Real-Time Monitoring via Patch-Type Piezoelectric Force Sensors for Internet of Things Based Logistics

Cheng-Hsin Chuang, Da-Huei Lee, Wan-Jung Chang, Wan-Ching Weng, Muhammad Omar Shaikh, and Chung-Lin Huang

***Abstract*— We propose the use of simple and low cost piezoelectric patch type force sensors for logistic applications to ensure safety of the package while also detecting damage suffered. The sensors are connected to a prototype readout system that can record the data and transfer it wirelessly via a Bluetooth module. The data can be received by an in-vehicle telematics device which can upload it directly to the cloud database, thus allowing real time monitoring of package condition during transportation. This logistics management model would aid in improving the quality of services provided by the logistics company while also earning consumer credibility. Thus, we believe that these patch type force sensors can be realistically implemented in logistics in the near future.**

***Index Terms*— Piezoelectric patch type sensor, logistics, real time monitoring.**

I. Introduction

THE internet of things (IOT) is a unique transition technology that involves the connection of things such as everyday objects and products to the internet, thus allowing them to send and receive data. In particular, the logistics industry was one of the first adopters of IOT technologies utilizing barcode scanners to digitalize the delivery process and sensors to monitor cargo condition [1]. In logistics, IOT technologies can connect different assets along the supply chain in a meaningful manner and data generated from these connections can enable real time visibility into operations and create new sources of value. This enhanced visibility can help logistic providers make better decisions as to how goods are monitored, routed and delivered to their customers. It is critical that loading mistakes and quality loss during transport can be detected and notified immediately.

The conventional barcode based system and more recently, radio frequency identification (RFID) technology, have already been widely implemented in logistics. These technologies combined with Global Positioning System (GPS) and other communication capabilities can enable identification and real time tracking of goods during transport. Rodrigo et. al. proposed an intelligent RFID logistics management model based on Geofencing algorithms that predicted the occurrence of route planning detours and effectively monitored the shipping process [2], [3].

While RFIDs can track and identify goods at various stages of delivery, there has been a growing trend where sensors are also being used to monitor variables like temperature (cold chain logistics and food products) or force (for perishable goods) experienced during transport. There are a number of novel IoT solutions being developed for logistics where sensors are being integrated with RFID and GPS to provide complete monitoring of goods in real time so that they arrive in the condition anticipated by the customer [4]. Prasanna et. al. proposed a system to overcome problems in cargo loaded vehicles like delay in delivery, overloading and misplacement of goods [5]. The system uses RFID to identify goods and avoid misplacement, a weight sensor to prevent overloading and GPS to track the vehicle and communicate details of goods. Gomez. et. al. developed a low power semi passive RFID enabled temperature sensor for cold chain management with an operation range of $-40°C$ to $85°C$ while only requiring an average of $8.4\mu W$ when active [6]. Other examples include the integration of gas sensors with flexible RFID tags for effective food monitoring during logistics and a real time monitoring and online decision support system based on RFID and sensor networks for improved delivery of perishable goods [7], [8]. Papatheocharous et. al. proposed a cargo tracking system called eTracer that managed the loading and unloading of goods in an automated way [9]. It involved the integration of a series of sensor technologies and the utilization of protocols like Bluetooth and wireless local area network (WLAN) for providing operational, territorial and time-based information.

Wireless sensor networks (WSN) that are wireless networks consisting of spatially distributed autonomous sensors to monitor environmental and physical conditions are also been increasingly employed in logistics. The data obtained by

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these sensors can be cooperatively passed along the network and communicated to the outside world via a gateway in the transport vehicle [10]–[12]. Logistics can greatly benefit from the sensing and communication possibilities of WSNs where events like damage to the package can be detected early and at the point of origin. Smart delivery vehicles with a RFID system and a WSN allows better decision making by effectively monitoring the condition of the shipment at every stage of delivery [13]. A low-cost model capable of continuous tracking of goods was proposed that combined the cargo tracking and the tracing dynamic model and uses Global Positioning System (GPS) and WSN for obtaining the location of the vehicle and the cargo [14]. Li et. al. demonstrated a wireless sensor module (WSM) using GPS to upload data to the cloud system for real-time monitoring of both the temperature of the cold chain logistics and the temperature of the surrounding environment with an accuracy of about 95% [15].

