Thermally Controlled, Active Imperceptible Artificial Skin in Visible-to-Infrared Range

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Cephalopods’ extraordinary ability to hide into any background has inspired researchers to reproduce the intriguing ability to readily camouflage in the infrared (IR) and visible spectrum but this still remains as a conundrum. In this study, a multispectral imperceptible skin that enables human skin to actively blend into the background both in the IR-visible integrated spectrum only by simple temperature control with a flexible bi-functional device (active cooling and heating) is developed. The thermochromic layer on the outer surface of the device, which produces various colors based on device surface temperature, expands the cloaking range to the visible spectrum (thus visible-to-IR) and ultimately completes day-and-night stealth platform simply by controlling device temperature. In addition, the scalable pixelization of the device allows localized control of each autonomous pixel, enabling the artificial skin surface to adapt to the background of the sophisticated pattern with higher resolution and eventually heightening the level of imperceptibility. As this proof-of-concept can be directly worn and conceals the human skin in multispectral ranges, the work is expected to contribute to the development of next-generation soft covert military wearables and perhaps a multispectral cloak that belongs to cephalopods or futuristic camouflage gadgets in the movies.

1. Introduction

Several species in nature actively blend into the environment since these traits aid predation for predators and also prevent from being attacked for prey, thereby substantively increasing the chance of survival for various species. The epidermis of cephalopods (such as octopus, cuttlefish, and squids), which can reflect the visible and IR wavelength separately depending on its need, best exemplifies the on-demand active cloaking and helps them match with the environment by rearrangement of chromatophores in the dermal layer by rapid neural and muscle signals.[3–5] Human skin, on the other hand, does not exhibit such a trait despite the outstanding tactile senses and versatile functionalities. For this reason, there has been extensive research on developing such stealth technology, since it is proved to be quite effective for the covert military operations or against surveilling applications to disguise and stay undetected from the enemy. Yet, unlike the active cloaking of the cephalopods, which reflect the visible-to-IR spectrum on demand, most of the commercialized and widely-used products are only confined to the passive camouflage-patterned textile that mimics the chromatic pattern of the surrounding environment.

Inspired by the active and autonomous cloaking system from nature, recent technological advances offered a number of physical mechanisms to reconstruct the cloaking functionalities of cephalopods. Much of previous literature concentrated on altering colors within the visible wavelength using various methods such as electrochromic, thermochromic, and mechanochromic phenomena,[4–11] while several researches also delved into the cloaking techniques in the IR regime utilizing the metamaterials,[12–16] electro-actuation for IR reflection[15] or simply by adjusting device temperature to match background temperature[16] since the temperature (or radiated heat) can be directly translated into the IR signals. However, most of them realized either visible or IR imperceptible systems only; not dual modes in a single device structure that can readily switch between the visible and IR mode depending on a desirable situation.

To the best of the authors’ knowledge, Morin et al. developed soft machines with the visible and thermal cloaking functions for the first time by pumping controlled fluids of different temperatures and colors through microfluidic channels inside the soft robot.[17] Although the novel concept mimicked functionalities of the cephalopods to a certain extent, it requires extreme
difficulty to match the temperature and color of the fluids to the background with high uniformity throughout the entire microfluidic system. In addition to the static cloaking case, such a system lacks high responsiveness to switch to other colors or temperatures since it would rather require an inconvenient procedure of emptying and filling the microfluidic channels with other fluids of different properties. Lastly, the soft machine involves two independent input variables, color, and temperature of fluids, to generate cloaking effects, and yet such a running mechanism would further complicate the operation of the soft robot.

