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EMFI - VERSATILE MATERIAL FOR MONITORING OF HUMAN FUNCTIONS

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Abstract: ElectroMechanical Film (EMFi[1]) is a thin, plastic material that can be utilized as a sensor and actuator. We have tested the material in three different applications. A prototype of a chair equipped with EMFi sensors was constructed in order to monitor pulse, breathing and other activities of a person sitting on the chair. Measured information can be used to study human behavior during computer use. Pulse and breathing were noticed to be easily found from measurement signals of a person sitting restfully on chair. Ultrasonic radar that is based on EMFi has been built and studied. EMFi is quite new material in the field of ultrasonics and has favorable properties like good matching to air in comparison to present transducer materials. The device detects, if there is an object in front of the transducer. Measurements of directivity pattern of the built transducer, transmitter output and receiver sensitivity are presented. Some experiments were carried out to determine device's ability to detect different objects. A flexible and thin headset prototype including microphone and earphone was realized by using EMFi material. According to the preliminary tests the sensitivity of the microphone is adequate.

Keywords: sensor, actuator, ultrasonic, headset, EMFi.

1. INTRODUCTION

ElectroMechanical Film (EMFi) is a thin, cellular, biaxially oriented polypropylene film that can be used as an electret-type active material. It is capable of measuring pressure and force changes offering large application potential in different fields of technology including different sensors and actuators [1]. High sensitivity, light weight and relatively low cost are the main advantages of EMFi. It is thin and easy to cut to almost any shape and size. So, it can be easily integrated as a functional part in different mechanical structures. Flexible and thin sensors are useful especially in physiological applications where sensors or sensor arrays are often used in contact with skin or clothing. The film can be also laminated between plastic films to protect the material mechanically in harsh environment. This construction also gives a good protection against water and humidity.

The base material is low-priced polypropylene, which makes EMFi-sensors competitive also in large area applications like in surveillance sensor systems installed on the floor [2]. EMFi based guitar microphones and special sensors for health care applications are commercially available [3,4]. Various EMFi actuators have been developed and tested for audio and active noise cancellation applications [5]. In this paper we will present three prototypes of EMFi based human interface devices. In section 2 the Electromechanical Film is introduced. Section 3 represents the constructed prototypes, and in section 4 some test results are described. Finally, section 5 gives a short conclusion of the research.

2. ELECTROMECHANICAL FILM

The EMFi is an electret film with cellular internal structure, which is created by biaxially orienting a specially fabricated polymer preform. Having a special voided internal structure and high resistivity it is capable of storing large permanent charge. The charge is injected during manufacturing by a corona method using a high electric field. The material shows a strong quasi-piezoelectric response when compressed [6]. The sensitivity coefficient of EMFi is typically $d_e = 25\text{-}100\ \mathrm{pCN^{-1}}$ [4].

2.1. Modeling of operation

The operation of the film has been modeled in details based on the structure of the material and its internal charge distribution [6-8]. A general and more simplified model is described here.

EMFi material behaves like a capacitive generator type sensor. The charge signal ΔQ at the electrodes is proportional to the dynamic force ΔF exerted to film surface. The signal voltage across the sensor film is

$$\Delta V = \frac{\Delta Q}{C_s} = \frac{d_e \Delta F}{C_s} \qquad (1)$$

where d_e is the sensitivity coefficient corresponding piezoelectric coefficient in a piezoelectric material

$$d_e = \frac{\Delta \sigma}{\Delta p} = \frac{\Delta Q}{\Delta F} \qquad (2)$$

and C_s is the capacitance of the sensor film. $\Delta\sigma$ is the change of the charge density on the electrodes and

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[1] EMFi is a registered trademark of Emfit Ltd [4].

$\Delta p = \Delta F/A$ is the amplitude of the dynamic pressure within the area A where the force is acting.

The reciprocity of the electromechanical coefficient can be utilized to calculate the thickness change Δs of the film in the actuator mode

$$\Delta s = d_e \Delta V \tag{3}$$

where ΔV is the external driving voltage, and d_e is in this case typically 25 – 100 $m^{-12}V^{-1}$.

