# Supplemental Online Material

for

# **Camouflage and Display for Soft Machines**

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#### **Materials and Methods**

**Materials.** Soft robots and the various color layers were fabricated from silicone rubbers and polyethylene tubing. Ecoflex<sup>®</sup> two part platinum cure silicone rubber kits (0010, 0030, and 0050) were purchased from Smooth-On, Inc. Polydimethylsiloxane (PDMS) was purchased from Dow Corning Corp. (Sylgard<sup>®</sup> 184). Polyethylene tubing, Intramedic<sup>TM</sup> PE60 and PE160 by Becton Dickinson and Company, for creating both pneumatic inlets and microfluidic inlets/outlets was purchased from VWR<sup>®</sup>. All materials were used as received and prepared following the manufacturers protocols.

Solutions flowed through the color layers were prepared in-house. Opaque watercolor gouache paints were purchased from Savoir-Faire. Bis(2,4,6-trichlorophenyl) oxalate (TCPO) was purchased from Fluka. Fluorescent dyes were created from Premium Décor® paints purchased from General Paint and Manufacturing Company. All other reagents and solvents were purchased from Sigma-Aldrich<sup>®</sup>. All chemicals were used as received without further purification.

**Preparation of Visible Wavelength Dye Solutions.** With the exception of the blue and red solutions used to show the design of the various color layers (Fig. 1, Fig. S1), we made aqueous solutions colored in the visible spectrum (and ultraviolet, although we have not demonstrated this capability; silicone elastomers such as polydimethylsiloxane, PDMS, are transparent to 250 nm (*31*)), by mixing and adjusting the relative proportions of different colored gouache watercolor paints and diluting the resulting mixtures with water. The blue and red dye solutions were prepared by diluting aqueous stock solutions of methylene blue (0.6 mg/mL) and of amaranth dye (0.5 mg/mL) with water respectively. More hydrophobic dyes, such as methylene blue, were

absorbed by the color layers over time (several minutes), but the absorbed dye was easily removed by pumping solvents such as ethanol or methanol through the color layer.

**Preparation of Chemiluminescent Solutions.** A mixture of TCPO (179 mg, 0.4 mmol) and 9,10-bis(phenylethynyl)-anthracene (10 mg) was dissolved in diethyl phthalate (100 mL) and vigorously stirred with a magnetic stirbar in a 125-mL Erlenmyer flask for 30 min at room temperature to afford a yellow solution (reagent A). In a separate 125-mL Erlenmyer flask, a solution of 80:20 diethyl phthalate/ tert-butanol (v/v) (60 mL) was added 50% aqueous hydrogen peroxide solution (w/w) (20 mL), forming a mixture of two immiscible liquids (reagent B). Immediately before the initiation of chemiluminescence, reagent B was vigorously swirled and a volume of 20 mL of the reagent was measured out with a 100-mL graduated cylinder. The reagent B (20 mL) was subsequently transferred to a 50-mL Falcon<sup>TM</sup> tube containing reagent A (20 mL). Mixing of the two reagents by shaking led to chemiluminescence (emission of green light with this dye) and the addition of catalytic amount of sodium salicylate to the reaction mixture (5–10 mg, 0.03-0.06 mmol) increased the intensity of light emission. Once prepared, the glow stick solution was immediately transferred to the color layer of the soft robots via a 10-mL plastic syringe. To create a blue chemiluminescence solution the same procedure was followed except that 9,10-bis(phenylethynyl)-anthracene was replaced with 9,10-diphenylanthracene (10 mg). This chemistry is standard for commercially available glow sticks (32).

**Preparation of Fluorescent Solutions.** Fluorescent solutions were created by dispensing approximately 2 mL of fluorescent DayGlo<sup>®</sup> paint into a 50 mL conical tube. It was then diluted to a volume of 25 ml using acetone, which does not significantly swell or react with silicone elastomers (*33*), and thoroughly mixed to achieve a homogeneous solution.

**Robot and Color Layer Fabrication.** We are developing "soft" robots (a type of soft machine) that are actuated pneumatically, are deformable, simple to fabricate, and potentially inexpensive. In prior publications, we have described the fabrication of pneu-net actuators (*6*), using soft lithography (*34*), and illustrated how simple arrays of pneumatic channels can enable complex functions such as gripping and locomotion (*6-8*). The quadrupedal soft robots we used here, were fabricated as described in Ref. #7.