Here, we demonstrate the visible-to-IR active imperceptible artificial skin that provides an on-demand cloaking both in daylight and at night by a single input variable: Temperature (T). The bi-functional nature (capable of active cooling and heating) of the thermo-electric (TE) unit facilitates the fine temperature tunability of each pixel and therefore enables thermal cloaking in the IR range by matching the ambient temperature (i.e., \( T = T_{\text{ambient}} \)). We further stretched the imperceptible spectrum from the IR-to-visible region by incorporating thermochromic liquid crystal at the surface, which changes the light reflectance (R) based on its temperature, thus allowing the generation of a diverse number of colors by controlling temperature. The cloaking in the visible range is therefore achieved separately by matching the ambient color. (i.e., \( R(T) = R_{\text{ambient}} \)). As a whole, we integrated two independent spectral cloaking spectrums into a “full spectrum” with a single soft device structure, which operates by simply adjusting a single input variable, “temperature”. Therefore, this imperceptible wearable can readily switch between dual modes (visible and IR imperceptible modes) based on the user’s need without wearing two separate imperceptible devices on top of the other (which would make the device bulkier and hinder heat transfer between two devices). Moreover, highly scalable pixelization of the device allows spatiotemporal and autonomous control of each pixel by adjusting the temperature of each pixel, thus creating a platform with a high resolution, which would be exceptionally useful when cloaking at the background of sophisticated patterns or when transiently moving from one background to another (as opposed to the device that works as a bulk). Then, to construct its practical platform for the imperceptible artificial skin, we fabricated a thermal display that delivers a variety of optical information. Finally, to scrutinize its practicality to cloaking in the multispectral regime, we mounted the device on the human epidermis and examined its potential as imperceptible artificial skin using both optical and IR visions.

2. Result and Discussion

2.1. The Source of Biological Inspiration and the Concept of the Device

Graphic representations in Figure 1 include the snapshots of cephalopod species (blue-ringed octopus or Hapalochlaena) under the visible-to-infrared spectrum, preview demonstration of the multispectral cloaking on the face and basic material make-ups. Figure 1a consists of the image that illustrates the instantaneous camouflage of cephalopods to blend into the environment by the autonomous reorganization of multilayered nano-sized chromatophores with muscular action of the soft cephalopod dermis. Rearranging chromatophores of cephalopods not only conceals its appearance in the visual wavelength but also in the IR spectrum since these cellular lamellae function as the multi-layers of the periodic Bragg reflector that reflect the broad-band wavelengths of light by a cascade of the biological synaptic signaling.

Figure 1b portrays each pixel that consists of the bi-functional TE operation unit, which can cool and heat up by applying a reverse electric current, thus facilitating the accurate thermal control of every pixel. The accurate control of temperature in each autonomous pixel enables IR cloaking by adjusting to the radiated heat of the surrounding. Meanwhile, the thermochromic layer, which changes its color from red, green to blue depending on temperature, facilitates the deliberate chromatic control of each pixel, completing the full cloaking both in the IR and visible regime overall. In addition to thermal and chromatic control, its highly deformable and skin-like structure of the device conforms to the various curvatures of the epidermal surface and therefore allows the device to be worn as the artificial skin. Thus, despite the difference in mechanisms to invoke the multispectral cloaking effect, the proposed device herein can reproduce the comparable cloaking functionalities of cephalopod dermis, only with a single input variable (temperature) to integrate two bands of spectrums into one full imperceptible mode. When compared to the previous reports, it should also be noted that this new type of cloaking system operates in a simpler yet more advanced way than 1) using two separate spectrum cloaking devices one at a time or 2) even using multiple input variables to operate two different spectrum cloaking systems in one device.

2.2. Optimizing the Design Parameters of the Device

To explore and determine the design parameters of the device, we numerically simulated the device performance based on TE leg dimensions as in Figure 2a, which demonstrates the optimization of the device structure. Note that cooling is much challenging to achieve because Joule heating serves to counteract the cooling process at high current input as it is explicated in Note S1. Supporting Information, and for this reason, we only considered the cooling capacity of the device. We set the cross-sectional area of the leg base as 1.5 mm × 1.5 mm to secure enough cross-sectional area to solder the dice to the interconnecting Cu electrode since electrical conductivity at the inter-metallic interfaces between the copper electrode and solder agent becomes a practical limiting factor. The result implies that the device cooling performance generally exhibits a parabolic relationship with the increasing electrical current because the effect of Joule heating starts to overtake the cooling effect at high current input. Furthermore, the height of the dice serves to increase the cooling capacity of the device, because the reduction in the dice height results in increased heat conduction from the hot junction of the device. This trend begins to plateau after a certain point (h = 2.5 mm) with the increasing leg height because it would lower electrical conductivity. In addition to the cooling capacity, the increasing dice height also augments the bending stiffness and aggravates device wearability.
due to the rigid nature of the dice. For this reason, we set the optimal dice height as 2.5 mm.

