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# Proceedings of a Workshop

IN BRIEF

January 2020

# Bio-Inspired Signature Management for the U.S. Army

## Proceedings of a Workshop—in Brief

The National Academies of Sciences, Engineering, and Medicine convened a workshop of subject-matter experts on September 16, 2019, to gather information that will improve understanding of the science and technology (S&T) issues and opportunities in signature management for future U.S. Army missions. This workshop was part of a series of S&T activities under the National Academies Board on Army Research and Development (BOARD). The workshop was co-chaired by Andrew Alleyne, University of Illinois, Urbana-Champaign, and Michael Bear, BAE Systems. Alleyne opened the proceedings by welcoming the attendees, including Thomas Russell, Deputy Assistant Secretary of the Army for Research and Technology and BOARD sponsor.

After the introductions, Alleyne explained the main themes of this meeting: learning how biological systems effectively manage signatures across multiple domains of perception; how that knowledge can be used to improve the abilities of some humans to minimize their being seen and maximize the detectability of others trying to avoid being seen ("seen" to be read broadly, not just the visible spectrum); what technical knowledge gaps exist in achieving the desired capabilities; and how S&T can be used to fill those gaps. He noted that ideas to address all gaps would be unlikely for a one-day meeting, but a successful outcome would be to identify clear paths that illuminate knowledge of how biological systems sense prey and mask their signatures, of promising S&T avenues to pursue, of improving information sharing (e.g., a reference library), and of seeding a community of scholars to pursue these ideas further.

After offering some concepts to keep in mind, such as reducing signatures in both static and dynamic regimes and working across multiple spectra (infrared [IR] as well as visual), which consisted of subject-oriented panel presentations followed by focused discussion sessions. The three panels and first two discussions were led by individual workshop participants. The final discussion session was led by the co-chairs and focused on a summary of participant views on gaps, potential actions to reduce them, and promising areas for exploration with research and development (R&D).

### PANEL 1: CEPHALOPOD-INSPIRED DYNAMIC MATERIALS AND ANIMAL CAMOUFLAGE

Roger Hanlon, Woods Hole Marine Biological Laboratory, moderated the first panel and introduced the first speaker, Alon Gorodetsky, University of California, Irvine, to discuss dynamic materials inspired by cephalopods (e.g., octopus or squid). After some historical and science-fiction backdrops and colorful examples of camouflage in nature, Gorodetsky described research on the innervated skin of the longfin inshore squid (specifically, on the under-epidermis chromatophores and iridophores, which discussion revealed can change properties in fractions of a second to a few seconds [both elements were addressed

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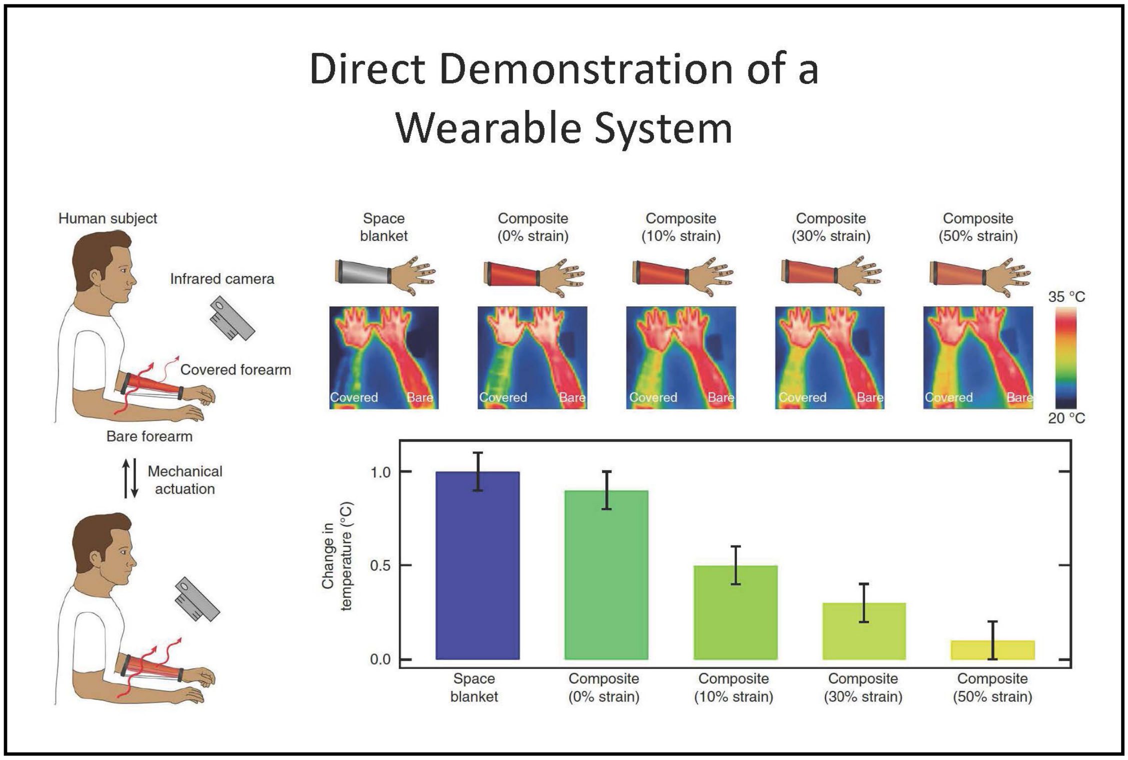


**FIGURE 1** Direct demonstration of a wearable system. SOURCE: Alon Gorodetsky, University of California, Irvine presentation to the workshop; from Leung et al., A dynamic thermoregulatory material inspired by squid skin, *Nature Communications* 10:1497, 2019.

in detail later by speaker Leila Deravi]). He then illustrated how understanding biological capabilities could inspire the engineering of dynamic materials for human camouflage applications, such as reconfigurable IR camouflage coatings and IR invisibility covering. He pointed to the possibility of adaptive thermal IR camouflage. Moving through more technical discussions of bio-inspired design strategies, Gorodetsky illustrated potential thermo-comfort and thermo-regulatory materials, along with the fabrication and technical characterization of such material, all of which could lead to a potential application in personal thermal signature management. He also showed comparisons of temperature-change using these materials as part of a wearable system (on the forearm, in this case) under various levels of strain, as shown in Figure 1.