3. PROTOTYPES

Prototypes of a sensing chair to monitor heart rate and breathing, an ultrasonic system for detecting an object in front of it, and a flexible headset, all based on EMFi-material, are presented in the following subsections.

3.1. EMFi chair

The goal was to construct a prototype of a chair equipped with EMFi sensors in order to measure pulse, breathing and other activities of a person sitting on the chair. Measured information can be used to study human behavior in different computer using situations.

First, all padding material was removed from an ordinary office chair. Then two-layer EMFi sensors were fixed by gluing them directly on the plastic body of the chair. In the sensor structure the outer aluminum foils act as grounded electric shields and the inner foil as a signal electrode (Fig. 1). Plastic films were used as mechanical protection layers.

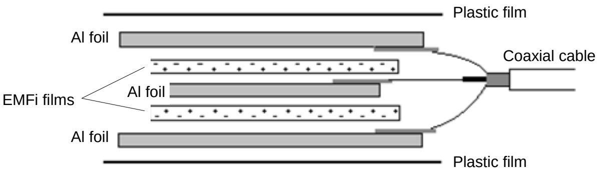

Fig. 1. Structure of EMFi sensors glued on the chair.

Totally 11 EMFi sensors were placed on the chair's seat, backrest and armrests as shown in Fig. 2. In placing of the sensors one goal was to use optimal positions to monitor heart pulses and breathing from a sitting person. The pulse signal is arising from ballistocardiographic phenomenon [9]. That is caused by the recoil movement of human body when heart pumps blood into aorta. Thus, it was assumed that the sensors 1 and 2 would give the highest pulse signal. Sensor locations 7-9 were potential for breathing measurements. Furthermore, other sensors (3-6) were fixed in places which are sensitive to body movements but nor or less sensitive to pulse or breathing signals. The idea was to use their signals to compensate errors caused by the body movements during pulse and breathing recordings. The sensors on armrests (10 and 11) were added to get information on hand movements when using mouse and keyboard. Finally, the chair sensors were covered by the original padding material on the seat and backrest.

Charge amplifiers and active filters based on operational amplifiers were designed to amplify and process sensor signals. The voltage gain of each amplifier was adjusted to 20 dB. The low and high cut-off frequencies of the filter stage were 1 Hz and 185 Hz, respectively. The electronics and two 9 V batteries as power source were encapsulated and placed under the seat. A cable was used to connect the chair to a measurement card in a computer.

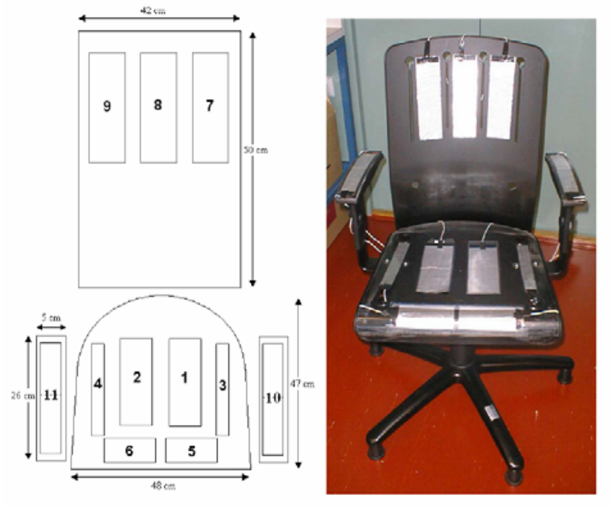

Fig. 2. EMFi sensors fixed on an office chair.

3.2. EMFi-based ultrasonic radar

The goal of this part of the study was to develop a prototype of the ultrasonic radar that is based on EMFi. The radar detects, if there is an object in front of the device. The planned range of the device was a few meters indoors. In the future, the device could be integrated into a smart user interface. This can enhance its adaptability and reliability in different applications.

