Wearable

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Introduction

When the U.S. first arrived in Afghanistan more than two decades ago, a typical unit required 2.07 kilowatt-hours (kWh) to power its devices [1]. Today, unit power consumption has increased to 31.35 kWh due to the proliferation of mission-critical electronics on which soldiers rely [1]. This power demand means the warfighter now carries an additional 16 pounds of batteries, equivalent to an unloaded Squad Automatic Weapon, on top of the 60-120 pounds of standard gear [2]. Portable power sources are a critical issue in military operations due to the logistical challenge of battery swaps. This additional weight may increase the risk of musculoskeletal injury and greatly diminishes mobility and combat radius [1,3]. An increase in this power requirement is likely as the military intends to implement more energy-hungry technologies such as lightweight, body-armored exoskeletons, vital sensor monitoring, flexible displays embedded in electronic textiles, improved heads-up display for communications, and electronic wearables [4]. Although these technologies are still in their infancy, existing technologies demand lighter, safer, conformal batteries that do not compromise power or efficiency. This concept is an important planning factor for future warfighter needs.

In the past, soldiers were given 3-pound, brick-shaped batteries that were specifically designed for battery boxes and nonportable devices. As soldiers began to pack more electronics, these bulky batteries multiplied with them [5]. The U.S. Army Communications-Electronics Research, Development and Engineering Center developed a solution called the Soldier Wearable Integrated Power Equipment System, known as SWIPES, that provides an integrated solution for mission-critical electronics that can flex and stretch with the body while reducing weight [5]. SWIPES integrates all electronics carried by the warfighter into one tactical vest. Each electronic device is housed in a specific pocket with an associated power cord, and all devices connect to one conformal battery [5]. The conformal battery is a thin (>1/2-inch thick) and flexible lithium-ion battery weighing just over 2 pounds [5]. Due to flammability associated with lithium-ion batteries, especially from ballistic damage, the battery is treated with a ballistic coating to protect the battery [5].

Benefits

The benefits of the conformal battery were studied with a squad power manager kit, as shown in Figure 1 [3]. A United States Military Academy study compared the confor-

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mal battery over battery swaps to power a PRC-154 Rifleman Radio and an end user device, an Android smartphone [3]. The study revealed use of the small unit power (SUP) kit provided a 10-30 percent reduction in weight load compared to battery swaps [3]. Also, the large power reservoir of the conformal battery provided constant connection over interrupted battery swaps, and prevented swapping out a partially-charged battery with a fully-charged battery [3]. The study concluded the use of conformal batteries reduces weight load and the physical and mental toll on warfighters on how, when, and where to swap a battery [3,5].

Battery Chemistries

Although the current conformal battery has shown potential benefits to replace swappable batteries, significant improvements to the battery chemistry, level of conformability, and fabrication cost are critical to the military's effort to power mission-critical electronics. The availability of numerous battery chemistries such as magnesium, aluminum, iron, zinc, and lithium-ion has been explored for rechargeable batteries, as shown in Figure 2 [6]. There has been significant interest in lithium-ion and many of its sub-chemistries due to their high theoretical specific energy (5,928 Wh/kg) and

