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Low - Cost Artificial Potato for Impact Force and Vibration Measurements

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ABSTRACT

Instrumented devices (ID) are useful for quantifying impact and vibration forces in postharvest supply chains of horticultural crops. In this study, a low-cost ID was developed capable of measuring impact force (G) and vibration. The ID was composed of an Adafruit Feather Adalogger microcontroller fitted with a triaxial accelerometer (± 200G range) shield and real-time clock stored time-stamped impact data in flash memory. A 3.7-volt lithium polymer battery served as the power source. The ID was encased in a semi-ellipsoidal shell fabricated from 3D-printed thermoplastic urethane (TPU95A) filament; the shell was printed at 25% fill density. The device weighed 80 g, which is representative of a medium-sized potato tuber. Drop tests showed a high correlation (R2 = 0923) between computed and measured peak acceleration in terms of G-force. The ID was tested by placing it in bulk-loaded potato tubers brought from Buguias to La Trinidad in Benguet province. GPS data was obtained using a mobile app to map the transport route and locate extreme impact events. Mean vibration of 1.18G intensity at 14Hz frequency was recorded throughout the 4-hour trip. Impact forces ranging from 4.6G to 6.61G were measured at certain points during transport. The device was assembled from commercially-available microcontrollers, sensors and other electronic components; total cost of fabrication was 94-98% less than comparable devices available in the market.

Keywords: *Instrumented device, microcontroller, potato, impact recording device*

INTRODUCTION

Mechanical injuries of fresh produce may be associated with rough handling during packing, filling, loading/unloading, or transportation. Most mechanical injuries are typically from impacts, compression, cuts and punctures, and abrasion. Bruising resulting from improper handling causes increase in storage losses due to shrinkage and disease, lowers the quality of the product, increases disease incidence and decreases shelf life, and reduces the appeal of fresh produce to wholesale and retail customers (Thornton, 1998). Since an incubation period of up to 12 hours must elapse before the injury is apparent, damaged produce is often detected only at the retail level (Opara and Pathare, 2014). In the Philippines, reported postharvest losses for fresh fruits, vegetables and tubers/bulb crops are 3-44%, 10-29%, and 7-50%, respectively (Nuevo and Apaga, 2010). The multi-layered supply chain prevalent in the Philippines, as well as the challenges involved in inter-island shipping and transport results in multiple handling steps. Manual handling, poor road conditions, and inappropriate packaging and transport practices contribute to postharvest losses (Mopera, 2016).

The capability to monitor the response of products to stress, especially during handling, is important in designing the best postharvest management processes. Knowledge on the primary mechanisms that mechanically injures fresh produce helps in the design of postharvest handling processes to minimize the adverse effects of the stress or to modify the postharvest procedures to prevent these damages (Laurie, 2009). Instrumented or electronic spheres or product-shaped impact recording devices, or artificial fruits are often used to measure rough handling of fresh produce in order to reduce economic losses for farmers and traders due to mechanical damages (van Canneyt et al., 2003).

When mixed with the produce, instrumented devices (ID) can quantify and record impact forces and vibration experienced by the produce on different stages of the postharvest handling chain. Bruising-risk zones can then be identified and improved for better handling, resulting to less postharvest losses and better product quality. At present, IDs are not locally available in the Philippines and are expensive. Devices such as the Techmark Impact Recording Device (IRD) (priced at $5,900 in 2016; approximately PhP 300,000) and the Tuberlog ESYS GmbH (priced at ₤1,295 in 2017; approximately PhP 91,000) can be imported, but the cost is prohibitive for many laboratories (private and government institutions). A cost-effective ID for monitoring impact and vibration stress would help scientists and engineers to adequately study postharvest handling systems and institute appropriate loss reduction measures.

The general objective of this study was to develop an instrumented device to autonomously record impact and vibration during simulated handling. The specific objectives were to identify electronic components that are compatible with each other for developing a prototype ID, and calibrate the prototype unit when subjected to impact forces. This will serve as a tool for future studies investigating postharvest handling and transport problems.

METHODOLOGY

Instrumented Device Development

Hardware Development

An ID that measures impact and vibrations must have the capacity to measure acceleration and save the data to a memory card. These functions are provided by an accelerometer shield and an SD card shield, respectively. To have a tracking function, it must contain at least a time stamp that can be provided by a real-time clock shield. For a more accurate tracking, a GPS shield can be included to the device. But in this study, the ID did not contain a GPS shield because of the limited capacity of the microprocessor and the resulting size of the instrument would be significantly larger with respect to the target size, i.e., potato tuber. All these functions will only work harmoniously when combined with an appropriate microprocessor, powered by a battery, which distributes the required power and command to the individual components. In this study, different types of the discussed electronic components, except for the GPS shield, were considered in the design. Their compatibility with each other and Arduino IDE programming software and their size were also factoring in the development of the ID.

Arduino-based microcontrollers with relatively small dimensions to fit in a small casing, approximately the size of a mango or a potato tuber, were selected in this study. During the period of the study, the available microcontroller boards in the Philippines that met the size requirements were the Gizduino+Mini USB, Arduino MEGA 2560, Gizduino X ATmega1281, DF Robot Beetle v1.1 and the Adafruit Feather Adalogger. The specifications of these microcontrollers are shown in Table 1. These microcontrollers were tested for compatibility with the Arduino IDE and the different electrical components were discussed below.

Accelerometers were used to measure acceleration with a unit based on gravitational acceleration (1G = 9.81 m s^{-2}). Three accelerometers were tested for compatibility: the Adafruit Flora Accelerometer with a range of ±2G, the E-Gizmo ADXL345 with a range of ±16G, and the Sparkfun ADXL377 with a range of ±200G.

