

Article

Ultralong Carbon Nanotube Yarns Integrated as Electronic Functional Elements in Smart Textiles

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Abstract: Smart textiles are an evolving field, but challenges in durability, washing, interfacing, and sustainability persist. Widespread adoption requires robust, lightweight, fully integrated fiber-based conductors. This paper proposes using ultralong carbon nanotube (UCNT) yarns with a width-to-length ratio of several orders of magnitude larger than typical carbon nanotube fibers. These yarns enable the manufacturing of stable, workable structures, composed of a network of twisted fibers (tows), which are suitable for fabric integration. Our research includes the creation of textile prototype demonstrators integrated with coated and non-coated UCNT yarns, tested under military-grade standards for both mechanical durability and electric functionality. The demonstrators were evaluated for their electrical and mechanical properties under washability, abrasion, and weathering. Notably, polymer-coated UCNT yarns demonstrated improved mechanical durability and electrical performance, showing promising results. However, washing tests revealed the presence of UCNT nanofibers in the residue, raising concerns due to their classification as hazards by the World Health Organization. This paper examines the sources of fiber release and discusses necessary improvements to coating formulations and testing protocols to mitigate fiber loss and enhance their practical viability. These findings underscore both the potential and limitations of UCNT yarns in military textile applications.

Keywords: smart textiles; e-textiles; weaving; nanofibers; carbon nanotubes



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1. Introduction

There has been renewed interest in recent years in the development of smart textiles (also known as e-textiles), specifically in the area of wearable garments, for multiple applications of both civil and military uses [1–6]. This interest is fueled by the miniaturization and prevalence of electronic components, coupled with the development of new flexible material systems. In addition, advancements in wireless networks, cloud computing, energy harvesting, sensors, and battery power all contribute to the growing research in this field [7–9]. Several different conductive yarns are currently being explored for smart textile

applications; they differ from one another in their electrical and mechanical properties, production process, and cost.

This research utilizes ultralong carbon nanotube (UCNT) yarns as the primary conductive infrastructure for smart textiles. Among the various conductive yarns, copper wires and stainless-steel threads are the most commonly used. While they offer excellent electrical properties (typically exhibiting low resistance of considerably less than 1 ohm/m), they are relatively inflexible, high in weight, and, due to their mechanical properties, usually unsuitable for smooth integration in industrial textile manufacturing processes. Other alternatives include intrinsically conductive polymers (ICPs) and extrinsically conductive fibers, which consist of nonconductive thread materials either filled or coated with conductive properties [10]. Common fillers include metallic powder, metallic nanowires, or ICPs, which are added into or onto nonconductive commonly used polymer threads. However, these alternatives often suffer from high manufacturing costs, stiffness, brittleness, increased weight, low durability, and limited signal capacity [11].

Recent developments in conductive yarns have incorporated carbon-based materials, primarily carbon fibers (CF) and carbon nanotube (CNT) fibers, which are tubular fibrous structures composed entirely of graphitic carbon planes. CNTs have the potential mechanical properties to perform better than any commercially available conductive yarn [12]. In comparison to CFs, CNTs offer higher electrical and thermal conductivity, greater strength and enhanced flexibility, making them a promising candidate for wearable and stretchable smart textiles.

CNT diameter typically ranges from 1 to 50 nanometers [13], with most CNTs measuring 1–10 microns in length. Due to their short length, CNTs are generally produced as a fine black powder which is extremely difficult to process and apply. These powders are synthesized using Chemical Vapor Deposition (CVD) and subsequently harvested [14]. However, CNT powders pose significant challenges for wearable textile applications:

- Nanopowders are a health hazard;
- It is not a continuous material;
- They are extremely hard to disperse in solution;
- They have suboptimal electrical, thermal, and mechanical properties due to their short length.

While conventional CNT powders present significant challenges for textile applications, UCNT technology presents a promising solution to these challenges, offering a lightweight, flexible, and scalable alternative. Once UCNT technology reaches mass production, its costs are expected to be competitive with existing market solutions, estimated at a few tens of dollars per kg. Due to the low density of UCNTs, even small quantities are sufficient; for example, producing one square meter of “smart” fabric may require only 10–50 gr of UCNT yarn.

Conductive fibers are commonly integrated into an e-textile by using either knitting or weaving [15,16]. Beyond their use in wearable garments, conductive fibers are also being used in applications such as electrostatic dissipation, EMI shielding, signal and power transfer, and as thermal regulation elements. In parallel with efforts to develop new materials and applications for smart textiles, standardization protocols are being proposed to establish regulations that will further define the requirements and limitations of smart textile products in the future [17]. Given these advancements, research in this field must consider not only the material and functional aspects, but also the long-term usability of smart textiles throughout their lifecycle, from inception to end of use.

This study advances the development of UCNT-based smart textiles, specifically designed for next-generation military uniforms. These smart uniforms aim to provide real-time physiological and environmental data, enhancing situational awareness and soldier

safety. A key contribution of this research is the dual-role integration of UCNT conductive yarns—both as the electric infrastructure interconnecting electronic components, and as activation sites for distributed sensing and actuation functionalities. The UCNT yarns used in this research were custom-manufactured specifically for this project [18], marking a step forward in the scalability and practical application of UCNT technology.

Building on previous research demonstrating UCNT's potential as textile-based electrodes and wearable sensors for real-time medical monitoring [19–21], this study demonstrates the feasibility of integrating UCNT into large-scale, durable, and functional smart textile systems. By addressing challenges in material processing, textile integration and testing, it paves the way for future developments in both military and civilian applications.

This research further advances existing knowledge in four key aspects: Material-wise, it employs ultralong CNT fibers with high electrical conductivity, and provides a detailed account of the patented yarn fabrication process and its characterization. Structure-wise, it introduces UCNT woven into fabric using standard textile manufacturing techniques, specifically a double plain weave structure, and implements a novel multilayer weaving technique to enable multiple sensing and actuation capabilities. Application-wise, this study develops and evaluates several textile demonstrators, showcasing UCNT's functional integration in textiles. Durability-wise, it assesses UCNT textiles through standardized abrasion, washability, and durability tests, offering critical insights into their resilience and long-term performance.

The primary objective of these textile demonstrators was to validate the suitability of UCNT for smart textiles, particularly regarding high conductivity, rapid thermal response, durability, and chemical stability. Given the novelty of UCNT, its specific suitability for wearable applications remains an open challenge [22,23]. By defining a realistic use case scenario for military uniforms, and subjecting UCNT fabrics to standardized textile testing protocols, this research provides a structured evaluation of their integration potential in wearable garments. The findings not only underscore UCNT's advantages, such as their lightweight, flexible, and scalable nature, but also identify necessary areas for future research and development, particularly in optimizing UCNT textiles for long-term usability, large-scale production, and safety for use in wearable applications.

2. Materials and Methods

The experimental work presented in this paper involves four main aspects. These include (1) the novel UCNT yarns, (2) the textile prototype tors, (3) the weaving structure, and (4) the textile testing procedures. In this section, we describe in detail the materials and methods involved.

2.1. UCNT Yarns

2.1.1. 6 Tow UCNT

The UCNT used in this research is a continuous CNT material in the form of fibers that can also be manufactured as mats [24]. The core technology of the production process for these nanofibers is based on a novel patented process [25,26]. The process is a continuous gas phase catalytic reaction via Floating Catalyst Chemical Vapor Deposition (FC-CVD) between a floating catalyst and a hydrocarbon source. The result of this catalytic reaction is a dense cloud of very long CNTs (ranging from 1 mm onwards) that creates a continuous network of UCNTs. This UCNT cloud can be drawn out of the reactor and spun on a drum to create a nonwoven mat or spun on a bobbin to create UCNT yarns. UCNT yarns can be produced at lengths of several kilometers. A single ultralong CNT is estimated to be in the range of 5–10 nanometers in diameter with a length of sub to mm long (aspect ratio of 1:100,000).

2.1.2. UCNT Coating

The 6-tow fiber's initial properties were further enhanced using a simple post-processing technique of coating with polyvinyl fluoride (PVDF, 400 K, Sigma-Aldrich, Rehovot, Israel an affiliate of Merck KGaA, Darmstadt, Germany) for reasons of safety, processability, robustness, and abrasion resistance. PVDF is a highly non-reactive thermoplastic fluoropolymer, with low density (1.78 g/cm^3) and resistance to solvents, acids, and hydrocarbons, and was found to be suitable for this application by previous research work [27]. Table 1 shows the entire range of coating materials that were initially considered and tested. Of them, PVDF 400 K showed the most promising performance in terms of workability and compatibility with the CNT yarn. 400 K refers to the average weight of the polymer chains; higher molecular weight increases toughness and strength, enhances heat resistance, and impacts viscosity and processing. The enhancement in properties of the impregnation with thermosetting resins is described in Table 2.

Table 1. Coating types.