Ultrasonic EMFi transducers and a preamplifier were built as a separate unit. All other electronics like power source, analog signal processing and microcontroller were placed to a main unit. The block diagram of the constructed radar system is shown in Fig. 3. The built device is powered with two 9 V alkaline batteries. The measurement system is controlled with an AVR 8-bit AT90S2313 microcontroller.

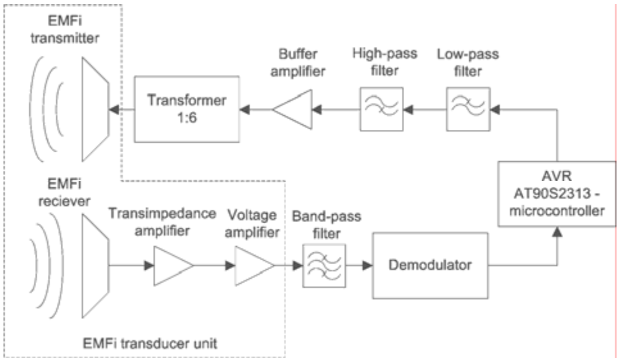

Fig. 3. Block diagram of the ultrasonic radar system realized by using EMFi material.

The operation of the radar is quite conventional. The constructed device sends ultrasonic bursts and then detects, whether there are echoes present within a certain time window. At the beginning of a detection cycle the microcontroller produces a series of excitation pulses at frequency of 34 kHz. This signal is filtered and then fed to a buffer amplifier stage that is able to drive a transformer. The ferrite core step-up transformer is used to increase the driving voltage level of the EMFi transmitter element up to 122 $V_{p\text{-}p}$.

The EMFi receiver element is used to convert acoustic echo back into electrical signal. The received signal is amplified and band-pass filtered to improve signal-to-noise ratio. AM demodulator is used to detect received burst. The demodulator produces a positive voltage pulse and the height of the pulse is proportional to average signal level of the incident ultrasonic burst. If the level of the pulse crosses a pre-set threshold level, the flight time of the ultrasound burst is calculated. This is realized with a comparator in the microcontroller unit. If the burst arrives in preset time window an object is assumed to be present.

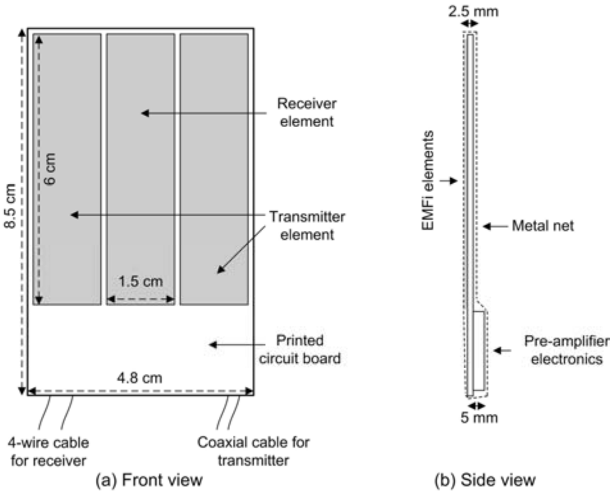

Fig. 4. EMFi transducer built on PCB. Two EMFi transmitter elements on the edges of the PCB were used to send ultrasound. The one in the middle acts as a receiver.

The transducer unit includes thin EMFi transmitter elements, receiver element and the first two amplifier stages of the receiver circuitry. The structure of the transducer unit is illustrated in Fig. 4. Three similar EMFi elements were clued on a printed circuit board (PCB). This procedure supports ductile EMFi elements and helps to create firm and reliable contacts. The capacitance of one element is 0.4 nF. Because preamplifier is located near to EMFi elements, on the back side of the PCB, it is possible to keep transmission lines short and maintain good electrical shielding. This is important because EMFi receiver element is prone to electrical interference. The receiver element was placed between the two transmitter elements. Two separate transmitter elements increase the output signal but make directivity pattern of the transmitter a bit complex. This kind of transducer configuration is symmetrical and still relatively easy to build.

