Marangoni-Propulsion Micro-Robots Integrated with a Wireless Photonic Colloidal Crystal Hydrogel Sensor for Exploring the Aquatic Environment

Koki Yoshida and Hiroaki Onoe*

In nature, some insects can rapidly propel by using the Marangoni effect without employing the oscillatory movements of legs. Inspired by nature's Marangoni-propulsion principles, various Marangoni-propulsion untethered micro-robots are achieved to propel with small energy storage. For practical use of Marangoni-propulsion micro-robots, it is required to have the intelligence to detect the external environment. However, previous Marangoni-propulsion micro-robots integrated with wireless micro-scale sensors that can sense the external environment and transmit the obtained information are not achieved. Herein, Marangoni propulsion micro-robots integrated with a wireless photonic gel sensor for exploring the aquatic environment and transmitting the environmental information are proposed. The proposed micro-robots can propel at the water–air interface by the Marangoni effect. The integrated photonic gel sensor can sense the external stimuli and transmit the information by the color change. In this research, the responsivity of the micro-robots is evaluated by the propulsion velocity and the response time of the photonic gel. It is shown that the propulsion velocity is changed by the outlet area. The response time decreased as the diameter of the photonic gel decreased. Finally, it is demonstrated that the photonic gel sensor can dynamically sense the external stimuli while the micro-robots propel.

1. Introduction

The ability to walk on water has evolved independently throughout the animal kingdom, among over 1200 species of insects, spiders, birds, fish, reptiles, and mammals. While the many creatures, such as basilisk lizards or water striders, physically stroke when walking on water, few creatures including larva of the water lily leaf beetle, mesovelia, and microvelia can propel on the water surface by other principles based on the surface tension. In particular, microvelia and rove beetle can propel for rapid escape from the presence of a potential predator by using the Marangoni effect without employing the oscillatory movements of legs. Marangoni effect is a mass transfer phenomenon between two fluids with different surface tension. Those creatures can propel by the Marangoni effect caused by releasing only a small amount of surfactant. Because Marangoni propulsion did not require any mechanical systems and propulsion velocity is faster than physical swimming, the Marangoni propulsion is an attractive candidate for the driving method for untethered micro-robots. Untethered micro-robots are micro- to millimeter-scale robots without any constraints by a tethered connection to energy sources and processors such as support pneumatic or electrical wires. Untethered micro-robots could be expected to various applications including field robotics for exploring environments and medical micro-robots for diagnostics, treatment, and target drug delivery. Inspired by nature's Marangoni-propulsion principles, various Marangoni-propulsion untethered micro-robots have been proposed and achieved to propel with small energy storage. Previous works have reported that the propulsion velocity of the Marangoni micro-robots depending on the surface tension of the fuel and the propulsion direction was affected by their shape. In addition, previous Marangoni-propulsion micro-robots achieved environmental remediation application light-driven micro-robots and programmable motion by photo-patterning of hydrogel. For practical use of Marangoni-propulsion micro-robots, it is required to have the intelligence to detect the external environment for acting autonomously. However, previous works have been mainly focused on the motility of the Marangoni micro-robots and thus the Marangoni-propulsion micro-robots integrated with wireless micro-scale sensors that can sense the external environment and transmit the obtained information have not been achieved.

Here, we propose Marangoni-propulsion micro-robots integrated with a wireless temperature sensor for exploring the aquatic environment and transmitting the environmental information under https://doi.org/10.1002/aisy.202100248.

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information by a color change (Figure 1a). The proposed micro-robot was mainly divided into three components: a photonic colloidal crystal hydrogel sensor (photonic gel sensor) as the wireless temperature sensor, energy storage made of agarose hydrogel, and a silicone body (Figure 1b). The micro-robot can stay at the water–air interface by the buoyancy force and the surface tension (Figure 1c). The ethanol released from the energy storage generates surface tension gradients, leading to the Marangoni propulsion of the micro-robot. The integrated photonic gel sensor can detect external stimuli by the heat transfer and diffusion of the surrounding fluid. In this study, we experimentally analyze the propulsion velocity of the micro-robots and the response time of the photonic gel sensor to evaluate the responsivity of the proposed micro-robots. Then, the relationship between the external temperature and the color of the photonic gel sensor is revealed. Finally, we demonstrate that the micro-robots can dynamically sense the external temperature while the micro-robots propel at the water–air interface.