Polyurethane (WBPU)	Epoxy	PVDF
UD-104 75% (25% Water)	RIMR 135 + 137 100%	PVDF 1000 K 15% (85% Acetone)
UD-108 100%	RIMR 135 + 137 90% (10% Acetone)	PVDF 400 K 15% (85% Acetone)
UD-108 75% (25% Water)	RIMR 135 + 137 70% (30% Acetone)	-
UD-375 50% (50% Water)	RIMR 135 + 137 50% (50% Acetone)	-
UD-302 25% (75% Water)	RIMR 135 + 137 30% (70% Acetone)	-
UD-215 100%	RIMR 135 + 137 10% (90% Acetone)	-

Table 2. Comparative properties of CNT yarns.

Tow	Linear Density [g/km]	Diameter [μm]	Resistivity [Ohm/m]	Tenacity [N/tex]	Tensile Stress [MPa]
1	4	200	880	0.22	28
6	27	400	120	0.25	55
6 coated with PVDF	28	80	50	0.30	1604

The PVDF coating was applied using the setup described below (Figure 1). In addition to the reasons mentioned above, PVDF was chosen due to its low cost and ease of application. During initial testing, it was clear that many different parameters affect the coating quality, such as polymer and solvent type, polymer concentration, drying temperature, mechanical setup, bath residence time, and tow twisting. Therefore, although full uniform coverage of the CNT surface was achieved (see Figure 2), coating optimization research should be further continued. For the test samples provided, UCNT yarns were coated with a single (Figure 2c) and double layer of PVDF (Figure 2d). Scanning electron microscopy (SEM) images of the UCNT yarn cross-section shows that double coating provides a more substantial overall coating, with non-uniform thickness along the circumference of the yarn (Figure 2d). Weaved test samples were integrated with both yarn types, and tested comparatively. Although reducing yarn's overall resistance, the PVDF coating provides

some insulation to the outer layer of the fiber. Therefore, yarn edges that needed to be connected to the electronic testing devices with a reliable low-resistance connection were exposed using a solvent that locally removed the coating from the yarn edges [28]. The exposed yarn tips were used to measure the electrical properties of specimens before and after the mechanical impact tests. The ability to entirely remove the coating upon choice is important for future testing methods, and will be further discussed.

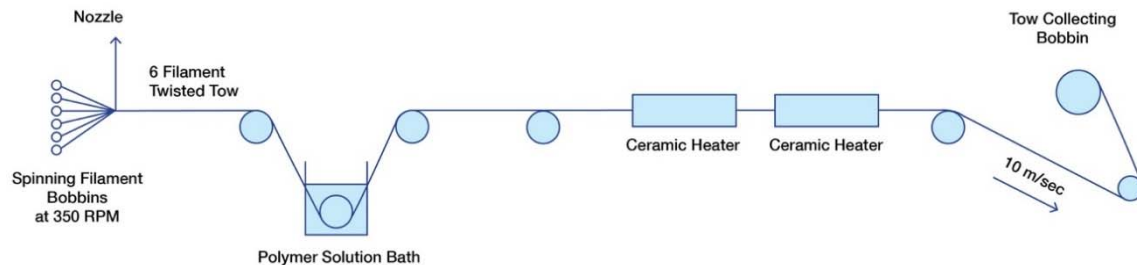


Figure 1. Configuration of tow and coating scheme of the fiber.

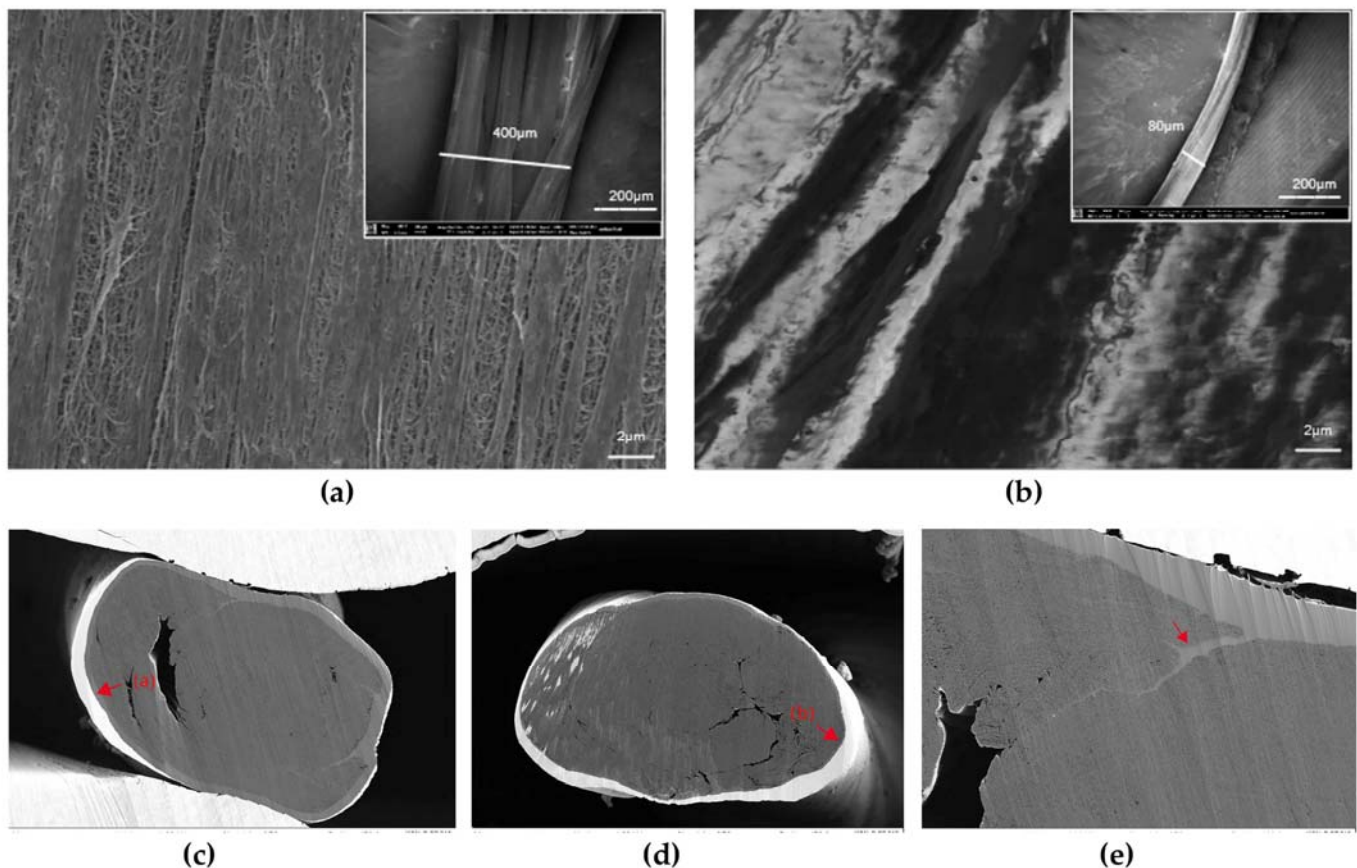


Figure 2. HRSEM (high-resolution scanning electron microscopy) images of CNT fiber: (a) pristine; (b) coated with PVDF. The images were obtained by using a Zeiss UltraPlus SEM system. HRSEM images ($\times 500$): scale bar 20 μm . UCNT 6-tow yarns coated with a (c) single layer and a (d) double layer of PVDF coating. HRSEM image ($\times 2000$): scale bar 10 μm . (e) PVDF coating penetrating from the outer circumference of the UCNT 6-tow yarn towards the core.

Figure 2e shows the PVDF coating of the outer circumference of the 6-tow UCNT yarn, with instances of deeper penetration in between filaments. Empty gaps can be detected in the inner core of the yarn, especially where the different tows are intertwined (see also Figure 2c,d). Complete penetration of the coating to the entire core of the yarn will likely improve yarn properties, in line with previous research [27]. Due to the unique

properties of UCNTs, we found that the compressible nature of the bulk material preserves the conduction path of electrons, ensuring that the holes have little to no effect on the yarn's bulk conductivity.

2.2. Textile Prototype Demonstrators

The notion of future soldiers provided the rationale for developing a series of textile demonstrators. The demonstrators comprised a woven fabric, which is normally the type of textile used in uniforms. Additionally, in comparison to other textile fabrication methods, such as knitting, weaving was identified as being better suited for the mechanical attributes of UCNT yarns, considering properties such as yarn curvature requirement, yarn elongation, and strength [29]. The weaving pattern consisted of a recurring grid of functional “pixels”, measuring 4×5 cm, in which UCNT yarn was integrated. Each pixel consisted of a rupture/disconnection electrode and a resistive touch/wetness electrode (Figure 3). The pixels were designed to have a specific sensing or actuation function (and could contain multiple concurrent functionalities). Pixel functionality was defined according to the location of each pixel in relation to the wearer's body, the weaving pattern (circuitry configuration), and the microcontroller code activating the system.

