A piezoresistive dual-tip stiffness tactile sensor for mango ripeness assessment

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A piezoresistive dual-tip stiffness tactile sensor for mango ripeness assessment

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Abstract: Fruit ripeness detection (FRD) has been a very important research area. FRD has focused more on colour segmentation, image processing, odor of fruits and its size. However, fruit stiffness can be an evidence of its ripening. Developing a sensor that focuses on the stiffness of fruit becomes very important. This work presents an approach of mango ripeness detection based on its stiffness using a tactile sensor. A resistance change-based micro tactile sensor is designed for FRD in which it utilizes two cantilevers with different stiffness to estimate mangoes ripeness levels based on their stiffness. The tactile sensor parameters were analyzed and selected to ensure high sensitivity and linearity of the sensor output (Force ratio). The sensor was developed and experimentally tested with five test pieces of known stiffness for proof-of-concept. A finite element analysis was carried out to test the sensor with the same stiffness values of test pieces to compare the results with the analytical results. The

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PUBLIC INTEREST STATEMENT

Recent fruit ripeness detection research has centered on image processing, color segmentation and fruit size to predict the ripeness level of fruits without taking their stiffness into account. Fruits like mangoes, where many species retain their original color even when ripe, may not completely fit into the category of color segmentation and image recognition. In most cases, ripeness is determined by pressing the mangoes to check their softness, which is inefficient because the process of pressing exposes the mangoes to non-uniform ripeness, which affects the taste and quality of the mangoes, resulting in wastage of these valuable resources. This necessitates the development of a tactile sensor that will supplement existing studies by measuring mango ripeness based on stiffness.

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error between the analytical and experimental results of the test pieces did not exceed 7%, while the error between the analytical and simulation results of the stiffness of the test pieces did not exceed 2.7%. Finally, the sensor was tested with five mangoes at different ripeness levels, and the sensor clearly differentiated among the mangoes and obtained stiffness values of 1792.95 N/m, 1395.70 N/m, 1078.86 N/m, 317.15 N/m and 67.81 N/m from the stiffest to the softest mango (Mango A—Mango E), respectively. This tactile sensor can be used in fruit sorting industries to complement the existing fruit sorting approaches.

**Subjects:** Mechanical Engineering; Testing; Technology

**Keywords:** Stiffness; Mango fruit; tactile sensor; Force ratio

1. Introduction

Recent researches on fruit ripeness detection has focused more on image processing, colour segmentation and size of fruits to predict the ripeness level of fruits without considering their stiffness. Fruits like mangoes where a lot of species maintains original colour even when ripe might not completely fit into the category of colour segmentation and image recognition; in most cases, ripeness is determined by pressing the mangoes to check its softness, and this technique is not optimal because, in the process of pressing, it expose the mangoes to non-uniform ripeness, which eventually affects the taste and quality of the mangoes, thereby leading to wastage of these mangoes. This is why the need for a tactile sensor that will complement the existing research by detecting ripeness of mangoes based on the stiffness becomes important. The act of touching may be the most unique detecting methodology as compared with seeing, hearing, smelling and tasting.

Several works in fruit sorting and ripeness detection based on imaging system have carried out by a lot of researchers (Dadwal & Banga, 2012; Fitmawati et al., 2017; Sa et al., 2016; Yassy et al., 2017), based on gas sensors and electronic nose (Gomez et al., 2006; Proveena, 2017) and based on the parameters affecting fruit quality (Cárdenas-Pérez et al., 2018; Grotte et al., 2007; Jarimopas & Kitchawee, 2007; Verzhuk et al., 2012). However, little work has been recorded so far in fruit sorting based on its stiffness as a function of its modulus of elasticity. Alan et al. (2017) carried out a mechanical characterization of mango fruit using compression tests to determine the elastic modulus of the two varieties of mangoes they worked with. Their results showed that the range of elastic modulus on radial loading of the mangoes varies from 1 MPa to 2.5 MPa. Nnodocm et al. (2019a) experimentally estimated the modulus of elasticity of mango using two varieties of mangoes having different levels of ripeness. Authors estimated the modulus of elasticity of mangoes utilizing a compression test on five samples of two types of mangoes have different ripeness levels. Results showed that modulus of elasticity to be within the range of 1 MPa for the ripest mango and 3.3 MPa for the rawest mango. Their results prove that the modulus of elasticity of mangoes reduces as the ripeness levels increase and vice versa. Same authors in (Nnodocm, Fath El-Bab, Ikuu, Sila et al., 2019b) also carried out a simulation on the tactile sensor for fruit ripeness detection using Ansys software simulating the fruit with different values of elastic modulus and carrying out a finite element analysis (FEA) and found that the sensor can distinguish between all the stiffness simulated.