2.3. Thermally Conductive Elastomer and its Effect on the Device Performance

Selective thermal engineering in the device structure contributes to enhancing the device performance by controlling the thermal properties of material constituents. Introducing various metallic fillers of different structures into the elastomer and orienting the fillers to the lateral direction boost up its in-plane thermal conductivity (details are elucidated in Figure S1, Supporting Information) when compared to the base elastomer.

The Section 4 elaborates on the procedure to fabricate thermally conductive elastomer (TCE) in detail. Figure 2b exhibits that the in-plane thermal conductivity of TCE with 70 wt% of metallic fillers is almost 8.8-fold higher than that of base elastomer. Please note that the TCE film used in the device is only a few hundred micrometers thin.

The high in-plane anisotropic nature of the elastomer serves to enhance both thermal and chromatic uniformity within a pixel so that each pixel delivers an accurate and uniform output as in Figure 2c. In order to delineate a clear distinction from base elastomer, we compared thermal and chromatic uniformity within a pixel using both the IR camera and normal digital camera when 0.6 A and −1.5 A were applied for heating and cooling modes respectively (applying the reverse voltage causes...
(a) Maximum cooling $\Delta T$ (°C) vs Current (A)

(b) Thermal conductivity (K/Wm) vs Number of Ag plate intercalating layer

(c) Optical image: Chromatically uniform and fast temperature change during heating

Thermal conductive elastomer
Base elastomer

IR image: Thermally uniform and fast temperature change

(d) IR image and Optical image of heating and cooling modes

Pixels under the cooling mode stay in black throughout the entire time
the device to switch to the cooling mode). The IR snapshots indicate that the pixel made up of TCE produces a relatively higher thermal uniformity than the one with base elastomer due to the high in-plane thermal conductivity of TCE to spread the heat uniformly throughout the pixel. Maintaining the high-temperature uniformity in each pixel for an elongated amount of time is of great importance in cloaking application since the inability to attain thermal uniformity in pixels might lead to malfunctioning in the entire application. Figure S2, Supporting Information, presents the quantitative difference between the two conditions by comparing the temperature standard deviation of the entire unit-pixel area for every 10 s after the electrical current was applied. It implies that the temperature standard deviation for both cooling and heating modes escalated to 3.8 and 3.1 °C, respectively, after 80 s for the sample with base elastomer. On the other hand, the temperature standard deviation of the TCE remains within 1.5 and 1.7 °C for both cooling and heating modes, validating the role of in-plane thermal conductivity of TCE to attain temperature uniformity within each pixel.

Thermal uniformity plays an essential role in expressing chromatic cloaking as well since there exist several distinctive color zones for different temperature ranges. Notably, the multiple colors (the dark green color at the center and the reddish color toward the edge of the pixel) appear on the unit pixel with the base elastomer even after 20 s when only the blue color is expected to be displayed, whereas TCE presents rather a uniform and expected color throughout the entire pixel. The heat generation (or heat removal for the cooling mode) mainly occurs on the interfacial surface between the Bi₂Te₃ dice and copper electrode, indicating that the highly anisotropic nature of TCE plays an essential role in providing a material and structural platform for faster thermal conduction in the lateral direction to achieve temperature uniformity within the pixel.

The TCE also yields a considerable effect on the device performance to heat up and cool down when compared with the base elastomer, since it is closely related to the cross-plane conductivity rather than the in-plane conductivity. The cross-plane thermal conductivity of TCE was still 3.28-fold higher than that of the base elastomer despite the relatively lower thermal conductivity value than the in-plane direction (the right y-axis of Figure 2b). The graphical representation of the average temperature of the pixel validates this point as in Figure 2c, in which ΔT_{TCE} ≈ 40 °C whereas ΔT_{TCE} ≈ 20 °C even when the equivalent electrical current was applied. It is anticipated that lower specific heat of TCE than that of base elastomer helps boost the device performance in general because it requires less energy to reach the arbitrary temperature.

