CONDUCTIVE PATHS AND INFLUENCE OF THEIR INTERCONNECTION ON TRANMISSION OF ELECTRIC SIGNAL IN SMART CLOTHING

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Abstract: *Smart clothing containing electroconductive fibres, integrated into construction of textile material, are an alternative for continuous long-term monitoring of human biomedical signals. Operational elements located in the smart clothing are interconnected by conductive paths enabling transmission of data gained via textile sensors to a control and communication unit from where they are transferred to mobile or PC using wireless technology. Method of interconnection of the conductive paths with operational elements of the clothing depends mainly on character of materials used (electroconductive fibre – metal/plastic/textile material). Emphasis is placed on establishment of a stable connection with required transmission characteristics. The paper present results of measuring transmission characteristics of the conductive paths, embroidered with electroconductive thread on a non-conductive textile material, terminated with metal press fasteners. Electrical resistance of the conductive paths for the whole uninterrupted conductive path length, specific segments (right and left) of the conductive path with the metal press fastener and the both segments connected with the metal press fastener was evaluated. Transmission characteristics of harmonic signal (sin) and non-harmonic rectangular signal for frequency ranging from 1 Hz up to 300 kHz with input voltage of 1 V and 3 V were evaluated on a solid joint made by closure of the metal press fasteners. Results of the measurement confirmed trouble-free transmission of the harmonic and non-harmonic signal using proposed conductive paths and satisfactory quality of the output signal without any deformations.*

Keywords: *smart clothing, electroconductive sewing thread, conductive path, metal press fasteners, electric resistance, harmonic signal, non-harmonic signal*

1 INTRODUCTION

Monitoring of human physiological signals using intelligent clothing is based on a concept of so-called Body Sensor Networks (BNS) with an emphasis placed on sensing systems, autonomous primary data processing, miniaturization and last but not least also on reliable interconnection of specific BNS components [1-4]. The sensors have analog outputs, representing physiological parameters, from which a picture about health condition of a patient is established. Conductive paths (Wired Body Area Network) or wireless interconnections (Wireless Body Area Network) are used in the system for power supply, signal transmission to the sensors and data transmission to a data bus. Analog data are converted to digital form in the data bus and they are transmitted to a local central unit e.g. smartphone (PDA). They can be further wirelessly transmitted from the local central unit e.g. to a healthcare system (Remote System) [5, 6].

Major task of the conductive paths is transmission of electrical biosignals, sensed from textile electrodes (e.g. ECG sensors [7, 8]), which are manifestation of electrical activity in a living organism. The biosignals are based on electrical properties of muscle and neural tissue. Electrocardiography (ECG), using electrodes placed on the human body, measures difference of voltage as manifestation of propagation of action potential in myocardium. The active electrodes act as sensors, detecting electrical signals, generated by the heart and conducted through the heart tissue. Electrocardiography (ECG) is a process of recording electrical activity of the heart in a form of electrocardiogram, i.e. recording time change of electrical potential caused by heart's electrical activity in a form of ECG curves [9].

Quality of the output electrical biosignals transmitted by means of conductive paths is influenced by properties of materials used to prepare the conductive paths, by way of incorporation of the conductive paths into the structure of textile material and by stability of interconnection of the conductive paths with functional components of the intelligent clothing. Basically, the conductive paths consist of electroconductive fibres made from 100% metal (e.g. copper, silver) or polymer containing conductive particles (e.g. carbon) and/or fibres with conductive surface treatment (core/shell structured bicomponent fibres – e.g.

polyamide/silver). A possibility how to create conductive paths is embroidering electrical circuit on a textile substrate with an electroconductive sewing thread incorporating electroconductive fibres, enabling electrical signal transmission. This embroidering technology substitutes an uncomfortable system of cables common on traditional ECG monitoring methods. Special attention should be given to the method of interconnection of the conductive paths with functional components of the clothing. Emphasis should be placed on establishment of a stable interconnection with required transmission characteristics. A necessary condition is to ensure resistance of the connection to mechanical stress and propose an appropriate configuration responding to the required application.

