33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Textile electrodes and integrated smart textile for reliable biomonitoring

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Abstract — **Since birth the first and the most natural interface for the body is fabric, a soft, warm and reassuring material. Cloth is usually covering more than 80 % of the skin; which leads us to consider textile material as the most appropriate interface where new sensorial and interactive functions can be implemented. The new generation of personalised monitoring systems is based on this paradigm: functions like sensing, transmission and elaboration are implementable in the materials through the textile technology. Functional yarns and fibres are usable to realise garments where electrical and computing properties are combined with the traditional mechanical characteristics, giving rise to textile platforms that are comparable with the cloths that are normally used to produce our garments. The feel of the fabric is the same, but the functionality is augmented.**

Nowadays, consumers demand user-friendly connectivity and interactivity; sensing clothes are the most natural and ordinary interface able to follow us, everywhere in a non-intrusive way, in natural harmony with our body.

I. INTRODUCTION

IN the last few years the intrinsic potentiality of textile technology has been exploited for new high-tech applications [1]. The innovation in terms of textile is related to the use of functional yarns integrated in the fabric structure for sensing and acquisition of signals like electrocardiogram, electromyogram, respiratory activity, skin conductivity, index of motion.

Conductive yarns and fibers made of pure metals or by a combination of textile and metallic fibres are available from textile market; their main applications have been for technical fabrics such as for shielding and motor industry or for bacteriostatic and antistatic purposes, for apparel and furnishings, as well as for pure fashion reasons since the presence of metal changes the mechanical properties of fabric. Such yarns and fibres fall into two main categories: silver coated polyamide fibres, staple spun stainless steel yarns and metal continuous filaments. Metal threads twisted around a standard textile yarn have been used in the past to give a wrinkle effect to fabric; metals like copper are usually coated to avoid oxidation problems, while stainless steel wires are stable and enough conductive to allow e-textile applications. From conductivity, textile handle and drape perspective, fibres with silver would be considered the best option for the production of electrodes to be worn close to the body. Due to abrasion resistance and sweat oxidization problems, they are less appropriate than fibres and yarns made of stainless steel, also if during the last years several more stable products based on silver have appeared on the market (Xstatic [2], Shieldex [3]). At present selected yarns that contain pure stainless steel fibres (Bekinox® [4]) are more suitable for e-textile application, the concentration of fibre to be blended depends upon the nature of textile fibre and the technical requirements of the applications. Such yarns and fibres are easy to process, corrosion resistant, inert and stable in the presence of O_2 and can guarantee long lifetime.

Conductive fabric cannot be realized only with metal yarns otherwise this region of the garment will be too rigid and not conformable; the amount of metal in the fabric is a compromise between the required electrical properties and the necessity to maintain the mechanical behaviour compatible with textile applications.

Within the area of textiles there are two main fabric manufacturing techniques: woven textiles and knitted textiles. Onto both of these fabrics, embellishments can be added by means of printing, embroidery, coating or finishing process. A system based on textile technology, where sensors are realised with fibers and yarns, is based on a fabric containing shaped regions where sensors are located, and these regions correspond to specific parts on the body. For this reason the textile sensing interface has to be integrated in a garment that is perfectly fitting the body, to avoid any possible mismatch between the body and the sensors. This cloth will act as a second skin; it has to be elastic and comfortable. These considerations lead to the use of weft knitting technology, as this technology allows to realise isolated areas where a specific type of yarn is confined (through intarsia), while other technologies like weaving requires to run the same yarn all long the weft and the warp direction. The position of sensors is designed on the knitted fabric, and the final panel is cut and sewed to get the sensors with the desired configuration and orientation.

All the electrodes need to be in close contact with the skin; for this reason the textile feeling and the cloth model refer to underwear "second skin" style. For this reason among textile technologies, seamless knitting dedicated machines have been used for e textile application. Seamless

Manuscript received April 15, 2011. This work was supported by the European Commission under the grant agreement n° IST-2001-37778, n° IST-2002-507816, and FP6-2004-IST-4 contract n° 26987.

