03	0.35	3.00	0.34

3.1 Kurtosis statistics for a single person

Now consider a single person walking. Figure 7 shows the kurtosis distribution for a person walking in a circle around the sensor. Data was taken at radii of 10, 20, 30, 40, and 50m. The mean kurtosis is approximately 6 with a variance of 2.5 We repeated the experiment with a person jogging and got similar results (a kurtosis of 7 and a variance of 3.4, see Figure 8) A summary of the data is presented in tables 3 and 4.

Table 3 . Person walking in circles (Ft. Devens)
(50, 40, 30, 20, 10 m radius)

Run	Radius	μ_{kur}	σ_{kur}
fde015	50	6.12	2.41
fde016	40	5.78	2.60
fde017	30	5.13	1.91
fde018	20	6.77	3.27
fde019	10	8.07	5.01

Tables 4. Person jogging in circles (Ft. Devens)
(50, 40, 30, 20, 10 m radius)

Run	Radius	μ_{kur}	σ_{kur}
fde026	50	5.91	1.94
fde027	40	6.81	2.46
fde028	30	7.89	3.21
fde029	20	9.27	5.03
fde030	10	9.44	4.79

Close inspection of tables 3 and 4 show that the kurtosis is proportional to the distance of the person from the sensor. The mean of the kurtosis with distance is given in figure 9. Though the correlation is weak, it might be used as an approximate measure of distance from the sensor. The measure of distance can be improved if the kurtosis is used in combination with signal amplitude.

We repeated the test of a single person walking in a circle at a different site (Ft. Irwin) and got similar results. Here the mean kurtosis varied between 10 and 13. During this test we took data on 3 sensors: (1) a commercial geospace 3 axis geophone attached to the ground with a 3" spike, (2) a single geophone mounted in a cylindrical container buried 1" in the ground, and (3) a single geophone mounted in cylindrical container lying on the ground. These three sensors differ in the contact impedance, but give very similar mean kurtosis measurements. Sensors (2) and (3) were prototypes of the DARPA 40 mm grenade launched sensor. In addition to the mean and variance we list the minimum kurtosis computed. This minimum is always above 5. Setting a kurtosis threshold of 5 means a near100% probability of detection of a person walking this close to the sensor.

Table 5 Person walking in 10 meter circles (Ft Irwin)

	Sensor 1			Sensor 2			Sensor 3		
Run	μ_{kur}	σ_{kur}	Min	μ_{kur}	σ_{kur}	Min	μ_{kur}	σ_{kur}	Min
fid015	13.2	4.0	5.6	12.8	5.0	6.6	13.1	5.5	4.9
fid016	12.2	4.8	7.2	11.8	3.6	7.5	11.8	3.4	6.4
fid017	12.1	3.8	6.2	12.4	4.0	5.4	12.3	3.6	5.8
fid018	10.8	4.0	4.9	10.8	5.9	3.6	12.2	4.6	5.9

3.2 Kurtosis statistics for many people

In this section we review data for multiple targets. The data was taken at fort Irwin, and the targets approached, circled, and then left the sensor area. The first two tests were done with two people walking. The mean kurtosis is about 7.5. (figure 11) In the second test 8 . (figure 12) people of differing size, carrying different loads , approached circled and left the sensor area in much the same manner. The mean kurtosis is now closer to 5, still above that for a vehicle or background noise, but not as much as one or two people

Table 6. "Troop movements"

	Sensor 1 (blue)			
Run	μ_{kur}	σ_{kur}	Min	
fid313	7.25	4.21	2.63	2 people
fid314	8.85	6.27	2.63	2 people
fid415	4.96	3.43	2.32	8 people

4.0 ROC Curves

From the kurtosis distribution we can construct ROC (Receiver Operating Characteristic) curves[3]. These curves are normally constructed assuming Gaussian distribution of a signal amplitude. It is also possible to consider the non Gaussian distribution of the kurtosis. The "noise" distribution can be constructed from the measure of ambient noise, or from that of the vehicle signature. The "signal" distribution can be that of any combination of walker and jogger. For each kurtosis level, the probability of false alarm is the integral under the tail of the "noise" distribution. The probability of correct detection is the corresponding (much larger) integral under the signal distribution. Figure 13 illustrates the process.

5.0 Cadence

Another good indicator of personnel in the seismic signature is cadence: the interval between events. We compute cadence for each 4 second record. The interval between footsteps is approximately ½ second (2 Hz). We compute the interval by identifying each event in the time record, and then measuring the interval between peaks. The alternative, to compute the Fourier transform, does not work with a four second record. The reason is that the bandwidth (1/4 Hz per bin) is not small enough compared to the 2 Hz interval. Expanding the record to longer times does not work because the target moves (or, even worse, stops moving)

Figure 14a depicts the cadence versus time for a single walker. Figure 14b depicts the histogram of the cadence. Notice that the cadence is a narrow distribution centered at 2 Hz. Figure 15 presents the same data for 2 walkers. The measured cadence is approximately the same (2Hz) , but the distribution is much broader.

