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Design and Development of a Triboelectric Sensor for a Generic Counting Application

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Abstract

In today's consumer-oriented market, researchers are increasingly focusing on harvesting energy from ambient and renewable sources to enable sustainable power generation and reduce dependency on conventional energy resources such as batteries and fossil-fuel-based electricity. The rapid growth of portable electronics, wireless sensor networks, and Internet of Things (IoT) devices has created a significant demand for low-power, long-life, and maintenance-free energy solutions. In many practical situations, frequent battery replacement is difficult, costly, and environmentally harmful. Therefore, energy harvesting has emerged as an effective alternative to power such low-energy devices by utilizing naturally available energy in the surrounding environment. Energy harvesting methods offer enormous opportunities to derive power from sources such as mechanical vibrations, human motion, thermal gradients, airflow, and other forms of wasted or unused energy. In general, energy harvesters operate like transducers, where the available ambient energy is extracted and converted into usable electrical power. Among different techniques, triboelectric and thermoelectric harvesting are considered highly promising due to their simplicity, compactness, and suitability for small-scale applications. This research aims to demonstrate the practical implementation and performance validation of thermoelectric energy harvesting (THEH) through developed hardware prototypes and experimental setups. A usable amount of electrical energy is extracted from both harvesters under real-world operating conditions. The generated output is measured, analyzed, and further validated using the developed hardware model to ensure feasibility for real-time applications. The results indicate that ambient energy harvesting using triboelectric and thermoelectric principles can provide an effective solution for powering low-power electronics and self-sustained sensing systems in future smart applications.

Keywords: Arduino IDE, generic counting system, microcontroller, PTFE (Polytetrafluoroethylene) Film, triboelectricity

INTRODUCTION

The study of triboelectricity is based on the concept of frictional contact between two triboelectric materials to generate an electron flow. We used a conductor with a polymer material from the available materials that possessed a contact electrification property [1–6]. Numerous materials have this property; however, the low-cost and easy availability of the material played a role in the material selection. Based on the electrical induction phenomenon, these materials become electrically charged subsequent to frictional contact with another adequate material. Figure 1 shows the assembly of two materials for sensor fabrication.

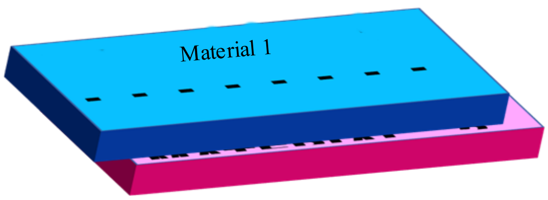

Figure 1. Arrangement of materials for triboelectrification.

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A generic counting system has applications such as estimating passenger density in a public transportation system, detecting and counting vehicles, and counting the number of visitors at an event. These applications require capacity information to plan for maximizing available capacity and, consequently, optimize efficiency through resource management. A large number of existing systems are available for the above-mentioned applications [7–9]. The prototype presented herein demonstrates the feasibility of creating a general portable system capable of detecting the presence of humans, vehicles, or any other moving objects. This can aid researchers in developing an automatic system for calculating the density of people in a given area or the number of vehicles entering a designated area. To further illustrate, the possible applications of the designed setup are discussed below [10].

A passenger counting system is used in public transportation systems to estimate the relationship between the number of passengers and a geographical area or station. This can aid in predicting the number of daily passengers in various public transportation systems, allowing for better fleet management, advanced planning, and frequent fleet services in densely populated areas. Another application for such systems is customer/visitor footfall counting, which can be used to register and analyze the number of visitors or customers who visit a public event or a simple shopping mall. By tracking promotional outcomes, organizers or owners can more efficiently reschedule their staff and other resources. These practices aid in the structuring of proposals for future planning and arrangement, which undoubtedly aid in improving enterprise operational efficiency. Because it is a generic setup, this system can also be used as a low-cost, low-power automatic vehicle counting system to check the occupancy and availability of parking lots in a parking zone or any other premise. When the parking lot is full, an automatic barrier closure mechanism can be integrated with the system to manage parking lot availability information for customers, resulting in a reduction in the manpower required. It can also help manage traffic in free-parking zones, where cars are often parked haphazardly, resulting in vehicle overcrowding.