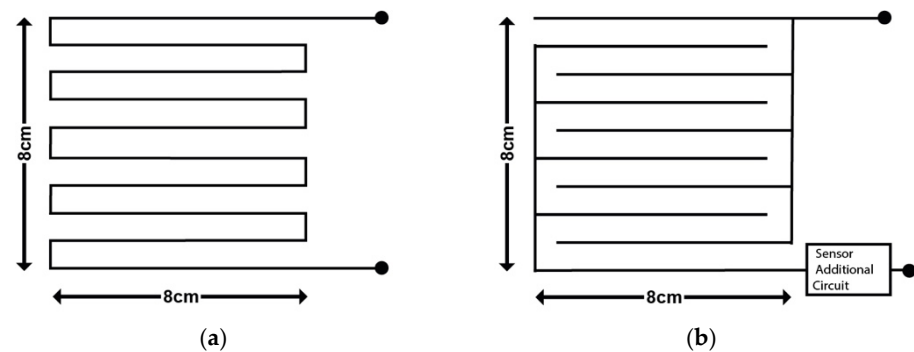


Figure 3. (a) Rupture/disconnection electrode; (b) resistive touch/wetness electrode.

The demonstrators included a rigid-to-flexible multilayer construction which enabled us to connect the necessary rigid electronic components (such as, e.g., circuit boards and buzzers) to the conducting UCNT yarns. The flexible layer, which was added to the fabric after its production, was made of Pyralux® (DuPont, Circleville, OH, USA), a clad of laminated composites made of a flexible copper layer with a bonding film of dielectric materials made with Teflon® and Kapton® (polyimide) films [30]. Special connecting points, formed on the Pyralux® substrate, allow for manually sewing the UCNT yarns directly onto the substrate, creating a reliable and consistent electrical connection between the fabric-integrated UCNT yarns and rigid electronics (Figure 4).

The sensing and actuation functionalities of the prototype demonstrators included tear detection, resistive touch, wetness detection, and pressure sensing. Initial actuation capability included heating and haptic alert (by integrating an off-the-shelf electronic buzzer). Future demonstrators may further include functionalities such as pH and temperature sensing.

The communication and data transfer were based on multiple “hubs” consisting of a rigid printed circuit board (PCB), based on Arduino Nano microcontroller unit (MCU) and NanoRF v1.5 Breakout Board for radio frequency (RF) wireless communication. The smart garment is designed to store information locally (vs. cloud) and transmit data via RF for privacy and security reasons, while analytics takes place remotely, away from the wearable garment. Some of the rigid components were designed to be removable, which facilitates future interchangeability, software updates, and reconfiguration, which typically needs to

be carried out away from the garment. Furthermore, it will allow for component removal before washing if needed.

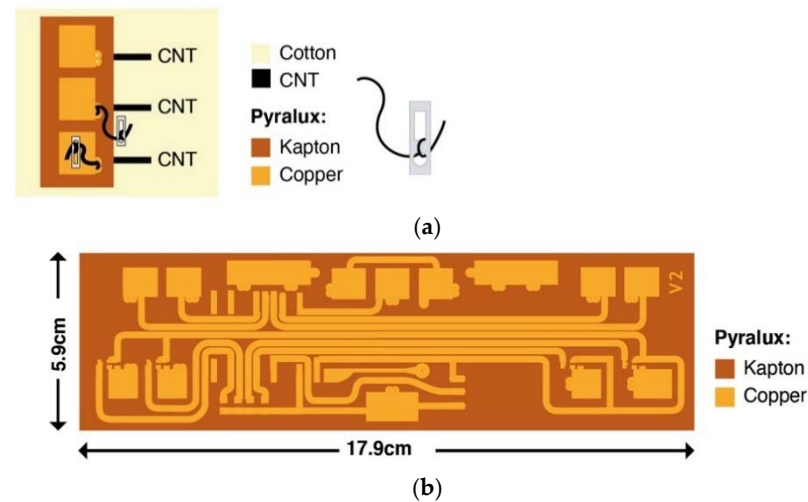


Figure 4. (a) CNT to flexible PCB—soft connections; (b) flexible PCB design soft to rigid connection interface, with points achieved by manual stitch.

2.3. Weaving

2.3.1. Multilayer Weaving Structure

The demonstrators and the test samples were woven on an ARM manual loom. The basic fabric is constructed from two weaved interconnected layers, creating a double-face fabric. The front face contains the conductive fiber, and is the active layer, while the back face is a non-active face functioning as an insulating layer between the wearer's body and the outer-layer fabric. The layers are interconnected by an interlacing stitch occurring in each repeat, which contains 4 thread counts on the weft and 12 thread counts on the warp. Both weft and warp threads are of cotton 20/2 ne (ne = English cotton count signifying 2 ply yarn with 20 yarn count per ply). In every 1 cm fabric width, the weft thread count is 14. The textile is weaved in a double plain weave structure. Plain weave is a basic geometric structure where the first weft yarn passes below the first warp yarn and then above the second warp yarn and continues in an alternating manner. The second weft yarn starts in the opposite direction, above the first warp yarn and below the second one, and continues to alternate. Each layer of the plain weave receives a total of 6 warp yarns and 2 weft yarns. The first and third weft yarns construct the upper layer and the second and fourth yarns construct the bottom layer. On its way, the fourth yarn grabs the first warp yarn of the upper layer, creating an interlacing stitch connecting between the two layers. This sequence repeats throughout the fabric.

A conductive UCNT coated 6-tow yarn is integrated together with each fourth weft yarn of the repeat sequence. The conductive yarn does not go through the entire width of the fabric, like the rest of the weft yarns, but is integrated in designated positions planned in advance (Figure 5). The UCNT yarn can do one of two things: it can either join the weft yarn, in parallel to the width of the fabric, or it can join one of the warp yarns at 90° in parallel to the length of the fabric (within the plain of the fabric). The integration of the conductive yarns is administered during the weaving process continuously, as the fabric is forming, without obstructing the progression of the manufacturing process. Under the requirement of continuous production, the conductive yarn cannot be weaved in the opposite direction of the manufactured fabric, meaning its pattern needs to take into consideration the progression of manufacturing and the directionality of the weft and warp yarns.

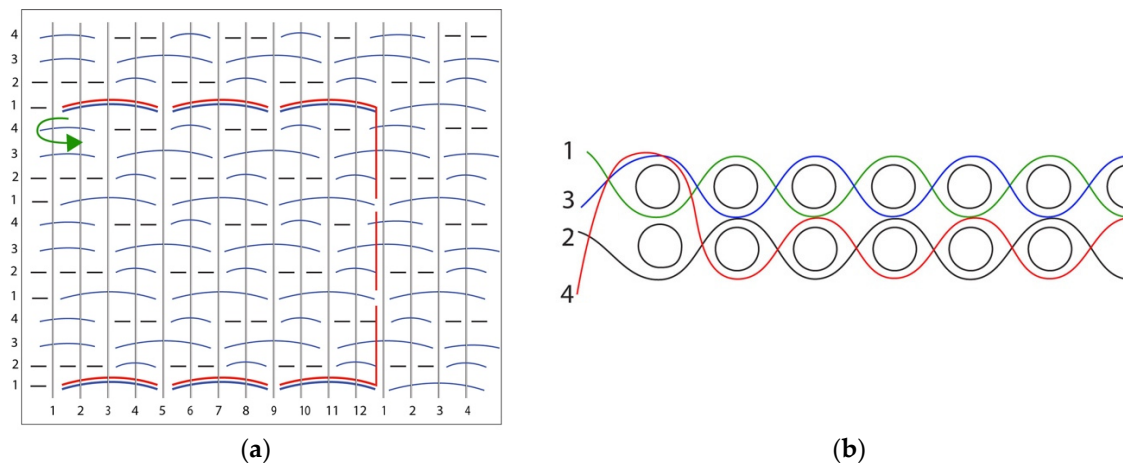


Figure 5. Plain double-weaved diagram with conductive CNT yarn represented in red: (a) top view; (b) cross-section view: blue and green lines represent weft alternating yarns, black cross-section circles represent warp yarns, and red line represents conductive yarn. The green arrow represents the UCNT weaving direction.

Additional to the double-layer weave described above, a triple-layer weave was developed, creating a double-face fabric with three interconnected layers, all in a plain weave structure. The front face contains the conductive fiber, and is an active layer, the middle layer is a non-active insulating layer, and the back face contains conductive fiber, and is an active layer interacting with the wearer's skin. On each repeat there is a total of 12 warp yarns and 6 weft yarns; therefore, each layer receives 4 warp yarns and 2 weft yarns. The first and fourth weft yarns construct the upper layer, the third and sixth yarns construct the bottom layer, and the second and fifth yarns construct the middle layer. On its way, the fifth yarn grabs the first warp yarn of the upper layer and the fourth warp yarn of the bottom layer, creating interlacing stitches connecting between the three layers. This sequence repeats throughout the fabric.

A conductive UCNT coated 6-tow yarn is integrated together with the six weft yarns of the repeat. It does not go through the entire width on the fabric like the rest of the weft yarns, but is integrated in designated areas which were planned beforehand, as explained previously (Figure 6).

