NANOTUBES APPLICATION IN MILITARY DOMAIN

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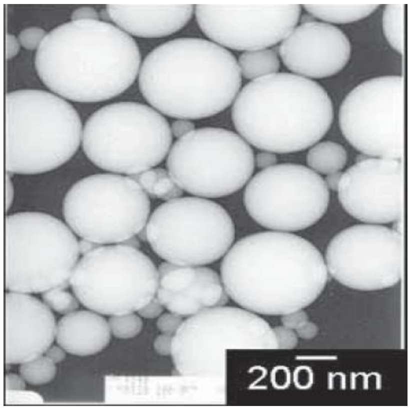
Abstract:*Nanotubes should enhance body-armor stealth and strength. This proposed research direction extrapolates applied and theoretical findings. We present a review of nanoenhanced materials, our experimental analysis of body-armor performance, and a proposed adaptive camouflage that support the informed extrapolation. Researchers have demonstrated that nanotube additives strengthen fibers and toughen ceramics and so can help body armor resist ballistic impacts. Researchers have also demonstrated that nanoparticle-treated fabric armor can adapt to stimuli and can reduce physiological costs of wearing armor.*

Nanotubes can reduce physiological costs such as bruising because strengthened materials can reduce body-armor deformation. Nanoparticle-enhanced armor stiffens on impact to reduce deformation and so should reduce or eliminate the bruising effect of bullets that deform soft body armor. The enhanced materials may further reduce heat exhaustion because they can decrease body-armor stiffness, thickness, and weight as well as increase body-armor heat-carrying capacity.

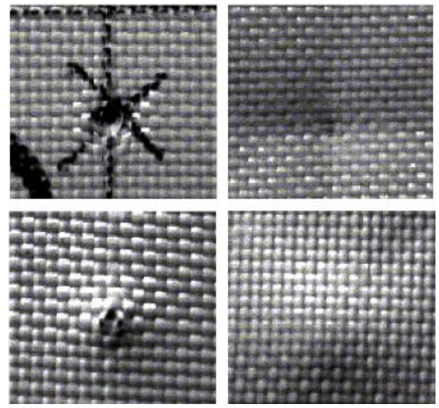
We modeled body-armor bruising effects to study a physiological cost of wearing armor. Field experiments measured body-armor performance with a bruise profile. We modeled the bruising effect of nonpenetrating bullet impacts with statistical and fuzzy methods. The analysis techniques can also model the bruising effects of nano-enhanced body armor. Nanotube electronics should adapt camouflage patterns to disguise armor. A proposed adaptive camouflage uses nanotubes and nanoparticles to help conceal armor. The proposed camouflage uses octopus-model artificial color organs to display changing camouflage patterns and uses nanotube sensors and processors to coordinate the displayed patterns.

1. NANOMATERIALS CAN ENHANCE BODY-ARMOR STRENGTH AND ABAPTABILITY

Nanotubes and nanoparticles can strengthen armor materials and make adaptive and programmable armor materials. Nanotubes can strengthen polymer fibers and ceramic composites in body armor whereas nanoparticles can help make armor fabric more flexible until external stimuli causes the armor to stiffen. Body armor materials include textiles, fiber composites, ceramic composites, and metal. Military flak jackets are a compromise between mobility and protection and can consist of camouflaged flexible Kevlar fabrics that cover the torso and composite or metal-plate inserts that reinforce key areas. Mobility is important because it makes the armor user harder to target. The flexible fabrics allow more mobility but do not stop rifle bullets. The metal or composite plates stop rifle bullets but are heavy so protect only parts of the torso. The flak jackets optimize ballistic protection by covering the torso and shoulders with flexible fabric and reinforcing the front and back with ceramic or metal plates. Flak jackets optimize mobility by exposing the limbs and joints. The joints are unprotected to retain mobility because thick fabric armor can be stiff and resists bending. An effective camouflage should enhance armor stealth and further improve armor performance.



a. **Nanoparticles**



b. Ballistic materials (left – normal material, right – strengthen material with nanotubes)

c. Traditional Kevlar

d. Kevlar made by special materiel

Fig. 1 – Smart models used to fabricate ballistic protection equipment

Alumina ceramic-composite armor can be harder than bullets and can often fracture a bullet on impact without deforming. But ceramics are inflexible and heavy and inhibit movement and heat dissipation. Thin and flexible armor give the armor user more mobility and reduce physiological costs such as heat exhaustion. Nanotube additives strengthen ceramics and polymers. The strengthened materials can make armor thinner and lighter and so reduce physiological costs.