Time stamp was provided by a real-time clock (RTC) for accurate monitoring or tracking of the stages of the postharvest handling where the field test was conducted. Recorded data (in terms of gravitational acceleration, G) together with a time stamp accurately pinpoints the activity when an extreme impact occurs. DS3231 and DS3232 RTC models were tested in this study.

A 16-gigabyte microSD card was used as a memory or data storage and to record data, a microSD card shield must be included. DFRobot microSD card shield, Catalex microSD card adapter, and Adafruit Feather Adalogger were the only ones

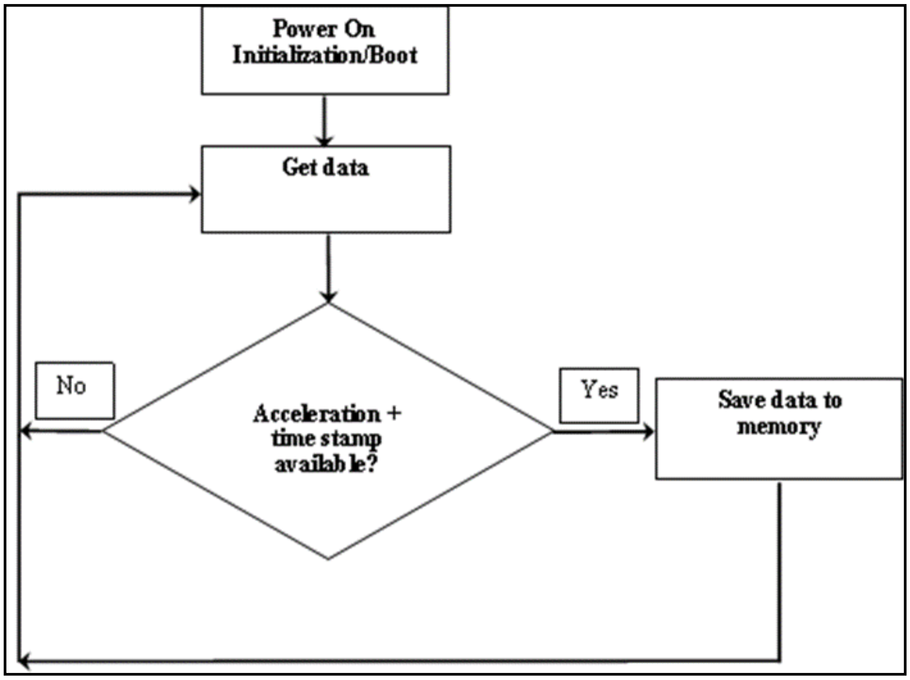

Figure 1. Flowchart of the sensor program during sampling.

Table 1. Comparison of microcontroller boards for the development of an instrumented device for impact data logging.

MANUFACTURER/ BRAND	ADVANTAGES	DISADVANTAGES
Arduino MEGA 2560	Compatible with most shields, large capacity with ATmega 2560, 54 digital I/O pins, 16 analog inputs	Large dimensions (101.5 mm x 53.3 mm)
E-Gizmo Gizduino X ATmega 1281	Compatible with accelerometer, SD card, real-time clock shields	Large dimensions (80 mm x 53 mm)
E-Gizmo Gizduino+Mini USB	Small dimensions (73 mm x 23 mm), built-in USB connection which is very accessible when uploading the sketch and data retrieval	Incompatible with SD card shields
DFRobot Beetle v1.1	Small dimensions (20 mm x 22 mm_, contains enough memory for codes of accelerometer, SD card, and real-time clock shields	Only contains 10 I/O pins (accelerometer, SD card, and real-time clock shields need 13 pins)
Adafruit Feather Adalogger	Small dimensions (50 mm x 23 mm), enough memory for accelerometer, SD card and real-time clock-shield codes/sketch, contains enough I/O pins for the shields, built-in lithium polymer battery port, built-in micro-SD card module	None

considered because other shields are specified to be incompatible with Arduino IDE, microcontrollers, RTC, and other electronic components.

A rechargeable lithium-ion battery was used in the study which provides 3.7 volts of power to the system, where the microcontroller will regulate the voltage for each component's power requirement. All the components' power consumption should be small to provide longer data gathering capability.

Once power is supplied to the ID, it makes the necessary initialization for the hardware and program. After booting, the ID will automatically read the acceleration experienced by the accelerometer and the time stamp, then the data will be recorded in the microSD card. It can then be mixed together with fresh produce in the handling chain stage, e.g. transport, where it records the impacts that are experienced by the produce in the said handling stage. The sensor reads acceleration data every 100 milliseconds and the data, together with the time stamp will be logged into the memory. The flowchart of the sensor program is shown in Figure 2.

Arduino IDE was used in the development of the software program called a *sketch*. All libraries that are needed and compatible with the available hardware were downloaded from Arduino libraries (https://www.arduino.cc/en/Reference/Libraries) and included in the sketch. Individual libraries of the different components were tested if they are compatible in working with each other. Different sketches of each component were merged to form a single sketch and was uploaded to the microcontroller of the ID. The recorded data can be retrieved in Microsoft Notepad and transferred to Microsoft Excel for plotting and analysis.

Development of the Artificial Shell

TPU95A filament was used for printing the artificial shell with a 3D printer (Ultimaker 3). This material was selected because it can regain its original form when force is repeatedly applied and removed from it. Using a 3D printer, practically any desired shape that represents the commodity being tested can be fabricated, and the fill density can be manipulated to closely replicate the firmness of the fresh produce being emulated.

