EXPANDING THE ROLE OF ELECTRO-THERMAL ACTUATORS BASED ON CARBON NANOTUBES WITHIN THE FABRICATION OF PRE-PROGRAMMED MATERIAL COMPOSITES.

EREZ EZRA[1] and SHANY BARATH[2]
[1,2] *Technion, Israel Institute of Technology*
[1] *arch.erezezra@gmail.com* [2] *barathshany@technion.ac.il*

Abstract. Taking a cue from research at the crossroads between chemistry, material science, and nanotechnology this paper examines the role of material-driven fabrication methods that enable the integration of pre-programmed geometrical expression onto customized thin-film composites from within a design mindset. Recent developments in electrothermal actuators (ETAs) have demonstrated low cost and ease of fabrication with relatively high precision deformation capabilities. We, therefore, explore ETAs based on Carbon Nanotubes (CNT) capable of reversible actuation in a controlled fashion by external stimuli. Our interest focuses on the ability to pre-program deflection through intervention with the CNT application and composite layer configuration as well as exploring affordable and relatively accessible fabrication methodologies. These adaptive mechanisms displaying; controllable movements, unique actuations, and high thermal insulation suggest affordable and responsive opportunities for developing design applications capable of expanding the role of material agency in the physical context.

Keywords. Material computation; Pre-programmed geometry; Electro-thermal actuation; Carbon Nanotubes; Composite fabrication.

1. Introduction

The re-invention of materials through the assimilation of new technologies has been essential to the way that architecture has evolved in form, expression, and performance over the centuries. Such impact can be demonstrated through early concepts of adaptive and responsive architecture that evolved in the ‘60s and ’70s, mainly due to the developments in cybernetics, artificial intelligence, and information technologies (Kolarevic and Parlac, 2015). Ideas seeking spatial intelligence and adaptability through material novelty have been described by novelist James Graham Ballard in the ‘plastex’ as early as 1962. However, current alternatives addressing responsiveness through a material perspective have emerged due to technological advancements and automation processes that enable elaborated research into material performance and its possible integration into a spatial context. Shifting from an understanding of isolated architectural systems

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 1, 613-622.

into a logic of integration and inclusiveness, we enter a context where materials themselves can be active and intentional. What does it mean to 'program' matter to fulfill architectural needs and adapt to a changing context and stimuli? How can a material agency become instrumental in the design of responsive systems?

Current exposure to new modes of production through advances in the fields of biotechnology, material science, and design computation have given architects access to intricate material resolution colliding new form-making techniques with new manufacturing procedures in order to optimize standard material applications and propose novel architectural expressions. Examples for such qualities include; Living materials that incorporate living organisms or ecosystems as essential components (Myers and Antonelli, 2018), Smart Sensor Technology that processes environmental data towards pre-programmed code specifying material behavior (Abhari and Abhari, 2019) as well as flexible actuators in Soft Robotics that have seen a revival of interest in recent years within architectural discourse due to parallel developments in the state of the art robotics and material research (Decker, 2015; Poppinga et al., 2018). The potential to blur the distinction between machine and material i.e. to 'program matter', entails the design of physical matter capable of changing form and/or function in a programmable manner (Tibbits, 2012). As the practice of material design expands, the ability of materials to interact with the environment and respond to external stimuli has become technologically possible (Kretzer, 2017). Following advancements in soft robotics addressing electro-thermal actuators (ETAs) based on Carbon Nanotubes (CNT), this paper explores the role of these actuators beyond the crossroads of chemistry, material science, and nanotechnology, infusing the fabrication of such pre-programmed composite structures towards design intent.

