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4-D Printing of Pressure Sensors and Energy Harvesting Devices for Engineering Education

Prof. Tzu-Liang Bill Tseng, University of Texas, El Paso

Dr. Tseng is a Professor and Chair of Industrial, Manufacturing and Systems Engineering at UTEP. His research focuses on the computational intelligence, data mining, bio- informatics and advanced manufacturing. Dr. Tseng published in many refereed journals such as IEEE Transactions, IIE Transaction, Journal of Manufacturing Systems and others. He has been serving as a principle investigator of many research projects, funded by NSF, NASA, DoEd, KSEF and LMC. He is currently serving as an editor of Journal of Computer Standards & Interfaces.

Dr. Aditya Akundi, University of Texas, El Paso

Aditya Akundi is currently affiliated to Industrial Manufacturing and Systems Engineering department, and Research Institute for Manufacturing and Engineering Systems at University of Texas, ElPaso.

He earned a Bachelor of Technology in Electronics and Communication Engineering from Jawaharlal Nehru Technological University, India. He earned a Master of Science in Electrical and Computer Engineering at the University of Texas at El Paso (UTEP). Intrigued by Systems Engineering , he earned a Ph.D in Electrical and Computer Engineering, with a concentration in Industrial and Systems Engineering (ISE) at Unniversity of Texas in 2016. His research is focused on undersanding Complex Technical and Socio-Technical Systems from an Infromation Theortic approach. He has worked on a number of projects in the field of Electrical & Computer Engineering, Systems Engineering, Additive Manufacturing and Green Energy Manufacturing. His research interests are in Systems Engineering & Architecture, Complex systems, Systems testing and Application of Entropy to Complex Systems.

Mr. Hoejin Kim, University of Texas, El Paso

Mr. Hoejin Kim is currently a Ph.D. student in Department of Mechanical Engineering at the University of Texas at El Paso. He received a bachelor degree in materials engineering technology at Korea Tech in 2008 and a master degree in manufacturing engineering technology at Oregon Institute of Technology in 2014. His research interests are focused on 3D printing of piezo-, pyro-, and dielelectric materials for pressure/temperature/strain sensors and energy storage.

4D Printing of Pressure Sensors Devices for Engineering Education

Abstract

This paper elaborates on the development of laboratory project modules in the Industrial manufacturing and systems engineering department at The University of Texas El Paso based on Four-Dimensional (4D) printing technology. These modules are aimed at introducing the students to interdisciplinary manufacturing and emerging dimensions in manufacturing technology. 4D printing is a new dimension in additive manufacturing wherein, the 3D printed structures react to the change of parameters within the environment such as temperature, and humidity, resulting in shape change or in functionality such as electricity output, and self-healing. Recently 4D printing of simple devices for pressure sensors application were identified and show high feasibility for commercialization due to low cost, freedom of design, and agile manufacturing process. This enables a high interdisciplinary platform for research and project modules suitable to be used in the academic environment for hands-on students training. Laboratory Modules based on 4D printing of pressure sensors is developed for student training that includes: 1) Design of piezoelectric nanocomposites; 2) 3-D model design of pressure sensor devices; 3) Using 3-D printers for 4-D printing, and involved post-processing techniques by which students can experience emerging manufacturing technologies, and; 4) Testing for piezoelectric properties.

Introduction & Background

In 2013, Skylar Tibbits from Massachusetts Institute of Technology introduced Four-dimensional (4D) printing where a component is created by Three-dimensional (3D) printing but a later time transforms into another shape or configuration [1]. Typically multi-composites materials (i.e. shape memory polymers) are used to offer different characteristics (functionalities) and performances to 3D structure such as, shape changing upon humidity or temperature change [2]. Emergence of the 4D printing technology is bringing many applications in several application areas. Nowadays, dynamic multi-functionality materials are being developed such as shape memory polymers using smart materials composites for sensor, energy storage, and harvesting [3]. Using piezoelectric materials and 4D printing technology, Kim (2017) studied on design of piezoelectric nanocomposites with a combination of polyvinylidene fluoride (PVDF), barium titanate (BT), and multiwall carbon nanotubes (CNT) and fabricated using material extrusion (ME) 3D printing technique [4-7].