Quality of the output biosignal can be characterized and evaluated by transmission characteristics such as e.g. harmonic and square signal for specific heart rate at particular input voltage. Periodic, indefinite, cyclic signals serving as a medium for information transfer are involved. Graphical evaluation of the transmission characteristics is a way how to confirm functionality of the electrical circuit in a form of conductive paths and biosignal transmission.

2 EXPERIMENTAL

Technology of conductive paths prepared from electroconductive sewing thread with metal accessories attached at the end of the conductive path for stable interconnection of the conductive paths and functional components of the intelligent clothing is described in the experimental part. Besides, method for measurement of transmission characteristics of the conductive paths used for evaluation of quality of the output signal is described as well.

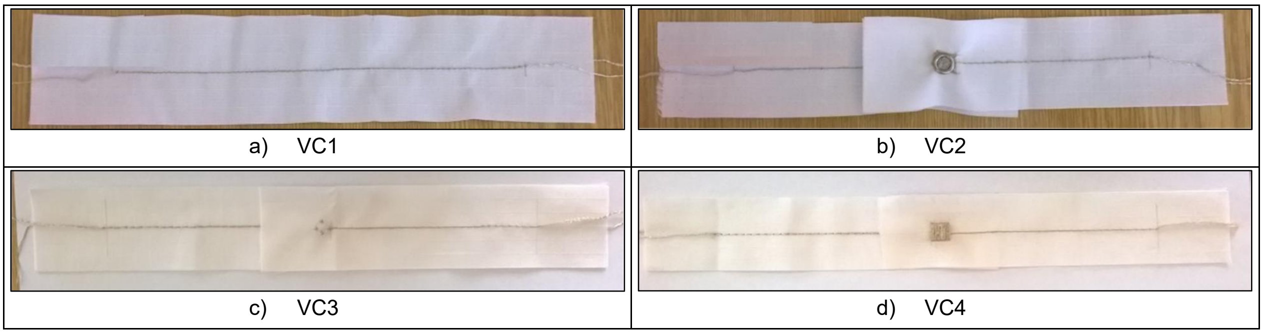
2.1 Materials

The conductive paths were prepared from electroconductive sewing thread containing Elitex®, commercially available conductive multifilament fibre, using embroidering technology. Core of the Elitex® conductive fibre is polyamide covered by a thin layer of pure silver. Electrical resistance of the sewing thread was on a level of cca 17 Ω/m.

The embroidering technology was used to achieve flexible interconnection of the functional modules/components of the electronic circuit. The conductive path consisted of a series of stitches created by interlocking upper and bottom electroconductive sewing thread. Each conductive path consisted of two independent segments (right and left segment) with a length of 10 cm. A system of metal textile accessories was proposed to connect two segments into one conductive path. Respective part of the metal textile accessories (metal button and/or metal snap fastener) was attached at one end of each segment. Strong bond and electrical contact was established by interlocking the conductive segments. A conductive path unbroken by metal accessories with a length of 20 cm was prepared as well. It was used to evaluate influence of interconnection of the conductive paths (fibres) with metal accessories on transmission characteristics of the electrical signal. Preparation of the conductive paths is described in Table 1 and photodocumentation of the conductive paths is shown in Figure 1a-1d.

Table 1 Characteristics of the prepared conductive paths

Designation of the conductive path	Description of preparation of the conductive path
VC1	Conductive path with a length of 20 cm
VC2	Conductive path consists of two independent segments of conductive paths with a length of 10 cm. At one end of the conductive path of each segment there is a conductive area with dimensions of 0.5 x 0.5 cm, created by irregular stitching with conductive sewing thread, to which respective part of a metal button was attached mechanically by riveting. The other end of the conductive path of each segment is finished by free end of the electroconductive sewing thread. A strong bond and interconnection of the both segments to one conductive path is established by interlocking the both parts of the metal button
VC3	Conductive path consists of two independent segments of conductive paths with a length of 10 cm. At one end of the conductive path of each segment there is respective part of a metal snap fastener (spring socket and stud) sewn by free end of the electroconductive sewing thread used to prepare the conductive path. The other end of each segment is finished by free end of the electroconductive sewing thread. A strong bond and interconnection of the both segments to one conductive path is established by interlocking the both parts of the metal snap fastener
VC4	Conductive path consists of two independent segments of conductive paths with a length of 10 cm. At one end of the conductive path of each segment there is a conductive area with dimensions of 0.5 x 0.5 cm, created by manual stitching with conductive sewing thread, on which respective part of metal snap fastener (spring socket and stud) was sewn. The other end of conductive part of each segment is finished by free end of the electroconductive sewing thread. A strong bond and interconnection of the both segments to one conductive path is established by interlocking the both parts of the metal snap fastener



a) VC1

b) VC2

c) VC3

d) VC4

Figure 1 Conductive paths

Electrical resistance and transmission characteristics were evaluated on samples prepared this way.

