Table of Equations for SCP Actuators

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1 Variable Names and Description

Variables		
Variable Name	Units	Description
k	N/m	Spring constant; provided in literature based off of material used
d	m	Movement; change in actuator length when load and heat are applied or change in position of load when actuator contracts
T	K	Temperature of the Actuator
T_0	K	Ambient Temperature
c	mN/ C°	Thermal Constant; converting change in temperature to change in force
P	W	Power
V	V	Voltage
R	Ω	Resistance
ρ	Ωm	Resistivity; provided in the literature and dependent on type of string used
l	m	Length of the actuator (coiled)
$l_{original}$	m	Length of string used to make actuator
A	m^2	Area; based on diameter of actuator
ΔT	N/A	Coil deformation due to change in fiber twist per initial fiber length; thermally induced fiber untwist; change in twist per length
LCF	N/A	Length contraction factor (ratio of non-twisted fiber length ($l_{original}$) to coil length (l); used from literature characterization of the actuators
N	N/A	Number of coil turns; (turns/m)*$l_{original}$
C	N/A	Known as the spring index, this is the ratio of the coil diameter to the fiber diameter [1]
V_{ss}	V	Step-Voltage Input

1.1 Length Contraction Factor and Turns/m for Each Type of Thread

LCF and Turns/m [1]		
LCF	Turns/m	Type of Thread
4.5	3020	127 μm nylon 6,6 monofilament
4.2	2430	180 μm silve plated nylon 6,6 multifilament
4.5	1430	270 μm nylon 6 monofilament
3.3	2270	130 μm fused polyethelene braid

2 Equations

$$F = kd + c(T - T_0) \tag{1}$$

Equation (1) describes the relationship between force, displacement, and temperature. The force refers to how much force the SCP actuator actually produces. The displacement is how much the SCP actuator contracts or expands from its rest length. The temperature is the temperature of the SCP actuator; this is controlled by Joule heating of the actuator[2].

$$Cth\frac{dT(t)}{dt} = P(t) - \lambda(T(t) - T_{amb}) \tag{2}$$

where T_{amb} is 25 C°

To attain a temperature of 150 C°

$$VoltagePotential = 0.2W/cm[2] \tag{3}$$

Also given as equivalent: Voltage Potential = 1.5 V/ cm of coil length

Relating Equation (1) (3) (4), displacement is the change in actuator length. Initial length is taken at the ambient temperature T_0 and T is taken to be 150 degrees Celsius. Resistance 25 Ω, Power is 0.2W/cm (multiplied by length of actuator will give you power), allowing you to solve for voltage.

$$T = \frac{Cth}{\lambda} \tag{4}$$

where T is tau, the rise-time and fall-time of the force profile. In the literature, it is approximated at 3 seconds.

$$T(t) = T_{amb} + \frac{V_{ss}^2}{\lambda * R}(1 - e^{\frac{\lambda}{Cth}t}) \tag{5}$$

where T_{amb} is 25 C°

$$P = \frac{V^2}{R} \tag{6}$$

$$R = \rho * l \tag{7}$$

$$I = \frac{V}{R} \tag{8}$$

$$l = \frac{l_{original}}{LCF} \tag{9}$$

Equation (6) correlates the LCF, which is a materialistic property for each type of polymer, to the length of the actuator itself. Therefore, the length of the actuator may be determined simply by knowing the length of the polymer used to create the actuator and the type of polymer used [1].

$$\frac{d}{l} = \frac{l_{original}^2 * \Delta T}{l * N}[1] \tag{10}$$

$$\Delta T = \frac{N * d}{l_{original}^2} \tag{11}$$

$$C = \frac{CoilDiameter}{FiberDiameter}[1] \tag{12}$$

Fully Coiled Polymers were formed at 392 $\pm$ 15 rotations/cm.

References

[1] Carter S. Haines et al. *Artificial Muscles from Fishing Line and Sewing Thread.* Science, 2014.

[2] Michael C Yip and Gunter Niemeyer. *High Performance Robotic Muscles from Conductive Nylon Sewing Thread.* IEEE, 2014.

[3] Michael C Yip and Gunter Niemeyer. *High Performance Robotic Muscles from Conductive Nylon Sewing Thread.* IEEE, 2017