The triboelectric sensor is the first component in the information acquisition process. In response to a surface contact on the upper layer, the sensor was designed to generate legitimate voltage pulses. This voltage is produced in response to the generation of a charge on the surface of the material used in the sensor strip. The amount of charge generated, and its polarity are significantly influenced by the material composition, surface roughness, ambient temperature, and humidity. To illustrate this phenomenon, when two materials come into contact and rub against each other, they generate static electricity, which is a collection of electrically charged particles on the surface of the materials [11]. The materials chosen for this study have a high proclivity to become positively charged by giving up electrons or negatively charged by acquiring electrons. Fur, leather, wool, aluminum, silver, gold, and other similar materials are examples. A careful selection of such available materials can be made by pairing materials with a high tendency to develop positive and negative charges. The chosen pair can be used in various configurations or arrangements to obtain voltage signals. A remarkable feature that distinguishes such voltage generation mechanisms is that they do not require any additional input voltage source [12]. This distinguishes our system in terms of internal power consumption. An Infrared Sensor which is also a low-power consumption device, is a close contender for sensors in such systems. Here is a brief comparison of our system to an IR sensor-based system. Previous IR sensors used for similar applications have an operational range of 2–30 cm and require a 5 V external power supply to operate [10–11]. When deployed in the field, IR sensors can also cause installation issues. This makes them difficult to replace and increases maintenance costs. The positioning of these sensors is a critical step in ensuring system reliability. If the sensor is placed at too high or too low an altitude, it is very likely that it will miss a passing person while counting. Furthermore, detection using IR sensors is dependent on the intensity of the color of the passing object or person [13–15]. This makes the sensor unreliable for detecting transparent and brightly colored objects or people. The sensor strip discussed here is placed on the floor, which eliminates the issue of optimal sensor height placement. Because IR sensors require a 5 V power supply to operate, they are reliant on a steady supply of power. This frequently necessitates a regular power supply arrangement or connecting a battery, which increases the overall system size. The sensor strip used in this design does not require any power supply to operate, resulting in a smaller device. Even the Passive Infrared Sensor used in [12] offers some unpredictability owing to the temperature dependency during sensor operation. It can work proficiently for ambient room temperatures of approximately 15–20°C. Any further increase in temperature to a value greater than 30°C makes the sensor less efficient, and a further temperature drop below 15°C will result in object detection at a much larger distance, which is not desired. The sensor strip used herein depends on temperature and can generate accurate results even at temperatures above 30°C. After a series of repeated experiments and trials, no flaws in the system were discovered, and consistent results were obtained. Even when the sensor strip was placed outside the room in direct sunlight, the reported results were consistent with the expected results [16].

System Design

We designed a sensor strip using two different materials arranged in vertical contact with a gap between them in the current design. When a force is applied to any one material, this sensor strip records the occurrence of an event. For example, when a person steps on this strip, the frictional contact between the two materials causes a voltage spike. This sensor strip sends data about the occurrence of an event to a data collection and processing device [17–20]. This device can be a basic microcontroller unit that accepts a voltage signal as an input into one of its ports. After capturing this input data, a well-designed software program can process it to program a counter value, which is then stored and displayed on a display device. This display is connected to one of the controller's output ports. We used a simple common anode 7-segment display device to demonstrate the operation of the counter. An LCD panel can be used to display additional information in addition to the counted value. Figure 2 shows a simple block diagram of the system. The following are descriptions of the prototype's various components:

A sensor, in technical terms, is any device or circuit that responds to an input from a dynamic environment. A sensor device detects the occurrence of an event (for example, a person entering a building or a car entering a parking lot) and transmits the data to a processing device. As shown in Figure 3, we used a thin tape of polymer material, polytetrafluoroethylene (PTFE), and conductor material, aluminum (Al), to fabricate a very low-cost self-powered sensor strip. To make our sensor strip more robust, we chose an acrylic base with the same dimensions as the strip, which provides strength and agility to the strip. A significant reduction in energy consumption for the power requirements of a system developed around this sensor occurred because no external electrical energy is required to power this sensor strip. It electrifies the surface of the material by utilizing mechanical frictional energy input. A 50-µm-thick tape of the same dimensions as the Al material was applied to the PTFE film. The gap between the Al and PTFE films acted as a dielectric material in this case. We did not investigate the fabrication mechanism or material composition prospects in this work because we used prefabricated tape for both materials. Because PTFE and Al tapes are both flexible and do not hold shape on their own, a strong base is required to paste the material. For base formation, a variety of material options are available.

