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# Epidermal Systems and Virtual Reality: Emerging Disruptive Technology for Military Applications

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**Abstract.** This review study, presented at the 2nd World Conference on Advanced Materials for Defense (AuxDefense 2020), focuses on skin as sensory interface and explores the latest discoveries in bioelectronic science. The work analyzes at what extent invisibility is possible by emulating nature, and if military applications can really benefit from technology that combines epidermal systems and virtual reality — and from next generation of wearable textile computing technologies.

## Introduction

Military camouflage is the use of camouflage by an armed force to protect personnel and equipment from observation by enemy forces. In practice, this means applying color and materials to military equipment of all kinds, including vehicles, ships, aircraft, gun positions and battledress, either to conceal it from observation (crypsis), or to make it appear as something else (mimicry). Camouflage and mimicry have a long-standing tradition in military applications and have been largely employed from the 19th century onwards [1] — during World War I the concept of visual deception developed into an essential part of modern military tactics.

In more recent times, it has been introduced a multi-scale camouflage that combines patterns at two or more scales, often (though not necessarily) with a digital camouflage pattern created with computer assistance. The function is to provide camouflage over a range of distances, or equivalently over a range of scales (scale-invariant camouflage), in the manner of fractals, so some approaches are called fractal camouflage [2]. An example is presented in Figure 1. Not all multiscale patterns are composed of rectangular pixels, even if they were designed using a computer. Further, not all pixelated patterns work at different scales, so being pixelated or digital does not of itself guarantee improved performance.

**Fig. 1.** Netherlands fractal pattern camouflage. Photo by Sjoerd Hilckmann, Defence Media Center (2019).

## Adaptive Camouflage

The human skin is the largest sensory organ; is a relatively underexplored sensory interface that could significantly enhance experiences. A series of case studies has explored the opportunities for slim and adherent "second skin" that incorporates circuitry [3]. The patchwork in Figure 2 provides a sample galley of these late discoveries.

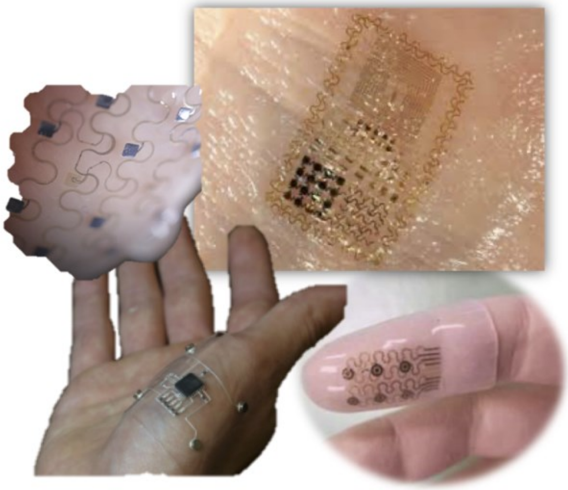

**Fig. 2.** Bio-integrated electronics: silicon nanomembranes and soft-skin-like-electronics.

Recent neuroscience research on advanced methodologies and engineering systems that are capable of interrogating and stimulating neural pathways — from single cells in small networks to interconnections that span the entire brain — suggests a huge potential in the relatively near future, with a primary focus on device technologies that address associated opportunities in electrical, optical and microfluidic neural interfaces [4]. Progress in three-dimensional (3D) functional systems with sizes in the micro and nanometer regime are of growing importance across a wide range of electrical, optical, and biological contexts, inter alia in constructing functional 3D structures and/or devices [5]. Flexible 3D electronic scaffolds with precisely defined dimensions and microelectrode configurations, aimed at achieving an enhanced level of control and regulation of functions relatively to that of other approaches, can be used to monitor and control functions through electrical stimulation and therefore provide opportunities in many fields [6], as illustrated in Figure 3.