Since logistic companies are required to deliver packages safely, there is a growing need for sensing forces experienced by the package during transport. In general, several force/torque sensing devices are currently employed in fields ranging from industrial automation to biomedical applications [16], [17]. The surge in these sensors can be largely credited to the widespread development of low cost microelectromechanical systems (MEMS) with novel designs that provide miniaturization capabilities while needing very low power [18]. Among the various transduction mechanisms utilized for force sensing, piezoelectric transducers offer a sensitive and simple approach because of their ability to generate analog voltage signals in response to applied dynamic mechanical forces. An interesting example for logistics is the battery less shock recording device developed by Ueda et. al. that converts the kinetic energy of a shock into a voltage output via piezoelectric transducer and this in turn changes the channel resistance of a ferroelectric-gate field effect transistor (FeFET) [19]. The change in the resistance of the FeFET can then be announced as the color of a lit light emitting diode (LED). In this study, we have designed two patch type piezoelectric force sensors to answer valid queries in logistics like package safety (has the package been opened) and present condition (has the package suffered damage). The voltage output response from the piezoelectric sensors is processed by a readout system which is also attached to the package. It converts the analog signals from the sensors to a digital signal and transmits them wirelessly via an inbuilt Bluetooth module. There is an infotainment system present in the logistics vehicle which can receive the transmitted data. It has an App that can monitor and analyze the received data and upload it to the cloud database via 3G/4G network connectivity, thus enabling real time monitoring of package condition.

II. Sensor Operation Principle

We propose the use patch-type piezoelectric force sensors for real-time monitoring of package condition by detecting if it has been opened or has suffered damage during transportation. The piezoelectric polyvinylidene fluoride PVDF film is the principal sensing element, which can generate an electric charge in response to an applied mechanical stress. A patch type tear-off sensor is taped to the top of the package. When the package is opened by removing the tape, a tensile stress is exerted on the PVDF film. A patch type impact sensor is taped to the bottom of the package. It consists of miniaturized ferrous balls attached to a PVDF film and is used to detect damage due to compressive stress exerted during impact. In each case, the tensile and compressive stress experienced by the PVDF film can be translated into a voltage output. The voltage output of two sensors obtained using the digital phosphor oscilloscope and the prototype readout system (after wireless transmission to the infotainment system) are compared as shown in Fig. 1. When the tape is torn off (CASE 1), the sensor experiences a tensile stress and the digital phosphor oscilloscope and the readout system show a sharp increase in output voltage which will slowly return to its original position (no stress state). During free fall (CASE 2), the package weight exerts a compressive stress on the sensor that corresponds to the first negative voltage peak (red dotted circle). As the package hits the ground, a second positive voltage peak (blue dotted circle) is generated which corresponds to the compressive force exerted on the sensor by the ground. A third output voltage is generated as goods are stabilized (dotted black circle) and the piezoelectric signal returns back to the original position (no stress state). The results obtained by the digital phosphor oscilloscope and the readout system are comparable for both patch type sensors. Thus we have developed sensors based on the piezoelectric effect that can provide information about the condition of the package during transportation.

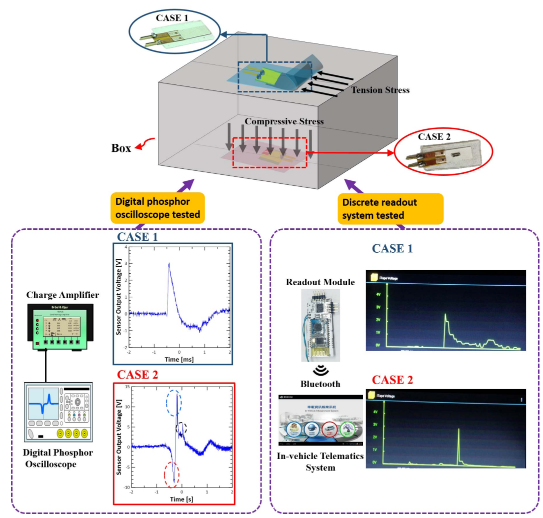

Fig. 1. Comparison of the voltage output response of the two force sensors obtained for the digital phosphor oscilloscope and the prototype readout system.

III. Design and Fabrication

A. Piezoelectric Force Sensors

The fabrication protocol of the patch type force sensors is illustrated in Fig. 2. A piezoelectric polyvinylidene

