Flexible wire-component for weaving electronic textiles

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In this paper, we present the development of a wire component suitable for direct integration to the textile during weaving. The components are used for the development of electronic textiles and wearable smart clothing prototypes. First, a 3D-printed adapter suitable for prototyping is discussed. The method focuses on attaching SO-8 chip to the conductive yarns on the surface of a knitted or woven textile. Second, a wire component processor is built, and an electronic textile developed. Finally, the problems of the electronic textiles are discussed.

Keywords-component; component; casing; yarn; eTextile; weaving

I. INTRODUCTION *(HEADING 1)*

Wearable computing[27], smart clothing[38] and eTextiles have been developing noticeably toward more integrated circuit structures over the last two decades. Technical integration has moved forward with relative independence from the design field, and the design of such textiles has been evolving through considerably more traditional components. This becomes more relevant when the comfort requirements[33] of wearables have to be designed for, meaning that the need for textile-like integration becomes more relevant: the textile designer should be able to utilize the components with the means they have at their disposal.

Textiles and fashion have been traditionally increasingly non-technical, the closer one gets to the end product: while a textile designer is typically capable of working with the requirements of traditional technical textiles such as designing for different heat insulation or breathability of the fabric, the electronic components and their integration have required cross-disciplinary experience. Definitions for eTextiles[34][28], or I-textiles, and smart textiles[1] have been developed, typically describing a textile which has inputs and outputs, i.e. the actuators and the sensors, within the textile structure, and the processing as an external entity, applied on top.

An increasing amount of research has been done after those defining papers, and the lines between sensing elements and computation, for example, have become more blurred. One of the earliest examples of integrating components into a fabric substrate utilizes the microwelding of processors to embroidered conductive yarns[36]. As the complexity and integration level of eTextile systems increase, there needs to be a way of addressing the dynamic nature of the textile. It has been suggested that the connectivity issues in a dynamic and unreliable system could be managed using computational power[41], however the electronics and the connections between them would have to be designed to allow such movement and wear. One such example was demonstrated in the stretchable electronic system[26], where thermoplastic polyurethane was used as to encapsulate stretchable PCBs, making them suitable for such dynamic structures.

Tools and methods [6] have already been established for enabling a crafts-type approach from the textile side, to a sufficient degree so as to have workshops within conferences[7], and electronic textiles have already been planned and used outside the area of wearables, such as for dewatering treatment[35] or for structural health monitoring[16]. However, there is a need for a component casing or a system which supports better integration of the electrical components with the textile structure. One major issue for the development of eTextiles is the lack of components directly suitable for textile-method based manufacturing. The existing components are designed to function in rigid or flexible circuit boards or thin-film systems, which are not necessarily suitable for drapable textile integration by means of weaving or knitting. Therefore, a casing for attaching a component for prototyping knitted or woven structures is presented, as well as an orientation-free component, suitable for weaving.

II. CREATING SMART TEXTILES

There are several different methods for attaching components to a textile, either during or after the textile is fabricated. As already mentioned, the Lilypad, for example, is intended to be sewn on top of a pre-made textile. Both hard components not intended for textiles and flexible PCBs can be attached by stitching or by embroidery, either directly[23] or by attaching microwelded conductive yarns[36]. The textile can be plain, without conductive elements, or can contain some conductive patterns. Some components, such as resistors, can be directly made using embroidery[14]. One example of a wearable sensor system sewn on top of a textile substrate is the carotid pulse sensor built into a scarf[8]. This system can be attached to any kind of substrate. Embroidered textile electrodes have been used to replace standard electrodes for sEMG measurement, achieving similar measurement quality[44]. Conductive threads coated with conductive silicone have been used to create a washable breathing sensor, applied on top of a fabric, with sewn-in data connections[15].

