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Novel Knitting Vision - Modern Ways for Integral Knitting of Intelligent Gloves for Tactile Internet Applications

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Abstract. The internet of things is a key driver for new developments in the fields of medicine, industry 4.0 and gaming. Consequently, the interaction of virtual and real world by smart interconnecting of devices in our everyday life is the basis idea of the Cluster of Excellence "Centre for Tactile Internet with Human-in-the-Loop" (CeTI) at TU Dresden. To enable a user-centric approach in CeTI innovative textile structures, mainly knitted smart gloves, and their functionalization by integration of sensors and sensory yarns are focus of research activities.

Introduction

The current Internet has created a key infrastructure component for our modern world, touching almost every aspect of our daily lives. The Internet democratised access to information and has enabled emerging economies to participate in the modern global economy. We are now approaching the next big wave of Internet innovation: the Tactile Internet. The IEEE standard P1918.1 defined the Tactile Internet as following: "A network or network of networks for remotely accessing, perceiving, manipulating or controlling real or virtual objects or processes in perceived real time by humans or machines." [1] Beyond the standard IEEE definition of the Tactile Internet, the key mission of CeTI project [2] at TU Dresden is to discover the new frontiers of the Tactile Internet with Human-in-the-Loop (TaHiL). By explicitly integrating human goal-oriented perception and action as well as human development and expertise as subfields of research into the new technological breakthroughs, TaHiL will allow human users to immerse themselves into virtual, remote, or inaccessible real environments to exchange skills and expertise.

Therefore, new functions (e.g. strain, movement and position detection, haptic feedback [3]) are being integrated into smart textiles (e.g. smart gloves, suits) within CeTI, for human-in-the-loop applications as a communication tools between virtual world and real world. Fundamental interactions between humans and machines, e.g. robots, become possible by the use of smart textiles with integrated sensors and actuators for haptic/tactile user-feedback.

One of the main objects of investigation is an interface device in form of a smart glove, which controls robotic hands and virtual objects. These gloves are manufactured with textile-integrated sensors and leads using electrically conductive yarns. These yarns are used to implement resistive strain sensors that change its resistance during finger flexion. Several developments are necessary for the production of these kind of knitted smart gloves. On the one hand, the damage to the electrically conductive yarn during processing must be investigated, and on the other hand, there are various binding aspects that must be taken into consideration which have a significant influence on the

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integrated strain sensor's measurement behaviour. In addition, some manual reworking is still necessary (such as the embedding of electronic components), because especially electrical interconnecting of conductive yarns with conventional circuit boards has not yet been automated.

Materials and Machines

The aim of this project is to develop a smart glove with directly integrated textile sensor technology, which will be extended by an actuator system at a later stage. For this purpose, it is important that the processed electrically conductive yarns are tested for their suitability. This includes, among other things, the knitability depending on the binding technique and the damage potential during processing. Use properties of electrically conductive yarns such as washability [4 – 6] have already been investigated and are not the focus of the investigations here. Two electrically conductive yarns are used for these investigations, a silver-coated PA yarn (Y1) is compared with a stainless steel/polyester hybrid yarn (Y2 cf. Table 1). Within Table 1, the electrical resistance according to the data sheets is compared with measured resistance in unstrained condition of the yarn. For this purpose, an average of 20 samples is taken directly from the bobbin (reference yarn) to perform four-wire resistance measurement. [7, 8]

Table 1 Overview of the yarns used and their basic electrical resistances [7, 8]

	manufacturer/ type/ yarn count	material	linear resistance [Ω/m]	
			data sheet	measured
Y1	Statex – Shieldex 117/17 dtex 2PLY HC+B	PA, Ag-coating	< 300.0	138.6
Y2	Amann – Steel-tech 100 930 dtex	PES, stainless steel	< 90.0	90.0

For the non-conductive basic structure of the smart glove, a polyamide 6.6 yarn (2x78 dtex) as base material is plated with a elastane yarn (135 dtex). For the production of gloves flat knitting machines Shima Seiki SWG 091N2 (gauge E15) [9] and Karl Mayer Stoll ADF 530-32 BW multi gauge (gauge E7.2) [10] are used. The Stoll ADF machine is used for the investigations into the damage behavior of the yarn, as this machine can handle all common feed variants. The Shima SWG has more specialized feeding elements and the results can therefore be transferred less easily to other machine types.

