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A Fiber Optic Seismic Sensor for Unattended Ground Sensing Applications

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Fiber optic seismic sensors have been increasingly recognized as promising technologies for many applications, such as intruder detection and perimeter defense systems. Among these, a military seismic sensor is especially challenging because it requires a robust, compact, reliable, easily installable and operated product. This article reports on our recent experimental investigations of a military fiber optic seismic sensor. In particular, an improved sensor design and new signal processing techniques are illustrated in this article, which include: (a) a scanning laser wavelength-based demodulation system; (b) a digital lock-in amplifier and field programmable gate array techniques for weak signal detection and processing; and (c) overall improved seismic sensitivity based on carbon fiber composite cantilever and fiber-Bragg-grating sensing technology. The experimental results show that the fiber-Bragg-grating seismic sensor frequency response band is between 10 and 300 Hz and that it has a higher sensitivity than the conventional electromagnetic geophone within the frequency response band most important for battlefield monitoring. The fiber-Bragg-grating seismic sensor is totally immune to electromagnetic interference and has a working temperature between −40°C and +50°C for military harsh environments. Comparisons are also presented of the fiber-Bragg-grating seismic sensor with the commercial REMBASS sensor in a series of field tests.

Key words: Fiber-Bragg-grating seismic sensor; unattended sensor; intruder detection; perimeter defense; battlefield monitoring; sensors; signal detection; electromagnetic geophone; laser-based optical demodulation.

Fiber optic sensor technology has been and is being increasingly exploited by the research community because of its relatively simple design, low power consumption, low cost, relatively low maintenance cost, and the flexibility it offers for both commercial and military applications. In particular, fiber optic seismic sensors have been recognized as promising technologies for numerous applications, which include intruder detection and perimeter defense systems for military applications. However, seismic military sensors are required to be robust, reliable, compact, and easy to install and operate to be effective in the battlefield environment. This article addresses the challenges presented by the design of military seismic sensors and reports on experimental investigations of fiber optic seismic sensors. Specifically, we address three types of sensor technologies that provide improved design and novel signal processing techniques: (a) a wavelength scanning, pulsed-laser–based demodulation system, (b) digital lock-in amplifier and field programmable gate array (techniques) for weak signal detection and processing, and (c) improved seismic sensitivity based on carbon fiber optic composite cantilever and fiber-Bragg-grating (FBG). We present our experimental results on the FBG seismic sensor frequency response along with comparisons of those with the REMBASS II sensor (Remotely Monitored Battlefield Sensor System II) resulting from field tests.

We have developed a new scheme of laser-based optical demodulation with excellent results. At 100-Hz scanning speed we were able to demodulate the wavelength down to 1.1 pm. The signal is completely digital, clear, with excellent signal-to-noise ratio. At lower scanning speeds we can achieve subpicometer wavelength resolution. The dynamic following range is about 10 nm with a dynamic range of 120 dB.

Principle and design

The design of the seismic sensor is illustrated in *Figure 1*. The detection is implemented by the FBG dynamic strain sensor, which is attached on a spring-mass system (Pastore, 2006). The acceleration of ground motion is transformed into strain variation on the FBG sensor through this mechanical design and, after the optical demodulation, generates the analog voltage output proportional to the strain changes. By adjusting the mechanical parameter of the spring–mass configuration, we can mechanically tune the natural response frequency of the system within a certain range in adapting to the different frequencies of seismic wave sources (signals of personnel and vehicles). This sensor head has a compact size and a mass of only a few grams. It has the advantage that the sensor can be easily embedded and hidden in the battlefield without any radio frequency emission or thermal signature to the environment. The optical fiber–based sensor itself is resistant to corrosion, high temperature, and fatigue, and so is suitable for deployment in the harsh environment of battlefield. A damping mechanism is incorporated into the design with critical damping provided so that the mass–spring system will return quickly to its ready state after detecting a signal. This damping mechanism is shown in *Figure 1*, where a Faraday induction loop and a permanent magnet provide the damping. The small induced current in the Faraday loop is properly sealed so that no electromagnetic signal will go in or out of the sensor head. By using the carbon fiber composite cantilever, the overall sensor performance is improved, which leads to a higher sensitivity, better linearity, and smaller weight on the sensor head.