3.3. Flexible Headset

A surface rescuer normally carries a dry or wet suit with a neoprene hood. To communicate with the supervisor of the rescue operation a radio together with a water-proof headset inside the hood is needed. A flexible and thin headset prototype was constructed for this application. Both the microphone and earphone of the headset were realized by using EMFi material. The EMFi-headset was implemented in co-operation with Emergency Service College (Kuopio, Finland) and a local fire station.

The EMFi earphone and microphone were integrated separately into the inner surface of the hood, inside textile pockets. The structure of the microphone was similar as sensors used in EMFi chair (Fig. 1). In earphone six layers of EMFi material was used. By stacking several film layers on top of each other the emitted sound level can be increased nearly linearly [10].

In Fig. 5 the first prototype of the headset integrated the the neoprene hood is shown. The earphone was placed against user's ear. The microphone was located so that the hood presses it tightly to cheek. Thus it detects mechanical vibrations from the cheek when a person is talking. The wires connecting earphone and microphone to the electronics were hidden inside textile alleys.

The present headset has separate small plastic box for the amplifier electronics and 9 V batteries. The microphone preamplifier is realized with a transimpedance amplifier, which is followed by an AC-coupled voltage amplifier to produce line level signal. The emitted sound pressure level of EMFi earphone depends on the driving voltage. The input

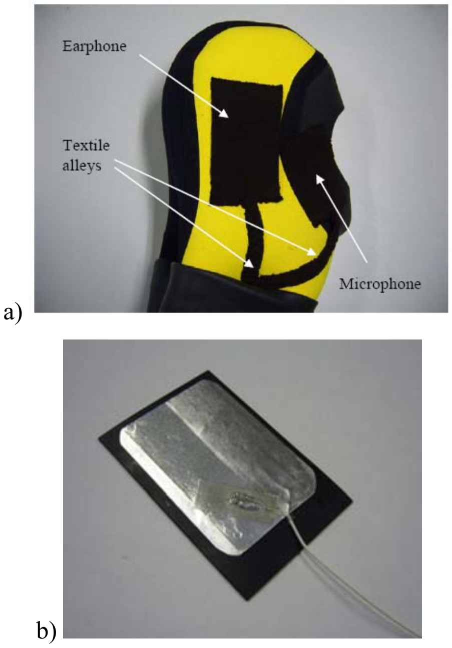

Fig. 5. a) Implementation of the first EMFi headset prototype, and b) layout of the EMFi microphone.

line-level signal of the EMFi earphone is amplified with a rail-to-rail operational amplifier LM7301 in order to achieve maximum output from the 9V supply voltage. The measured gain of the earphone amplifier is 5.7 and bandwidth 20 Hz - 30 kHz. The capacitive load of the EMFi earphone is compensated with a 470 Ω resistor in series with operational amplifier output.

4. RESULTS

The following subsections represent the results obtained in the test measurements of the three different prototypes of EMFi based human interface devices.

4.1. EMFi chair

Detailed testing was performed for the measurement system. Sensitivity of each sensor was determined experimentally by using calibrating weights. The sensitivity of the sensors varied from 67 mV/N to 170 mV/N and the measured capacitance from 2 nF to 7 nF depending on the sensor size. The measurement signals were collected by using Data Translation DT3010 measurement card with 1 kHz sampling frequency and saved to a computer.

Test measurements for the entire system in different computer using situations were done to get information about the performance of the chair in its future purpose of use. Measured signals were processed in MATLAB-environment and algorithms to determine pulse, breathing and activeness were implemented.

In Fig. 6 one minute recording of raw signals from the sensors 1 and 2 are shown in a normal situation where a person is sitting on the chair at rest. The signal includes a periodic breathing signal, amplitude about 20 mV, low amplitude pulse signal mixed with the breathing and some noise. Amplitude of the breathing signal measured from the backrest edge sensors (7 and 9 in Fig. 2) was about 50 mV and from the middle sensor (8) even 100 mV. However, the breathing signal on the back sensors decreases if the person is resting against back sensors only slightly. Therefore the seat sensors or combination of seat and back sensors might be more reliable in monitoring breathing.