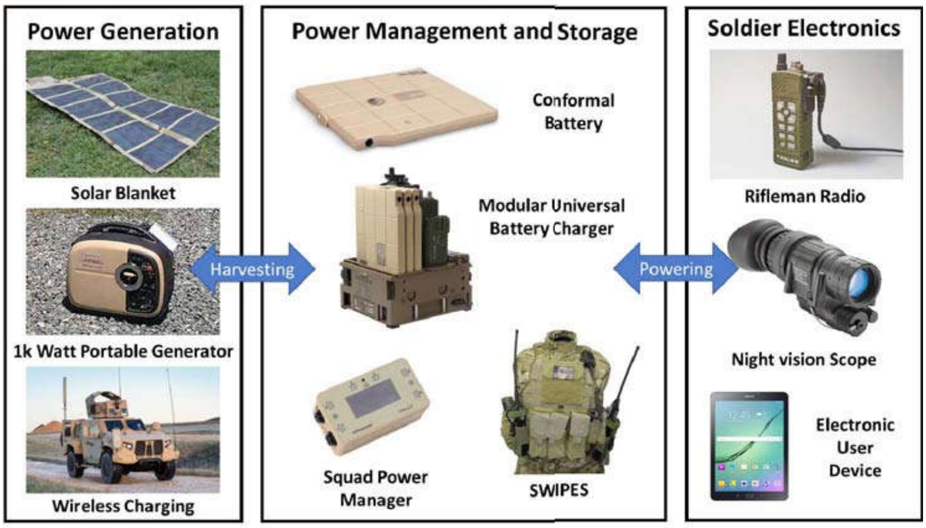

Figure 1: Operational view of power management for platoon [21-30].

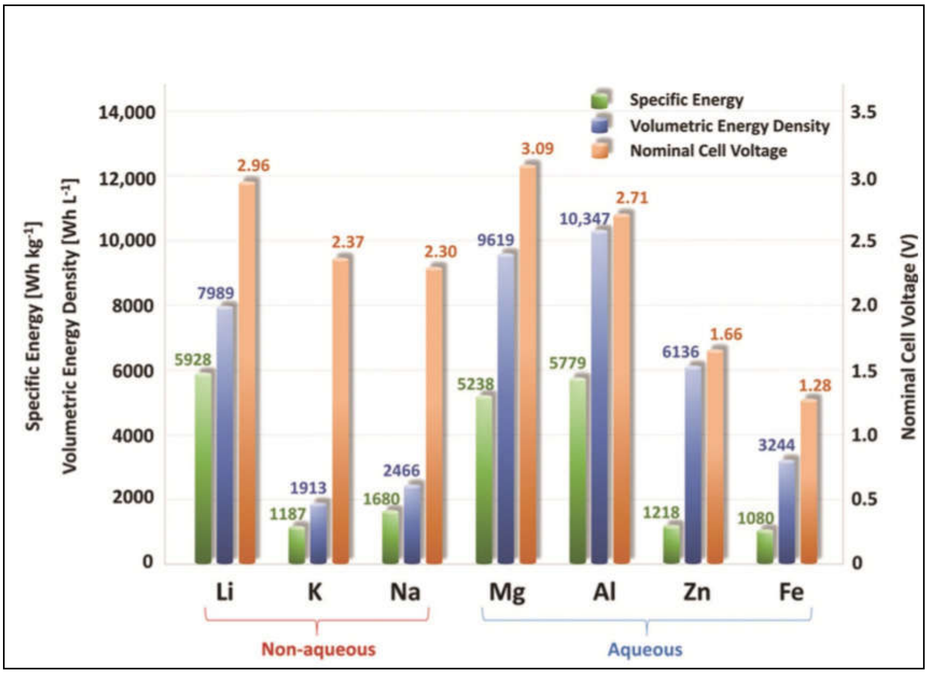

Figure 2: Theoretical specific energies, volumetric energy densities, and nominal cell voltages various metal anodes in aqueous and non-aqueous batteries [6]. (Released)

high cell voltage (2.96 V) [6]. For example, the military has recently funded research on lithium-sulfur batteries [7]. As for the next generation of lithium-ion batteries, many are looking to silicon anode because it has reported the highest known theoretical charge capacity (4,200 mAh/g) [8].

Silicon lithium-ion batteries remain in the prototype stage because of the large volume change (~400 percent) upon the insertion and extraction of lithium-ion, compared to the 10 percent volume change of graphite anodes [8]. The large volume change causes significant deformation and poor electronic contact thereby diminishing the capacity over time, with a cycle life no more than 10 cycles. Many groups have reported new approaches using silicon nanowires, incorporating self-healing polymers, and porous architecture resemblance of seeds packed in pomegranate [8-10]. Unfortunately, any type of lithium-ion chemistry will present safety issues due to its inherent instability and flammability, making it especially vulnerable to ballistic damage from ground combat [6]. The risks associated with the lithium-ion battery have grounded many technologies including the Boeing 787 Dreamliner, Samsung Note 7, and Fitbit Flex 2 [11-13]. Many wearable electronics companies are looking for safer battery chemistries, but the cost and performance of those batteries must be competitive before they can challenge lithium-ion.

