Review

How to Hide: Camouflage from Ultraviolet to Infrared

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Abstract:
Effective concealment in outdoor environments requires an understanding of basic camouflage principles and the specifics of light spectrum in which detection may occur. Light is mainly reflected and absorbed (from ultraviolet (UV) to near-infrared (NIR)) or emitted (from mid-infrared (MIR) onwards) for a subject with a typical surface temperature of 37°C. In the visible spectrum, concealment is achieved by matching the background reflectance (using appropriate colours) or using disruptive patterns to break up recognizable shapes. These patterns can be applied manually or generated using specialized algorithms that allow for rapid adaptation to different environments. Camouflage in the UV range requires highly absorbing coatings that remain transparent in the visible spectrum, while in the NIR, similar effects can be achieved using absorbing metallic flakes in a polymer binder or carbon black nanoparticles. Beyond the NIR, emittance becomes the dominant factor, and concealment requires controlling an object's thermal signature. This can be done by lowering its temperature, improving thermal insulation, or utilizing selective heat emission through radiative cooling in the atmospheric window (5–8 μm). By carefully considering these principles, effective multispectral camouflage can be achieved.

Keywords: Camouflage; Light spectrum; Pattern generation; Diffuse reflectance; Emittance; Thermal signature

1. Introduction

Camouflage, as defined by the Merriam-Webster dictionary, is concealment by means of disguise. It signifies one's goal to remain hidden from unwanted eyes. Motivations for such behaviour are diverse. Prey species increase their chances of survival by minimizing their visibility within their environment or by hindering attempts to distinguish individual members within a group. Similarly, predators gain an advantage by getting closer to their prey without being recognized as a threat. Surveillance for scientific purposes requires the observed subjects not changing their behaviour upon the realization that they are being monitored. All these instances can benefit considerably by using effective camouflage that follows these basic principles:

- Background matching: blending with the environment is achieved by matching the surrounding colours (**Figure 1a**). This technique is effective only for specific environments and seasons. Some animals circumvent this problem by having a whiter winter coat that replaces the grey and brown colouring of the warmer seasons.
- Disruption: elements with strong contrast break up the outlines of an object and hide its actual shape, therefore hindering recognition (**Figure 1b**). An example is a zebra hiding among other members of its herd or a snake hiding among ground fallen leaves. Additional enhancement is possible by making the edges of darker areas even darker and the same for lighter areas, thus achieving a 3D effect (Sharman et al., 2018).
- Multi-scale patterns: fractal features on micro-, midi- and macro-scale allow effective concealment at various distances while preventing isoluminance. This undesirable effect occurs when patches of similar colour blend together as they are viewed from a distance, making the object appear uniform in colour and therefore stand out considerably from the environment.

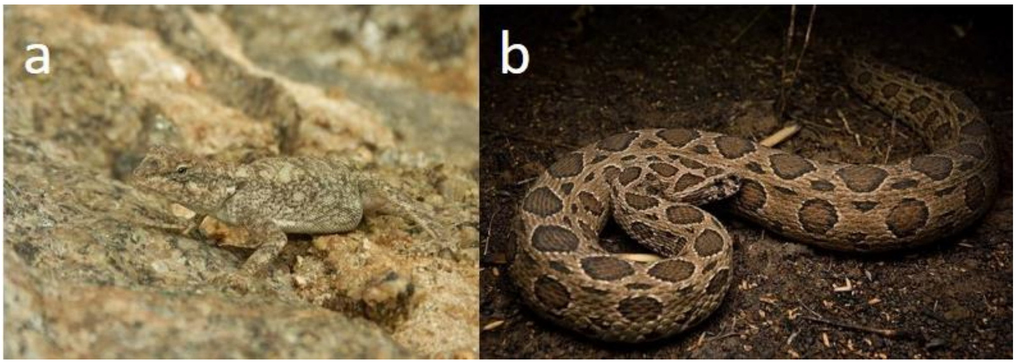

Figure 1. a) Lizard camouflaged on a stone (Photograph by Praveen Illa / CC BY-SA 4.0). b) Disruptive colouring of a Siamese Russell's viper (Photograph by Tontan Travel (www.tontantravel.com) / CC BY-SA 2.0).