Figure 2d shows the time-dependent graphical representation of various temperatures along with IR and optical snapshots for both cooling mode and heating mode of the device. We applied the calibrated current input to generated equivalent ΔT for the cooling and heating modes for 60 s to articulate the bi-functional nature of the single device and the high controllability of temperature for a prolonged period of time to reach the various target temperature. Temperature sustainability for a prolonged period of time serves as a critical factor in articulating colors in the visible spectrum since there exists a narrow temperature zone for each color, and the pixel temperature must stay within the corresponding temperature zone over time in order to express the desired color for an arbitrary amount of time. It is notable that the discrete control of temperature produces an extensive variety of intermediate colors in between red and blue (such as sky blue and turquoise), enriching the chromatic options for potential chromatic cloaking applications. Besides, IR cloaking also requires high controllability and sustainability of pixel temperature for the device to conceal the human skin temperature from the background. Especially, the cooling mode of the device performs a significant role in IR cloaking, because the human thermoregulation autonomously maintains the body temperature to be higher than the room temperature. The result substantiates the device controllability and sustainability of temperature even under the room temperature as well, therefore demonstrating the feasibility of the artificial skin to thermally cloak the skin temperature from the environment.

2.4. Device Characterization and Examination

One of the significant prerequisites in cloaking devices lies in the in situ dynamic responsiveness to the demand by switching from an arbitrary temperature to another. Yet, most of the reported wearable thermal devices consist of only a single heater or cooler, implying that they can only heat or cool and rely on the natural convection to return to the original temperature or to switch the direction to reach another temperature (as in cooling to heating or heating to cooling). This would obviously slow down the response time and degrade the overall performance in their potential applications, which is the major technological shortcomings of the typical thermochromic displays. Thus, we manipulated the electrical current input in cooling and heating modes of the multispectral imperceptible skin (MIS) to reach an arbitrary temperature faster than the passive mode (constant current) and to enhance the response speed of the device as in Figure 3a, which pinpoints the response difference between an active fast and passive slow mode in expressing various colors. For instance, it takes quite a long time to reach the "red color zone" from room temperature in the passive mode by applying constant current because it requires low electrical current to approach and maintain the temperature within the "red color zone". To address this problem, we applied step-wise current input as in Figure S3,
Figure 3. Device characterization and mechanical stability. a) Comparison between slow passive mode and fast active mode on attaining different target colors zones. b) The magnified initial head (left) and terminating tail (right) regions of the overlapped red color graph for both slow passive mode
Supporting Information, from high to low current, so that it quickly heated up to the “red color zone” at high current and stabilized to remain within the temperature zone. As a result, it only took 5.1 s to reach the “red color zone” with fast active heating, while it took roughly double the amount of time with the passive mode as in Figure 3b. Besides, the major forte of the device lies in the fact that it can heat and cool with a single device. Therefore, whereas other thermal devices that can only function as a separate heater or cooler has to passively depend on natural convection to switch to the other direction, the bifunctional device proposed herein can quickly approach the desired temperature as exemplified with the fast active cooling (by applying reverse voltage), thereby addressing the problem of the thermochromic device reported so far. Figure 3b, for example, shows that \( t_{\text{fast active}} \) (the time it takes to return to room temperature from the “blue color zone”), was only 6.4 s while the passive cooling (natural convection) took 59.7 s to reach such temperature, which corresponds to 9.3 times longer than the fast active cooling. As a result, the fast active mode undergoes approximately 2 cycles during when the slow passive mode goes through only one cycle in Figure S4, Supporting Information, corroborating the applicability of the device to cloak skin, which requires fast response and recovery time as the foremost features.

Since our body temperature (varies from 28 to 32 °C depending upon the body parts[20]) is usually higher than that of the environment, the device must be able to approach the surrounding temperature rapidly to blend into the environment for the IR cloaking mode. For this reason, the device must reach to target temperature actively to conceal skin temperature and ultimately cloak ourselves from IR radiation detection. To articulate the strength of the device, Figure 3c compares it with the separate simple heater and shows the device capability to generate abrupt temperature changes by actively utilizing both cooling and heating modes of the device. The result indicates that the device can quickly switch from one temperature to another and then to the other temperature (above and below room temperature), owing to its bi-directional nature, and this feature serves a highly significant role in realizing the active cloaking device due to the sudden change in the surrounding temperature. On the other hand, the separate simple heater (or the separate cooler) can only heat up (or cool down) in one direction only, and it fails to switch to temperature lower (or higher) than the room temperature, therefore performing only half a function as a cloaking application.