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An early example of larger scale integration, with a power and data bus built into suspenders, utilized snaps to connect large external devices through the suspender bus[12]. Even though textiles support complex applications, they are typically seen as only a substrate for signaling, and as a base on which to embed more rigid, traditional circuits[47]. Another example of an integrated communication bus utilizing traditional hard components is a jumpsuit where conductive yarns and tinsel were woven in, with the rest of the electronics attached to the bus via an IDC[30].

Thin-film electronics have been used to create functional blocks, which are connected together with conductive yarns by attaching them together on top of a pre-woven textile substrate[46]. Similarly, LEDS can be inserted into a pre-woven structure, with future work suggesting that they can be woven in[5]. This approach was also utilized in an adaptive and fault-tolerant medical vest with mesh-like interconnections on the fabric, but using otherwise traditional electronics[17]. Another wearable healthcare jacket utilized woven inductors, suggesting that a fabric structure could be used for creating an air-core inductor[21].

Textiles have also been used as a substrate for printing multilayered conductive patterns on, such as for the creation of loudspeakers and buzzers[22]. Another textile substrate structure focused on manufacturing a photovoltaic cell on top of a polyester textile, suggesting it to be a more energy-effective alternative to build on than other substrates, such as glass[24].

Another way of utilizing textiles is to sandwich the electronic or active structures between two textile layers. Sensor structures have been implemented to measure force, even with an actuator to periodically create known forces and improve accuracy, in an otherwise dynamic and noisy textile[40]. Similarly, active yarns can be inlayed or inserted into existing or specifically pre-made structures, such as electroluminescent yarn into a knitted textile[10].

Apart from creating the textile as a substrate, knitting and weaving allow the inclusion of active elements and conductive yarns during the fabrication process, making them integral to the textile structure. Conductive yarns have been successfully used in knitted structures for a long time [11][37], with examples also supporting textile interactions[13], implying the significance of the method. As knitting costs relatively less to fabricate with than weaving, it is a good candidate for the rapid prototyping of smart clothing and wearables. In addition, industrial knitting machines are also already able to create “complete” knitted ready-to-wear structures.

Weaving, on the other hand, produces textiles which need work before they are usable in an end product. The benefit is that there are more possibilities for integrating the active elements during the fabrication. As weaving typically utilizes a two-yarn system, i.e., it has a separate warp and weft, this naturally supports the use of different yarns, whereas knitting uses only one yarn. These can be varied, and even though looms require considerably more time and effort to set up, they seem to provide a more reliable base for building electronic systems.

While interconnections are critical in the textiles, and in large-sized woven textiles has been addressed with conductive polymer-based micro-scale contact arrays[18] for example, the choice of yarns is the building block of the fabric’s properties. The conductive yarns used in the weaving are important, as is the selection of the yarns which insulate them from the user [29]. Woven fabric with conductive yarns in select warp threads, for example, has been used as a base for creating a light therapy blanket. The combination of hard components and the overall structure, using woven fabric and insulation to achieve a safe behavior, has been critical for achieving a fully functional product[45].

The scale on which weaving can be done varies from larger, meter-scale products, such as pressure sensors created by weaving polymer-coated conductive fibers[43], to very small systems at the fiber level. At the smallest level, semiconductor devices can be created utilizing the warp-weft connection points. Weave-patterned transistors have been built directly on fibers, inspired by a woven structure: the transistor consists of elements distributed to either weft or warp, with the functional transistor consisting of at least two connected fibers and their doped connection points[20]. In a similar manner, a cylindrical OFET-structure was built, suggesting that the transistor can be built in a single yarn, with just the gate connection brought across from another yarn[25]. Even an inverter has been woven using amorphous silicon thin-film transistors with kapton-based insulators[4].