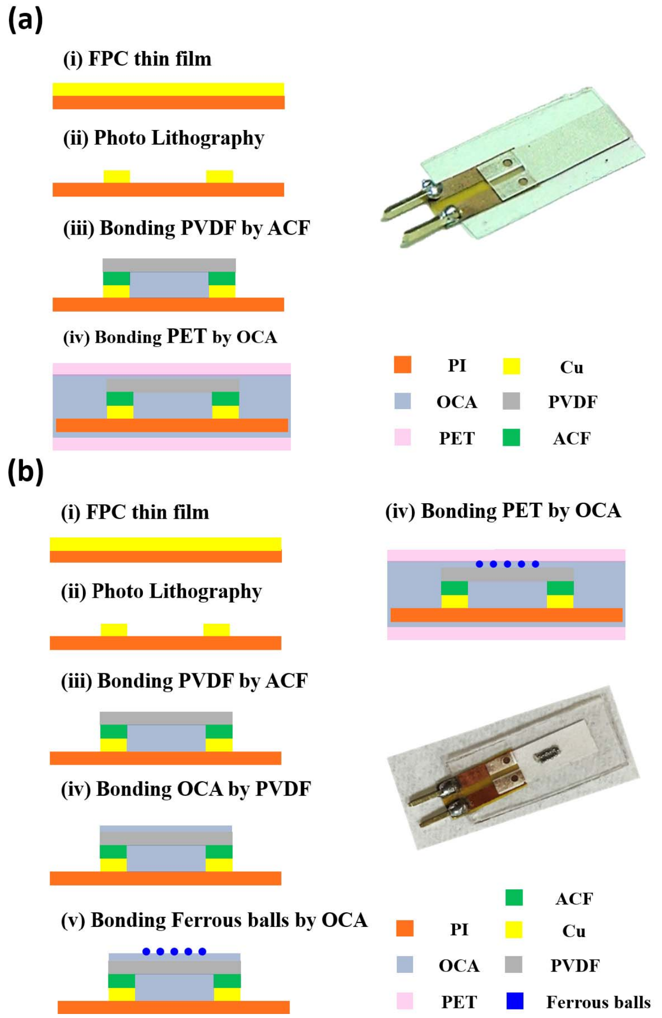

Fig. 2. Schematic of fabrication process for (a) patch type tear-off sensor and (b) patch type impact sensor.

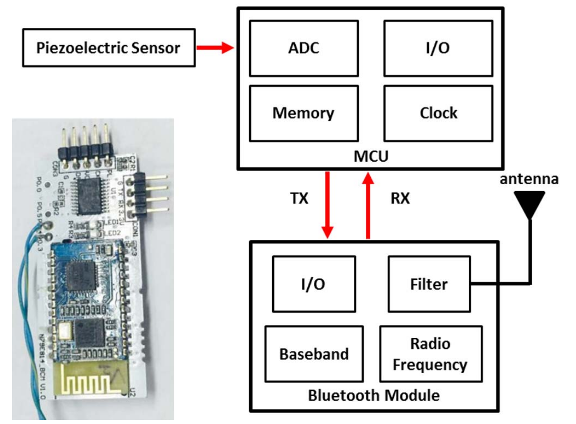

Fig. 3. An image and block diagram of the prototype readout module.

fluoride (28 μm PVDF, Measurement Specialties Inc., USA) film is used as the sensing element. A patterned flexible printed circuit FPC) board of thickness 30 μm is used to connect two electrodes on each side of the PVDF film to the readout module. A standard photolithographic protocol is used to pattern the FPC. First, the FPC is coated with positive photoresist using a spin coater (WS-400-6NPP-LITE, Laurell Technology Co., USA). This is followed by soft baking on a hot plate for 5 min at 60°C and exposure to UV light to define the pattern. A developer solution (EPD-1000) is used to expose the pattern followed by washing in de-ionized water. Lastly, the FPC is immersed in an 80°C ferric chloride solution for etching the Cu metal and treated with acetone to remove the photoresist, followed by washing and drying with an air gun. Two patches of anisotropic conductive film (ACF - 74μm, 7303, 3M., USA) are cut and selectively coated on the Cu metal of the patterned FPC using tweezers. The ACF enables the bonding of the two screen-printed silver electrodes of the PVDF sensing film to the Cu metal while maintaining an electrical contact. Finally, two rectangular patches of 0.1 mm Polyethylene Terephthalate (PET) film are coated with an optically clear adhesive (OCA - 100μm, 8171, 3M., USA) and then used to encapsulate the sensor on both sides. This protects the sensors and improves stability of the piezoelectric response.

In this study, we have developed two kinds of flexible patch type force sensors that can be attached to the package. The first patch type sensor (10 × 20× 0.4 mm) attached to the top can detect if the tape has been torn and the package has been opened. The second patch type sensor (10 × 20 × 0.5 mm) is located at the bottom of the package. It has five ferrous balls, each with a diameter of 0.4 mm, attached to the top of the piezoelectric film and can detect impact when the package is dropped in free fall motion. The charge generated by the piezoelectric PVDF film in response to an applied stress during tape tear off or under impact can be expressed mathematically using the equation below:

$$D = \frac{Q}{A} = d_{3n} X_n \tag{1}$$

where D is the charge density, Q is the charge generated, A is the conductive electrode area, d_{3n} is the appropriate piezoelectric coefficient for the axis of applied stress or strain, n is the axis of applied stress or strain and X_n is the stress applied in the relevant direction. Using the d_{33} piezoelectric coefficient of PVDF film (20 x 10^{-12} C/N), the charge generated is found to be 1.22 × 10^{-11} C when the applied stress is about 10 kN/m^2 (compressive stress experienced by a package containing a weight of 1 Kg after being dropped in free fall from a height of 90 cm). Under conditions when the impedance of the source sensor matches the input impedance of the ADC, the charge measured by the readout module should be comparable to the charge generated by the piezoelectric sensing element.