2.5. Mechanical Properties of the Device Against Various Stresses

Figure 3d examines the thermal stability of MIS while its operation in extreme condition. Since the device operates as a cloaking application involves a series of abrupt temperature changes within seconds, the device might undergo severe thermal stress due to the thermal mismatch between the interfacial materials of the device. Thus, we alternated cooling and heating modes in cycles with \( \Delta T = 40 ^\circ \text{C} \) to determine the potential effect of thermal shock and its effect on the device performance in the long-term cyclic operation. The device lasted longer than 6000 s without noticeable performance deterioration. The IR and optical RGB (red, green, and blue) images after the cyclic test resemble the ones after the test, and therefore the result corroborates the decent device stability under the frequent temperature changes required to operate the cloaking device.

The device for cloaking applications needs to demonstrate its robustness to mechanical stress for the device to be fully wearable as artificial skin. Since the fatigue stress mainly causes mechanical failure considering the nature of wearable electronics, we measured the change in resistance \( \frac{R}{R_0} \) under flexing the entire device (1 × 5 independent pixel array) in cycles with the bending radius of 2 cm as demonstrated in Figure 3e. Note that each pixel (which operates independently when it works as an artificial skin device) was connected in series to confirm that all pixels remain free of electrical failure. The device withstood cyclic bending of more than 20 k cycles with an extremely small maximum electrical resistance change of 2.43% during the whole course of the cyclic test, thus validating the outstanding durability of the device to the external quotidian stress in the real world. Along with the strong intermetallic bonding between soldering agents and Cu electrode/dice, the low modulus of TCE appears to be responsible for the exceptional mechanical stability of the device because soft TCE and the thin Cu electrode serves to absorb most of the bending stress, leaving more rigid constituents (dice and solders) relatively intact.

2.6. Color Expression Based on CIE 1931

To accurately quantify the chromatic profile acquired with MIS, we transformed obtained colors into the \( x-y \) coordinates and plotted them in the CIE 1931 graph as in Figure 3e, where the \( x-y \) coordinates of RGB colors correspond to \((0.584, 0.369), (0.155, 0.677)\), and \((0.155, 0.7033)\) respectively. Compared to the thermochromic devices that mostly exhibited a narrow range of color,[21] MIS exhibits a rich variety of colors including RGB with a single thermochromic material using its highly accurate control of the pixel temperature. The increase in temperature causes the helical pitch of cholesteric liquid crystals to decrease as it is simply clarified in the following equation \( \lambda = \hat{n} P \cos \Theta \), where \( \lambda \) corresponds to the wavelength of the reflected light, \( \hat{n} \) and \( P \) are the pitch and the number of turns. However, the applied voltage \( V \) causes the helical pitch of cholesteric liquid crystals to decrease. For this reason, the device must reach to target temperature actively to conceal skin temperature and ultimately cloak ourselves from IR radiation detection. To articulate the strength of the device, Figure 3c compares it with the separate simple heater and shows the device capability to generate abrupt temperature changes by actively utilizing both cooling and heating modes of the device. Thus, we alternated cooling and heating modes in cycles with \( \Delta T = 40 ^\circ \text{C} \) to determine the potential effect of thermal shock and its effect on the device performance in the long-term cyclic operation. The device lasted longer than 6000 s without noticeable performance deterioration. The IR and optical RGB (red, green, and blue) images after the cyclic test resemble the ones after the test, and therefore the result corroborates the decent device stability under the frequent temperature changes required to operate the cloaking device.
stands for the mean refractive index of the film, $P$ is the helical pitch length, and $\theta$ represents the angle between the incident light and the normal to the liquid crystal plane. The winding of liquid crystal helix serves to decrease the spacing between liquid crystals and reflects light with the shorter wavelength as a result. On the other hand, the unwinding of the liquid crystals helix shifts reflected light toward the red in the electromagnetic spectrum.\(^{[22]}\) This entire thermochromic process is highly reversible and occurs rapidly as it could be observed in previous figures of this work.