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provide elastic, adherent, comfortable garments with these inherent properties. This technology consists in the fusion of two fields: the hosiery one, joined together with knitting machinery. Seamless wear approach allows to get elastic and well fitting second skin models, in a reduced interval of time, very effective for functional aspects is the possibility to implement different mesh area with differentiated compression properties.

Flat knitting and seamless technology allow to confine specific yarns in defined regions of the fabric, working with yarn carries it is possible to process different yarns together with a desired topology. Sensors, electrodes and connections are fully integrated in the fabric and produced in one single step, by combining conductive and non-conductive yarns.

II. Flat-knitting

A "Flat" or Vee Bed knitting machine consists of 2 flat needle beds arranged in an upside-down "V" formation. These needle beds can be up to 2.5 metres wide. A carriage, also known as a Cambox or Head, moves backwards and forwards across these needle beds, working the needles to selectively, knit, tuck or transfer stitches. A flat knitting machine is very flexible, allowing complex stitch designs, jacquard, plated and intarsia patterns, double jersey, shaped knitting and precise width adjustment [5], [6],[7]. It is, however relatively slow when compared to a circular machine.

Usually the machines are equipped with several independently motorised yarn-carriers, and allow the electronic selection on each single needle.

A. *Fabric electrodes:*

Stainless steel monofilament (ϕ=35µm) twisted around a standard textile yarn has been used to realise textile electrode [8]. Flat knitting technology allows to manufacture a double face, using the external non-conductive part to isolate the electrode from the external environment, while the use of another yarn in vanisé configuration allows to get multi layered structures where the conductive surface is sandwiched between two insulated standard textile surfaces. The use of hydro gel membrane could be necessary to improve the electrical signal in dynamic condition as well as to improve the comfort in case of prolonged contact with the skin.

B. *Electrical connections*

Isolate electrical connections fully integrated in the fabric can be produced with the same technology, by means of vanisé procedure; two different yarns can be knitted together by the same needle, while the other yarn is running in parallel on the second bed. The result is that the conductive yarn is knitted between two faces of fabric. With this process it is possible to realize an insolate track that came out from the textile electrode Fig. 1. In this way the contact resistance value is kept lower than 10% of sensor resistance, as the strictest requirement is to maintain this value constant, or with a very low range of variation when compared with sensor sensitivity.

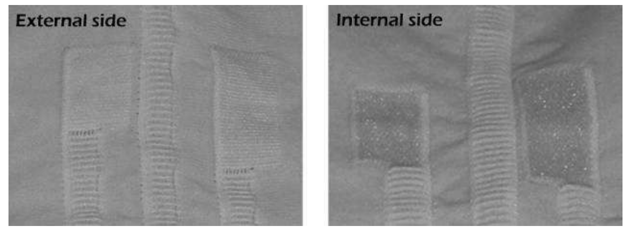

Fig. 1 Electrodes and connections, on the left the external side, on the right the internal side with the conductive regions.

Conductive connections realized along warp or weft directions behave very differently. The reason is that the electrical properties of fabric are due to the interaction among the fibres inside the yarn and the interaction among the single loops inside the fabric. The whole textile structure has to be considered as an array of electrical impedances.

Another possibility is to connect the electrode with a conductive yarn fully integrated in the fabric structure during the knitting process [9],[10]. Each integrated interconnection is realized by two elastic conductive yarns, specially designed to be processed with the machine needles; yarn conductivity is due to one monofilament of stain steel twisted around an elastic core (Lycra®), and both the yarns are covered with polyester. The final aspect of the connections and the conductive yarns is shown in Fig. 2.

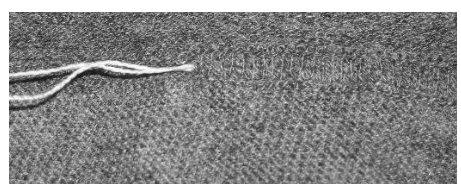
Fig. 2 Integrated interconnections

For this construction a machine equipped with two separated working heads, each one fitted with one open carriage allowing direct yarn feeding, has been used. The machine is equipped with 24 independently motorized yarn-carriers per head; each single needle can be electronically selected, leading to the possibility to handle 24 different yarns.