Hanlon next introduced Innes Cuthill, University of Bristol, to discuss animal camouflage in the context of "evolutionary biology meeting visionary science." Cuthill relied on numerous visuals to convey important information about animal camouflage and which species have adapted over time to help conceal themselves from predators or prey. He presented two key technical principles to bear in mind when studying camouflage: the need to minimize signal-to-noise ratio and to filter signatures in species-specific ways. Cuthill discussed ways to study camouflage, for example, by showing how a predator's coat color and patterns can blend into various surroundings and allow it to be hidden from prey. He emphasized in various ways the principle of minimizing signal-to-noise ratio and discussed approaches such as hiding in noisy backgrounds, looking like the backgrounds, changing shape cues, and avoiding targeting in a group. Cuthill noted that motion breaks camouflage but can confuse targeting, especially with dynamic dazzle (also addressed later by speaker Martin Stevens). Cuthill closed with illustrations of the differences and similarities between biology and technology. He noted, for example, that while sensors and materials are often different, technology is often inspired by biology, and commonalities such as multi-function patterns abound (i.e., a pattern that camouflages at a distance may serve as a warning up close). One participant noted that it was interesting that Cuthill's illustrations showed more similarities than differences between biology and technology.

## WORKING DISCUSSION 1: MATERIALS AND STRUCTURES

Paul Schomber, Defense Intelligence Agency, led the workshop participants in a working discussion on a range of topics related to bio-inspired materials and structures, including, for example, polarization,[1] reflectivity, and multi-spectral functionality. Concerning studies of properties of materials, Cuthill observed that spectral matching is not usually what goes on in nature because that is not what counts in terms of detectability. Gorodetsky indicated that nature is never static; hence biological systems that are always changing can have an advantage, at least as a source of inspiration. On a question of how sensory networks perceive the environment, Hanlon offered the example of the cuttlefish, which although seemingly color blind manages to change its color to match its background. Researchers think the animals can detect light with their skin, but that does not address the color issue. Regarding iridescence as being a way of passively and efficiently changing animal shape cues, or changing thermal reflectants or transmissibility to generate different shape cues, Cuthill suggested it is signal unreliability (both detectability as well as shape) that makes iridescence effective at hiding its host. Gorodetsky added that with IR, in which distinction between texture and color starts to blur, one can give the observer the impression of a different shape. Referring to adjusting IR cues, Bear said, "So maybe it's an edge, a piece of it. You don't alter the whole shape." Pamela Abshire, University of Maryland, brought up angular dependence, which Cuthill said was "hugely important," and that triggered a very long discussion by Hanlon involving the natural world's combination of pigmentary and structural coloration as (1) the secret to coloration-pattern diversity in nature and (2) the suggestion that this might inspire some human applications.

Following discussion of materials with angle-independent structural-color elements, Alleyne moved to manufacturing—specifically, "I don't know if there's a way with this bio-inspired theme to sort of meet in the middle to say what is the level of disorder in manufacturing certain systems, material systems again, that nature is comfortable tolerating, and does that overlap with where we can build cost effectively at scale for the types of materials we're looking at using for camouflage." He added that more defect tolerance means cheaper to make. Gorodetsky weighed in at length, making the point that one does not want to be in a nano-fabrication mode (making perfect little structures over a tiny area); he added that micro-fabrication is incredibly advanced, but from a practical perspective one has to think about capabilities like tolerance to damage and wear, so making perfect structures and maintaining them over time and wear is more challenging. Michelle Povinelli, University of Southern California, challenged the assertion by noting that, given manufacturing improvements, the possibility of getting meter-scale micro-structure materials in a commercial or manufacturable basis is nearing short-term now. As the discussion on matching biologically derived designs and real fabrication continued, Cuthill succinctly noted that biology is evolving continuously and might offer a design shortcut, thus "we're talking about biologically inspired design, not biologically dictated design."

Toward the end of the discussion, much attention was paid to design optimization, an important consideration for biological as well as nonbiological systems, and to related models, including their key parameters and metrics. Richard Osgood, Army Combat Capabilities Development Command (Soldier Center), homed in on the military aspects by focusing the discussion on capability, for soldiers, airmen, pilots, drones, and so on. He said, "it's about fitness and survivability, and we need to get to those solutions faster." He pressed for a better understanding of key hurdles in facing the available opportunities and the imperative to arrive rapidly at solutions for the complex environment. "It's not about one wavelength, it's about multiple environments, just like biology. That's really what we need to do in chang-

[1] Polarization refers to the capability to perceive the orientation of light waves.

