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Assessing the Signal Quality of an Ultrasonic Sensor on Different Conductive Yarns Used as Transmission Lines

Abstract

The field of electronic textiles is still relatively new and extending due to technology miniaturisation. In this article, the integration of an ultrasonic sensor into a textile structure was realised and analysed in order to develop a system able to help visually impaired people. The performance of ultrasonic sensors was tested by means of five different conductive yarns used as transmission lines, in three different configurations for the purpose of detecting the eventual existing off disturbances and their values. Finally, the influence of the conductive yarn type on the performance of the ultrasonic sensor was discussed. The results highlighted that the linear resistance of conductive yarn has a strong influence on the sensor's signal quality.

Key words: *ultrasonic sensor, e-textiles, signal quality, conductive yarn, signal to noise ratio.*

Introduction

With the technology of miniaturisation, the field of e-textiles and wearable electronics is becoming more and more extensive due to new sensing elements, multifunctional fibres, flexible technologies, MEMS actuators, etc. According to the literature, e-textiles and wearable electronics are generally used for emergency detection, medical treatment and health care management. They not only allow long-term, continuous, and unobstructed monitoring of physiological information, such as biopotential, photoplethysmogram (PPG), heart rate (HR) and respiration but also provide a more realistic indication of the patient's health status, as well as information that is otherwise unobtainable in clinical settings. Furthermore, apart from medical treatment and healthcare management, the use of e-textiles plays a great role in military and professional activities, athletes' performance and condition, public safety, space experiments, and wearable mobile information-entertainment infrastructures [1 - 7]. Innovative e-textile products are generally developed by weaving or knitting yarn-like electronics and/or by the integration of electronics into textiles by coating or lamination. In these products, the yarn-like materials used are traditional yarns, conductive yarns, conventional yarns modified with various functional materials, optic fibres, conducting polymers, carbon nanotube fibres, piezoelectric materials, etc. [1, 8]. For monitoring applications, knitted fabrics are generally preferred when stretchiness and deformation are necessary, whereas woven fabrics are preferred when dimensional stability is required [9 - 11].

The key factor when monitoring applications in a weaving or knitting structure is to form an electrical circuit network in the location of the garment desired, including conductive tracks, electronic devices and connections. In recent studies, it is generally seen that conductive silver-coated yarns [14, 16, 20], stainless steel yarns [10, 12, 13, 15, 18, 19], copper core insulated yarns [17, 18, 20, 21], and carbon yarns [19, 22] have been widely used to create electrical circuits in woven or knitted fabrics.

However, when the literature is reviewed, most of the researches in e-textile field have concentrated on constructing systems and ensuring their simple functioning instead of monitoring performance, signal quality and accuracy. A literature survey revealed very few works on the monitoring performance, signal quality and accuracy of e-textiles. Hertleer et. al analysed the influence of relative humidity on the performance of a textile antenna designed by them [23]. Dhawan et. al studied the signal crosstalk between neighboring conductive threads in woven electrical circuits. In their study, to minimise crosstalk, they used coaxial and twisted pair copper threads. They showed that crosstalk noise was reduced when coaxial and twisted pair copper threads were used for a woven electrical network instead of bare copper or insulated conductive threads [24]. In another study, Kim et. al investigated the effect of contact pressure and moisture on the signal quality of a textile ECG sensor shirt. In order to assess the influence of contact pressure and moisture on the signal quality, they firstly increased the contact pressure of their textile electrodes, and secondly they moisturised their textile electrodes and reference electrode alternately in order to get four different dry/wet combinations. To compare signal quality values, they used a signal to noise ratio calculation. The result of their study showed better signal quality with both the moisturised electrode and reference one [25]. Furthermore, in a study on the signal quality of textile electrodes, Puurtinen et al. researched how the electrode size and preparation of the electrode (dry electrode/wet electrode/ electrode covered with a hydrogel membrane) affect the measurement of noise. To show the noise level of configurations, they made noise amplitude and power spectral density (PSD) calculations by processing the signals in MATLAB. Their results show that the noise level of dry textile electrodes is notably higher than that of textile electrodes moistened with water and textile electrodes covered with hydrogel. Besides this they reported that there is no significant difference in the performance of wet textile electrodes and textile electrodes covered with hydrogel [26].

Accordingly, we conducted a comprehensive study in order to investigate the effect of the behaviour of conductive yarns on the signal quality of an ultrasonic sensor integrated into a textile structure. Our further aim was to develop a garment for visually impaired people. Therefore, in order to detect obstacles in front of the wearer, ultrasonic sensors were integrated into a smart clothing system. Despite the main idea, it is also important to know the effect of the behaviour of conductive yarns on the working performance of the ultrasonic sensor that will be integrated into the garment. Therefore, in order to decide which conductive yarn was more suitable for the planned smart clothing system regarding its monitoring performance, signal quality and accuracy, five different conductive yarns were used to integrate the ultrasonic sensor and construct electrical circuits in the woven fabric.

Thus, this paper not only demonstrates the integration of an ultrasonic sensor into a textile structure but also shows the influence of conductive yarn types on the monitoring performance of an ultrasonic sensor. Hence, the originality of the research is that for the first time in literature, the signal quality of an ultrasonic sensor integrated into a textile structure was compared by taking a variety of conductive yarn types into consideration.

Possible applications of sonars integrated into textile structures are obstacle detection [27], object recognition, as well as real time mapping for military, police and security applications.