Piezoelectric materials have long been investigated due to their unique characteristic of converting mechanical stress to electric charges and vice versa [8, 9]. Of the piezoelectric polymers and ceramics, PVDF and BT have seen wide applications in electronics, sensing/energy harvesting, and bioengineering [10-12]. The combination of these two materials yields both excellent mechanical and piezoelectric properties so that BT/PVDF nanocomposites are attractive for energy harvesting and sensor applications due to their simple and convenient fabrication process, low cost, and excellent properties [13, 14]. However, it has an intrinsic low direct piezoelectric coupling coefficient which is a drawback with regard to the piezoelectric effect and sensor applications [14-16]. Therefore, graphitic carbon such as MWCNT was utilized to enhance both electric and stress transfer to the ceramic particles and uniform dispersion [5]. It is reported that the ME based 3D printing process significantly improves homogeneous dispersion of BT nanoparticles in the PVDF matrix, enhancing piezoelectric properties [4]. In addition, the ME 3D printing technique is integrated with corona poling, which is one of the traditional poling processes, to simplify fabrication of piezoelectric PVDF films through sequential processes [17]. Kim et. al invented a 3D printing technique to optically fabricate photosensitive polymer based-BT nanocomposites with surface modification [18]. A photopolymer was induced to encapsulate piezoelectric nanoparticles during photo-polymerization. This technique can produce 3D structure of piezoelectric nanocomposites but is limited to combination with photosensitive polymers. Different types of 3D printing techniques were applied to many researches related to piezoelectric materials for sensing applications to enable low cost fabrication and mass production process.

This emerging 3D/4D printing techniques will be combining more and more with other domain of knowledge and moving toward future mainstream occupying industry. Therefore, it is a great teaching tool for college students to be able to learn not only the concept and operation on 3D/4D printing but also understanding of smart materials in class as lab project module. In addition, college students will be exposed to basic knowledge of material science, manufacturing, and mechanical engineering to understand 4D printing of piezoelectric pressure sensor device.

We developed modules for laboratory project consisting of 1) design of piezoelectric nanocomposites where materials engineering background can be taught, 2) 3D model design of pressure sensor devices and testing for piezoelectric property where mechanical engineering skills can be trained, and 3) operation of 3D printer and post-processing where students can experience emerging manufacturing technology.

Nanocomposites Synthesis and Fabrication

For synthesis of nanocomposites and continuous filament, commercial PVDF powder (MW~534,000; Sigma-Aldrich, USA), BT powder (700nm; Inframat®, USA), and multiwall carbon nanotubes (MWCNT) powder (Diameter: 8-15 nm, length: 10-50 µm, Cheaptubes®, USA) were mixed with N-Dimethylformamide solvent (DMF, OmniSolv®) via the solvent-casting method. As schematic illustration of the synthesis process is shown in *Figure 1*.

The BT and CNTs powder were introduced to DMF solvent and this solution was then placed in a bath sonication for 30 min in order for uniform distribution of nanoparticles. The solution is prepared by dissolving PVDF powder (1:10 weight ratio in PVDF:DMF solvent). The solution is then placed in a water bath at 80°C and is stirred using a magnetic stir bar at 300rpm for approximately 30 minutes. After the PVDF powder fully dissolves for approximately 15 minutes, BT and CNTs built up at the bottom of solution is addressed by ultra-sonication (Branson Sonifier 450) for 20 minutes. DMF solvent is then evaporated by dispersing nanocomposites solution onto a glass substrate and heated to a temperature of 90°C for 12 hrs. The procedure yields a thin sheet of CNT/BT/PVDF nanocomposite. The casted nanocomposites were sliced down to be easily extruded by filament extruder machine. The nanocomposite filament is used to 3D print a thick film by a fused deposition modeling 3D printer for a pressure sensor.