B. Readout System

While the piezoelectric response from the patch type force sensors can be analyzed using an oscilloscope in laboratory settings, this is not viable for practical logistic applications. Therefore, we have developed a miniaturized prototype readout system that can be attached to the package and contains a microcontroller unit (MCU, MG84FG516) for storing the recorded signal as shown in Fig. 3 The analog signal from

(b)

Sensor Number	Time	Event	GPS
dsfafas132	2015-11-28 20:18:09	Tear Off	
dsfafas250	2015-11-27 18:34:50	Tear Off	
dsfafas186	2015-11-27 16:58:40	Fall Down	
dsfafas943	2015-11-26 19:48:27	Tear Off	
dsfafas751	2015-11-25 11:17:35	Fall Down	
dsfafas483	2015-11-25 09:23:45	Fall Down	

Fig. 4. (a) The In-Vehicle Infotainment System showing the App (iTape) for analyzing the results transmitted by the readout system. (b) Online Cloud monitoring and management platform.

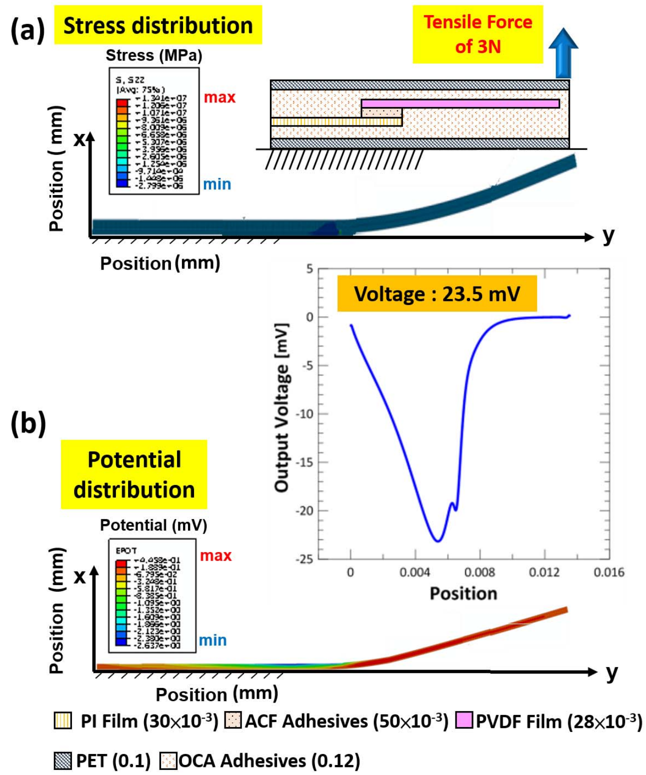

Fig. 5. Numerical simulation results for tear-off sensor showing (a) stress distribution and (b) the resultant potential distribution and output voltage response of the PVDF sensing film.

the patch type sensors is converted to a digital signal via the analog-to-digital converter (ADC) with a reference voltage of 3.3 V. The front-end circuitry between the sensor and the ADC does not contain a charge amplifier. However, there is an additional circuit comprising of three resistors in series (100 MΩ each) which are connected in parallel to a capacitor (1000 pF) to enable impedance matching between the sensor and the ADC. A 10-bit ADC is used which utilizes a sampling rate of 1 KHz.

The impedance matching circuit must provide enough series resistance between the electrical discharge of sensor and the ADC input pin to prevent damage of the input. The charge measured by the ADC, Q, can be mathematically expressed using equation 2:

$$Q = \int Idt = \frac{1}{R}\int Vdt \tag{2}$$

Where R is the total resistance provided by the impedance matching circuit, V is the voltage output of the sensor as measured using the readout module and t is the sampling time of the ADC. Using a total resistance of 300 MΩ, a voltage output value of about 1.5 V (observed for a package containing a weight of 1 kg after being dropped from a height of 90 cm) and a sampling time of 10 ms, the charge measured by the ADC can be calculated to be about 1.67 x 10^{-11} C. This value shows good agreement with calculations of charge generated by the PVDF film (obtained using Eq. 1) under same applied stress conditions. Consequently, the matching circuit improves signal processing by preventing prominent reflections that heavily distort the input signal. Once the ADC digitalizes the analog signal, it can be transferred to the Bluetooth module via the MCU_TX pin. After modulating the digital signal, an antenna is employed for wireless transmission. In addition, the transmission distance of the Bluetooth module can reach 60 meters when line of sight channel condition is achieved. Furthermore, an LED as a function indicator is used to determine the operating state of the data transmission. To be viable for application in logistics, it is critical that the readout module should utilize a wireless technology which fulfills certain requirements like low cost, ease of implementation, low power consumption and ability to send and receive data from multiple packages with low interference. While lower frequency radio waves enable longer-range wireless transmission, they consume more power as compared to technologies like Bluetooth (short wavelength radio waves with ultra-high frequency of about 2.4GHz) which would be more efficient when short-range data transfer between the readout module and the vehicle telematics system is required. In order to be applicable for monitoring goods which are transported over a longer time duration (e.g. cargo on ships that may take months to arrive at their final destination), the Bluetooth Low Energy (BLE) technology can be used as it can support very small transmission bursts between long idle periods with extremely low power sleep modes. The transmitted signals from the readout system can be received and analyzed by the in-vehicle infotainment system (IVI, Tiny210V2, Smart210, JAPAN) using an APP (iTape) that we have developed as shown in Fig. 4a. The data can