Alternative chemistries such as magnesium and aluminum-air batteries are compatible with aqueous electrolytes and have demonstrated higher energy densities than lithium, but they experience rapid self-discharge and poor charging efficiency [6]. Zinc and iron have proven to be stable and safe chemistries, especially zinc-air and zinc-silver oxide. Zinc-based batteries are inherently safer, inexpensive, and more abundant, especially in the U.S., compared to lithium [6]. More importantly, zinc batteries have a relatively high specific energy (1,218 Wh/kg) and volumetric energy density (6,136 Wh/L) [6]. Recently, a U.S. Naval Research Laboratory team developed a novel, rechargeable, nickel-3D zinc battery as an energy-dense, safer alternative to lithium-ion [14]. When a zinc battery undergoes charging, dendrites will form and eventually grow to short the battery [14]. By implementing a porous zinc structure, the formation of dendrites is mitigated while maintaining a high capacity of 216 Wh/L along with tens of thousands recharge cycles [14].

This zinc chemistry presents a safer and cheaper battery chemistry alternative to lithium-ion with an estimated cost of $160 per kWh, when average lithium-ion battery prices are not expected to reach that value until 2025 [6,14]. Because zinc is inherently safer and all components can be exposed to air, simpler and inexpensive fabrication methods can be implemented. The complexity of lithium-ion battery fabrication amounts to nearly 40 percent of its overall cost, but screen printing can reduce the fabrication cost [6]. Screen printing is a low-cost, high-throughput fabrication where conductive inks can be applied to a patterned stencil, then a doctor blade will deposit the conductive inks onto the substrate through the holes of the pattern. Zinc batteries can be printed in four to five simple coating steps and in any desired shape. The use of conductive inks and printing technologies allows for battery conformability, enabling them to stretch, bend, flex, and twist.

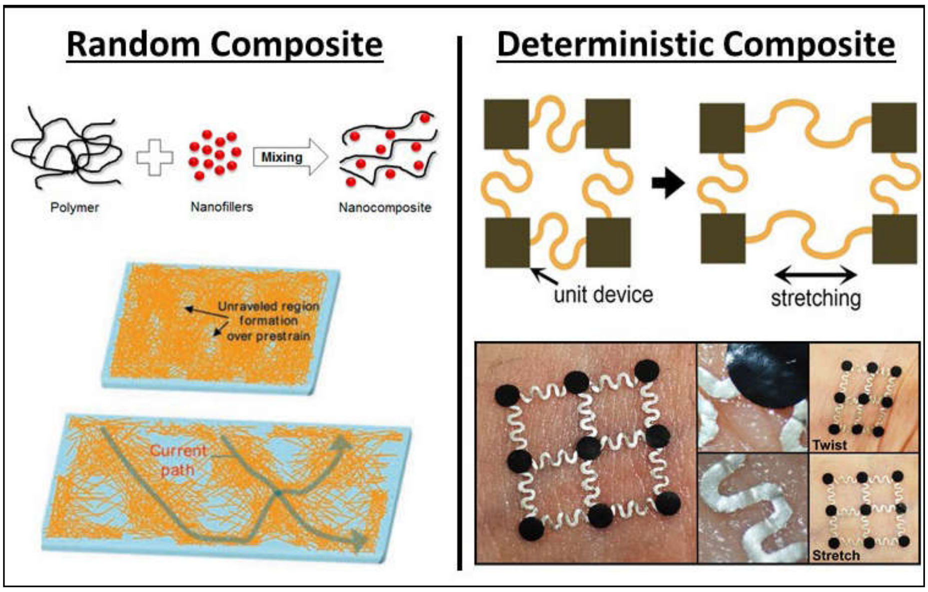

Figure 3: Approaches for engineering stretchable electronics [31] [32] (Licensed under Creative Commons) [33].