Thus, little work has been recorded in the application of tactile sensor on fruit sorting and ripeness detection based on the fruit stiffness as a function of its elastic modulus. Sensors that have been employed by many researchers in stiffness sensing of objects are tactile sensors. Tactile sensors have a variety of industrial applications, including robotics (Suwanratchatamanee et al., 2010, 2011), haptic devices (Peterlik & Filipovic, 2011), biomedical sensing (Aoyagi & Yoshiida, 2004) and polymer characterization (Sanchez et al., 2008). According to Lee and Nicholls (1999),
a tactile sensor is a device or system that can characterize mechanical properties of the targeted object or of the contact between the sensor and the object. Tactile sensors for contact force measurement have been well documented, and a number of prototype sensors have been developed (Cecchi et al., 2015; Tsuji et al., 2009).

Different concepts have been applied in tactile sensor development for stiffness measurement; however, the 2-tip configuration concept employed by Fath El-Bab et al. (2008) has an advantage of being independent of the applied displacement and applied force on the sensor. Fath El Bab et al. (2007, 2008) worked on softness of tissue compliance detection applying the two springs concept to differentiate soft tissues with different stiffness; they also showed that springs with cubic tip gives more stable output than springs with spherical tip. Fouly et al. (Fouly, Fath El-Bab, Nasr, Abouelsoud et al., 2017a; Fouly et al., 2015) modified the two springs concept to a three tip concept based on the fact that most applications have irregular surfaces and developed a new tactile sensor that compensates for surface irregularities, and they could differentiate between tissues with different stiffness.

In this work, the design, development and experimental testing of a dual tip resistance change-based tactile sensor on test pieces and mangoes was carried out. The parameters of the sensor were designed to increase the sensitivity and linearity of the sensor output (force ratio). This tactile sensor assesses the stiffness of mangoes and classify them based on their ripeness level. The developed sensor will complement existing fruit sorting techniques.

2. Sensor design

2.1. Mathematical model
The sensor design consists of two springs with different stiffnesses ($K_l$) and ($K_h$) on the left and right hands, respectively, as shown in Figure 1. The mango stiffness ($K_m$) is modeled as an elastic spring (Engel et al., 2005). ($K_l$) is the relative low stiffness spring, while ($K_h$) is the relative high stiffness spring. As the sensor is pushed at a distance ($x$) to contact the mango, forces are generated on the low and high stiffness springs. These forces are ($F_l$) and ($F_h$), respectively. It can be seen in (Figure 1) that ($K_l$) and ($K_h$) are in series with the mango spring ($K_m$); therefore, their equivalent stiffnesses ($K_{eq}$) and ($K_{eq}$) as shown in Figure 2 is mathematically shown in Equation (1) and Equation (2).

\[
K_{eq} = \frac{K_hK_m}{K_h + K_m}
\]  
\[K_{eq} = \frac{K_lK_m}{K_l + K_m}
\]

Furthermore, by measuring the ratio of the forces ($P$) i.e. the sensor output in Equation (3) generated in the springs when pushed to the mango, the stiffness of the mango can be measured, as shown in Equation (4).

\[
P = \frac{F_h}{F_l} = \frac{K_h(K_m + K_l)}{K_l(K_m + K_h)}
\]

Where $P$ is a dimensionless parameter.
Figure 1. Sensor model.

Figure 2. Equivalent model of the sensor.
\[ K_m = \frac{K_l K_h (1 - P)}{P R_k - K_h} \]  

(4)

2.2. Mango fruit stiffness range

Hayes et al. (1972) provided a mathematical model based on indentation principle as shown in Figure 3 to calculate the stiffness of a soft object as a function of its elastic modulus, as shown in Equation (5).

\[ E_{\text{max}} = \frac{(1 - \nu^2)F}{2rdC_k} \]  

(5)

\[ K_{\text{max}} = \frac{2rE_{\text{max}}C_k}{(1 - \nu^2)} \]  

(6)

Where: \( F \), \( \nu \), \( d \), \( r \), \( E_m \), \( C_k \) and \( h \) are the applied force, Poisson’s ratio of mango, the indentation depth, the indenter radius, the Elastic modulus of mango, the scaling factor and the radial height of the mango, respectively.