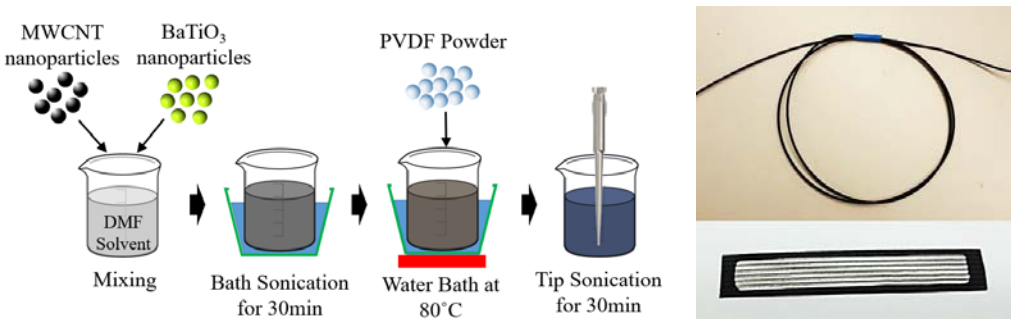


Figure 1. Synthesis procedure of CNT/BT/PVDF nanocomposites.

Software & Hardware

Software

A 3D model for piezoelectric pressure sensor device was designed by SolidWorks software with a dimension of 8 × 35 × 0.5 mm as shown in *Figure 2*(a) and saved as STL file so that it can be uploaded to Slic3r software where is a tool that converts digital 3D models into printing instruction and customize printing parameters such as tool path, fill pattern, etc. as shown in *Figure 2*(b). General printing layer pattern such as zigzag will decrease tensile strength perpendicular to build axis and poor surface finish in order for dynamic testing. Therefore, a concentric fill pattern was set up using Slic3r software to maximize tensile strength for dynamic load frame testing. The saved file was then loaded to Cura software to run 3D printer as shown in *Figure 2*(c). For the printing parameter, the film is printed at 220 °C of nozzle temperature, 50 °C of heating bed temperature, and 15 mm/s of extrusion speed. Final film was 0.55 mm in thickness with dimensions of 8 × 35 mm.

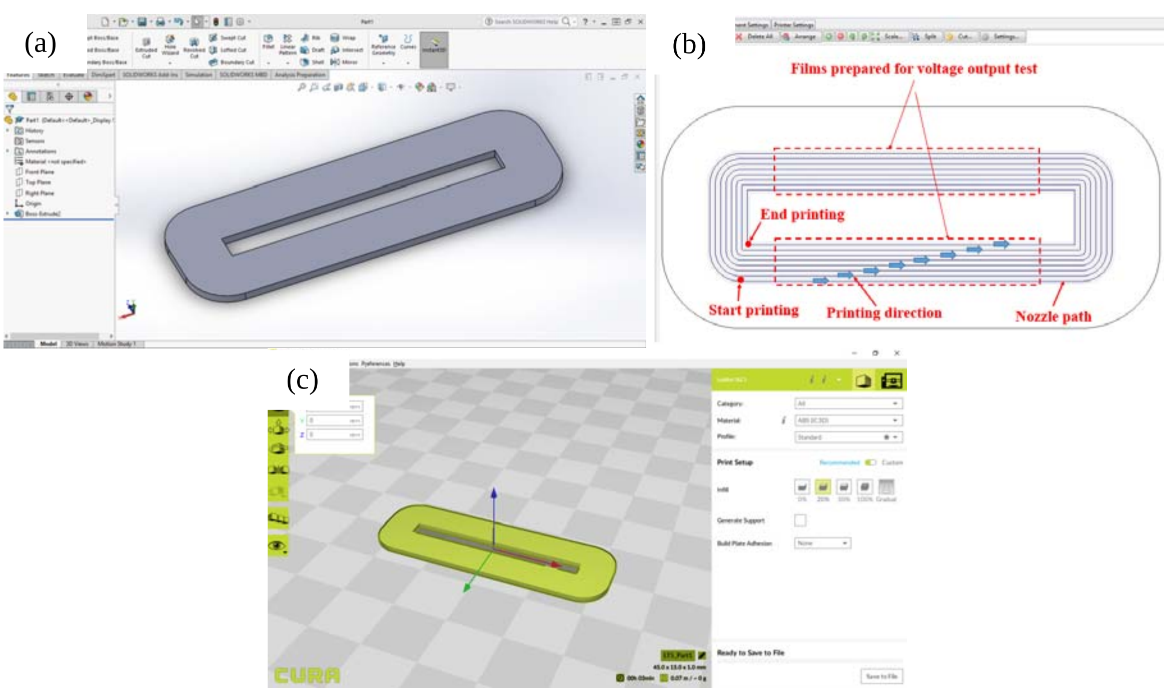


Figure 2. Screen captured images of (a) 3D model designed in SolidWorks, (b) concentric fill pattern designed in Slic3r, and (c) processed 3D model uploaded in Cura software with printing parameter.