We fabricated the color layers via soft lithography. The microchannels used here were much larger (the smallest dimension was 380  $\mu$ m Fig. 1A main text) than the 25  $\mu$ m lateral resolutions routinely used in microfluidic devices (dimensions down to 10 nm are accessible) (*35*). To create the color layers (Fig. S1), masters were fabricated from acrylonitrile butadiene styrene (ABS) using a 3D printer (Dimension 3D, Stratasys Inc.). We molded the color layers from Ecoflex® (0010 or 0030) and then sealed them against a thin (0.25 mm) Ecoflex® film (Fig. 1 main text). An optimal color layer thickness of 1.5 mm minimized the pressure drop across the channels, while providing a useful path length for light absorption by the dye. Ecoflex<sup>®</sup> is not as transparent as other polymers, such as polydimethylsiloxane or polycarbonate; however, these other polymers do not stretch without plastic deformation to the extent necessary to match the pneu-net layer's range of motion. The inlet/outlets for the color layer were created with polyethylene tubing (I.D. 0.08 cm). Finished color layers were bonded to the top of the quadrupedal soft robots by coating each contact surface with liquid Ecoflex®, pressing them together, and curing the assembly at 70 °C for 20 minutes.

**Pneumatic Actuation, Color Layer Operation, and Heating/Cooling of Colorants.** We illustrated soft robot camouflage using tethers—the pressurized gases, heated/cooled liquids, and control systems necessary to run the robots were kept off-board. For many applications tethered

robots are perfectly suited (e.g., assembly lines). Tethered operation reduces the size and weight of the robots by leaving power sources and pumps off-board.

We ran the pneumatic actuation sequence for locomotion using a system of solenoid valves controlled by Labview © as reported previously (7). We pumped the various heated/cooled dye solutions, pigment dispersions, chemiluminescent solutions, fluorescent solutions, and water through the color layers (Fig. S1) to change the visual impression of the robots in the visible and infrared (IR). We pumped the solutions manually with syringes or automatically with syringe pumps (the typical pumping rate was 2.25 mL/min); in a more highly developed or autonomous (and probably larger) machine, liquids could be carried on-board (1.5 mL of liquid provides coloration to 54 cm<sup>2</sup> of surface). To control the thermal radiance of the soft robots we used heated/cooled solutions (Fig. 4 main text). We heated the solutions using an oven set to 70 °C and cooled them using a refrigerator at 2 °C (the working temperatures of PDMS and Ecoflex are between ~ -20 °C and ~250 °C and the thermal conductivity is 0.16 Wm<sup>-1</sup>K<sup>-1</sup>(*31*)). We removed the coloration or luminescence by pumping water, followed by air, through the channels. The ability to tailor the color of the spectrum using temperature-controlled solutions of dyes or pigment dispersions was an advantage of pumped fluids.

**Image Analysis of Soft Robot Camouflage.** We camouflaged the robot using disruptive coloration and background matching to hide its location. To quantify the effectiveness of the camouflage, we performed a basic image analysis (Mathematica<sup>®</sup>, from Wolfram Research) focusing on brightness, contrast, and edge comparison between the robot and its background (29). We first collected images of an un-camouflaged and a camouflaged robot on a rock bed (Fig. 2B, main text).

We converted each image to grayscale with pixel brightness represented by an 8-bit number between 0 (black) and 255 (white). The images in Fig. 2B of the main text have roughly equal contributions from each of the RGB channels; therefore, we present the image analysis in grayscale. The same analysis could be performed on each color channel separately without changing the conclusion. We partitioned each into 6 regions (Fig. S4A), one containing the robot, and the rest containing regions of background. We applied a manually drawn masking layer (Gimp, from GNU Project) to the regions with a robot to isolate it from the background (Fig. S4C), and pixel brightness histograms were computed for the camouflaged and uncamouflaged robots, as well as the rocky background, and are shown as normalized histograms in Fig. 3 of the main text. The background distribution shows contribution from all background regions. We then computed the mean brightness,  $\bar{I}$ , and RMS contrast,  $\bar{I}_{RMS}$ , for each region (Fig. S4B) according to,

$$\bar{I} = \frac{1}{N} \sum_{i} I_i \tag{1}$$

$$\bar{I}_{RMS} = \sqrt{\frac{1}{N} \sum_{i} (I_i - \bar{I})^2}$$
<sup>(2)</sup>

where *N* was the total number of pixels, *i* is the pixel index, and *I* is the pixel intensity. We tabulated the computed values in Fig. S4D. The background values are the average of all background regions. We find, for this particular robot, that the mean brightness and contrast of the robot with camouflage is closer to that of the background than the robot without camouflage. In fact, the mean brightness of the robot with camouflage is within the RMS contrast of the mean background brightness.