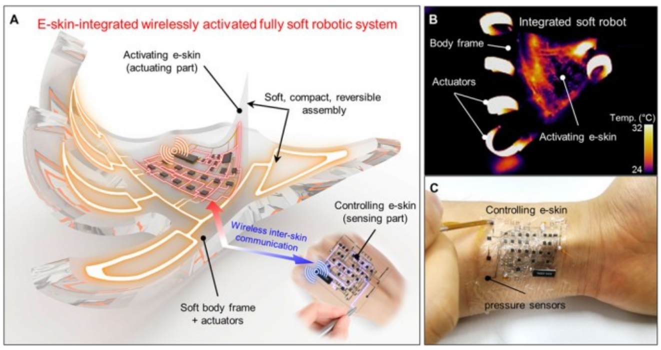


**Fig. 3.** Skin-like soft driving system for wirelessly activated fully soft robots [7].

The transfer printing method to form multiple structures of stretchable and flexible bioelectronic devices based on crystalline silicon carbide (SiC) can integrate sensing materials onto flexible substrates; material covered by this technique is not only limited to inorganic semiconductors, but also includes carbon-based materials (e.g., graphene) and organic semiconductors [8].

The research has made progress in the field of silicon field-effect transistors which, combined with other functional materials to create hybrid structures for enhanced sensing performance, are suitable for bio-integration across a variety of use cases [9].

Electronics with transient characteristics that "disappear without a trace" are suitable for triggered transient devices with active operation [10]. Transient electronics represents a class of technology defined by components that physically or chemically disintegrate, dissolve, or otherwise disappear in a controlled manner for application opportunities that lie outside of those that can be addressed with conventional, permanent devices. Progress relies on the development of advanced materials for this purpose and on a detailed understanding of the mechanisms by which they respond to various physicochemical stimuli, such as changes in temperature, exposure to water, illumination with light.

The research focuses on the fundamental and applied aspects of silicon nanomembranes, ranging from synthesis and manipulation to manufacturing, device integration and system level applications, including uses in bio-integrated electronics, three-dimensional integrated photonics, solar cells, and transient electronics [11]. Although it is complex to mimic key skin features using existing tactile sensors, the researchers have developed electronic artificial skin (e-skin) that reacts just like a real one [12].

E-skin can be augmented with capabilities beyond those of the normal human skin by incorporating advanced bioelectronics materials and devices, building this way a flexible and fully perspiration-powered integrated electronic skin (PPES) [13]. Figure 4 & 5 provide examples of these applications. A late research on peripheral nervous system however warned about the devices' susceptibility to electromagnetic interference from any sources and the hypersensitivity of users [14].

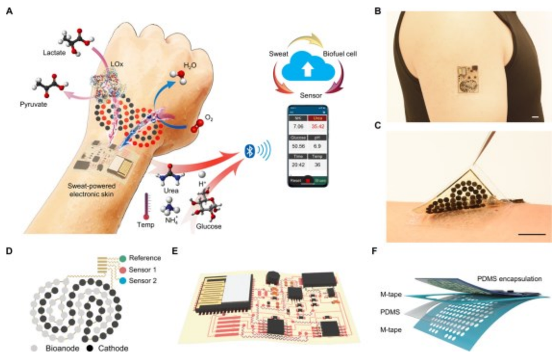

**Fig. 4.** Perspiration-powered soft electronic skin (e-skin) for multiplexed wireless sensing [13].

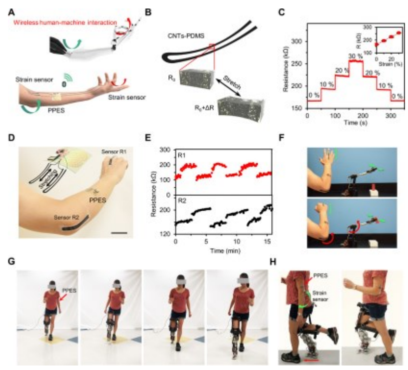

**Fig. 5.** On-body evaluation of the PPES as a wireless human-machine interface for robotic electronic [13].

**Fig. 6.** Learning from Nature, the master of disguise.

The research brought to light the connections between areas such as ecology, evolution, visual deception and warfare, thus highlighting that animal and military camouflage share many similar design principles [15, 16], as you can infere from Figure 6. We are on the road to creating materials that render things almost invisible.