TABLE I
MATERIAL PROPERTIES USED FOR NUMERICAL SIMULATION

	PVDF	PET Film	OCA	Ferrous balls
Density (kg/m^3)	1780	133.27	52.1	2650
Young`s modulus (Pa)	3×10^9	3.11×10^9	3.5×10^7	6.54×10^{10}
Poisson`s ratio	0.35	0.33	0.25	0.26
Dielectric constant	12			
d_{211},d_{233}(m/Volt)	2.3×10^{-11}			
d_{222}(m/Volt)	-3.3×10^{-11}			

TABLE II
MATERIAL SPECIFICATION FOR NUMERICAL SIMULATION

Materials	Area (mm²)	Thickness (mm)
PVDF Film (Sensing Element)	13 × 5	28×10^{-3}
OCA Film	20 × 5	0.12
PET	20 × 15	0.1
Ferrous-balls	0.3 × 0.3	0.3
ACF Film	3 × 1.5	50×10^{-3}
FPC Film (PI/Cu Film)	10 × 5	30×10^{-3}

then be uploaded to the cloud database shown in Fig. 4b via 3G/4G communication capabilities of the infotainment system and records the time and type of event (tear off or fall down) and the location at which event occurred, thus enabling real time monitoring of package condition during transportation.

IV. NUMERICAL SIMULATION

A. Patch Type Tear-Off Sensor

We have used commercial finite element software, ABAQUS, to simulate the stress distribution and the voltage output response on the PVDF sensing film during tear-off and impact. The material properties and specifications used for finite element analysis of the two patch type sensors are shown in Table 1 and 2, respectively. The physical dimensions of the patch type tear-off sensor are 25 × 10 × 0.4mm (area and thickness) with a rectangular structure. A tensile force of 3N is applied to simulate tape tear-off and the resulting stress and potential distribution is analyzed as shown in Fig. 5. The base of the sensor is partially fixed while part of it can move and undergoes bending under an applied tensile stress. The voltage output increases to a maximum value (23.5 mV) at the position where the applied stress on the PVDF sensing element is the largest (the hinge point which separates the fixed and movable part of the sensor).

B. Patch Type Impact Sensor

The patch type impact sensor is located at the bottom of the package and experiences a compressive force when

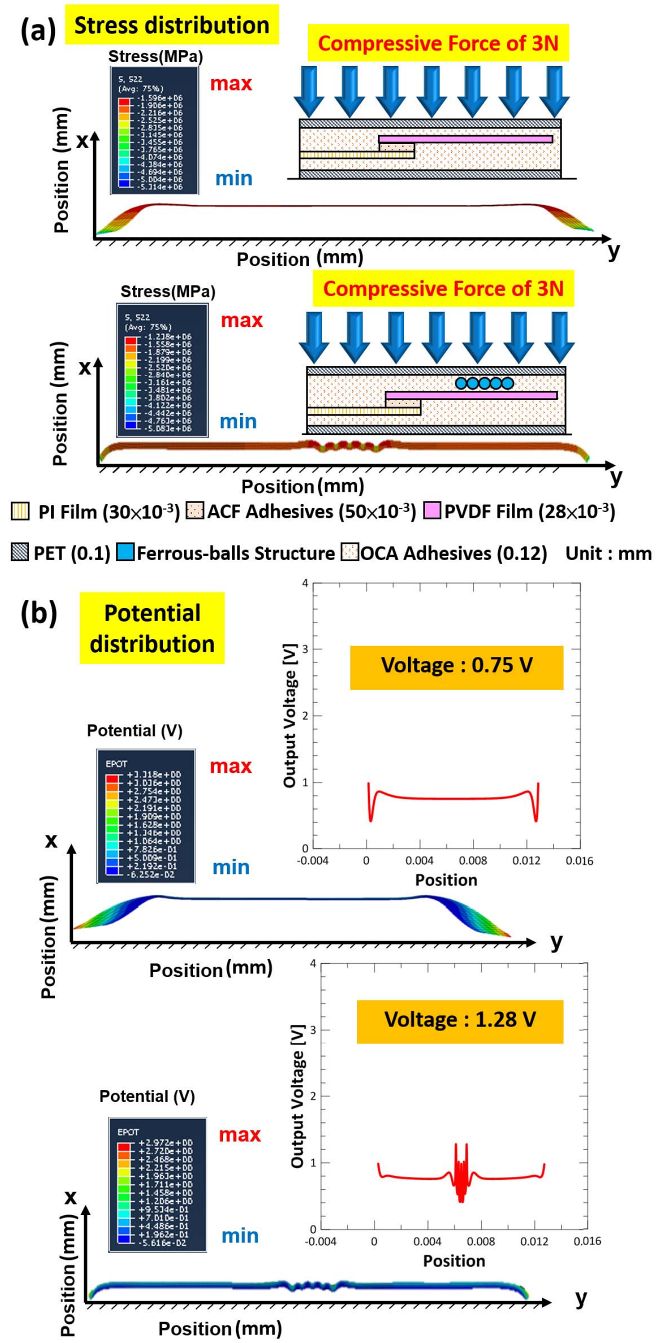

Fig. 6. Numerical simulation results for impact sensor showing (a) stress distribution and (b) resultant potential distribution with and without the presence of ferrous balls on the PVDF film.