On the larger scale, typical approaches use thin-film structures or woven-in flexible PCBs. Such an approach has been successfully used on several occasions, starting with metallic contact plastic strips for woven highly integrated circuits, attached using a commercial weaving machine[9]; or a thin-film sensor strip intended for integration into a woven structure, built on a thin wire-width polymer foil, with connections made using conductive glue[19]. Larger foils with printed sensor structures have been used in weaving as well, using conductive epoxy for the connections[31]. Bus-based communication [49], as well as control of individual LED-drivers[48] have been implemented by having the active component in a thin-film structure (in the weft) and the signaling lines as conductive yarns (in the warp) both woven into the textile. Scaling upwards, microelectronic components have been suggested to be integrated into a PDMS fiber, where stretchable spring-like interconnections are used to link MEMS devices. Such encapsulation provides protection against twisting, stretching and strain, making it suitable for large-scale weaving[42].

All of these focus on the technical qualities, however weaving provides numerous possibilities for design, both electronic and textile. One issue with substrates that are thin in one dimension and wide in the two others is the limited bending angle. They are naturally flexible in the direction of the thinnest dimension. The material qualities of the fibers are seen as important from the textile designer’s point of view[2]. Having the textile qualities of drapability and flexibility, as well as good tactile and visual properties, are seen as important. The technical properties of a yarn have been utilized in a woven display, to design a color effect based on photonic band-gap fibers[3].

Figure 1. Knitted fabric using floats (L) and inlay-knitted fabric (R).

Another example of the utilization of design in a woven electronic textile hides the components within a two-layer weave structure, integrating the power and signaling within the weave[32]. One example of a weavable component is electronically functional yarn with an encapsulated LED[39], similar in function to the LED yarn mentioned earlier[5].

III. 3D-PRINTED CASING

When exploring aspects of prototyping with suitability for knitting and weaving, we focused on the problem of attaching components without soldering. The yarns and materials used cannot necessarily withstand the temperatures needed for soldering, and utilizing an IDC would create a large volume, with the resultant textile losing some of its tactility: it simply would not be flat and small. Since there were no components that would directly suit the purpose, an adapter supporting the use of traditional IC components, in this case SO-8, was created. As conductive yarns have demonstrably offered straightforward integration of signaling, designing a textile with interconnects can be seen as similar to a PCB design: conductive patterns in an otherwise non-conductive substrate.

The designed adapter requires that the knitted (or woven) substrate has conductive yarns, with the spacing depending on the yarn and knitting-loop size. The adapter and the IC are attached to either floating conductive yarns, or to a conductive yarn added as inlay knitting one line at a time, with both shown in Figure 1. Each 8-pin component requires four yarns, which are kept uncut until the component has been fixed in place. The adapter itself is a 3D-printed frame with a lid, fabricated with Objet Connex350, using the Verowhite+ material. The frame has grooves for guiding the IC pins, as well as placing the conductive yarns. The yarns are latched onto the pins manually, by pressing the component into place. Since the connection is mechanical, each of the pins needs to be pressed down, locking it onto the yarn. This also helps to latch the lid firmly in placed.

A. Workshops

Two workshops were held using the adapter. The first workshop focused on the use of different conductive threads and base materials, and the second focused on creating applications. At the first workshop, it was found that multifilament threads made from silver and copper, such as Karl Grimm High-Flex 3981 3x5 Silber 14/ooo worked best, and that steel yarns, such as Bekinox VN 12/1x275/100Z did not work very well. Drawing on this, the second workshop utilized only the Karl Grimm High-Flex threads.

Figure 2. Temperature-alerting headband.

During the second workshop, eleven patches and seven prototypes were knitted and programmed over the course of three days. The patches were similar to those shown in Figure 1., however the prototypes were all different. Each of the patches was tested for connectivity and functionality by programming them after assembly, and confirmed to be working. The prototypes were mostly garments, with functionalities such as simply blinking lights, or reacting to a light or temperature change. There were also two prototypes which utilized heat, and all but one were controlled by a microprocessor attached using the 3D-printed adapter. One example prototype, activating a vibration alarm if the temperature drops below a pre-set threshold, is shown in Figure 2.

