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Development of Electronic Textiles to Support Networks, Communications, and Medical Applications in Future U.S. Military Protective Clothing Systems

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Abstract—**The focus of this paper is on the development of textile-based wearable electronics that can be integrated into military protective clothing. A materials and manufacturing survey was conducted to determine the best performing and most durable materials to withstand the rigors of textile manufacturing and potential military use. Narrow woven technology was selected as one of the most promising textile manufacturing methods. A working wearable narrow fabric version of the Universal Serial Bus (USB), as well as a radiating conductor, were successfully developed and fabricated. A circular knit T-shirt with an integrated spiral bus was also developed. Military products developed include components of a personal area network providing data and power transport, and a body-borne antenna integrated into a load-bearing vest.**

Index Terms—**Electronic textiles, military, personal area network, soldier.**

I. Introduction

The need for real-time information technology on the battlefield has been well documented in military development programs such as Land Warrior, Scorpion and Future Force Warrior (FFW). Military combat clothing materials are passive and the ability to integrate electronics into textiles provides the potential to achieve revolutionary improvements in performance and the realization of capabilities never before imagined on the battlefield. Electronic devices are being miniaturized for personal use both in the commercial and military sectors. Materials and methods are being investigated to facilitate the integration of these electronics into textiles. While there are an increasing number of commercial electro-textile products on the market such as Vivometrics' Lifeshirt, The North Face's Met 5 Jacket, and the Malden Mill's Heat Blanket this effort focuses on the development of working prototypes specifically designed to support rugged military use in future protective clothing systems.

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Two selected military applications are textile-based cables to support a wearable electronic network providing data and power transport, and a textile-based double loop antenna that can be integrated into protective clothing. Projected capability enhancements on the battlefield provided by these products include an individual soldier network to process and use information in real time resulting in increased situational awareness and enhanced communications.

The objectives of this effort are to investigate the feasibility of integrating conductive materials and components into textiles and to develop working prototypes of electronic textiles for potential future military use. A materials and textile manufacturing survey [1] was conducted to determine the best performing and most durable materials to withstand the rigors of textile manufacturing and military use. A variety of commercial materials were investigated, tested, and evaluated including conductive polymers, metallic fibers, novelty embroidery materials, and materials not commonly used in textile manufacture such as tinsel wire and optical fiber. Litz wire was not used due to its stiffness and cost. Copper wire of 32 American Wire Gauge (AWG) was used as a benchmark for conductivity and has a value of 186 S/cm. None of the fiber-forming polymers investigated demonstrated the desired conductivity of copper. Embroidery materials, such as metalized Mylar wrapped around core fibers, demonstrated relatively high resistance and poor mechanical properties. Tinsel wire, commonly used in the telecommunications industry, typically consists of a metallic ribbon that is double wrapped in a helix around a polyester or Kevlar strength member. The typical resistance of an individual tinsel wire is 0.015 Ω/cm. Resistance of 36 AWG copper wire is 0.014 Ω/cm. Due to the lack of highly conductive fiber-based materials, traditional conductors such as copper wire and tinsel wire were used in this development effort. Glass and plastic optical fiber can also be used to transport data in electro-textile bus structures. Optical transport of data can take place at rates in excess of 1 Gb/s. Glass has been optimized for use in the telecommunications industry; however, their characteristic large bandwidths and operational distances are not necessary for use in protective clothing. Plastic optical fiber was selected because distance requirements are moderate (< 5 m) and fine glass fragments may complicate battlefield wounds. Other factors to be considered when selecting plastic optical fiber are the following:

1) high bandwidth, reduces the number of data transmission lines;
2) electromagnetic interference (EMI) shielding is not required;
3) resistant to nicks, can be melted together in the field to repair;
4) bend radii are small (<1 mm);
5) bend radii less than 25 mm results in transmission loss;
6) compatible connector systems not well developed.