To determine the appropriate fill density of the artificial shell, a firmness test was conducted on 25 potato pulp samples from Buguias, Benguet. Pulp samples with a 25-mm diameter were extracted using a stainless-steel tube; samples with a height of 10 mm were cut from the middle section of the extracted pulp. Printed TPU95A samples with fill densities of 100%, 75%, 50%, and 25% were produced, with 3 replicate samples per fill density. Firmness of TPU95A and potato samples were measured at room temperature using an Instron universal testing machine (UTM) model 4411. A static load cell of 0.5 kN was used to obtain force-deformation curves with the crosshead speed set at 10 mm per minute (Mohsenin, 1986). A steel probe (7.9 mm in diameter) with a rounded tip of 6.9 mm radius of curvature was used to apply pressure to the samples (Figure 2).

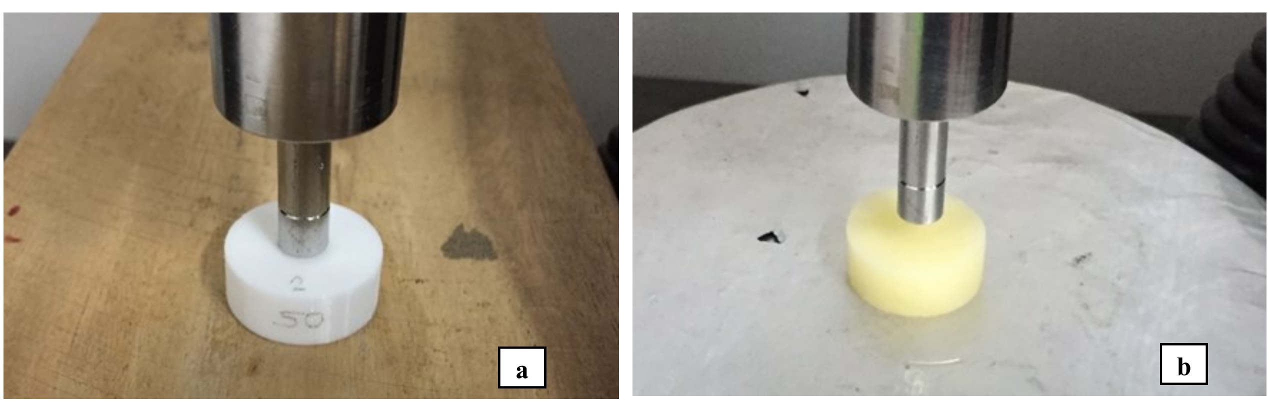

Figure 2. (a) TPU 95A sample 2 at 50% density and (b) potato sample undergoing firmness test.

Mohsenin (1986) defined stiffness as the slope of the initial linear segment of a force-deformation plot. However, since the force-deformation test in the present study was limited to a deformation of 1 mm only, the resulting plot was curved and non-linear regression was necessary to determine coefficients of the best-fit curve. Equation 1 was fitted to the force-deformation data, where ***F*** = load (kN), ***d*** = deformation (mm), and ***A*** and ***B*** are regression constants. The stiffness (kN mm^{-1}) was obtained from the ***B*** coefficient (Yaptenco, 2013):

$$\boldsymbol{F = A \cdot d^B} \qquad \textit{Equation 1}$$

Values of stiffness B were analyzed by ANOVA and Tukey's Honestly Significant Difference (HSD) test at 5% level of significance and type of material was used as the independent factor. Once the fill density that best approximates the firmness of potato pulp was identified, a potato computer model was designed using Ultimaker Cura, an open -source software used to create 3D objects.

Sensor Development
(Software Code/ Arduino Sketch)

Calibration of the Prototype Unit

To check whether the ID works properly and is getting accurate acceleration measurements, it was calibrated by drop test at different heights based on the test done by Xu and Li, (2015) . The artificial potato was dropped 40 times at four different heights: 25, 50, 75, and 100 cm. A concrete floor was selected as the contact material. There were several impacts or bounces during testing, but only the first impact of each drop was considered.

The means of the peak G were compared to theoretical impacts computed from the different heights and total weight of the artificial potato. Theoretical impact forces (F_i) at different drop heights were computed by using Equation 2, 3 and 4, where *KE* is the kinetic energy of the drop, *d* is the depth of deformation, *m* is the mass of the prototype unit, *v* is the velocity on impact, *g* is the acceleration due to gravity, and *h* is the drop height.

$$F_i = \frac{KE}{d} \qquad \textit{Equation 2}$$

$$KE = \frac{1}{2}mv^2 \qquad \textit{Equation 3}$$

$$v = \sqrt{2gh} \qquad \textit{Equation 4}$$

The depth of deformation of the ID during impact is the deformation which absorbs the energy of the drop before bouncing. To determine d, a separate drop test was conducted where the ID was dropped 20 times on a concrete floor from drop heights of 25, 50, 75, and 100 cm. Carbon paper was used to mark the area of deformation. Figure 3 shows the schematic diagram of elastic deformation of a falling sphere on a rigid surface (Mohsenin 1986).