Considerations for field applications

For rough environments, such as the battlefield environment, two things are of serious concern. First, the sensor needs to be strictly waterproof, dustproof, and adaptable to vast temperature changes in excess of $-40°C$ to $+60°C$. Two of the advantages of a fiber optic device are that the device is intrinsically waterproof and dustproof, but it is also very sensitive to temperature changes. Our sensor uses a pair of matched FBGs; one is the sensing element and the other is the demodulator. A thermostat and a temperature control make sure that the two FBGs are always kept at the same temperature.

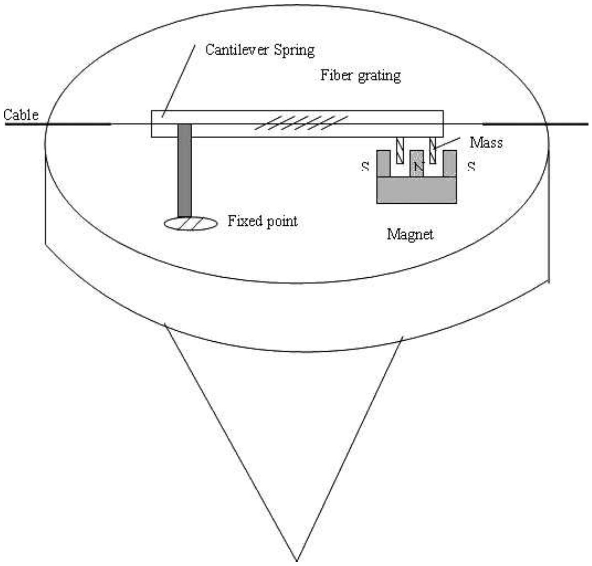

Figure 1. Basic structure of the FBG sensor head.

Power consumption is another consideration for unattended system design. We employ a solar cell on the top cover of the sensor and a high-density battery inside the sensor. A digital control block permits cycling of wake–sleep configuration. Sleep time is set as long as possible based on average current consumption, and the ratio of wake–sleep is set depending on the required reliability of detection, alarm level, and the states of neighboring sensors.

Improvement of signal detection

One of the most profound challenges in the design of the seismic sensor is acquiring and separating weak seismic signals from strong background noise (for example, wind); another is distinguishing signals from different sources. Basic requirements for a practical unattended seismic sensor are that it has to be very sensitive to small vibrations but also have a proper strategy to decrease the false alarm rate (FAR). To solve these problems, we designed an original algorithm. We illustrate the workings of this algorithm by using the example of detecting the signals of a human walking. First, the system records the seismic response of a person walking, saving the basic digital model on the sensor. Second, the system compares the sensor's subsequently acquired seismic signal with the basic digital model using a correlation operation. Third, the system estimates the degree of correlation. If the degree of correlation is higher than a preset level, it is counted as a signal impulse. Finally, the system sums the number of impulses in a given time interval. If this sum matches the rate of previous signals, the sensor

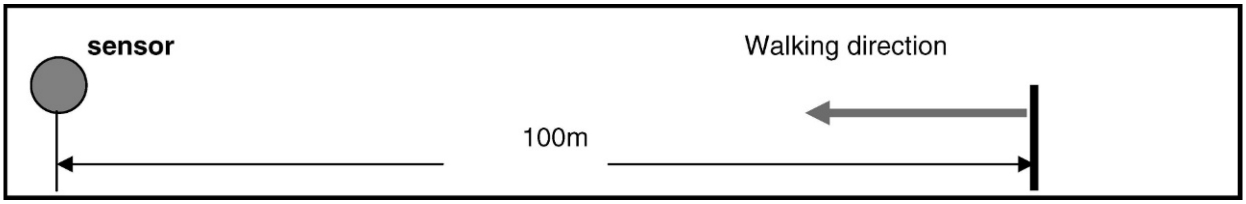

Figure 2. Experimental setup.

initiates an alarm. Both improved signal detecting ability and decreasing false alarm rate are achieved with this algorithm.

We have carried out a preliminary experimental study to investigate the applicability of our algorithm. Both a fiber-optic Bragg-grating geophone and an electromagnetic geophone were used for this work. *Figure 2* shows the experimental setup with a person walking directly to the geophone from 100 m away. *Figure 3* (top) shows the geophone response without any signal processing, where we could only see a few high-quality signal cycles. *Figure 3* (bottom) shows that more cycles of the walking signal were detected by our processing method of signal correlation even though the signal was buried under noise.