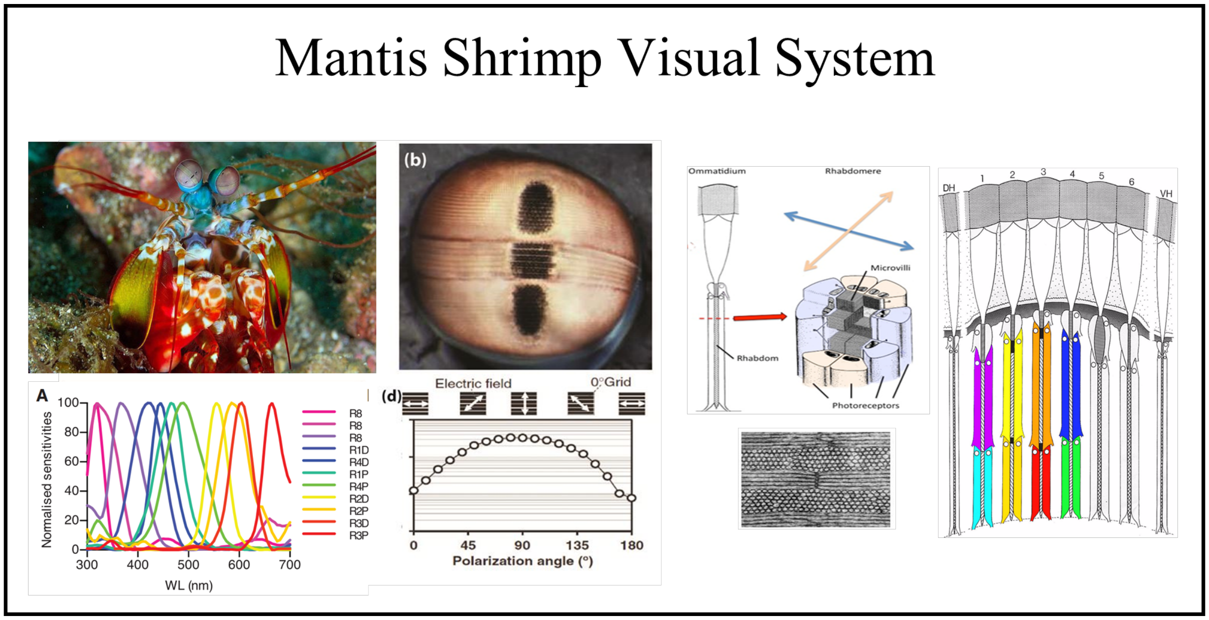


**FIGURE 2** Nature and bio-inspired imaging: mantis shrimp visual system. SOURCE: Viktor Gruev, University of Illinois, presentation to the workshop, from Thoen et al., Note: some images taken from, "A Different Form of Color Vision in Mantis Shrimp", *Science* 343, 2014, pg 411.

ing how we engineer and deploy these types of concepts." Osgood was interested in tools, not merely intuition.

During this discussion, several tools, methods, and suggestions were offered by some participants that might serve Osgood's interest. One participant noted the need to understand the basic decision-making processes in biological camouflage and their underlying principles in order to better adapt them to the technology space. Some participants suggested focusing on those principles and processes in biological systems that meet the technology requirements rather than full biomimicry. With regard to adapting computational methods, a participant suggested that a focus on the environmental perspective rather than the cellular-level approach might be more effective.

## PANEL 2: BIO-INSPIRED SENSORS; CAMOUFLAGE STRATEGIES AND VISION

Pamela Abshire, University of Maryland, moderated the second panel and introduced Viktor Gruev, University of Illinois, Urbana-Champaign, to discuss bio-inspired sensors from the ocean to the operating room. Gruev covered what is found in nature, how biology has inspired polarization and spectral imagers, and applications in both clinical and underwater settings. Figures 2 and 3 show Gruev's illustrations of the mantis shrimp visual system and a bio-inspired imager. Gruev went on to discuss an array of bio-inspired capabilities, such as polarization imaging for autonomous vehicles, underwater polarization and geolocalization, and imaging for clinical purposes.

He concluded with the following observations: (1) the mantis shrimp has an incredible vision system consisting of 16 spectral and 6 polarization channels; (2) mimicking the mantis shrimp visual system has allowed the creation of a compact, low-power, ultra-sensitive, spectral-polarization sensor; (3) due to their ultra-sensitivity, bio-inspired imagers have enabled many biomedical applications, such as image-guided surgery; and (4) a new modality for underwater navigation based on polarization information has been established.

Abshire next introduced Martin Stevens, University of Exeter, to discuss camouflage strategies and vision. Stevens described a wide range of camouflage techniques both from nature and manufactured by humans. Specific areas of focused research are types of camouflage that exist and how they work; how camouflage should be optimized in different habitats and visual backgrounds; how camouflage can work when matching one background alone is not possible; the influence of observer cognition on camouflage types; how color change and behavior facilitates camouflage; and use of camouflage to mask movement. On the point that motion breaks camouflage, he used a graphic illustrating how dazzle markings make estimates of speed and trajectory difficult. He postulated that the lesson from nature is that some prey markings could prevent their capture when trying to escape. Overall, Stevens showed that (1) different types of camouflage work in different ways; (2) disruptive camouflage is more effective than background-matching camouflage; (3) optimizing camouflage is not straightforward and not just an issue of independent contrast and pattern placement; (4) much natural camouflage is flexible through behavior and color change; and (5) success varies as a function of the observer's observation and prey's ability to camouflage its movements. Responding to a question, Stevens said, "Disruptive coloration really is about specifically placing markings on the body peripheries or on key features so that they break up and destroy the appearance of shape."

## WORKING DISCUSSION 2: MATERIALS, STRUCTURES, AND ENSEMBLES

Marianne Alleyne, University of Illinois, Urbana-Champaign, moderated this session, which had the same general focus and structure as the first session. Highlights are exemplified below. Stevens responded to a question about dynamic range with, "It's an interesting question as to whether there are certain parts of the visible spectrum that are more important to make camouflage effective." Stevens believes that camouflage should normally operate across the range of wavelengths that the observer sees. In response to a question about the effectiveness of disruptive coloration on nonbiological things, Stevens said, "Generally, it's very effective, but there are different ways that you can implement those algorithms." He indicated that more effectiveness against edge-detection algorithms, for example, meant less effectiveness against algorithms that quantify object size or orientation, and increased general dependence on how coloration interferes with an algorithm's processes. Moving to a question about predators using camouflage, Stevens responded that the focus has mainly been on the camouflage of prey because the cost to prey of getting caught is death, whereas the predator's cost of its camouflage not working is a lost meal; he also mentioned that predators will sometimes use color patterns to lure prey. Hanlon added that a cuttlefish might do five primary camouflage changes in the course of 20 minutes to approach a prey, and Cuthill noted that a predator is likely to have more control over the prey's perspective because the predator could appear from anywhere. Regarding background markings versus dazzle-type markings to confuse a predator, Stevens's perception was that background-matching camouflage is more common than high-contrast strategies, although there are animals, particularly group-living species with prominent stripes, that could mislead about speed and direction and maybe create group-confusion effects. The other possibility could be relatively conspicuous isolated markings called eye spots, which might divert attacks to less-important body parts, like the edge of a fin or a butterfly wing.

