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Seismic Sensor Using Piezo-Film

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Abstract:

The presented paper focuses on the possibilities of technical methods designed to detect a trespasser under the ground, and in general on the possibilities of detection a trespasser behind an obstruction. The paper analyses method of detection of a trespasser that were practically verified by the author of the paper. The first part of the paper discusses the characteristics and use of piezoelectric films that could be used as a replacement for the traditional geophone for detection of underground mining operation. It also provides a block connection diagram of the measuring chain and photos of the practical implementation of the sensor. The paper is supplemented with illustrative photos and results of numeric processing of signals in the form of graphs and courses.

Keywords:

Seismic detection, Unattended ground sensor, Piezo-film sensor

1. Introduction

The history of excavating and using tunnels spans long into the past. Tunnels were used not only as storage for food and war material but mainly as effective means of protection against attackers. A significant motivating factor for constructing tunnels lies in the hidden possibility of movement of people and transfer of material under the ground of a protected perimeter. At present some tunnels are used as roads for smuggling drugs, weapons, ammunition or illegal passages of people. There are even cases, not exceptional, when tunnels were excavated with the aim to rob a bank safe etc. The fact that construction of tunnels, often quite primitive ones, is not sporadic, can be continually documented not only by historical sources but often also by the daily news summary.

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The concurrent lack of proper technological means results in the renaissance of using tunnels for illegal purposes even at present. The presented paper focuses on the above mentioned area and points to little used physical principles of detection underground activities of trespassers.

Tunnels weave their way under the Egyptian pyramids, churches and temples and other historical buildings whose purpose at that time was mainly to ensure safe leaving of the buildings at the time of a siege. Massive construction of tunnels was under way during the French revolution, the civil war in Japan as well as during the First and Second World War in Europe. Quite unique is a 1,100 meters long tunnel known as the Ferrat drift in Lagazuoi from the time of WWI hollowed out in the rock in the Dolomites. In Vietnam, a system of tunnels began to arise as hideaway and a means of communication between guerrilla groups during the independence war against France. After a short period of negligence it gained importance again during the Vietnam War. More than 250 km of these strategically important tunnels were constructed, and they spanned from the Cambodia borders up to Saigon.

If we look into the recent past, tunnels for smuggling drugs, cigarettes, alcohol, weapons and ammunition were found on the Israeli-Egyptian border in the Gaza strip or in Sarajevo in Bosnia. The MSNBC report from January 2006 speaks about the finding of a tunnel for smuggling drugs 800 meters long between the cities of Tiujana, Mexico and Otay Mensa in California. The tunnel is so huge that it is possible to use a car inside. A year before this event the first tunnel on the border between Canada and the USA intended for smuggling drugs was discovered. This tunnel was 120 meters long, built in the depth of 3 meters and ended on the Canadian side in a living room of a dwelling house.

Regarding the nature of tunnels and the environment in which they are constructed there are not many technical means to detect them easily and efficiently. The most pressing problem is the fact that tunnels for the purposes of smuggling or illegal passages of persons are constructed in places where the borders between states are very close to each other. These are usually built-up areas with established infrastructure where there is commotion and traffic in the streets. Tunnel entrances and exits are hidden in buildings or hangars and visually well camouflaged. Tunnels are relatively short, they are build several meters under the surface and all activity going on in the tunnels is shaded by common life on the surface. Generally the most convenient approach to detection of already built tunnels are methods based on seismic principles. Satisfactory results were also reached using the principle of micro-gravitational measurement, penetration radars etc. The methods mentioned provide information about whether there is a tunnel or a drift under the ground or not. If we take a wider look at these questions, there are methods that are able to detect the presence of persons behind an obstacle formed by several meters of soil. In this case we do not carry out the detection of tunnels as such but we detect the presence of persons in them. In this respect we speak about detection of presence of persons behind an obstacle that can be based on:

- Analysis of surface seismic waves generated by movement of persons
- Existence of human electromagnetic emissions in the ELF band
- Measuring the changes of geomagnetic field

The above mentioned methods of detecting the human presence behind an obstacle can be used both during the tunnel excavation phase and in the phase of using the already constructed tunnels. The presented paper deals only with the first option.