the package is dropped. It has a similar architecture to the tear-off sensor with the only difference being the addition of the ferrous micro-balls on the surface of the piezoelectric sensing film. The material parameters are similar to the tear-off sensor while the physical dimensions of the impact sensor are 25 × 10 × 0.5 mm (area and thickness) with a rectangular structure. We have used finite element analysis to observe the effect of the micro-balls on the sensor response when a uniform compressive force of 3N is applied to simulate impact when package is dropped. Without the micro-balls, the peak

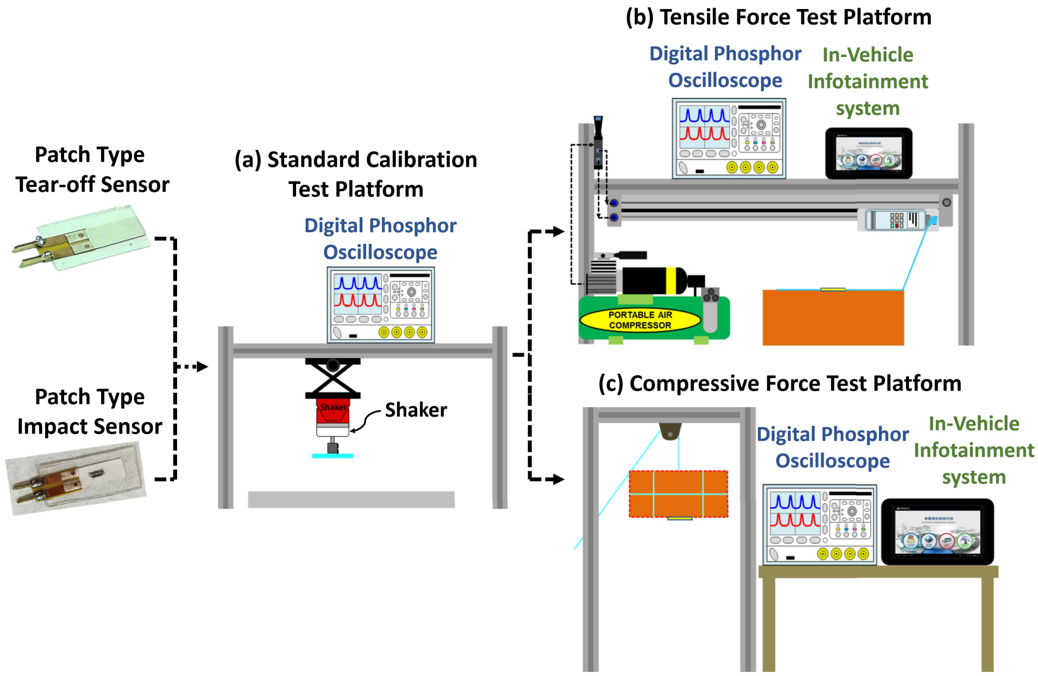

Fig. 7. (a) Testing reliability of the force sensors using a standard calibration platform. (b) Tensile force platform to detect tape tear off. (c) Compressive force platform to detect impact.

voltage output shows a value of 0.75V which is lower than the value of 1.28V observed with the micro-balls as shown in Fig.6. Under applied compressive force, most of the stress on the piezoelectric sensing film is concentrated under the hard micro-balls, thus resulting in a higher voltage output and consequently higher sensitivity.

V. Experimental Setup

To ensure reliability of sensor response, we have first tested the patch type tear off and impact sensors using a dynamic testing platform as shown in Fig 7a. An acrylic sheet ($5 \times 5mm^2$, 2mm thickness) is attached to the front end of a force sensor which has a sensitivity of 494.604 mV/N. The force sensor (209C01, PCB Piezotronics Inc., USA) is installed on a shaker (GW-V4, Data Physics Co, USA) and contacts the surface of the patch type tear off and impact sensor in a periodic manner exerting a compressive force of 2N each time. A function generator (AFG3022, Tektronix Inc, USA) is used to drive the shaker at a frequency of 1 Hz and an amplitude of 500 mV p-p. The force sensor output signals are passed through a signal conditioner to an oscilloscope through channel 1 for real-time monitoring. The piezoelectric response of the patch type sensors generates a voltage output which passes through a charge amplifier (B&K NEXUS2690A) to the digital phosphor oscilloscope (DPO3014, Tektronix Inc., USA) through channel 2. Each sensor is contacted 10000 times to study the variability in output response. Furthermore, we have compared the response of 10 different sensors to test reproducibility. Next, we test the sensor response during actual tape tear off and impact by using a dynamic tensile and compressive testing platform as shown in Fig. 7 b, c. The tear off sensor is taped to the top of the package. The tape is then torn off using a linear pneumatic actuator, simulating package opening. The speed of tear off can be varied by adjusting the working pressure using a pneumatic valve. The angle of tape tear off is also varied from 20° - 80° . The impact sensor is taped to the bottom of the package. Packages containing different weights from 1 to 15Kg are raised to a height of 90 cm and dropped under free fall. The voltage output during tape tear off and impact is obtained using a digital phosphor oscilloscope after charge amplification and alternatively by the readout module after wireless transmission to the infotainment system.