2. A NATURAL MODEL OF ADAPTIVE CAMOUFLAGE

Nanotubes can coordinate octopus-model artificial color organs to disguise body armor. The proposed adaptive camouflage models an octopus that changes skin patterns to avoid detection. The adaptive camouflage can match a background by using nanotube signal processing to change displayed patterns. Nanotube optical sensors can sample a background image. Nanotube processors can quickly select a preset pattern or compose a custom pattern that optimally matches a background. Nanotubes can interconnect the sensors, processors, and color organ by applying embedded wired connection in a flexible substrate or by applying wireless connection in a distributed network. This section reviews how *Octopus vulgaris* and other cephalopods camouflage or disguise their bodies and proposes an octopus-model adaptive camouflage that uses nanotubes and nanoparticles.

An octopus can abruptly change its appearance or mimic other animals by changing its color, texture, posture, and locomotion. The octopus responds to visual input and selects an appropriate body pattern from a small set of patterns that are "hardwired" into the central nervous system. The preset patterns either help the animal match its background or break up the outline of its body. Researchers have further documented nine octopus specimens that mimic poisonous animals (see Figure 2). These octopuses use posture and locomotion to mimic swimming fish and sea snake both in appearance and in motion. The octopus camouflage changes whole body patterns to either blend in with the background by matching the color, brightness, and texture or break up the body outline by displaying disruptive patterns. A whole body pattern consists of organized collections of skin patches or units.

Individual skin patches have chromatophores and iridophores that display different colors, leucophores that adjust brightness, and papillae musculature that changes skin texture. The chromatophores and the iridophores occur across the whole skin patch. The leucophores occur only in the central region of the patch and beneath the chromatophores and the iridophores. A skin papilla occurs exactly at the center of a patch. It contracts to stretch the patch into a spike.

The octopus camouflage is an orchestration between chromatophores, iridophores, leucophores and skin muscles. *Octopus vulgaris* has up to 230 chromatophores per square millimeter of skin and devotes millions of neurons to control them. Chromatophore motoneurons send pulses to expand specific sets of chromatophores in the skin. Banks of chromatophore motoneurons act in concert to produce the bars, bands, and lines in *Octopus vulgaris* skin. An octopus selects a stipple, mottle, or disruptive pattern if it sees discontinuities. The octopuses match the background brightness by manipulating the chromatophores and the leucophores. Relaxing the dark-colored chromatophores reduces their size and uncovers the underlying leucophores that reflect the surrounding light and help match both the color and brightness of a low-light background (see Figure 3).