2. Analysis of Surface Seismic Wave Signals

Seismology is a branch of geophysics dealing with the research of earthquakes and related phenomena. The so-called large seismology is divided into *Macroseismology* that studies earthquakes without using apparatuses according to associate phenomena observed in people, objects and the nature, *Microseismology* that evaluates earthquake-related phenomena according to apparatuses (seismographs) and *Seismometry* that develops the measurement methods for earthquakes produced by seismic waves. Besides these fields also the exploration fields have been advancing - *Applied seismology*, which is a set o methods for examining the geological composition of the earth crust based on the study of artificially produced seismic elastic waves. Surface seismic waves are also used to study the upper part of the earth body (the earth crust and the upper jacket) [1].

A body that gets deformed under the influence of an external force (changes its shape and volume) and gets its original form again when the influence of the external force stops, is denoted as an elastic body. The ration between the force and the area on which it influences is called tension. There is a relationship between the tension and the deformation that can be under certain circumstances expressed by the Hook law, according to which the deformation is directly proportional to the size of the tension.

Deformations that arise in elastic environment are of two kinds, *volume* and *shape*. Each deformation in elastic environment can be considered a result of parallel volume and shape deformations. The outer force that has the character of an impulse produces in limitless environment, in the area of its influence, deformations variable in time with which is connected the movement of the material particles of the environment. The movement of those particles produces tension if the part of the environment surrounding the initial disturbance area. Changes of tension produce also here the deformations variable in time. Environment particles move, produce tension in their surrounding and thus a deformations and tension are spreading in the form of an impulse to all directions from the initial disturbance point. Material particles oscillate briefly around their balanced position. Oscillations spread to long distance from the source by gradual transfer of movement by the environment particles, thus creating an elastic seismic wave spreading through the environment. According to the nature of particle oscillations with respect to the direction of the wave, we can divide the elastic wave motion in an unlimited environment into longitudinal and transversal.

The longitudinal wave (P-wave) is connected only with volume deformations. If such a wave spreads through environment, it gradually gives rise of compression and attenuation zones in the direction of the wave that are caused by oscillation of environment material particles around their balanced position. The transversal wave (S-wave) is connected only to shear deformations. If a transversal wave spreads through environment, individual environment material particles shift mutually, the material particles oscillate around their balanced positions in planes perpendicular to the direction of the wave. Beside longitudinal and transversal waves there is no other elastic wave motion in unlimited homogeneous and isotropic elastic space. If the environment is limited, another type of wave motion arises on the boundaries by interference of spatial waves. Those waves are called surface, as their intensity decreases with the distance from the boundary. The two basic types of surface elastic waves are Rayleigh and Love waves [2-4].

In case of Rayleigh wave the particle movement in the surface wave is not linear as in the volume wave but the particles move on elliptical trajectories in vertical planes parallel to the direction of the wave. The shift amplitude on transition of these waves gets the maximum value on the surface and with growing distance from the surface it decreases exponentially and after the distance of several wave lengths it practically disappears. Mechanical energy transmitted by the surface wave is concentrated in the surface layer with a thickness approximately equal to its wave length.

Mechanical movement of surface elastic waves can be converted to an electric signal using a geophone. For example, during the WWI a flask filled with water and buried in the ground was used to detect underground activity as a primitive replacement for at that time nonexistent suitable type of a geophone. An illustrative photo of a vertical induction geophone is in Fig. 1.

Directional characteristics of a geophone depend on the direction of the movement of the environment with which it is connected, and is called the sensitivity axis. In seismology applications the induction geophone with vertical sensitivity axis is used most often; it is used in almost all special monitoring sensors, often referred to as ***UGS*** **-** Unattended ground sensor. Typical examples of UGS are these systems: ***Rembass*** – Remotely Monitored Battlefield Sensor System*,* ***Classic*** – Cover Local Area Sensor System for Intruder Classification*,* ***MIDS*** – Mini Intrusion Detection System, ***MIS*** – miniature Intrusion Sensor, and other examples could be found as well.