Referring to Figure 3, the diameter ***2a*** at each drop height was measured and the averages were taken. The depth of deformation, ***d***, was computed using the Pythagorean Theorem, $\boldsymbol{R^2 = a^2 + (R - d)^2}$, where

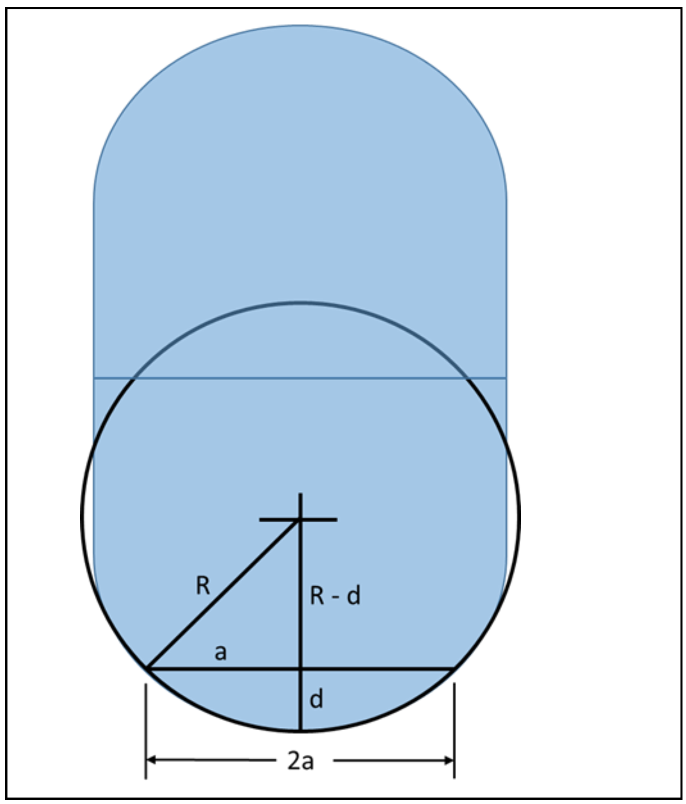

Figure 3. Schematic diagram of elastic deformation of a falling sphere on a rigid surface (Mohsenin, 1986).

diameter of curvature = 76 mm, radius of curvature (R) = 38 mm, depth of deformation ***(d)*** = unknown, diameter of deformation ***(2a)*** is measured from the drop test, and radius of deformation ***(a) = 2a/2***. The quantity d can then be computed for each drop height.

Field Testing

In this study, the developed ID was mixed with potatoes during transport immediately after harvest in Sitio Daligdig, Buguias, Benguet to the wholesale market or trading post in La Trinidad, Benguet. A total of five different trips were conducted in evaluating the device. The device measured impacts and evaluated the transport condition of potatoes.

The ID prototype was tested in the field by mixing it with potato tubers (Figure 4a) during transport in a six-wheeler truck from a farm in Sitio Daligdig, Buguias, Benguet to the trading post in La Trinidad, Benguet. The 85-km trip took about 3.5 to 4.5 hours from the farm to the trading post depending on the traffic situation along the way. As shown in Figure 4b, the data logger was placed vertically in-line with the rear axle and at the upper 1/3 layer of the produce to measure the maximum possible impact force or vibration experienced by the produce during transport (Mohsenin, 1986).

The data gathered were plotted and analyzed using Microsoft Excel. Major impact zones and vibration frequency, intensity and duration which can contribute to bruising were identified to help improve the handling chain of fruits and vegetables in the area. The route of the transport truck was recorded using Sports Tracker by Amer Sports Digital, a free mobile software from the Apple Store for iOS users that records the GPS data even at offline mode. The data gathered by Sports Tracker can be uploaded on their website (https://www.sports-tracker.com/) where the route, distance, speed, time of travel and elevation at any point of the journey can be obtained. The device's RTC was initially set to 00:00:00.00 and Sports

Figure 4. Instrumented device (encircled) located in the middle of bulk-loaded potatoes (a). The ID was positioned directly above the rear axle of the vehicle (b).

Tracker's initial GPS clock recording was at 14:43:04.40 on September 30, 2017 and the transport of potatoes started at 3:00 pm. The same RTC setting was used for the other transport trials, but with different initial GPS clock recordings.

The GPS data gathered by Sports Tracker, in KML file, was extracted and overlaid on Google Earth Pro for editing and locating peak impact events during transport trials.

Vibration Measurement

Vibration forces are often encountered during transport as a series of small impacts on container walls or produce; excessive vibration will eventually result in bruising, often becoming visible as a discoloration under the

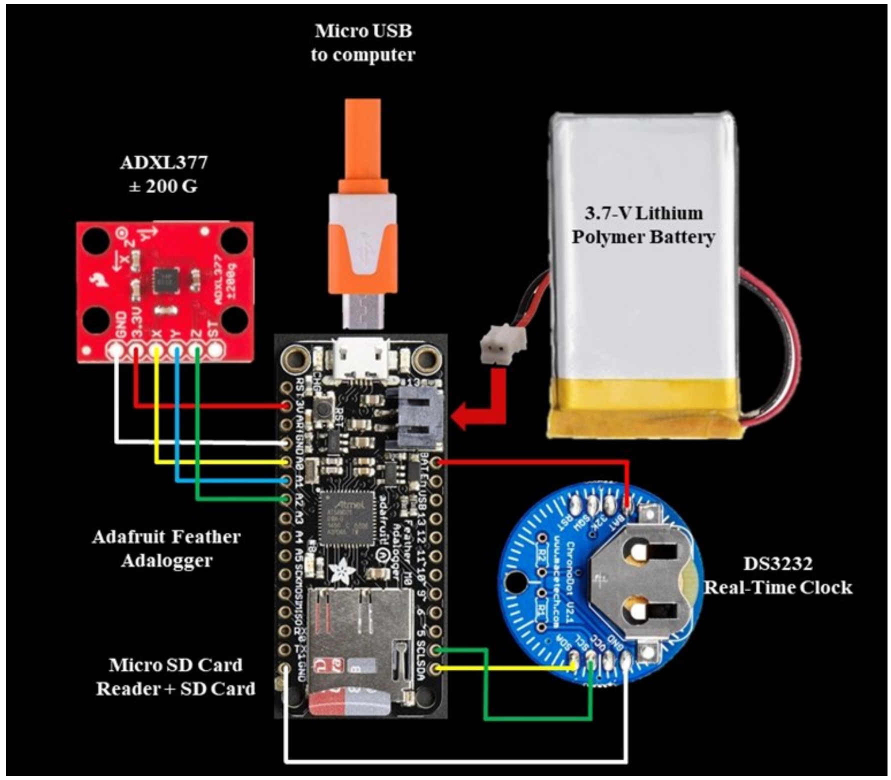

Figure 5. Wiring diagram of the instrumented for acquiring impact data.