VI. Results and Discussion

A. Reliability of the Sensors

To be useful in logistics, the obtained information from the force sensors should be reliable each time the package is opened or suffers damage. We have tested the reliability of the fabricated patch type impact and tear off sensors by analyzing the piezoelectric response when a compressive force of 2N is exerted on the sensor surface. This force is applied 10000 times periodically at a frequency of 1 Hz and the voltage output is analyzed using a digital phosphor oscilloscope ash shown in Fig. 8 a, b. The sensor signal is recorded every minute which gives a total of 333 measured signals. The voltage output range for the tear off sensor is 2-2.2 V with a value of 2.1 V observed for about 150 signals. As for the impact sensor, the voltage output range is 4.6-5.3 V with most of the readings concentrated at 5 V. The higher voltage output for the impact sensor can be attributed to increased stress exerted on the piezoelectric film due to the presence of ferrous micro balls on its surface. The ability to get a similar voltage output each time the sensor surface is contacted highlights

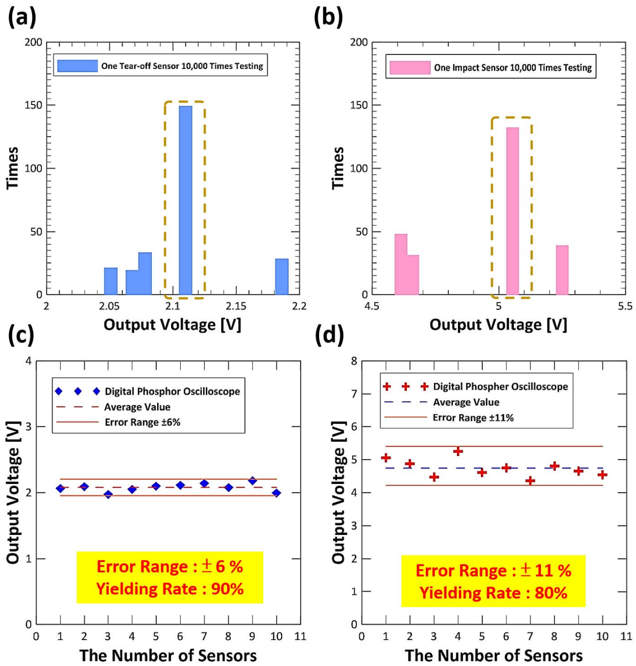

Fig. 8. The voltage output of the patch type tear off and impact sensor for (a, b) 10000 times of testing and (c, d) 10 different sensors, respectively.

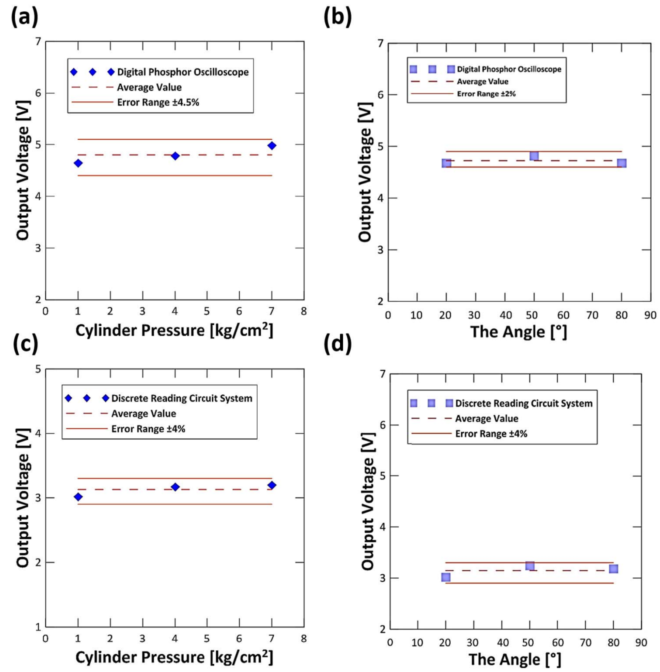

Fig. 9. Voltage output results for the tear-off sensor for different tear off speeds (working pressure of pneumatic cylinder) and angles obtained using (a, b) the digital phosphor oscilloscope and (c, d) the prototype readout system.

the reliability of the sensor response. We have also tested 10 different tear off and impact sensors and obtain an average voltage output of 2.1 V and 4.8 V, respectively as shown in Fig. 8c, d. This shows good agreement with results obtained for individual tear off and impact sensors that have been tested 10000 times each. The variation in the obtained values for the 10 different sensors is low with an error range of ±6% for the tear off sensor and ±11% for the impact sensor. Consequently, the piezoelectric response of the patch type sensors is reliable and reproducible.