As it was already mentioned, the activity of persons moving in a tunnel is from the point of view of seismic surface wave analysis shielded by vibrations caused by usual traffic and activities on the surface. Even when placing the geophone to the depth of several meters, it is problematic to distinguish whether the detected data are related to activity on the surface or under the ground. Its vertical sensitivity axis here becomes inconvenient; possible solution is to carry out relatively complicated spatial numeric filtration of the signal. Using geophones with horizontal sensitivity axis does not contribute to the required result either.

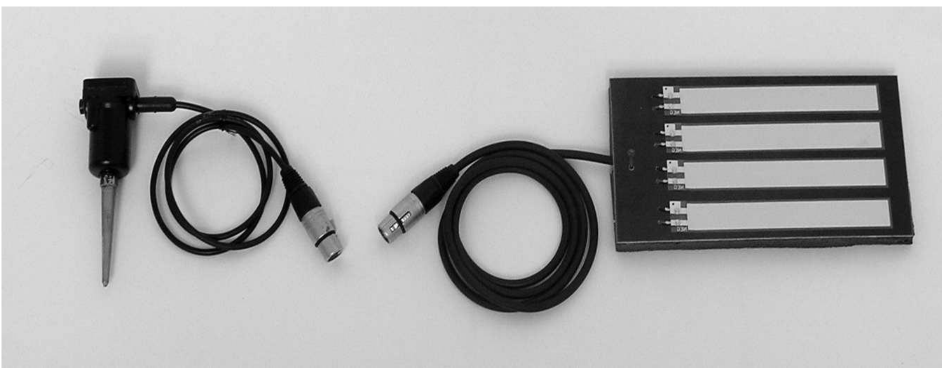

Fig. 1. The Picture of a geophone build in a case PE 3-D (left), Piezo Film type LTD (right).

Another possible solution to this problem is using piezoelectric materials. Piezoelectricity was discovered by the Curie brothers more than 100 years ago. They found that quartz changed its dimensions when subjected to an electrical field, and conversely, generated electrical charge when mechanically deformed. One of the first practical applications of the technology was made in the 1920's by another

Frenchman, Langevin, who developed a quartz transmitter and receiver for underwater sound - the first SONAR. In 1969, Kawai found very high piezo activity in the polarized fluoropolymer, ***PVDF*** **-** Polyvinylidene fluoride. While other materials, like nylon and PVC exhibit the effect, none are as highly piezoelectric as PVDF and its copolymers. Like some other ferroelectric materials, PVDF is also highly pyroelectric, producing electrical charge in response to a change in temperature. PVDF is strongly absorbing of infrared energy. One of the most recent developments in piezo polymer technology is Piezo Cable and Piezo Film.

The Piezo Cable has the appearance of standard coaxial cable, but is constructed with a piezoelectric polymer insulator between the copper braid outer shield and the inner conductor. Protected by a rugged polyethylene jacket, the cable is used in buried or fence security systems, traffic sensors including vehicle classification and weight-in-motion systems, and taxiway sensors for aircraft identification, safety and security applications. Other applications include sensors for anti-tampering, door edge safety monitoring, touch pads and panels, and patient mattress monitors. The output voltage is proportional to the stress imparted to the cable. The long, thin piezoelectric insulating layer provides relatively low output impedance (600pF/m), unusual for a piezoelectric device. The dynamic range of the cable is substantial (> 200 dB), sensing distant, small amplitude vibrations caused by rain. The cables have withstood pressures of 100 MPa. The typical operating temperature range is –40 to +125 °C. The Piezo cable type 20-AWG is, for example, delivered as a component of the CLASSIC-2000 system, 1,000 meters long, for monitoring large perimeters. The new cables feature the same piezoelectric properties that are characteristic of Piezo Film sensors.