Hardware

Filament extruder and 3D printer were purchased from Filabot® and Lulzbot® and used to 3D print nanocomposite film as shown in *Figure 3*. For voltage output test using cyclic load frame, a film consisting of eight layers was printed with 18 wt. % of BT powders and 0.4 wt. % of MWCNTs. Increasing the weight content above 18%-BT would increase severe clogging within the nozzle which could potentially damage the 3D printer. In addition, increasing the weight content above 0.4%-MWCNTs would increase the electrical break down during the electric poling process.

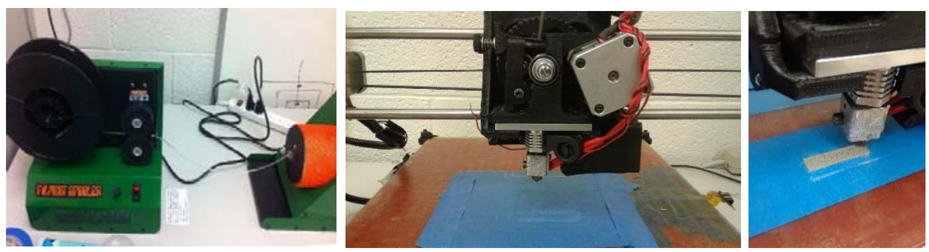
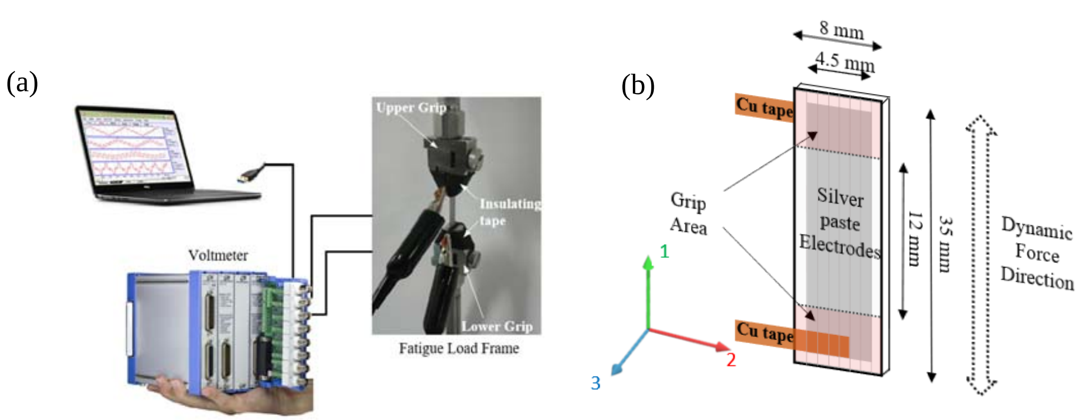


Figure 3. Filament extruder machine, ME 3D printer, and piezoelectric nanocomposites being printed by ME 3D printer.

Pressure Sensor Application

For piezoelectric property analysis, piezoelectric output voltage and current in a fatigue load frame (Bose ElectroForce-BioDynamic, TA Instruments), were measured by Voltmeter (InstruNet i-400) as shown in *Figure 4*(a) [4, 17]. Samples can be fabricated of large surface area, but due to the geometry of the fatigue grip, nanocomposites samples were printed with dimensions of 8 × 35 × 0.55 mm as shown in *Figure 4*(b). To quantify the piezoelectric property of the printed film, samples were prepared with silver conductive paint electrodes on both surfaces. The electrodes are then attached with copper (Cu) tape to allow a proper connection to the Voltmeter as shown in *Figure 4*(b). Cyclic force was applied on the printed nanocomposites to measure periodic voltage output; the fatigue load frame generated 30 cyclic loads on the sample at 0.5 – 4 Hz while the Voltmeter measured the voltage output [4]. To prevent noise and artifacts from the fatigue machine during measurement, the two grips handling the film are covered with electrical insulating tape.