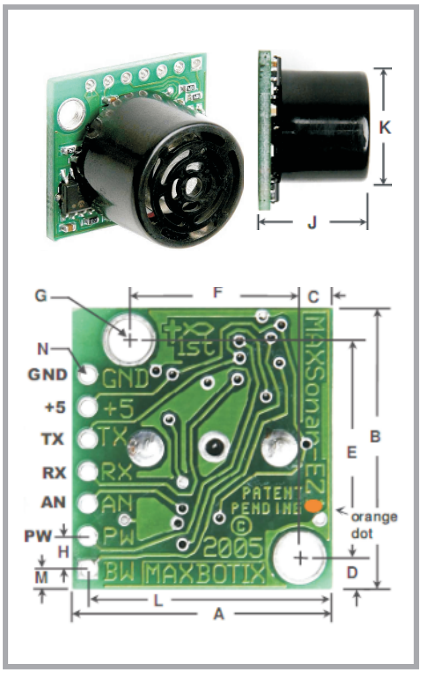

Figure 1. Overview of the ultrasonic sensor and its dimensions; A - 19.9 mm, H - 2.54 mm, B - 22.1 mm, J - 16.4 mm, C - 2.54 mm, K - 15.5 mm, D - 2.54 mm, L - 18.7 mm, E - 17.0 mm, M - 1.7 mm, F - 12.6 mm, N - 1.0 mm diameter, G - 3.1 mm diameter, Weight, 4.3 grams [28].

Table 1. *Characteristics of yarns.*

Sample no	Role of yarn in fabric	Material type	Yarn count, dtex	Linear resistance, ohm/m
	Non-conductive Yarn	Polyester Microfibre	330	-
1	Conductive Yarn	100% Stainless Steel	2600 2-ply	< 15
2		Silver Plated Nylon 66-4 ply	312/34f 4-ply	< 50
3		Silver Plated Nylon 66-2 ply	140/17f 2-ply	< 230
4		Silver Plated Nylon 66	312/34f	< 240
5		Insulated Copper Yarn	1440	< 10

Experiments

Materials

In this study, to test the signal quality of an ultrasonic sensor, five different conductive yarns with different linear resistances were used to form electrical circuits in woven fabric samples. The linear resistance of a conductive yarn is a measure of its opposition to the passage of electric current in a specified length. The linear resistance of the conductive yarns was measured in ohm per meter (Ω/m) using a TT*i* 1906 computing multimeter. Polyester yarn was used to form an insulating area in the structure. Details of these materials are listed in ***Table 1***.

As an ultrasonic sensor, LV-MaxSonar ®-EZ3™ (MaxBotix), was chosen due to its small dimensions and low power requirements, a 2.5 V to 5.5 V supply with a low (2 mA) typical current draw [28]. ***Figure 1*** shows the ultrasonic sensor with its dimensions. Considering these dimensions, the position of conductive yarns inside the woven fabric structure was determined. This ultrasonic sensor enables the detection of objects or to measure the distance to an object through the use of reflected sound waves, and thus it gives information from 6 to 254 inches.

Design of the woven fabric structure and integration of sensor methodology

For a given ultrasonic sensor, the interface output formats included are the pulse width output, analogue voltage output, and serial digital output. According to our study, only the analogue voltage output was used as a signal output. The analogue voltage works with a scaling factor of (Vcc/512) per inch, which means that a supply of 5 V yields ~ 9.8 mV/inch (5V/512 ≈ 9.8 mV), whereas 3V (3V/512 ≈ 5.8 mV) yields 5.8 mV/inch [28]. In other words, if the distance of an obstacle to the sensor is 2.54 cm then, with a power supply of 5 volts, it is expected to obtain 9.8 mV as a signal output.

To integrate the sensor into a textile structure, three electrical connection points: Ground, Feeding Voltage (Vcc) and Analogue Voltage (V_{AN}-Signal Output) were created using conductive yarns of specified dimensions. To prevent the formation of short circuits, the conductive yarns were hidden into the structure. The fabric structure was considered as a double-woven fabric, and the conductive yarns were placed in the middle layer of the structure. A double woven cloth containing weft stuffer yarns was woven with polyester yarns on an ARM loom. The set of warp yarns of the upper layer was linked to the set of weft yarns from the bottom layer, and thus the two layers were held together, making the weft stuffers secure inside the fabric. A four harness satin weave was chosen for both layers. ***Figure 2*** shows a diagram representing the drawdown, threading and liftplan for the double-woven cloth with weft stuffers. The design process was created using Pointcarre Textile Software [29].

During the weaving process, some of the polyester weft stuffers were replaced with conductive yarns at distances required by the sonar devices technical data book [28]. The conductive yarns were positioned in the middle of the fabric, having a straight trajectory without undulation. Thus, in each sample the same conductive yarn was used three times in the weft direction at distances desired to satisfy the three electrical connection points. Fi-

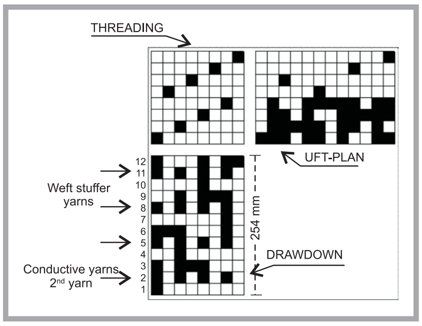

Figure 2. *Draft for double-woven cloth with weft stuffers and the position of conductive yarn.*

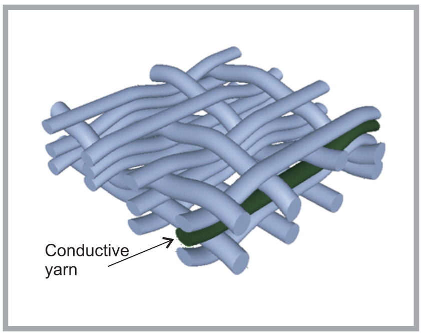

Figure 3. 3D representation of the double-woven cloth (TexGen software).