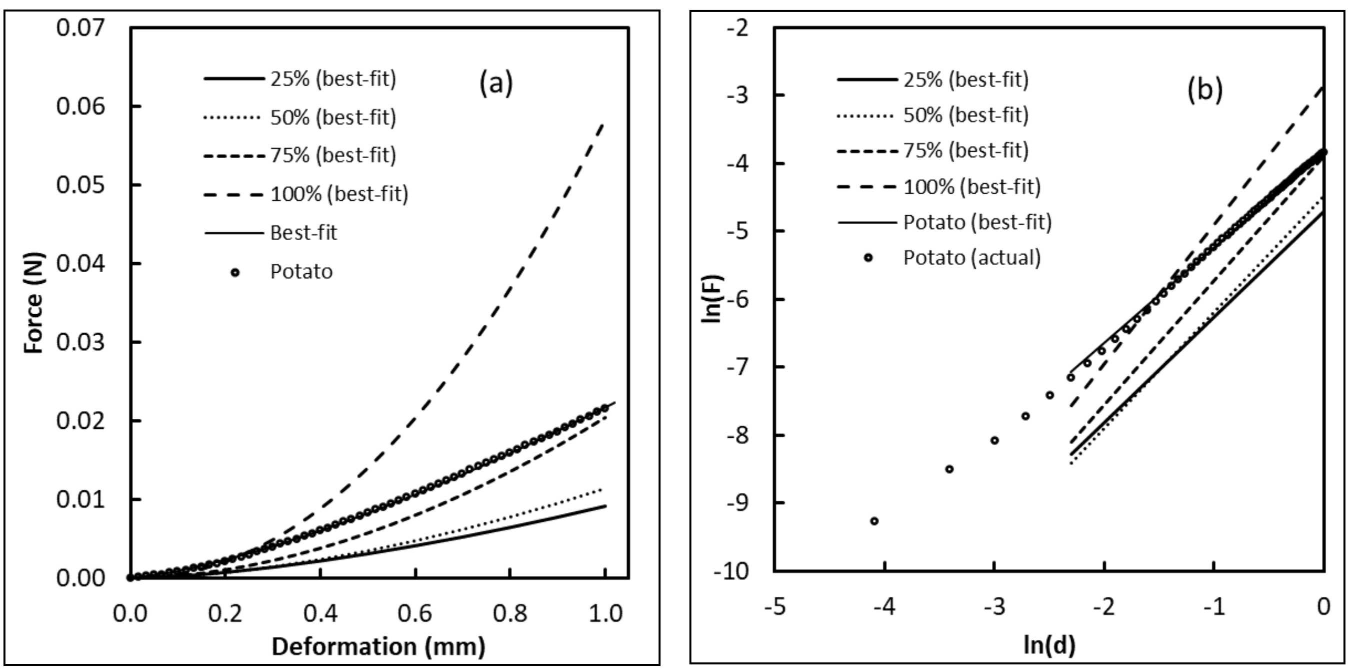

Figure 6. Comparison of best-fit force (F) - deformation (d) curves for 3D-printed TPU95A samples printed at different fill densities and a representative potato pulp sample (a). Plotting ln(F) versus ln(d) shows the slope of 25% fill density is the closest to the slope of the potato sample (b).

peel. The severity of the damage is determined by the intensity (G), frequency (Hz) and duration (time) of vibration. In evaluating the intensity of vibration, the magnitude is measured in G (1G = $9.81ms^{-2}$) by using an accelerometer and the frequency is determined by the number of cycles per second from the acceleration data (Mohsenin, 1986). The frequency was determined by counting the number of cycles per second (Hz) from the graph of time-stamped peak acceleration data acquired from the ID.

RESULTS AND DISCUSSION

Hardware Development (Electronic Components)

The final selection of electronic components satisfied our initial requirements: (1) size – must be small enough to fit in a potato-sized housing material; (2) memory size for microcontroller – must have enough flash memory to contain the combined sketch for accelerometer, microSD card, and real-time clock shields; and (3) compatibility with other electronic components. Adafruit Feather Adalogger was the best choice for the microcontroller because it only measures 51 mm x 23 mm, with built-in USB and battery charging, has 32K of flash memory and 2K RAM, it also has a connector for any 3.7V lithium polymer battery, 7 PWM pins and 10 analog pins. It also has a built-in microSD card module which greatly helps in reducing the size of the combined electrical components. Thus, there was no need to test other microSD card shields.

Table 2. Stiffness of potato pulp and TPU95A samples 3D-printed at different fill densities

MATERIAL	STIFFNESS^{z}, kN mm^{-1}	
TPU 100%	$2.054 \pm 1.539 \times 10^{-3}$	a
TPU 75%	$1.829 \pm 0.058 \times 10^{-3}$	ab
TPU 50%	$1.707 \pm 1.320 \times 10^{-3}$	bc
TPU 25%	$1.559 \pm 0.586 \times 10^{-3}$	cd
Potato	$1.500 \pm 3.870 \times 10^{-3}$	d

^{z}Values represent the mean ± SD of 3 replicate samples for all TPU samples, and 30 replicate samples for potato. Means with a common letter are not significantly different by Tukeys HSD test at the 5% level of significance.