While the adapter was used successfully to create prototypes in a relatively short time, fulfilling the purpose of prototyping, there were problems. The 3D-printed frame sometimes broke during assembly, and the press-to-latch connections proved to be problematic. Even though the participants were able to test the prototypes, some of the yarns became loose, and the prototypes ceased to function. Considering the time put into the work, arranging the knit such that the threads are soldered to the component pins would be a better option durability-wise. However, this should only be considered if the materials for the knitting are sensitive to heat.

IV. Weaving a PCB

While the 3D-printed casing performed adequately, it does not allow the component to be woven inside the textile, and in practice works only if the component is intended to be on the surface. As weaving is suitable for embedding electronic components into the textile during the weaving process, it also allows the encapsulation of the components between different layers. The woven textile forms from a combination of thousands of threads in the warp and the weft. The warp has considerable tension, and warp threads move up and down during the weaving process, according to the harnesses they are connected to. The programmed pattern, which dictates how the threads connect within the weave, is realized with the weft. These yarns move orthogonally to the warp, and have typically low tension, with only the forces from the warp threads pressing against the weft.

By combining different threads, and using a sophisticated weaving pattern in a multiple thread system, a two- or multilayer fabric can be created. A typical structure for a multilayer fabric is an empty space sandwiched between two or more fabrics. During fabrication, the fabrics are woven separately at the same time, and the weaving pattern can be used to connect them together at selected points. This allows for the development of hidden layers, as well as manufacturing structures similar to multilayer PCBs, in addition to hiding the components as an essential part of the fabric structure. As fabrics can be created with a combination of threads with different properties, it is possible to create fabrics with computational, sensorial and actuating properties.

A. *The wire component*

The most natural way to include a component into the weave is to have it in the form of a thread or a yarn. Connecting components with multiple threads, or applying them afterwards is slow, and adds additional work stages. Multilayer structures cannot be fully utilized, and the possibilities of the weaving process are limited. In order to find a solution suitable for the majority of existing looms, a wire component with multiple connection points was developed. The component is intended to be used in the weft, to be connected either to the conductive yarns in the warp, or via multilayer fabric connection points to other components or conductive yarns.

The wire component was constructed using the ATtiny84V-10SSU microcontroller as a base, and the warp system was created specifically for the component. Even though the ATtiny84 has 14 pins, only 11 of them were used for the construction. The pins were individually soldered to the LITZ-wire strands, which had the enamel removed from pin-specific distances, creating a so-called pin-wire. The de-enameled regions were designed to fit together with the warp, where the electric connections would be formed. After soldering, the connection points between the pins and the LITZ were covered with epoxy, to electrically isolate the adjacent connection points, as well as to protect them from physical strain. The processor and the pin-wires were braided together with silk threads to form the wire structure, and the contact points were enhanced with conductive yarn. The partially constructed component, final wire component and structural drawing are shown in Figure 3.: in the bottom picture, gray indicates the silk, red is the contact, and the blue is the LITZ. We also prepared two LEDs and a thin lithium-polymer battery in a similar way, to be incorporated in the fabric.

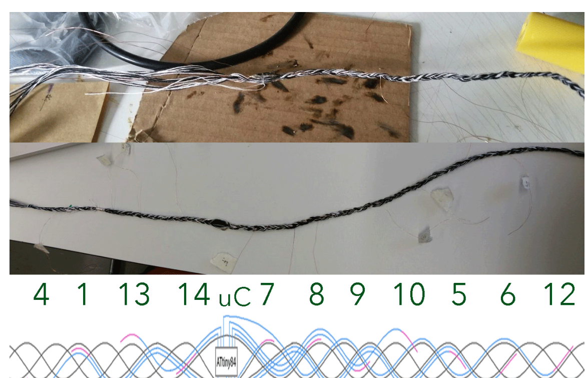

Figure 3. Constructing the component (T), the wire component (M) and the structure of the component (B)

B. *The fabric*

Another important aspect in the fabrication process was the design of the warp system. The intent was to design a pattern, which would connect the "processor-wire" pin threads with a direct galvanic contact to the conductive lines in the warp. These conductive lines would also be used to control LED wires, as well as for signaling and other purposes, such as programming the processor. In essence, the warp would act as a base to which the other components would naturally connect as part of the textile structure, without the need to attach components afterwards.

