

Prof. Palani Iyamperumal Anand
Department of Mechanical Engineering
Indian Institute of Technology, Indore

Week- 7

Lecture No- 35

Micro Sensors and Micro Transducers - Module 10

Hello everyone, I am Dr. Anshu Sau, Research Associate, and I am currently working under the supervision of Prof. I. A. Palani. In today's lecture, we are going to discuss triboelectric nanogenerators. The significance of the name is that it is a nanogenerator. It generates energy from the nano level to the micro level. So, why is it called triboelectric? Because it transfers energy from triboelectric applications. I think everyone has faced that electric shock during the winters with our sweaters, or we can say with a comb and then papers when we used to rub our comb with our hair. So, what will happen if you take that comb to the paper? Both will stick, and that is why there will be a charge developed during the rubbing on our hair and on our comb. When we touch the paper, it has negative charges. When both charges come together, they will transfer to each other and get stuck. That is, again, the principle is the same; that principle is also called a triboelectric generator. So, here we will see the principle of the triboelectric generator, then how it performs and what kind of energy it can harvest from our surroundings.

So, triboelectric generators require two different surfaces: one with a charge affinity and one with charge abundance. One has a positive charge, and one has negative charges. So, when this positive charge and negative charge come in contact, what will happen? If they come in contact, the positive charge and negative charge will try to transfer to other surfaces. Because of this transfer of charges, the electric current will flow in the outer circuit. So, we will see the principle. Here, the blue one is our positive charge, the tribo-positive surfaces, and the pink one is our tribo-negative surfaces. we have connected with our external circuits. Once we make it closer to each other, what will happen? The charge transformation will take place because of its nature, because blue one is having a positive charge efficiency and blue one the pink one is having negative charge efficiency. So, the transfer charge will take place, and then the current will flow on the external surface. Thus, we can see a current signal in the positive direction.

When the surfaces are moving far from each other, and then again if you try to come back, the charge transfer between the positive surface and the negative surface state occurs again. The negative cycle will be rectified. So, while in continuous contact and separation, we can obtain an AC output. This is one of the triboelectric systems that is based on the contact and separation mode. So, this is the principle of a triboelectric nanogenerator. Now, I will show you how it works. Here we have two surfaces: one is a positive surface, which we have taken as aluminum. Aluminum has a positive charge efficiency on the surface, and for the negative charge efficiency, we have taken a FEP polymer. Then, since FEP is dielectric in nature, to collect the charges from the surfaces, we put one copper tape on the backside. And then we have attached some electrical wires so that we can collect those charges from external circuits. So, we have designed this tribo device in such a way that it maintains its position. So, now you can see this triboelectric nanogenerator. It is in the separation mode, and once the external load is applied, it will come into contact, and once this external load is released, it will again come to the separation mode. So, this is called the contact and separation mode one-dimensional triboelectric nanogenerator. So, now we will see the performance of this triboelectric nanogenerator.

Now I am connecting the FEP negative terminal to the FEP and the positive terminal to the aluminum. Now, I am going to apply some vibration to that, so that I can provide some contact and separation forces, allowing charge transfer to take place. Now you can see that if I tap both surfaces. You can see that as I release both surfaces, another peak will be generated. You can see that while meeting the negative cycle, a negative cycle is generated, and while releasing it, a positive cycle will be generated. So, this is how the AC is generated with the contact and separation mode. So, now apart from the contact and separation mode, we also have sliding TENG. So, both surfaces will rub against each other. Again, in this case, we have FEP as well as aluminum, and both surfaces will rub against each other. So, we have applied some springs so that with continuous vibration, there will be motion between both surfaces. So, why is this charge being generated? Because there is some texture on both surfaces. So, what is happening? There are continuous contact and separation between the textures on the surfaces. That is why this sliding TENG is providing performance to us. So, the third one has a three-dimensional triboelectric nanogenerator. We have a different electrode in this one, and there is a bulb inside that triboelectric nanogenerator.

So, if the vibration is generated in the three-dimensional. In this case, we can obtain the three-dimensional performance of those triboelectric nanogenerators. Now, the point is, where can we use this kind of triboelectric nanogenerator in micro robotics? One thing is that it can be used as small as possible because we now have a sample size of 2 centimeters by 2 centimeters. So, if we can reduce these surfaces to 1 centimeter, 0.