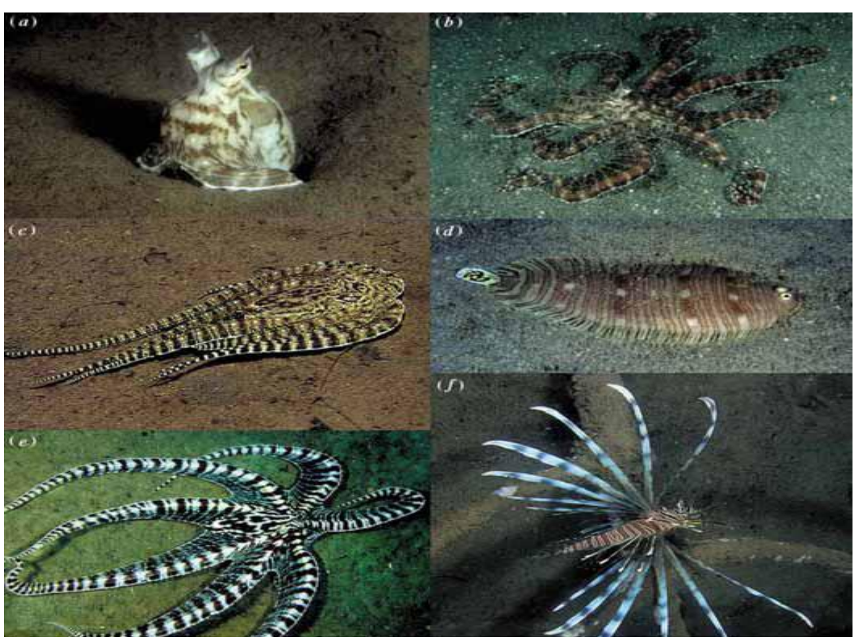
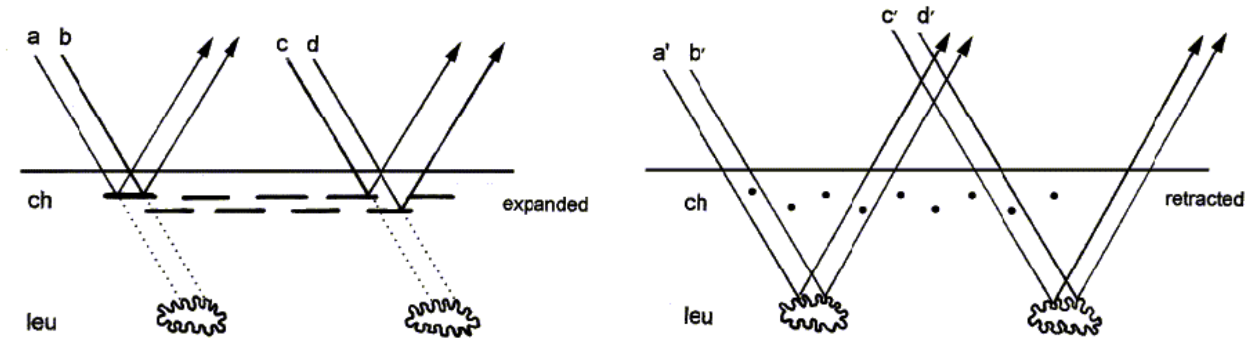


Figure 2: Mimic octopus: (a) sentinel state in mouth of burrow; (b) normal foraging color pattern; (c) flatfish mimicry; (d) flatfish model, banded sole; (e) lionfish mimicry; (f) lion-fish model.



(a) Bright Background (b) Low-light Background

Figure 3: Schematics of background matching with chromatophores (ch) and Leucophores (leu). (a) The chromatophores contract their muscle fibers and expand to absorb light and let their pigment color show for well-lit backgrounds. (b) The chromatophores relax and reduce their size for low-light backgrounds. This uncovers the leucophores that reflect the background light.

3. A PROPOSED ADAPTIVE CAMOUFLAGE MODEL

A proposed adaptive camouflage can help conceal armor by modeling octopuses to match camouflage patterns to backgrounds. The proposed architecture loosely follows the schematic in Figure 3. Artificial color organs can display programmable patterns. Nanotube detectors and processors can select a camouflage pattern that optimally matches a background. A prototype adaptive camouflage may use available components. Researchers have developed a color-change gel in Figure 4 (a) that models octopus chromatophore organs. Commercial cadmium selenide (CdSe) semiconductor quantum dots or q-dots in Figure 4 (c) can be superior pigments in artificial chromatophores. Retro-reflective materials in Figure 4 (d) can be efficient artificial leucophores. Nanotube-based actuators can implement artificial papillae that alter surface textures. Programmable MR-treated fabrics can help an armor user maintain a posture to remain hidden. The MR-treated armor can programmably stiffen to support joints and so can help with posture.