A wooden base and an acrylic sheet were chosen as base materials because of their ease of availability and fabrication. When compared to a smoother surface, a rough surface can collect a greater number of charges. Therefore, an acrylic strip was used as a base for attaching the tapes, which were etched to make them rough to increase the charge concentration. A simple copper wire was connected to the ends of the aluminum tape for electrode contact. This was the sensor terminal, which was connected to a measuring instrument and grounded to collect the produced voltage. By designing a single-electrode-based voltage measurement sensor device, this arrangement is a classic style for voltage measurement. Physical contact between the surfaces of these materials is required to generate an electrostatic charge. When two material surfaces are separated by a mechanical force, the induced charges produce a potential difference. As shown in Figure 4, this causes a flow of charge carriers (electrons) among the terminals of the surface of the material. The motion used in this setup is a perpendicular or lateral contact between the two surfaces, in contrast to the sliding motion of friction. The phenomenon of charge generation with an opposite polarity on the surface under contact is depicted in Figure 4(a). When the upper surface of a PTFE film is pressed due to sudden movement or mechanical force, it becomes negatively charged. The aluminum layer beneath the PTFE layer also responds equally with an equal amount of positive charge deposition, and the charges accumulate on the outer surface [21]. As shown in Figure 4, when the lateral force applied to the material surface is released, subsequent voltage spikes are registered in the measuring device owing to static electrification Figure 4 (b).

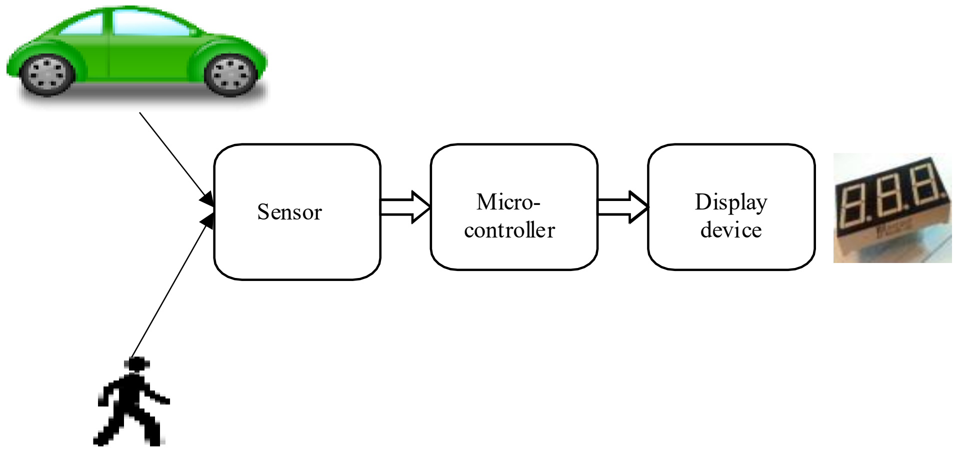

Figure 2. Block diagram of the counter system sensor.

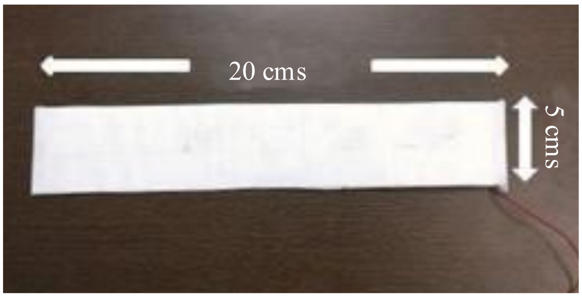

Figure 3. Actual sensor strip.