The Piezo Film is available in different film sizes and thicknesses. These can be fabricated into simple transducers or for use as full size sheets for applications such as speakers. Metallization options include a compliant silver ink as well as sputtered metallization. The silver ink is best for applications where mechanical stress is being applied to the film. Thin sputtered metallization is brittle and used where signal to noise requirements dictate very low mass loading by the electrodes. These are only general rules, and a discussion with our applications engineers will help you to make the best choice for your specific application. Silver ink lends itself to custom metallization patterns for easy lead attachment. The standard sputtered metallization is a nickel copper alloy, which has good conductivity and is resistant to oxidation. Other metallizations such as gold are available on a custom basis. Piezo Film is available in different thicknesses. Thinner films (28 and 52 μm) are the most common, due to their higher capacitance and good mechanical qualities. Thicker film (110 μm) is used where maximum robustness is needed, or if the sensor is being used in a thickness mode application. The LDT series of Piezo Film sensors elements are rectangular elements of Piezo Film with silver ink screen printed electrodes. They are available in a variety of different sizes. Typically, a 125μm polyester layer is laminated to a 28 μm or 52 μm piezo film element. The laminated film elements develop much higher voltage output when flexed non-laminated elements.

Generally, for detection of underground activities it is possible to use the following sensors: geophone, piezoelectric cable, Piezo Film or sensors based on the MEMS technology, possibly others. Practical experience with all of the above mentioned sensors and a series of experiments showed that the most convenient for maximal suppression of surrounding interfering signals of surface seismic waves of the application of underground activity of trespassers is the Piezo Film. For this purpose four serially connected LDT Piezo Films with the total active area of 117 cm^2 were used. Piezo Films were glued onto a solid base and covered with a foil protecting them from mechanical damage, as shown in Fig. 2. In practice the base was buried horizontally in soil and burdened with a concrete block weighing 21 kg in order to achieve perfect contact of the Piezo Film matrix with the surrounding environment [5].

Fig. 2. Position of the Piezo Film matrix on the measurement site.

Electric signal from the Piezo Film was amplified; its frequency band was reduced and recorded on a DAT tape recorder. The whole measurement set, including the DAT tape recorder, was supplied from batteries. The total tension amplification was 95 dB in the band 4 Hz – 10 kHz. Measurement was carried out on a building site ground where a concrete sewer piping of a diameter of 1.4 m was laid in the depth of 2.3 m. During the experiment the interfering seismic background signal, movement of a person in the piping and hammer strikes on the piping wall were recorded. On the other track of the DAT tape recorder it was recorded, for comparison, the signal from a geophone. The data stored by the DAT tape recorded was transmitted via the SPDIF interface to a standard PC and then their analysis as for the time and frequency plane was carried out in Matlab software. Fig. 3 shows the waveform of the recorded signal corresponding to a person waling inside the piping, and Fig. 4 shows its spectrogram for 40 sec. Fig. 5 shows the waveform corresponding to a signal from repeated hammer strikes on the piping wall, and Fig. 6 shows its spectrogram for 40 s. To evaluate the PSD, Welch method of modified periodograms weighted by Hann window [6-9].

Subsequently a spectral analysis was carried out with the recorded waveforms and a suggestion for an optimal limitation of the frequency range was made with respect to the most efficient suppressing the interfering signals of surface seismic waves. The results of the analysis of recorded signals allow us to make the following summary:

- The dynamic range of recorded signals reached up to 45 dB.
- The absence of interfering element in the value of industrial supply system of 50 Hz (Europe) was reached by efficient shielding of the whole measuring set and by using battery power supply.

