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Human footstep detection using seismic sensors

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***Abstract* – This paper is focused on the hardware and software implementation of DSP algorithms for footstep detection using seismic signal. The main contribution of this research consists in a hardware design and in a software application that process the signals received from the seismic sensor of type SM-24 using PC sound card. The signal samples received from the sensor are stored in a .wav file. The main application is written in C# programming language and uses Matlab library (it was created a DLL library that was used in C#) in order to process the seismic signals on a low level.**

Keywords – Seismic footstep detection; DSP algorithms; Kurtosis; Cadence; Feature extraction.

I. INTRODUCTION

Seismic detection and identification systems used in combination with other detection devices such as video cameras (with local processing for the automatic discrimination of relevant information) have a very broad spectrum for the advanced protection of critical military infrastructures and other civil security applications. The advantage of seismic sensors is that can be easily hidden into the ground and an intruder cannot see them through visual inspection. Also, the generation of artificial vibration with the same characteristics as human footstep is very difficult.

When a person walks or runs on the ground generates seismic waves that propagate through the soil as a result of the impact. Measurement of the amplitude of these seismic waves in the soil is realized using sensors named geophones. Geophones do not require an external power source and consist from a spring-mounted coil surrounding a magnet, generating a voltage signal as a response to vibration.

During the past few years seismic signal characteristics have been used for a set of various targets as human walking, running and jumping, vehicles (light or heavy), helicopters and other vibration sources. The detection methods are generally based on either frequency or time domain. In the frequency domain, two types of spectrum analyses methods are presented for the vibration detection: the first one is named wide band spectrum analyses and it is focused on detection of single footstep and vehicle vibration [1]; the second one, named narrow band spectrum analyses, it is focused on several footsteps and vehicle components [2]. The both methods require FFT algorithms and large memory to store the data. In the time domain, one widely accepted detection method is based on the computation of Kurtosis, which measures extreme deviations from the mean signal [3]. In this case, the clear identification of vibration source is very difficult because different types of noise can readily generate deviations very closely to the human footstep [3]. Copula theory presented in [4] is another human footstep detection method and it is based on the measure of statistical dependence between random variables. Another human footstep detection method is based on Markov models and multimodal fusion of sensor data [5].

The paper is structured as follows. In section II it is presented the entire block diagram of the proposed human footstep detection system and are described all the components used. In this section is analyzed the seismic sensor used (SM-24) and is presented an electronic circuit that includes filtering and amplification of the analog signal received from the sensor. The signal is received through the sound card and is processed in order to generate optical and acoustical alarms. Also, in this section, subsection C, is presented the designed algorithm based on a combination of two methods: kurtosis calculation and cadence calculation and analyses where human footstep and other vibration sources classification can be achieved. Section III contains testing and experimental results obtained including performance evaluation. In this section the proposed detection system was tested and verified using different data received from the geophone placed at the test location from the Romanian Transgaz company. Conclusion and future research are discussed in section IV.

II. PROPOSED FOOTSTEP DETECTION SYSTEM

Fig. 1 illustrates how the seismic footstep detector is designed to work. Individual geophone sensors was placed in line along the pipe border of the Romanian Transgaz company and through a cable we collect seismic data from the protected area on a data processing unit (PC). The received data will be saved to a .wav file and will be processed in order to make a decision on whether the seismic activity is in fact human footstep. Once a positive detection occurs, an optical and acoustical alarms will be started. The users will then take an action accordingly with the type of alarm.

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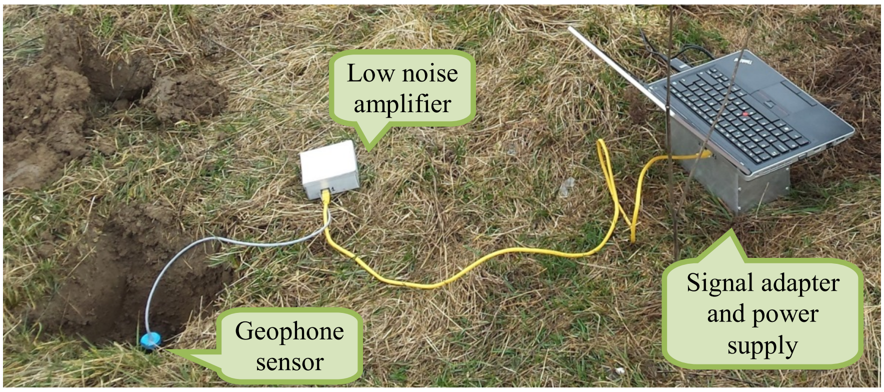

Figure 1. The footstep detection system

The entire project is composed from three primary modules: ***hardware design***, ***data acquisition***, and ***the algorithm used for human footstep detection***.