(c)

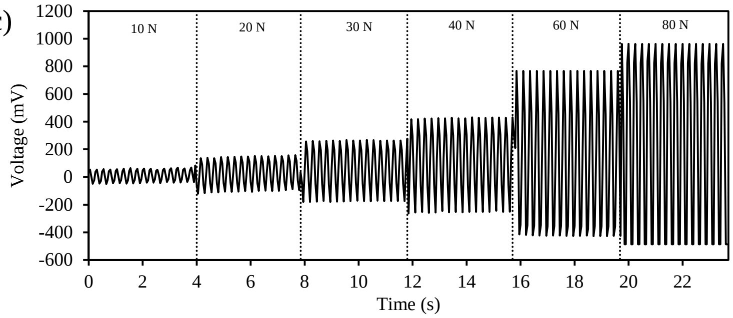


Figure 4. (a) Experimental setup for piezoelectric output measurement, (b) schematic illustration of sample design, and (c) voltage output results generated by 0.4wt.%-MWCNT/18wt.%-BT/PVDF under various forces (10, 20, 30, 40, 60, and 80 N).

Before applying cyclic load, electric poling was applied with positive on one electrode and negative on the other side of sample under 3 MV/m (about DC 3000 V) for 15 hours to transform regular 3D printed nanocomposite film to electro-active nanocomposites after 3D printing fabrication. This process would enhance piezoelectric response. *Figure 4*(c) show voltage output produced by the 3D printed nanocomposites film after the electric poling process. Amplitude of voltage outputs generated from the nanocomposite films output voltages were measured under various external forces from 10 to 80 N applied by fatigue load frame. It shows that a higher amplitude of output voltages was produced at higher external forces, increased by ± 725 mV under 80 N. To calculate the piezoelectric coefficient (d_{31}) by using the equation (1) below:

$$D_i = d_{ij}\sigma_j \qquad (1)$$

where D_i is the electrical displacement, d_{ij} is the piezoelectric coefficient, and σ_j is the applied stress. In this case, subscripts i and j are defined as 3 (induced polarization in 3 direction) and 1 (applied stress direction) respectively as shown in *Figure 4*(b). Therefore, the equation can then be expressed as $D_3 = d_{31}\sigma_1$. Considering the areas of the electrode and cross-section of the sample, equation (1) can then be expressed as

$$\frac{Q}{A_{elect}} = d_{31}\frac{\nu F}{A_{cross}} \qquad (2)$$

where Q is charge, A_{elect} and A_{cross} are areas of electrode and cross-section respectively, ν is Poisson's ratio which is 0.34 [19], and F is an applied force. The Q is equal to CV which are capacitance and voltage, respectively. C can be expressed to $\varepsilon_r\varepsilon_0 A_{elect}/d$. Then, the piezoelectric coefficient can be expressed as

$$d_{31} = \frac{\varepsilon_r\varepsilon_0 A_{cross}V}{\nu dF} \qquad (3)$$

where ε_r is 74 measured by LCR meter which is relative permittivity of the 3D printed nanocomposites film, ε_0 is 8.854×10^{-12} C/Vm which is vacuum permittivity, and d is its thickness. A_{cross} are 2.47 mm^2. Then d_{31}^{max} and d_{31}^{min} are determined at maximum and minimum of voltages and forces as equation (4) describes.

$$d_{31}^{max-min} = \frac{\varepsilon_r\varepsilon_0 A_{cross}V_{max} - V_{min}}{\nu dF_{max} - F_{min}} \qquad (4)$$

F_{max} and F_{min} are 5 N and 85 N, respectively. Each attained d_{31} is divided by 2 for $\pm\, d_{31}$ as shown in following equation (5)

$$\pm d_{31} = \frac{d_{31}^{max-min}}{2} \quad (5)$$

Based on the voltage output results of *Figure 4*(c), final value of piezoelectric coefficients (d_{31}) of 3D printed nanocomposite film calculated was 0.13 pC/N. This indicates that the addition of MWCNTs enhances performance of stress reinforcing between BT particles and the matrix, thus overcomes the low direct piezoelectric coupling associated with piezoelectric polymer composites.