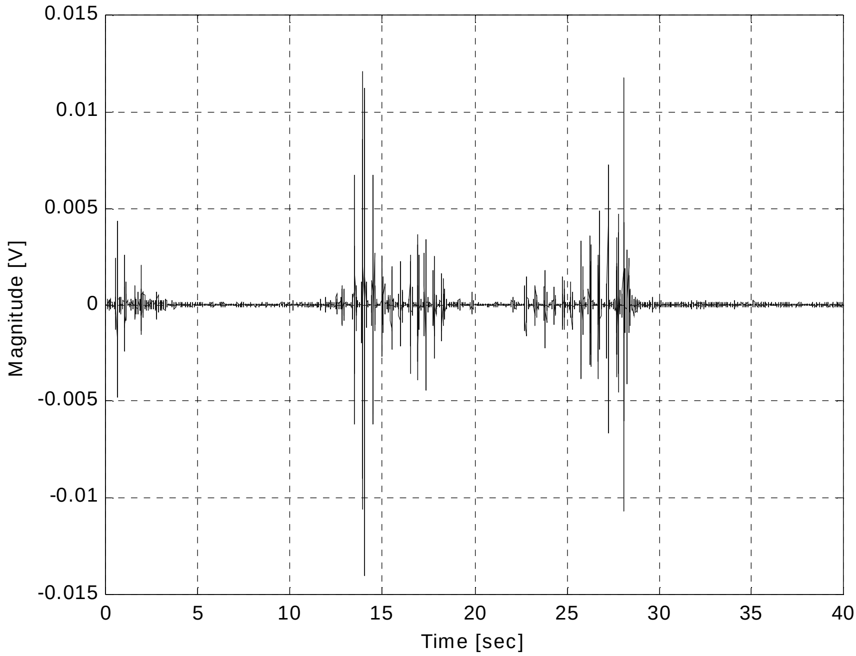

Fig. 3. Waveform of recorded signal – movement of a person in piping.

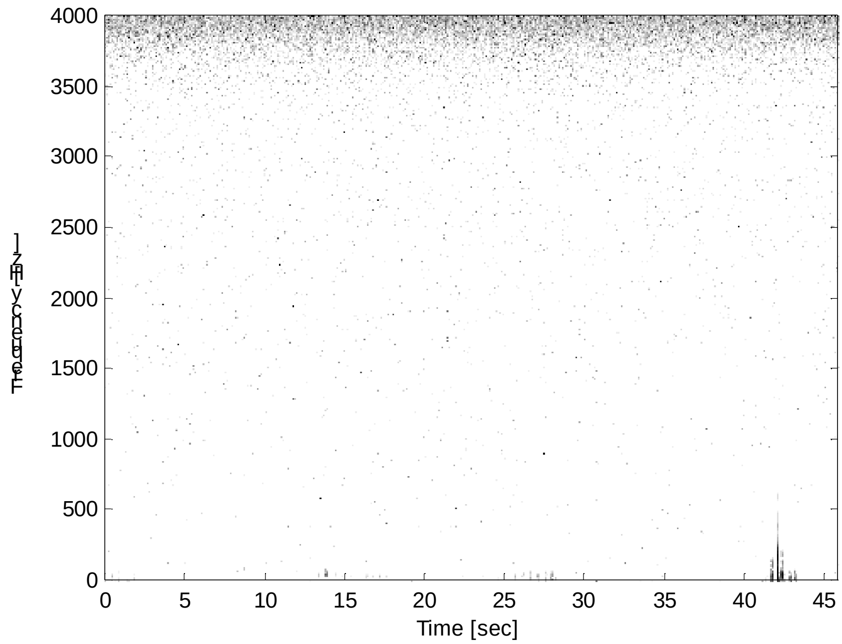

Fig. 4. Spectrogram of recorded signal – movement of a person in piping.