Material scientists have developed a colour-changing sheet inspired by squid and octopus whose skin can transform to blend with its surroundings [17]. The basic idea, illustrated in Figure 7 & 8, is that the creatures use light-sensitive molecules in the skin to register the light coming from the background against which they sit, and then use this information to alter the appearance of colour-changing cells. Octopus skin can in fact do more than match a background's colour — it can even mimic its texture.

Military counter-illumination camouflage was first investigated during World War II for marine use. More recent research has aimed to achieve crypsis by using cameras to sense the visible background, and by controlling Peltier panels or coatings that can vary their appearance.

To make the adaptive displays, the researchers began by imprinting a 16x16 grid of cells on a soft plastic. The cells, each about a millimetre across, contain a colour-changing dye embedded in a polymer. The dye is black at room temperature, but when warmed to around 47 °C (117 °F) its chemical structure changes and it becomes transparent. Cool it, and it becomes black again. At the corners of each cell the researchers added tiny light sensors that record how much light falls on the cell, and this signal is used to control an electric current that helps warm up the dye. Shine a light on the material, and the black dye will turn transparent and expose a reflective silvery material beneath. The result is similar, at a crude level, to the way that octopus skin works.

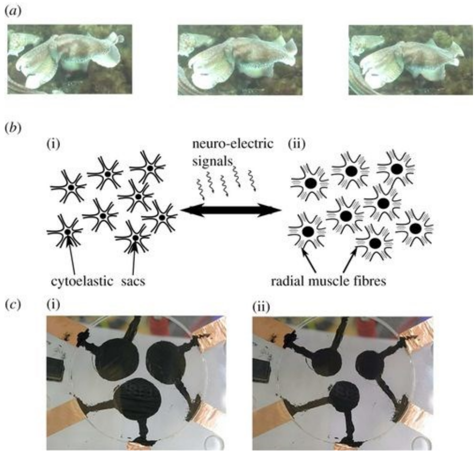


**Fig. 7.** Hiding the squid: patterns in artificial cephalopod skin [18].

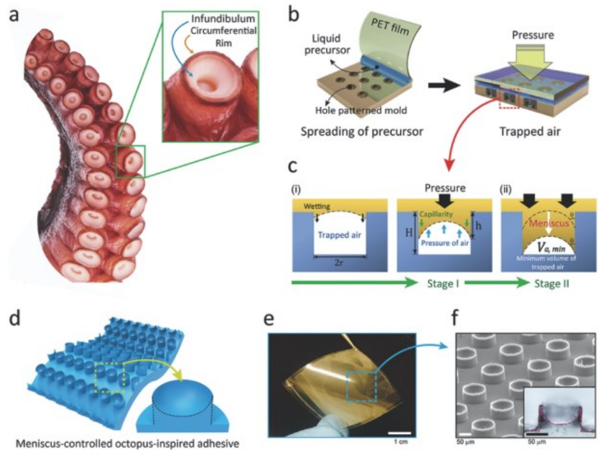


**Fig. 8.** Highly Adaptable and Biocompatible Octopus-Like Adhesive Patches with Meniscus-Controlled Unfoldable 3D Microtips [19].

Active camouflage or adaptive camouflage is camouflage that adapts, often rapidly, to the surroundings of an object such as an animal or military vehicle [20]. It provides concealment by making an object not merely generally similar to its surroundings, but effectively invisible with "illusory transparency" through accurate mimicry, and by changing the appearance of the object as changes occur in its background. In theory, active camouflage could provide perfect concealment from visual detection. It's something different from what is known as "dazzle" or "motion camouflage" that mimicks the optic flow of the background, and which has proved to have a limited effectiveness [21].

This seminal research on adaptive camouflage was supported by the US Office of Naval Research (ONR) Warfighter Protection and Applications Division, which saw potential military applications of this work [22]. The program, carried out by ONR Division 342, aims to discover biologically-inspired adaptations and bioengineered solutions to expand current warfighter capabilities in detection mitigation and undersea navigational challenges. This will be accomplished through multidisciplinary research in science and technology fields such as bio-inspired/biomimetic materials, visual and sensory perception, and bio-optics/bioelectronics. Basic research to understand bio-inspired adaptive camouflage include texture and shape modulation, colour adaptation, signature concealment and mechanisms for tunable regulation of multi-functional materials.