Traditional textile manufacturing methods were investigated to determine if fine gauge wire as well as tinsel wire and optical fiber could be integrated into a manufactured fabric. Broad loom and narrow woven fabrics, knits, and embroidery methods were reviewed. A mass producible, flexible, washable, and low cost wearable textile fabric was desired. Whereas conductive materials can be easily integrated into broadloom woven and warp knit fabrics the problem is that the conductive path is lost when pattern pieces are cut and sewn together. By definition, narrow fabrics are woven or braided and usually are no wider than 12 in. The narrow fabrics developed in this study were 1–1.5 in wide and had finished selvage edges. Narrow woven fabric can be used to create a continuous network on or within a garment or clothing system without addressing the breaks in conductivity that

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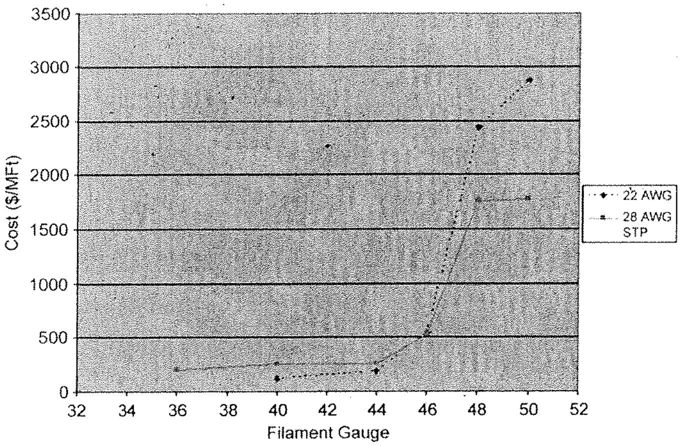

Fig. 1. Cost of 22 AWG power wire and 28 shielded twisted pairs versus filament gauge.

would occur when joining different pattern pieces together. Narrow fabrics need only be terminated at the ends. In addition, narrow fabric manufacturing technology showed promise because the double plain weave fabric construction is uniquely compatible with our interests to integrate both conductive and optical materials into the base fabric. The double plain weave, which is one of the most common types of weaves used for medium weight industrial webbings, is a type of fabric construction consisting of two layers of fabric, one above the other, each woven with a separate warp and filling system. Binder yarns are commonly used to stitch the top and bottom layers together. The binders divide the space between the two layers into warp-wise tubes, providing space for stuffer components. Stuffer components do not interlace with any yarns, lay flat, and are not visible from the face of the cloth. Traditionally, stuffer yarns are used to increase thickness and strength, or provide a rib effect. In our experiment, we used conductive and optical fibers as the stuffer components. In addition, narrow woven double cloths usually have one woven selvage and one knitted selvage. The knitted selvage incorporates a catch cord that can be used to facilitate unraveling of the narrow fabric for subsequent connection purposes.

II. Materials and Methods

While copper wire is not generally thought of as being flexible or textile compatible, it is compatible with all wire and data transmission standards investigated in this development effort. Solid copper wire is stiff and it was recognized that by constructing wire using a larger number of high gauge, i.e., small diameter, fine filaments it might be possible to increase flexibility. However, when 22 AWG power wire and 28 AWG shielded twisted pair products were compared on a cost basis it was found that as the filament gauge increased, so did the cost. Fig. 1 shows the relationship between the cost per 1000 ft of wire and filament gauge, and demonstrates that copper wire filaments greater than 44–46 AWG in size are not cost effective.

A. Electro-Textile Data and Power Transmission Device

The standard Universal Serial Bus (USB) 2.0 protocol was selected to prove the technical feasibility of manufacturing textile-based components of a point-to-point wearable personal area network because it is a cable bus that supports data exchange between a host computer and a broad range of peripherals, and it is commonly used and well understood. A typical USB cable (Fig. 2) is composed of a nontwisted power pair, twisted data pair, a drain wire, and various shielding. The first textile prototype [2] was manufactured in accordance with the industry standard USB 2.0 specifications [3] and the following materials were used.