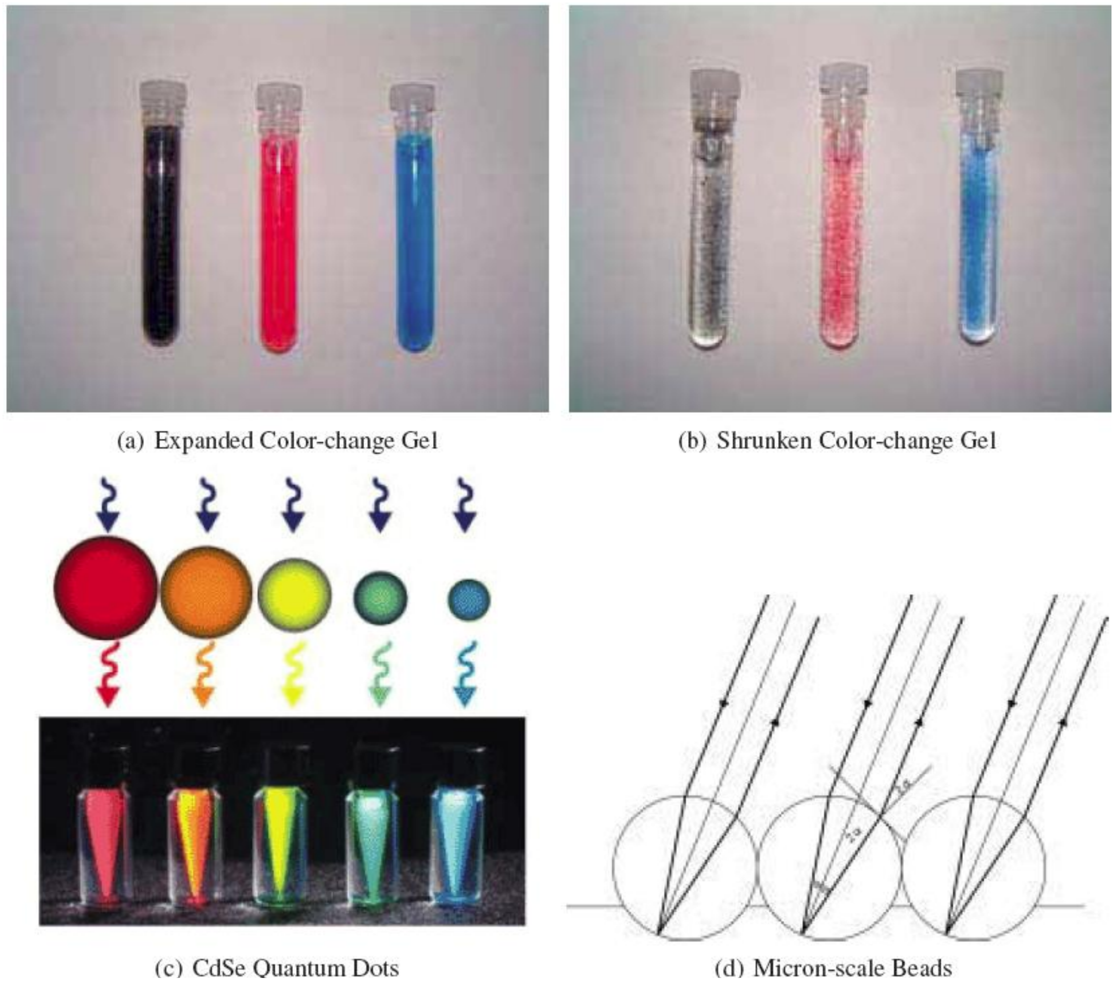


Figure 4: Micro and nano scale materials for adaptive camouflage. (a) and (b) - Dispersions of color change gel particles that contain black, magenta and blue dye. (a) Expanded state at 20^0C. (b) Shrunken state at 40^0C. (c) Vials of nano scale quantum dots under UV illumination. The colored spheres illustrate the relative sizes of the CdSe quantum dots in the vials. (d) Micron scale beads converts a reflective surface into a retro-reflective surface: Light reflects back toward the source.