2. Light detection

To develop an effective concealment, one must understand some of the basic properties of light. It can be described as an electromagnetic wave with specific energy and therefore a specific wavelength (it can be described as a particle as well, however, the wave-particle duality will not be important for this work). Wavelengths from 380 to 700 nm correspond roughly to what we call the visible spectrum (VIS). Lower wavelengths correspond to ultraviolet (UV) and higher to infrared (IR) light. Here, the focus will mostly be on the UV-A part from 315 to 380 nm, in the near- (NIR, 700–1500 nm), mid- (MIR, 1500–5600 nm) and far-infrared (FIR, >5600 nm). Light can be absorbed or scattered in the material as well as reflected (**Figure 2a**). Every object also emits light (**Figure 2b**) and its spectrum depends on the surface temperature (e.g., a body with surface temperature of 37°C emits mostly in the IR, with a peak at around 10 μm).

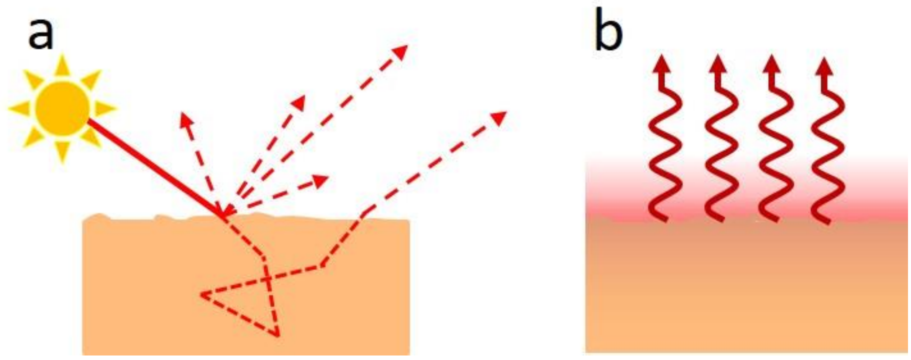

Figure 2. Types of light interaction with a material. a) Specular and diffuse reflection of light (UV to near-IR). Specularly reflected light is reflected off the surface while diffusely reflected light enters the material, where it is absorbed and scattered before it exits again. b) Emission of light due to black body radiation (mid- to far-IR).

For the light to be detected, it has to reach a suitable sensor (e.g., eye, camera) and interact with it. Humans are equipped with photoreceptors capable of detecting visible light (cones and rods on the eye's retina), and the range can be extended further. Individuals with the eye lens removed report being able to see further into the UV (Griswold & Stark, 1992), since the lens absorbs a significant amount of UV light to protect the retina. Extending the range into the NIR requires the use of photoreceptor-binding upconverting nanoparticles (Dhankhar et al., 2020; Ma et al., 2019) or the exchange of vitamin A1 for A2 in the subject's diet (Science For The Masses, 2013), with a side effect of diminished sensitivity to blue light. It is easier to achieve a wider range of detection with man-made sensors. CCD (charged-coupled device) and CMOS (complementary metal–oxide–semiconductor) sensors are used for light wavelengths spanning from 300 to 1000 nm, InGaAs sensors are used from 1000 to 2500 μm and thermal cameras are used for higher wavelengths.

The range of detectable light in the animal kingdom also outperforms that of a human. Animals such as reindeer (Hogg et al., 2011), blue tits (Rajchard, 2009) or butterflies (Finkbeiner & Briscoe, 2021) can detect UV light. The mantis shrimp has a staggering 12 different types of cones, being able to detect light from the UV to the far red (Thoen et al., 2014). Detection of heat signatures in the MIR and FIR is possible with specialized organs (e.g., pit vipers (Goris, 2011), vampire bats (Kürten & Schmidt, 1982) or mosquitos (Zermoglio et al., 2017)).