2. Flexible Actuators in Soft Robotics

Soft robotics has opened new perspectives for robot design and control by using highly compliant materials capable of high deformations during interaction (Laschi et al., 2012). Flexible actuators and materials which can vary their stiffness are used, and their control is partially embedded in the body morphology and in their capacity to interact with the environment (Brooks, 1991; Trivedi et al., 2008). New requirements for robots to deliver performance similar to natural motions (gripping, crawling, walking, etc.) have triggered research into soft materials avoiding heavy motors and rigid links that can be greatly attributed to the evolution of flexible actuators activated by various stimuli, such as light, magnetic field, pneumatic pressure and electric field (Yang et al., 2020). Within electrically activated actuation, electro-thermal actuators (ETAs) are considered active materials capable of producing different deformation motions without the use of printed circuit boards (PCBs) or embedded flexible printed circuits (FPCs) and can be activated from thermal expansion induced by the amount of joule heating and the coefficient of thermal expansion (CTE) of the material (Sun et al., 2019). Common bi-layer ETAs consist of a polymer carrier layer such as polyimide (Kapton), PDMS, polypropylene, and a flexible electrode layer. Once the voltage is applied, the electrode layer heats up and the actuator bends towards the material with the smaller thermal expansion. Parameters defining the actuation deflection include the use of different polymers, electrical conductivity, flexibility, chemical and thermal stability of the electrode layer, and the expansion of the actuator composite structure with additional layers (Wang et al., 2013).

3. Electro-thermal Actuators based on Carbon Nanotubes

Within composite ETAs, Carbon nanotubes (CNTs) are highly compatible as an electrode layer since they can result in flexible films with sufficient electrical and thermal conductivity. They have a significantly lower CTE than many common polymers and are capable of visual transparency which makes them relevant for both optical and electrical applications (Wu et al., 2004; Kim et al., 2017). These qualities also suggest potential compatibility for spatial frameworks such as façade surface film applications and their possible extension towards increased human and environment feedback and interaction. Another advantage of the CNT composite actuator can be seen in its low-cost and ease of fabrication. Electrothermal actuators usually require easy fabrication processes, compatible with the standard Integrated Circuits (IC) and Micro-electromechanical systems (MEMS) and open a wide range of relatively accessible prototyping exercises (Tarun and Wang, 2012). Their integration within common devices and implementation within existing fabrication flows (Potekhina and Wang, 2019) enable us to test relevant prototype methods for composite film printing in relation to design applications.

Composite ETAs based on CNTs have been of particular interest in the research group of Prof. S. Magdassi at the Center for Nanoscience and Nanotechnology and the Institute of Chemistry in the HUJI. By reconfiguring a bi-layer CNT-Kapton soft actuator and adding a thermally triggered shape memory polymer (SMP), they have formed a tri-layer composite structure capable of extremely high bending curvature movements (300°) and reversible pre-programmed deformations (Sachyani Keneth et al., 2020). The successful restructuring of the bi-layer CNT-Kapton ETA enables exploring alternatives that lend themselves towards spatial performance. The width of research and application of carbon nanotubes in electronic devices (solar cells, electronic displays) along with their distinct qualities as conducting films, capable of transparency, motion flexibility, and integration within common fabrication processes, all serve as a starting point for our design experimentations.

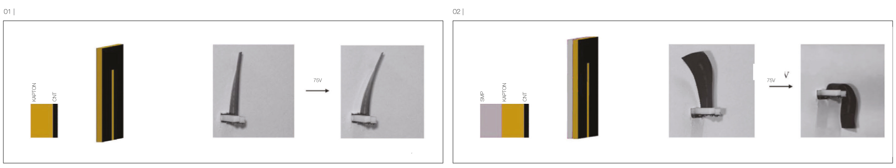

Figure 1. Composite ETAs based on CNTs (Sachyani Keneth et al. 2020), (1) Bi-layer CNT-Kapton (2) tri-layer CNT-Kapton-SMP.

4. Assembly and operation of fabrication workflow

Experiments were designed in order to test possible control of reversible pre-programmed geometrical displacements based on changes in the CNT deposition location, layering structure, and substrate dimensions. The following components were used in the laboratory experiments:

Kapton (Carrier layer): The polyimide film developed mainly for spacecraft and satellites, is used as a flexible yet durable carrier material capable of absorbing extreme temperatures (−269 to +400 °C.) without losing its material properties. (Dementyev et al., 2018).

Carbon Nanotube Ink (Electrode layer): CNT ink can be applied in several ways: Inkjet printer, Airspray, Brushing, or Painting. Ink quantity, application, and coverage on the carrier layer affect the actuator deflection as they reconfigure the material weight, flexibility, and energy consumption. Applying voltage between 5 and 200v on a CNT flexible electrode deposited onto polymeric films results in the heating of the electrode layer, and consequently, in actuation (Sachyani et al. 2017).