A question arose about predators camouflaging in the same or in a different signal spectrum than used to acquire the prey; examples included owl and prey (visual and audible), tiger and prey (both visible), and bats and moths (both sonar). Stevens believes that there is a range of possibilities, some in the same modality and some even in exactly the same parts of the spectrum, but he added that it is easy to overlook other sensory modalities—for instance, smell is often important in tracking, with vision being used to home in on the target. He explained that camouflage research is generally fixed on vision, but there are small but growing efforts looking into other areas (olfactory, audible). As to whether there is an advantage to operating in the same or different spectra, or modality, he noted that accuracy is often very important for a predator, so owls, using both sound and vision, can do something called sensory integration (for example, combine hearing and visual information to remove uncertainty and improve accuracy), which enables them to more effectively localize what they are attacking. Gruev amplified that

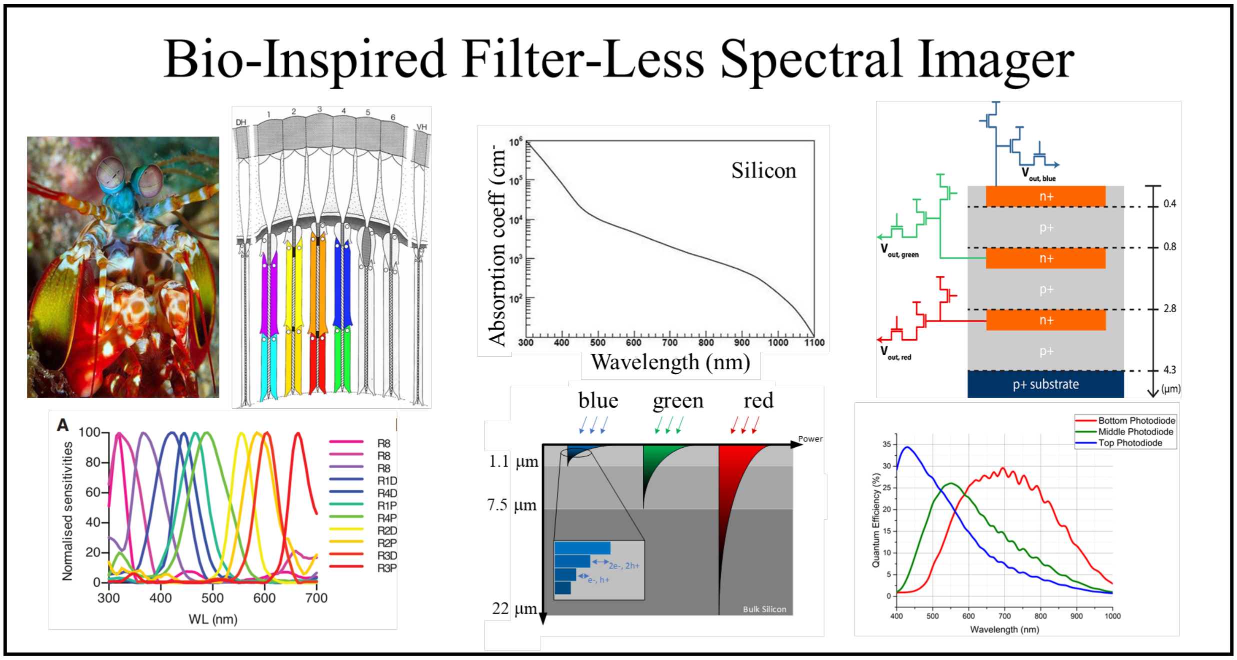


**FIGURE 3** Nature and bio-inspired imaging: bio-inspired filter-less spectral imager. SOURCE: Viktor Gruev, University of Illinois Urbana-Champaign, presentation to the workshop, from Garcia, et al., Note: some images taken from, "A Different Form of Color Vision in Mantis Shrimp", *Science* 343 , 2014, pg 411. See also: Bio-inspired color-polarization imager for real-time in situ imaging, *Optica* 4(10), 2017.

mantis shrimp do not camouflage, but they do integrate polarization and spectral information together for target detection, and experiments indicate multi-modality integration, including motion.

There was some focused discussion of IR. For example, given the amount of attention to visual, there was a general question about strictly IR camouflage, and a couple of examples exhibiting an IR modality for predation were mentioned (vampire bat, viper). Stevens said, "Not so much IR camouflage, but IR signaling." He mentioned squirrels heating their tails to confuse rattlesnakes, but he could not think of IR-camouflage examples. Gorodetsky said, "Most examples of being able to change IR properties are associated with thermal regulation in some sense." He did not think that there had been demonstration of an animal in the wild being able to see past some short range in near-IR. During other interchanges, mention of IR also occurred. At one point, Gruev commented that in seawater, near-IR is attenuated very quickly, but still there is a lot of near-IR within the first meter. On the connection between IR and thermal regulation, a question was raised about a thermal-regulation system creating monochromatic camouflage as a by-product of the ability to create channels for thermal management. Gorodetsky replied, "Thermal camouflage would just be a consequence of having visible camouflage." He gave an example of silver Saharan ants, which use the fibers on their exterior for thermal management; because of that, they look silver. Moving to polar bears, Gorodetsky said, "The white color of polar bears is somewhat related to that. And I think that you do see, because it's very hard to have a specific band or window that's very narrow, that you're working in terms of thermal regulation." He believes, especially if one is working in the near-IR or short-wavelength-IR regions, that there will always be a bit of bleed-over into the visible spectrum in a biological system.