5 mm, or 0.5 centimeter, then both nanogenerators will perform for us. So, the advantage is that in the miniaturized devices, this triboelectric nanogenerator can provide its performance. Another advantage of this triboelectric nanogenerator is that it can be used as a self-powered device. So, since it is harvesting energy from vibrations in the environment, it has a natural tendency to collect charges from the environment. Once the surface becomes neutral, the positive charge comes from the environment because the surface tends to charge abundantly. So, it is taking a positive charge from the environment. That is why this can be used as a self-powered system. Therefore, it does not require any external power source. Again, if you see the voltage rating of this one. The voltage rating is around 400 to 500, but the current is in the order of a few microamperes. So, we can say that a few microamperes is 20 to 40 microamperes. However, 20 to 40 microamperes cannot be used for micro devices or microscale robotics. So, what we can do is use some energy harvesting circuits. The high voltage is reduced to a low voltage, and this microampere will be converted to some milliamperes. By storing this energy in a capacitor bank and using some electric energy harvesting circuits, we can use this energy to power micro devices, so the third advantage of this process is its material versatility; we can use either a soft material or a hard material.

The soft material gives us the freedom to use it in soft robotics applications. The third advantage is that these changes can be used for different applications, such as using it as a sensor; for instance, we can use it as a vibration sensor where a lot of vibration is present, allowing us to detect the vibration frequency based on the contact and separation mode. Then, the same TENG can be used for energy harvesting. The same energy, the same TENG, can be used for IoT by developing an IoT module. So, our TENG will act as a sensor, and then this sensor data will be fed into the system; that data can be used to monitor some machine tools, like if we have soft robotics and we have attached some TENG. Due to the vibration of the soft robots, some amount of energy or some amount of voltage or current signal will be generated, so we can analyze these signals based on their performance to see the performance of our software. So, this is how our triboelectric nanogenerator can be used for our micro robotics applications. So, another application, as you can see from our real world, is that these triboelectric materials can be used for harvesting mechanical energy from human motion. So, in our lab, what we have developed is an integrated triboelectric nanogenerator. So, what will happen is that you can see there are two layers of triboelectric nanogenerators.

So, these triboelectric nanogenerators are placed in the front as well as the back. So, why? Because when we walk, we walk like this; there will be continuous contact and separation, contact and separation. So, once the first contact is made, this will be at the separation position, and through that, we can obtain the energy and store it in a battery pack. So, what we have done here is harvest that energy from human motion, and then we store the energy

in the form of a battery. So, what is this stored energy we are using to power some RFID and GPS modules, and we have developed these tools for soldier applications. Now, another application is that we have developed an IoT module where our TENG is used as a sensor for machine tool monitoring. So let us suppose we have some old machine, and we do not know when it will fail. What will happen is that we can attach this triboelectric nanogenerator to the machine tools. Based on the vibration, it will generate some amount of voltage and current signals. Further, we can analyze and use the current and voltage signals to predict the maintenance of the machine tools. If some part of the machine fails, then what will happen to the voltage generated from the TENG? It will increase. This is how the TENG can be used for IoT-based systems. To test the fabricated triboelectric nanogenerator, we have connected it to an oscilloscope. By repeated contact separation, we can see that we are getting AC voltage peaks of 99 volts peak to peak. On one side of the removable shoe sole, we have integrated two TENGs with an energy harvesting module, which will power a 100 mAh LiPo battery that is used to power the RF transmitter. This output can be seen at the receiver's end. On the other hand, we have integrated two TENGs with an energy harvesting module that will be used to power a GPS module integrated with a Wi-Fi module. These signals will be transmitted to this receiver end. Here, the signal will be transmitted over the cloud. So, we will be able to see the GPS separation on mobile devices. Now, these removable shoe soles are packed so that all the electronics and TENGs are secure inside, ensuring that they are free from contamination and physical damage.

Inside the shoe, we can integrate the shoe sole in such a manner that our shoe sole is inside the shoe and ready to be worn. So, we have been discussing the different types of electrostatic configurations. In fact, if you remember, we have also had some discussion about triboelectric nanogenerators. So, these triboelectric nanogenerators are quite an interesting concept. Like today, it is almost competing with the piezoelectric structures. So, appropriately, we can create, we can just channel the charge. The principle behind these triboelectric nanogenerators is that they work on the electrostatic charge principle. We will have two materials: one is the tribo-positive material, and the other is the tribo-negative material. The interaction between the tribo-positive and the tribo-negative will impact the charge that is being diffused. So, with reference to the diffusion of this charge, we can appropriately channel this charge; we can use this system for vibration sensing, condition monitoring, etc. Most preferably, wherever there is a need to focus on the low-frequency system, these systems play a vital role. As far as these triboelectric nanogenerators are concerned, we might have given a demonstration about the machine skin, showing how a triboelectric nanogenerator is used for machine skin-related applications. Now let us discuss how these triboelectric nanogenerators can be used to power these soft robots, which are made of a type of unidirectional dielectric elastomer. So as far as these, we call it a kind of TENG-based self-powered nanobot, which is mainly made from a soft actuator. This soft actuator is made from a unidirectional dielectric elastomer.