Electronic power supply (Activation source for laboratory experiments): Each actuator is activated by a stream of voltage from an external energy source. Two Horizon Dual DC power supplies were (50v) connected, in order to reach a maximum of 100v.

Digital model: Designing variations in electrical conductivity can be controlled through differentiation within the electrode layer. As the CNT application is responsible for the way the voltage is passed through the composite sheet the electrical heating of elements in different locations and distributions across the substrate has a major influence on the actuator shape-changing behavior. A 3D digital model is used to explore possible CNT layouts for defined geometrical deformations.

Composite fabrication: Experiments are assembled with a single Kapton film thickness of 50.8 microns (200 HN, Dupont, USA) cut to size and a homogeneous operable 4-micron electrode layer of brushed CNT ink (Sachyani et al., 2017). Draw-down was performed with an 8R Brush and dried using a hot electric plate (Goldline ALT-500, 82 celsius) between each layer application. The CNT layer used was post-treated with 70% nitric acid for 5 min, in order to improve conductivity similar to the experiments conducted at the Magdassi Lab. The power source is applied in a chain connection to the composite sheet using double-sided brass tape and attaching +- electrodes. Voltage is applied using a dimmer switch enabling a controlled range of power supply until 100v. Applying electricity equals turning on the system. The experiments were framed in two categories:

1. Geometrical deflection within the dimensions of the actuator; Testing the ability to create pre-programmed behavior through differentiated CNT application patterns.
2. Geometrical deflection beyond the dimensions of the actuator; Understanding the capability for actuation within a larger spatial configuration through the expansion of the carrier layer beyond the dimensions of the electrode layer.

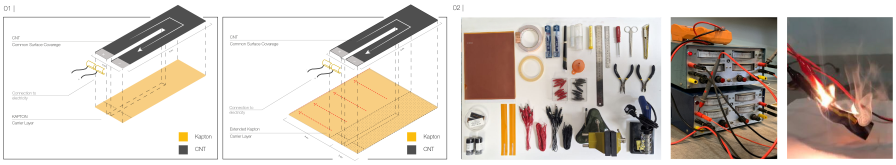

Figure 2. (1) Experiment setup diagrams within and beyond the actuator dimensions (2) Fabrication assembly equipment and initial operability testing .

5. Results

Geometrical deflection within the dimensions of the actuator:

Bending actuation (fig. 3.1): The common actuation mechanism of the basic bi-layer ETA is bending. We first tested the initial operability of actuation through the proposed fabrication workflow on a typical bi-layer . When applying a voltage through the actuator we achieved reversible bending. The actuator deflection is affected by a few parameters such as CTE differences, thermal conductivity, electrical voltage, electrical connectivity (i.e. tape used and electrodes connected), and mechanical properties. In the following experiments, we kept the same parameters of the initial bending actuation apart from the CNT distribution on the kapton. Our aim was to examine the dependency of area and location of heating patterns on bending angles and direction of deflection.

Twist actuation (fig. 3.2): The actuator bends in the direction of the CNT layer due to the CTE differences. Therefore in order to pre-program double bending deformation resulting in a twist at the edge of the actuator, we fabricated a tri-layer composite. CNT ink was applied on both sides of the kapton layer in strategic areas that would define opposite curvature directions of the kapton. However, when applying 100v through the actuator we achieved minor material deformation. We suspect that the edge width dimension of 20mm might have been a limiting factor and have expanded on this in experiment 4.3.

Bifurcation actuation (fig. 3.3): Continuing to test dual-direction curvature, the actuator was fabricated with a cut of 2cm at the loose edge of the carrier layer and positioned in the center of the layer width. CNT ink was once again applied on both sides of the carrier layer to form a tri-layer actuator. Our aim to actuate a reversible bifurcation of the composite was successful when applying a voltage through the actuator.

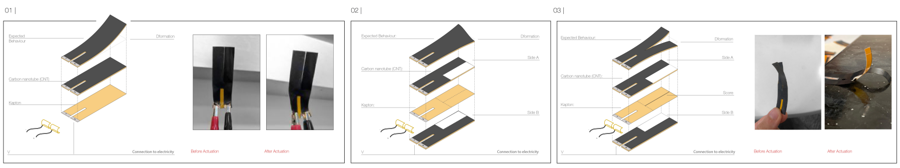

Figure 3. (1) Bi-Layer Bending (2) Tri-Layer Twisting(3) Tri-Layer Bifurcation.