2. Characteristics of the Micro-Robots

2.1. Design of the Micro-Robots

First, the design of the proposed micro-robots is described (Figure 1b). The length, width, and height of the micro-robots were 27, 6, and 5 mm, respectively (detail design was described in Figure S1, Supporting Information). The body of the micro-robots was made with a polydimethylsiloxane (PDMS, base material: curing agent = 10:1). The bottom of the micro-robots was colored black for improving the color visibility of the photonic gel sensor. The body of micro-robots has two chambers: an energy storage chamber and a photonic gel chamber. An agarose gel (1% [w/w]) was filled in the energy storage chamber for storing the ethanol (50% [v/v]) as driving energy. The photonic gel chamber has through holes for the heat transfer and the diffusion of fluids. The fabricated micro-robots can stay at the water–air interface mainly because of the buoyancy force (Figure 1c).

For realizing wireless micro-scale sensors, photonic colloidal crystal hydrogels (photonic gel) that are stimuli-responsive hydrogels encapsulating regularly arranged colloidal particles (diameter is hundreds of nanometer) was used because the photonic gel can convert external stimuli to the visible wavelength change without any tethered connection. The photonic gel can reflect the visible-light wavelength through Bragg’s diffraction. The wavelength was depending on the distance of the colloidal particles. This colorizing phenomenon is called structural color. The structural color can be seen in various situations such as the wings of Morpho butterflies. The structural color is nonfading, making it suitable for long-term sensing. In addition, the stimuli-responsive hydrogel that composed the photonic gel can change its volume responding to the external stimuli.

Figure 1. The proposed Marangoni-propulsion micro-robots integrated with the photonic colloidal crystal hydrogel sensor. a) The schematic image of the sensing and transmitting the environmental information by the color change of the photonic gel sensor while the micro-robots propel. b) The design of the proposed micro-robots. c) The fabricated micro-robots can stay at the water–air interface. Scale bars are of 10 mm. d) The condition whether the photonic gel sensor can sense the external stimuli while the micro-robots propel. When $\tau_{\text{res}} < 1$, the micro-robots pass through the stimuli before sensing. When $\tau_{\text{res}} \geq 1$, the photonic gel sensor can sense the external stimuli.
external stimuli (temperature, \cite{29,30} pH, \cite{31–33} light, \cite{34} chemical compounds, \cite{35,36}), leading to the change of distance of the colloidal particles. Thus, the photonic gel can convert an intensity of external stimuli to a visible-light wavelength change. In this research, a N-isopropylacrylamide (NIPAM, 10% [w/w]) that is the most common thermal-responsive hydrogel \cite{29} and colloidal particles (15% [w/w], diameter: ≈130 nm) were used for the thermal photonic gel sensor to confirm the brief concept of this research. The principle proposed in this research could be applied to other stimuli-responsive hydrogels for detecting other stimuli.

2.2. Responsivity of Micro-Robots

Next, we considered the parameters related to the responsivity of proposed micro-robots. The situation that the micro-robots propel in one direction at the water–air interface with the propulsion velocity, \( v \), and through the external stimuli with the length, \( L \), was considered (Figure 1d). By using these parameters, the duration of applying the external stimuli, \( T_{\text{stimuli}} \), was represented as

\[
T_{\text{stimuli}} = \frac{L}{v}
\]

By using this definition, the photonic gel sensor integrated into the micro-robots can change their color responding to the external stimuli when \( \tau_{\text{res}} \geq 1 \) (Figure 1d, left). In contrast, the micro-robot pass through the external stimuli before changing their color when \( \tau_{\text{res}} < 1 \) (Figure 1d, right). In this research, we measured the propulsion velocity, \( v \), and the response time required for sensing, \( T_{\text{sense}} \), to evaluate the responsivity of the micro-robot, \( \tau_{\text{res}} \).