Yarn Damage

Method. The yarn infeed on flat knitting machines is generally from the rear to the front. The bobbins are generally arranged behind the working station and the yarn guides. Above the machine, the feeding elements, yarn control units and feeders are arranged in a superstructure. These elements form the different feed variants (FV). For the investigations, only the paths up to the yarn guides are considered, as in further tests the yarn guide, the needles, the needle bed and the fabric take-off are investigated individually. This is intended to determine crucial machinery components responsible for any yarn damage. In addition, the yarn take-off speed is varied so that different machine speeds can be mapped. The machine elements of each feed variant are listed below:

- FV I: bobbin – feeding elements – Karl Mayer Stoll ADF yarn control unit
- FV II: bobbin - feeding elements – storage feeder Memminger-Iro MSF-3 [11] - Karl Mayer Stoll ADF yarn control unit
- FV III: bobbin - feeding elements – electronic yarn feeder Memminger-Iro EFS920 [12]

The main differences of the used devices are the different modes of action and therefore incoming specific yarn damage. On the yarn control unit (Karl Mayer Stoll Textilmaschinenfabrik GmbH – ADF yarn control unit) the yarn is stressed abrasively by disc brakes and the knot monitor, on the tension unit by yarn accelerations and small deflection angles. On the winding body of the storage feeder (Memminger-Iro Gmbh – MSF 3), the yarn is wound by a force controlled winding transport system. This system has the advantage that no stretching movement of the yarn is caused by the winding of the storage feeder. In contrast, the electronic yarn feeder EFS 920 (Memminger-Iro GmbH) winds the yarn by means of the rotation of a yarn wheel. The geometry and design of the winding body and yarn wheel have different characteristics and therefore indicate results in differences to the damage potential.

Results and discussion. Two yarns with different textures were tested, a silver-coated yarn (Y1: cf. Table 1) and a stainless steel/polyester hybrid yarn (Y2). Regarding the yarn construction, it is to be expected that the damage potential differs enormously between the two variants. The silver coating (which generates the electrical conductivity) of yarn Y1 is inevitably more susceptible to abrasion [13], compared to a yarn that gets its electrical properties from the fiber material alone. The yarn Y2 did not receive any significant damage from the feed variant to the knitting machine, the resistance is approx. 90 Ω/m for all samples (Fig. 1). It can be observed that the resistance depends on the processing speed and its value at 1.4 m/s is on average 2.4% higher than at 1.0 m/s. This could be related to abrasion of the finishing [14], that can be seen in the SEM images (Table 2). It is exemplified that the fibres of the reference yarn have a strong adhesion and are closer to each other than after processing which led to the slight separation for all three feed variants FV I-III.