Experiment results

The sensitivity test of the FBG seismic sensor was carried out on a vibration stage that is driven by a series of sinusoidal waves. We use the conventional electromagnetic geophone for comparison. *Figure 4* is the result of the FBG seismic sensor and the geophone response to the vibration at 30 Hz. Comparison tests at different frequencies showed that the FBG seismic sensor has a higher sensitivity than the conventional electromagnetic geophone—between 10 and 70 Hz. The frequency analysis results showed that the FBG seismic sensor frequency response band is between 10 and 300 Hz, which covers the major frequency band of the military seismic signals.

The electromagnetic interference test of the FBG seismic sensor was carried out and compared with the electromagnetic geophone *(Figure 5)*. Both geophones were initially still and placed near an AC current supply (power: 80W; frequency: 60 Hz) at equal distances of 20 cm. The conventional electromagnetic geophone was severely disturbed by the output signal at 60 Hz. The FBG seismic sensor did not exhibit

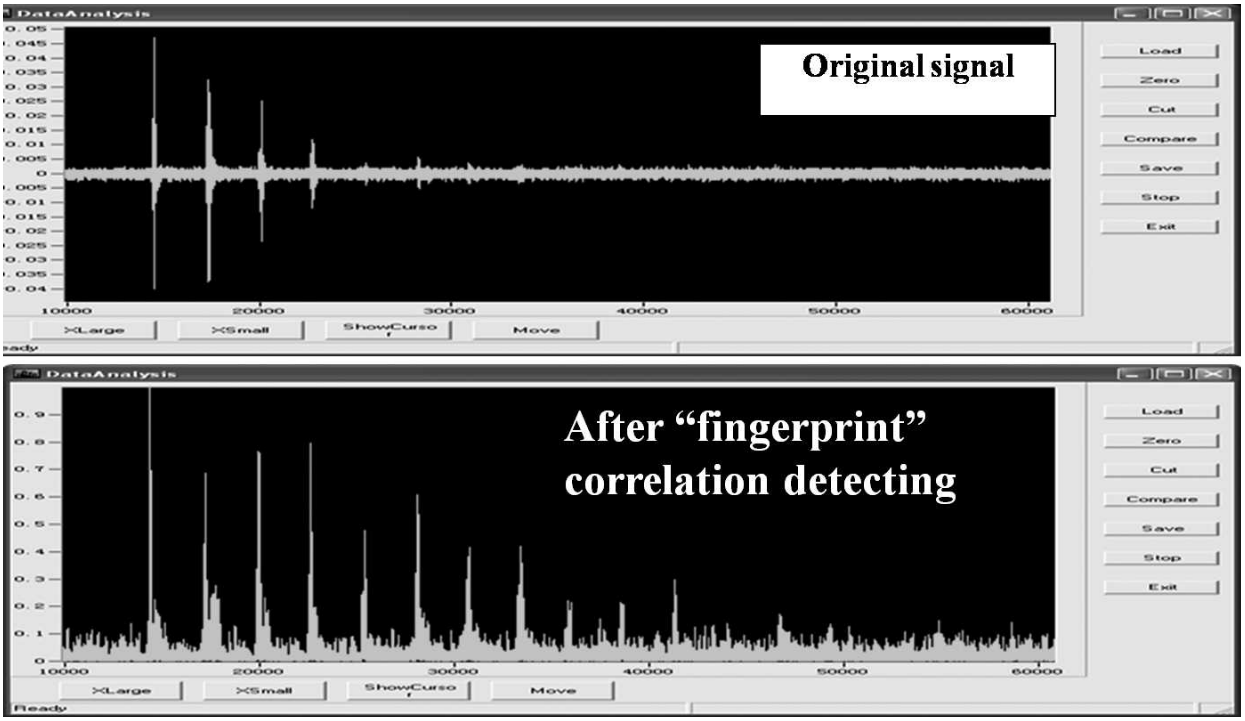

Figure 3. (top) Geophone response without any signal processing; (bottom) geophone response with signal processing.

