Supplementary information

Dynamic surface deformation of silicone elastomers for management of marine biofouling: laboratory and field studies using pneumatic actuation

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Design and features of 3D printed plastic template

3D printed plastic (acrylonitrile butadiene polystyrene, ABS) templates (Figure S1a), consisting of vertical and horizontal strips, were used for the fabrication of elastomer pneumatic network. Each of the long (40 mm) parallel stripes in the plastic mold forms an air channel in the prepared elastomer network (Figure S1b). The air channels are separated from one another by 5 mm and interconnected by the opening formed by smaller stripes (Figure 1Sb).

Figure S1: Fabrication and calibration of elastomer pneumatic networks. Schematic and dimensions of the plastic 3-D-printed template used for making the prototype elastomer
pneumatic networks (a), cross-section schematic of an Ecoflex elastomer pneumatic network connected to a pneumatic pump for actuation (b).

Shear moduli of Ecoflex silicone elastomer

Using the Arruda-Boyce model (Arruda and Boyce 1993), the nominal stress \( s \) for plane-strain uniaxial tension is given by,

\[
    s = \mu [(\varepsilon + 1) - (\varepsilon + 1)^{-3}] \left[ 1 + \frac{I_1}{5N} + \frac{11I_1}{175N^2} \right]
\]

Equation (S.1)

where, \( \mu \) is shear modulus of the Ecoflex film, \( \varepsilon \) is the uniaxial strain, \( I_1 = (\varepsilon + 1)^2 + (\varepsilon + 1)^2 + 1 \), and \( N \) is a parameter that accounts for the stiffening effect. This equation was fitted to the experimental data obtained from uniaxial tension tests (Figure S2) using parameters \( \mu = 10.5 \text{ kPa} \) and \( N = 7.28 \) for Ecoflex-10, and \( \mu = 50.2 \text{ kPa} \) and \( N = 7.17 \) for Ecoflex-50.

![Figure S2: Effect of applied nominal stress on generated surface strain (\( \varepsilon \)).](image)
2-D plane strain model for theoretical prediction of surface strain

A 2D plane-strain model was used by considering the deformation of a long strip of thin Ecoflex membrane on the top of a pneumatic channel. Under an applied uniform pressure $P$ (> atmospheric pressure), the Ecoflex film on top of the pneumatic network will deform outwards as an arc with radius $R$ (Figure S3); the force balance is given by,

$$PR = \sigma_\theta h$$  \hspace{1cm} \text{Equation (S.2)}

where $\sigma_\theta$ is the membrane stress. By denoting the initial and inflated lengths as $2L$ and $2l$, and the initial and deformed thicknesses of the film as $H$ and $h$ respectively, the two principal stretches in the film are given by,

$$\lambda_\theta = \frac{l}{L} = \frac{\theta}{\sin \theta}, \quad \lambda_r = \frac{h}{H} = \frac{1}{\lambda_\theta}$$  \hspace{1cm} \text{Equation (S.3)}

where $2\theta$ is the angle of the arc (Figure 1e). The Ecoflex film obeys the Arruda-Boyce model ie,

$$\sigma_\theta = -p_0 + \mu \lambda_\theta^2 \left(1 + \frac{l_1}{5N} + \frac{11l_2}{175N^2}\right)$$  \hspace{1cm} \text{Equation (S.4)}

$$\sigma_r = -p_0 + \mu \lambda_r^2 \left(1 + \frac{l_1}{5N} + \frac{11l_2}{175N^2}\right)$$  \hspace{1cm} \text{Equation (S.5)}

where $p_0$ is the hydrostatic stress in the elastomer, $\mu$ is the shear modulus of the Ecoflex film, and $l_1 = \lambda_\theta^2 + \lambda_r^2 + 1$. Given that the radial stress $\sigma_r = 0$, the membrane stress can be expressed as

$$\sigma_\theta = \mu (\lambda_\theta^2 - \lambda_r^2) \left(1 + \frac{l_1}{5N} + \frac{11l_2}{175N^2}\right)$$  \hspace{1cm} \text{Equation (S.6)}

Based on Equations (S.2) – (S.6), the relationship between the applied pressure and applied surface linear strain is calculated using the resulting equation $\varepsilon = (\lambda_\theta - 1)$. 
Figure S3: Schematic shows the 2D cross-section view of deformation of a thin elastomer membrane, caused by increase in air pressure (P > atmospheric pressure).

Effect of applied substrate strain on *C. marina* and *E. Coli* biofilm

The experimental data of biofilm released from Ecoflex-10 (b) and Ecoflex-50 (c) elastomer networks for different amounts of applied strain via pneumatic actuation (Figure 2) were fitted an empirical equation (Equation 2). Using the fitted data substrate strain needed to detach 20% ($\varepsilon_{20}$), 50% ($\varepsilon_{50}$) and 80% ($\varepsilon_{80}$) of biofilm was determined and plotted (Figure S4) for comparison.

Figure S4: Effect of substrate strain on bacterial biofilm release. The percentage of substrate strain needed to detach 20% ($\varepsilon_{20}$), 50% ($\varepsilon_{50}$) and 80% ($\varepsilon_{80}$) of *C. marina* and *E. coli* biofilms from Ecoflex-10 and Ecoflex-50 was measured by fitting the experimental data to Equation (2).
References