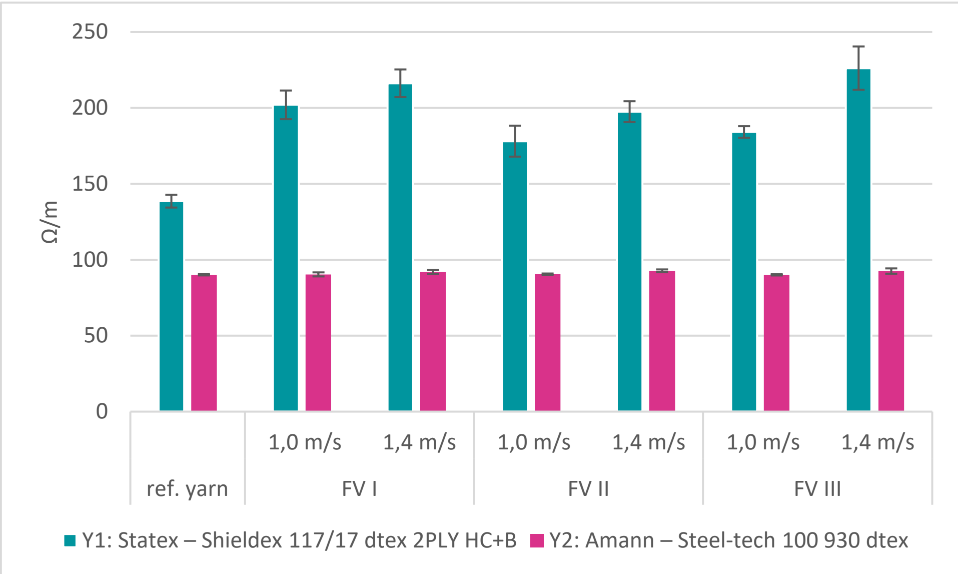
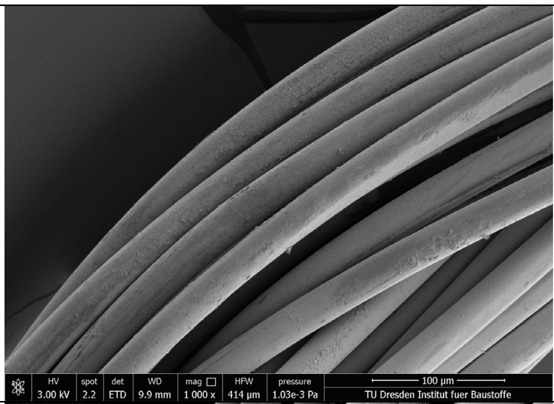
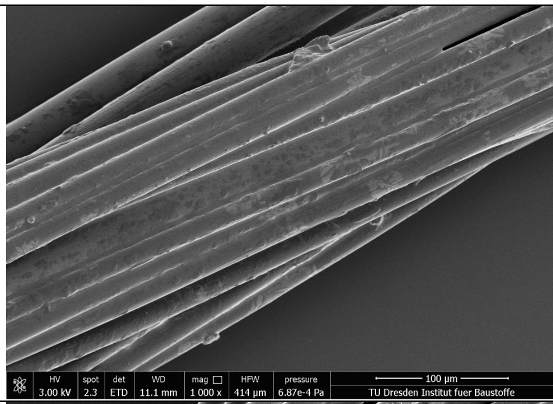


Fig. 1 Lineic resistance of yarns Y1 and Y2 depending on FV and the test speed

More significant differences can be seen with yarn Y1. Due to fiber damage at processing speed of 1 m/s are the resulting resistances are on average about 35.7 % and at a speed of 1.4 m/s about 53.9 % higher than the reference value. These values and the SEM images demonstrate that the increase in resistance is due to damage (abrasion/tearing) of the silver coating. In addition, a correlation between the degree of damage and the test speed can be established. Furthermore, it can be seen that there is a correlation between feed variant (FV) and yarn damage. FV II has a lower impact on the resistance compared to FV I (FV I 56.0 %, FV II 42.5 %). In this case, the intermediate storage feeder reduces the abrasion by pulling off the bobbin more evenly. The increase in resistance at lower speed with the electronic yarn feeder (FV III) is comparable with FV II, but with an increase in speed to 1.4 m/s the resistance increases by 22.8 % to 226.2 Ω/m. It is obvious that this effect is favored by the operating principle and the design of the feeder due to rising friction at increased speeds between the yarns, which are laid in tight coils around a yarn wheel.