The color layer (Fig. 1, main text) used for this soft robot also disrupts the familiar profile of a quadrupedal soft robot. Images of a quadrupedal robot without (Fig. S5A) and with (Fig. S5B)

the color layer were taken on a rock bed and converted to grayscale. A "Canny" edge-finding algorithm with 15-pixel width was applied to the images and is shown in Fig. S5C and S5D.

**Reflectance Characterization of Color Layers.** We photographed the color layers using diffuse incandescent or fluorescent (or combinations of both) lighting. This lighting avoided excessive shadows and reflectance hot spots, which could have been further reduced using antireflective coatings (though we did not investigate them here). To characterize the performance of our color layers in the "on" (filled with colored liquid) and "off" (filled with uncolored water) state, we collected reflectance spectra using two defined light sources like those used in the photography of the color layers. Specifically, we used a fluorescent lamp with three fluorescent bulbs (Alzo digital, FL360, Temp. 5500K, 120 ACV, 27 W, 42 A) covered by a diffuser and a standard desk lamp with a single incandescent bulb purchased from Phillips<sup>®</sup> (100W, soft white). We illuminated the color layer (Fig. S1B) with the light source positioned parallel to its surface and we collected the reflectance signal through a fiber optic probe (Ocean Optics Inc., R200-7-UV-Vis,  $D = 200 \mu m$ , N.A. = 0.22) that we mounted 5 cm from the color layer surface at an angle of 45°. We held the fluorescent lamp and incandescent lamp at 60 cm and 40 cm from the surface of the color layer, respectively. We processed the reflected signal with a high resolution spectrometer (Ocean Optics Inc., HR4000, 300-500 msec. integration time, 10 scan averaging). This setup samples a circular area of  $\sim 3.8 \text{ cm}^2$  that covers roughly the entire center portion of the color layer.

We show the reflectance data, for each source, in Fig. S6 and include the reflectance spectrum for the "off" state ( $I_{off}$ ) followed by the relative reflectance spectra ( $I_{on}/I_{off}$ ) for each of the "on" color states tested. We observed the expected result in each experiment; for example, when in the blue "on" state (Fig. S6B) reflectance from ~550 to 700 nm was depressed by more

than 40%. The opposite held for the red "on" state (Fig. S6B). Black decreased the reflection from all wavelengths. When we filled the color layer with white, the reflection increased relative to when the color layer was empty.

### References

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**Fig. S1.** (**A-D**) Various color layers fabricated. In each case (from right to left), a top schematic, a cross sectional schematic (as indicated by the dotted red line in top schematic), and a photograph of the color layer filled with dye.





Fig. S2. (A) Close up image of an un-camouflaged soft robot with regularly patterned microfluidic network in an artificial, man-made environment different from that shown in the main text. (B) The same soft robot from A camouflaged using background matching. (C) Image of the robot from B in three different regions adopting appropriate coloration. The positions are marked with dashed boxes that also indicate the borders of each super imposed image.





**Fig. S3.** The artificial, man-made environment from Fig. 2F of the main text annotated with dashed boxes to show the five positions of the soft robot. The dashed boxes also indicate the borders of each super imposed photograph.

**Fig. S3.** 



Fig. S4. (A) Image partitions of un-camouflaged (red border) and camouflaged (blue border)robots on rock bed. (B) Mean Brightness vs. RMS Contrast of each partitioned region. (C)Masking used to isolate robots from background. (D) Computed values of mean brightness andRMS contrast for un-camouflaged robot, camouflaged robot, and full background.





**Fig. S5.** (**A-B**) Grayscale images of a soft robotic quadruped with and without a camouflage layer. (**C-D**) "Canny" edge finding algorithm applied to images **A** and **B**.

Fig. S5.



Fig. S6. Reflectance spectra collected for color layers in the "on" and "off" states. The left column (A, B) was collected using an incandescent light source and the right column (C, D) was collected using a fluorescent light source. Each spectrum includes a photograph of the area sampled as an inset. (A, C) Reflectance spectra of the empty color layer in the "off" state. (B, D) Stacked spectra for four different "on" states. The intensities of the spectra are expressed relative to the intensity of the "off" state where relative intensity equals *I*<sub>on</sub>/*I*<sub>off</sub>.





## **Supporting Movies**

Movie S1. A soft robot walks onto a bed of rocks and is camouflaged (2m 27s actual duration).

Movie S2. A soft robot walks onto a bed of rocks covered in leaves and is displayed with

fluorescent coloration (1m 4s actual duration).

Movie S3. A soft robot is displayed in the dark using chemiluminescence (1.5X actual speed).

**Movie S4.** Simultaneous operation of visible and IR camouflage/display sequence (4X actual speed).