Conformal Battery Development

Deterministic and random composite architecture are two approaches used to develop

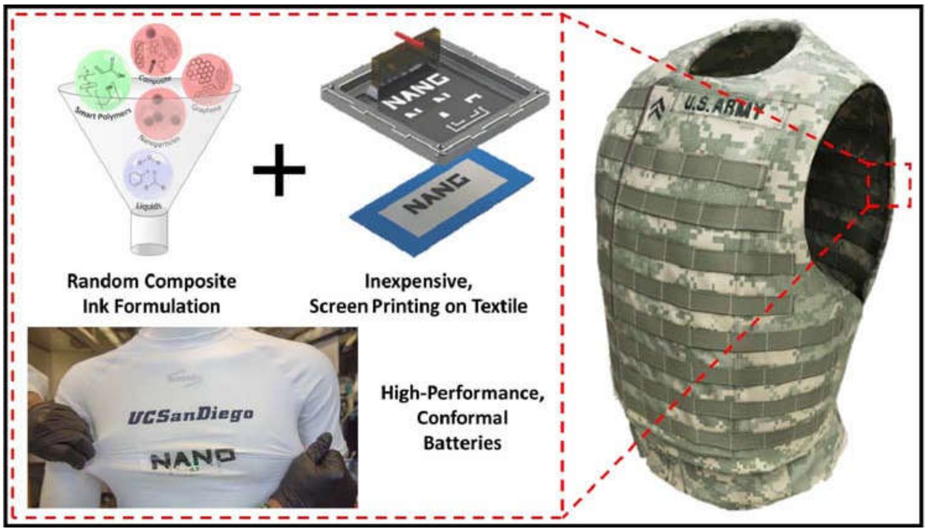

Figure 4: Random composite and screen-printing for high-performance, conformal batteries.

conformal batteries, as shown in Figure 3 [15]. In the deterministic approach, nonelastic, inorganic materials, such as metals are geometrically patterned into ultra-thin, serpentine bridges connected to rigid islands [15]. This method of strain engineering allows typically rigid materials to be more conformal by undergoing stretching and flexing. The random composite approach randomly embeds highly conductive fillers into an elastomeric matrix [15]. While random composite is highly strain-sensitive to any type of deformation, the ability to incorporate any combination of materials [15] is specifically attractive for developing conformal batteries that comprise various metallic and polymeric additives. The precise composition of conductive fillers, elastic binders, and solvents will result in formulations that can be readily applicable to inexpensive, printing technologies. This approach is compatible with air-stable, zinc-based chemistries that can be used to inexpensively print conformal batteries into a military vest.

Researchers at the University of California, San Diego Department of NanoEngineering have demonstrated the first fully-printed, stretchable, rechargeable battery using low-cost, screen printing of highly elastic, conductive inks [16]. Through the unique formulation of inks and screen printing, the batteries were printed in the form of “NANO” onto a polyurethane-coated spandex, as shown in Figure 4 [16]. The battery demonstrated a high, reversible areal capacity of ~2.5 mAh/cm^2 density even after multiple iterations of deformation including bending, twisting, indentations, and stretching twice its length [16]. Other approaches were attempted in order to produce stretchable batteries, but none of the systems were completely elastic [16] as traditional battery chemistries require encasement in a rigid protective shell. In addition, many of these approaches relied on lithographic, spray/dip coating, or “cut-and-paste” methods of fabrication that were extremely expensive and resulted in low-throughput [16].

While most applications do not require a significant amount of stretch (other than electronic textiles), flexibility is an essential form factor. For example, solar blankets in the SUP kit have ultra-thin solar cells that allow warfighters to either roll up or fold the blanket. Along with flexibility, the ability for batteries to recharge is another essential factor. Printable, zinc batteries are being developed but very few are rechargeable. Blue Spark Technologies Inc. developed a printed battery with a capacity less than <1 mAh/cm^2, and they combined printed batteries and temperature sensors for a disposable temperature monitor for newborns [17]. Imprint Energy Inc. developed the only printed zinc battery that is rechargeable because of an innovative ionic-liquid electrolyte. However, this battery has a poor capacity of <1.5 mAh/cm^2 over the course of 100 recharge cycles [18].