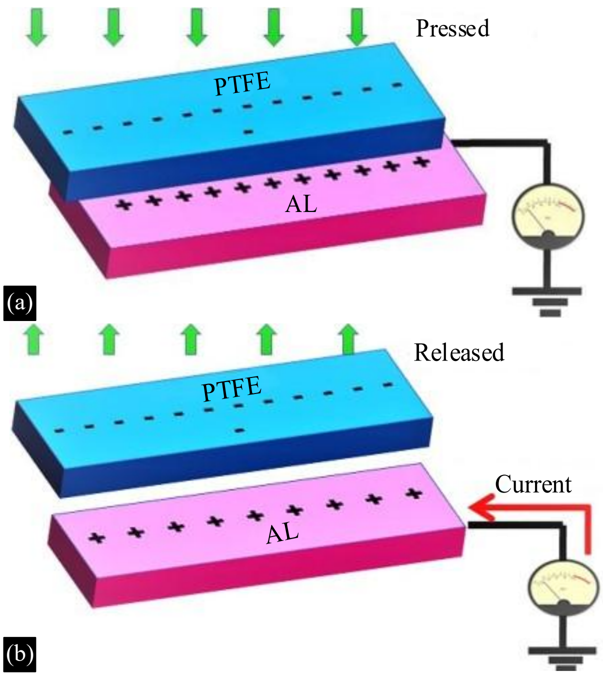

Figure 4. (a) to (b) Triboelectric charge generation: (a) pressed state of the sensor strip, and (b) released state of the sensor strip.

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This potential formation occurs as a result of the separation of two surfaces that were in contact. Only charge transfer between the two surfaces occurs during contact; therefore, no potential difference is generated because the charges are in the same plane. After separation, charges are generated, and the corresponding potential difference is observed. The contact site is a copper wire sandwiched between an aluminum film and a substrate (base) PTFE film. The two opposing surfaces are perfectly aligned in their current positions. A lateral relative displacement occurs when a contact force is applied.

This further misaligns and displaces the two surfaces. The opposing force causes them to return to their aligned position. Charge transfer occurs at the surface when the PTFE and aluminum films come into contact, owing to the triboelectric effect. In the aligned position, the induced negative triboelectric charges on the PTFE are completely compensated by their positive counterpart charges on the aluminum. No electric field is observed in the surrounding space because the electric field at the edges is negligible. In areas of displacement mismatch, uncompensated triboelectric charges generate dipole polarization in the direction parallel to the relative displacement. Consequently, a net electric potential difference exists between the copper terminal and the ground [22].

Microcontroller

After an output voltage signal is generated, it must be captured and processed for further processing. This necessitates a data acquisition and processing setup that is both efficient and low-power consuming. To input the voltage data and complete the counting process using an appropriate software code, a microcontroller unit was chosen. The microcontroller board and display device used in the system are depicted in Figure 5. The microcontroller device, which is a processing unit, serves as the system's brain and is used for automatic data conversion. The microcontroller unit intends to receive an input voltage spike generated by the sensor on one of its available ports to update the counting event. Upon the generation of a spike, a well-written C program controller was programmed to register a person or car count and increase the count accordingly. We chose a low-cost basic Arduino Uno development board (Figure 5(a)) for data processing requirements because we wanted to keep the system cost as low as possible. A microcontroller that is commercially available, the Arduino Uno, is a general-purpose development board based on the ATmega328P microcontroller. It has six analog pins that can be used to directly acquire data from analog sensors. Any of these six pins can be used to capture input voltage spikes from the sensor strip. A well-written code in a compatible language can instruct the controller to intercept the signal and convert it to digital data accordingly. The required code on the board memory of 2 KB RAM and 32 KB flash was sufficient for editing and further debugging. A program code for an infinite loop cycle was created to allow for continuous monitoring of input data. The open-source Arduino software (IDE) was downloaded from the official Arduino website for programming. This is open-source software with a good support system. Writing and uploading the program to the board does not necessitate the purchase of a device license. This played a significant role in the microcontroller selection process.

