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A wearable yarn-based piezo-resistive sensor

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Abstract

Smart textiles using fabric-based sensors to monitor gesture, posture or respiration have been exploited in many applications. Most of fabric-based sensors were fabricated by either coating piezo-resistive materials on a fabric or directly knitting conductive fibers into fabrics. Obviously, structures of textiles, including yarn structure and fabric structure, will affect the performances of sensors. However, researches on the effects of the structures have not been explored yet. In this paper, yarn-based sensors were fabricated by using piezo-resistive fibers, elastic, and regular polyester fibers. Single and double wrapping methods were employed to fabricate the yarn-based sensors. Performances of the designed yarn-based sensors were evaluated by measuring their resistance changes under variable loading. It is shown that slippage occurs between the piezo-resistive fibers and the core fibers. The relationship of the resistance versus the strain cannot be described as a linear function and should be modeled as a second order equation. Due to the symmetric structure, the double wrapping yarn could resist the slippage and higher linearity in the resistance curve can be provided. Thus it can be served as a better sensing element. The study also investigates the issue of the twist per meter (TPM) and finds that there are no significant effects for using different TPM. Finally, experiments were conducted on a respiration monitoring system to prove the feasibility of the yarn-based sensors and the results demonstrate that the yarn-based sensor can track the respiratory signals precisely.

Keywords: Smart textile; Yarn-based sensor; Piezoresistive

1. Introduction

Smart textiles are becoming very popular in the past decade [1]. One advanced study was to develop a wearable-computing technique which integrated smart textures with semiconductors. An intelligent textile was proposed to fabricate silicon flexible skins with regular textiles [2]. Another application in semiconductors was to form flexible transistors on textile fibers [3,4]. Although inspiring results have been reported in the past, problems such as complicated process, mass production, washability, and wearing comforts are still under investigation.

The other study was to develop textiles which can detect environmental conditions, and then react and adapt to environmental changes. These smart textiles can measure and monitor the physiological conditions of the wearer. Thus they could be applied in healthcare systems. One type of the smart sensing textures was developed by using fabrics having piezo-resistive properties. The approach for fabricating the fabrics was to coat a thin layer of piezo-resistive materials, such as polypyrrole (PPy, a $\prod$-electron conjugated conducting polymer) or a mixture of rubbers and carbons, on conventional fabrics to form fabric-based sensors [5–7,9,12]. The function of the developed sensors is similar to that of flexible strain gauges which can measure strains when they are subjected to a tensile stress. Many applications based on this kind of sensing fabrics were developed. One typical application was to capture posture or motion [6,11,13,14]. The others were related to measuring biomechanical signals for healthcare, especially for respiration detections [15–19]. The coated fabrics were highly dependent upon knitting or weaving topology. Performances can be quite limited if structures of fabrics and yarns were not properly designed or optimized. Therefore, the piezo-resistive sensing fabrics might have some shortcomings such as low dynamic range, poor repeatability, performance deterioration

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after washing or repeated folding, and complicated manufacturing process.

Besides the development of the piezo-resistive sensing fabrics, another approach was to knit conductive fibers with non-conductive base fibers [8]. The knitted fabrics sensors can be regarded as equivalent circuits with a network of resistances, capacitances, and inductances. As the deformation of the fabrics sensor occurs, the electrical properties of the elements will be changed. The changes were measured to calculate the deformation [8–10]. Although the integration of conductive fibers improve the sensing performance even after washing, the sensor can only be made by using knitting process and a large knitting cloth is needed in order to obtain satisfactory results. This requirement might limit the freedom in design of modern clothes. Furthermore, the fabric-based sensor is considered only as two-dimensions because it is made by plane knitting. Space resolution is not high and the obtained information from the average area change could be quite limited. Moreover, the research issues such as yarn topology and structural deformation of fabrics-based sensors have not been investigated yet.