A. Hardware Design

The hardware system includes a seismic sensor, a low noise amplifier (LNA) and an amplifier for adapting the signal (SA) to the desired level as it is presented in Fig. 2.

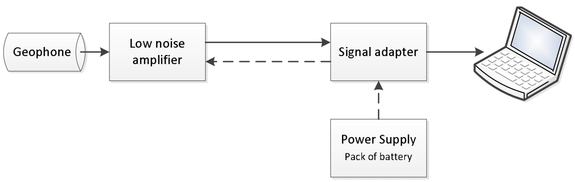

Figure 2. Block diagram of the footstep detection system

The LNA is based on a ultra-low noise operational amplifier with input voltage noise up to 1.2nv/(Hz)1/2. The op amplifier is connected in a non-inverting amp configuration [6] as is shown in Fig. 3.

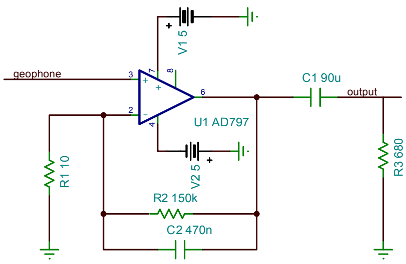

Figure 3. Low noise amplifier schematic

The signal is taken from the geophone and amplified by the LNA via a very short cable for avoidance of additive noise. The amplitude of the output signal from the LNA is large enough that it can be transmitted on a twisted cable to SA on a distance of at least 10m. The signal from the SA is taken through sound card and processed on the computer. The power supply consists of the battery pack and different supply voltages for hardware modules are obtained only by linear sources.

The seismic sensor used is a SM 24 type. This is a low cost geophone that can operate at 10 Hz natural frequency of, with +/- 2.5% tolerance, sub-harmonic distortion is fewer than <0.1% with sensitivity and coil resistance booth +/- 2.5% at damping set at + 5% and - 0%. Maximum operating frequency is 240Hz and the sensitivity is 28.8V/m/s [7]. The output voltage is given by equation (1).

$$V_{out} = \frac{R_1 + (R_2 // C_2)}{R_1} V_{in} \quad (1)$$

Configuration C1, R3 is a high pass filter with cut frequency at 3 Hz which is designed to eliminate the offset component of LNA.

Fig. 4 presents the gain characteristic and Fig. 5 shows the total noise characteristic.

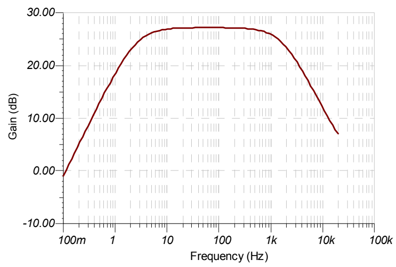

Figure 4. Gain characteristic

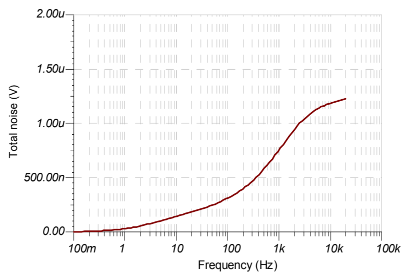

Figure 5. Total noise characteristic

The signal adapter module is given in Fig. 6. It is composed of two sub-modules: the first is a logarithmic attenuator and the second is an inverting amplifier with adjustable gain. The logarithmic attenuator module consists of D1-D4 diodes and U2 operational amplifier. By adjusting the potentiometer P1, the logarithmic attenuator can become a logarithmic amplifier or antilogarithmic. The signal is taken from the second sub-module that is based on operational amplifier U2, which adjust the output level and apply a low pass filtering with cutoff frequency at 1 KHz.

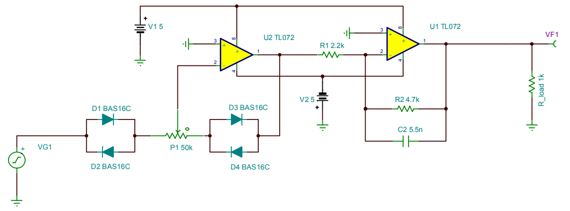

Figure 6. Signal adapter schematic

Fig. 7 outlines the input signal (VG1) and output signal (VF1) when contributes the logarithmic attenuations.