In addition to the panel-led discussion, multiple additional discussions took place during this session. There was considerable discussion about creatures that can sense polarization. One participant indicated that many underwater creatures are polarization sensitive (cuttlefish, octopus) and appear to use polarization in various ways. Other participants noted that birds and terrestrial invertebrates in general also sense polarization, and researchers are looking at the use of background polarization information for geolocalization and navigational purposes (creatures hunt for food and seem to recall their home's polarization state for return). There is also a hypothesis, offered one participant, about a collective early-morning behavior—for example, birds flying in patterns and refining or calibrating magnetic compasses based on optical information, including polarization. Others noted that similar behavior is seen in migratory fish or marine animals early in the morning, when there are highly structured polarization fields and a collective pattern of swarming behavior. Some participants mention that polarized vision is sometimes used as a way to defeat camouflage because it shows edges and flat surfaces, a way of getting around some of the texture and other features that might make an image harder to interpret. After much discussion on polarization and camouflage, Gruev hypothesized that underwater, "closer maybe to the bottom where there is scattering . . . so with some of these fish, they're definitely [in] the environment where they live, the polarization does play into effect to sort of naturally camouflage," whereas "above water definitely helps you have polarization to break camouflage."

One participant suggested that camouflage is not the only defense used by animals against predators, and it is rare to find a heavily targeted prey animal that would not have some form of defense, such as hiding, dispersing some kind of toxins it might signal with warning colors, emerging only during times when its primary predators are not active or do not have the visual system to see in that lighting condition, achieving escape speed, and so on. In addition, one participant described what is known as a "startle response," which is triggered when camouflage fails and serves a means to delay a predator's attack.

One participant mentioned the phenomenon of group camouflage, in which prey are able to confuse a predator by utilizing their numbers rather than individual capabilities. One example mentioned by a few participants was a school of stripe-patterned fish, which utilize their speed and shifting direction to confuse predators. One participant mentioned the symbiotic camouflage in the Hawaiian bobtail squid, where bio-luminous bacteria live inside the animal's light organ and shine, making it harder for a predator to pick it out from a starry night sky; this was suggested by another participant as a type of cooperative camouflage. Another example offered by some participants was group-living spiders that somehow form aggregations that make them look like something else, making it more difficult for a predator to identify them. Birds also exhibit flocking behavior, flying together in a certain configuration, perhaps to represent a kind of group camouflage and confuse predators. Another participant mentioned zebras, whose stripes, when they are running on in a group, make it more difficult for predators to lock on to one specific animal or identify the weakest individual.

One participant brought up the issue of how biological systems balance the amount of energy spent on camouflage relative to their overall performance. One participant suggested that it is difficult to quantify the energy expenditure of certain forms of camouflage, such as color change. However, another participant suggested that one can look at the overall energy budget (e.g., how much a cephalopod will eat, what it will consume, what its daily metabolic rate is, etc.), then consider the total number of chromatophores in the skin (including the 18 to 30 muscle fibers around them), and from a basic mechanical perspective, actually back-calculate what will be the energy consumed per chromatophore to get the coloration effects.

## PANEL 3: EVALUATION OF BIOLOGY TO INFLUENCE CAMOUFLAGE, CONCEALMENT, DECOY APPROACHES; ADDRESS ART OF THE POSSIBLE

Pamela Abshire, University of Maryland, moderated the third panel, which had four speakers. Abshire began with Roger Hanlon, Marine Biological Laboratory, who explained that his work was undertaken within the following conceptual framework: (1) in nature's most complex environment (coral reef); (2) with a model preyed upon by a wide range of visual systems and animals that change the fastest (neural) and with greatest flexibility and effectiveness; and (3) to determine their secret (visual input to motor output) and whether there is a parsimonious solution that reduces complexity. Based on cuttlefish, he described a bio-inspired step toward controllable soft actuators for a type of synthetic camouflaging skin. He next described how disruptive patterning can help retard detection and recognition. Introducing the hypothesis that if there are only a few basic pattern designs, then ultra-fast camouflage changes require a relatively simple algorithm, Hanlon discussed "smart skin" along with biological skin-based light sensors that, with technology, could enable adaptive optoelectronic camouflage systems inspired by cephalopod skins. Hanlon presented the image shown in Figure 4 to indicate biological and technological capabilities in eight relevant "smart-skin" directions.

Abshire turned next to Leila Deravi, Northeastern University, who discussed the question of thermal management in the ocean due to unexpected short-wave IR color modulation from nanostructures in cephalopod chromatophores. Deravi described components that contribute to coloration in the chromatophore light organ, which exhibits controllable pigmentation (red, yellow, brown). Her hypothesis was that the pigment granules behave as photonic nanostructures optimized to enhance extraction and absorption of light for distributed skin patterning. After some additional technical points, Deravi addressed the possibility of researchers manipulating the direction of light to enhance color similar to the squid, and she depicted a laboratory capability to enhance reflected and scattered color from chromatophore pigment granules even when they are only one particle layer thick. These results led her to imagine a new class of multifunctional materials inspired by, or derived from, cephalopods; to accomplish this feat, she listed important technological hurdles that remain. Figure 5 shows both possible new materials and hurdles.