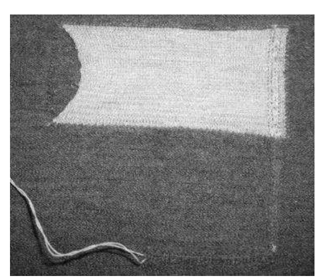
Fig. 3 Interconnection between the electrodes and the conductive elastic yarns

The connection between the electrode and the conductive yarns is realized at the level of the four external wales, visible on the right side of Fig. 3, then a local melting treatment is applied to remove the coating of the conductive yarns, at the level of the interconnections.

C. *Connectors*

Special custom-made textile compatible connectors have been developed in the frame of Proetex project [11] in close collaboration with Ohmatex:

- A 9-pin connector
- A 4-pin connector

Both the 9 pins and the 4 pins connector are composed by a washable part and a non-washable part.

The non-washable part is encapsulated in a band including the electronics whereas the washable part is encapsulated in the shirt. The whole connector (washable part + no washable part) fulfils the IP class protection 44 or alike to withstand the damp environment inside a fire fighter garment.

The washable part is realized in two different versions: either with plastic back cap to be used with the detachable sensors or with a textile support in order to be embedded directly in the shirt.

Fig. 4 Washable part with plastic cap back and non-washable part of 9 pins connector on the shirt

Placement on the Garment

The fabric backing of the connector may be cut into any desired shape and mounted by stitching, lamination or a combination of both. The solution that has been chosen for the final prototype is the stitching. Once secured in the garment, the wires are sold on the PCB connector. Finally, once the wires are securely connected to the connectors, the cavity is filled with silicone.

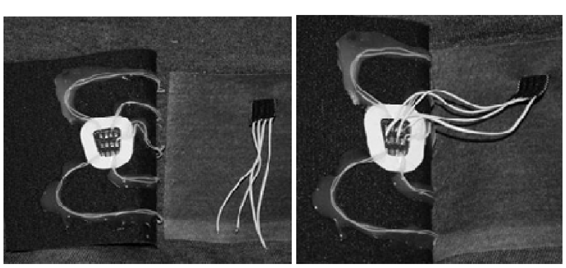

Fig. 5: Connections on the garment side, on the left the textile sensors, on the right the flexible cables from the textile bus for the temperature transducer.

In Fig. 5 is shown the assembling of the 9-pin textile compatible connector, the connection yarns from the textile sensors (electrodes and piezoresistive fabric) are sold on the PCB.

III. The Circular machine (Seamless)

The first prototype of seamless knitting machines (LM1 from Lonati Group [12], Italy) was introduced on the market in the 80s; the new machine was built using a technology similar to the hosiery one. Seamless technology allows the production of tubular fabrics without seams, laid-in elastic yarns inserted in the welt bands and equipped with areas having gradual compression. Therefore, the garments knitted on seamless machines merge comfort with functional performance as they allow the making of different stitches like rib, net, jacquard, piquet, stripes, laces, as well as pre-shaped structures; the main contribution of seamless to e-textile construction is given by the capability of this technology to realize areas with differentiated elasticity.

A. *Fabric electrodes:*

Seamless knitting technology can provide very elastic, adherent, comfortable garments, which can therefore be used for sensing applications where adherence, elasticity and comfort are the main requirements. It is possible to realize seamless systems, where electrodes and sensors are knitted in the same production step, through intarsia technology in the same way as have been described for flat knitting technology. The main difference between the two technologies is in the possibility for flat knitting to combine intarsia and double knitting, while seamless can only manage these two processes separately. However, seamless technology is unique in combining elasticity, comfort and low production costs [13].