2.2 Measurements and evaluation methodology

The transmission characteristics of the conductive threads and interconnection of left and right segments (sample VC2, VC3 and VC4) were evaluated by measuring the electrical resistance [Ω] and quality of signal transmission (amplitude measurements and visual inspection of the wave form).

The first phase included a simple evaluation of the electrical resistance measured using the Agilent 34404A laboratory precision multimeter from defined points of measurement. The average value from three measurements was calculated and is listed in the corresponding table of results - left segment, right segment and interconnected segments, from which we calculated the resistance of the snap fastener interconnection itself. Sample VC1 only includes the total impedance of the electro conductive thread since no snap fastener interconnection is present.

The second phase included the testing of harmonic signal transmission. The harmonic signal was generated using the Rigol DG4162 signal generator within the 1Hz to 300 kHz range, with a peak-to-peak amplitude of 1 V and transmitted over the electro conductive threads.

The third phase of measurements included the testing of square signal transmission - to mimic the 3 V transistor-transistor logic (TTL) used in subsequent application of the electro conductive threads in our intelligent clothing prototype. Square signal with frequencies from 1 Hz to 300 kHz was evaluated and transmitted over the electro conductive threads.

For phase 2 and phase 3 we evaluated the amplitude of the transmitted signal and also visually inspected the waveforms - comparing the original and transmitted signal using the KEYSIGHT MSO-X 3012A oscilloscope.

3 RESULTS AND DISCUSSION

Phase one results are listed in Tables 2 - 4. They include the measured impedance of individual left and right segments (VC2, VC3, VC4), the total impedance of both connected segments and the calculated impedance of the snap fastener interconnection..

Table 2 Measured impedance values for VC2 - mechanically pressed snap fastener

	Meas. n.1	**Meas. n.2**	**Meas. n.3**	**Average**	**Snap fastener**
Left segment impedance	8.1 Ω	8.0 Ω	8.3 Ω	**8.1 Ω**	**-**
Right segment impedance	7.0 Ω	7.3 Ω	7.1 Ω	**7.1 Ω**	**-**
Total impedance	24.2 Ω	23.8 Ω	22.5 Ω	**23.5 Ω**	**8.3 Ω**

Table 3 Measured impedance values for VC3 – 4 point sewed snap fastener

	Meas. n.1	**Meas. n.2**	**Meas. n.3**	**Average**	**Snap fastener**
Left segment impedance	3.6 Ω	3.5 Ω	3.6 Ω	**3.6 Ω**	**-**
Right segment impedance	3.7 Ω	3.8 Ω	3.4 Ω	**3.6 Ω**	**-**
Total impedance	8.2 Ω	9.1 Ω	8.1 Ω	**8.5 Ω**	**1.3 Ω**

Table 4 Measured impedance values for VC4 – area sewed under snap fastener

	Meas. n.1	***Meas. n.2***	***Meas. n.3***	***Average***	***Snap fastener***
Left segment impedance	5.5 Ω	5.7 Ω	6.1 Ω	**5.8 Ω**	**-**
Right segment impedance	12.0 Ω	11.8 Ω	12.3 Ω	**12.0 Ω**	**-**
Total impedance	18.1 Ω	19.6 Ω	19.8 Ω	**19.2 Ω**	**1.4 Ω**

The lowest impedance was obtained from VC3 wherein the snap fastener was sewed in 4 positions (see Figure 1c) - thus we opted to use this method of connecting the electro conductive threads with snap fasteners in all future designs instead of mechanical pressing method (Figure 1b, VC2). The additional area created under the snap fastener by sewing the electro conductive thread also increased the impedance of the interconnection (Figure 1d, VC4) and significantly increased the impedance of the right segment

Phase two results have confirmed excellent transmission of the harmonic signal in all samples; see Figure 2 for amplitude plot results using VC1 and Figure 3 for amplitude plot results using VC2. The input waveform is transmitted undistorted with appropriate amplitude for all tested samples, regardless of the presence of the snap fastener interconnection.