Now, as far as soft robotics is concerned, soft robotics and micro robotics go hand in glove for an effective formulation of these structures. These soft robotic structures are developed by elegantly integrating soft actuators like compliant structures and stretchable sensors. They have demonstrated promising potential in medical operations, underwater manipulations, human assistance, etc. One of the key soft actuators is this DEA, which we call a dielectric elastomer actuator. These are kind of an emerging class of soft actuators with advantages such as a fast response, high energy densities, and they almost resemble human muscle, which means they can withstand a good amount of large strain. So, different types of such DEAs have been reported efficiently. As far as this case is concerned, the DEA exhibits a kind of flexible body, and it also exhibits a type of locomotion that we call dexterous locomotion. Especially, such types of dexterous locomotion are exhibited in an unstructured environment. When we try to use some kind of conventional type DEA, it poses an obstacle for such small-scale robotic systems. However, these TENG-based structures can harvest kinetic energy from the environment to generate power that matches this DEA. Therefore, this DEA-based robot is hindered by the non-linear and insufficient mechanical transmission in robotic motion. There are some case studies where people have attempted to use these triboelectric nanogenerators to harness the energy from this unidirectional DEA drive so that it can be effectively used for a robotic conjugation system built using a free-standing TENG. Now, let us see how these TENG-based robots are structured. So ideally, if you try to look into the overall construction of this, there will be a kind of structure, and then there is a free-standing mode TENG. This is a kind of charge that is available, and then it is directly connected to the structure.

The structure looks something like this, where this is a kind of dielectric elastomer, this is a kind of PET frame, and this is a one-way bearing belt. So, this is a kind of soft robotic structure. We have a type of dielectric structure that is available, and these dielectric structures are connected in the form of a TENG. So, in the proposed system, what we have is a kind of TENG-based soft robot conjugation system. So, in this soft robot conjugation system, a free-standing TENG is directly connected to the soft robot, which is composed of a dielectric elastomer actuator, a compliant arc-shaped body, and three one-way bearing wheels. When sliding the TENG voltage, it's something like this: when we have three or four different configurations, one configuration includes the sliding left and the sliding right mechanism. So, in the case of a sliding left mechanism, we have a kind of voltage-off configuration and the voltage-decrease configuration. Similarly, we have a kind of voltage increase configuration. This is the dielectric medium that is available. This is the dielectric medium, this is the voltage increase configuration, and we have a voltage max configuration.

So, this is a kind of sliding left, and this is a kind of sliding rate configuration that is

available, so this sliding TENG voltage is generated to actuate this DEA. The DEA elongates and retracts, producing a displacement of the robot. In one sliding cycle, the soft robot completes a locomotion step, and the conjugation step is established in this fashion. So, the power off and the power max states of the robot show a forward displacement. As far as this case is concerned, it almost depicts the TNG bot as a kind of TNG-based soft robotic conjugation system. A freestanding mode of TNG is designed and connected to a soft robotic structure. In the freestanding TNG, the moving component can slide freely on the two fixed substrates. Since the mobile layer is electrode-free, it eliminates the electrostatic shielding effect that leads to the creation of a high charge in the system. The characterization arises when we try to examine the soft robotic structure. These kinds of soft robotic structures are a type of unidirectional structure. So, if you closely observe this unidirectional structure, these unidirectional structures go back and forth, and the linear mechanical performance of the soft robotic structures is considered one of the key characteristics of this robot, the soft robot. The relationship between the speed of the robot and the voltage frequency is like when you try to give a variety of waveforms to the system. Therefore, we can appropriately establish the different voltage and frequency of these structures. One of the important characteristics of the structure is the response time. Once we investigate the response time of these structures, it plays a vital role in the usage of the system under different conditions. Now, in that aspect, if we try to investigate its performance, these kinds of unidirectional soft robotic, DEA-driven soft robotic structures are of concern. They align the direction of the DEA in extension with the robotic motion to achieve high energy conversion and high energy efficiency. It also aligns the DEA in extension with the robotic motion to achieve a payload capacity of close to 40 grams because we have an alternative deflection occurring here. Thus, there will be a kind of deflection and actuation exhibited in this system. The TENG soft robotic conjugation system is built using a kind of freestanding TENG that benefits from the simple structure and high efficiency of the robot, and the electricity generated by the TENG can directly drive the robot without additional control panels.