Movement artifacts are the main cause of poor signal quality for physiological signals, especially if the measure is taken during normal physical activity. Movement artifacts affect traditional electrodes and sensors, as well as smart and intelligent fabric. Standard skin electrode contact foresees the use of an electrolyte and for that reason hydrogel membranes are used to reduce noise and movement artifacts [8].

To avoid the use of hydrogel, the requirements in terms of clinical parameters have to be reduced; a system with these characteristics cannot acquire information at the clinical level; instead it can give daily indication about health status and users' physical behavior in a context that cannot be monitored in other ways, without interfering the users' life; the location of sensors has to be considered, which leads to select according ergonomic criteria the best place for sensors and electrodes in order to reduce the effect of movement artifacts; sensor pressure on the skin can be increased, playing with the elastic properties of the garment; finally local environmental conditions in terms of temperature and humidity can be used to increase functionality; the objective is to increase in the electrode region the amount of sweat by decreasing breathable properties. Sweat can act as electrolyte to decrease skin-electrode contact impedance.

In Fig. 6 these considerations are summarised: it is showed a seamless system (very high elastic recover), where fabric electrodes are placed on the thorax in a position that is less affected by movement artefacts, a multilayer structure is used to increase the pressure and the amount of sweat.

The electrode is pushed on the skin by the filling cushion, while the third layer is reducing the evaporation rate at local level.

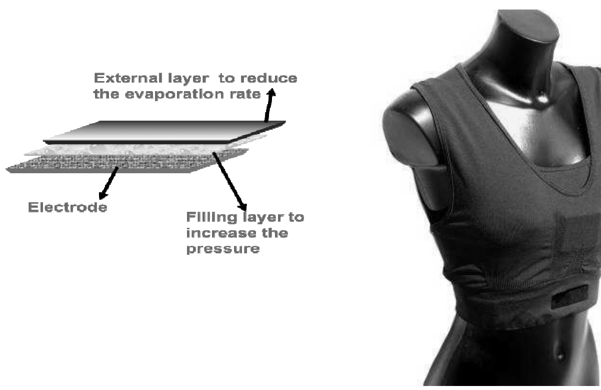

Fig. 6 On the left the multilayered structure at the level of electrodes, on the right, seamless system

Skin-electrode contact, the role of local insulation

In Fig. 7 and Fig. 8 are reported results of an experiment done to evaluate the effect of insulation, for this test a PVC layer is used to reduce the breathability of the fabric in the electrode region.

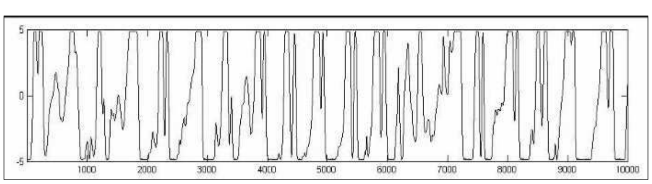

Fig. 7 ECG signal without PVC in walking condition.

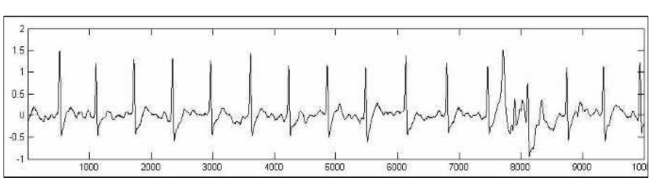

Fig. 8 ECG signal with PVC in walking condition.

It can be seen from the comparison of the two ECG signals acquired through electrodes located at thorax level, that the quality of the signal increase enormously if we use the insulating layer. Both the signals are acquired during a daily physical activity (walking condition).

CONCLUSION

The integration into garment of electronic functionalities is a fundamental issue, more complex of simply sew or embed small dispositive onto a textile substrate. In this paper several technical solutions addressing smart sensing integration have been presented, the possibility to use advanced textile technology has been demonstrated.

ACKNOWLEDGMENT

The authors would like to thank all the partners involved in the Wealthy, MyHeart and Proetex projects.

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