### 2.7. Thermal Display Proof-of-Concept Using Thermal Pixels

Utilizing the characterized features of the device, we fabricated the multi-pixelized device as a proof-of-concept and recorded its simultaneous performance both with the typical digital camera as well as the IR thermal imaging camera to examine the feasibility of the device. Figure 4a includes the digital IR photosnapshots, displaying alphabets, A, N, T, and S (in azure blue, green, royal blue, and red, respectively) in the visible spectrum and S, N, and U in the IR region (at hot, near room temperature and cold temperature, respectively). Pixelization of the device allows the localized operation of the thermal display and thus delivers a richer amount of information with a higher degree of freedom. The result demonstrates that each thermochromatic pixel operates independently of other pixels without any thermal interference between pixels, owing to the thermally engineered design, which is further elaborated in Figure S5, Supporting Information. Above all, we believe that the thermal display demonstrated herein validates its potential in basic visual communication and further lays the groundwork for the ultimate aim of this work.

### 2.8. Active Imperceptible Artificial Skin on the Multispectral Regions

The MIS demonstrates a high degree of flexibility, multiple color expression, pixelized thermal screen, and rapid response time, owing to the accurate control of the temperature via the bi-functional device: it satiates all the requirements to be utilized as the imperceptible artificial skin from the visible to IR bands.

In order to better present the fortes of the MIS, we came up with a virtual map of the various backgrounds with diverse colors (red, green, and blue) and temperatures (10 and 50 °C) as featured in the center image of Figure 4b (note that the upper half of the map represents a day while the other lower half exemplifies a night). The device-mounted human hand moved across the map, and the individual pixels in the imperceptible artificial skin quickly adjusted to the background environment to such an accuracy that it appears as if there is an empty hole on the hand. The maple leaves, grass field, and deep blue ocean comprise the natural backgrounds in the upper half of the map that we often encounter in the real-life, and the device reproduces the background colors from red, green and blue and green concurrently as it proceeds in the visible region of the map (video clip 1 in Supporting Information). Likewise, the lower half of the map functions as the direct counterpart for the nocturnal setting, because objects can not be easily spotted in the complete absence of light, and the thermal imaging devices are usually employed to distinguish the homeothermic entities from the background in the military operations. Thus, the device pixels autonomously reach the background temperature as soon as it approaches different thermal sources of designated temperature in the IR part of the map (video clip 2 in Supporting Information).

The physical environment in the real-life is not comprised of a simple single color/temperature, and it is often the case in the actual world that we encounter a sophisticated background in which more than one color/temperature exists spatially adjacent to each other. Thus, it is of high significance for the artificial skin pixels to quickly adjust to different colors/temperatures to better describe the background features for both the visible and IR regions. The upper and lower snapshots of Figure 4b demonstrate the pixelized transition from one background to another (for instance from red to green and to blue or 10 to 50 °C) as the hand moves across different backgrounds (whether it is a visible or IR cloaking mode), and each pixel sequentially switches its color/temperature based on their relative positions. While a simple cloaking device that works as an entire bulk is only capable of generating one color or temperature at a time, the incorporation of active pixelization enables the device to blend into the complex background of colors or temperature, making the artificial imperceptible skin even much harder to spot and thus demonstrating a substantial advance.

Lastly, Figure 4c shows the actual cloaking demonstration of the device when it is worn on the human cheek in the background of the bushes. To highlight the effectiveness and wearability of the device, we wore the device only on the cheek as shown in the inset figure. The pixelization of the device shows its clear strength in the cloaking technique again during the day to generate disruptive coloration, which is known to hinder detection and disturbs cognitive mechanisms in nature.\(^{[21]}\) making the cloaked face much more difficult to detect in the visible spectrum. For this reason, we deliberately applied the electrical current of the definite magnitude only to a designated region of pixels, making the human skin far less recognizable in the forest bushes. As a result, the human skin that is covered with the device matches well with the background, and it even appears as if it is an extended part of the camouflage-patterned military uniform. On the contrary, the bare skin without the device clearly stands out even with the naked eyes.