Geometrical deflection beyond the actuator dimensions:

The next experiments examine larger geometrical configurations of singular and multiple actuation. In these experiments, we extend the carrier layer beyond the dimensions of actuation i.e. beyond the dimensions of the electrode layer, in an attempt to examine the impact of deformation as part of a continuous surface.

Surface Bending (fig. 4.1): Applying a standard CNT electrode layer of 20X60mm to an extended Kapton carrier layer 40X60mm. This setup demonstrated the ability of the Kapton surface to potentially amplify the geometrical deflection beyond its thermally activated dimensions. Another possibility that emerges from this setup is the ability of the Kapton extension to serve as a connection area with other materials without interfering with the electrical circuit.

Differentiated Surface Bending (fig. 4.2): Applying two standard electrode layers 20X60mm to the edge of a continuous carrier layer 80X60mm. This experiment requires separate connections to the power supply to enable two actuations on a single surface. Here we test the bending deformation of the full carrier layer when activated homogeneously from both edges and also by applying a different voltage on each edge to achieve gradient reversible curvature. In both experiments, we achieved the actuation of the full surface as predicted in the digital model and experiment setup.

Twisting Surface (fig. 4.3): Continuing with a double actuation setup CNT was applied on a continuous carrier layer 80X60mm on opposite sides of the Kapton). As the direction of deformation is towards the CNT layer due to the CTE differences with the kapton carrier layer we expected each edge to curve in the opposite direction resulting in multiple variations of twisted surfaces. When applying a voltage through the actuators the desired deformation was achieved.

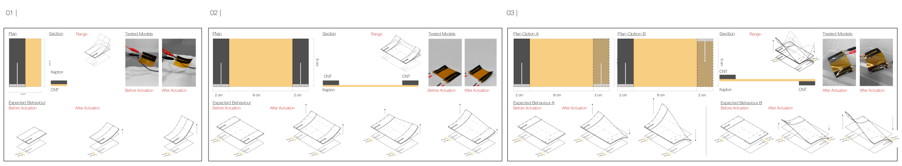

Figure 4. Gradient surfaces (1) Bi-Layer Bending Surface (2) Bi-Layer Dual Activation Bending Surface (3) Tri-Layer Dual Activation Twisting Surface .

6. Discussion

The aspiration for a material agency capable of robotic-like transformation is currently being explored widely within the design and manufacturing of architecture. The demonstration of inherent behavioural features achieved through variations in the fabrication of a tri-layer CNT-Kapton-CNT composite inspires a range of useful characteristics such as reversible actuation, shape modulation, direct interaction with the surroundings and the extension of these qualities within a continuous surface. Nonetheless, when reflecting on these characteristics towards significant spatial performance, questions of scalability and applicability arise regarding (1) Precision and impact of the achieved geometrical deflections

(2) Energy efficiency (3) Integration of the fabrication workflow within possible design applications and the inclusion of additional layers for material performance beyond geometrical deflection.

Geometrical tolerance: Surface articulation within digital architecture has enabled us to re-formulate the resolution of tectonic expressions, and therefore, it is important allowing such control intricacy within the proposed geometrical actuations. The ink deposition has a significant impact on the electrical conductivity and functional motion of the actuator. However, the application method tested enabled mainly aerial CNT layers or simple area divisions attributing mostly homogeneous heating schemes to the actuator and lacking possible enhanced tolerance of deformation through patterning (fig. 5.1). Increasing the application resolution of the CNT ink on the carrier surface would enable investigating ink patterning within the digital model similar to the applications of printed electronics (Heibeck et al., 2015), including potential parameters such as line weight and density (fig. 5.2). Differentiated CNT layer thickness has been demonstrated to influence the deflection of the actuator to a certain extent i.e. sheet resistance decreased with the increase in layer thickness (Sachyani et al., 2017) (fig. 5.3). These potential control variables suggest micro-variations of geometrical deflections that could potentially gain spatial presence through systemic multiplicity on extended surfaces.