Table 2. Summary of measurement procedure.

Cases	Situation
I. Without a phone	-
	-
II. With a phone in the vertical direction	Calling
	No calling (standby)
III. With a phone in the horizontal direction	Calling
	No calling (standby)

nally with five different conductive yarns, five different samples with the same fabric design were produced. The lengths of the samples produced were 20 cm. Since the conductive yarns were inserted horizontally without any undulation in the structure, their lengths in the structure were approximately 20 cm as well.

3D-graphical representations of the woven fabric structure (TexGen software [30]) and final sample showing the sensor's connection points are shown in ***Figures 3*** and ***4***, respectively.

As seen in ***Figure 4***, the conductive yarns are in a grey colour in the middle part of the fabric, whereas the non-conductive polyester microfibres are in white. Conductive yarns were placed in order to match the Ground, Feeding Voltage (Vcc) and Analogue Voltage (V_{AN}-Signal Output) pins. Furthermore, to construct an electrical circuit and to connect the sensor to the fabric, loops were formed among the conductive yarns, and snap fasteners were sewn onto these loops.

Measurement set up

The main function of an ultrasonic sensor is to detect obstacles and to measure the distance to an obstacle through the use of reflected sound waves. In sonar systems, an electrical impulse is converted into sound waves, and the echoes of reflected sound waves are picked up by the sonar equipment. Thus, in the ultrasonic sensor system the distance to an object is identified by measurement of the time from the transmission of a pulse to reception [31]. To control this system, a 5 volt power supply was attached to the Vcc

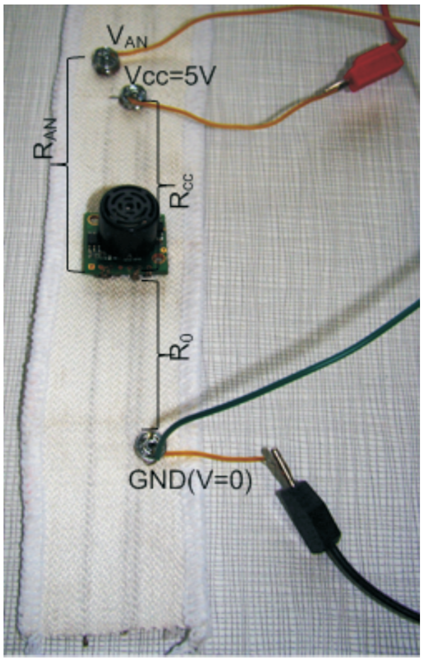

Figure 5. Electrical circuit of the integrated ultrasonic sensor.

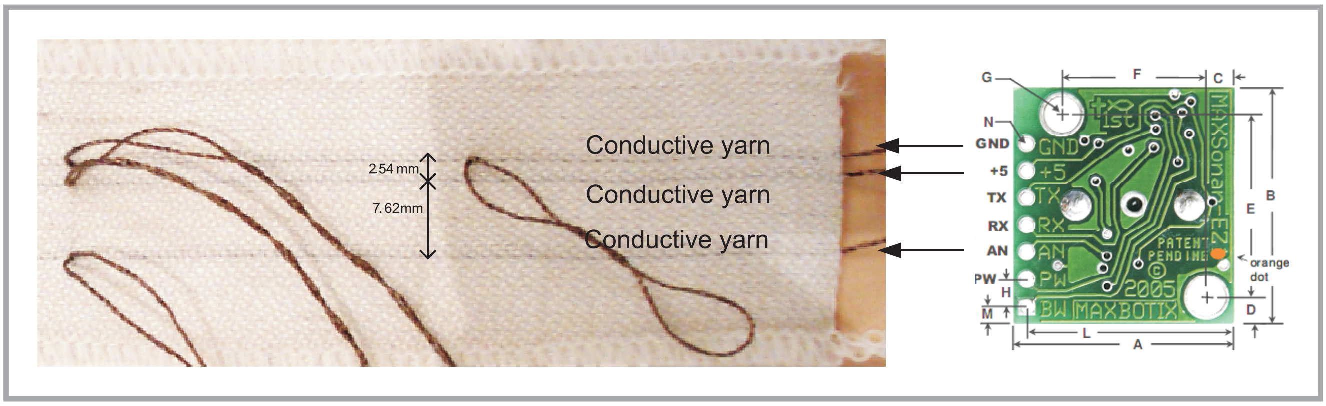

Figure 4. Sample overview. conductive yarns connected to the sensor ground, Vcc and analogue voltage output points.