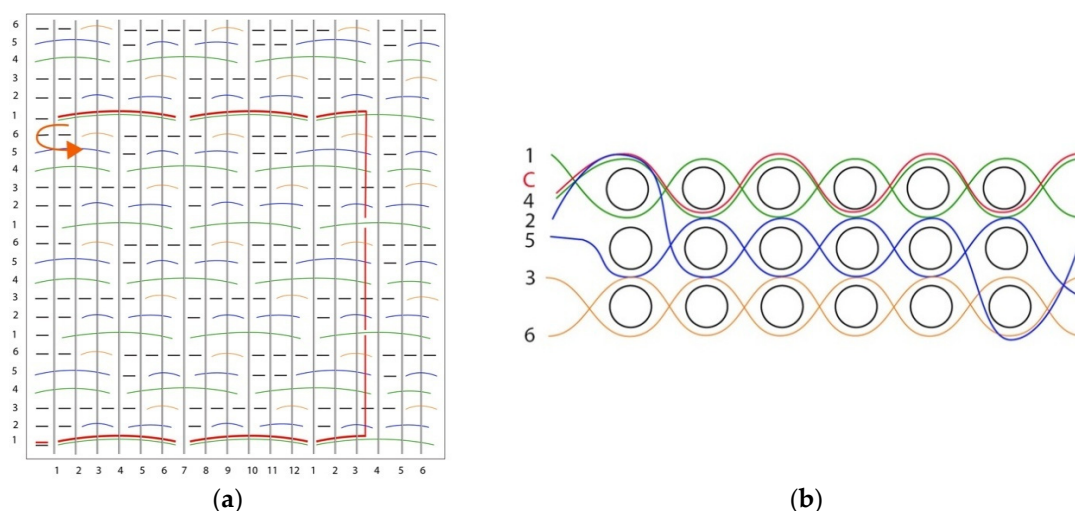


Figure 6. Plain triple-weaved diagram with conductive CNT yarn: (a) Top view; (b) cross-section view: green, blue, and yellow lines represent weft alternating yarns, black cross-section circles represent warp yarns, and red line represents conductive yarn (marked as C). The red arrow represents the UCNT weaving direction.

2.3.2. Multilayer Fabric

Another option to incorporate electronic circuit elements in woven textiles is by integrating a pocket by splitting the fabric into a double-layer structure (Figure 7d). This method allows for the integration of electronic circuitry; in this example, this is a layer of piezo-resistive nonwoven off-the-shelf mat (EeonTex™, Pinole, CA, USA). EeonTex™ sheet is a pressure-sensitive conductive nonwoven microfiber textile made using a proprietary coating technology, based on doped polypyrrole (PPY), an inherently conducting polymer. EeonTex™ is piezo-resistive and is commonly used in dynamic sensors to map and measure pressure, bend, angle stretch, and torsion (surface resistivity tunable from 8 to 105 Ω/sq). Pockets can be integrated along the width and length of the fabric, and their edges can be kept either open or closed.

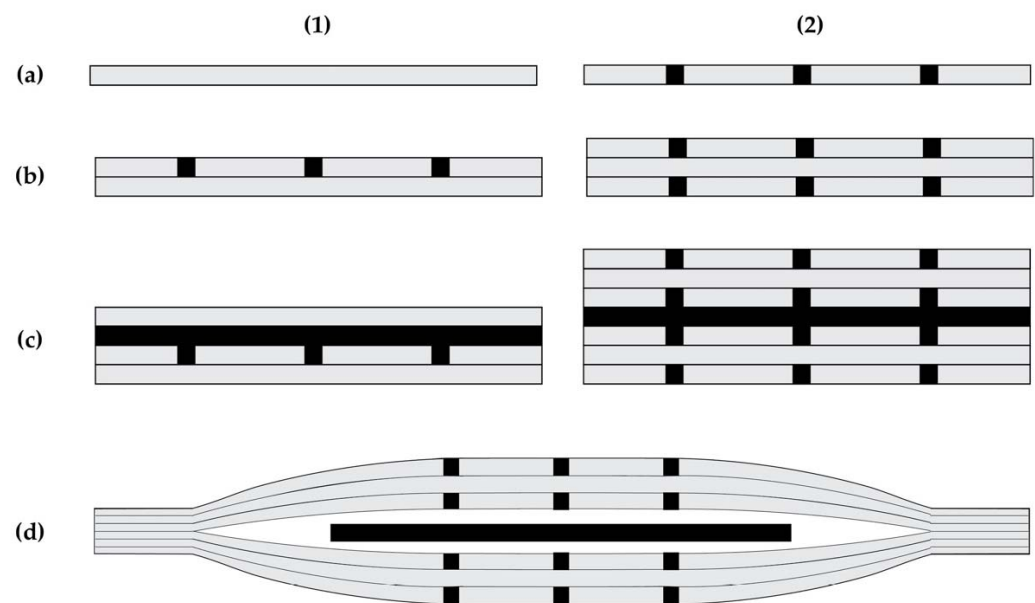


Figure 7. Multi-layer configuration: Single layer without (1a) and with (2a) conductive yarn (presented as black squares). Double layer with insulating back (1b) and triple layer with insulating middle layer (2b). Multilayer configuration with EeonTex™ (presented as black line), conductive yarn layer and two insulating layers (1c), and multilayer configuration with 4 conductive yarn layers, two insulating layers, and EeonTex™ (2c). Multilayer configuration with a pocket for EeonTex™ nonwoven pressure sensor (d).

2.4. Standard Textile Testing

All the standard textile tests were conducted on weaved fabric samples containing the UCNT, without the flexible PCB. Abrasion tests were divided into two types of tests, raising the intensity of the abrasive counterpart material, wool fabric in the first test, and abrasive paper in the second. Abrasion resistance tests were based on the standards [31] for test 1 and [32] for test 2, reflecting the two counterpart materials, respectively. The tests were conducted using a Martindale machine with a weight of 12 kPa. The woven samples measured 70 mm² and contain a “pixel” pattern (Figure 3), integrated with UCNT yarn coated with either a single or double layers of PVDF.

Washability tests were categorized as industrial or domestic according to [33,34] standards. Samples measuring 100 × 40 mm contained three consecutive pixels integrated with UCNT yarn coated with either a single or double layer of PVDF. The domestic test comprised 5 washing cycles at 60 °C for 45 min with 50 steel beads. The industrial test comprised a single wash at 75 °C for 60 min with 25 steel beads. Residual washing water was then filtered with an 800 nm nuclear pore filter followed by a 200 nm filter. The filter was analyzed by SEM inspection to search for residual CNT. The following samples were

tested: 4 samples of cotton only as a control, 4 samples of cotton and PVDF, and 4 samples of cotton with CNT coated with PVDF, wash solution without fabric, and demineralized water. To obtain a solution which could be filtered more easily, 10 mL of each wash liquor was diluted in a measuring flask with demineralized water to a total volume of 50 mL (dilution 1:5). Each measuring flask was rinsed with a small amount of water, thus the solutions obtained were passed through the corresponding filter. The filters were dried in a drying oven at a temperature of 50 °C and subjected to SEM analysis.

To identify the source of fibrous structures, a semiquantitative analysis for the presence of the carbon elements, oxygen and fluorine, was performed on several fibers using energy-dispersive X-ray spectroscopy (EDX). Apart from the actual wash trials, blanks were run to ensure that any fiber material found could be clearly traced either to the CNT material or to another source.

Artificial weathering tests were conducted according to the standard [35]. The samples provided were of $140 \times 150 \text{ mm}^2$ and contained three 6-towed UCNT yarns. Samples were taken out from the designated weathering chamber at incremental times and were measured for their visual appearance and resistivity (using an ELABO-90-3k resistance meter, Crailsheim, Germany, and a FLUKE 8845A 6.5 digit precision multimeter, Fluke Corporation, Everett, WA, USA)

3. Results

3.1. Demonstrator Prototype

The working prototype operates in two ways, both as a sensor and actuator, containing a field of four pixels; however, the intention is to increase the number of pixels in the future so that the fabric is eventually entirely integrated with active units.

The two patterns of pixel electrodes are (1) a digital switch electrode, comprising a continuous UCNT tow (Figure 8a), and (2) an analog resistive touch electrode comprising two separate UCNT tows that are weaved in parallel (Figure 8b). The first type of electrode serves as a rupture detector and as a heating element. When the yarn is interrupted along its continuum, the electronic signal is detected by the system and interpreted as rupture. As a heating element, the continuous yarn is heated by a low current, which is controlled with a thermostat in the range of 34.2–62.2 °C. This work builds on numerous research papers, reporting on e-textile heating elements [36,37].

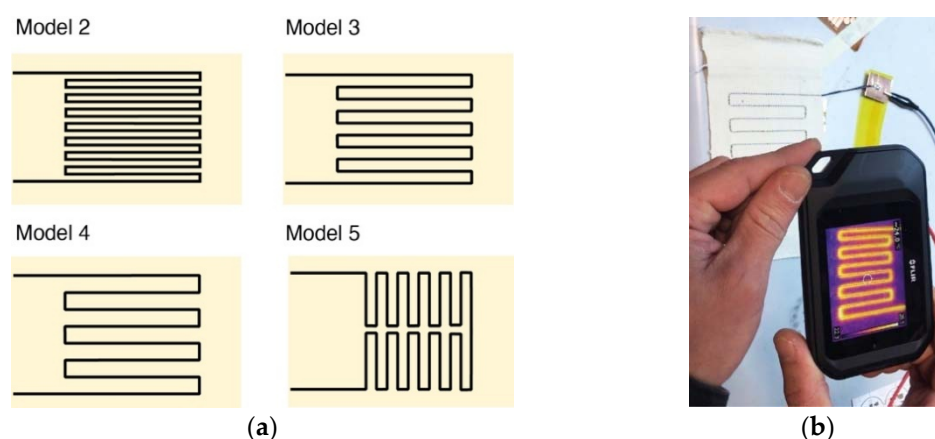


Figure 8. (a) Different UCNT weave configurations; (b) heating demonstrator using FLIR pocket camera.