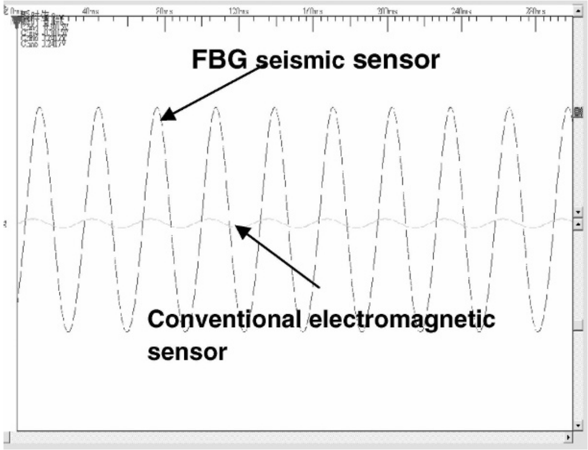

Figure 4. FBG sensor vs. electromagnetic sensor sensitivity comparison.

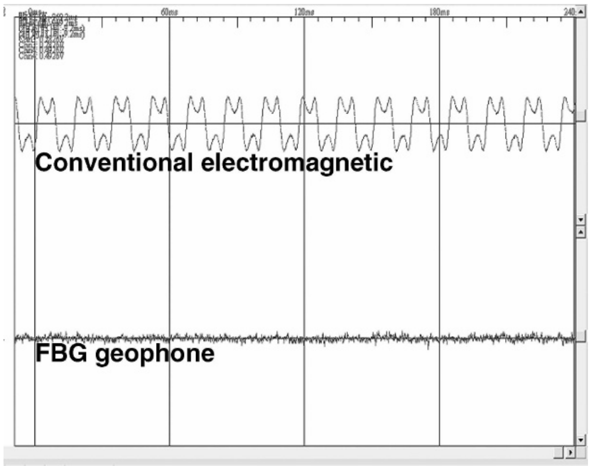

Figure 5. FBG sensor vs. electromagnetic sensor electromagnetic interference.

electromagnetic interference. This demonstrates the advantage of a FBG unattended seismic sensor in a military environment, an attribute that is one of the intrinsic properties of the fiber optic sensor.

The military field test was carried out at one of the U.S. Army shooting ranges. The REMBASS-II S/A sensor was used as a benchmark. *Figure 6* is the sample test result of the FBG seismic sensor response to military vehicle generated signals. The detection distance was calculated by an on-board global positioning system receiver on each vehicle, and it can be interpreted as the maximum distance over which the sensor can respond to the target. In these tests we used the first impulse of the seismic signal as the trigger signal to discriminate the sensor response instantaneously. A series of field tests showed that the FBG sensor equaled or outperformed the REMBASS-II system with both personnel signals and detection of almost every wheeled vehicle signal.

Estimated delays with time of arrival for two pair of sensors

For a pair of signals from two sensors,

$$S_1(t) = a_1 x(t - t_1) + n_1$$
$$S_2(t) = a_2 x(t - t_2) + n_2,$$

where $x(t)$ is the common signal received at both sensors, n_1 and n_2 are additive interferences, and a_1 and a_2 are the attenuation factors at the two sensors.

The relative time of arrival can be computed as

$$dt = \arg\max S_1(t - \tau) \cdot S_2(t).$$

We know the delay of time of arrival can be translated into distance difference because the transmission speed is constant. That is, if we know the transmission speed Sp, we have the distance difference, *dl*, between two sensors

$$dl = \mathrm{Sp}\ dt.$$

For a given *dl*, the object of interest will be on a hyperbolic curve where every point has the same distance difference to the two sensors.

If we have one more pair of sensors, we have one more distance difference on another hyperbolic curve. For two hyperbolic curves, the intersection point indicates the exact object location.

The time difference plot in *Figure 7* shows that for both the sensor pair 2 and 13 and the sensor pair 2 and 14 the time difference gets smaller as time progresses, which corresponds to the one approaching from sensor 2 to sensor 4. At sensor 2 the distance difference is largest, and therefore the time difference is also largest. When the person stops at sensor 4, the time difference between two sensors, corresponding to the distance

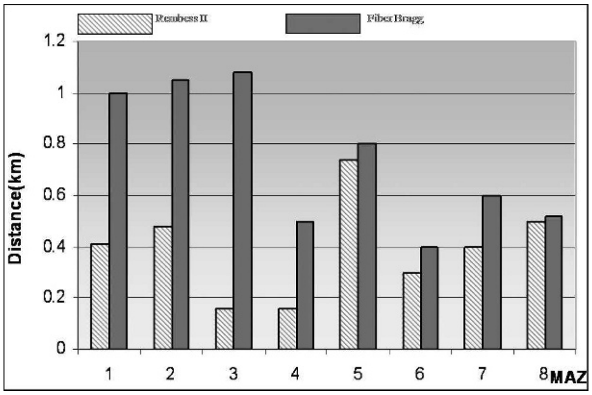

Figure 6. Sample of field test results of FBG response to military vehicles signals (in comparison with REMBASS II sensor).