3. Experimental Results

3.1. Marangoni Propulsion

The propulsion velocity of micro-robots, \( v \), was measured while the micro-robots propel in the one-directional channel. It is considered that the propulsion velocity, \( v \), is dependent on the diffusion speed of the ethanol, and the diffusion speed of ethanol is influenced by the outlet area, \( A \). We compare the propulsion velocity, \( v \), when changing the outlet area, \( A \) (2.25, 4.00, 6.25, 9.00, 12.25 mm\(^2\), Figure 2a). All of the outlets were square.

![Figure 2. The measurement of the propulsion velocity, \( v \). a) The propulsion conditions of the micro-robots. b) The propulsion image of the micro-robots. Scale bar is of 10 mm. c) The relationship between the propulsion velocity, \( v \), and the outlet area, \( A \).](image-url)
and proportionally varied in order to ignore differences due to the cross-sectional shape. The micro-robots were propelled on the deionized water (depth: 10 mm, width: 15 mm, Figure 2a) by the Marangoni effect. The average propulsion velocity during the first 10 s was adopted as the propulsion velocity, \( v \). When the outlet area was small (\( A = 2.25 \text{ mm}^2 \)), the micro-robots propel slowly with \( v = 3.99 \text{ mm s}^{-1} \) (Figure 2b, left, Movie 1, Supporting Information). The propulsion velocity, \( v \), increased as the outlet area, \( A \), increased (Figure 2b, right, Movie 2, Supporting Information). The propulsion velocities for each outlet area were 8.16 mm s\(^{-1}\) (\( A = 4.00 \text{ mm}^2 \)), 10.51 mm s\(^{-1}\) (\( A = 6.25 \text{ mm}^2 \)), 12.08 mm s\(^{-1}\) (\( A = 9.00 \text{ mm}^2 \)), and 12.18 mm s\(^{-1}\) (\( A = 12.25 \text{ mm}^2 \)) (Figure 2c, blue bars). These results showed that the propulsion velocity of the micro-robots could be changed by the outlet area according to their applications. In addition, the micro-robots could propel over 10 min with even small energy storage (storage volume: 32 mm\(^3\), \( A = 4.00 \text{ mm}^2 \)) and micro-robots with large energy storage could propel over 30 min (storage volume: 72 mm\(^3\), \( A = 9.00 \text{ mm}^2 \)). Then, we observed the influence of the temperature on the propulsion velocity of the micro-robots, because it is estimated that the temperature would affect the surface tension and the evaporation of ethanol from the air–water interface. When the micro-robots were propelled at 36°C, the tendency of the propulsion velocity was similar to the propulsion velocity when propelled at 24°C (Figure 2c, red bars). This result indicated that the influence of the temperature difference between 24 and 36°C was small on the propulsion velocity.

3.2. Temperature Sensing

3.2.1. Response Time of the Photonic Colloidal Crystal Hydrogel Sensor

Since the photonic gel responds to the thermal stimuli by the heat transfer and the diffusion, the response time required for sensing, \( T_{\text{sense}} \), is dependent on the surface–volume ratio. Thus, we compared the response time required for sensing, \( T_{\text{sense}} \), when changing the diameter of the photonic gel. The diameters of acryl molds that were used for fabricating the photonic gels were \( \phi 1, \phi 2, \) and \( \phi 3 \) mm. The diameters of the photonic gels after fabrication were 1.6 mm (acryl mold: \( \phi 1 \) mm, Figure 3a, left), 3.0 mm (acryl mold: \( \phi 2 \) mm), 4.7 mm (acryl mold: \( \phi 3 \) mm, Figure 3a, right). When applying the thermal stimuli (50°C), the photonic gels were successfully shrunk (Figure 3a). A shrinking ratio, \( \varepsilon \), was defined as

\[
\varepsilon = \frac{d_t}{d_0}
\]

where \( d_0 \) was an initial diameter of the photonic gel and \( d_t \) was a diameter at a time, \( t \). The plotted shrinking ratios were