These results indicate that cadence can also be used in footstep detection

6.0 Bearing

Bearing can also be used to identify groups. If we allow ourselves a 3-component geophone, the bearing of each footstep event can be computed. The average bearing for a 4-second interval for a single walker was plotted in figure 1. It is also possible to plot the bearings of each event in time. Such a plot looks similar to figure 1a, but not as smooth. It becomes useful if there are two walkers separated by a large (>15 degree) angle. In such cases it is possible to distinguish the individual trajectories of the targets.

7.0 Conclusion

A walker can be detected by computing the kurtosis of the seismic signature. This detection measure can also distinguish a walker from vehicle traffic. The measure itself depends on the shape of the signature, and is independent of absolute amplitude. A second measure, cadence, can also be computed from the signature, and used in combination with kurtosis to detect footsteps in the seismic record.

8.0 Acknowledgements

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9.0 References

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2 G. Succi et al**, "**On the Design of a Small Passive Sensor for Locating Vehicles, Footsteps and Gunshots" Defense Law Enforcement Conference, ***Proceedings of SPIE***, Boston 2000.

3 Urick, Principles of Underwater Sound, McGraw Hill, 1967.

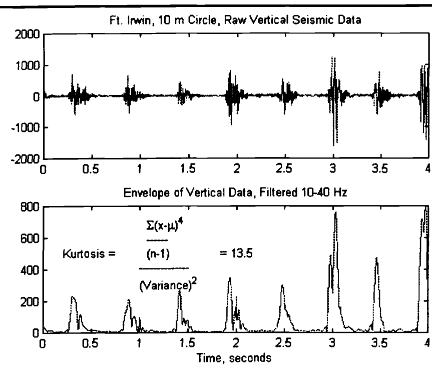

Figure 1 Seismic signal (a) and its envelope (b) of a walker

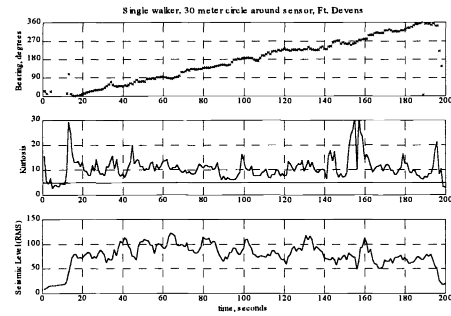

Figure 2 Seismic signal of a walker going in a circle,Bearing, Kurtosis and Level versus time

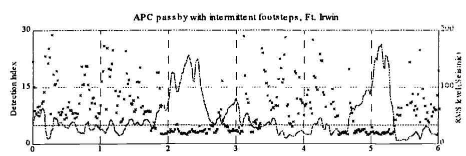

Figure 3A Seismic level during vehicle passby (solid line) and kurtosis

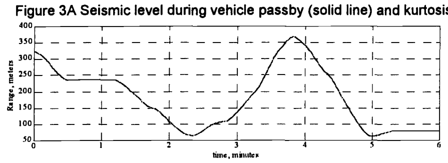

Figure 3 B Vehicle range. Note that when the vehicle is far away,the kurtosis rises as the seismic signal is dominated by the nearby observers