The fabric was designed to be a three-layer structure, implemented with silk and silver yarns. Silk was used as an isolating warp in 12 harnesses, whereas the Karl Grimm High-Flex 3981 1-fach Silber 14/ooo was used for the conductive warp, using 4 harnesses and 8 yarns per conductive warp line. The silk was selected for its smooth structure, being easy to weave and capable of providing a dense warp. Karl Grimm was chosen because it is polymer-reinforced uncoated silver capable of withstanding the tension in the warp. The resulting base fabric consisted of 20 threads/cm, made from 100% silk, and in another warp system, the conductive threads had 8 threads /cm, made from silver. The design pattern is shown in Figure 4. The resulting fabric was hand-woven using Toika EWS16, with a weft width of 34cm.

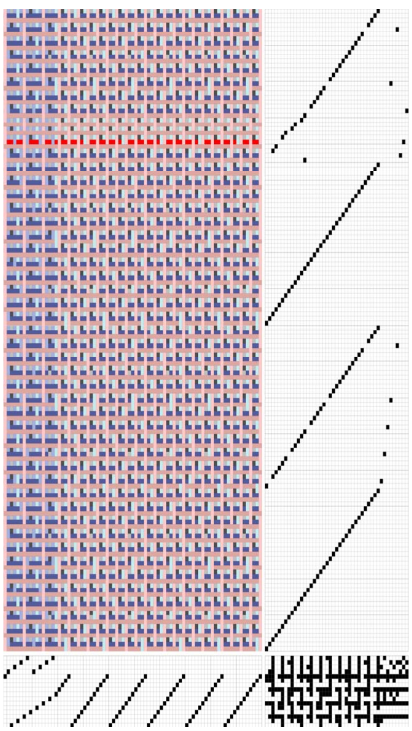

Figure 4. The weave pattern.

Each fabric layer consisted of four harness weaves: the bottom layer was plain weave, mid layer satin weave, and the top layer pebble weave. The purpose of the external layers was to protect the mid layer from being exposed, while being bound together. As the mid layer had the conductive signals, having three layers would both create aesthetically pleasing fabric and isolate the signals. The materials used for the weft were mohair/silk yarn with leather and silk for the top layer, pure silk for the mid layer and mohair/silk yarn for the bottom layer. The mohair/silk ratio in the mixture-yarn was 70%/30%. The woven fabric, with the LEDs powered, is shown in Figure 5. The processor is only visible as a small bump, due to the large size of the processor, in an otherwise flexible fabric. The close-up is shown in Figure 6. The overall layout of the connections is shown in Figure 7., where the warp-lines are in the vertical direction. The woven battery is on the top, with processor wire component connected to all of the conductive warp lines. At the bottom, there are three controllable wire component LEDs.

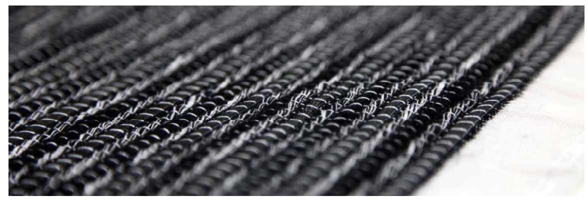

Figure 6. Fabric close-up, showing the bump caused by the integrated wire component.

Figure 5. Draping fabric, a still from a video.