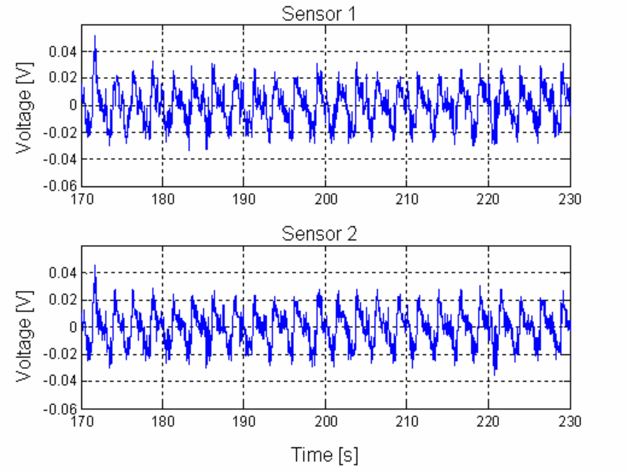

Fig. 6. Signal recorded from the seat sensors 1 and 2. The main component is coming from breathing, which is mixed with heart pulses and noise.

The breathing component can be seen also on the seat edge sensors (3 and 4) but the amplitude is rather low. The edge sensors give best information on the large movements of the test person. The thigh sensors (sensors 5 and 6 on the seat) are also sensitive to movements, especially leg movements, but in some cases strong pulse signal was seen in these channels. The armrest sensors mainly recorded the movement of arms when using mouse and keyboard. At rest these sensors also recorded breathing and pulse signal but with low amplitude.

Normal breathing rate is about 12 – 14 times per minute. So, the signal should be in the frequency range of 0.2 – 0.5 Hz. The highest signals were found in the middle sensors of seat and backrest. A combination signal was created by first synchronizing the peaks by using cross-correlation and time shifting, and then summing all three signals together. This sum signal was then low-pass filtered with a digital FIR filter (Pass band: 0 – 0.5 Hz, stop band: 1 – 500 Hz, attenuation > 50 dB) and is shown in Fig. 7 as a 100 s long sample. For calculating breathing rate a reference level to recognize a breathing cycle was created. The reference level (Fig. 7) is obtained as an average value of the maximum and average signal values calculated from 5000 samples in every 5 seconds. All peaks that cross the reference level are counted as breathing cycles.

Similar procedure was used to analyze heart pulses and calculate heart rate, that is normally around 60 beats per minute but can in maximum reach 205 beats per minute. Thus the pulse component should be found in the frequency range of 1 – 3.4 Hz. A combination signal from sensors 1 and 5, which gave the highest pulse signal, was created. The breathing was filtered out by using an FIR low-pass filter (Pass band: 1 – 3.5 Hz, stop band 1: 0 – 0.5 Hz, stop band 2: 4 – 500 Hz, attenuation > 40 dB). A 30 second sample of the filtered signal is shown in Fig. 8. The reference level for pulse detection was made as with the breathing signal. In this case the average value was calculated with 1 second period. The red balls in Fig. 8 describe the identified pulses.

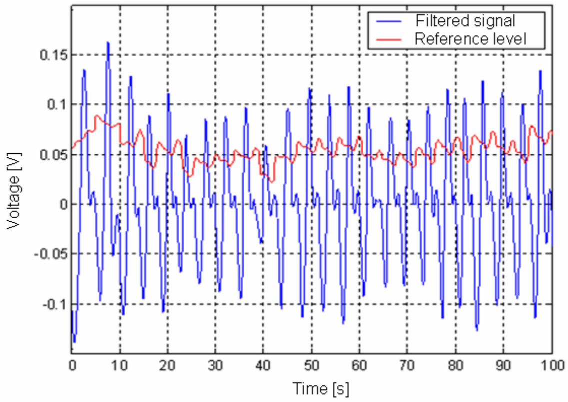

Fig. 7. Filtered combination signal from sensors 1, 2 and 8. Breathing is clearly shown. Reference level is used to identify a breathing signal.