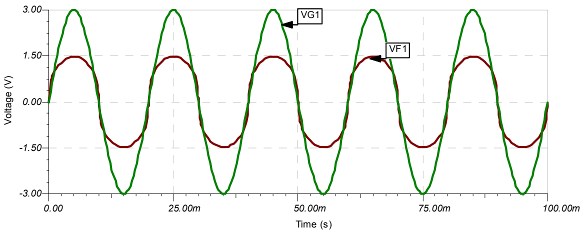

Figure 7. Time domain diagram of input and output signal

For input signal of 3V amplitude, the output will receive limited signal amplitude of up to 1.5V.

B. Data Acquisition

The entire seismic data, after initial filtering and amplification, will be sent through a cable to a central PC using sound card. The signal samples received from the sensor are stored in a .wav file and a software application will analyze the received data in order to make a decision on whether there is human's footsteps or not.

C. The algorithm used for human footstep detection

The important part, after receiving signals from the geophone, is to establish algorithms in order to differentiate between different seismic waves coming from footsteps or other seismic sources. Once the data has been received and saved in a .wav file on central PC, two methods used in combination were used in order to determine whether the seismic signal is human footstep or not. The two methods used are kurtosis calculation and cadence calculation and analyses. Kurtosis generates the measure of the flat and peaked of the seismic signal relative to a normal distribution. The Kurtosis is based on equation (2).

$$Kurtosis = \frac{\dfrac{\sum_{i=1}^{n}(x_i-\mu)^4}{n-1}}{Variance^2} = \frac{\dfrac{\sum_{i=1}^{n}(x_i-\mu)^4}{n-1}}{\left(\dfrac{\sum_{i=1}^{n}(x_i-\mu)^2}{n-1}\right)^2} \qquad (2)$$

In equation (2), μ represent the mean over n samples received form the sensor. The data with high Kurtosis tend to have a distinct peak near the mean and data with low Kurtosis tend to have a flat top near the mean rather than a sharp peak. This value is used to distinguish a periodic seismic signal from random background noise. All in all, as it is also presented in [3] only Kurtosis cannot make a certain decision if the signal received is human footstep or maybe a seismic signal produced by other sources. For this reason, the second method, named cadence calculation and analyses is used to determine the periodicity of the received seismic signal. The cadence values are used to discern between human footsteps and other vibration sources. The usual cadence between footsteps is approximately 2 Hz (half of a second).

The Kurtosis and cadence based algorithm to solve the footsteps detection is presented in Fig. 8.

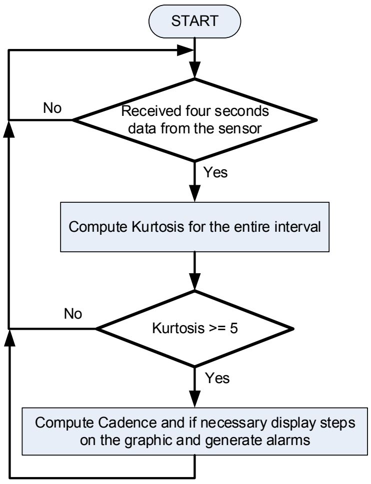

Figure 8. The diagram of the footstep detection algorithm

The same algorithm was also applied to the .wav files that contains large samples received from the sensors. In this case, the data from the files was partitioned in four seconds intervals and for each interval kurtosis was computed. In the same way as in Fig. 8, for each interval, if the Kurtosis value was equal or higher than the threshold (in our case the threshold value is established to 5) than cadence was applied and if the conditions were satisfied (it is estimated that the cadence of the humans lies between 250 ms and 1s) then the results was displayed on the chart and an alarm was initiated. When a group of people are walking on a path they tend to synchronize their steps with each other and walk more or less at the same cadence. In this way we can estimate the cadence and after that classify the results.

III. Testing and Results Obtained

The SM-24 geophone is buried in an open grass field (see Fig. 1) and human footsteps are used to generate seismic events starting from the sensor and ending when losing the footstep signal. In all tests, the signal is down-sampled to 8000Hz for processing.

Fig. 9 shows the signature of a person walking under quiet conditions.