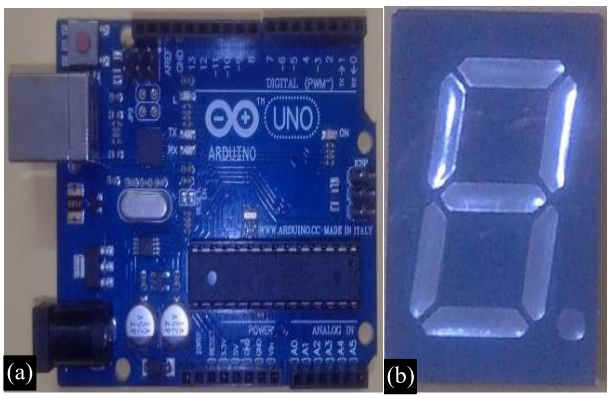

Figure 5. (a) to (b) Components of the counter system: (a) Arduino Uno board, and (b) 7-segment display.

Because it includes a pre-burned boot loader, the Uno board allows users to upload code to the controller without using an external programmer. In the event of a controller failure, the controller chip can be replaced without replacing the entire board. This extends the life of the system integrated with the board. After a survey of similar controller boards during the system design phase, it was discovered that the Arduino Uno board was the least expensive among those with similar functionalities.

The data from the sensor strip is analog; however, because the Arduino Uno is a digital processing device, it requires digital data to run the code. In particular, the on-board analog-to-digital converter (ADC) in the Uno board allows for a smooth transition of data from an analog input device to the on-board processor. This is particularly useful for directly connecting sensors to a microcontroller board. A 10-bit ADC converter converts any incoming analog signal into a digital value ranging from 0 to 1023. Following fabrication, the sensor was subjected to force application and digital data generation. The serial monitor included with the Arduino IDE was used to verify the results.

Display Device

Following the verification of the results on the serial monitor, a display system was designed to display the results in a real-time scenario. Currently, a wide range of commercial display devices is available that are fully compatible with and easily interfaced with the chosen microcontroller board. To keep costs down, a low-cost 7-segment display module was chosen to display the counter values. An LCD module is one of the preferred devices for displaying results and is valued for its ability to display additional data to the user in addition to counter readings. However, because our demonstration was primarily for sensor fabrication and testing, we chose a simple common anode-type segment display device. The module, as shown in Figure 5(b), has eight legs (pins) that must be interfaced to a controlling device or the output port of a controlling device. The module includes an in-built mechanism for providing a proper biasing voltage to the module's eight LEDs. A combination of corresponding LEDs glows or emits light that displays a specific decimal number based on the input biasing voltage. The correct counting sequence was calculated and displayed on the 7-segment display by a code written in the C language and pre-loaded on the microcontroller board. This display module can be connected to the controller via any of the 10 digital input/output pins on the Arduino board. Additionally, the counting sequence can be viewed on the serial port available in the IDE. To synchronize the data transfer rate to the serial port, the best baud rate for serial data transfer should be chosen. A baud rate of 9600 was chosen to allow the serial port monitor to display the count value in a decimal sequence. The serial port is a useful tool for debugging programs and validating results prior to connecting output devices. While writing the code, an appropriate time delay should be selected to display the results on the output segment for proper observation. This delay will help to capture the data correctly in the case of two incoming pulses with a very small-time gap in between. Such short-distance pulses can be missed if not properly programmed, resulting in unreliable results.

Experimental

The sensor strip was fabricated using two identical materials. For physical stability, the assembly was placed on an acrylic sheet. A copper wire was connected to serve as an electrode and to provide a physical connection to the processing unit. This electrode terminal end was connected to one of the analog port pins of the Arduino Uno board. This input port was used to capture and detect the presence of a voltage spike in the input (Figure 6). This voltage spike can be caused by the lateral contact between the opposite surfaces of PTFE and aluminum that face each other. When a moving person or vehicle crosses the strip, frictional contact is made with the sensor, and a voltage signal is registered.