The Sparkfun ADXL377 accelerometer was selected for its wide range of measurement (±200G), simple

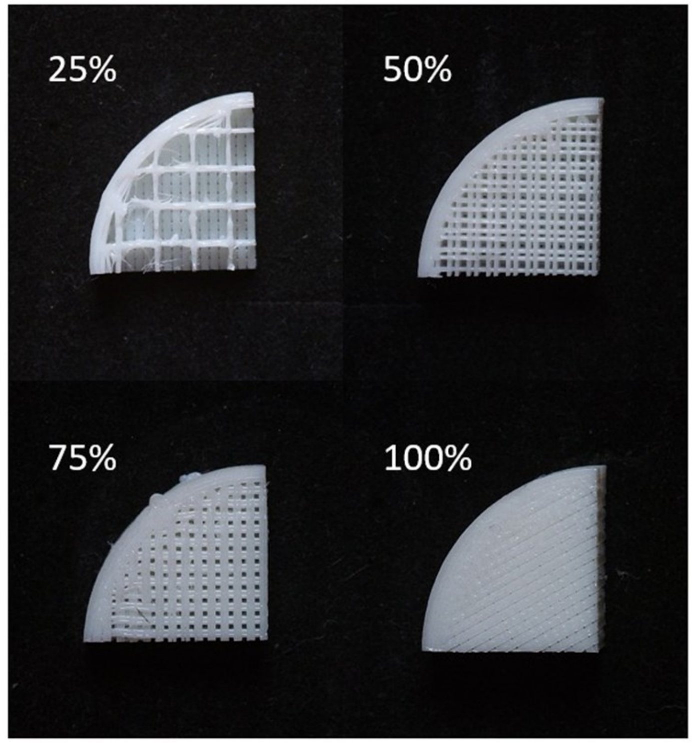

Figure 7. Magnified cross-section of TPU95A samples printed at different fill densities

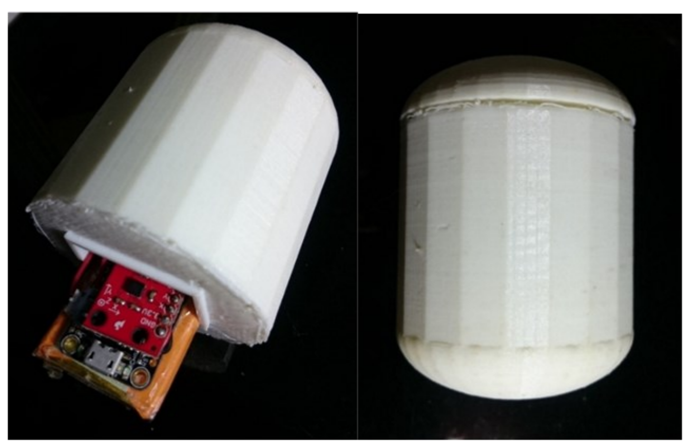

Figure 8. Assembled Instrumented Sphere without and with cap.

yet effective code, and is compatible with every shield and microcontroller. For the real-time clock, both DS3231 and DS3232 models were compatible with the other components. The Chronodot DS3232 model was used in this study because its pin orientation is exactly in-line with the input pins of the Adafruit Adalogger which made the fabrication easier. One lithium polymer (LiPo) battery could provide sufficient power for 5 hours of data logging. Figure 5 shows the wiring diagram of the individual components of the ID developed in this study.

Hardware Development (Housing Material)

The selection of housing material for instrumented spheres or artificial fruits is very critical in the design of these devices. It is a major component that protects all of the other components from moisture, shock, and other factors that can cause damage to the hardware. But, most importantly, it must simulate as closely as possible the properties of pulp or flesh of the commodity being studied in order to acquire accurate data.

Figure 6a shows the best-fit lines for force-deformation (F-d) curves of TPU95A samples printed at different fill densities; a representative F-d for potato pulp is superimposed for comparison. The curve fit for Equation 1 was acceptable, with R2 values higher than 0.993 and 0.997 for TPU95A and potato samples, respectively. The F-d curves for TPU95A samples clearly show the effect of fill density on firmness; stiffness of the material increased as fill density was raised. By taking the natural log of the F-d data, as shown in Figure 6b, the similarity of TPU95A printed at 25% fill density to potato pulp can be seen based on the slope of their respective best-fit lines. TPU95A printed at fill densities of 50% or higher had significantly higher stiffness values (Table 2); only samples printed at 25% fill density were not significantly different. On this basis, the 25% fill density was used for fabricating the artificial shell of the ID.

Magnified images of the cross-sections of TPU95A samples printed at different fill densities are shown in Figure 7. The fill pattern used is a crisscross pattern at a 90-degree angle. The 100% filling shows that there are minimal spaces in between the layers. As the percent filling decreases, each layer is spaced further at a certain amount. The 25% TPU95A filling has a 3-mm spacing in between layers and has the largest spacing compared with the other percentage fillings as shown in Figure 6.

With the codes running, components combined, and housing material fabricated, the instrumented sphere was assembled and ready to gather data as shown in Figure 8. The ID has an elongated semi-ellipsoidal shape measuring 65mm in diameter and 85mm in total length which is more comparable to medium potato tubers than a spherical design.

Table 3 shows the comparison of price of commercially available instrumented spheres that were developed overseas and the prototype ID

Table 3. Price Comparison of Commercially Available Instrumented Spheres and the Developed Artificial Fruit

DEVICE NAME (MANUFAC-TURER)	PRICE	MATERIAL	SCANNING RATE (kHz) [z]	THRESHOLD [z]	MAXIMUM MEASURE-MENT [z]	RESOLU-TION [z]
IRD (Techmark USA)	$5950 (PhP300,000)	Plastic	4	30G	500G	2G
TuberLog (ESYS GmbH, UK)	₤1,295 (PhP91,000)	Plastic	3	30G	250G	0.1G
This study	(PhP5,200)	Thermo-plastic urethane	2		200G	

[z] Praeger et al (2013), Xu and Li (2015)

developed in this study. As expected, the IDs price is much cheaper compared with IRD and TuberLog. But the difference in price between the two commercially available devices is still significant because TuberLog is still a lot cheaper by PhP 209,000.