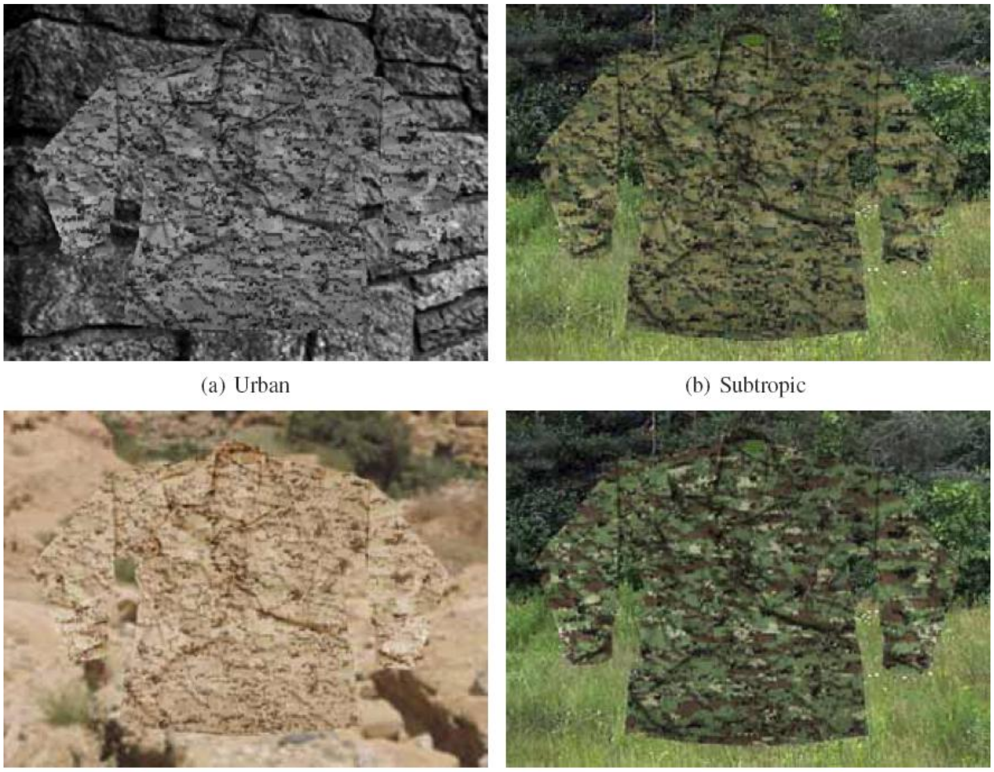
Nanotube signal processing should further help disguise armor by approximating invisibility. Researchers have demonstrated an “optical camouflage” that approximates invisibility by duplicating the background image. The adaptive camouflage should approximate invisibility by simulating a transmissive medium at the pixel level. Nanotubes and nanoparticles can model an artificial chromatophore organ or chromatomotor that consists of photoemitters, reflecter/scatterers, and photoabsorbers. Stimuli-responsive polymer particles can combine with mature products such as CdSe q-dots and retro-reflective beads and prisms to produce prototype chromatomotors. A 20–60 μm diameter particle of N-isopropylacrylamide (NIPAM) polymer shrinks by a factor of ten for heating that increases the temperature to 34 ^{0}C from room temperature. Particles smaller than 20 μm in diameter absorb light poorly so the shrunken particles show little color.

Figure 5: Matching background brightness and color improves camouflage. The center soldier appears brighter than the surroundings. The fourth soldier on the right appears darker than the immediate surroundings. This shows that brightness-matching and color-matching improves camouflage effectiveness.

Commercial CdSe q-dots should improve the pigments in because q-dots are more stable than most dye and offer many more color choices. A 50 μm diameter bead rests on a reflective surface and reflects an incident light back to its source with high reflective efficiency. Commercial retro-reflective beads should improve the leucophores. *Octopus vulgaris* chromatophores measure 300 μm in diameter (see Figure 3 (a)) so an artificial chromatophore of a similar size would use tens of NIPAM particles and reflective beads.

One possible architecture resembles a modified liquid-crystal display (LCD) (see Figure 3 (b)): The expanded polymer particles display color from the q-dots and cover the retro-reflective beads in each artificial chromatomotor pixel. Other possible architectures can use electromechanical switches to cover and uncover the q-dots and the reflectors or use switchable reflective substrates. The artificial chromatophores can incorporate a light source to conceal an armor user in backlit conditions or when the armor user appears darker than the background (see Figure 5). An ultraviolet emitter can stimulate a cluster of artificial chromatophores and cause their q-dots to emit light in low-light conditions. Nanotube field emitters can generate ultraviolet light with an electron beam. Effective camouflage requires only a fixed set of patterns that can match most backgrounds as the octopuses demonstrate. A central control architecture models the optic-lobe controlled camouflage in an octopus that selects an optimal pattern based on visual information. A camouflage pattern can be hardwired for designed patterns (Figure 6) and can also be adapted for new or changing patterns. An adaptive camouflage can take a snapshot of its surroundings, compare the image sample with stored patterns, and select the best hardwired pattern using little computation.