In this paper, yarn-based sensors were developed to improve sensing characteristics [20]. Instead of using fabrics as base elements, we first fabricated the yarns by using piezo-resistive fibers, elastic, and regular polyester fibers. Then the yarn was used as raw materials to make cloth, dress and sensing textiles. As compared to fabric-based sensors, the yarn itself is a sensing element and thus it is easier to be used in smart textiles by conventional knitting or weaving processes. Dependent upon different applications, several sensing segments can be embedded into textiles such that distributed strains can be measured with the sensors. This approach has the advantages such as higher space resolutions, more comforts, better functionality and easier in style design. For fabrication process, single and double wrapping methods were employed. Experiments were performed to measure the resistance changes of the yarn under variable loading. The linearity of the single and double wrapping yarn sensors was evaluated. It is found that the double wrapping method can achieve higher linearity than the single wrapping approach. Physical interpretations are given to illustrate this phenomenon. Furthermore, different twists per meter (TPM) of carbon coated fibers (CCF) wrapping on the core yarn was also investigated. No significant effects on different TPM were found in the experiments. Finally, a respiration monitoring system was used as a test bed to prove the feasibility of the yarn-based sensors and the results demonstrate that the yarn-based sensor can track the respiratory signals precisely.

2. Materials and methods of the yarn-based sensors

Yarns are normally considered as the basic elements of forming fabrics and textiles. But fibers are truly the raw elements of yarns. Yarns are made by combining different types of fibers into a skein. Fiber materials and forming process can have dramatically effects on the characteristics of the yarn. The process of forming a yarn can be categorized into three main methods. One simplest method is the doubling which the fibers are put in parallel to form the yarn. The fibers are bonded together by mutual friction forces. As the yarn is subjected to tensile stress, the fibers can overcome friction force such that mutual slippage can occur. Another method is the entangling approach. This approach is to use pressured air to entangle fibers in fabricating the yarn. The structure of the yarn by this method is not regular and the uniformity of the yarn might be a problem when used as a sensing device. The other method is the wrapping process. This method is to helically wrap one or two fibers on the core yarn. The approach of wrapping one fiber on a core yarn is called the single wrapping. Another approach is to wrap one fiber in clockwise direction and the other fiber in counterclockwise direction. This approach is called the double wrapping. Normally, the twist per meter (TPM) is used to describe the twist density of the wrapping.

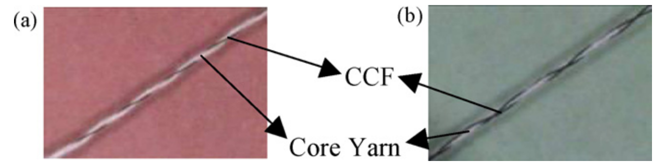

Fig. 1. The yarn structure of yarn-based sensors: (a) single wrapping and (b) double wrapping.

In this paper, the wrapping process was adopted to fabricate the yarn-based sensor as shown in Fig. 1. Three different kinds of fibers which include piezo-resistive fibers, elastic fibers, and polyester were used to form the yarn. The piezo-resistive fiber was chosen as the carbon-coated fiber (CCF) (resistivity 3×10^5 Ω/cm, RESISTAT F901). The fabrication process was to integrate the polyester fibers with elastic fibers into a composite core yarn at first. The length of the elastic fiber was stretched three times in the process. Then the CCF was wrapped on the core yarn by using the single and double wrapping approaches.

The motivations of integrating three kinds of fibers were given as follows. In forming the fabrics, the yarns should have the similar linear density and the strength capability must be high enough for weaving or knitting process. Since the linear density of the CCF is only 24 dtex, where dtex equals to gram per 10,000 m, the CCF should be combined with other fibers to increase linear density and force capability. In this paper, a 56 dtex/48 f polyester filament was chosen to integrate with the CCF. The 48 f means that 48 filaments are contained in a 56 dtex skein. The adding of the elastic fibers (Lycra, 22 dtex) could improve the elasticity of the sensing yarn. The linear densities of the yarns using the single and double wrapping approaches are approximately within 90–110 dtex which are close to regular yarns.

To evaluate the effects of the twist, samples were fabricated with TPM equal to 150, 275 and 450. The 450 TPM means that the CCF wraps the core yarn 450 times per meter. Six different types of samples were fabricated and listed in Table 1. In the next section, experiments were performed to evaluate the performances of the samples.

3. Experimental results of the yarn-based sensors

To evaluate the sensing behaviors of the yarn, experiments on resistance changes under different loadings were conducted in