Calibration

Figure 9 shows the mean peak accelerations measured during the drop test, and computed peak accelerations at different drop heights; measured and computed values were well correlated with R2 of 0.923. Table 4 shows the mean, SD and range of peak accelerations measured at the different drop heights.

The BIRD II (UGA) that was used to measure acceleration in blueberry mechanical harvesters had peak G measured on padding sheet and steel surface had standard deviations ranging from 0.64G to 1.91G and ranges from 3.52G to 5.95G, respectively (Xu and Li, 2015).

Praeger, et al. (2013) concluded in their study that elasticity and hardness of the housing material of instrumented spheres strongly influence the peak acceleration values when dropped at different heights. Devices differ in their capabilities for data evaluation and handling during measuring operations, and the most suitable for research purposes are the devices that provide all acceleration values in three axes related to the time throughout the entire measuring process.

Field Test

The transport route was mapped in Google Earth as shown in Figure 10. The average speed during the 85-km trip was 25 km h^{-1} and the maximum speed reached by the truck was 61.3 km h^{-1}. The figure also shows the location and values of multiple peak G exceeding 4.0G throughout the transport of potatoes.

The data logger recorded vibrations during the transport trial for 3.5 to 4.5 hours. The average vibration frequency was 14 Hz at an average velocity of 25 kph. A representative graph of recorded vibration during transport is shown in Figure 11. The average vibration magnitude in G

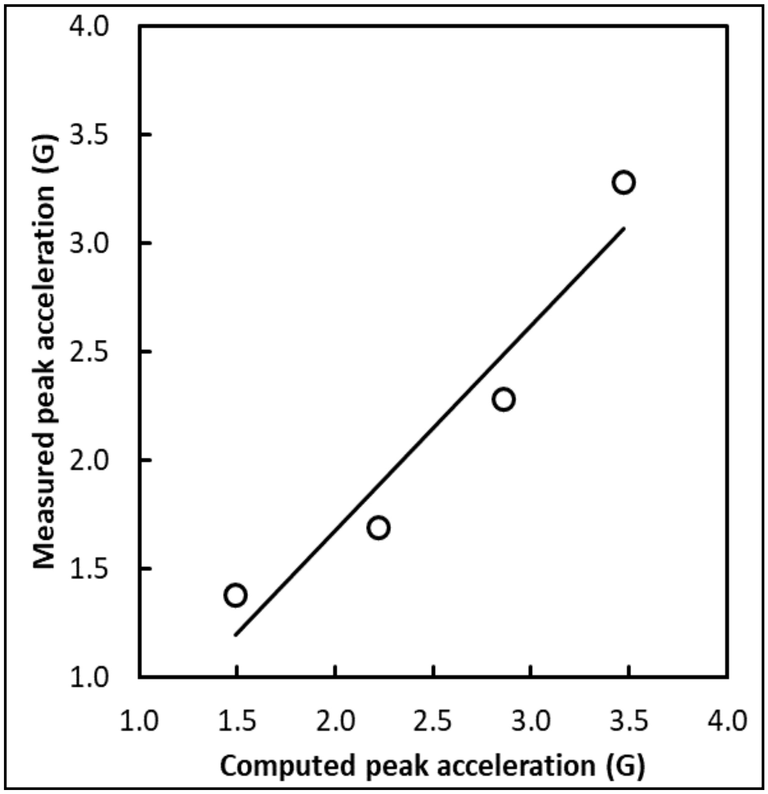

Figure 9. Comparison of actual (measured) versus theoretical peak acceleration data from drop test of instrumented device at 5 different drop heights.

Table 4. Measured peak acceleration (G) during drop tests of the instrument-

DROP HEIGHT (cm)	MEAN	SD	RANGE
25	1.38	0.09	1.26 – 1.53
50	1.69	0.22	1.46 – 2.04
75	2.28	0.40	1.59 – 2.80
100	3.28	0.56	2.47 – 4.29

from five different sets of trips that were measured by the data logger ranged from 0.93G to 1.18G. For comparison, bruising can increase in pears, which has relatively thicker skin than potatoes, if the intensity of vibration is increased from 1.0 G to 1.5 G (Mohsenin 1986). Apples stacked to a depth of 075 m and exposed to a peak acceleration of 0.5G to 0.8G (vibration frequency of 4 Hz) resulted in bruising in 26.5% and 59% of fruit, respectively (Van Zeebroeck et al 2005).

The maximum impact acceleration that was recorded was 6.61G at 77.80 kph in Barangay Kaliking, Atok, in Benguet province where the road is completely paved but with occasional potholes in the area. A value of 6.26G at 73.77 kph was also recorded in Barangay Ambassador, Tublay, in Benguet province with the same road conditions as Barangay Kaliking. However, these were rare occurrences, and the majority of the recorded acceleration was below 3G (Figure 11). The results show that the data logger can detect impact points in the transport of produce with the aid of GPS data. For smaller research purposes, like impact detection in packing houses, the time stamp can help in locating impact or drop points that can cause damage during packing house operations.