UCNT fibers coated with PVDF respond well to heat, and cool down relatively quickly after heating, reaching the original temperature after 1 to 2 min. In a preliminary study, different woven configurations were tested, with a goal to achieve a homogenous heat

distribution on the fabric surface, tested using a heat camera (Pocket Thermographic Camera FLIR C2, Teledyne FLIR, Wilsonville, OR, USA). Tests were conducted at room temperature of 24 °C. The yarn resistance was measured to be 81.82–82.76 Ω . A relatively low current (0.061–0.122 A) was sufficient to raise the yarn temperature in the range indicated above. The tests included using different levels of voltage (3–9 V) and changing the distances between the yarns, resulting in pixels of varying sizes and configurations. The chosen configuration is model 3 (Figure 8).

Analog resistive touch pixels operate in the demonstrators as touch and wetness sensors, initially integrated as binary sensors indicating the presence of touch and/or wetness. When the two separated yarns in the pixel are bridged through touch or wetness, the effective resistance changes, and a respective electrical signal is detected by the system. When the fabric is wet, charged particles (ions) in the water carry some electrical current through the fabric. Human touch activates the circuit by creating a parallel current path through the body. The current is low enough (~ 0.043 Ampere) to be undetected by the person. Resistive pixels can also be integrated with EeonTexTM as a double-layer weaved structure (Figure 7d). In this configuration, the changing resistivity of the EeonTexTM is registered by the adjacent UCNT yarns.

The pixels are arranged as a network grid of active cells, which can operate both as receivers and transmitters of data, connected by wireless communication. The activated cells can be situated on the same garment or can be located on a different fabric segment (possibly on a different person), providing infrastructure for group communication. In parallel, any cross communication can be simultaneously sent to a main computer for display, registration, and/or analysis. The scenario presented in Figure 9 presents two interacting demonstrators. Panel 9a shows a demonstrator integrated with a haptic navigation system which activates four vibration motors arranged like a compass, indicating to the wearer the directions of left, right, front, and back. Panel 9b presents a demonstrator consisting of resistive touch pixels, which are arranged in a grid layout, remotely operating the motors according to their position in the grid. Touching each one of the four resistive touch pixels transmits a signal to both the master node, and to the specific haptic navigation receiver. The wireless communication network, of 2.4 GHz RF communication, may not be an optimal choice in a field application, due to reasons like its range, the power consumption of the nodes, its required bandwidth, etc. This type of communication was used here only for the purpose of demonstration. Also, with respect to the power consumption of such sensing pixels, note that the sampling rate required here is low, and is essentially dictated by the human response time, of the order of few tens of Hz or lower.

3.2. Textile Testing Results

Textile standardization tests are the backbone of industrial production and are required for integration in any real-life application. Standardization will promote the acceptance of new technology. Therefore, in parallel to developing functionalities and application scenarios via the prototype demonstrator, we produced identical textile samples which contained all the configurations mentioned above for the purpose of conducting an ensemble of mechanical and electronic tests. The standardization of smart textiles or smart textile products and systems is not straightforward, because it involves an overlap between the standardization of the “traditional” textile product and the standardization of the additional intrinsic functional properties of the smart product [17]. In addition, due to the integration of nanomaterials, standardization tests also include the World Health Organization (WHO) standardization for the integration of nanomaterials.

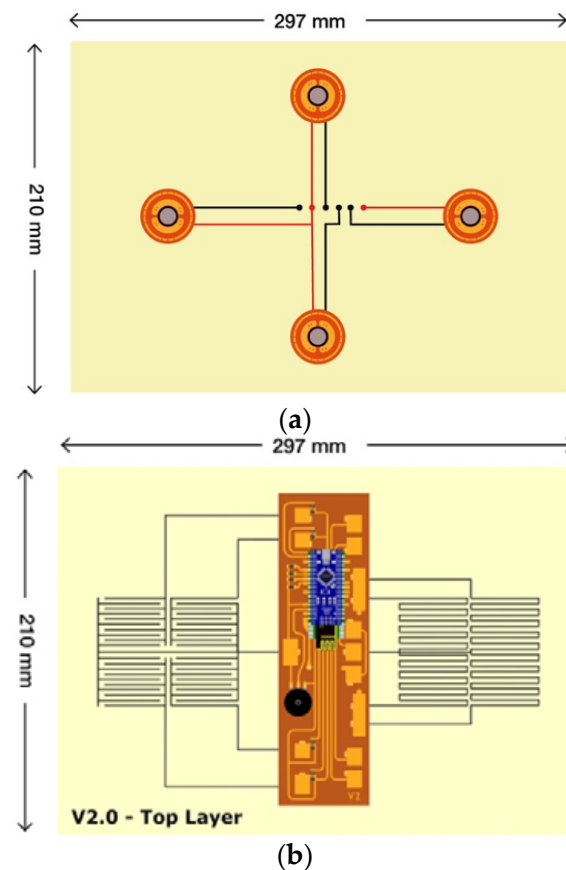


Figure 9. (a) Haptic navigation system: top view. (b) Resistive touch system: top view.

In order to test electronic functionality, we followed the “traditional” textile standardization tests and added a component of resistivity measurement before and after the test cycles. We also conducted washing water filtration tests and SEM inspection analyses to detect nanoparticle residue. The WHO definition of dangerous fibers in terms of their dimensions is a length of $>5\ \mu\text{m}$, a diameter $< 3\ \text{nm}$, and a length-to-diameter ratio of $>3:1$.

3.2.1. Abrasion Resistance—Wool Counterpart

The results of the abrasion resistance tests using wool as a counterpart (EN-ISO 12947-3-d) were conducted until the UCNT fibers were visually pulverized (See Figure 10a,b). Resistivity remained steady until pulverization. Single-coated fibers were pulverized after 20,000–40,000 cycles, and the double-coated fibers withstood 55,000 cycles. On average, the target point with standard uniform garments is between 30,000 and 40,000 cycles, which situates the samples’ performance within the required range, especially for the double-coated samples (see Table 3).

3.2.2. Abrasion Resistance—Sandpaper Counterpart

The results of the abrasion resistance tests using sandpaper as a counterpart (DIN 5363-2) (see Figure 10c,d) show single-coated fibers pulverized after 300–500 cycles. Resistivity remained steady until pulverization. Double-coated fibers produced similar results. While the double coating improved fiber protection against the wool fabric, it did not offer any advantage against sandpaper abrasion (see Table 4).

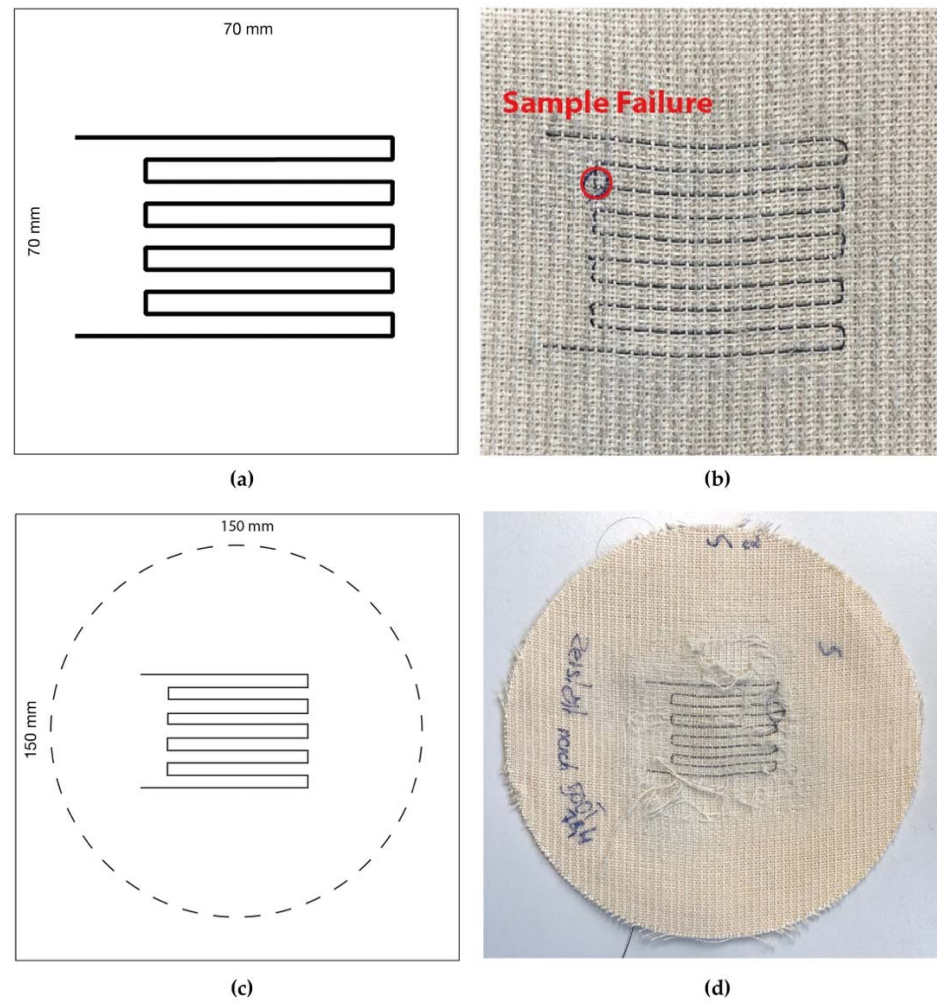


Figure 10. (a) Sample for abrasion resistance test under EN-ISO 12947-3-d. (b) Image of sample after testing. (c) Sample for abrasion resistance test under DIN 5363-2 with sandpaper. (d) Image of sample after testing.