Quite a good number of experiments have been demonstrated here. There are reports from the Zong-Ling Wang Group in nano energy. So, I will be sharing that paper in the references, where we can go through it. In this concept, they have proved the idea of a self-energized system. So, it's a kind of free charge that you are trying to get out of it, and how you channel these free charges, and how these channeled free charges can be effectively used for a micro robotic application. In fact, this is completely a new area that people are exploring, and there are quite a good number of challenges; if we can address these challenges, then appropriately we can use it for soft robotics-related applications. In fact, as an extension of this, we can use this for actuating piezoelectric structures; we can even use it for actuating muzzle-like structures. In fact, we can integrate that triboelectric and shape memory alloy for effective actuation so that we can reuse these actuated structures for condition monitoring-related applications. So there will be some video demonstrations

related to TENG so that you will get an idea of it and how you can effectively use it for a robotic application that we can discuss through different case studies, and I will also give you some assignments related to it so that you can go through some of the literature and report it back. This is a triboelectric nanogenerator, also known as TENG. It has the capability to convert ambient mechanical energy into electrical energy. As we can see, by manually tapping on this triboelectric nanogenerator, we are able to generate AC electrical output. It works on the principle of triboelectrification and electrostatic induction. Now, to demonstrate the sensing capabilities of these TENGs, we have mounted one TENG over the air compressor.

Initially, we are getting some minimum noise. As we turn on the air compressor, you can see that voltage signals are being generated corresponding to the vibration generated by the machine, which is being detected by the TNG. And as we are turning off the machine, we are not getting those voltage signals which show that TNG has the capacity to detect the working conditions of any machine. Now, if we look at these signals, they are mixed signals. These are not just simple sinusoidal curves. This signal tells us a lot about the condition of the machine and whether there is any defect in it. Because if there is any defect or any wear and tear, we can identify it easily by analyzing this vibration signal. So, we will record this signal, and then we will process it to understand the vibration characteristics. Now we have collected the data generated by the TENG corresponding to the vibration signal produced by the air compressor. So here, as we collected this data, we learned that the TENG was able to detect the working state of this air compressor. When the air compressor was turned on, we received the corresponding signals, and when we turned it off, we did not get any signals.

We processed these mixed signals by applying a fast Fourier transform so that we could detect the working frequency and the vibration frequency. Firstly, we obtained a frequency of 24 hertz, which corresponds to 1440 rpm of the motor in this air compressor, and we are getting the second harmonic at 48 Hz and the third harmonic at 72 Hz, and so on. Here, additionally, we are getting 50 Hz, which corresponds to the frequency of AC current input in our power supplies. So, this demonstrates that it can work very well as a vibration sensor. Now if we strategically plan where a sensor can be implanted, we can understand the workings of the machine or monitor its condition, as we can learn a lot about a machine by studying the vibration signal. Any near-occurring defect or fault can be detected by the change in the vibration characteristics of the machines. By mapping the vibration characteristics of any machine, such as determining what kind of vibration is present—whether it is one-dimensional, two-dimensional, in-plane vibration, or perpendicular vibration—we can implant different TNGs in different locations to analyze the entire machine. This forms a machine skin. Here, we have implanted two TNGs: one on the induction motor and one on the hydraulic cylinder part. So here we are able to see that, firstly, if we analyze the data on the TNG, which is implanted on the piston-cylinder

arrangement, as the piston is moving to the top dead center or the bottom dead center, we are getting vibration signals there because of the vibrations due to the change in the direction of motion and if we are adding an external load over the piston, we are getting a voltage signal of higher amplitude, so we will be able to understand at what time it is changing its direction and whether it is under external loading conditions or not.

Secondly, when we are putting a TENG acting as a vibration sensor on the motor, we are able to detect its working state when the motor is on, when the motor is being turned off, and upon taking a Fourier fast transform (FFT) on these signals, we are able to get the vibration frequency of 24 Hertz, which corresponds to the RPM of 1440. Now, to get this data on our computer and our mobile for remote monitoring, we can integrate an IoT module. As TENG is a good energy harvester, it can act as a self-powering vibration sensor so that it works autonomously without the requirement of an external power supply. So when we integrate an IoT module into it, we can receive this data wirelessly on our mobiles, computers, and smart devices. Now, firstly, when TENG is placed on a motor, as it is turned on, we will get a signal of turning on over here and a corresponding voltage signal can be seen on the dashboard as well as the FFT corresponding to it.

Now, if some defect is occurring in our motor, we will get an additional frequency peak that corresponds to that defect. Normally, we won't get those differences in the FFT signal or changes in the pattern of the voltage values. But whenever there is an abnormality there, an anomaly can be detected in this signal or the FFT of this signal. Secondly, on the piston, we have integrated the TENG. We can detect when it is moving up, when it is changing its direction, and when it is moving in the downward direction. In this way, we can condition monitor the entire machine wirelessly without the requirement of any external power supply. So, these TENGs are very helpful as a power source and as sensors for vibration sensing applications, pressure sensing applications, and proximity sensing applications in micro robotics.