Table 2 SEM images of reference yarn and the feed variants (FV) I - III tested at 1.4m/s

<table>
<tr><th></th><th>Y1</th><th>Y2</th></tr>
<tr><td>reference yarn</td><td>
</td><td>
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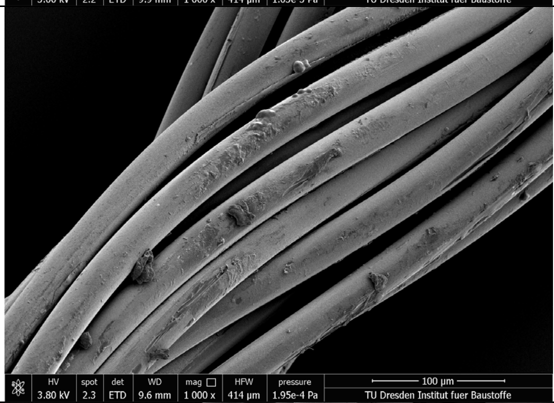
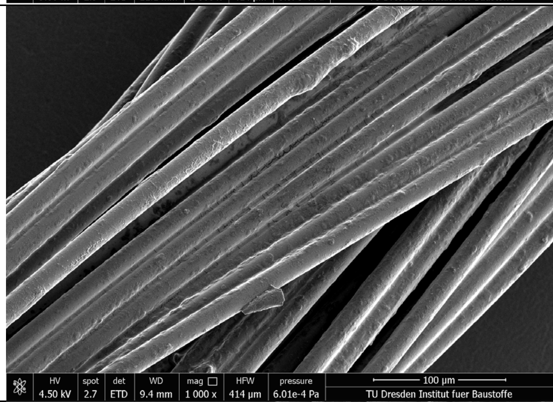
<tr><td>feed variant (FV) I</td><td>
</td><td>
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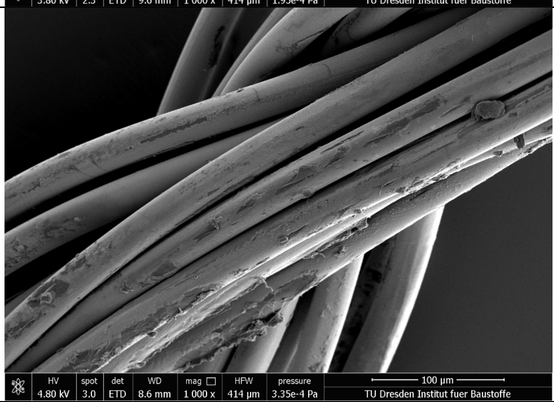
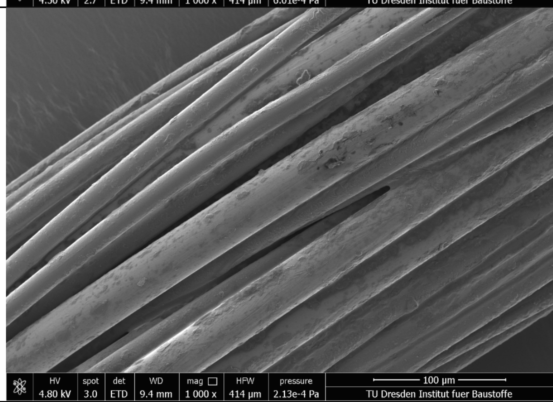
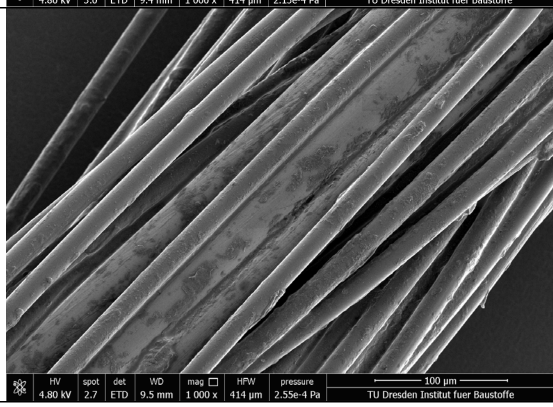
<tr><td>FV II</td><td>
</td><td>
</td></tr>
<tr><td>FV III</td><td>
</td><td>
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Summary. The investigations have shown that the damaging of the electrically conductive coating of the yarn Y1 has a high influence on resistance. Previous studies [6] have shown that an average durability of at least 10 washing cycles is given before the conductivity is significantly reduced. This effect can be transferred in parts, especially the mechanical stress, which is also generated during washing, has a high damage potential for coated yarns. Above all, the high friction with the machine parts is decisive here. The investigations have shown that even the short section between the bobbin and the yarn carrier infeed has a significant potential for damage. On the other hand, the investigations have also shown that a yarn which is conductive solely due to its material composition (Y2) is not significantly affected by abrasion.