Abshire followed with Michelle Povinelli, University of Southern California, who succinctly addressed a viewpoint from photonics on bio-inspired camouflage. She began with the simple but important concept that a "better detector needs better camouflage" and showed examples in nature of multi-channeled detectors (e.g., snakes use visible, IR, and smell). She also showed that increased scene

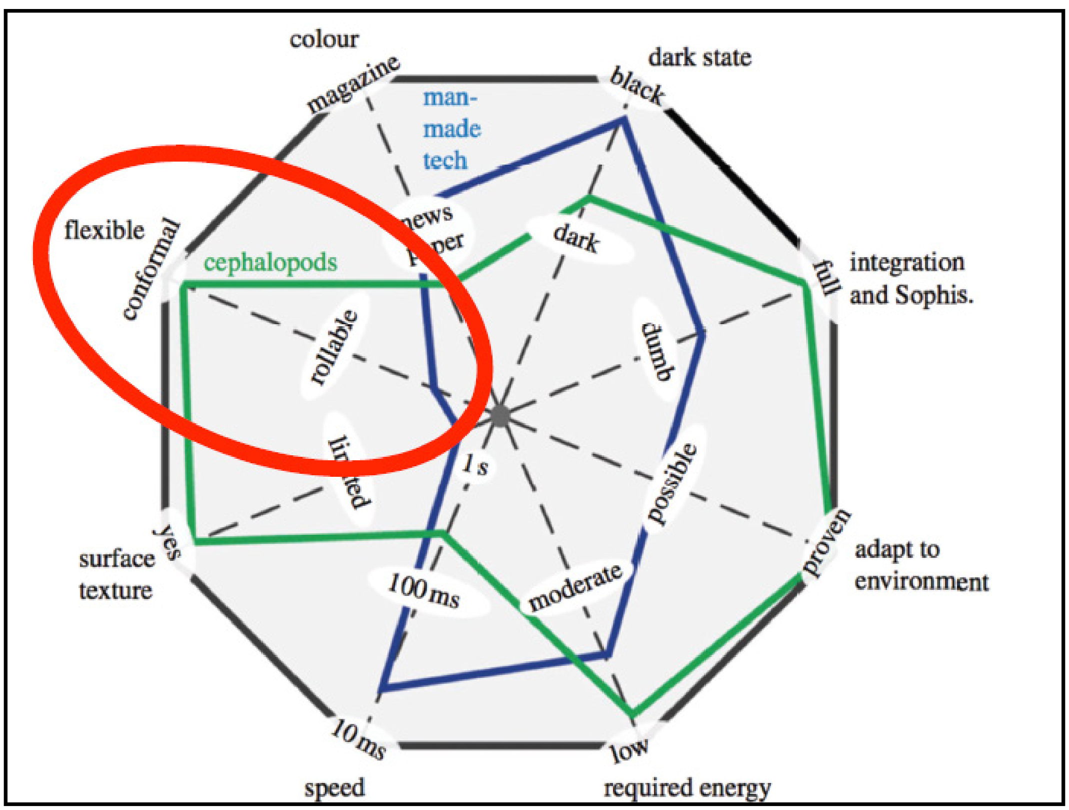


**FIGURE 4** Biological and technological capabilities. SOURCE: Roger Hanlon, Marine Biological Laboratory, presentation to the workshop.

complexity means increased solution space (i.e., being sand-colored is good for hiding in a desert scene, but not in a multi-colored forest scene), and she followed by reiterating the influence of motion on camouflage. Povinelli next covered the basics of thermal emission, noted that the emission spectrum can be engineered using micro-structures, provided a partial taxonomy of engineered materials (metals and dielectrics), and asked, “Are engineers missing mechanisms that biology has found?” Observing that adaptive responses, like self-regulation of temperature, are of increasing interest, she showed some relevant synthetic materials. Povinelli closed with a graphic illustrating faster optimization through parametric design (see Figure 6).

Abshire introduced the last panel speaker, Naomi Halas, Rice University, who discussed biologically inspired routes to sense and respond in adaptive and intelligent metamaterials. She and other researchers are grappling with the color- and texture-matching challenges of integrating into materials both sense-and-response and local-imaging-and-response. Turning to biology, Halas noted that cephalopods, nature’s sense-and-response masters, have capabilities that technology could emulate. Her overall R&D goals are to study underlying physical principles and mechanisms that can be used for development of active optical metamaterials; advance understanding of optical detection and recognition as well as the role of skin opsins in cephalopods; develop concepts and mechanisms of compact optical detection that can be integrated with active composite media to facilitate intelligent response; and design an architecture and algorithms for dynamic color and pattern change analogous to the biological camouflage response. Halas illustrated these goals covering elements of R&D on components, platforms, and sensor network-based imaging. She closed with a long list of accomplishments (e.g., establishing spectrum-selective nanodetectors in multiple material systems; design, fabrication, and demonstration of a platform for responsive materials; demonstration of lens-less imaging with distributed light collectors), which were followed by “big-picture” next steps: integrate selected responsive components with a platform architecture; investigate distinct neural pathways identified in cephalopods relative to remote optical-detection capabilities; relate behavioral assays to optical response of cephalopods; and demonstrate image acquisition experimentally with an incoherent detector network.

## WORKING DISCUSSION 3: GAPS AND POTENTIAL ACTIONS TO REDUCE THEM; PROMISING AREAS TO EXPLORE WITH RESEARCH AND DEVELOPMENT

Co-chairs Alleyne and Bear led and moderated the contributions of all remaining participants during this final workshop session. The following is a summarization of the discussions of participant’s views and observations. As part of the discussion that considered gaps and their potential reductions, participants summarized their views on identifying nature’s solutions and relevant engineering or technical barriers and examining paths to manufacturing or fabrication, estimating levels of achievable success, and considering potential resources needed. These general areas, along with identifying promising avenues to explore with R&D, were dealt with collectively during the wide-ranging discussions. Key elements of the discussions fell generally under four broad topical questions: (1) What are biology’s desirable camouflage solutions that human technology has not yet adopted (i.e., gaps)? (2) What are potential engineering or technical barriers to achieving the bio-inspired designs (i.e., solutions)? (3) How can barriers be removed? (4) What is being missed in bio-inspired camouflage? Summaries of responses are below.