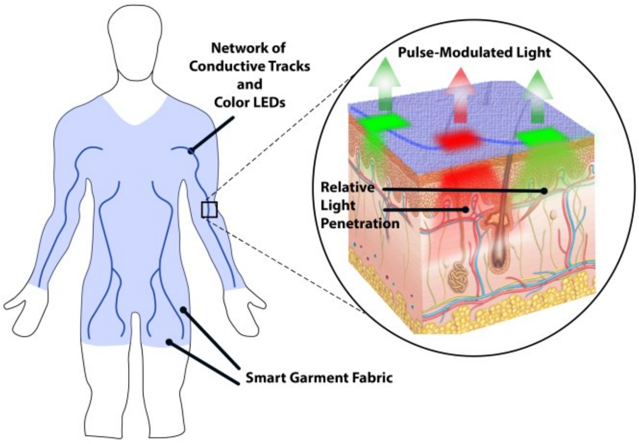


**Fig. 9.** Illustration of the experimental smart garment with conductive tracks and light emitting diodes (LEDs) facing the tissue surface [23].

Active camouflage may now develop using Organic Light Emitting Diodes (OLEDs) and other technologies which allow for images to be projected onto irregularly shaped surfaces. An example is shown in Figure 9. Using visual data from a camera, an object could perhaps be camouflaged well enough to avoid detection by the human eye and optical sensors when stationary. Camouflage is weakened by motion, but active camouflage could still make moving targets more difficult to see. However, active camouflage works best in one direction at a time, requiring knowledge of the relative positions of the observer and the concealed object.

If the researchers can master the art of copying colours instead of working in black and white, they might be in reach of a single fabric that achieves a genuine kind of invisibility by exactly replicating the appearance of its surroundings in any environment, the material that the military has always wanted. A fabric coated with miniaturised Light Emitting Diodes (LEDs) and cameras that, by projecting the appropriate background image in all directions, could confer genuine invisibility.

**Epidermal Virtual Reality**

One step beyond is the development of a new thin, wireless and battery-free system that adds a sense of touch to any virtual reality (VR) experience [24]. It is a platform of electronic systems and haptic (that is, touch-based) interfaces capable of softly laminating onto the curved surfaces of the skin to communicate information via spatio-temporally programmable patterns of localized mechanical vibrations – the apparatus communicates through near-field communication (NFC) protocols. Referred to as an "epidermal VR" system, this equipment communicates touch through a fast, programmable array of individually programmable, millimeter-scale actuators, fused in an advanced architecture designed as a skin-interfaced wearable scalable device. Miniaturized actuators generate a discrete sense of touch at a corresponding location on the skin, with almost no encumbrances on the user. Figure 10, 11 & 12 illustrate the epidermal VR system developed at Northwestern University by the Rogers Research Group.

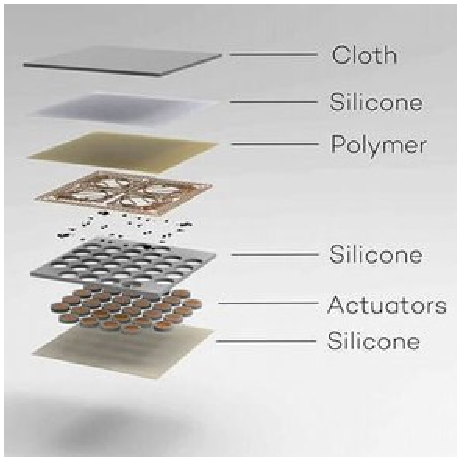


**Fig. 10 & 11**. Epidermal VR patch simulates touch. Functional components are integrated into a thin elastomeric layer with a thickness of only 3 mm. A total of 32 haptic actuators are controlled in 4 groups, by 8 independently controllable communication ports in the device (Querrey Simpson Institute for Bioelectronics).