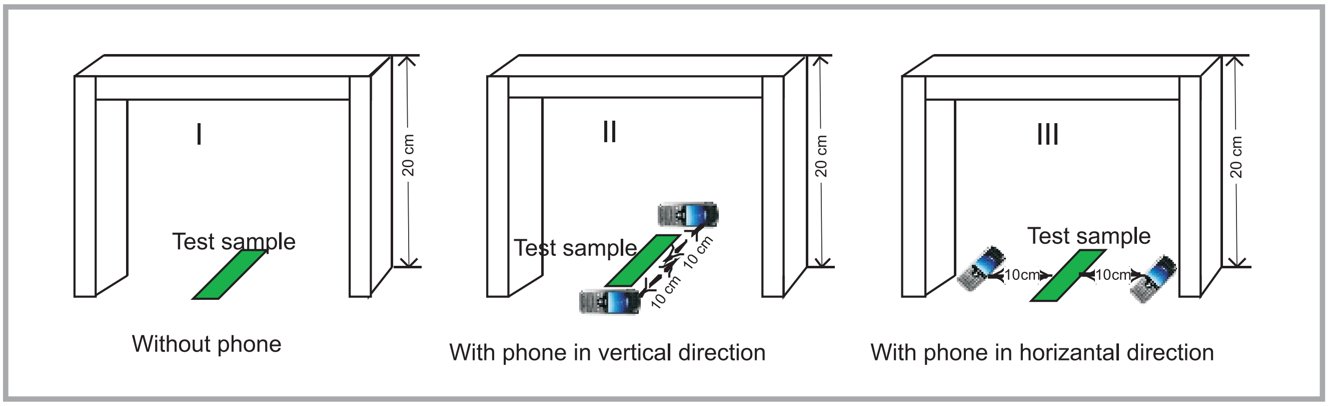

Figure 6. Measurement cases.

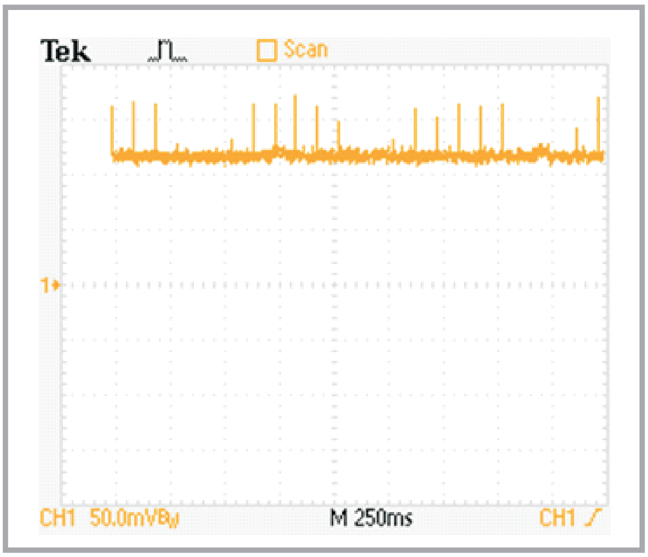

Figure 7. Signal recorded by sample 3, woven with silver-plated nylon 66-2 ply yarn, during sensor measurement with case I (without a phone).

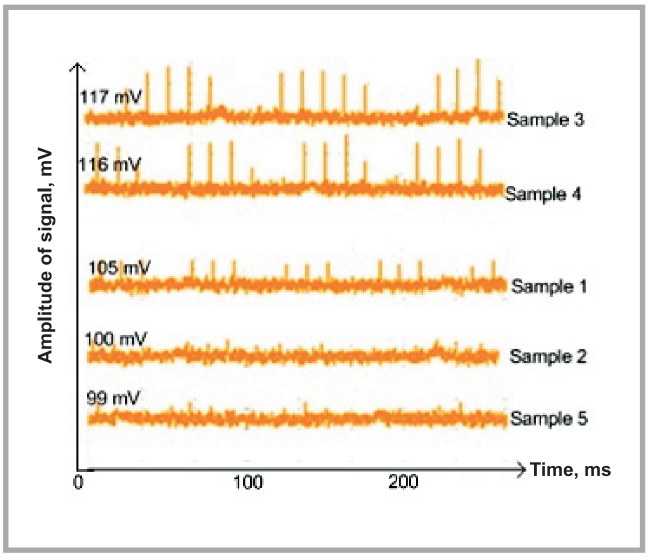

Figure 8. Comparison of signals during sensor measurement with case I (without a phone).

snap fastener, and the ground point was connected by a GND snap fastener. To evaluate the performance of the integrated sensor, a Textronix®TDS 210 scope was connected by a V_{AN} (Signal output) snap fastener (***Figure 5***).

Measurement procedure

Measurements were conducted for three different cases using an obstacle above the height of 20 cm, as seen in ***Figure 6***. In the first case, the ultrasonic sensor integrated into the fabric sample was tested only using an obstacle. In the second and third cases, mobile phones were used in order to disturb measurements and simulate real conditions of sonar utilisation. Our further aim was to develop an intelligent garment to be integrated with sonars. During the utilisation of the garment, the user can carry mobile phones in his/her pockets. Therefore, considering this real condition, mobile phones were only taken into account as a type of disturbance. They were placed vertically and horizontally, depending on the test sample, at the same distance of 10 cm. In the 2nd and 3rd cases, to observe if there are any differences between calling and non-calling situations, the phones were subjected to ringing. As a result, in order to present the performance of the ultrasonic sensor and show the effect of yarn type on the signal quality of the sensor, samples woven with five different conductive yarns were tested in three different cases, details of which are summarised in ***Table 2***. All tests were carried out in laboratory conditions (20 °C and 65% RH).

Determining the noise level

The noise level (unwanted signal) and noise amplitude were determined by signal processing in MATLAB. The first signals were recorded in MATLAB, and then the amplitudes of the signals were taken. The signal to noise ratio (*SNR*) can be estimated by calculating the ratio of signal power to noise power. Since the signal and noise were measured using the same impedance, the SNR was obtained by calculating the square of the amplitude ratio, where A is the root mean square (RMS) amplitude:

$$SNR = \left(\frac{A_{signal}}{A_{noise}}\right)^2, \qquad (1)$$

Generally, SNRs are expressed in the logarithmic decibel scale. Therefore, in order to quantify the signal quality of each sample, the SNR_{dB} value of each sample was calculated using the following equations [32].