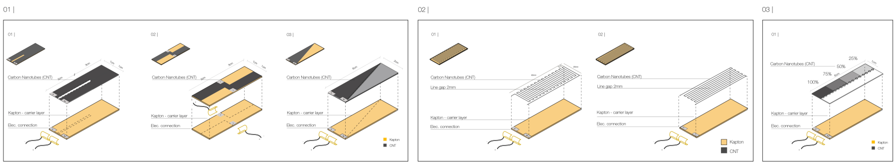

Figure 5. CNT Ink distribution digital inquiry: (1) Aerial (2) Patterned (3) Gradient .

Energy efficiency towards multi actuation surfaces: multiple actuations require exploring alternative power sources that can be incorporated within the extended structure for partial or full activation by environmental parameters (heat, light, etc.), also contextualizing activation in relation to environmental modulation. Possible directions can be seen in recent studies of solar actuation for electricity generation (Xiong et al., 2018) and in developments of printing processes within the photovoltaic solar industry such as Inkjet printing of thin-film solar cells that have also made the technology affordable and accessible (Rardin and Xu, 2011). Within these possibilities, we are able to reflect onwards towards larger configurations of multiple actuation surfaces. The framework needs to be further developed in order to integrate the electrical connectivity between actuations within the material system to avoid exposed wiring and external limitations of the surface deformation. Whereas rigid robotic systems typically employ central control, the use of conductive inks for printed electronics can be investigated in order to support a spatial network of material deformations, distinguishing between deposition of ink for material deformation and deposition of ink for electrical conductivity, defining resistive and non-resistive heating patterns. Accordingly, we have designed an initial test for the fabrication of a multi-actuation surface setup (fig. 6) based on the presented bifurcation experiment. Here we plan to incorporate the two control systems on a single carrier layer in order to test selective control over material deformation and electrical conductivity.

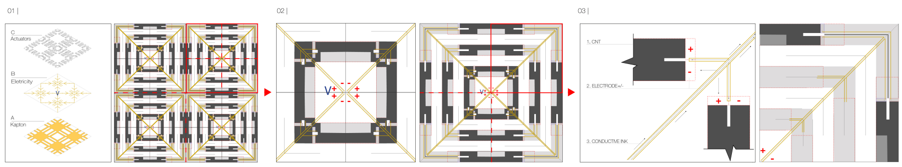

Figure 6. Multi actuation surface diagram (1) Surface layering structure defined through resistive and non-resistive heating patterns (2) Electrical distribution supports minimum connections to external power sources (3) conductive ink to support multiple activations .

Composite Film Printing: Currently, we have initiated the printing of CNT circuits by re-configuring Inkjet printer cartridges, thus testing the transfer of multiple CNT deposition variables from the digital model onto a carrier surface. Our initial tests examined printing articulated thicknesses and geometrical CNT configurations. Similar to applications enabled by printing processes in thin film solar cells and conductive electronics, this opens up potential possibilities for the scalability and integration of thin-film responsive composites based on distributed heat actuations for exterior and interior building surface applications. Multiple challenges are yet to be addressed within the printing process; (1) Compared to regular ink, a relatively thick layer is required to achieve high conductivity (Lin et al., 2013). (2) The possibility to deposit multiple inks both heat resistive and non-heat resistive through cartridge reconfiguration. Further reflections relate to additional layers that will be tested to introduce visual expression of the composite beyond geometrical deflection such as color and opacity modulation that are impactful within a spatial setting. Material composites demonstrating such behavior have been developed for epidermal sensors and on-skin interfaces (Kao et al., 2016; Shi et al., 2018) that are activated through contextual conditions (UV levels, temperature). The potential to extend such material expression through the fabrication of additional performative layers suggests highly intricate material agency within surface interfaces.

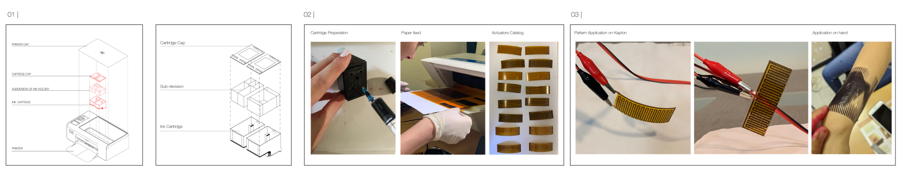

Figure 7. (1) Inkjet HP 1015 printer cartridge configuration(2) Printed CNT testing density & thicknesses (3) Initial printing tests on kapton and adhesive layer .