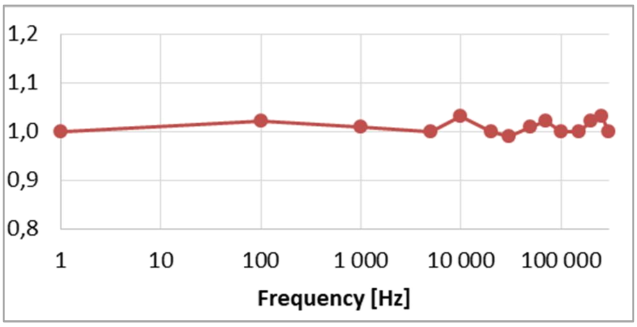


Figure 2 Transfer characteristic of textile without snap fastener (VC1) - sine wave - input amplitude 1V

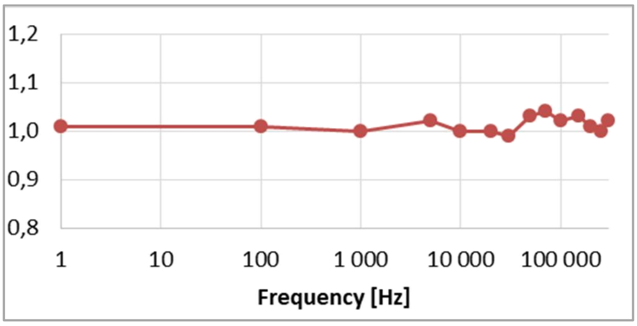
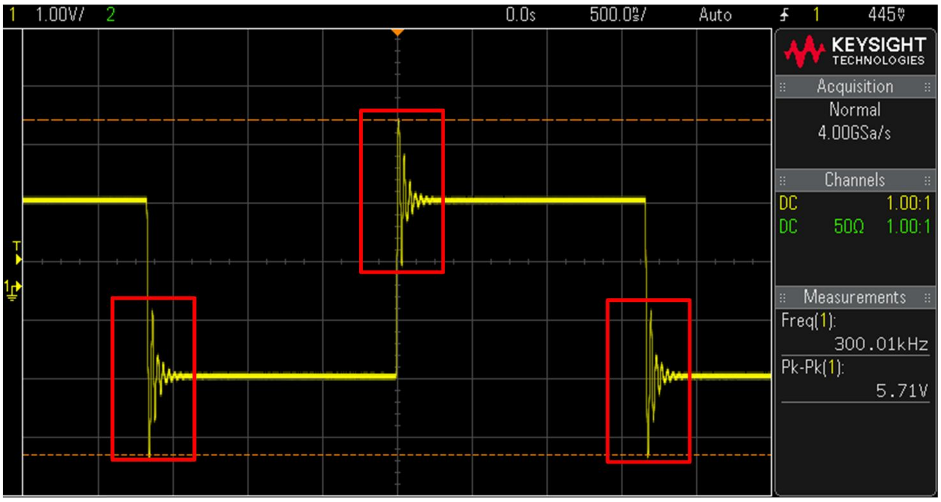


Figure 3 Transfer characteristic of textile with snap fastener (VC2) - sine wave - input amplitude 1V

Phase three results are more interesting. Due to the nature of the square signal a transient effect is visible at the rise and fall slopes of the waveform, especially for higher frequencies (beyond 20 kHz) – see Figure 4. However, the average amplitude is well within the expected TTL levels and the transmitted signal can be processed without any errors. We verified this by transmission of a real digital signal over the I^2C (Inter-Integrated Circuit) bus – see Figure 5. The TMP275 IC from Texas Instruments [10] was powered by a pair of electro conductive threads and the digital temperature output was transmitted using another pair. The PCB with the electric components (pictured left, disconnected for more detail) was connected with the electro conductive fibres using four snap fasteners, as was the receiving side connector (pictured right, connected).