$$SNR_{dB} = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) = P_{signal,dB} - P_{noise,dB} \qquad (2)$$

$$SNR_{dB} = 10\log_{10}\left(\frac{A_{signal}}{A_{noise}}\right)^2 = 20\log_{10}\left(\frac{A_{signal}}{A_{noise}}\right) \qquad (3)$$

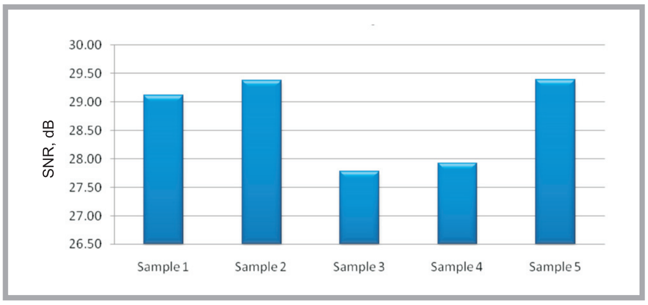

Figure 9. Comparison of SNRs during sensor measurement with case I (without a phone).

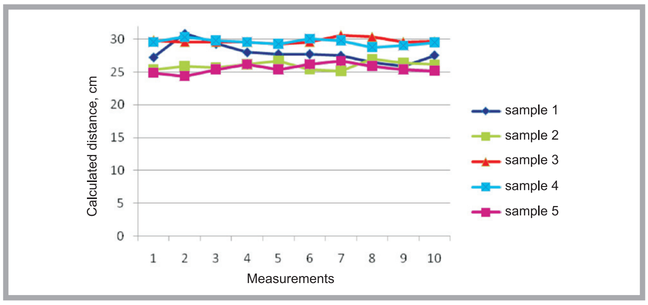

Figure 10. Comparison of distances calculated.

Table 3. Comparison of samples with respect to signal characteristics during calling.

Calling situation and sample		Amplitude, V		Oscillation type	Average number of peaks/s
		$Signal_{RMSS}$	$Noise_{RMS}$		
horizontal	Sample 1	0.1026	0.00341	(1) high frequency oscillations with low amplitude	-
	Sample 2	0.1001	0.00327	(1) high frequency oscillations with low amplitude	-
	Sample 3	0.1183	0.00487	(2) randomly occurring peaks in a very small time interval	52
	Sample 4	0.1177	0.00488	(2) randomly occurring peaks in a very small time interval	56
	Sample 5	0.0968	0.00315	(1) high frequency oscillations with low amplitude	-
vertical	Sample 1	0.1041	0.00416	(1) high frequency oscillations with low amplitude	-
	Sample 2	0.1000	0.00607	(3) randomly occurring peaks in a greater time interval	4
	Sample 3	0.1172	0.00867	(3) randomly occurring peaks in a greater time interval (2) randomly occurring peaks in a very small time interval	8 56
	Sample 4	0.1204	0.0148	(3) randomly occurring peaks in a greater time interval (2) randomly occurring peaks in a very small time interval	8 60
	Sample 5	0.0984	0.00337	(1) high frequency oscillations with low amplitude	-

Table 4. Comparison of samples with respect to signal characteristics during standby.

Standby situation and sample		Amplitude, V		Oscillation type	Average number of peaks/s
		$Signal_{RMSS}$	$Noise_{RMS}$		
horizontal	Sample 1	0.1029	0.00357	(1) high frequency oscillations with low amplitude	-
	Sample 2	0.0999	0.00342	(1) high frequency oscillations with low amplitude	-
	Sample 3	0.1176	0.00469	(2) randomly occurring peaks in a very small time interval	56
	Sample 4	0.1166	0.00472	(2) randomly occurring peaks in a very small time interval	56
	Sample 5	0.0973	0.00321	(1) high frequency oscillations with low amplitude	-
vertical	Sample 1	0.1034	0.00364	(1) high frequency oscillations with low amplitude	-
	Sample 2	0.0998	0.00352	(1) high frequency oscillations with low amplitude	-
	Sample 3	0.1176	0.00477	(2) randomly occurring peaks in a very small time interval	56
	Sample 4	0.1165	0.00476	(2) randomly occurring peaks in a very small time interval	52
	Sample 5	0.0978	0.00338	(1) high frequency oscillations with low amplitude	-

Results

A random fluctuation in the electrical signal is called electronic noise. The level of noise, which is the level of unwanted alteration of the signal waveform, gives an idea about the signal quality [33]. In our case study, due to the material characteristics, the conductive yarns, woven extremely close to each other, created an undesirable effect on one other when they were transmitting signals. Thus, they acted as sources of noise between each other, creating crosstalk [24]. For instance, in **Figure 7** a noisy signal with a signal amplitude of 117 mV recorded by sample 3, woven with silver-plated nylon 66-2 ply yarn, can be easily seen.

Figures 8 and ***9*** show a comparison of signals and SNRs during the sensor measurement without using mobile phones, respectively. Moreover, ***Figure 10*** shows the distance values calculated. It is possible to notice that there is significant difference in the morphology of the signals. Samples woven with 100% stainless steel, silver plated nylon 66-4 ply yarn and insulated copper yarn, which have a linear resistance of < 15 ohm/m, < 50 ohm/m, < 10 ohm/m respectively, show better signal quality than those woven with silver plated nylon 66-2 ply yarn and silver plated nylon 66 yarn with a linear resistance of < 230 ohm/m and < 240 ohm/m, respectively (***Figure 8***).

