Dumitru, S.I., Brisan, C., Dumitriu, D. and Chiroiu, V., 2017. On the soft robotics constitutive laws. *Romanian Journal of Technical Sciences – Applied Mechanics, 62(1)*, pp.68–79.

# ON THE SOFT ROBOTICS CONSTITUTIVE LAWS

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*Abstract*. Soft robotics is a class of hard and soft robots that contain a rigid internal structure and nonrigid body parts. The elastic components consist of nanostructured materials which exhibit new features such as the echoes reflected from skin and surrounding components, the autonomy of power, audio and video sensing, visionary capabilities of self-repair and the capacity to carry large loads for a desired mission. In this paper, we try to find a class of constitutive laws of soft-bodied robots by using the pseudospherical reduction approach which associates to the governing equations a pseudospherical surface with negative Gaussian curvature. The pseudospherical surface permits to manipulate the Gaussian curvature and therefore to obtain a maximum tensile strength for nanostructures made from carbon nanotubes. The aim of the article is to develop constitutive laws for a class of nanoropes based on carbon nanotubes with adjustable mechanical properties in order to match the compliance of natural tissues without advanced feedback control.

*Key words:* soft robotics, nanostructured materials, pseudospherical reduction method, carbon nanotubes, Tzitzeica surface, negative Gaussian curvature.

## 1. INTRODUCTION

The term "Soft Robotics" is used to designate a new class of robots able to deform and adapt the shape to external loadings, constraints and obstacles [1–4]. Unlike rigid robots, soft robots are made of soft nanostructured materials similarly to biological material, able to interact with biological systems for different purposes. The compliance matching of soft robots with living tissues reduce interfacial stresses and increase the comfort and safety of the human user [5, 6].

Researchers look for inspirations in nature, to exploit the elastic mechanisms with which the animals settle a variety of tasks starting with stepping dampers, jumping catapults, energy storage for motion, jumping off water's surface and ending with learning the collective behaviour from ant colonies.

It is interesting to see that soft robotics represents a part of the educational research for students, for example in the Harvard Biodesign Lab. Ingenious initiatives for real-world applications have been advanced by students. The soft wheel robot (Cornell University, NY, USA) utilizes a cylindrical shell with inflatable channels on the exterior to induce a rolling speed of about 6 m/min. The

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smart braids (University of Michigan, MI, USA) with conductive reinforcing fibers provides a way of sensing the deformation and force output of fiber-reinforced actuators without any external transducers. Myglove (Olympia High School, WA, USA) is a wearable glove that detects and controls tremors using pneumatic actuators and so on.

Nanostructured materials such carbon nanotubes have unique mechanical and electronic properties for soft, bendable and stretchable materials that can replace conventional stiff and brittle materials, for sensing and actuation equipment [7–11].

The tensile strength of the carbon nanotube is maximum 30 GPa, the density for normalized strength is 56 times that of steel wire, the tensile strength is about 200 GPa for comparison to the graphite fibres 4.7 GPa and stainless steel 1.5 GPa [8–10].

Conventional continuum theories are unable to capture the principal features of soft-bodied robots experimentally observed, due to the lack of intrinsic length scales that represent the measures of internal structure in the constitutive relations.

In order to overcome this deficiency, different theory have been used. The Mooney-Rivlin, Ogden and Yeoh constitutive models and other theories are empirical models based on experiment data and able to simulate the nonlinear elasticity of soft materials [12]. The nonlinear stress-strain relationship to moderate and large strains represents the principal feature of soft materials. Currently, there no exist theoretical solutions for kinematic or dynamic modelling problems of soft materials [13–17]. A soft-bodied robot is approximating the continuum system as many modular elements connected in a special pattern, for example the band shaped robots, or serial arrangement of Voigt models, or series of parallel mechanisms [18]. A constitutive law must describe the global nonlinear mechanical properties of the soft-bodies robots, which cannot be treated empirically.

In this paper, we try to find a class of nonlocal constitutive laws for nanorods made from single-wall carbon nanotubes, by applying the pseudospherical reduction method for which the motion equations are associated to a pseudospherical surface, with negative Gaussian curvature [19, 20].

If the ratio $K/d^4$, where $d$ is the distance from the origin to the tangent plane at an arbitrary point is constant, we obtain a Tzitzeica surface [21, 22]. The Tzitzeica surfaces are invariants under the group of centro-affine transformations, being analogues of spheres in affine differential geometry.