Figure 3. The measurement of the color change. a) The shrinking behavior of the photonic gel. Scale bars are of 1 mm. b) Time variation of the shrinking ratio when applied the thermal stimuli (50°C). c) The color change of the photonic gel sensor responding to the applied thermal stimuli. Scale bar is of 5 mm. d) The reflected wavelength spectrum of the photonic gel sensor. e) The relationship between the value of the hue and the temperature.
approximated by an exponential function (Figure 3b). The response time required for sensing, $T_{\text{sense}}$, was determined to be five times the time constant of the exponential function. The small photonic gel (acryl mold: $\varnothing 1$ mm, Figure 3b, red dot) shrunk faster than the large photonic gel (acryl mold: $\varnothing 3$ mm, Figure 3b, green dot). The response time required for sensing, $T_{\text{sense}}$, were 37 s (acryl mold: $\varnothing 1$ mm), 72 s (acryl mold: $\varnothing 2$ mm), and 133 s (acryl mold: $\varnothing 3$ mm). These results showed that the response time of the photonic gel sensor could be improved by decreasing the diameter of the photonic gel.

3.2.2. Color Change of the Photonic Gel Sensor

Then, the color change of the photonic gel sensor was evaluated in two ways: the reflected wavelength spectrum and the value of the hue. The color of the photonic gel sensor was gradually changed from red color to blue color responding to the intensity of applied thermal stimuli (Figure 3c). When the temperature was increased from 24 to 36 °C, the peak reflected wavelength was shifted from orange–red color (24 °C, 592 nm) to green color (30 °C, 512 nm), then blue color (36 °C, 441 nm) (Figure 3d). These results showed that the photonic gel sensor can sense the external temperature by the reflected wavelength spectrum measurement. The value of the hue was also gradually changed from orange–red color (24 °C, 8.9') to blue color (36 °C, 189') responding to the applied thermal stimuli (Figure 3e). Therefore, this result showed that the color change of the photonic gel sensor can be evaluated from the value of the hue as well as the reflected wavelength spectrum. In addition, the red-green-blue (RGB) values of the photonic gel sensor were also gradually changed responding to the surrounding temperature (Table S1, Supporting Information). In other words, the color changes of the photonic gel sensor can be measured from the image without extensive equipment such as a spectrophotometer.

3.3. Dynamic Sensing

We demonstrated dynamic sensing of the external temperature while the micro-robot propelled at the one-directional channel with temperature variations (Figure 4a). The temperature of the starting point (distance, $d = 0$) was 27 °C. The temperature of the channel increased gradually, and then the temperature was converged at 36 °C from distance, $d = 90$ mm (Figure 4c, red squares). The photonic gel sensor fabricated with $\varnothing 2$ mm acryl mold and the micro-robots with outlet area, $A = 9.00$ mm$^2$, were used for dynamic sensing. Before
propulsion, the value of the hue was 26.8° (Figure 4b, left). The micro-robot propelled through the channel with average propulsion velocity, $v = 1.64 \text{ mm s}^{-1}$ (Movie 3, Supporting Information). Over $d = 210 \text{ mm}$, the color of the photonic gel sensor was changed to blue color responding to the external thermal stimuli (Figure 4b, right), and the value of the hue was converged at 189° (Figure 4c, black dots). These results showed that the proposed photonic gel sensor can dynamically sense the external stimuli and convert the obtained information while the micro-robots propel at the water–air interface.

Then, we compared the responsivity of the micro-robot, $\tau_{res}$, to the theoretical design of the micro-robots. The micro-robot propelled 130 mm from the point of the thermal stimuli applied ($d = 90 \text{ mm}$) to the point of the color change ($d = 210 \text{ mm}$). This propulsion distance was used for the stimuli length, $L$. By using $v = 1.64 \text{ mm s}^{-1}$ and $L = 130 \text{ mm}$, the duration of applying the external stimuli for the micro-robot, $T_{stimuli}$, was calculated as $79 \text{ s}$ from the Equation (1). In Section 3.2.1, the response time required for sensing, $T_{sense}$, was measured as $72 \text{ s}$ (acryl mold: $\phi 2 \text{ mm}$). By using these results, the responsivity of this micro-robot, $\tau_{res}$, was calculated as 1.1 from Equation (2). The responsivity satisfied $\tau_{res} \geq 1$, and thus these results also confirmed that the micro-robot was able to detect the external temperature sufficiently.