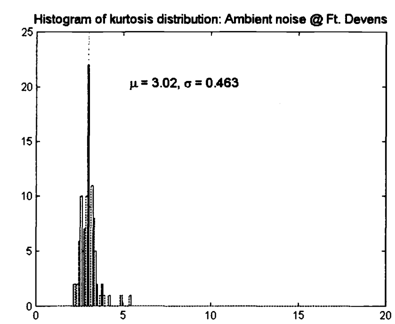

Figure 4 Kurtosis of ambient seismic noise

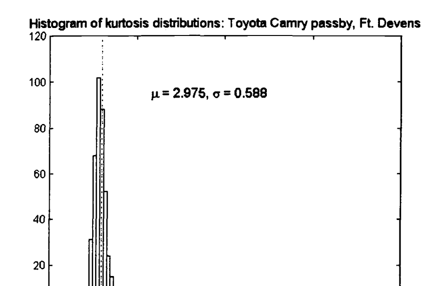

Figure 5 Kurtosis of light vehicle seismic signature

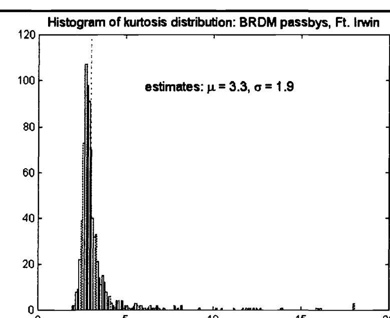

Figure 5 Kurtosis of heavy vehicle seismic signature

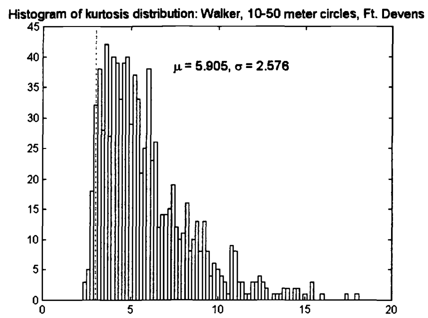

Figure 7 Kurtosis of walker seismic signature, distances from 10 – 50 meters

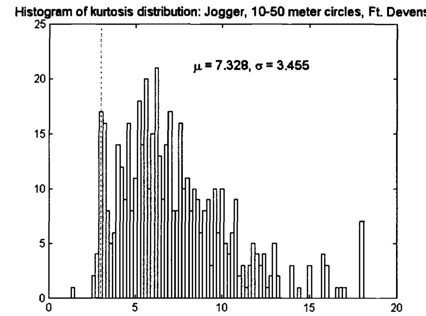

Figure 8 Kurtosis of jogger seismic signature, distances from 10 – 50 meters

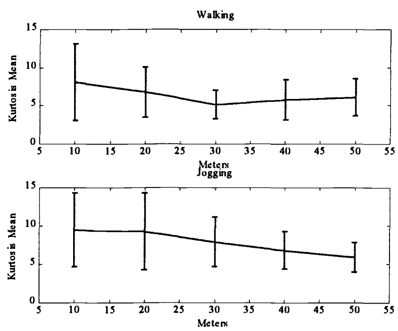

Figure 9 Weak correlation of kurtosis with range

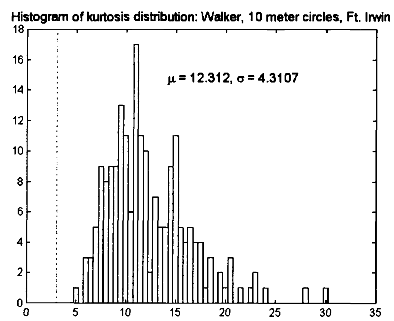

Figure 10 Kurtosis of walker seismic signature, 11 meters from sensor

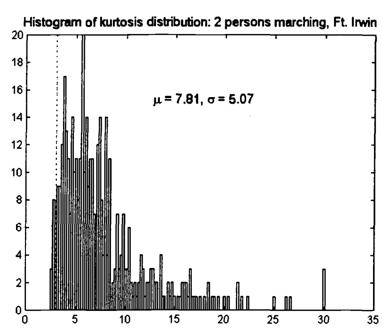

Figure 11 Kurtosis of seismic signature of 2 walkers, various distances

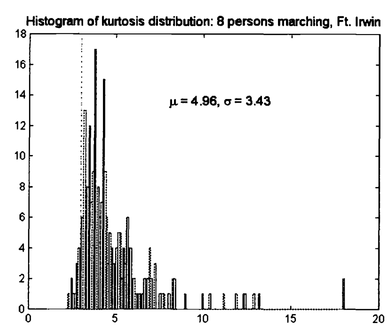

Figure 12 Kurtosis of seismic signature of 8 walkers

Probability density distribution of

Noise and Signal plus Noise

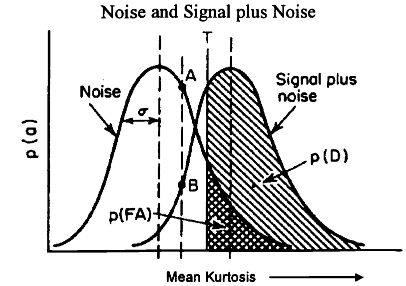

Figure 13 Kurtosis distribution used to construct ROC curves

Interval Between Events One Walker

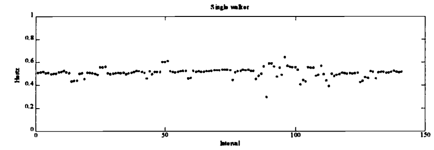

Figure 14a Cadence versus time

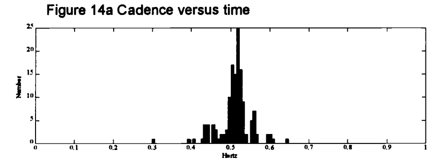

Figure 14a Cadence distribution

Interval Between Events Two Walkers

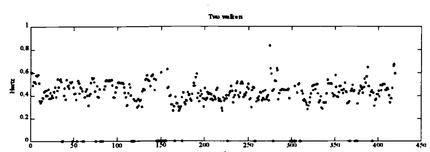

Figure 15a Cadence versus time

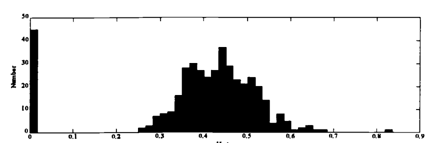

Figure 15b Cadence distribution