If the distance $d$ is interpreted as a characteristic length of the body (atomic distance), then the long-range interactions among the atoms in carbon nanotubes can be described by a nonlocal theory. In the case of carbon nanotubes, $d$ is the diameter of the carbon nanotube.

In the nonlocal theory, the stress at an atom location is determined by the interatomic interactions in the neighbours around that location [23,24]. The domain of applicability of a continuum theory depends on the ratio $\left(d/l, \tau/\tau_0\right)$ or $\left(d/l, \omega_0/\omega\right)$, where $l$ is the external characteristic length associated with the external forces (waves, distances over which load distribution change sharply, geometrical and surface discontinuities), $\tau$ the time scale (or frequency $\omega$) which is the minimum transmission time of a signal (or a frequency), and $\tau_0$ is the external characteristic time or frequency) associated with the external forces. All classical theories assume $d/l << 1$ and $\tau/\tau_0 << 1$, i.e. the external forces act simultaneously on a large number of regions, so that these regions interact and the result is a statistical average of the individual responses. For $d/l = 1$ and $\tau/\tau_0 = 1$, the individual fields of intermolecular and atomic forces are important [26–28].

## 2. THE PSEUDOSPHERICAL REDUCTION METHOD

For understanding the method, let us consider the simplest example of the uniaxial deformation of a nanorope made from single-wall carbon nanotubes.

The nanorope is made from 6 subropes, each subrope being composed from 7 groups of single wall carbon nanotubes. Each group contains 25 carbon nanotubes with two different radii (zigzag and armchair 6.26Å, $h = 0.617$Å and 16.33Å, $h = 0.998$Å), and the core group consists of 49 chiral carbon nanotube with the same radius (3.22Å and $h = 0.6$Å), into a polymeric matrix [29]. Figure1 shows the nanorope.

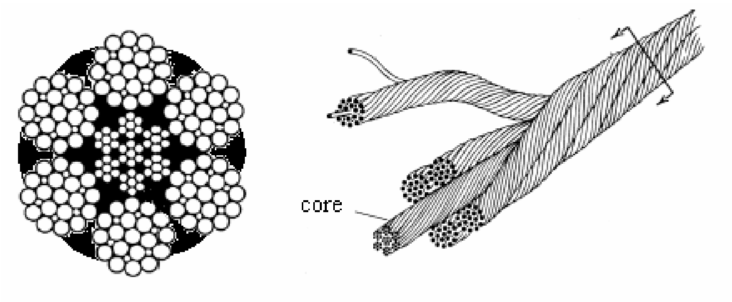


Fig. 1 – Nanorope [29].

The motion Lagrangean equations of the nanorope written in $(X,t)$ coordinate system, are written as

$$\varepsilon_t = v_X \,, \quad \rho_0 v_t = \sigma_X \,. \tag{1}$$

where $\sigma$ is the uniaxial stress and $\rho$ is the density of the material which depend on $|X - X'|$, where $X'$ is any other point in the nanorope, $\varepsilon = \frac{\rho_0}{\rho} - 1$ is the stretch, $\rho_0$ is the density of the material in the non-deformed state, and $v\left(|X - X'|, t\right)$ is the material velocity. In a general form, (1) is rewritten as

$$\sigma = \sigma\left(\varepsilon, |X - X'|\right). \tag{2}$$

In terms of the Eulerian coordinates $x = x(X,t)$, we write

$$\mathrm{d}x = (\varepsilon + 1)\,\mathrm{d}|X - X'| = v\,\mathrm{d}t\,, \tag{3}$$

and

$$\rho_0\,\mathrm{d}|X - X'| = \rho\,\mathrm{d}x - \rho v\,\mathrm{d}t\,, \tag{4}$$

where ρ depends on $|X - X'|$, and $X, X'$ correspond to the particle function ψ or $\psi'$ of the Martin formulation. The independent variables are σ and ψ. In the case of $\rho_0 = 1$, the Monge–Ampère equation is obtained

$$\xi_{\sigma\sigma}\xi_{\psi\psi} - \xi_{\sigma\sigma}\xi_{\psi'\psi'} - \xi_{\sigma\psi}^2 - \xi_{\sigma\psi'}^2 = \varepsilon_\sigma\,, \quad t = \xi_\sigma\,, \quad v = \xi_\psi\,, \tag{5}$$

$$\mathrm{d}x = \left[\xi_\psi\xi_{\sigma\sigma} + \xi_{\psi'}\xi_{\sigma\sigma} + (\xi_\psi\xi_{\sigma\psi} + \xi_{\psi'}\xi_{\sigma\psi'} + \varepsilon)\right]\mathrm{d}\psi\,, \quad 0 < |\xi_{\sigma\sigma}\varepsilon| < \infty\,. \tag{6}$$