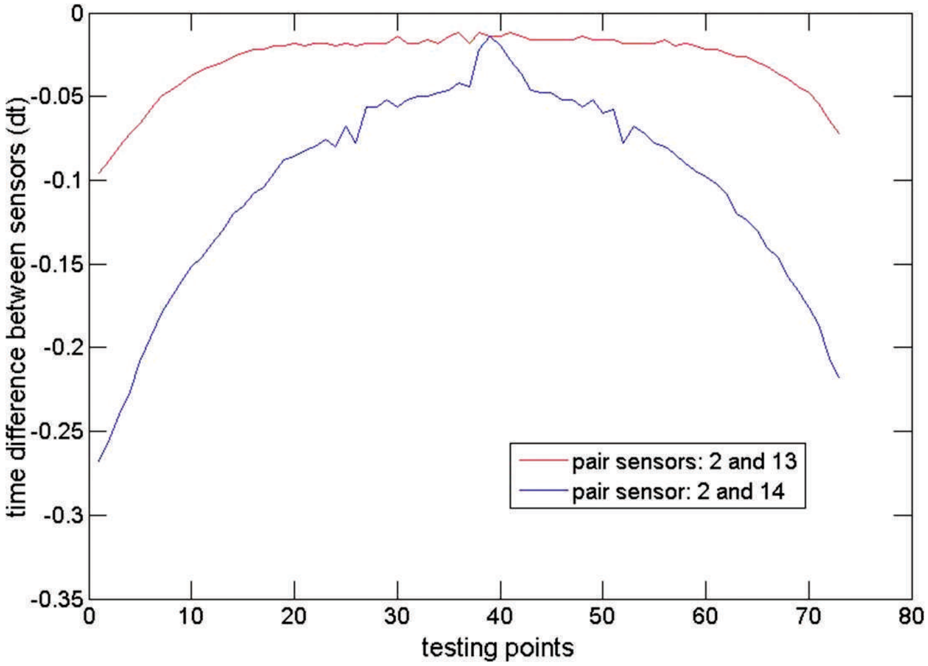

Figure 7. Corresponding location estimates from pair of time delays.

difference, has the smallest value. Then the person turned around and walked backward. One can see that the time difference gap gets larger and larger as sensor 2 is approached. Moreover, we find that two pairs of sensors have two different time difference values because the distances from the person to the sensor pairs are different. The sensor pair 2 and 14 has a larger time difference value.

Summary

We have demonstrated and discussed the feasibility of an unattended FBG seismic sensor in the battlefield monitoring and intrusion detection application. Based on a novel yet practical design, the FBG seismic sensor meets most of the military requirements such as being light weight, of compact size, easy to use, reliable, all-weather, and consuming little power, etc. The performance of the FBG seismic sensor in laboratory tests and field tests exceeds several commercial seismic sensors. We could expect FBG unattended seismic sensors to have the potential capability of detecting time-critical targets (personnel and vehicles) in battlefield applications.

More systematic research by our team is currently focused on combining FBG magnetic sensors with the FBG geophone and improving the algorithm to obtain both signal enhancement and reduced FAR. Also, further engineering measures of sealing and packaging are underway to ensure that the sensor can be deployed in the harsh military environment for extended periods. ❑

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Thomas Koscica is presently a principal engineer with L.C. Pegasus, where he leads the effort to design and implement fiber optic and microwave sensors in structural health monitoring, methane gas detection, and distributed temperature and pressure monitoring in oil wells, as well as THz sensors for chemical and biological warfare agent detection. He served as a consulting designer to Smith and Nephew for next-generation therapeutic ultrasound products that leverage embedded software to maximize product flexibility and minimize costs during the entire product lifecycle. From 1987–1996, while working at the U.S. Army Research Laboratory in Ft. Monmouth, New Jersey, Dr. Koscica was involved in advanced electronics engineering development for high-performance military systems; during the last 2 years there he served as team leader. For his doctoral thesis, completed at Rutgers University's Electrical Engineering Department in 1997, he explored novel semiconductor device development to utilize the physics of "real space transfer" within a semiconductor to express compound device behavior from a single device. Dr. Koscica holds more than 40 U.S. patents and has numerous publications and presentations.

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