The magnitude of the voltage is determined by the amount of force applied. This input spike had to be successfully captured using a controller connected to the system. C code was written to collect this data, and the analog port data was read to register a legal voltage spike (which is here considered as a signal above 5 V). It was also necessary to reduce the noise that accompanied this voltage signal. This step was required to reduce the possibility of capturing a false reading at lower voltage levels. Dry runs and debugging were performed prior to deploying the actual hardware setup for real-time testing and results. On a 4-channel Agilent digital oscilloscope (model no.: DSO-X 2014A), the voltage spike produced by a single person passing was observed. The procedure was repeated several times to ensure that the results were correct. The next step was to check for multiple entries at a rapid pace, which more closely resembled an actual scenario. The sensor was subjected to repeated lateral force at a much faster rate, and the corresponding number of spikes was captured without error by the DSO. This data was sent as an input to one of the Arduino Uno board's analog input pins. The serial monitor display option built into the Arduino IDE is capable of displaying results at a synchronized speed. Because this sensor strip is a single-electrode device, a copper wire connected to the aluminum tape formed the solo terminal. This terminal was linked to the DSO probe. The ground terminal for component testing in the DSO was used to ground the system, which also completed the circuit. These spikes were then fed into an Arduino port, which generated a digital value for each analog voltage input using the in-built ADC. Because our goal was only to collect information about the occurrence of an event, the count value was incremented after acquiring a spike with a magnitude equal to or greater than 5 V. During the testing phase, the sensor was tested for situations where a relatively light force was applied. When a very small amount of force was applied, the magnitude of the voltage pulse was negligible. This is similar to what happens when an object falls on the strip accidentally. Only when the pressure of a human foot was applied was an appreciable magnitude of 5 V or greater generated. This case was tested and validated using various people as test objects. The required voltage pulse was observed even when a child was asked to step over the sensor. This condition was used in the C code that was written to process the input data provided by the Arduino Uno microcontroller board.

RESULTS AND DISCUSSION

After validating the results on the serial monitor, it was determined that the module setup would provide reliable readings. To test the system in a real-time scenario, all hardware components were linked together. The results were recorded under various conditions to ensure their dependability. The voltage output plot acquired by the DSO when a single person walked on the sensor strip is shown in Figure 7. Another person walked on the strip, this time, with a slightly larger body weight. The corresponding DSO voltage graph is shown in Figure 8. The magnitude of the voltage pulse generated by the sensor strip was found to be dependent on the intensity of the lateral force applied to the sensor strip by foot pressure. As the intensity of the force applied was lower in the first test, the magnitude of the voltage spike was lower, as shown in Figure 7, whereas a high-intensity force applied to the sensor produced a high-magnitude voltage pulse, as shown by the DSO in Figure 8. After testing the setup with a known number of people, the module and system were installed on the room’s front door. Several people passed by the door, and the readings on the display were recorded. As people passed by, the count was incremented and displayed accurately by the 7-segment display. The DSO graph for multiple people passing through the door while pressing the sensor with their feet is shown in Figure 9. Figure 10 shows the counting sequence displayed on the 7-segment display. Because the purpose of this work was primarily to fabricate and test the sensor, only a single-digit count was displayed. However, the number of digits to be displayed can be increased in this system. The counting sequence will be a larger number when used in a real-world person or event counting application. In this case, multiple 7-segment displays can be linked. For example, four 7-segment display modules are required to count the sequence 0000–9999.

Interfacing is simple with a modified software code for the Arduino Uno microcontroller. If the sequence is larger than that in the example above, an LCD module is a more convenient method than increasing the module interfacing. Again, a well-written software code in the C language is required for interfacing the LCD, and the required counting is displayed.

Thus, the counting capability of the current system can be modified to meet the needs. Replacement of the sensor module or the controller board is not required. The new display module can be interfaced with the controller ports, and the modified code will work with the same system.

Interfacing an LCD or multiple display modules was not investigated in this work. Figure 10 shows the increased count values as observed on the serial monitor of the Arduino IDE when people walked through the sensor strip. The count value was displayed on the serial monitor to verify the results. The value shown here can be saved and compared with the actual count. It was assumed that the system was only installed at the entry door, where no exit was permitted. This was done to eliminate the possibility of a count update if a person returned from the same door. This experiment was repeated several times to ensure the validity of the results and the accuracy of the counting sequence. There were no errors in the actual or displayed results at room temperature. The effect of changes in the sensor's temperature and humidity is a separate field of study that was not considered in this work. Multiple tests were performed on the sensor in the laboratory and at the actual site location (an entrance area of a room), and no damage to the upper layer of the sensor strip was reported (Figure 11).