3. Camouflage

The range of detection discussed in the previous section shows that it is not sufficient to hide in the visible, but it is also necessary to consider the UV and IR spectral ranges. One way to successfully blend with the surroundings in the visible spectrum, is to use a combination of pigments that match the desired reflectance (Asofiei et al., 2021; Goudarzi et al., 2012). A spectral VIS–NIR analysis of the colours of two camouflage patterns is shown in Figure 3, with a comparison to the spectrum of the environment with fresh and dry green leaves. Most of the darker measured camouflage colours correspond well to the environment in the VIS spectrum. A considerable difference in spectral behaviour can be ascertained in the NIR region, where the MultiCam camouflage shows little contrast between patches of different colour. This better corresponds to the spectra of green leaves than the Multi-Terrain Pattern and could lead to better concealment in such environments.

Patterns used for camouflage can consist of flat coloured geometric shapes of varying sizes, pixelated patches, or gradients. For greater ease in pattern adaptation for other environments, a generating algorithm can be programmed. There are several existing open source algorithms; CamoEvo is an artificial camouflage evolution experiment using genetic algorithms to determine patterns that increase concealment in a specified environment with each additional generation (Hancock & Troscianko, 2022), CamoGen is a digital camouflage generator (Lederrey, 2023), while CONCEAL creates a digital/fractal camouflage based upon provided images of the environment and supplied required colours (Peters, 2023).