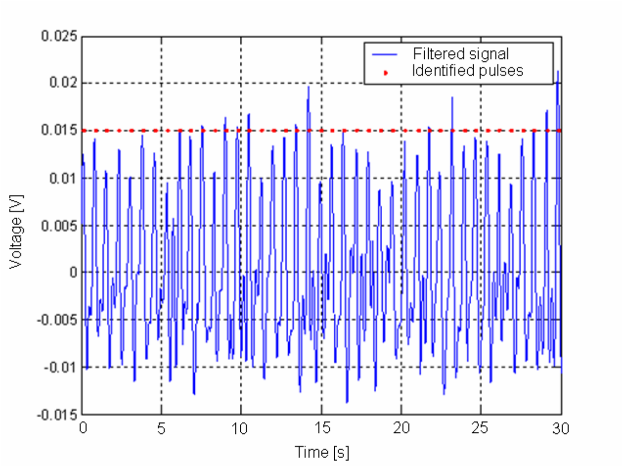

Fig. 8. Filtered combination signal of heart pulses from sensors 1 and 5. Red balls describe the identified pulses.

4.2. EMFi-based ultrasonic radar

The acoustic pressure was measured in front of EMFi transmitter as a function of distance. The acoustic pressure values were recorded at 34 kHz with a calibrated B&K Type 4135 microphone. Sound pressure levels (SPL) are presented in Fig. 9. Sound pressure decreases as a function of distance because of atmospheric absorption and geometric attenuation. At distance of 1 m SPL of the measured transmitter is 79 dB.

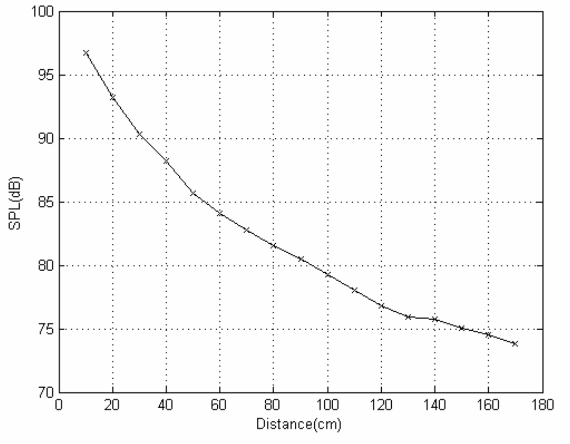

Fig. 9. Sound pressure level of ultrasonic EMFi transmitter as a function of distance.

The sensitivity of the receiver was estimated with comparing the output of built transducer with output of a reference microphone. A separate EMFi transmitter (2 cm in diameter) was utilized to produce a 34 kHz ultrasonic burst stimulus. This signal was measured at distance of 30 cm with calibrated microphone (B&K Type 4135). Five measurements were taken in the area corresponding to the front surface of the transducer unit. Average pressure was 54 mPa with standard deviation of 1.3 mPa. It was presumed that the acoustic pressure is relatively uniform on the surface of the receiver. After reference measurement the same acoustic signal was recorded with the EMFi receiver. As a result the sensitivity for the combination of the EMFi receiver element and transimpedance amplifier is about 3 mV/Pa.

The combined horizontal directivity pattern of the EMFi transducer unit including the EMFi transmitter elements and EMFi receiver was measured by using a plastic cylinder with diameter of 6.5 cm in front of the EMFi transducer unit at a distance of 50 cm. The transmitter element was used to send a 34 kHz ultrasonic burst towards the cylinder and the reflected echo was measured with the receiver element as a function of angle in horizontal plane. At angle of 0°, the plastic cylinder is at the line normal to the plane of transducer unit. The directivity pattern is presented in Fig. 10.

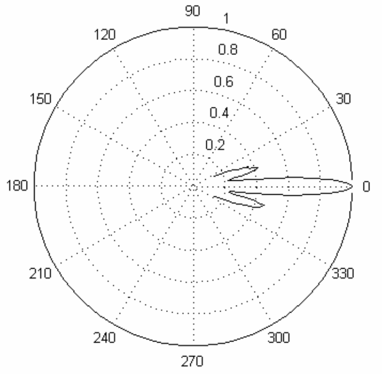

Fig. 10. The horizontal directivity pattern of ultrasonic EMFi transducer unit including both the transmitter and receiver elements.