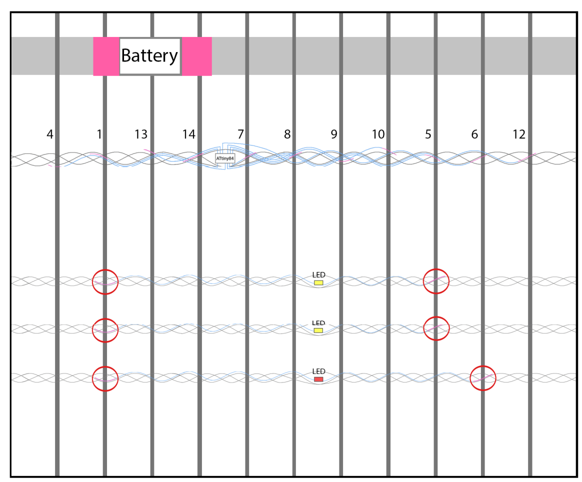

Figure 7. Connections inside the fabric.

After the fabric had been woven, it was cut out and the and the connections were examined by programming the processor through the conductive warp lines. As the processor can operate without any external components, such as a clock source, being able to program it indicated that at least the minimal amount of connections were functional.

With the program burned in, the rest of the warp signals could be measured using an oscilloscope, comparing them to the signal patterns in the program. Finally, a program blinking the LEDs was burned, so that visual inspection could be undertaken while handling the fabric.

V. Analysis

Since the weaving is done with a “stretched fabric”, i.e. the tension and the harnesses will push toward slightly larger dimensions for the fabric, the component in the weft and the conductive warp will have to accommodate and withstand this movement. The wire component is flexible and can shrink; however, the connection points should be wide enough to survive this. Once released from the loom, the width decreased by roughly 5%, but no breakages were found.

The silver thread used in the warp had some issues and breakages. While the threads did not fully break, the silver yarns did sometimes break and tear. Some were already damaged during the creation of the warp, before it was attached to the loom, however the mechanical wear from the metallic beater had a more damaging effect. The signals were nevertheless functional, as each of the conductive warp lines had several parallel lines. This can be improved with the material selection, as well as using a different type of beater. However, when examining the fabric at a later stage, it was found that the connections are sometimes loose, and the fabric needs to be moved slightly to get a signal. We suspect that this is due to a combination of oxidation and damage from handling; however, the fabric and component wear behavior will need to be evaluated with a larger sample set, as the plain weave is very strong at fixing the warp-weft connection in place.

VI. Conclusions

In this paper, two examples of attaching active components to a fabric have been shown, developed from the textile designers point of view. The 3D-printed casing works as an adapter for existing hard components; however, it is prone to mechanical stress during both assembly and use. As it does not require heat, it is suitable for prototyping with temperature-sensitive materials. The wire component is a processor, which can be directly woven into the fabric, similar to a normal yarn. Even though it is built from existing hard components, it suggests a direction for the development of programmable wires which can be used for prototyping and manufacturing “embedded textiles”. In this case, a specific microcontroller was used, however, for an electronic textile to be mass-produced and more electronically flexible, programmable hardware such as an FPGA with a soft processor could be used.

The work benefited from the cooperation of a textile designer and an electronics engineer, and the development areas which need further focus are divided between those two domains. On the one hand, the resulting textile needs to look, feel and behave like a textile. At the moment, the component is bulky. On the other hand, the chip or the functionality embedded into the component wire should withstand the stresses that typical threads are subjected to, as well as being able to cope with the dynamic nature of the textile structure. These together suggest that the traditional approach of expecting a good galvanic connection should not be assumed, and the component wires should be designed in the expectation of breakages, random galvanic contacts and mechanical noise, topped with oxidation.

There is also a need for a very different intra-textile communication and power distribution mind-set, which expects the wire components to have their own limited power storage, with signaling which does not require or expect a fully functional direct galvanic connection, able to communicate with e.g. capacitive signals over the oxidation and breaks.

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