With respect to the first question, workshop presentations consistently indicated that many species excel at camouflage. For example, various creatures can conceal or provide information to different receivers in a multi-spectral way. They can exhibit distance-dependent signaling, possibly by utilizing different sensing modalities (temperature, visual, etc.), and they can create texture statically as well as dynamically while maintaining functionality of underlying components (e.g., optical functionality, functionality of shape). Camouflage capability has been observed across a wide range of operating conditions, such as scenes, temperature, lighting, and polarization. Also observed has been an ability to read an environment and rapidly adapt to it (within 200 msec for cephalopods to achieve visual camouflage). Gaps beyond current human technical abilities were highlighted by the minimal size, weight, power, and cost needed to achieve the complex signaling, control, and actuation system for color control and the ability of cephalopods to perform complex shape control.

On the second question, participants identified several distinct barriers to achieving success in bio-inspired designs. One participant noted the lack of clear specifications for biological systems as a major barrier to developing a technological equivalent. This equivalency issue was also mentioned by another participant with regard to achieving comparable levels of defect tolerance between biological and technological systems. Balancing performance against manufacturability and decision-making processes against realistic expectations for cost, size, weight, and power parameters was also noted by some participants. Last, some participants identified the existing barriers between different scientific disciplines (e.g., biological and physical sciences, or biological and computational sciences) as a key challenge to understanding and adapting biological systems to technological systems. Regarding the third question, which involved the removal of barriers, workshop participants made several suggestions. One participant highlighted the need for a systems understanding and representation of how camouflage in the natural world works, and that breaks down the key functional steps from sensing the environment to response generation. A key step, suggested one participant, would be to develop a prototype based on a biological system that helps researchers test and understand the learning and response system in biological camouflage. Other participants noted the need to identify computational tools and

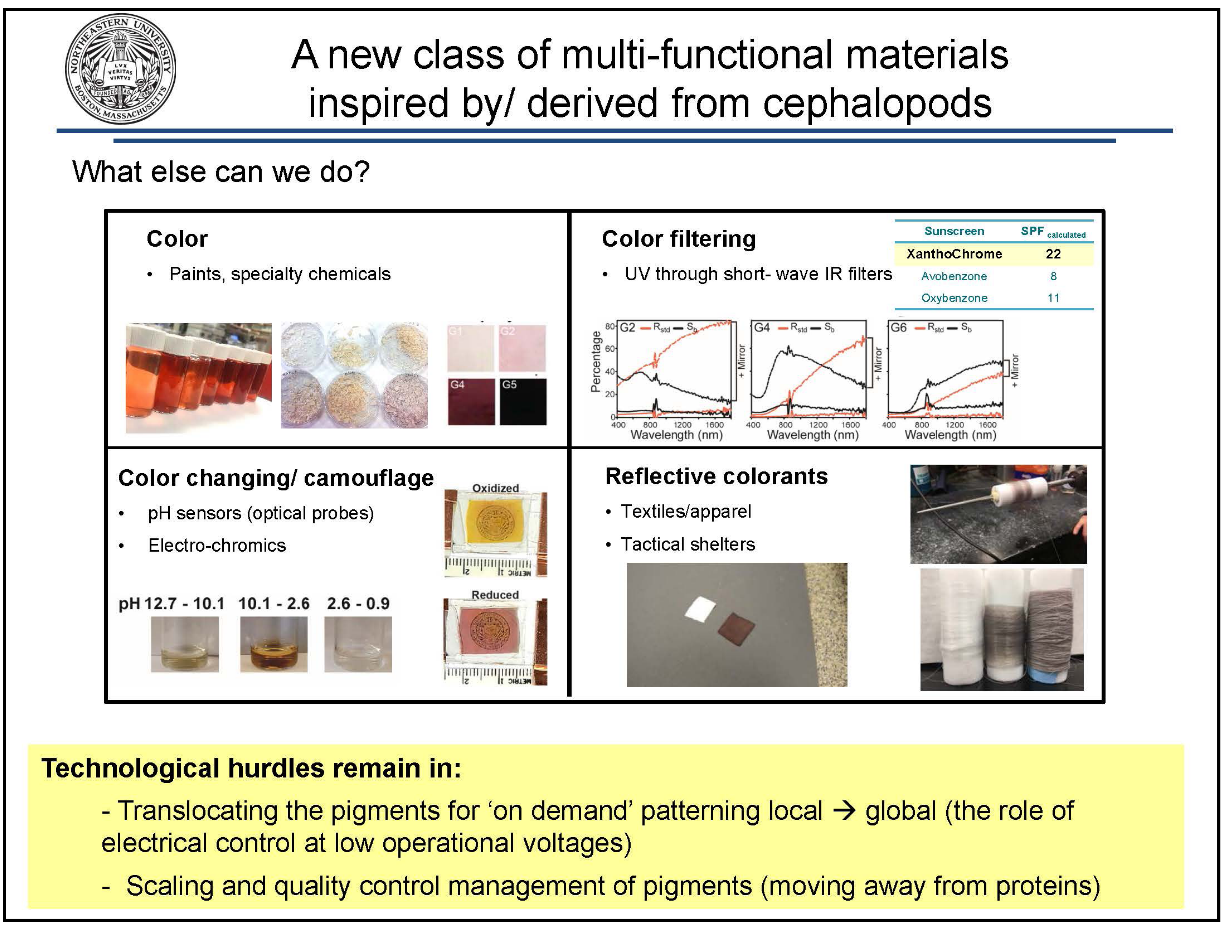


**FIGURE 5** A possible new class of materials and technological hurdles. SOURCE: Leila Deravi, Northeastern University, presentation to the workshop.