In addition to the cloaking in the visible region, the device presents an outstanding capability to thermally cloak the human skin epidermis when viewed with the thermal imaging camera as well. While the device helps the human match with the background, the human bare skin clearly stands out because the human body usually regulates its temperature to be higher than that of the surrounding environment. This is the very reason that cooling plays an essential role in the thermal cloaking because most of the thermal devices can only heat the temperature, and there are only a few physical phenomena that are capable of both cooling and heating with a single device. Thus, whereas the bare human face maintains its temperature as 36 °C, the IR imperceptible mode of the device conceals the human skin by matching the device temperature to
Figure 4. Wearable thermal display and multispectral imperceptible artificial skin. a) Thermal display displaying visible and IR letters (A, N, T, S in visible colors and S, N, U in various temperature). b) Multispectral cloaking in the visible and IR regimes on the virtual map, in which the device worn on the hand moves across different visible and thermal backgrounds. The background in the visible spectrum consists of red maple leaves, green grass, and deep blue ocean, and the IR backgrounds with different temperature includes 10 and 50 °C. Note that each device pixel can autonomously express different colors/temperatures based on its relative positions as the hand moves across various backgrounds owing to the pixelization of the device. c) Actual demonstration of multispectral imperceptible artificial skin worn on half of the face for military stealth application. The pixelization of the device allows an autonomous control of each pixel and thus is employed to exemplify disruptive coloration to blend into the environment. In the IR cloaking mode, the device temperature was programmed to approach the background temperature (26 °C), whereas the face temperature stays unchanged (36 °C).
that of the background. It is highly significant that the device does cloak the human body actively with high wearability and switchability between the visible and IR spectrum bands as a complete working wearable device because most of the previously reported devices so far only suggested the fundamental concepts that merely examine prospective potential.[10,15,24,25]

3. Conclusion

Inspired by the intriguing cloaking properties of cephalopods, we presented the demonstration of the soft and skin-like imperceptible device that provides the instantaneous cloaking ability in the visible and IR region with the pixelized thermal operation. Rather than each separate cloaking device for the visible and IR spectrum band, we integrated these individual spectrum bands into one full-spectrum system that operates just by adjusting device temperature, thus exhibiting the active multi-spectral cloaking capability that is highly comparable to that of cephalopods. The skin-like cloaking platform not only translates fundamental camouflage features of cephalopods, but it also exhibits high practicality for the direct usage on the human skin unlike previous literature, which only examined the potential of their works in stealth application.[9,15,17,25,26] We believe that the unprecedented properties of MIS, which provides a complete multispectral cloaking ability with a single device, would make a significant contribution to wearable military covert applications and can also serve to be a step forward to complete invisibility shorty.

4. Experimental Section

Material Preparation: Various materials of different structures such as silver flake (Sigma Aldrich), synthesized silver plate, and EGaIn (Alfa Aesar) comprise of metallic fillers in the thermally conductive elastomer (TCE). To prevent potential alloying reaction between Ag and Ga in EGaIn,[27] 0.1 g of EGaIn was oxidized by mixing it with 50 mL of aceton under vigorous stirring for 24 h. This way, Ga on the very outer surface becomes oxidized to Ga2O3.

To synthesize silver plate, 0.25 g of PVP was dissolved (Sigma Aldrich, 36k MW) into 5 mL of DI water, and 0.0849 g of AgNO3 was prepared (Sigma Aldrich) in 0.5 mL of DI water in a separate vial. Then, PVP and AgNO3 were mixed in two vials with additional 39.65 mL of DI water. The mixture was spin-cast at 500 rpm for a minute and cured at 60 °C for 30 s. The result of each separate cloaking device for the visible and IR spectrum band, we integrated these individual spectrum bands into one full-spectrum system that operates just by adjusting device temperature, thus exhibiting the active multi-spectral cloaking capability that is highly comparable to that of cephalopods. The skin-like cloaking platform not only translates fundamental camouflage features of cephalopods, but it also exhibits high practicality for the direct usage on the human skin unlike previous literature, which only examined the potential of their works in stealth application.[9,15,17,25,26] We believe that the unprecedented properties of MIS, which provides a complete multispectral cloaking ability with a single device, would make a significant contribution to wearable military covert applications and can also serve to be a step forward to complete invisibility shorty.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

J.L. and H.S. contributed equally to this research. This work was supported by the National Research Foundation of Korea (NRF) Grant funded through the Basic Science Research Program (2017R1A2B3005706).

Conflict of Interest

The authors declare no conflict of interest.

Keywords

biomimetic, e-skin, imperceptible skin, thermochromic, thermo-display, wearable electronics