Finally, we demonstrated dynamic sensing of the external temperature while the micro-robot propelled at the 2D environment with thermal stimuli (Figure 5a). The temperature of the two-dimensional environment before propulsion was 29°C. The thermal stimuli were applied to the specific region of the 2D environment (Figure 5b, area of the white circle). The photonic gel sensor fabricated with $\phi 2 \text{ mm}$ acryl mold and the micro-robots with outlet area, $A = 12.25 \text{ mm}^2$, were used for dynamic sensing. Before propulsion, the value of the hue was 0° (Figure 5c). The micro-robot propelled freely at the 2D environment with average propulsion velocity, $v = 17.1 \text{ mm s}^{-1}$ (Figure 5b, red line showed the trace of the propulsion, Movie 4, Supporting Information). When passing near the thermal stimuli, the color of the photonic gel sensor was changed. After passing near the thermal stimuli, the hue was 208° (Figure 5c) and the temperature of the thermal stimuli was 36°C. This result showed that our proposed micro-robots could freely propel and dynamically detect the temperature of the complex environment.

4. Discussion

Our proposed Marangoni-propulsion micro-robots integrated with the photonic gel sensor showed that the dynamically sensing the external temperature and converting the information to the visible-light wavelength change while the micro-robot propel at the water–air interface. This is the first proposed concept for integrating the wireless biochemical sensor into the Marangoni-propulsion micro-robots and transmitting the environmental information by the color change. The responsivity of the micro-robots was dependent on the propulsion velocity, $v$, and the response time required for sensing, $T_{sense}$. In this research, it is shown that the propulsion velocity, $v$, increased as the outlet
area, $A$, increased. The propulsion velocity affects not only the responsivity but also the exploration speed and the exploration area of the external environment. Thus, it is considered that the improvement of the response time required for sensing, $T_{\text{sense}}$, is more important for improving the ability to rapidly detect short-range environmental stimuli. The response time required for sensing, $T_{\text{sense}}$, was affected by the heat transfer and the diffusion of fluid from the outside to the photonic gel sensor and the volume change of the photonic gel sensor. It is considered that the response speed of the photonic gel sensor could be improved without affecting the propulsion by reducing not the entire micro-robots but only the size of the gel sensor. In this research, by increasing the surface–volume ratio, $R_{sv}$, the response time decreased from 133 s (acryl mold: $\varphi 3$ mm, $R_{sv} = 3.33$) to 37 s (acryl mold: $\varphi 1$ mm, $R_{sv} = 6$). Therefore, our proposed photonic gel sensor could improve by increasing the surface–volume ratio. The miniaturization of the photonic gel is expected by using micro-fabrication techniques including photolithography techniques. In contrast, it is concerned that the miniaturization of the photonic gel makes it more difficult to observe color changes. To overcome this problem, it is expected to arrange numerous micro-scale photonic gels for convenient information transmission.$^{[25,26]}$ As with other methods for improving the response speed, the previous research reported the highly improving response speed of stimuli-responsive hydrogel by using the porous structure that improves the diffusion speed of the solution.$^{[14]}$ The porous stimuli-responsive hydrogel can rapidly change their volume within 0.5 s responding to the applied stimuli. Thus, it is considered that the response speed of our proposed photonic gel sensor could also be highly improved by using the porous structure for improving the speed of the heat transfer and the diffusion of the fluids.