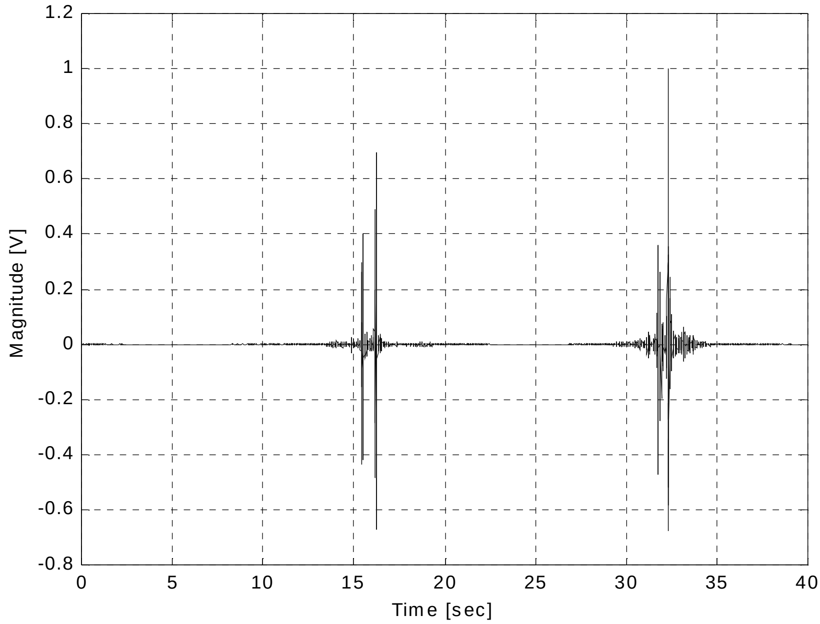

Fig. 5. Waveform of recorded signal – hammer strikes on pipe wall.

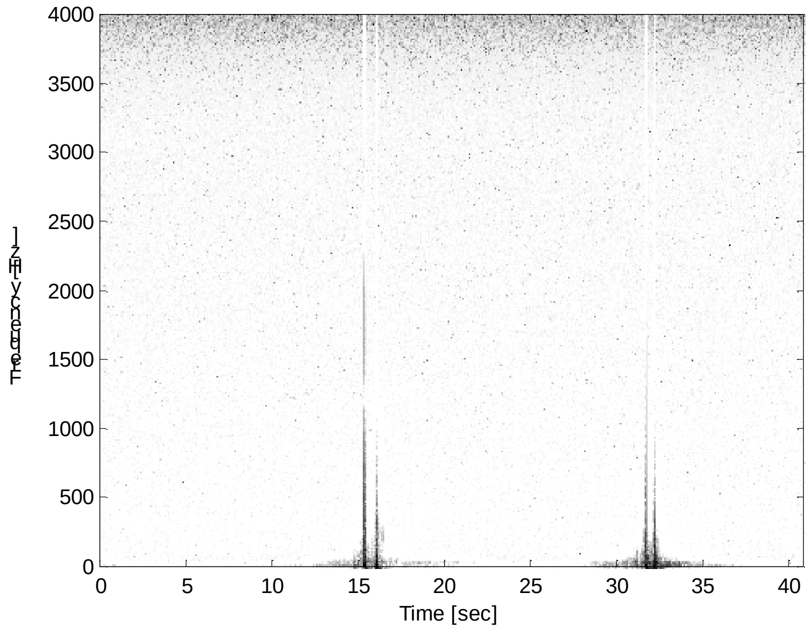

Fig. 6. Spectrogram of recorded signal – hammer strikes on pipe wall.

- The relative high purity of signals, in comparison to the geophone signal, confirmed the suitability of Piezo Film to reduce interfering seismic background coming from the Earth surface.
- Significant elements of the interfering background in the frequency band over 350 Hz exist only in case of direct mechanical manipulation with the Piezo Film matrix.
- Without using the low-pass filter, frequency elements can be observed, in case of hammer strikes on the piping wall reaching the values up to 4 kHz.
- The spectral analysis of recorded signals confirmed that for the purposes of detection of underground activity the processed signal range can be limited to the band of approximately 4 – 150 Hz; this frequency band contains the maximum of processed signal power of surface seismic waves.