B. Patch Type Tear-Off Sensor

We have tested the piezoelectric response of the patch type tear off sensor by taping it to the top of the package and using a linear pneumatic actuator to perform tape tear off at different speeds and angles. The induced tensile stress exerted on the PVDF film during tape tear off results in a voltage output which can be observed using a digital phosphor oscilloscope (after charge amplification) and compared with the value obtained from the readout module (after wireless transmission to the infotainment system). The average voltage output obtained for different tear off speeds by varying the working pressure in the pneumatic cylinder from 1 to 7 kg/cm^2 was about 4.8 V for the oscilloscope and 3.1 V for the readout module as shown in Fig. 9 a, c. It was observed that different tear off speeds did not significantly affect the sensor response with a maximum deviation of about ± 4% from the average value observed for both the oscilloscope and the readout system. The average voltage output observed for tape tear off at different angles of 20° to 80° was about 4.7 V and 3.1V for the oscilloscope and the readout system, respectively, as shown in Fig. 9 b, d. As observed for different tear off speeds, the sensor response did not vary significantly from the average value for different tear off angles. The voltage output from the readout system is relatively lower than the oscilloscope as the reference voltage of the ADC in the readout module is 3.3 V. Consequently, we have demonstrated the practical applicability of the tear off sensor to detect package opening without being influenced by the manner in which the tape was torn off.

C. Patch Type Impact Sensor

The piezoelectric response of the patch type impact sensor is tested by dropping the packages containing different weights from a height of 90 cm using a free fall setup. We have tested the impact of each weight (1-15 Kg) using 10 sensors and the error bars have been included. The output voltages from both the oscilloscope and the prototype readout system show a similar rising trend with increasing package weight. For the digital phosphor oscilloscope, we observe an output voltage of 1.8 V for a package containing a weight of 1 Kg which increases linearly to 8.1 V as the package weight increases to 15 Kg (coefficient of determination of 0.87) as shown in Fig. 10 a. Similarly, the prototype readout system shows an output voltage of 0.8 V for a package containing a weight of 1Kg that increases linearly to 3.21 V (coefficient of determination of 0.97) as the package weight increases to 15 Kg as shown in Fig. 10 b. The maximum analog input or reference voltage that the ADC of the prototype readout system can achieve is 3.3V. Therefore, the output voltage obtained by the readout module saturated as the package weight approaches 15 Kgs. A low voltage ADC is preferred in this study for the miniaturized readout module due to lower power consumption and lesser board complexity and the low

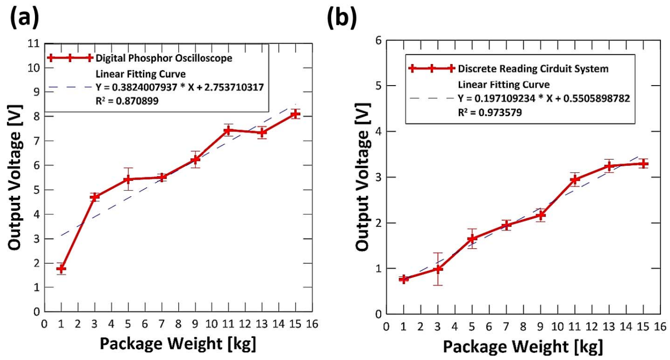

Fig. 10. Voltage output results of the impact sensor for 1-15 kg packages obtained from (a) the digital phosphor oscilloscope and (b) the prototype readout system.

reference voltage can improve absolute resolution while using a converter with the same number of bits. However, to enable practical applications in logistics with wide voltage swings, the analog signal must be scaled down (divided) before the A/D conversion to ensure that the largest expected input signal is lower than the reference voltage without compromising signal to noise ratio and this will be further developed in our future work. Consequently, this sensor can be used to detect the impact stress exerted on packages when they are dropped and can be used to evaluate damage to goods during transportation.

VII. Conclusions

We have developed low cost patch type piezoelectric sensors that can detect if the package was opened or subjected to damage during transportation. We have also developed a prototype readout system that can convert the analog data to digital and has an inbuilt Bluetooth module that can transfer the data wirelessly. We have also shown the viability of having an inbuilt vehicle telematics system that can collect and analyze the data and transfer it directly to the cloud. We believe that this IOT based approach will enable real time monitoring of the package condition and aid in providing improved logistic services.

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