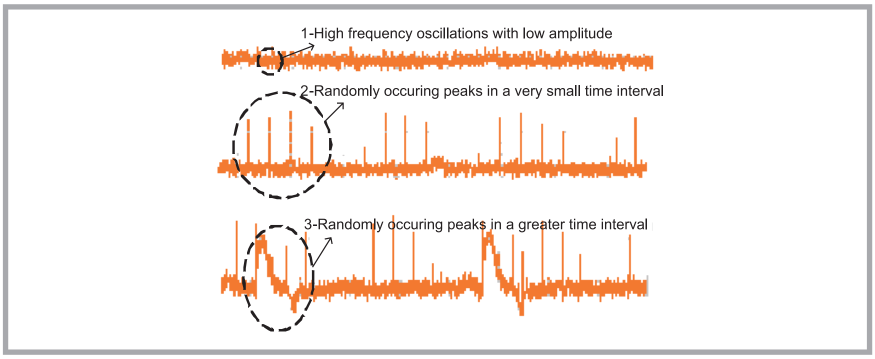

__Figure 11.__ Examples of the three types of oscillations obtained.

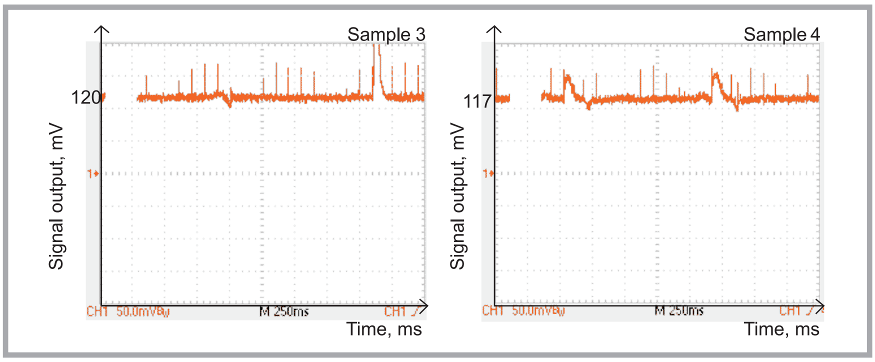

__Figure 12.__ Different peaks obtained with samples 3 and 4 during calling in a vertical position.

Furthermore, as seen in ***Figure 9***, SNR values of samples woven with 100% stainless steel (29.11), silver plated nylon

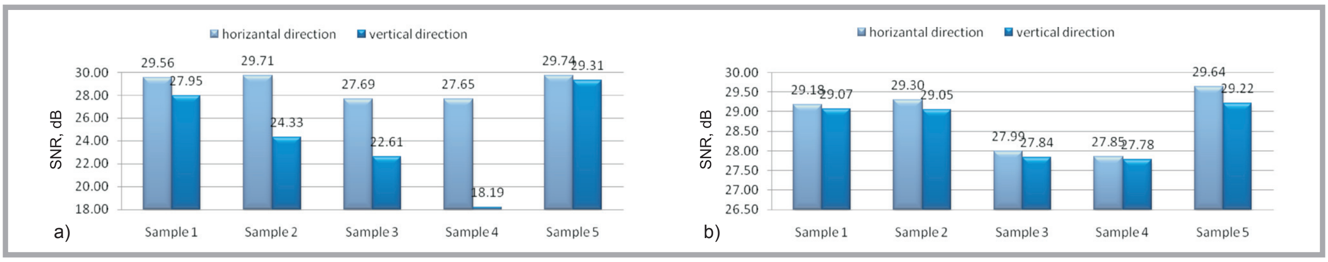

***Figure 13.** Comparison of SNRs during sensor measurement with cases II and III (with the phone in a horizontal and vertical direction during: calling - a and standby - b).*

66-4 ply yarn (29.37) and insulated copper yarn (29.38) are higher than those of samples woven with silver plated nylon 66-2 ply yarn (27.77) and silver plated nylon 66 yarn (27.92). The SNR values of the samples also show that the signal quality of samples 1, 2 & 5 is better than that of samples 3 and 4. Additionally, according to ***Figure 10***, the distance values calculated generally increased with the linear resistance. It was also noted that samples 1, 2 and 5 detected the obstacle at around 25 cm, whereas for samples 3 and 4 it was at around 30 cm. These differences in signal quality permit us to state that as the linear resistance of the yarn increases, the noise level also rises.

In order to check if the calling situation influences the performance of the sensor due to the direction, the phones were subjected to ringing and placed in different positions according to the sensor range. Additionally, there were further tests on the samples in order to distinguish if there was any difference between the horizontal and vertical position during standby. Thus, when the three different situations were considered, three different types of oscillations on the morphology of the signals were noticed. ***Figure 11*** shows examples of the three oscillation types obtained on the morphology of the signals, namely (1) high frequency oscillations with low amplitude, (2) randomly occurring peaks in a very small time interval, and (3) randomly occurring peaks in a greater time interval. By considering the oscillation types and numbers of peaks per time, the signal amplitudes and noise amplitudes of the samples were compared. ***Tables 3*** and ***4*** show a comparison of signals during calling, as well as standby situations in the horizontal and vertical position, respectively. When the phones were placed in a vertical position (see ***Figure 6*** case II), the calling situation presented a significant effect on the signal performance, whereas it had no significant effect when the phones were placed in a horizontal position (see ***Figure 6*** case III). According to the results, randomly occurring peaks over a greater time interval were only noticed during calling in a vertical position (***Tables 3 - 4***). For instance, different peaks were clearly obtained with samples 3 and 4 during calling in a vertical position (***Figure 12***). Moreover, as seen in ***Table 3***, the amplitude of noise increased with the calling situation in a vertical position, which can be attributed to the randomly occurring peaks, over a greater time interval, affecting the signal quality negatively. Furthermore, the SNR value of each sample decreases during calling in a vertical position (***Figure 13.a***), which can be linked to the working range of the sensor. Therefore, it should be outlined that if the working range of the sensor is parallel to the position of the calling situation, it may cause a decrease in signal quality. Despite this phenomenon, the sample woven with insulated copper yarn showed good signal quality once again. According to ***Table 4***, it can be said that the standby situation of phones has no considerable effect on the signal quality of the sensor due to the direction. Even if the morphology of signals presented similar results for both the vertical and horizontal directions, a slight decrease was seen in the SNR value of each sample when the phones were placed in a vertical direction as compared to that in the horizontal direction (see ***Figure 13.b***). Hence, this proves that if the working range of the sensor is parallel to the position of standby, it may also cause a slight decrease in signal quality.