7. Conclusion

The development of smart materials and flexible systems, such as ETAs based on CNT ink, opens up mechanisms of movement and actuation that demonstrate a range of encouraging possibilities for both accessible and articulated composite behavior. In our explorative studies, we have demonstrated geometrical control through the direct application of CNT ink (electrode layer) on Kapton (carrier layer) expanding from a typical bi-layer to a tri-layer configuration and pre-defining assigned deformations beyond the actuator and onto a surface configuration. The affordable and relatively accessible fabrication methodology has been restructured into a printing method through the configuration of a standard Inkjet printer. We aim to increase control capability over ink thickness, density and type in order to test higher tolerance and threshold of applications. Potential spatial frameworks for expressive thin film composites include; Surface applications for human and environment stimulus-response control systems, Monitor coatings for screens and facades, and new media applications for standard and non-standard geometrical surfaces. The research into additional composite layers would enable the integration of new performance variables that can function as atmospheric and environmental indicators, i.e. the ability to detect PH level, temperature, or humidity conditions and translate them into programmable visual signals, color transformations, and/or opacity levels. Understanding the operability of material composites emerging from the crossroads of different scientific communities enables us to discover new narratives for material performance and explore how may their dynamic behavior be designed and experienced in the space of architecture.

Acknowledgment

We would like to thank Prof. Shlomo Magdassi and Ela Sachyani Keneth at the Magdassi Group,HUJI, for their knowledge and support. The students at the D.Dlab studio namely: Donia Ibraheem, Noa Einhorn, Lour Fahoum & Shireen Saad, and Mr. Kobi Kohai from CRML at the EE Department in the Technion - IIT.

References

Abhari, M. and Abhari, K.: 2019, Design with Perfect Sense: The Adoption of Smart Sensor Technologies in Architectural Practice, *HICSS 2019*.

Brooks, R.A.: 1991, New Approaches to Robotics, *Science*, **253**(5025), 1227-1232.

Decker, M.: 2015, Soft Robotics and Emergent Materials in Architecture, *eCAADe 2015 - 33rd Annual Conference 16th-18th September 2015*.

Dementyev, A., Qi, J., Ou, J. and Paradiso, J.: 2018, Mass Manufacturing of Self-Actuating Robots: Integrating Sensors and Actuators Using Flexible Electronics, *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 6099-6104.

Heibeck, F., Tome, B., Della Silva, C.D. and Ishii, H.: 2015, uniMorph: Fabricating Thin Film Composites for Shape-Changing Interfaces, *28th Annual ACM Symposium on User Interface Software & Technology - UIST '15 Adjunct*, 233-242.

Kao, H.L.(, Holz, C., Roseway, A., Calvo, A. and Schmandt, C.: 2016, DuoSkin: rapidly prototyping on-skin user interfaces using skin-friendly materials, *Proceedings of the 2016 ACM International Symposium on Wearable Computers*, New York, NY, USA, 16-23.

Kim, C.L., Jung, C.W., Oh, Y.J. and Kim, D.E.: 2017, A highly flexible transparent conductive electrode based on nanomaterials, *NPG Asia Materials*, **9**(10), e438-e438.

B. Kolarevic and V. Parlac (eds.): 2015, *Building Dynamics: Exploring Architecture of Change*, Routledge, London ; New York.

Kretzer, M.: 2017, *Information Materials: Smart Materials for Adaptive Architecture*, Springer International Publishing.

Laschi, C., Cianchetti, M., Mazzolai, B., Margheri, L., Follador, M. and Dario, P.: 2012, Soft Robot Arm Inspired by the Octopus, *Advanced Robotics*, **26**(7), 709-727.

Lin, Z., Le, T., Song, X., Yao, Y., Li, Z., Moon, K.s., Tentzeris, M. and Wong, C.: 2013, Preparation of Water-Based Carbon Nanotube Inks and Application in the Inkjet Printing of Carbon Nanotube Gas Sensors, *Journal of Electronic Packaging*, **135**, 011001.