1) *Data Transmission Medium*: 28 AWG twisted copper pair, PVC insulated, wrapped with aluminum Mylar foil for EMI shielding.
2) *Power Wires*: 20 AWG stranded, tinned copper with PVC insulation.
3) *Drain*: 28 AWG copper wire in contact with data medium.
4) *Warp and Filling Yarn*: Filament nylon.

The components selected for use in the narrow fabric version were similar to those used in the concentric design except they were laid out in a flat arrangement (Fig. 3). The double plain weave construction was utilized except the traditional stuffer components were substituted for electronic components. The gray stripe down the middle identifies the location of the electronic components to alert garment manufacturers to avoid stitching in this area.

B. Radiating Conductor

Narrow fabric manufacturing technology was also used to develop a radiating conductor for body borne antenna applications. A double plain weave fabric (Fig. 4) was manufactured with binder and stuffer components. Four 0.25–in-wide parallel conductive stripes made from tinsel warp yarns are separated by 0.125-in-wide insulators of nylon filament warp yarn. The optical fibers, which have a low bending radius, were integrated into the structure as the stuffer components. Nylon filament yarn was used for the binder and filling components. The textile based radiating conductor was waterproofed by dip coating in a thinned thermoplastic resin.

C. Conformal Spiral Bus

Circular weft knitting technology was used to develop a body conformal T-shirt with an integrated spiral bus [4] to serve as a platform to integrate medical instrumentation and/or sensors that are required to be in close contact with the body. Conductive fiber and stretch fiber were combined to form stretch conductive yarn that was knitted into a circular knit tube with both vertical and horizontal stretch. The continuous bus wraps around the torso of the mannequin (Fig. 5 and 6) and can be spaced closely together or far apart to support a variety of electronic subsystems.

III. Results, Discussion, and Military Applications

The prototype electrotextile cable was tested and evaluated against a variety of tests including Group 6 Signal Integrity tests and shielding effectiveness for the USB 2.0 (Table I) in accordance with industry standards [5], [6]. While the USB 2.0 tests are not intended for body worn applications, we selected those that would be appropriate for soldier applications. Overall the cables passed all body worn related requirements. Impedance is a parameter that determines a cable's ability to pass energy efficiently. The specification requires that the impedance register between 76.5 and 103.4 Ω. All cables passed this test. Propagation delay is the time required for the digital signal to travel from the input of a cable to the output. To pass the low speed spec the propagation delay must be no more than 5.2 ns/m. The 0.5-4 m cables meet this requirement. The 5.0 cable is at the threshold with an average speed of 26.03 ns and a requirement of 26.0 ns. The propagation delay skew tests verify that the signal of both the D^+ and D^- lines arrive at the receiver at the same time. The standards require a differential of less than 100 ps. All cables passed this test. Attenuation is a measure of signal loss in a cable. Attenuation tests are only required for high or full speed cables and were performed to ensure that adequate signal strength was presented to the receiver to maintain low error rates. The