Each actuator — currently they have diameters of 18 millimeters and thicknesses of 2.5 millimeters — embedded into a thin, soft, flexible and slightly tacky silicone polymer that adheres to the skin without tape or straps, resonates most strongly at 200 cycles per second, where the skin exhibits maximum sensitivity. The frequency and amplitude of each actuator can be adjusted quickly and on-the-fly through a graphical user interface, to maximize the sensory perception of the vibratory force delivered to the skin. The patch wirelessly connects to a touchscreen interface (on a smartphone or tablet). When a user touches the touchscreen, that pattern of touch transmits to the patch — the devices produce a sensory pattern, simultaneously and in real-time, through the vibratory interface to the skin.

This emerging disruptive technology, that creates many opportunities for use where the skin provides an electronically programmable communication and sensory input channel to the body, could be combined with a VR headset to create more interactive and immersive experiences. Eventually, the devices could be thin and flexible enough to be woven into clothes. And along with VR headsets, people could wear suits to become fully immersed into VR, a very important emerging area of technology.

**Fig. 12.** VR touch (Querrey Simpson Institute for Bioelectronics, 2019).

The result is a thin, lightweight system that can be worn and used without constraint, indefinitely. This kind of technology is suitable to have several military applications. It's a step ahead of the skinput technology that was developed in 2010 by Harrison, Tan and Morris at Microsoft Research [25, 26] and pictured in Figure 13.

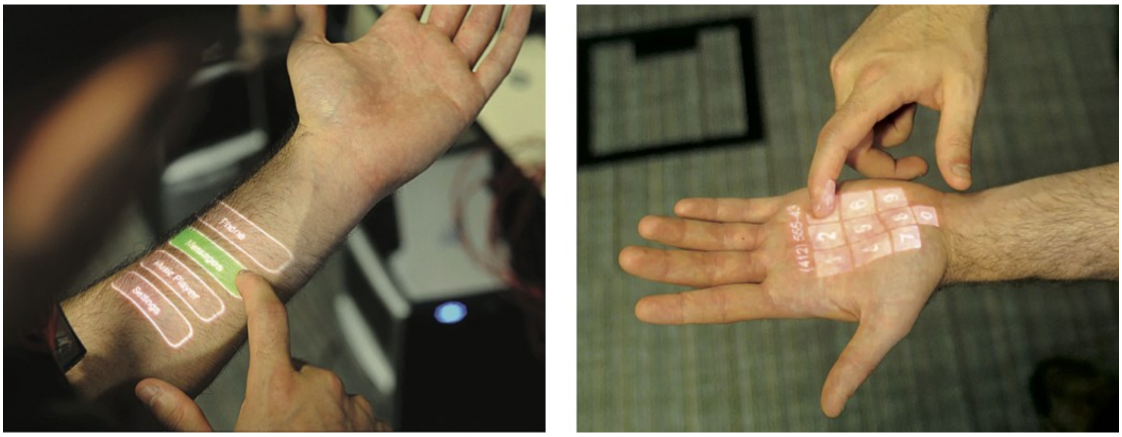

**Fig. 13.** Skinput technology turns your arm into a touchscreen [25, 26].

Skinput is a technology that appropriates the skin as an input surface by analyzing mechanical vibrations that propagate through the body. Specifically, we resolve the location of finger taps on the arm and hand using a novel sensor array, worn as an armband. This approach provides an onbody finger input system that is always available, naturally portable, and minimally invasive. When coupled with a pico-projector, a fully interactive graphical interface can be rendered directly on the body.

## Perspectives

The next generation of wearable technologies – textile computing technologies that can sense and react to the human body – is designed to enhance the experience of the users to provide a fully integrated human-computer interaction through digitization of human biodata, activities, behaviors and relationships. This way, textiles turn into bidirectional interfaces for human-computer interaction.

The industry (Myant Inc.) is developing a full-body interface with the human nervous system through the skin, implemented through textile, that grants the ability to capture different biometric data types and react via thermal, electrical, and haptic stimuli. Military applications are listed among the possible applications of this textile-based full-body interface. Now, we can easily imagine the future soldier (Figure 14).

**Fig. 14.** Bioengineered soldier (The Sociable, 12 Mar. 2020).

## Conclusions

This study shows that, to be effective, camouflage needs to match the environment and to be disruptive. A combination of technologies such as adaptive and epidermal VR and textiles, connected to the body through the skin, will provide a bidirectional and full-body interface for human-computer interaction and can be a on the edge technology that might find effective military applications.

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