Printable Batteries

Researchers at the University of California, San Diego initially used printed batteries for small patches to power wearable electronics. However, screen printing can be utilized to coat the entire inner area of a military vest. A typical military vest for an average male torso covers a surface area of 0.6 m^2 [19]. The areal capacity of printed batteries will be greater than 3.5 mAh/cm^2 to achieve a capacity nearly three times the capacity of the current conformal battery (7.3 Ah) used by SWIPES. Since technology implemented by the military must be more durable than conventional consumer electronics, a higher number of charge cycles is essential. If these screen printed batteries can meet this durability requirement, they would provide a low-cost, conformal, high-performance battery solution for the dismounted warfighter.

The ability to accomplish an area capacity beyond 3.5 mAh/cm^2 and a cycle life beyond 200 cycles is possible using zinc-silver oxide chemistry implemented in the printed, stretchable battery. The initial proof-of-concept was designed for more stretchable textiles, such as spandex or nylon. For military application, flexibility with some stretch is needed to enable the printed battery to be worn inside the shell of a military vest. The random composite can control the composition of elastomer and conductive fillers, where some stretch (<20 percent) can be reformulated for the printed battery. The design of the printed battery was in a lateral design, whereas a typical battery stacks the anode, cathode, and electrolyte. The stacked design will be a far more efficient use of the printed area. The current limitation for the stacked design is a printable electrolyte that is both flexible and stretchable. A printable electrolyte will require structural durability and high ionic conductivity for high-current charge/discharging. Further improvement of anode, cathode, and electrolyte materials as well as inexpensive screen printing techniques will enhance the production of high-performance, conformal batteries.

The printed, conformal battery integrated into a tactical vest addresses the military’s vision to eliminate bulk cables using electronic textiles [5]. Ultra-thin, conductive wiring and a conformal battery can be printed into the textile to power various electronics in each designated pocket. The addition of printed, power transfer antenna in the back of the vest for wireless charging will simplify the top-down integration by enabling wireless charging by a vehicle. When a warfighter sits in a vehicle, wireless charging components embedded in the seat would seamlessly charge the printed power vest [5]. This presents a great tactical advantage in the event a warfighter must quickly abandon the vehicle.

The conformal, wearable battery will require durability and performance testing under actual environmental conditions and power expectations of a 72-hour mission. Factors such as varied temperature and humidity could affect battery performance, especially in a 24-hour cycle. Therefore, these environmental factors must be evaluated. Additionally, determining if the battery is washable, especially when exposed to detergents or harsh temperatures and deformations from a typical tumble dry, must also be evaluated.

This concept can be further applied to other devices in the SUP kit. For example, batteries can be printed on the opposite side of a solar blanket, which would allow for additional energy storage and eliminate the setup time for the solar blanket with a modular universal battery charger and battery. The military has been considering implementing energy harvesting technologies into the warfighter uniform, such as wearable solar panels on the helmet or rucksack [5]. Other small kinetic devices that oscillate back and forth for harvesting energy from walking have also gained significant investment from the military [20]. Numerous energy harvesting technologies such as thermoelectric, piezoelectric, biofuel cells, and triboelectric have been studied to self-power wearable electronics, and all of these energy harvesting technologies could provide trickle charge to extend the life of the printed, conformal battery [5].

Conclusion

The Department of Defense has been at the forefront of developing and supporting new battery chemistries to maintain its technological advantage on the ground. As reliance on wearable electronics continues to grow, so does the burden of these conformal power technologies on warfighter mental and physical stamina. Debate will continue on which materials and battery chemistry will prevail based on cost and performance, but the fabrication and conformability of batteries is equally critical to the success of warfighter wearable systems. Inexpensive printing technologies offer a solution that enables the combination of deterministic and random architectures for implementation of conformal batteries into a tactical vest. Merging printing technologies and advanced materials will lessen warfighter weight load and seamlessly power warfighter electronics, allowing warfighters to focus on their mission and not on battery replacement. ■

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