In this work, mango is assumed to be isotropic and linear elastic especially when deformed slightly, its Poisson’s ratio is assumed to be 0.3 (Jarimopas & Kitthawee, 2007), and the maximum range of elastic modulus is 3 MPa (Nnodim, Fath El-Bab, Ikua, Sila et al., 2019a), which is equal to a stiffness value of 3300 N/m according to Equation (6). Also, the indenter is designed to be a cube with side length of 1 mm and the radial height of the mango is 70 mm. However, the scaling factor \( C_k \) depends on \( \nu \), \( (r/h) \) and \( (d/h) \); Zhang et al. (1997) developed tables from a finite element analysis to estimate \( C_k \), and obtained \( C_k = 1 \). Finally, from the experiment carried out in this work, the stiffness values will range from 0 N/m to 3300 N/m based on Equation (6).

2.3. Sensor parameters

The sensor parameters are the low stiffness sensor \((K_l)\), the high stiffness sensor \((K_h)\) and maximum force ratio \((P_{\text{max}})\). The maximum force ratio \((P_{\text{max}})\) can be calculated by defining \((K_l)\) and \((K_h)\)
Figure 4. Nonlinear and expected sensor output vs mango stiffness.

Figure 5. High stiffness sensor, $K_h (N/m)$ versus the low sensor stiffness, $K_l (N/m)$.

Figure 6. Isometric view of the 3-D axisymmetric finite element model.
However, doing that will increase the error in $P$ due to crosstalk (interference) effect and cause a very large difference between ($K_l$) and ($K_h$). Fath El Bab et al. (2008) carried out a crosstalk effect analysis and found the $P_{\text{max}}$ to be 5; thus, the selected $P_{\text{max}}$ value in this work based on Equation (3) is 5. As stated earlier, the relationship between $P$ and $k_m$ as in Equation (3), is nonlinear when arbitrary values of $K_l$ and $K_h$ as shown in Figure 4; however, a non-linearity error analysis was done in order to get the desired $K_l$ and $K_h$ that gives a linear output. (Figure 4) shows that the maximum non linearity occurs at the mid-range of the mango stiffness.
Therefore, the maximum nonlinearity error (NL) from Figure 4 is represented mathematically in Equation (7)

$$NL = \frac{m}{P_{\text{max}} - 1} = \frac{(P_{1650} - 1) - (P_{\text{max}} - 1)/2}{P_{\text{max}} - 1}$$

(7)

Where, $P_{1650}$ is the sensor output at the mid-range of the mango stiffness designed, $m$ is the distance between the maximum point of non-linearity to the corresponding linear point, as shown in Figure 4. Therefore, for $P_{\text{max}} = 5$, Equation (7) becomes

$$NL = \frac{P_{1650} - 3}{4}$$

(8)

Also from Equation (3),
Figure 11. Loading of masses on the high stiffness sensor.

Figure 12. Unloading of masses on the high stiffness sensor.

Figure 13. Loading of masses on the low stiffness sensor.
\[ P_{1650} = \frac{K_h(1650 + K_i)}{K_i(1650 + K_h)} \]  \quad (9)
Figure 17. Quarter bridge circuit.

Figure 18. Test pieces with different known stiffness representing mangoes, dimensions in mm.

Figure 19. Experimental set up for the test pieces.
The relationship between $K_i$ and $K_h$ at $P_{max}$ from Equation (310) becomes

$$K_h = \frac{K_m P_{max}}{1 + (K_m/K_i) - P_{max}} = \frac{4125K_i}{825 - K_i}$$

(10)

Substituting Equation (10) into Equation (9) gives
Subsequently, substituting Equation (11) into Equation (8) yields

\[ P_{1650} = \frac{8250 + 5K_1}{1650 + 3K_1} \]  

where \( K_1 \) is the stiffness of the test piece.
Equation (12) shows the relationship between $NL$ and $K_r$, which implies that $NL$ is a function of change in $K_r$. However, if a higher value of $K_r$ is selected, then the value of $K_h$ will be increased, which will make the strain on the high stiffness sensor very low, and this will consequently lead to a low output voltage. In this work, a non linearity error of 5% is assumed to be
allowed, and this gives a value of 645.7 N/m for $K_I$ and 14,855 N/m for $K_{h}$. The relationship between the high stiffness sensor ($K_h$) and the low stiffness sensor ($K_l$) is shown in Figure 5.