Acquisition
Normal
4.00GSa/s
Channels
DC 1.00:1
DC 50Ω 1.00:1
Measurements
Freq(1):
300.01kHz
Pk-Pk(1):
5.71V

Figure 4 Visible transient effects beyond 20 kHz, rise and fall slopes of square signal, 3V TTL

Figure 5 Sample I^2C bus digital signal transmission – PCB with TMP275 IC, snap fasteners, electro conductive threads

Figures 6 and 7 show the average amplitudes of the transmitted square signal, confirming our above findings.

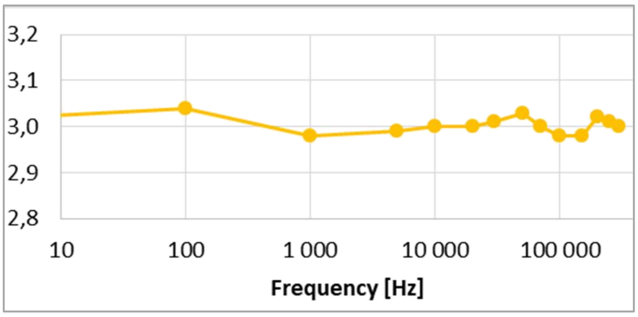


Figure 6 Transfer characteristic of textile without snap fastener (VC1) – square signal - input amplitude 3V

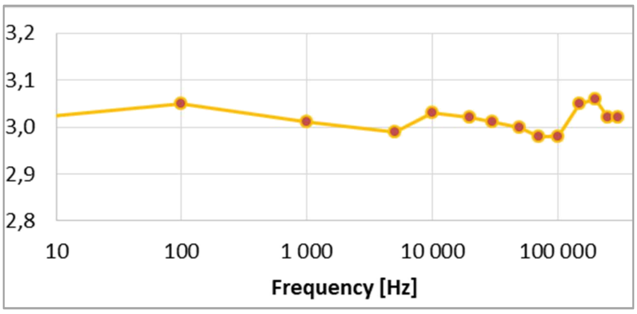


Figure 7 Transfer characteristic of textile with snap fastener (VC2) – square signal - input amplitude 3V

Similar transfer characteristics were obtained for VC3 and VC4 samples and are thus not pictured in this article.

4 CONCLUSION

Electro conductive threads are an important component of so-called intelligent textiles. Instead of using traditional wires which can be bulky and uncomfortable, all electrical connections are created using electro conductive threads which are sewn within the clothing itself. These are then used not only to power the necessary electronic components but also for signal harnessing and transmission thereof within the body signal network system.

Based on our results from phase 1 we can conclude that the interconnection of conductive threads using snap fasteners is possible and feasible. The lowest impedance was observed when the snap fasteners were sewed using the electro conductive thread in 4 locations. This method of attaching also lowered and equalized the right and left segment impedance values – especially when comparing samples VC3 and VC4. Additionally, phase 2 and phase 3 results have confirmed proper signal transmission over the electro conductive threads – both for harmonic and non-harmonic signals in a wide frequency range. The transient effects present in non-harmonic signal transmission do not influence signal quality when using 3V TTL logic as was verified by transferring a real-life digital signal over the I^2C bus.

The obtained results and methods have been further employed in the development of a wearable intelligent clothing prototype pictured in Figure 8 and will be subject to further testing of not only electrical but also mechanical properties in order to assure a functional unit.

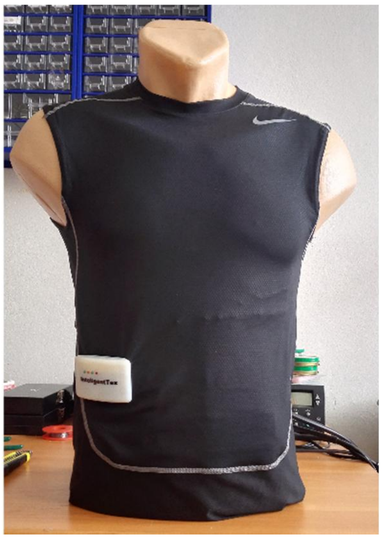


Figure 8 Developed intelligent clothing prototype with processing unit (white box) attached using snap fasteners connected by sewed electro conductive threads

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