As a conclusion of this chapter it can be said that Piezo Films are suitable for monitoring underground activities, not only to detect tunnel constructions but also to detect person movements in already built tunnels. A simple technical solution and the absence of complicated numerical methods for spatial filtration allow to place the Piezo Film based sensors under the bases of fence systems directly on the border of the guarded perimeter. This way of placement ensures good contact with the surrounding environment forms a protection of supply cables and measurement electronics and, last but not least, allows for hiding the whole system from the sight of unauthorized persons. Individual sensors can operate in defined sectors completely autonomously, which allow for relative precise localization of a possible threat of underground activity. Verification and detailed specification of the underground activity location can be targeted by other, at present time already existing technical means. Interfering vibrations of fence systems cause by wind gusts etc. can be eliminated by limiting the processed signal frequency band and by using an elastic pillow placed between the sensor and the base of the fence system.

From the practical point of view and because of the extent of the perimeter, the most convenient seems to be using independently operating sensors, in which only analogue amplification and filtration will be carried out. A piezoelectric film matrix is located directly on the lower side of the sensor cover, which is located under the base of the fence system. The amplified and filtered signal is converted in the sensor to a numeric form and stored in an internal memory. Data from individual sensors are transferred via the RS485 interface or LAN to a central numeric processing unit in which the signal analysis and detection of underground activity is carried out. Detected events from individual sensors than can be in regular intervals transmitted for example by GRPS to the supervision centre. The block diagram of such arrangement intended for perimeter guarding is provided in Fig. 7. With respect to the limit extent of the paper other results and experience are available from the author.

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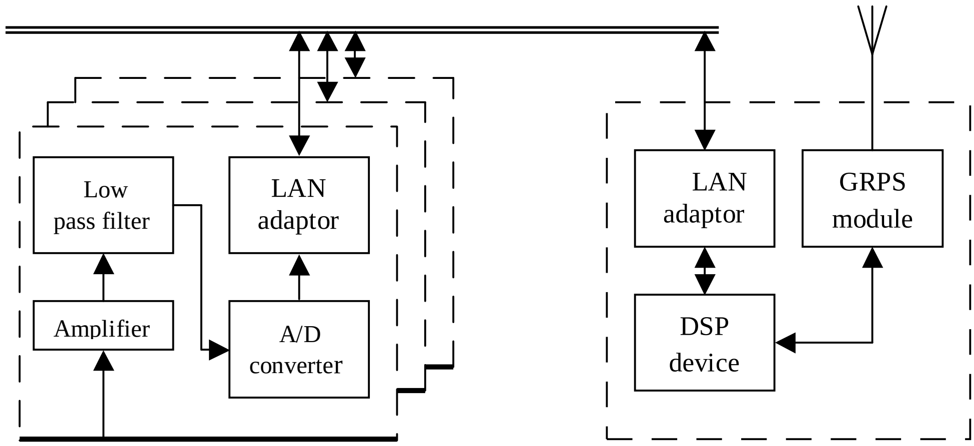

Fig. 7. Block diagram of the arrangement of independently operating sensors.

3. Conclusion

The presented paper was focused on detection of underground activities of trespassers, but this problem can be generally defined as human detection behind an obstacle. The obstacle in this case is formed by a layer of soil several meters thick. The paper focused only on analysis of surface seismic waves and detection of human emissions in the ELF band. It must be stated there are also other physical principles for detecting a human behind an obstacle, the research of which deserves attention and development in the future.

On the basis of obtained results it may be stated that seismic detection of underground activities is still worth attentions and that using piezoelectric films brings practical results and simplifies the mathematical detection algorithms capable of carrying out the trespasser detection in real time. By using piezoelectric films the need to carry out a complicated spatial filtration is reduced, moreover the resulting price of the sensor matrix is so low that it can be used in large amounts, even in conditions of a large perimeter. The defined sensitivity axis of a piezoelectric film and its smaller sensitivity in comparison with a traditional geophone becomes an advantage. Another characteristic of piezoelectric films that is prospectively utilizable is its wide operating frequency band which can be easily applied even in the form of an underground microphone. Data transfer from individual sensors, as given on Fig. 7, was tested in practice with RS-485 serial interface, which had galvanic separation of both data and supply so that the interference form the line voltage of 50Hz was eliminated. However it seems that in the future LAN components and their applications will be more perspective and will allow implementation of even very large network of sensors including the possibility to supervise different perimeters using the Internet.

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