Then, we discussed the limitations of the size of the micro-robots. The size of the micro-robot affects the size of the integrated photonic gel sensors and the volume of the energy storage. It is considered that reducing the size of the micro-robot will reduce the surface tension gradient between the head and tail of the micro-robots. However, the surface tension becomes more dominant than the volumetric power as the scale of the micro-robots gets smaller. Thus, it is thought that the smaller micro-robot could still propel by the Marangoni effect. In the case of larger micro-robots, previous works have successfully propelled large robots (length: $\approx 100$ mm)$^{[16,37]}$ by using other fuels. Therefore, the larger Marangoni-propulsion robots can also propel by using different fuels with larger surface tension and optimizing the robot designs.

For practical use of the proposed Marangoni-propulsion micro-robot integrated with the photonic gel sensor, it is necessary to realize other detection target substances such as heavy metals, explosives, and toxins because these substances can influence environments and animals. In recent years, DNA aptamer-linked hydrogels$^{[38–40]}$ are attractive for highly sensitive and stable biochemical sensors because of two features of a DNA aptamer: specifically binding to a target substance with high binding selectivity and high stability against thermal conditions.$^{[41]}$ For instance, previous DNA aptamer-linked hydrogel biochemical sensors have been realized to detect the wide range of $\text{Ag}^{+}$ ion concentrations (10$^{-3}$–10 mM) including the toxic range for various aquatic organisms.$^{[42]}$ Thus, other stimuli-responsive hydrogels and DNA aptamer-linked hydrogels are expected to be adopted to the photonic gel sensor integrated into the proposed micro-robots for realizing the detection of various target substances. In addition, the integration of multiple types of photonic gel sensors is also highly expected for micro-robots to detect multiple target substances simultaneously.

In this research, we mainly focused to obtain the environmental information by the color change of the micro-robots, but it is also expected to improve the intelligence of the micro-robots such as the autonomous motion control responding to the environment. The motion of the Marangoni-propulsion micro-robots could change by changing their shape.$^{[20]}$ In previous research, the motion control of the micro-robots has been reported by changing their morphology responding to the stimuli through the volume change of the stimuli-responsive hydrogel.$^{[9,23]}$ Thus, in the future, we believe that the autonomous untethered micro-robots with not only the detecting the environmental information but also the motion control is realized through the volume change of the stimuli-responsive hydrogel.

5. Conclusion

We proposed the Marangoni-propulsion micro-robots integrated with the photonic gel sensor for exploring the aquatic environment. The responsivity of the micro-robots could be evaluated by the propulsion velocity, $v$, and the response time required for sensing, $T_{\text{sense}}$. Proposed micro-robots can propel at the water–air interface by the Marangoni effect with $\nu = 3.39 – 12.18$ mm s$^{-1}$. The propulsion velocity, $v$, was dependent on the outlet area of the energy storage, $A$. In addition, the micro-robots could propel over 10 min with even small energy storage (storage volume: 32 mm$^3$, $A = 4.00$ mm$^2$). The photonic gel sensor could change its color from orange-red color ($24 ^\circ C$, peak wavelength: 592 nm, the value of the hue: 8.9$^{}$) to green color ($30 ^\circ C$, peak wavelength: 512 nm, the value of the hue: 160$^{}$) then to blue color ($36 ^\circ C$, peak wavelength: 441 nm, the value of the hue: 189$^{}$) responding to the external temperature. The response time required for sensing, $T_{\text{sense}}$, decreased as the diameter of the photonic gel (acryl mold $\varphi 1$ mm: 37 s, acryl mold $\varphi 2$ mm: 72 s, and acryl mold $\varphi 3$ mm: 133 s) decreased. Finally, we demonstrated that the micro-robots could dynamically sense the external temperature and transmit the temperature as the color change while the micro-robot propelled at the water–air interface. We believe that our proposed Marangoni-propulsion micro-robots integrated with photonic colloidal crystal gel sensor could open a new avenue for various microscale biochemical applications, such as autonomous exploring micro-robots and remote sensing systems for aqueous environments.