Table 3. Abrasion cycle tests: single and double-coated yarns. The data in columns 2–7 represent the fiber-resistance in Ohms [W]; note that fiber length is 55 mm.

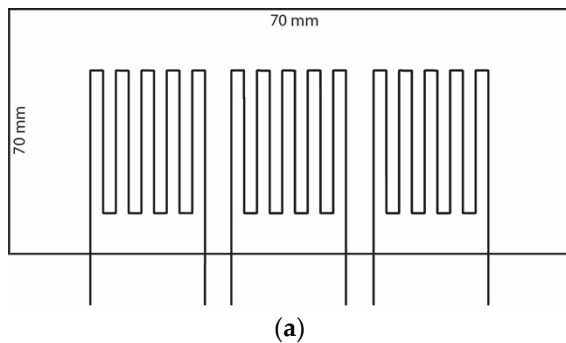
Number of Rubbing Cycles	Single-Coated Yarn—Sample 1	Single-Coated Yarn—Sample 2	Single-Coated Yarn—Sample 3	Double-Coated Yarn—Sample 1	Double-Coated Yarn—Sample 2	Double-Coated Yarn—Sample 3
0	-	79.1	80.2	85.4	87.0	87.0
5000	76.8	80.7	81.5	86.2	87.5	88.4
7500	78.3	-	-	-	-	-
10,000	79.3	81.5	84.2	88.4	88.1	91.7
15,000	85.6	83.1	88.0	-	-	-
20,000	-	86.1	Destroyed	107.9	92.0	128.9
25,000	Destroyed	90.2	-	-	-	-
30,000	96.3	-	-	138.7	98.5	137.3
35,000	118.7	-	-	-	-	-
40,000	Destroyed	-	-	168.3	120.2	Destroyed
50,000	-	-	-	197.7	240.0	-
55,000	-	-	-	Destroyed	Destroyed	-

Table 4. Combined abrasion cycle tests: single- and double-coated yarns. The data in columns 2–6 represent the fiber-resistance in Ohms [W]; note that fiber length is 55 mm.

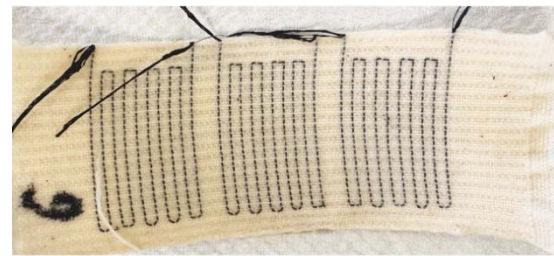
Number of Rubbing Cycles	Single-Coated Yarn—Sample 1	Single-Coated Yarn—Sample 2	Single-Coated Yarn—Sample 3	Double-Coated Yarn—Sample 1	Double-Coated Yarn—Sample 2	Double-Coated Yarn—Sample 3
0	78.4	81.9	78.7	89.1	91.3	87.4
100	79.7	83.8	80.9	90.9	95.2	90.2
200	82.1	87.5	86.0	94.5	103.2	95.2
300	86.3	99.0	Destroyed	99.5	Destroyed	140.2
400	91.0	116.2	-	106.5	Destroyed	-
500	Destroyed	Destroyed	-	115.7	-	-
600	-	-	-	Destroyed	-	-

3.2.3. Washability

The washability test results (EN-ISO 105-C06 and EN-ISO 105-C12) showed similar fabric deformation results for single- and double-coated samples (see Figure 11 for an example of a sample after washing). Both single- and double-coated fibers showed a 20 Ω increase in resistance after the washing cycle, a 25% drop in conductivity. For the domestic wash, however, double coating showed improved durability; while single-coated fibers showed a 15% increase in resistivity, double-coated fibers showed only a 9.27% change (Table 5).



(a)



(b)

Figure 11. (a) Sample for washability test under EN-ISO 105-C06 commercial laundry and EN-ISO 105-C12 industrial laundry; (b) image of the sample after testing.

Table 5. Washing test data (Ohms).

Test Type	Condition	Value 1	Value 2	Difference	Percentage Difference
105-C12-2S (Industrial Washing)	Single coated	58.67	73.83	15.17	25.85%
	Double coated	59.33	74.17	14.83	25.00%
105-C06-C1M (Domestic Washing)	Single coated	58.25	67.17	8.92	15.31%
	Double coated	59.33	64.83	5.50	9.27%
	Sealed Test	58.50	65.00	6.50	11.11%

The residual washing water was filtered in a double process, as previously described, and analyzed by SEM in search of CNT residuals. The filtration provided evidence of residual structures, most likely originating from the UCNT fibers, with a length-to-width ratio of 5 μm to 200 nm.

3.2.4. Artificial Weathering

The weathering test results (following EN-ISO 105-B10-A; see sample configuration (Figure 12)) indicate that over time, the double-coated fibers gave better protection to the fibers than the single-coated ones. However, there is relatively high inconsistency in the tests, with a high percentage of specimens failing the process (Figure 13).

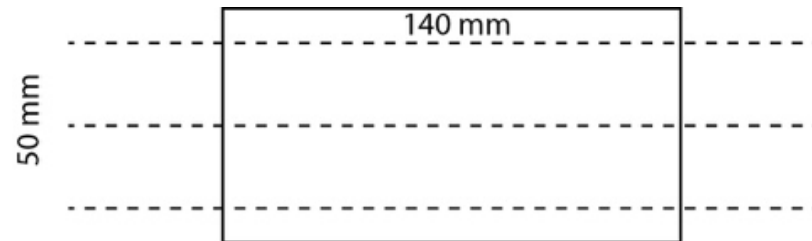


Figure 12. Sample of artificial weathering test under EN-ISO 105-B10-A. Dashed lines represent the position of the UCNT yarns.

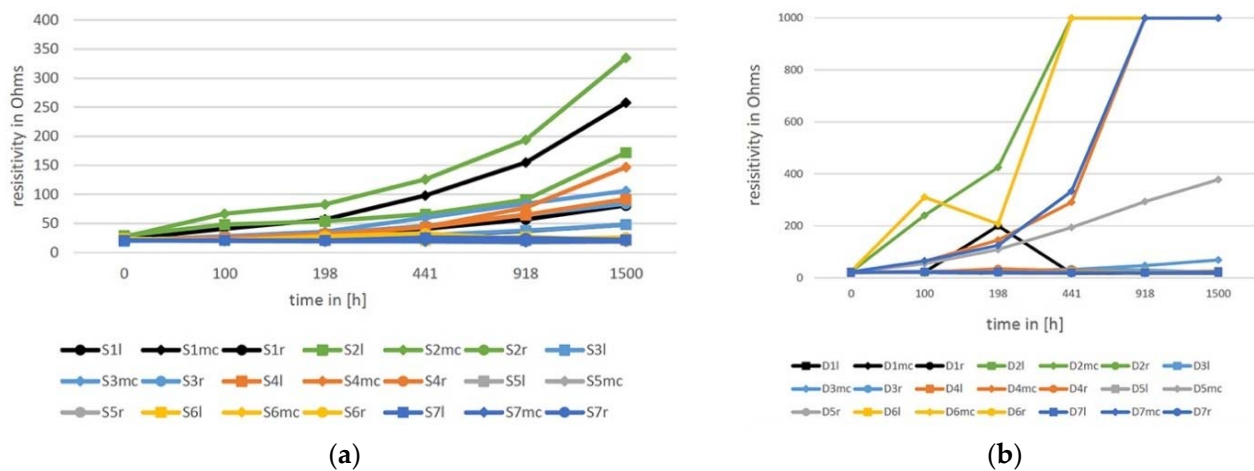


Figure 13. Artificial weathering CNT yarns: (a) single-coated; (b) double-coated.

3.2.5. Wash Liquor Testing for CNT Residuals

Testing of wash liquors for the presence of CNTs with the WHO fiber structure (see Figure 14) was conducted by examination of the residual wash liquors to determine whether the mechanical action of the washing process had released particles from the CNT yarn, which are considered bio-persistent and fall under the definition of WHO fibers in terms of their dimensions. The tests involved SEM scans, which followed VDI 3866 Paper 5, the standards of the Association of German Engineers, relating to scanning electron microscopy methods for the determination of nano-scale particles in technical products.