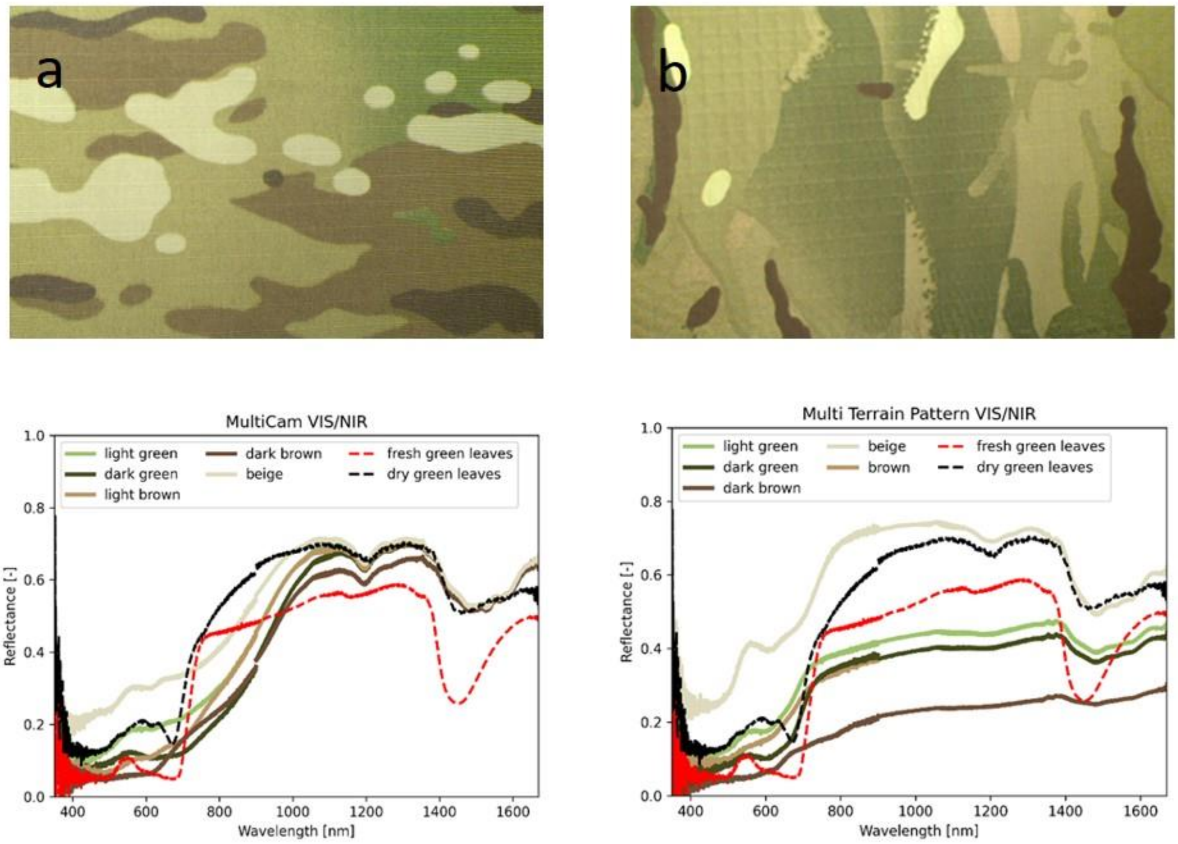

Figure 3. Diffuse reflectance of two camouflage patterns, a) MultiCam and b) Multi-Terrain Pattern. Circles represent sections of different colour used for the measurements. The dashed lines represent measurements on fresh and dry green leaves. The spectra were measured for the project MULKAM – Development of multispectral camouflage for vehicles, equipment and soldiers for the Ministry of Defence of the Republic of Slovenia.

Achieving acceptable camouflage in the UV region depends on the environment reflectance. Snow exhibits large reflectances (up to 80 %), which can be simulated with a coating of white pigment dispersions (e.g., calcium carbonate, barium sulphate (Wilhelm, 1967)). Other environments, e.g., forest or desert, require a decrease in reflectance, which can be achieved with the use of a UV absorbing agent. Available products are U-V-Killer spray (Atsko, USA), UVRC™ (UVR Defense Tech Ltd., USA) or chemical sunscreen based on organic molecules that absorb UV light, to hide exposed skin.

To change absorption in the NIR region, pigments such as perylene black, phthalocyanine blue, isoindoline derivatives, carbon black (soot), IRT black (Standard Colors, NC, USA) are used on the fabric. For coatings with low emissivity, metal pigments with an organic binder are often used, usually in the form of flakes (e.g. aluminum pigments in flakes with a water-based polymer binder (Hallberg et al., 2005); with titanium dioxide (TiO_2 in the form of rutile and anatase) (Wong et al.,2015); from polyurethane, aluminum and nano-pigments (Liang et al., 2018); polyvinyl butyral with nanoparticles of tungsten disulphide (Samolov et al., 2021).

Living creatures, with a temperature around 37°C, begin emitting light in the MIR and FIR regions, making them stand out in the often colder surroundings. To hide this thermal signature, different approaches can be undertaken. One option is to manipulate the surface emissivity, either with active cooling or thermal insulation (e.g., silica aerogel) with multi-layer films acting as wavelength-selective emitters (high emittance in the non-atmospheric window, where absorption in the atmosphere is significant (5–8 μm) and low in the atmospheric window (3–5 μm and 8–14 μm) (Jiang et al., 2023; Xu et al., 2020; Zhu et al., 2020)) or tri-layer structures with overall low emittance (Woo et al., 2022). One group (Hong et al., 2020) developed a flexible thermoelectric device capable of responding to the background temperature change via thermoelectric cooling and heating. A plethora of approaches is covered in several review articles (Degenstein et al., 2021; Su et al., 2023).

An additional tactic, suitable for the whole range of wavelengths, is to self-decorate by covering oneself with materials from the environment, which is utilized by masked hunter bugs or a ghillie suit. A Chinese group (Xie et al., 2023) also developed chlorophyll microcapsules that could be embedded in clothing and can mimic leaf reflectance better than traditional pigment combinations.

4. Conclusion

Concealment poses a difficult challenge, particularly when one considers the spectral range at which detection is possible. Achieving effective camouflage in the range across UV to IR necessitates adherence to basic principles of camouflage (matching the environment reflectance at multiple distances with the incorporation of disruptive patterns), as well as careful consideration of the specifics of background reflectance at these wavelength ranges. Various strategies exist for attaining more or less effective camouflage, with continuous developments each year indicating this specific field remains open to further research and improvements.

Conflicts of Interest: The author declares no conflict of interest.

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