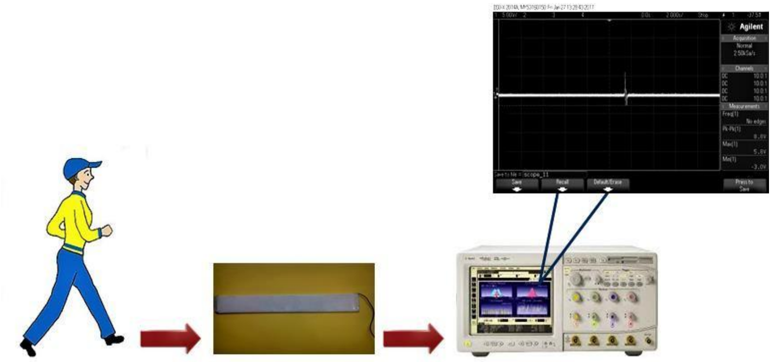

Figure 6. Voltage spikes from triboelectric sensors.

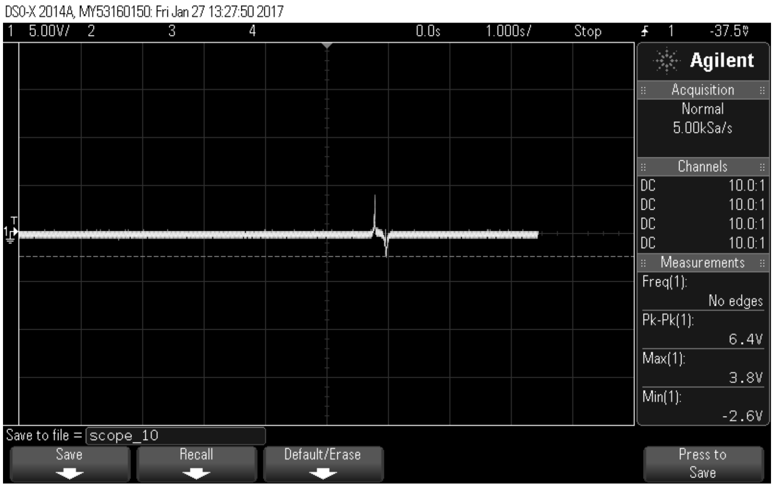

Figure 7. Voltage spikes when the first person walks on the sensor strip.

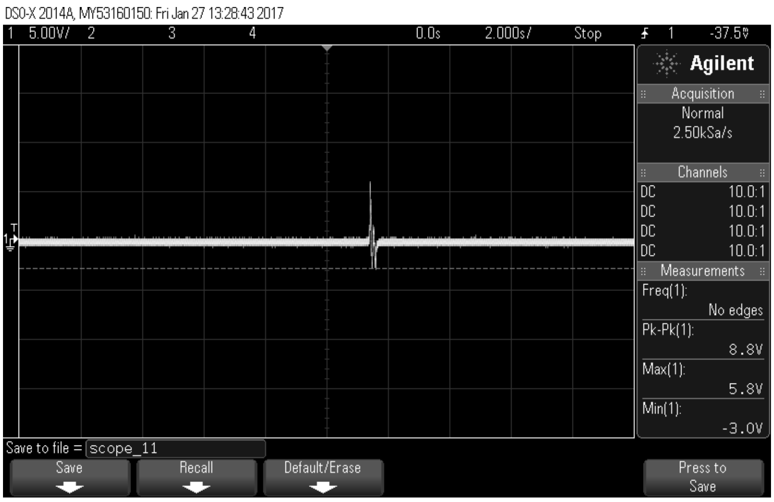

Figure 8. High-magnitude voltage spike plot when the second person walks on the sensor strip.

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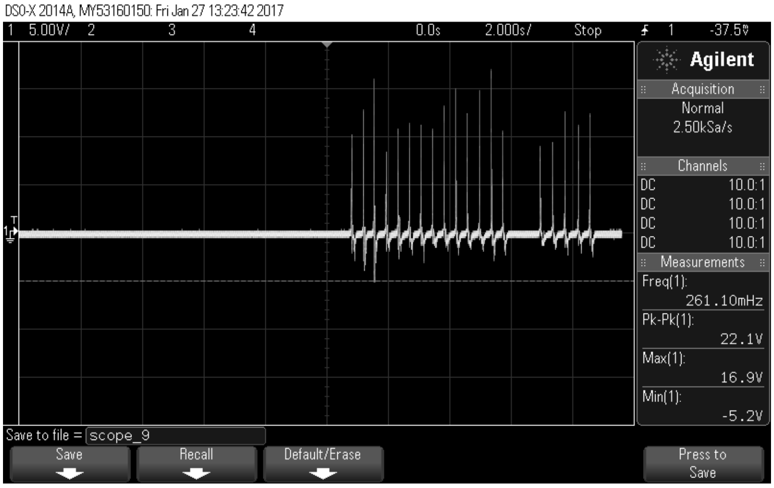