If $\xi(\sigma,\psi,\psi')$ is a solution of (6), then the particle trajectories are written as

$$x = \int\left[\xi_\psi\xi_{\sigma\sigma} + \xi_{\psi'}\xi_{\sigma\sigma} + (\xi_\psi\xi_{\sigma\psi} + \xi_{\psi'}\xi_{\sigma\psi'} + \varepsilon)\right]\mathrm{d}\psi\,, \quad t = \xi_p\,. \tag{7}$$

By solving (7), solution $\sigma(\psi,\psi',t)$ is obtained, and then the solution of (1) and (2) in terms of the Lagrangean variables, are

$$x = x(\psi,\psi',t)\,, \quad v = v(\psi,\psi',t)\,, \quad \sigma = \sigma(\psi,\psi',t)\,. \tag{8}$$

If Σ is a surface in $\mathbb{R}^3$ described in the Monge parametrisation

$$r = xe_1 + ye_2 + z(x,y)e_3\,, \tag{9}$$

for $r = r(x,y,z)$ the position vector of a point $P \in \Sigma$ on the surface, the first and second fundamental forms are defined as

$$I = E\mathrm{d}x^2 + 2F\mathrm{d}x\mathrm{d}y + G\mathrm{d}y^2 = (1 + z_x^2)\mathrm{d}x^2 + 2z_x z_y\mathrm{d}x\mathrm{d}y + (1 + z_y^2)\mathrm{d}y^2,$$

$$II = e\mathrm{d}x^2 + 2f\mathrm{d}x\mathrm{d}y + g\mathrm{d}y^2 = \frac{1}{\sqrt{1 + z_x^2 + z_y^2}}(z_{xx}\mathrm{d}x^2 + 2z_{xy}\mathrm{d}x\mathrm{d}y + z_{yy}\mathrm{d}y^2). \tag{10}$$

The Gaussian curvature of Σ is

$$\mathrm{K} = \frac{eg - f^2}{EG - F^2} = -\frac{z_{xx}z_{yy} - z_{xy}^2}{\left(1 + z_x^2 + z_y^2\right)^2}\,. \tag{11}$$

If Σ is a hyperbolic surface, the total curvature is negative and the asymptotic lines on Σ may be taken as parametric curves

$$\sigma = z_x, \quad \psi = z_y, \tag{12}$$

and

$$\xi_\sigma = x, \quad \xi_\psi = y, \tag{13}$$

where $\xi$ is a dependent variable. Therefore, we have

$$\xi_{\sigma\sigma} = \frac{z_{yy}}{z_{xx}z_{yy} - z_{xy}^2}, \quad \xi_{\psi\psi} = \frac{z_{xx}}{z_{xx}z_{yy} - z_{xy}^2}, \quad \xi_{\sigma\psi} = \frac{z_{xy}}{z_{xx}z_{yy} - z_{xy}^2}. \tag{14}$$

The Gaussian curvature (10) yields

$$\mathrm{K} = \frac{1}{\left(1+\sigma^2+\psi^2\right)^2 (\xi_{\sigma\sigma}\xi_{\psi\psi} - \xi_{\sigma\psi}^2)}. \tag{15}$$

The Gaussian curvature may be set into correspondence with the Martin's Monge-Ampère equation (5) by

$$\varepsilon_\sigma = \frac{1}{\mathrm{K}\left(1+\sigma^2+\psi^2\right)^2} \tag{16}$$

and

$$\mathrm{K} = \frac{A^2}{(1+\sigma^2+X^2)^2}, \tag{17}$$

where $A^2 = \dfrac{\partial\sigma}{\partial\varepsilon\,|_X}$ and $A$ is the Lagrangean wave velocity which depends on $\psi, \psi', t$. The surface $\Sigma$ is restricted to be pseudospherical, so that we have

$$\mathrm{K} = -c^2 d^4, \tag{18}$$

where $d$ is the distance from the origin to the tangent plane to $\Sigma$ and $c$ a constant.

The surface with the Gaussian curvature given by (18) is the Tzitzeica surface [20–22]. The importance of the Tzitzeica surface is related to the soliton theory [19]. Developments in the geometry of such surfaces gave a gradual clarification of predictable properties in natural phenomena.