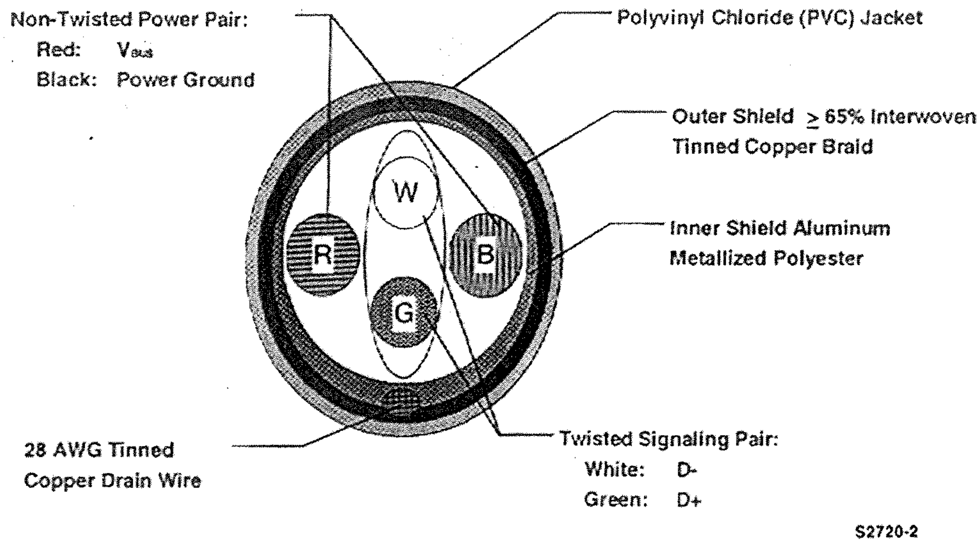

Fig. 2. Cross-section of a standard USB 2.0 cable.

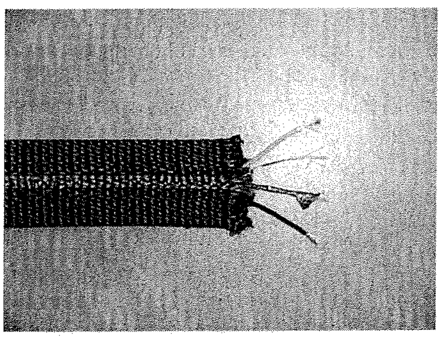

Fig. 3. Textile-based USB. From top: white power wire, drain wire, shielded twisted signaling (data) pair, and black power wire.

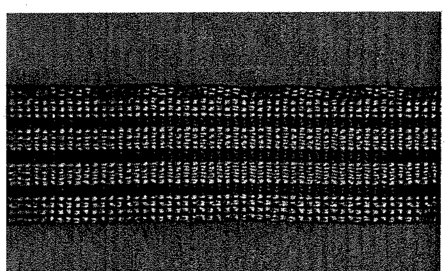

Fig. 4. Textile-based radiating conductor.

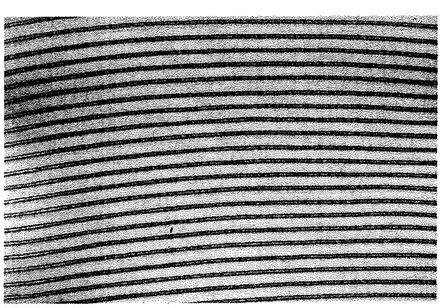

Fig. 5. Weft knit fabric.

Fig. 6. Body conformal T-shirt.

TABLE I
GROUP 6 SIGNAL INTEGRITY TEST RESULTS

Cable Length	Cable Impedance (full speed)	Propagation Delay	Propagation Delay Skew	Attenuation (full speed)
5.0m	Pass	Pass	Pass	Fail
4.0m	Pass	Pass	Pass	Fail
3.0m	Pass	Pass	Pass	Pass
2.5m	Pass	Pass	Pass	Pass
2.0m	Pass	Pass	Pass	Pass
1.0m	Pass	Pass	Pass	Pass
0.5m	Pass	Pass	Pass	Pass

USB cables failed at long lengths. For the purposes of the soldier, however, only short cable lengths will be required. The cables pass attenuation tests at lengths of 3.0 m and shorter. Shielding effectiveness tests were performed to determine the electromagnetic emission profile and susceptibility of the cable. The minimum attenuation required to pass the test is 20 dB. Testing occurred at 13 frequencies between 30 MHz and 1 GHz. All the USB cables achieved the 20-dB mark at all frequencies, with the lowest being 35.9 dB. To measure durability-related performance, the electrotextile cable was tested and evaluated after abrasion (4000 cycles [7]), and cyclic loading (0- to 250-lb load profile for