Figure 9. Voltage spikes when multiple people walk on the sensor strip.

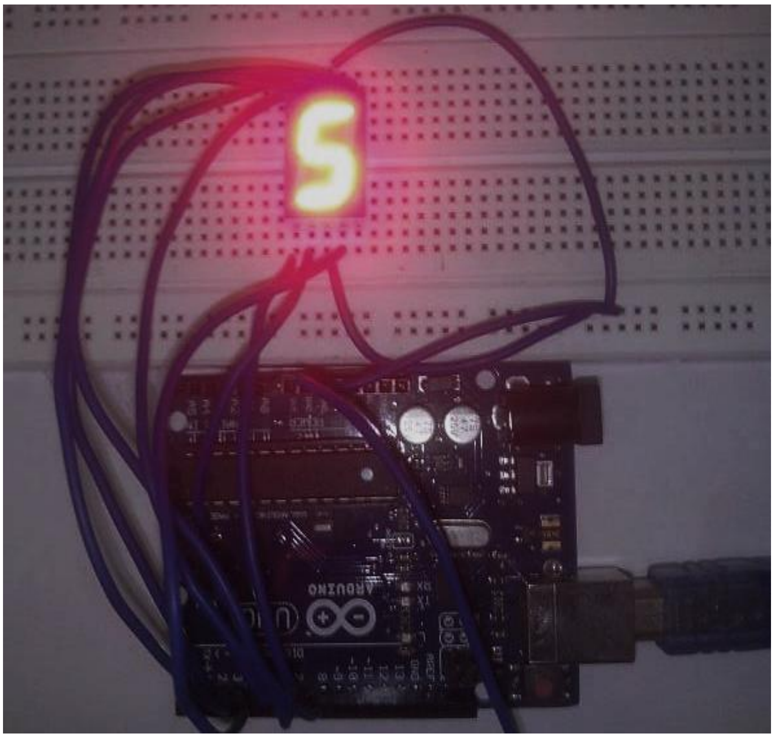

Figure 10. Count value on display.

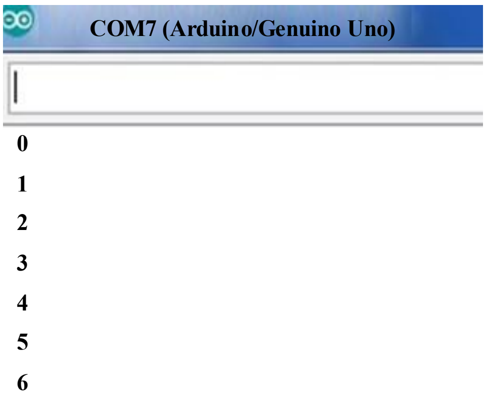

Figure 11. Serial monitor of Arduino IDE.

CONCLUSION

We herein propose and test a low-cost robust triboelectric pair material-based sensor. When frictional contact was applied to a sensor strip made of thin sheets of PTFE and aluminum, an output voltage was generated. The sensor strip was integrated with a generic counting application that can accurately count the number of events or people. A triboelectric sensor recorded the occurrence of an event or the passage of a person, which was then processed by a microcontroller unit. The results of the necessary analog-to-digital conversion of the data were displayed. The actual results were verified following successful testing of the entire system. When tested under various conditions, the system produced accurate results. A limitation of the designed system is reported herein for future improvements. Because the sensor used herein is in direct contact with the source of the applied force, it may experience some wear and tear over time. During testing, no such damage was reported; however, physical contact with the triboelectric layer may cause damage and reduce system accuracy. In this case, the upper material of the strip must be reconfigured by changing the upper sheet of PTFE material.

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