A remarkable number of evolution equations (sine-Gordon, Korteweg de Vries, Boussinesq, Schrödinger and others) considered by the end of the 19th century, radically changed the thinking of scientists about the nature of nonlinearity. These equations admit solitonic behavior characterized by an infinite number of conservation laws and an infinite number of exact solutions. Tzitzeica surfaces are the analogues of spheres in affine differential geometry and are known as affine spheres.

A class of Tzitzeica surfaces of revolution associated with the cnoidal solutions of the Tzitzeica equation $(\ln h)_{\alpha\beta} = h - h^{-2}$, is derived in [29].

The expression (17) gives

$$\frac{\partial^2\sigma}{\partial\varepsilon^2 |_X} = \frac{2}{a^2}(1+\sigma^2+X^2)\sigma\frac{\partial\sigma}{\partial\varepsilon}|_X > 0\,, \quad \sigma > 0\,. \tag{19}$$

From (19) we have

$$\varepsilon = \frac{a^2}{2\left(1+X^2\right)^{3/2}}\arctan\left(\frac{\sigma}{1+X^2}+\frac{\sigma\sqrt{1+X^2}}{1+\sigma^2+X^2}\right)+\alpha(X)\,, \tag{20}$$

with $\alpha(X)$ arbitrary. If $\sigma|_{\varepsilon=0} = 0$, it results $\alpha(X)$=0.

The relation (20) represents a class of constitutive laws for nanoropes, for which the equations (1) are associated to a pseudospherical surface $\Sigma$.

The constitutive laws of new tunable materials seem to be a key point to improve the soft robotic applications. For example, a simple application of (19) and (20) is the variable stiffness of the soft robots. For the uniaxial motion, the tunning of Gaussian curvature of the Tzitzeica surface given by (17) presents an intrinsic material effect as the variation of stiffness, when $a$ is a multipler of the distance $d$ from the origin to the tangent plane to $\Sigma$. This means that the physical response of any point in the material depends on the Gaussian curvature of the Tzitzeica surface which is a characteristic of the state of whole volume. This dependency is the main characteristics of the nonlocality [27, 28].

In this case, the constant $c$ is proportional to the micro or nano size of particles or other ingredient and fillers in the micro or nanopolymers used in artificial muscle [2, 34], and it is simply to show that the relationship between the Young's modulus and the area moment of inertia is given by $cEI = c_0 S$, with adjustable $c$ and $c_0$. This implies that two strategies can be used to variable stiffness approach: adjusting of material properties and alteration of structure geometries.

In contrast to rigid structures, the soft, malleable structures and new materials and surfaces permit achieving of performance that only the nature has. That's why the researchers inspire from humans, vertebrates, caterpillars, snakes, plant roots and others. By understanding them, the man is capable to create a new generation of robots – "soft robots", for using them in unsafe environments, to capture and manipulate unknown objects, to move in rough terrain, interacting with people in situations of top security and even to self-repair.

Starting from (20) we can obtain several constitutive laws for other soft materials which experience a variation of resistance, capacitance or inductance when subjected to mechanical loads (stress or deformation), temperature, electric signals.

For example, introducing in (19) the stress representation

$$\sigma = \sqrt{1+X^2}\tan\left(\frac{\sqrt{1+X^2}}{a}(c-c_0)\right), \tag{21}$$

we have

$$\varepsilon = \frac{a^2}{2(1+X^2)}\left[\frac{c-c_0}{a} + \frac{1}{\sqrt{1+X^2}}\right]\sin\left(\frac{2\sqrt{1+X^2}}{a}(c-c_0)\right). \tag{22}$$

Thus, relations (21) and (22) represent the parametric representation of $\sigma = \sigma(\varepsilon, X)$, for which the motion equations (1) are associated to a pseudospherical surface $\Sigma$. These equations lead to

$$\sigma_{XX} = \varepsilon_{tt}, \tag{23}$$

where $\sigma_{XX}$ is obtained from (16)

$$\sigma_{XX} = \left[\frac{a^2}{\left(1+\sigma^2+X^2\right)^2}\sigma_t\right]_t. \tag{24}$$

The equation (24) like others remarkable equations (Korteweg and de Vries, Burgers, sine-Gordon, Schrödinger, etc.) has interesting properties: an infinite number of local conserved quantities, an infinite number of exact solutions expressed in terms of the Jacobi elliptic functions or the hyperbolic functions, and the simple formulae for nonlinear superposition of explicit solutions. Such equations were considered integrable or more accurately, exactly solvable.