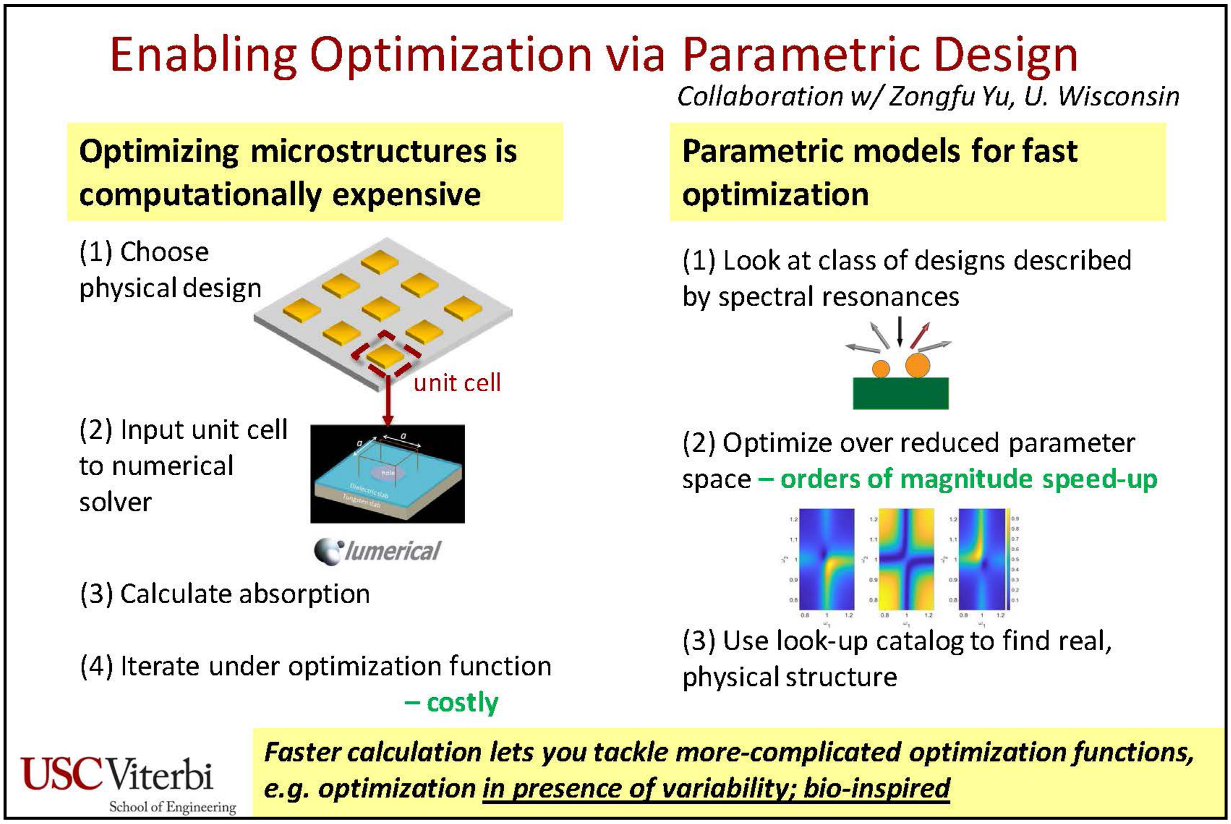


**FIGURE 6** Fast optimization. SOURCE: Michelle Povinelli, University of Southern California, presentation to the workshop, in collaboration with Zongfu Yu, University of Wisconsin.

other tools and methods from scientific disciplines outside the biological sciences to assist researchers in understanding biological designs and how they may be applied to technological systems. Other participants suggested that efforts to cultivate a community of scientists and engineers willing to work across scientific disciplines and government, industry, and academia would be beneficial to overcoming barriers. These might include dedicated conferences and targeted research efforts.

The last question, what is being missed, also received much attention from the participants. First is a need to understand disruptive coloration from a holistic perspective, including cognitive and physical elements, along with other characteristics such as pattern designs, to create metrics of performance. In addition, to date, the participants had not seen engineered systems actively change shape after receiving cues with an active skin. Knowledge is lacking as to the level of effort needed to understand these observed capabilities from biology and bring them to practical systems. Its associated timeline—be it a 1-year, 10-year, 20-year, or beyond challenge—is unknown as well. Further, given that there may be processes in biology for which there is not a good physical or chemical understanding, there was the question of how to obtain that understanding. Many workshop participants appeared to favor two-way feedback between the biology and engineering disciplines, a type of feedback that goes back to the concept of eliminating organizational silos (see the second question, above). Some participants also recognized the importance of ensuring uniformity in the ability to camouflage all extremities and parts of the animal, organism, or group at the same time and same level. Because of this workshop's look at the IR bands, a thought was that it could be useful to delve further into specific examples where biology utilizes IR in its camouflage efforts.

**DISCLAIMER:** This Proceedings of a Workshop—in Brief has been prepared by Norman Haller as a factual summary of what occurred at the meeting. He was assisted by William Millonig, Aanika Senn, and Steven Darbes. The committee's role was limited to planning the event. The statements made are those of the individual workshop participants and do not necessarily represent the views of all participants, the planning committee, or the National Academies. This Proceedings of a Workshop—in Brief was reviewed in draft form by Michael Bear, BAE Systems; Travis King, Office of the Deputy Assistant Secretary of the Army (Research and Technology); and Cherie Chauvin, Naval Studies Board, National Academies of Sciences, Engineering, and Medicine, to ensure that it meets institutional standards for quality and objectivity. The review comments and draft manuscript remain confidential to protect the integrity of the process.

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