6. Experimental Section

Fabrication of the Body of the Micro-Robots: The body of the micro-robots consisted of two parts: an upper layer and a bottom layer (the design details were described in Figure 5a, Supporting Information). The body has two chambers: an energy storage chamber and a photonic gel chamber. For fabricating the upper layer of the micro-robot body, PDMS (base material: curing agent = 10:1; Toray, SILPOT 184) was poured in an acrylic mold, thereafter cured at 75 °C over 2 h. For improving the coloration of the photonic gel sensor, the bottom layer of the micro-robot body was...
colored black by mixing a carbon powder (501-X8, BIO-RAD) in PDMS (base material: curing agent: carbon powder = 100:10:1) before curing. The fabricated upper layer and the bottom layer were bonded with additional PDMS (base material: curing agent = 10:1), then cured at 75 °C over 2 h. For the energy storage, a low-melting-point agarose solution (1% w/w; A2576, SIGMA-ALDRICH) was injected into the storage chamber of micro-robots and then was gelled by cooling (4 °C). To fill the driving energy into the agarose hydrogel, the micro-robots were soaked in ethanol (50% v/v) overnight.

Fabrication of the Photonic Colloidal Crystal Hydrogels: NIPAM (10% w/w; Wako Pure Chemical, 095-03692), N, N-Methylenebisacrylamide (MBAA; Wako Pure Chemical, 134-203332) as a crosslinker (Weight ratio W_{NIPAM}:W_{MBAA} = 50:1), photopolymerization initiator (0.5% w/w; Irgacure2959, BASF), and 15% (w/w) silica colloidal particles (diameter: 130 nm, MP-1040, Nissan Chemicals) were used for the pre-gel solution. The pre-gel solution was desalted by ion-exchange resins (ACS501-X, BIO-RAD), followed by pouring in acryl molds (diameter: 1, 1.5, and 2 mm; depth: 1 mm) and then was cured by UV irradiation (20 mW cm⁻², 5 min). The photonic gels were swollen by immersing in deionized water overnight. The swollen photonic gel was integrated into the micro-robots that energy storage was filled with ethanol.

Measurement of Propulsion Velocity: An aluminum channel (width: 15 mm, depth: 11 mm, thickness: 1 mm, length: 1 m) was used as a channel for propulsion of the micro-robots. Both ends of the aluminum channel were sealed with PDMS lids to prevent water leakage. The deionized water was poured into the aluminum channel (water depth: 10 mm). The propulsions of the micro-robots were analyzed by video analysis software (Keyence, VW-2). The diameter of the photonic gel was measured every 10 s by a digital microscope (Keyence, VH-5500) for calculating a shrinking ratio, ε. The thermal stimulation of the micro-robots was applied to the photonic gel by using a hot plate. The color of the photonic gel was observed directly above. The reflected wavelength spectra of the photonic gel were obtained using an epi-illuminated microscope (BX-50, Olympus) equipped with a VIS-NIR spectrometer (USB2000+, Ocean Optics) and an Olympus U-LH100 light source. For obtaining the value of the hue and the RGB, a photo taken by a smartphone (iPhone 7, Mac) was analyzed by ImageJ.

Setup for Dynamic Sensing: The aluminum channel (width: 15 mm, depth: 11 mm, thickness: 1 mm, length: 1 m) was also used as the channel for propulsion. The deionized water was poured into the aluminum channel (water depth: 10 mm). The part of the channel was heated at 36 °C by a large hot plate (length: 400 mm). The temperature of the channel was measured with a laser thermometer every 10 mm. The value of the hue was also obtained by ImageJ for every 10 mm the micro-robot propelled.

Setup for Dynamic Sensing at the 2D Environment: The stainless chamber (diameter: 200 mm) was used. The deionized water was poured into the stainless chamber (Water depth: 10 mm). After the micro-robots were placed on the stainless chamber, the specific region of the stainless chamber was heated by a Bunsen burner (5-S1010-21, Fuego Basic). The temperature of the thermal stimuli was measured with the laser thermometer. The value of the hue was obtained by ImageJ before and after propulsion.

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

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords
biomimetics, Marangoni effect, photonic, colloidal crystal hydrogel, stimuli-responsive hydrogel, structural color, untethered micro-robot, wireless sensor

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