The soft material which experiences a variation of resistance and long-range interactions among the atoms in carbon nanotubes. The aim is to develop nonlocal constitutive laws for materials with adjustable mechanical properties in order to match the compliance of natural tissues without advanced feedback control. This is possible due to relationship (17) between the Gaussian curvature and the Lagrangean wave velocity for long-range interactions among the atoms.

## 3. CARBON NANOTUBES

Due to their remarkable electronic and mechanical properties, carbon nanotubes offer good potential to create layered actuating structures exhibiting displacements in the cm range, forces in N range, and reaction rates in the s to ms range, for actuating devise (nano tweezers, gate systems) or filler within polymers and ionic liquid mixtures or tubular devices in surgical application [2].

We consider the nanorope shown in Fig. 1. The maximum curvature K for the nanorope is

$$\mathrm{K} = \frac{a_{rope}\varepsilon}{d(1+\varepsilon)}, \tag{25}$$

where $a_{rope}$ is a constant depending on the type and number of nanotubes, $\varepsilon = \frac{\rho_0}{\rho} - 1$ is the stretch, and $d$ the nanorope diameter. The type of carbon nanotube is given by a geometrical parameter $r$, $r = na + mb$, where $a$ and $b$ are the lattice unit vectors, and $(n,m)$ is a pair of integers. For $m = 0$ we have a zigzag form, for $n = m$ we obtain an armchair form, while in the general case a chiral form is obtained. The chiral angle is given by

$$\tan\theta = \frac{m\sqrt{3}}{2n+m}. \tag{26}$$

To determine the nonlocal density function $\rho\left(|X - X'|\right)$ for the nanorope, we express it in term of a nonlocal kernel function $\alpha$ which measures the effect of the strain at $X'$ on the stress at $X$

$$\rho\left(|X - X'|\right) = \alpha\left(|X - X'|\right)\rho_0, \tag{27}$$

where $\rho_0$ is the density of the nanorope in the non-deformed state.

The expression $\alpha\left(|X - X'|\right)$ is obtained from minimizing the potential functional $\Pi$ expressed in terms of the repulsive potential $V_R\left(|X - X'|\right)$, the attractive potential $V_A\left(|X - X'|\right)$ and the Lennard-Jones potential $V_{dvw}\left(|X - X'|\right)$

$$\Pi = \Pi_0 + \gamma\int_V \left[V_R - \beta V_A + V_{vdw}\right]\mathrm{d}V'(X'), \tag{28}$$

with $\gamma$ and $\beta$ the coupling factors, and

$$V_R\left(|X - X'|\right) = \frac{D_e f_c\left(|X - X'|\right)}{S-1}\exp\left(-A_1\left(|X - X'|\right)\right),$$

$$V_A\left(|X - X'|\right) = \frac{S D_e f_c\left(|X - X'|\right)}{S-1}\exp\left(-A_2\left(|X - X'|\right)\right),$$

$$V_{vdw} = 4\tilde{\varepsilon}\left[\left(\frac{r_0}{\left(|X - X'|\right)}\right)^{12} - \left(\frac{r_0}{\left(|X - X'|\right)}\right)^{6}\right],$$

$$2f_c = 1 + \cos\left[\frac{\pi\left(|X - X'| - R_1\right)}{R_2 - R_1}\right],$$

$$f_c\left(|X - X'|\right) = \begin{cases} 1, & |X - X'| < R_1, \\ f_{0c}, & R_1 < |X - X'| < R_2, \\ 0, & |X - X'| > R_2, \end{cases}$$

where $D_e = 6.32$eV, S = 1.29, $\tilde{\varepsilon}$ the energy at the minimum in $V_{vdw}$, and $r_0$ the distance between two carbon nanotubes at which $V_{vdw} = 0$, $\varepsilon_0 = 0.0556$ kcal/mol and $r_0 = 3.4$ Å. The function $f_c\left(|X - X'|\right)$ is an optional "cut-off" function and it may be used to smoothly limit the interactions in (28) within a predefined range of neighboring nanotubes, effectively defined by radii $R_1 = 1.70$ Å and $R_2 = 2.00$ Å [30, 31].