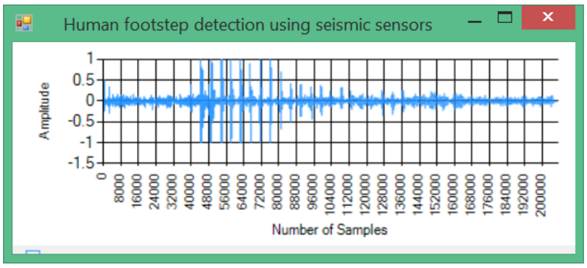

Figure 9. Seismic signal from single human walking

Once the received signal has been analyzed and classified as human footstep or not (using the algorithm presented in section II), the results are displayed to the user through the graphical user interface of the application developed in C# language. The results for a single walking intruder under quiet conditions are summarized in Fig. 10. In Fig. 10 and also in Fig. 12, the green dots represent peaks in the signal to be validated by Kurtosis and red dots indicate that an alert has been triggered and there is human activity (footsteps) in the region of the seismic sensor.

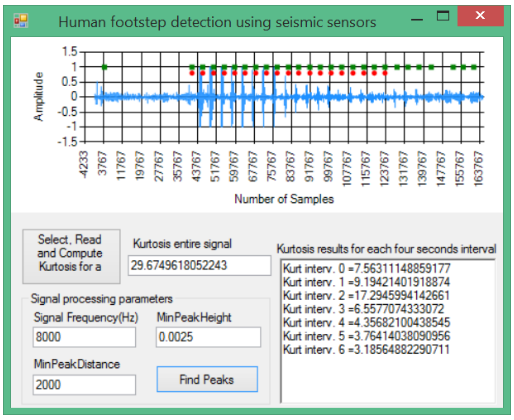

Figure 10. Detection of a walking intruder (red dots)

Fig. 11 shows the signature of two humans walking under quiet conditions.

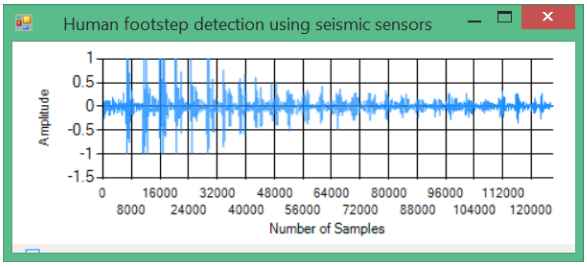

Figure 11. Seismic data from two people walking

The results for two walking intruders under quiet conditions are shown in Fig. 12.

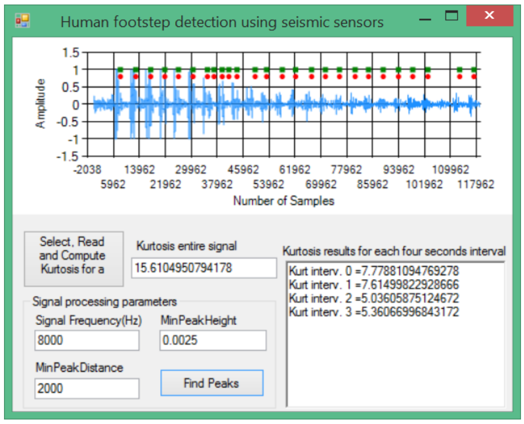

Figure 12. Detection of two walking intruders (red dots)

General remarks after testing the system under different scenarios (single or multiple humans walking and running) are as following: *Detecting range*: the system can detect walking and running people around 80Kg at a range of 0 – 20 m under quiet conditions; *accuracy of detection*: the system is able to detect the human footsteps correctly 100% of the time at 0–15m; *speed reporting*: the system detect trespasser in each 4 second interval.

IV. Conclusion and Future Research Directions

In this paper we have presented a hardware and software solution for a human footstep detection system with geophone of type SM – 24. This is an original design on 16-bits resolution that reduces the effort in data post processing and the algorithm presented demonstrates the ability of Kurtosis and Cadence working together to obtain good results. The obtained results through the use of seismic sensors in footstep detection indicates that geophones are good solutions due to their simplicity and high sensitivity.

In the immediate future, though until now different test scenarios were implemented (humans by different weights, walk, running and jumps), the algorithm will be verified using extensive field tests including other vibration sources such as: vehicles, animals, rain and different types of soil. Therefore, the integration of solutions based on neural networks in order to efficiently detect other classes of security breaches represent the immediate team focus.

Acknowledgment

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