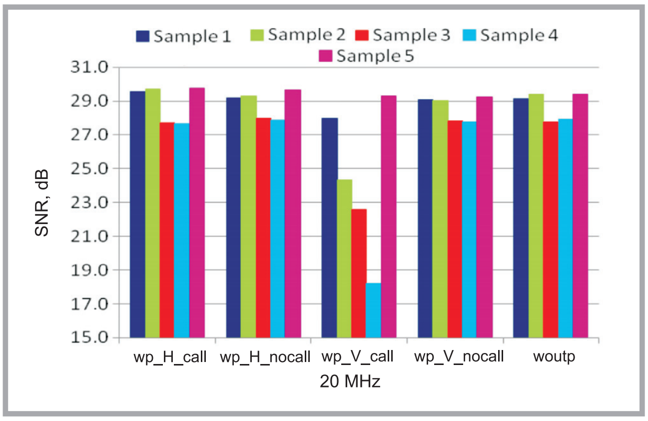

Figure 14. *Change in SNRs according to the situations.*

Figure 14 shows the change in SNRs according to the situations. In this figure, the codes are arranged according to the details of the cases. "wp" indicates with a phone, "H" indicates a horizontal position, "V" indicates a vertical position and "woutp" indicates without a phone. As seen in the figure, a change apparently occurs in the vertical position during calling. It was found that the change in the SNR value of sample 4 (silver plated nylon 66 yarn with a linear resistance of < 240 ohm/m) was extremely high, whereas the change in the SNR value of sample 5 (insulated copper yarn with a linear resistance of < 10 ohm/m) was low in a vertical position during calling. The changes in rank from highest to lowest are sample 4, sample 3, sample 2, sample 1 and sample 5, respectively, which can be attributed to the conductivity of yarns and working range of the sensors, as mentioned above. From ***Figure 14***, it is possible to notice that when the linear resistance increases, the change in SNRs also increases. Therefore, it can be concluded that the change in SNRs is proportional to the linear resistance of yarns, which means that when the conductivity of the yarn increases, the noise level decreases, resulting in better signal quality.

Conclusion

The innovative approach of this work is based on the successful implementation of ultrasonic sensor in a textile structure. Moreover, the performance of the ultrasonic sensor integrated into the textile structure using five different conductive yarns was analysed. In order to measure the signal quality of the ultrasonic sensor, measurements were performed for three different configurations of disturbances: without using phones, with phones in a vertical and horizontal direction, and during calling and standby.

The results reported in this work show that the linear resistance of conductive yarns affects the signal quality of sensors. It was found that when the linear resistance increases, the noise level rises, and the signal quality decreases. According to our results, insulated copper yarn showed the best signal quality. Nevertheless, our experiences showed that silver plated nylon 66-4 ply yarn achieves the best compromise between signal quality and preserving textile properties e.g. handle, stable and elastic, easy to weave, easy to integrate a sensor etc. Another result issuing from this study is that the direction of the calling and standby situation has an important effect on the signal quality of the sensor, giving us an idea about their working range. Therefore, it should be noted that the working range of the sensor is sensitive to noise.