Myers, W. and Antonelli, P.: 2018, *Bio Design: Nature • Science • Creativity*, Thames and Hudson Ltd.

Onal, C., Wood, R. and Rus, D.: 2013, An Origami-Inspired Approach to Worm Robots, *Mechatronics, IEEE/ASME Transactions on*, **18**, 430-438.

Poppinga, S., Zollfrank, C., Prucker, O., Rühe, J., Menges, A., Cheng, T. and Speck, T.: 2018, Toward a New Generation of Smart Biomimetic Actuators for Architecture, *Advanced Materials*, **30**(19), 1703653.

Potekhina, A. and Wang, C.: 2019, Review of Electrothermal Actuators and Applications, *Actuators*, **8**(4), 69.

Rardin, T. and Xu, R.: 2011, Printing Processes Used to Manufacture Photovoltaic Solar Cells, *The Journal of Technology Studies*, **37**, 2.

Sachyani, E., Layani, M., Tibi, G., Avidan, T., Degani, A. and Magdassi, S.: 2017, Enhanced Movement of CNT-Based Actuators by a Three-Layered Structure with Controlled Resistivity, *Sensors and Actuators B: Chemical*, **252**, 1071-1077.

Sachyani, E. K., Scalet, G., Layani, M., Tibi, G., Degani, A., Auricchio, F. and Magdassi, S.: 2019, Pre-Programmed Tri-Layer Electro-Thermal Actuators Composed of Shape Memory Polymer and Carbon Nanotubes, *Soft Robotics*, **7**(2), 123-129.

Shi, Y., Manco, M., Moyal, D., Huppert, G., Araki, H., Banks, A., Joshi, H., McKenzie, R., Seewald, A., Griffin, G., Sen-Gupta, E., Wright, D., Bastien, P., Valceschini, F., SEITE, S., Wright, J., Ghaffari, R., Rogers, J., Balooch, G. and Pielak, R.: 2018, Soft, stretchable, epidermal sensor with integrated electronics and photochemistry for measuring personal UV exposures, *PLOS ONE*, **13**, e0190233.

Sun, Y.C., Leaker, B.D., Lee, J.E., Nam, R. and Naguib, H.E.: 2019, Shape programming of polymeric based electrothermal actuator (ETA) via artificially induced stress relaxation, *Scientific Reports*, **9**(1), 11445.

Tarun, A.P. and Wang, P.: 2012, Designing and building inexpensive flexible circuits, *TEI '12*.

Tibbits, S.: 2012, Design to Self-Assembly, *Architectural Design*, **82**(2), 68-73.

Trivedi, D., Rahn, C.D., Kier, W.M. and Walker, I.D.: 2008, Soft Robotics: Biological Inspiration, State of the Art, and Future Research, *Applied Bionics and Biomechanics*, **5**, 99-117.

Wang, C., Nosaka, T., Yost, B., Zimmerman, B., Sutton, E.D., Kincaid, E., Keberle, K., Iqbal, Q.A., Mendez, R., Markowitz, S., Liu, P., Alford, T.L., Chan, C.K., Chan, K.S. and O'Connell, M.J.: 2013, Printed Carbon Nanotubes on Polymer Films for Active Origami, *Materials Research Letters*, **1**(1), 13-18.

Wu, Z., Chen, Z., Du, X., Logan, J.M., Sippel, J., Nikolou, M., Kamaras, K., Reynolds, J.R., Tanner, D.B., Hebard, A.F. and Rinzler, A.G.: 2004, Transparent, conductive carbon nanotube films, *Science (New York, N.Y.)*, **305**(5688), 1273-1276.

Xiong, Y., Zhang, L., Weis, P., Naumov, P. and Wu, S.: 2018, A solar actuator based on hydrogen-bonded azopolymers for electricity generation, *Journal of Materials Chemistry A*, **6**(8), 3361-3366.

Yang, Y., Wu, Y., Li, C., Yang, X. and Chen, W.: 2020, Flexible Actuators for Soft Robotics, *Advanced Intelligent Systems*, **2**(1), 1900077.