The 800 nm nuclear pore filters, used for collecting residue, were covered densely, making it impossible to find and identify CNT structures. The filter cake was so thick that the filter pores were no longer visible. Further, 200 nm nuclear pore filters, which were used subsequently, were densely covered with residue; however, empty spaces on the filter were detected, allowing us to visually examine the filter material. Fibrous structures were found, with comparably little search effort (see Figure 15a).

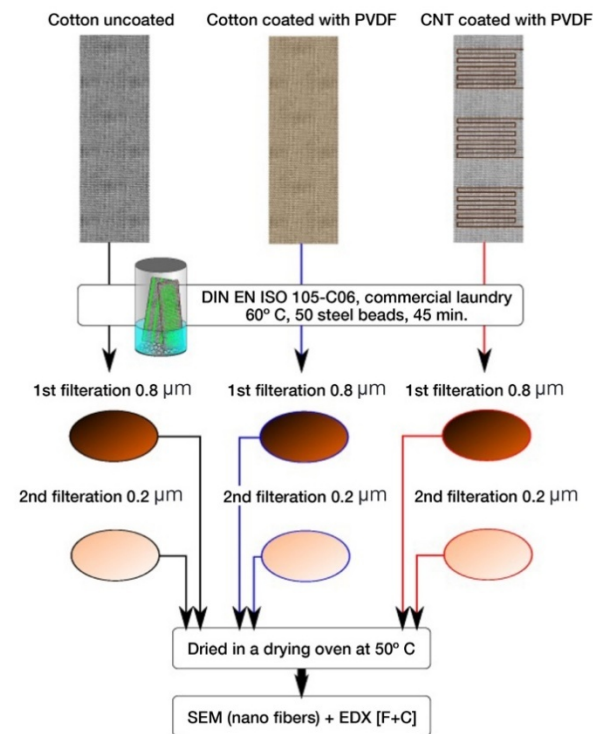


Figure 14. Scheme of the residue test method for qualitative hazardous WHO nanoparticles.

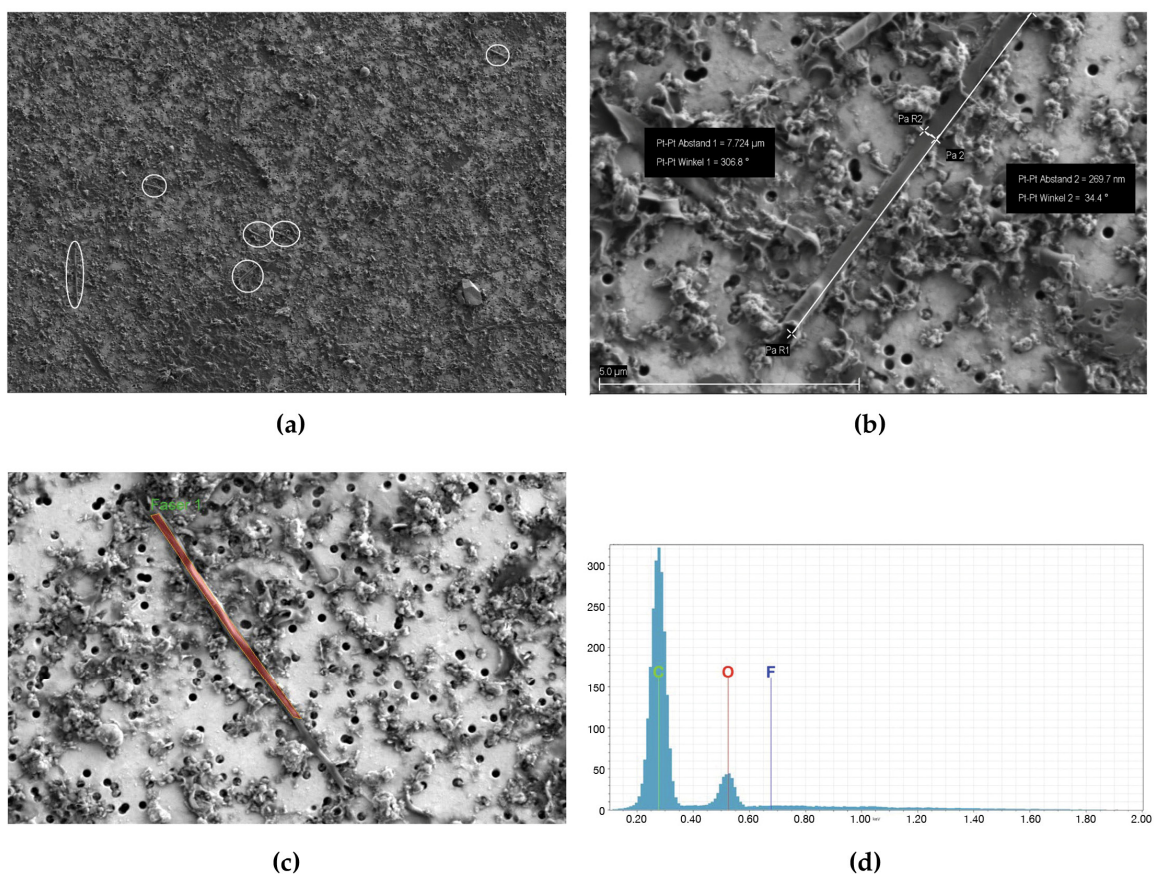


Figure 15. (a) An overview picture of the 200 nm nuclear pore filter with examples of fibrous structures (highlighted in circles). (b) These structures fall under the definition of WHO fiber dimensions (length > 5 μm, diameter < 3 nm, and length-to-diameter ratio of >3:1). (c) A fiber structure with WHO fiber geometry. The section subjected to EDX analysis is marked in orange. (d) EDX spectrum of the red section from (c).

The structures have a mean diameter of around 270 nm, but the diameters vary in a range from around 200 nm to 450 nm. A considerable proportion of these structures have a length of more than 5 μm (Figure 15b). Therefore, these structures fall under the definition of the WHO fibers in terms of their dimensions. Overall, it is interesting to note that the very smooth surface of the structures is markedly different from natural cotton fibers.

Figure 15c shows a fiber structure from a sample that possesses the geometry of the WHO dimensions. The section of the SEM image marked in red was subjected to EDX spectroscopy. Figure 15d depicts the resulting EDX spectrum. The image is dominated by a carbon peak on the left and a significantly smaller oxygen peak to its adjacent right. It is not possible to clearly distinguish between the section chosen for EDX analysis and its surroundings. Therefore, the image shows the presence of oxygen in the fiber, although the fiber only consists of carbon. More important, however, is the absence of fluorine, which shows that the fibrous structure does not originate from the fluoropolymer coating of the yarn.

4. Discussion

The need for special military-grade textiles, which on the one hand can conduct electrical current and on the other hand show above average tenacity, led to the research presented in this paper. The structure and properties of carbon nanotubes (CNT) give rise to a considerable number of applications for conductive textiles, which are robust enough to be used in future soldier uniforms. The ultralong carbon nanotube (UCNT) yarns used in this work were produced especially for this project, and were found to be evenly distributed and of roughly uniform shape and thickness, which shows that the manufacturing process can be well controlled. Knowing the exceptional material attributes of UCNT, we were able to generate different demonstrators, showing that this new material can essentially be used for sensing touch, wetness, and ruptures, as well as carrying current for the purpose of heating. To maintain resemblance to the intended use case, military cloth, which is usually a woven fabric, the fibers were processed as yarns and woven in a standardized textile manufacturing method, a double plain weave structure. For different applications, other weaving structures were integrated, as can be seen in Section 2, utilizing a multilayer approach to achieve multiple sensing and actuation capabilities.

A recurring grid pattern was created, designating the pixelated cells with special sensing and actuation functions. Additional applications could be implemented by integrating microcontrollers, weaving the electronic circuitry, and integration of a flexible substrate for the purpose of mounting additional electronic components. For example, an ergonomic textile-based haptic navigation prototype was presented, comprising vibration motors. This flexible e-textile system can be worn in-mission, potentially enhancing wearing comfort and usability by allowing for silent communication between individuals. Additionally, some combination of tear detection, resistive touch sensing, wetness detection, and pressure sensing could be used in the field, e.g., to detect an injury by interpreting the data obtained from a pixel array. This may also help identify trauma injuries and provide deeper insight for medical staff, since the pressure sensing functionality provides access to potentially high-resolution information concerning the diameter and force of an impact on the body. Future efforts shall include the addition of pH, temperature sensing, and hazardous material detection, which can provide medical personnel with a broader range of data. To realize this type of triage system, a telemedicinal information transmission system will be needed. Currently, thought has been given to creating a system capable of interconnectivity with additional, non-textile wearable devices.