In order to test how far targets can be detected, objects were placed in front of built device. SNR after band-pass filter was measured as a function of distance from object. This is illustrated in Fig. 11. SNR was measured at those distances where the built device detected corresponding object.

Common objects like a two-euro coin, a football and an aluminum can were used as targets. Effect of smooth clothing was tested by measuring reflected echo from lycra fabric covered and bare aluminum plate. Reflection from a

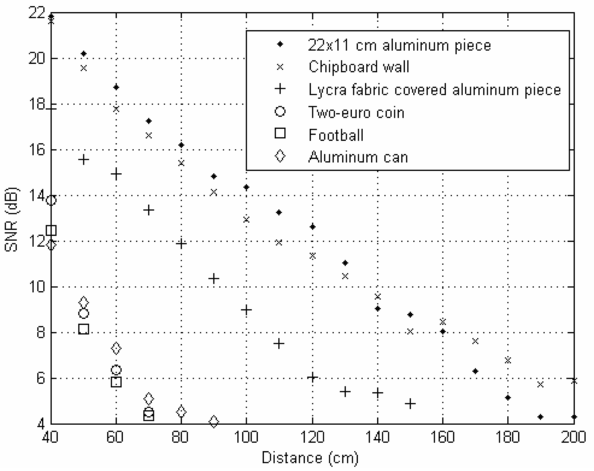

Fig. 11. EMFi radar's ability to detect various targets were estimated by measuring SNR ratio after band-pass filter at those distances where ultrasonic radar can see corresponding object.

chipboard wall is presented as a reference. Clearly, the area normal to incoming ultrasound and the reflection ratio between air and the target material determinates the amplitude of the echo. The device can see small objects like coin or aluminum can at distances shorter 70 cm. The piece of aluminum was detected at least a range of 2 m. However, even smooth and tight fabric seems to weaken echo substantially which may turn out to be problematic concerning user interface applications.

4.3. Flexible Headset

The constructed EMFi headset (Fig. 5a) is a preliminary prototype. Despite that, test results were promising. A functional testing was performed by listening and recording spoken sentences and vocals with the EMFi headset. A laptop computer was used to feed a line level signal to the headset and store recorded microphone signal. Quality of the sound was evaluated. The earphone is able to produce clearly audible and understandably voice in laboratory environment. However, additional testing by using an artificial head is required to ensure that the emitted sound pressure levels are high enough to ensure reliable communication in noisy surface rescue environments. On the other hand, the thick neoprene hood attenuates effectively noise outside the hood.

Spoken sentences were recorded with the microphone of the headset. The sentences were replayed with computer and quality of sound was judged. Recorded voice is understandable but it was noticed that the tone was slightly altered. Reason for this may be the measurement method. Sound is recorded directly from cheek not from air. Testing also revealed that the present microphone version has tendency to produce rustle when head was turned or moved. This problem may be solved by relocating and redesigning the microphone element.

5. CONCLUSION

Three different prototypes of EMFi based human interface devices have been constructed and their operation tested in different measurement and monitoring situations. A prototype of a chair equipped with EMFi sensors was studied in order to monitor pulse, breathing and other activities of a person sitting on the chair. Pulse and breathing were noticed to be easily found from measurement signals of a person sitting restfully on the chair with a simple filtering. However, when there were some movements of the body the detection of pulse and breathing was much more complicated. Ultrasonic radar based on EMFi was built and studied. The device can detect, if there is an object in front of the transducer. Some experiments were carried out to determine device’s ability to detect different objects. A flexible and thin EMFi headset prototype including microphone and earphone was realized. According to the preliminary tests the sensitivity of the microphone is adequate. The results show that the EMFi material provides interesting possibilities to integrate sensors and actuators in monitoring and user interface applications.

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