Binding Technique

Method. For the production of a smart glove with textile-integrated sensors for controlling virtual objects or robot arms, the previously mentioned electrically conductive yarns Y1 or Y2 (cf. Table 1) and their improvements are necessary. These are used to implement both sensors and power supply lines, and there binding-related special features that must be taken into due consideration. Thus, the design of a sensor depends on the bond, the structural and material elongation. Among other things, the following requirements are necessary for the production of a smart glove:

- Base material of knitted structure has to be electrically isolating,
- Yarn-based sensor and power supply line should be manufactured integrally on weft knitting machines,
- High elasticity of the sensory yarn to ensure dynamic movement measurement,
- Resistances:
  - Power supply lines should have low resistance (< 20 Ω/m) for reducing voltage drop,
  - Integral strain sensors need high resistance change for sufficient strain sensing capability.
- Good fit - light, comfortable and thin glove.

Results and discussion. A high number of variants is necessary to assess the function of the sensor design, since the basic operating principle of the knitted sensor setup must first be verified. In order to pick up the movements of the fingers with a smart glove, yarn-based strain sensors are used within this project. The effect bases on change in resistance due to change of the electro-conductive fibers geometry during tensile straining [15]. To demonstrate the functionality of the glove and the change in resistance due to movement, this value is measured with twice for the straight (R_0) and bended (R_1) sensor within the finger of the glove. The relative change can be determined with this differential measurement (Fig. 2 II). There are different textile approaches. On the one hand, the strain sensor is made of a single yarn, since the material's resistance correlates with the strain level and thus, theoretically, a very sensitive sensor can be implemented. A major disadvantage of this sensor design is that the relaxation behavior (decrease of the resistance towards R_0) of the knitted glove structure that is plated with elastane causes a faster relaxation and differs from the non-plated sensor yarn. In contrast, meshed yarn-based strain sensors offer higher structural integrity level, which has a positive effect on the relaxation behavior of the sensor. The principle, the structure of the conductive elements in Fig. 2 I consists of sensor lines (c) and power supply lines (d) which differ in their cross-section geometry and their resistance. The length of the sensor extends to the finger joint (b) with the subsequent power supply line (d), which extends to the structure-integrated electronics. Due to the anatomy of the hand, the length of the individual sensors and supply lines per finger differs. By varying the binding elements (stitch, tuck stitch, integrated warp yarn), sensors with different straining behavior and resistances can be implemented. Thus, the thickness of the sensor and the power supply lines (Fig. 3 G1 and G2) is relevant. Here, limited by the finger width and the binding structure, the respective thickness can be varied between one and three stitches in width. It can be assumed that a thicker power supply line has a lower resistance and thus a minimized unintentional influence on the strain measurement of the major strain sensing area of the integral sensor. In addition, the total resistance is significantly higher using a narrow design of the active measuring sensor lines (c), cf. Table 3. Another significant influencing factor is the use of the binding elements. Thus, the output resistance, for the structures with narrow/thin sensor, is significantly higher than for G1. By bending the finger and measuring the change in resistance, it is clearly visible that there are significant bond-related differences. For example, plating with the base material causes the sensor structure to solidify, so that a strain-induced change in resistance is marginal. However, because a strain sensor requires a high change in resistance to resolve different finger positions reliably, plating with elastane (G3) is more effective. This sensor design also favors a higher sensitivity of the sensor. As an additional parameter, the yarn material for the sensor is varied. Y1 and Y2 are equally suitable for the functionality of the strain sensor. However, the haptic feel of the structures differs, as the material combination of Y2 results in a noticeably harder and slightly stiffer sensor design.