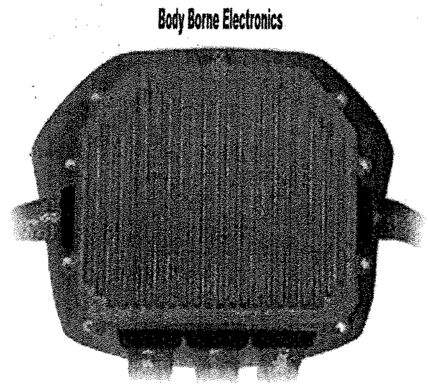

Fig. 7. FFW CPU with attached electrotextile cables.

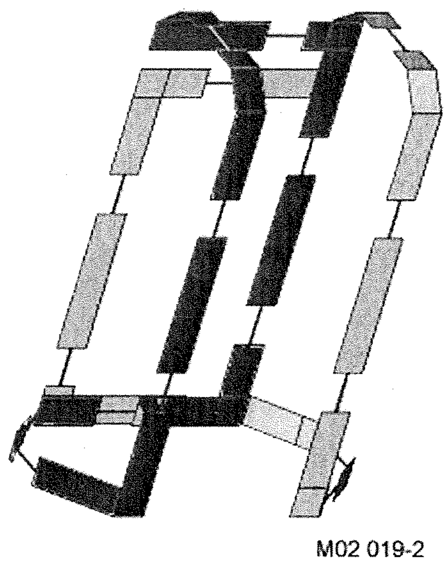

Fig. 8. Textile components in Merenda double loop antenna configuration.

40 000 cycles). The electrotextile cables maintained acceptable performance levels after being subjected to abrasion and cyclic loading [8]. Flexibility of the electrotextile cable was also tested and material alternatives were identified [9] that reduced overall stiffness without affecting performance including the following:

1) reduce hardness (durometer measurement) of wire insulation;
2) stranded conductors versus solid conductor;
3) replace foil shielding with round hollow braid of metallic fibers.

FFW is the future protective clothing system under development for soldiers of the U.S. Army. Components of a personal area network were developed utilizing the technology described above and integrated into the FFW prototype system to serve as the soldiers' electronic backbone. The textile-based power and data buses form a point-to-point network when hard wired to the central processing unit (CPU) (Fig. 7). The CPU was designed to be worn in the small of the soldier's back. Power from the two waist-worn battery packs, one on each side, is transported to the CPU via the two side electrotextile cables. The three textile-based cables at the bottom of the CPU wrap under it, then between layers within the FFW system emerging at the back of the neck to transport data and power to and from the wrist display, drink-o-meter, and headgear.

The narrow fabric technology and conductive materials were used to develop a body worn VHF antenna. Maintaining communications on the battlefield is critical to coordinate and control units and firepower. Antennas that protrude from the soldier's silhouette easily identify radio operators. Antennas are easily broken by tree branches and bushes, limit soldier mobility, and are relatively inefficient radiators. A rigid Merenda double-loop antenna [10]–[13] was transformed into a wearable textile based antenna that is compatible with the single channel ground and airborne radio system (SINCGARS) functioning in the 30–88 MHz range. The radiating conductors are attached to the antenna's high efficiency electronic switching components that increase the antenna's wide-band efficiency. The gaps in the conductors (Fig. 8) indicate where the switching modules are placed. The textile-based antenna was integrated into the modular lightweight load carrying equipment (MOLLE) vest (Fig. 9). A version with ergonomically designed switching modules was also developed and integrated into the MOLLE vest (Fig. 10). In this configuration, the body borne antenna has advantages over the standard 30-in whip antenna in that it is body conformal and visually covert, not compromising the soldier's silhouette. RF hazard and safety testing was conducted by the U.S. Army Communications and Electronics Command[1] at the U.S. Army's Electronic Proving Ground to measure permissible exposure levels (PEL) inside