The minimal potential functional Π is given by

$$\min \Pi = \frac{f_c(\gamma - \beta\alpha_{\min})}{\sqrt{1 + f_c^2}}, \tag{29}$$

where $\alpha_{\min}$ is defined as

$$\alpha_{\min}\left(|X - X'|\right) = \begin{cases} \sum_{p=1}^{m}\left[B\left(1 - \frac{|X - X'|}{d}\right)\right]^p, & |X - X'| < d, \\ 0, & |X - X'| > d. \end{cases} \tag{30}$$

where $d$ is the nanorope diameter, $B = 1/d$ and δ is the distance between two neighboring carbon nanotubes. In an equilibrium state, $\delta \approx 1.42$ Å.

We recognize in (30), the Artan form of expressing the α [32]. The expression (28) can be interpreted as a stationary Tzitzeica surface $z = z(\alpha)$ in cylindrical coordinates with Gaussian curvature $\mathrm{K} = \frac{z'z''}{\alpha\left(1 + z'^2\right)^2}$ and the distance $d$ from the origin to the tangent plane of a surface of revolution $r = r(\alpha, z)$ given by $d = \frac{z - \alpha z'}{\sqrt{1 + z'^2}}$. This stationary Titzeica surface representing the potential functional Π is displayed in Fig. 2. The minimum of the potential functional Π is obtained by intersecting the surface with the plane shown in figure.

The tensile strength of nanorope $\delta_{rope}$ is proportionally to α, and can be described by the following equation [33]

$$\delta_{rope} = \delta_{CNT} \cos\alpha(1 - d \operatorname{cosec}\alpha) , \tag{31}$$

where $\delta_{CNT}$ is the tensile strength of the single-wall carbon nanotubes.

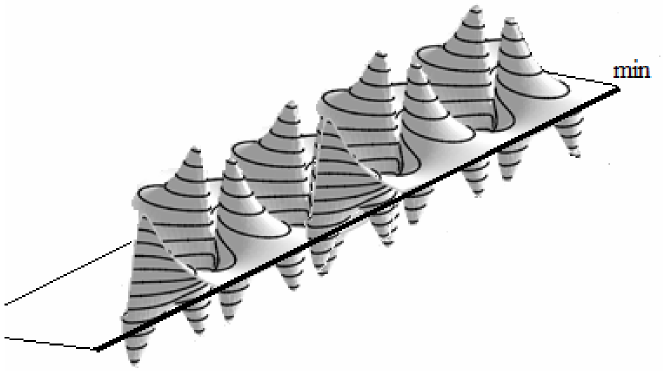


Fig. 2 – Stationary Titzeica surface representing the potential functional Π.

## 5. CONCLUSIONS

The soft robotics is a multidisciplinary field which includes materials science, advanced manufacturing, bioinspired design, robotics and medical devices. Soft robots contain rigid internal structures and nonrigid body parts. The elastic components consist of nanostructured materials which exhibit properties to feature high levels of functional integration: electronics, sensors, and drive technology, in order to enable robots to react reliably to the environment.

The goal of the paper is to determine a class of constitutive laws for a soft material which is a nanorope made from single-wall carbon nanotubes. Carbon nanotubes offer good potential foractuating structures exhibiting displacements in the cm range, forces in N range, and reaction rates in the s to ms range, for actuating devise (nano tweezers, gate systems) or filler within polymers and ionic liquid mixtures or tubular devices in surgical applications.

The scope is to obtain the adjustable mechanical properties in order to match the compliance of natural tissues without advanced feedback control. The research in the soft robotics field is still open. Our paper is related to other researchers in the field of soft robotics, as far as it is concerned to modeling and simulation of constitutive laws of soft materials [35]. Our main result consists in advancing of a simple method, which unlike the methods offered by the literature (FEM, classical deformable media theories) is able to capture and to describe the properties we specially want for a soft material, in particular the carbon nanotubes. The potential functional has an important role in fabrication of dielectric elastomer actuators that combines the acrylic polymers and nanoropes-electrodes made from single-wall carbon nanotubes. These actuators are artificial muscles that activate the movement of soft robots. The carbon nanotubes offer a good alternative to pneumatic actuators which are slow to respond and difficult to store.

We use the pseudospherical reduction approach which associates to the governing equations a pseudospherical surface with negative Gaussian curvature. The surface with a negative Gaussian curvature is the Tzitzeica surface. The Tzitzeica surfaces are related to the solving of certain practical problems in the fields of solid mechanics, fluid mechanics and biomechanics. The uniaxial deformation problem for nanoropes is discussed via the pseudospherical reduction technique. The pseudospherical surface permits to manipulate the Gaussian curvature and therefore to obtain a maximum tensile strength for nanostructures made from carbon nanotubes.

*Received on March 14, 2017*

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