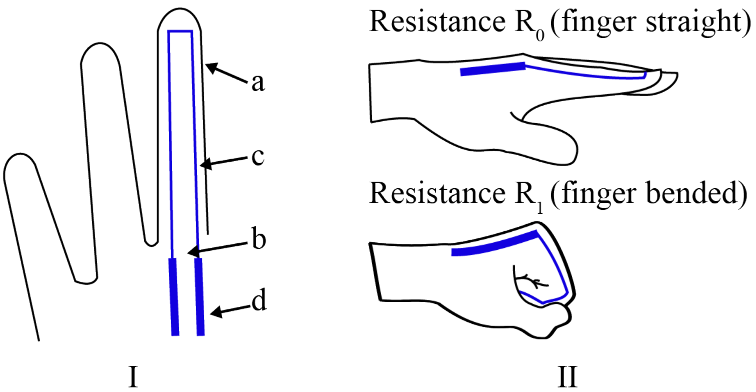

Fig. 2 Scheme of the glove (I) with resistive sensor finger (a), finger joint (b) and strain sensor lines (c) and power supply lines (d) and illustration of the hand positions for determining the resistance change (II)

Table 3 Change in resistance to finger flexing of the different glove versions

	G1	G2	G3	G4
Resistance R_0 finger straight [Ω]	25	78	80	98
Resistance R_1 finger bended [Ω]	29	97	107	103
Relative ΔR/R change [%]	18	24	34	5

Fig. 3 Different knitted sensor designs Intarsia (G1), Intarsia (different layout; G2), plated with elastane (G3), plated with base material (G4)

Summary. The manufacturing of a smart gloves with textile-integrated sensors is subject to many parameters. It can be stated that the sensor behavior is influenced by the bonding elements, the integration into the carrying knitted structure, the geometry of the sensor threads and the materials. One of the most important findings is that the electrically conductive material must be integrated into the structure and must also have similar elasticity (means by plating with elastane), otherwise the relaxation behavior of the basic structure and the sensor will be different. Due to this different mechanics, the finger movement cannot be clearly identified by resistance measurement in real time and perspectively the control of a robot becomes inaccurate.

Conclusion and Outlook

Integrally manufactured smart textiles, such as smart gloves, can be produced using flat knitting technology. Textile-based resistive strain sensors and the power supply lines can be integrated into the knitted structures during fabric formation process. The selection of a suitable and durable electro-conductive yarn material is crucial, because it can be damaged during processing. This damage is increased due to the usage of smart textiles (ageing due wearing), so it is important to develop novel coatings that make the yarn more durable against abrasion during processing and usage. Here, a compromise must be found between abrasion resistance and textile processability, because that higher the coating thickness that higher the yarn stiffness which reduces the diversity of knitting [13]. However, this is necessary to develop sensors with improved usage properties. Since only through an increased abrasion resistance, or a non-aging yarn resistance, despite processing and use of the yarn, a sensor with a long service life can be implemented. Within further test series, the dynamic sensor behavior has finally to be analyzed by recording the signal course of the integrated strain sensor during several load cycles of the sensor glove. Furthermore, the binding technology of the gloves/sensors will be further investigated in order to develop even more sensitive systems. The damage of the electrically conductive yarns during the knitting process will be further investigated. On the one hand, the damage caused by the yarn guide, but also by the needles and the take-down will be examined. Another important object of investigation will be focused on methods and types of electrical interconnection between the textile component and rigid electronic components.

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