Course Program Outline

Based on aforementioned, a suitable college interdisciplinary course can be developed with proposed class schedule for a course in 4D printing of piezoelectric pressure sensor as shown in Table 1. This proposed class schedule consists of three categories: 1) week-2, 5, and 8 contain about basic background of smart material knowledge and design of piezoelectric nanocomposites where materials engineering background can be taught, 2) week-3, 4, 7, and 9 contain 3D model design of pressure sensor devices and testing for piezoelectric property where mechanical engineering skills can be trained, 3) week-1 and 6 contain operation of 3D printer and post-processing where students can experience emerging manufacturing technology. These three different modules in the proposed class schedule provide students and instructors with a course across interdisciplinary including material science, manufacturing, and mechanical engineering.

Table 1. Proposed class schedule for a course in 4D printing of piezoelectric nanocomposite pressure sensor device.

Weeks	Subjects	Course details	Laboratory/Lecture
1	What is 3D/4D printing technology?	Discuss an overview of seven different techniques of additive manufacturing and 4D printing technology	Laboratory introduction and safety training
2	What are Smart Materials?	Discuss an overview of different kinds of smart materials (piezoelectric, dielectric, pyroelectric, elastomer, shape memory, self-healing materials, etc.) and their applications	Lab-1: students experience operation of commercial smart materials (PVDF polymer and PZT ceramics) and applications such as pressure sensing, energy harvesting, etc.)
3	Introduction to Software	Discuss about SolidWorks, AutoCAD, Slic3r, and Cura software	Lab-2: students learn how to use the 3D modeling software and 3D printing/slicing software and earn skills from 3D model capability to setting up printing parameters.
4	Introduction to Hardware	Discuss about a concept and operation of 3D printer, filament extruder, and dynamic load frame (fatigue machine)	Lab-3: students learn how to operate 3D printer and fabricate their own 3D structure that they designed in previous week.
5	Material Synthesis	Discuss about material property of nanomaterials and piezoelectric materials (PVDF, BT, and CNT), their	Lab-4: student learn how to use chemical lab equipment (beaker, heat plate, sonicator, water bath, etc.) and

		applications, and basic knowledge of chemistry on synthesis	experimental procedure to synthesize CNT/BT/PVDF nanocomposites (detail provided in experimental section)
6	3D printing piezoelectric nanocomposites film and post-process	Discuss about 3D printing of piezoelectric nanocomposite device and poling processes from other researches	Lab-5: student learn 3D printing piezoelectric pressure sensor and electrical poling process (applying two silver electrodes on top and bottom surface of sample described in Figure 4, and detail of poling procedure described in pressure sensor application section)
7	Testing 3D printed nanocomposites film, Data process, and analysis	Discuss how to prepare sample for testing and other testing method to measure piezoelectric property of the material and acquire data from piezoelectric device from other research works	Lab-6: student learn how to operate dynamic load frame (fatigue machine), Voltmeter, preparing sample for testing, and processing and analyzing data
8	Calculating piezoelectric coefficient	Discuss about theory of piezoelectric coefficient and calculating d_{31} and d_{33}	Lab-7: student learn how to calculate d_{31} from the result attained from the 3D printed piezoelectric sample
9	Mechanical test (tensile or fatigue)	Discuss an overview of different types of mechanical testing and their theory	Lab-8: student learn how to operate tensile or fatigue testing machine, processing and analyzing data
10	Review and Project	Work on team projects using 4D printing concept in order to accomplish a project goal	

Discussion & Conclusion

This paper portrays a proposed training plan on the basics of 3D/4D printing and fabrication of piezoelectric nanocomposites for pressure sensor application that would be useful, practical, and achievable for college students who are pursuing bachelor in materials, mechanical, and manufacturing engineering. Equipment for the class can be inexpensive because high quality and accuracy of 3D printed pressure sensor are not required for educational purposes. The increase in the use of 3D/4D printing technology and smart material in industry implies that companies will be looking for engineers with the interdisciplinary skills and knowledge required to operate and maintain these manufacturing systems. The proposed course is well designed for students to learn different aspects of skills and knowledge over a period one semester giving graduates a valuable advantage in an increasingly competitive job market. This proposed course can be a part of advanced material and manufacturing or 4D printing (e.g. self-healing and shape memory composites) courses for sophomore and junior levels.

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