Nanotube photodetectors can be compact and sensitive and fit in ultra-dense arrays. All-nanotube architecture for signal processing and interconnection can operate at high speeds. This nanotube signal processing can process the visual information, assemble a combination of fixed patterns, and control an array of photoemitters such as the artificial chromatomotors. Pure singlewall nanotube fibers have strength and conductivity that suggest super-strong and conductive fabrics that can be part of the armor and can connect the detector array to the signal processing integrated circuits. The nanotube sensors and circuits can also integrate on a flexible conductive polymer substrate that covers the armor.

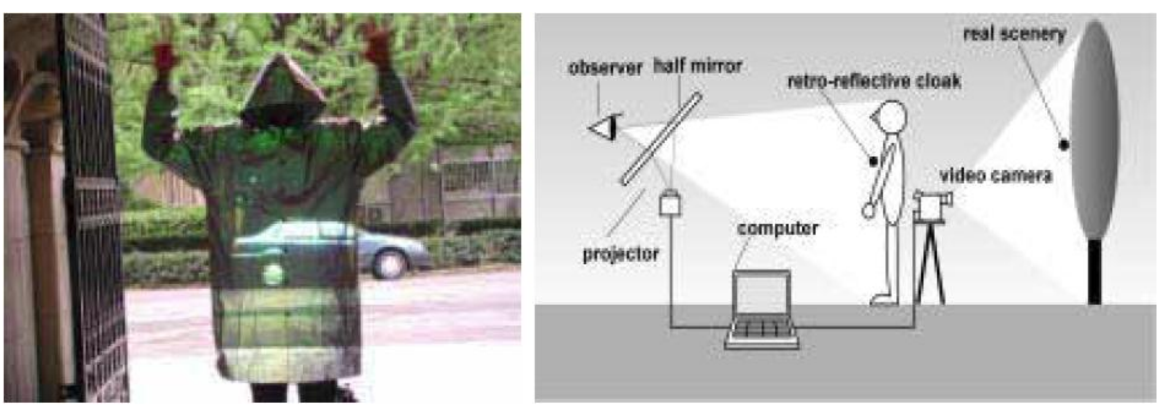


(a) Urban (b) Subtropic

(c) Desert (d) Woodland

Figure 6: Designed camouflage patterns. The designer developed these camouflage patterns using proprietary graphics techniques known as Camouflage Designated Enhanced Fractal Geometry.

Adaptive camouflage can approximate invisibility if it precisely duplicates the background. A so-called “optical camouflage” duplicates the background perfectly but only from certain viewing positions (see Figure 7). True invisibility requires duplicating almost all incident light as if the light passed through air. Nanotube signal processing may approach invisibility at the pixel level: A high-resolution wide-area array of photodetectors samples the incident light. A similarly distributed array of photoemitters displays the sampled image. A central or distributed signal processor extracts the frequency, phase, amplitude, and angle of arrival from the sampled image and computes the weights for each emitter to duplicate the optical field for almost all viewing positions. This should resemble a holographic display.



(a) Optical Camouflage (b) Video Projection

Figure 7: Video projection produces near invisibility. A camera behind the person records the background for projection onto the person’s cloak. The cloak has a coating of retro-reflective material.

Nanotube high-speed computation may perform the image and array signal processing in real time with a reduced resolution. Nanotube interconnection, switches, sensors, and emitters can enable compact and low-power designs. Single-electron transistor-based artificial molecules can improve on the octopus model. True hologram-like invisibility may be possible with large arrays of nanoscale photodetectors, emitters, and distributed signal processors. The artificial molecules can emit light using the same principle as the semiconductor quantum dots: excited electrons emit photons with energy equal to or greater than the semiconductor bandgap to return to its ground state. Each semiconductor nanoscale dot has an electronic density of states with a size-dependent bandgap. So a SET-based artificial molecule can tune its emission frequency because it can alter the electronic density of states by adding single electrons.

CONCLUSIONS

Nanotubes can enhance body-armor stealth and strength. We proposed a research direction for adaptive camouflage based on applied and theoretical analysis. We reviewed nanotube-enhanced armor materials and nanoparticle-enhanced body armor.

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