Most of the locations where the accelerations exceeded 4.0 G were at residential areas along the highway, same road conditions as the 6.61 G and 6.26 G accelerations were recorded. These impacts may have been caused by encounters with speed

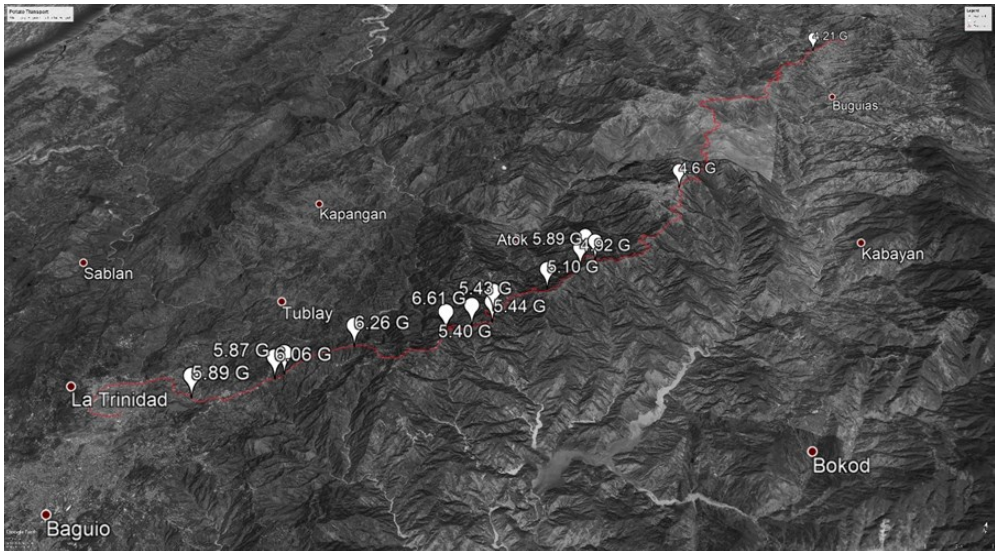

Figure 10. Mapped transport route of harvested potato from Buguias to La Trinidad, Benguet and impact points exceeding 4.0 G during transport.

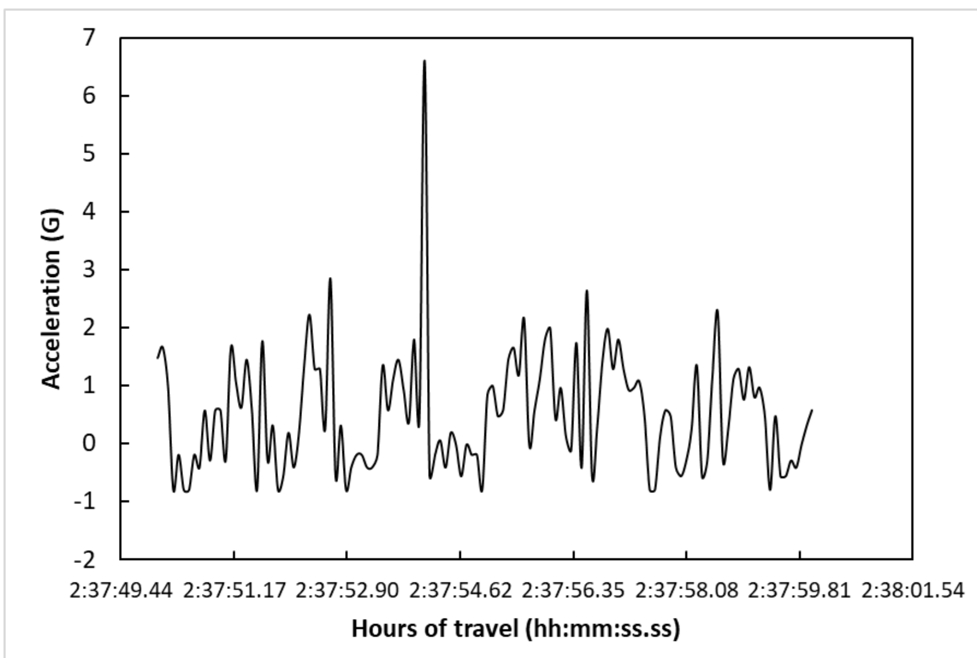

Figure 11. Representative acceleration data (10 seconds) of potatoes transported from Buguias to La Trinidad, Benguet.

bumps and pot holes while traveling at relatively high speed.

SUMMARY AND CONCLUSION

The study was able to assemble a low-cost instrumented device using a 3D-printed TPU45A artificial shell, an Adafruit Feather Adalogger microcontroller board with micro-SD card slot, ADXL377 triaxial accelerometer shield, DS3232 real-time clock shield and 3.7-volt lithium polymer battery. Transport trials showed that the instrument was capable of recording peak acceleration data for up to 5 hours, and can accommodate up to 32 GBytes of data depending on the micro SD card installed. The prototype unit represents a significant reduction in cost compared to commercially available models. However, further tests are needed to evaluate its accuracy, reliability, and operating life.

This study presents a proof-of-concept work, where low-cost microcontroller boards can be used to develop cost-effective instrumented devices that allow data to be gathered during actual handling, storage and transport operations. The study was limited to testing a single prototype fabricated from TPU95A filament and only one type of fill pattern was used. Further studies are needed to refine the design of the artificial shell, such that the firmness is able to closely approximate the natural texture of fresh produce. Advances in 3D printing hardware and software may allow different fill patterns, densities and filament materials to be used to develop custom shells for targeted commodities. Once accuracy and reliability of the instrument has been established, multiple units can be deployed in handling chains at relatively low cost Such investigations would be prohibitively expensive and financially risky with commercially available units, and would be beyond the reach of many laboratories. The prototype developed by the study would allow groups of these devices to collect data on mechanical stresses, as well as other variables such as temperature and humidity, to provide a complete profile of conditions in the supply chain.

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