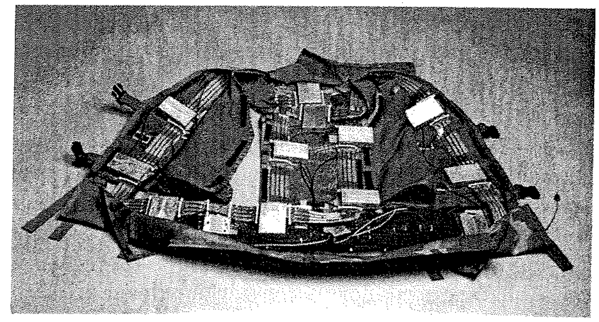

Fig. 9. Double loop antenna integrated into MOLLE vest.

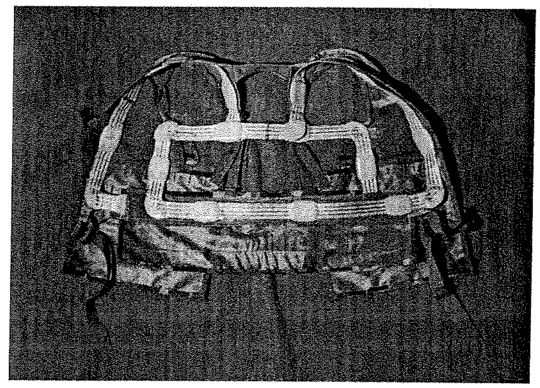

Fig. 10. Double loop antenna integrated into the MOLLE vest with ergonomic modules.

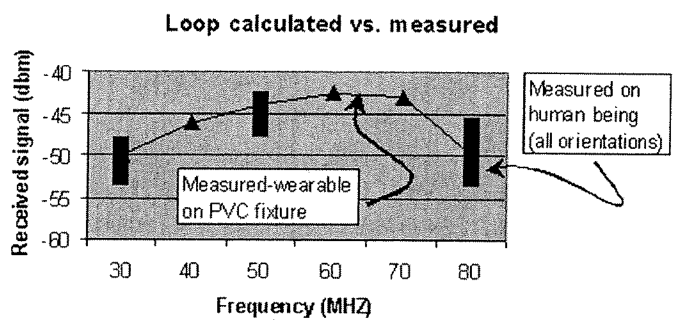

Fig. 11. Radiation levels on human and PVC fixtures.

[1]Space and Terrestrial Communications Directorate.

and around the antenna vest. These tests indicated that the antenna vest met all PEL standards across the 30–88-MHz band. Performance testing was conducted by BAE Systems Aerospace Inc., Greenlawn, NY, with a SINGCARS radio. The received signal strength was tested draped on a PVC fixture, and on a human volunteer. In order to measure its omni-directional performance the test was conducted while the volunteer was standing, kneeling, and crouching close to the ground. The received signal strength is plotted when supported by the holding fixture (Fig. 11). The deviation in signal strength as the wearer moves through a full range of positions is shown in three frequencies. The bars represent the extreme limits of the variation. For most orientations the level was near the center of the range. In the final analysis of the data, it was found that the radiated signal, while operating on a human being, had a 95% probability of falling within 3 dB of the predicted level, considering all operating frequencies and possible orientations.

IV. Conclusion

Electronic textiles were manufactured using commercially available materials and traditional textile manufacturing methods. Conductive materials such as copper wire, tinsel wire, and optical fiber were integrated into double plain weave narrow fabrics. Stranded copper wire filaments less than 44–46 AWG in size were found to be the most cost effective. Narrow woven electrotextile cables may be used to create a continuous network on or within a military garment or clothing system without seam discontinuities. A double plain weave narrow fabric with integrated conductive components was manufactured that met selected test requirements of the USB 2.0 initially, and after exposure to abrasion and cyclic loading. A radiating narrow fabric with integrated conductive and optical materials was manufactured that demonstrated communications ranges compatible with military communications equipment.

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