Acknowledgment

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References

1. Katragadda R. B., XuY.; A Novel Intelligent Textile Technology Based on Silicon Flexible Skins, Sensors and Actuators, Vol. A143, 2008 pp. 169–174.
2. Teller A.; A platform for wearable physiological computing, Interacting with Computers, Vol. 16, 2004 pp. 917–937.
3. Choi S., Jiang Z.; A Novel Wearable Sensor Device with Conductive Fabric and PVDF Film for Monitoring Cardiorespiratory Signals, Sensors and Actuators, Vol. A128, 2006 pp. 317–326.
4. Hung K., Zhang Y. T., Tai B.; Wearable Medical Devices for Tele-Home Healthcare, Proc. of the 26th Annual Int.Conference of the IEEE Engineering in Medicine and Biology, 2004 pp. 5384-5387.
5. Suenaga T., Sasaki H., Masuda Y., Imura M., Yasumuroa Y., Yutani A., Manabe Y., Oshirob O., Chihara K.; Wearable ultrasound device for ubiquitous medical care environments, International Congress Series, Vol. 1268, 2004 pp. 265–270.
6. Lin C. S., Hsu C. H, Lay L. Y., Chio C. C., Chao C. C.; Wearable device for real-time monitoring of human falls, Measurement, Vol. 40, 2007 pp. 831–840.
7. Rossi D. D., Carpi F., Scilingo E. P.; Polymer based interfaces as bioinspired smart skins, Advances in Colloid and Interface Science, Vol. 116, 2005 pp. 165-178.
8. Dittmar, A. Meffre R., Oliveira F., Gehin C., Delhomme C., Wearable Medical Devices Using Textile and Flexible Technologies for Ambulatory Monitoring, Proc. 2005 IEEE Engineering in Medicine and Biology 27th Annual Conference, 2005 pp. 7161-7164.
9. Tang S. P., Recent developments in flexible wearable electronics for monitoring applications, Transactions of the Institute of Measurement and Control, Vol. 29, 2007 pp. 283–300.
10. Zhang H., Tao X. Wang S., Yu T.; Electro-Mechanical Properties of Knitted Fabric Made From Conductive Multi-Filament Yarn Under Unidirectional Extension, Textile Research Journal, Vol. 75, 2005 p. 598.
11. Li L., Man W. AU., Wan K. M., Wan S. H., Chung W. Y., Wong K. S.; A Resistive Network Model for Conductive Knitting Stitches, Textile Research Journal, 2010 Vol. 80, No. 10, pp. 935-947.
12. Kayacan, O., Bulgun, E., and Sahin, O., Implementation of Steel-based Fabric Panels in a Heated Garment Design, Textile Research Journal, Vol. 79(16), 2009 pp. 1427–1437.
13. Su C. I., Chern J. T.; Effect of Stainless Steel-Containing Fabrics on Electromagnetic Shielding Effectiveness, Textile Research Journal, Vol. 74, 2004 pp. 51-54.
14. Li L., Man Au W., Li Y. Man Wan M. K, Wan S. H., Wong K. S.; Design of Intelligent Garment with Transcutaneous Electrical Nerve Stimulation Function Based on the Intarsia Knitting Technique, Textile Research Journal, Vol. 80(3), 2010 pp. 279–286.
15. Paradiso R., Loriga G., Taccini N.; A Wearable Health Care System Based on Knitted Integrated Sensors, IEEE Transactions On Information Technology In Biomedicine, Vol. 9 (3), 2005 pp. 337-344.
16. Li L., Au W. M., Li Y., Wan K. M., Chung W. Y., Wong K. S.; A Novel Design Method for an Intelligent Clothing Based on Garment Design and Knitting, Textile Research Journal, Vol. 79(18), 2009 pp. 1670-1679.
17. Locher I., Gerhard Tröster G.; Enabling Technologies for Electrical Circuits on a Woven Monofilament Hybrid Fabric, Textile Research Journal, Vol. 78(7), 2008 pp. 583-594.
18. Chen H. C., Lin J. H., Lee K. C.; Electromagnetic Shielding Effectiveness of Copper/Stainless Steel/Polyamide Fibre Co-Woven-Knitted Fabric Reinforced Polypropylene Composites, Journal of Reinforced Plastics and Composites, Vol. 27(2), 2008 pp. 187-203.
19. Zhang H., Tao X., Yu T., Wang S.; Conductive knitted fabric as large-strain gauge under high temperature, Sensors and Actuators, Vol. A126, 2006 pp. 129-140.
20. Lai K., Sun R-J., Chen M-Y., Wu H., Zha A-X.; A. Electromagnetic Shielding Effectiveness of Fabrics with Metallized Polyester Filaments, Textile Research Journal, Vol. 77(4), 2007 pp. 242–246.
21. Ramachandran T., Vigneswaran C., Design and Development of Copper Core Conductive Fabrics for Smart Textiles, Journal of Industrial Textiles, Vol. 39, 2009 pp. 81-92.
22. Huanga C-T., Shen C-L., Tang C-F., Changa S-H.; A wearable yarn-based piezo-resistive sensor, Sensors and Actuators, Vol. A141, 2008 pp. 396-403.
23. Hertleer C., Van Laere A., Rogier H., Langenhove L. V.; Influence of Relative Humidity on Textile Antenna Performance, Textile Research Journal, Vol. 80(2), 2010 pp. 177-183.
24. Dhawan, A., Tushar K.,Ghosh, Seyam, A. M. and Muth, J. F., Woven Fabric-Based Electrical Circuits: Part II: Yarn and Fabric Structures to Reduce Crosstalk Noise in Woven Fabric-Based Circuits, Textile Research Journal, 74(11), 955-960 (2004)
25. Kim S., Leonhardt S., Zimmermann N., Kranen P., Kensche D., Müller E., Quix E.; Influence of contact pressure and moisture on the signal quality of a newly developed textile ECG sensor shirt, Proceedings of the 5th International Workshop on Wearable and Implantable Body Sensor Networks, China. 2008 Jun 1-3, pp. 256-259.
26. Puurtinen M. M., Komulainen S. M., Kauppinen P. K., Malmivuo J. A. V., Hyttinen J. A.K.; Measurement of noise and impedance of dry and wet textile electrodes, and textile electrodes with hydrogel, Proceedings of the 28th IEEE EMBS Annual International Conference, New York City, USA, Aug 30-Sept 3, 2006
27. Cardin S. Thalmann D., Vexo F.; Wearable System for Mobility Improvement of Visually Impaired People, Visual Computer, Vol. 23(2), 2007 pp. 109-118.
28. www.maxbotix.com, LV-MaxSonar ®-EZ3™ Data Sheet, Maxbotix Inc.
29. www.pointcarre.com/Textile Design Software.
30. TexGen Software.
31. Kursun S. Kalaoglu F., Thomassey S., Cristian I. Koncar V.; Integration of sonar sensor to textile structure, HighTex 2010 Conference, Istanbul, 16-18 May 2010.
32. Choma A. M., Sarunic M. V., Yang C., Izatt J. I.; Sensitivity advantage of swept source and Fourier domain optical coherence tomography, Optics Express, Vol. 11(18), 2003.
33. Alvarezetal J., Yanez Y., Prego L., Turo A., Chavez J, Garcia M., Salazar J., Noise level analysis in bufferrod geometries for ultrasonic sensors, Ultrasonics, Vol. 44, 2006 pp. 1093–1100.

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