With respect to UCNT yarn fabrication, the wire reactor operated by the manufacturer generates continuous UCNT yarns with a diameter of 50–200. This process of producing

UCNT yarns utilizes inexpensive precursors, which can lead to a relatively inexpensive final product in a fully industrialized process. This technology enables the production of UCNTs with material properties that reach extremely high electrical, thermal, and mechanical properties (17), which are relevant for applications of e-textile and smart clothing, such as the following:

- High electrical conductivity—values of up to 1.3×10^6 S/m. For comparison, copper (Cu), which is one of the most abundant and commonly used conducting metals, has a conductivity value of 5.9×10^7 S/m,
- Low density—UCNT yarns have a typical density of $0.25\text{--}0.6$ g cm^{−3}. In comparison, copper has density of 8.96 g cm^{−3}.
- High chemical and thermal stability—the yarns are stable up to 400 °C and can easily withstand harsh chemical environments, including acids and other oxidizers.
- High mechanical strength—single yarns show mechanical strengths of 0.2 up to 1.2 N/tex, depending on the manufacturing configuration. For reference, cotton yarn's tenacity is 0.17 N/tex, and high-tenacity nylon yarns can reach up to 0.68 N/tex [38].

Despite showing promise in wire applications, UCNT have one clear disadvantage with regard to the possibility of achieving good electrical contact with copper wires, which are abundant in all electronic devices. Copper-to-copper contact is typically implemented by soldering. However, connection of UCNT fibers to copper usually results in high resistance and limited stability; therefore, electrical signal transfer is inefficient. Note that the electron transport mechanism in UCNT is different from that of metal-based wires. This problem can be partly overcome by the deposition or soldering of metal around the edges of UCNT fibers such as Ti, Cr, and Fe. Another solution is to deposit amorphous carbon between the UCNTs that will effectively solder its edges, without compromising its mechanical or electrical performance [39]. In this project, soldering was accompanied by forming mechanical connections, based on sewing between flexible and semi-rigid interfaces. In the future, this solution will need to be further developed, since it is a labor-intensive manual process.

The produced UCNT fibers have a sub-mm estimated length, at an average diameter of $D = 200$ μm. The average measured resistance per unit length of the single tow UCNT bundles is $R_l = 880$ Ω/m and the tenacity is 0.2 N/tex. Considering this diameter, and assuming fibers with a circular cross-section, the above average value of resistance translates to an electrical conductivity as follows:

$$\sigma_1 = \frac{1}{R_l \cdot \frac{\pi D^2}{4}} = \frac{1}{880 \cdot \frac{\pi (200 \cdot 10^{-6})^2}{4}} \simeq 4 \cdot 10^4 \text{ S/m} \quad (1)$$

For the 6-tow UCNT, coated with PVDF, the respective value is as follows (see Table 2 below).

$$\sigma_6 = \frac{1}{R_l \cdot \frac{\pi D^2}{4}} = \frac{1}{50 \cdot \frac{\pi (80 \cdot 10^{-6})^2}{4}} \simeq 1.3 \cdot 10^6 \text{ S/m} \quad (2)$$

Reference [40] provides a review of available CNT yarns produced by various spinning methods. Note, in particular, that the above calculated conductivity values of the UCNT are high, compared to the respective values in Table 1 in [40], which span the range $462\text{--}70,659$ S/m. Initial experiments with a single CNT filament showed that its tenacity is insufficient for processability due to the fiber's fragility under tension. Therefore, a twisting unit was engineered to allow for the combination of filaments arranged in a tow formation to increase the mechanical integrity of the yarn. Each tow is composed of an untwisted bundle of continuous filaments that are formed into a yarn by a winding process where several tows

are wound together. In this research, each yarn is composed of six tows of UCNT filaments, showing higher strength and better robustness.

The weaving fabric structures used, a double and triple weave, integrated with a coated non-insulated conductive UCNT yarn, were assembled into multiple configurations for a variety of functionalities (see Figure 7). Multiple-layer woven structures for electronic textiles can solve some of the challenges associated with single-layer fabrics [41]. In multilayer fabrics, single yarns can be moved between layers, away or towards each other, according to the desired configuration. In addition, an intermediate insulating layer can be woven in the fabric, providing the necessary division between non-insulated sensing/conductive elements, creating different usable faces to the fabric which can be positioned towards or away from the body in the case of wearable applications. Double-, triple-, and multiple-layer woven structures can be produced on readily available weaving machines with very little modifications [42].

The high conductivity and low density of the UNCT material led to the development of a heating demonstrator, which has been shown to produce very fast rates of heating and after-use cooling. This opens an opportunity for soldiers to use heated undergarments in the field, in harsh and cold conditions. For certain situations, a heating system like this could in fact be lifesaving, beyond being comfort-enhancing.

It is interesting to estimate the heating efficiency of the pixels. Based on the measurements, and considering a pixel area of $4\text{ cm} \times 4\text{ cm}$, (see Figure 1) we may deduce that, to raise the pixel temperature by $1\text{ }^{\circ}\text{C}$, the power input required is $\sim 2\text{ mW/cm}^2$. Further, assuming a torso area of $\sim 1000\text{ cm}^2$, this implies $P_{\text{torso}} \sim 2\text{ W/}^{\circ}\text{C}$. Note, however, that the actual warming of a human body was not tested. In such a case, the respective heat transfer efficiency would be substantially lower than 100%, depending specifically on various factors, such as the textile yarn, the body–textile air gaps, etc. For the sake of estimating the heating efficiency, let us assume a heat transfer efficiency of 60%. This implies that $P_{\text{torso}} \sim 3.3\text{ W/}^{\circ}\text{C}$. In other words, by this estimation, two AA type batteries, with 1.5 V, 2000 mAh capacity, would be able to induce warming by $10\text{ }^{\circ}\text{C}$ for about 11 min.

The communication and data transfer currently integrated in this study was demonstrated through multiple “hubs” consisting of rigid printed circuit boards. The information is stored locally instead of using cloud-based storage and transmitted via RF for privacy and security reasons. For the textile to be washable, as well as for interchangeability and cost consideration, removable hardware parts were integrated.

The UNCT fibers used in this research were treated with a polyvinyl fluoride (PVDF) coating, which protects the fibers from abrasion and enhances their resistance to impact without hampering their electrical properties. The goal is to achieve improved safety, processability, robustness, and abrasion resistance, which is reflected in the standardized textile tests that have been performed and are described in Section 3. Comparative results between single- and double-layer coating show that double-layer coating better contributed to the resistance of fabrics to abrasion, washing, and weathering and prevented some of the degradation in electrical conductivity. Electrical resistivity testing necessitated exposing the edges of the UCNT yarns in order to conduct the tests with the available electrical testing equipment. The removal of the coating did not affect the abrasion tests, but may have impacted weathering and washing as exposed edges of the fabrics were included in the procedure (See Figure 11).

Tests conducted after washing were aimed at determining the presence of CNT residue (or any other nano-scale material) in the washing solution to identify possible health risks according to the WHO criteria for fibrous structures in new products and use cases. A combination of standardized test methods for measuring nano-scale particles via SEM and EDX spectroscopy were conducted to test chemical elements produced by a washing

test, which simulates the everyday usage of the product (DIN EN ISO 105-C06). This combination of methods is intended to identify the source of the particles, whether they originated from the fabric, the coating, or the new nanofiber material. The results show that at this stage, CNT residue was detected, and originated from the UCNT yarns. The results reveal the challenge of creating a reliable electrical reading when standard electrical equipment, such as electrical alligator clips, are used in an attempt to connect the UCNT fibers, as well as in cases where soldering is commonly used. Attempts to locally remove the PVDF with a solvent to facilitate copper–CNT electrical contact proved to be challenging and may have contributed to the leakage of CNT residue into the washing solution. In addition, inconsistency in the coating as well as limited penetration of the coating to the inner layers of the yarn may have had an impact as well. In the future, optimizing the coating will enable UCNT utilization to its full capacity and promise.

5. Conclusions

This study demonstrates the feasibility of integrating ultralong carbon nanotube (UCNT) yarns into woven textiles for military-grade smart garments, enabling functionalities such as sensing, heating, and wireless communication. The development of textile demonstrators highlights UCNT's high conductivity, durability, and potential for applications in soldier uniforms, including injury detection and thermal regulation. Standardized textile tests confirmed the material's resilience, but also revealed CNT residue in washing solutions, underscoring the need for optimized coating strategies. These findings contribute to the understanding of UCNT's advantages and limitations in wearable applications and provide a foundation for future research focused on improving coating uniformity, enhancing electrical interfacing methods, and expanding sensor capabilities for real-world deployment.

The growing availability of conductive yarns and fabrics on the market is a positive trend for smart textiles, facilitating further technological advancements. However, different materials come with varying trade-offs in electrical performance, mechanical properties, production scalability, regulatory compliance, cost, and environmental impact. A comprehensive comparison between UCNT yarns and other commonly used conductive materials—such as metallic fibers, intrinsically conductive polymers, and conductive coated fibers—would be valuable in defining their specific advantages and potential adoption. Additionally, printed electronics offer an alternative approach to textile-based electronics, warranting further comparative assessment.

UCNT yarns occupy a unique category due to their exceptional mechanical and electrical properties. However, as nanomaterials, they present regulatory challenges, particularly concerning health and environmental impact. To fully realize their potential, industry standards must evolve to accommodate textile-based nanomaterials and integrated electronic components. Future research should focus on refining regulatory frameworks, developing standardized testing protocols, and exploring sustainable manufacturing processes to ensure the responsible and scalable integration of UCNT-based smart textiles.

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