2.4. Simulation of the sensor

The design parameters obtained in the previous section were used to build a finite element model using ANSYS Parametric Design Language (APDL) software to analyze the sensor performance and ensure that the two-tip configuration is feasible. The mango was constructed using a 3-D axisymmetric finite element model where the mango was assumed to be isotropic,
homogeneous, fixed below at its base and linearly elastic with a Poisson’s ratio of 0.3 with dimensions of 20 mm × 12 mm × 20 mm, as shown in Figure 6.

Also the stiffness of the mangoes simulated were 1998.89 N/m, 1469.07 N/m, 975.22 N/m, 810 N/m and 546.73 N/m. These values were selected so as to test for a wider range of stiffness and to compare with the analytical and experimental results. The distance between the sensor tips is 8 mm; this is narrow enough to assume that the surface of contact is flat. The sensor tips which is a rigid body attached to the spring during pushing is cubic with a side length of 1 mm, and the sensor tip in the model is at a distance 0.1 mm above the mango surface; hence, the simulation readings began to record results form 0.1 mm. The contact of the sensor tip with the mango was built with CONTA174 and TARGE170 elements located on its boundary. The sensors are the two springs of COMBIN14 elements, which represents the low stiffness sensor (K_l) = 645.7 N/m on the left and the high stiffness sensor (K_h) = 14,855 N/m on the right, as shown in Figure 6. Figure 7 illustrates that the sensor was able to differentiate between the different stiffness simulated. The simulated mango stiffness of k_m = 1998.89 N/m has the highest force ratio of 3.59, while the simulated mango of K_m = 546.73 N/m has lowest force ratio of 1.70. The maximum error of the simulation results did not exceed 2.7%.

### 2.5. Fabrication of sensor

#### 2.5.1. Design of the tactile sensor

The tactile sensor was fabricated using the 30 W CO₂ VersaLASER® (VLS) 3.50 laser cutter to verify the two-tip configuration sensor concept in distinguishing mango stiffness. (Figure 8) shows the image of the fabricated tactile sensor, which was used in this experiment after being drawn with SolidWorks® software, and the dimensions of the tactile sensor, as shown in Figure 9. The sensor comprises two cantilevers representing the two springs (sensing components) of high and low stiffness, as shown in Figure 9.

One end is fixed while the other end is deflected perpendicularly to the long axis of the beam. Sensing elements were selected as cantilevers because cantilever has a linear force-deflection behaviour (Fouly, Fath El-Bob, Nasr, Abouelsoud et al., 2017b). The sensor was first designed with SolidWorks® software with the dimensions of the cantilever, which equals the value of the K_l and K_h, respectively, as obtained from Equations (13) and (14)

\[ K_h = \frac{E_l W A t^3}{4 L^3} \]  
\[ K_l = \frac{E_l W A t^3}{4 L^3} \]  

Table 1. Test pieces lengths and their stiffness

| Test piece length,(mm) | Test piece stiffness,(N/m) |
|------------------------|---------------------------|
| 37                     | 1998.89                   |
| 41                     | 1469.07                   |
| 47                     | 975.22                    |
| 50                     | 810                       |
| 57                     | 546.73                    |
Table 2. Comparison of the experimental force ratio and the simulated force ratio of the test pieces relative to the analytical force ratio

| Specimen stiffness (N/m) | Analytical $P$ | Simulated $P$ | Experimental $P$ | Simulation error, % | Experimental error, % |
|-------------------------|----------------|---------------|------------------|---------------------|-----------------------|
| 1998.89                 | 3.61           | 3.59          | 3.64             | 0.55                | 0.83                  |
| 1469.07                 | 2.98           | 2.9           | 3.0              | 2.68                | 3.69                  |
| 975.22                  | 2.36           | 2.3           | 2.5              | 2.5                 | 5.9                   |
| 810                     | 2.14           | 2.1           | 2.2              | 1.87                | 2.8                   |
| 546.73                  | 1.78           | 1.7           | 1.9              | 4.49                | 6.7                   |

\[ K_i = \frac{E_i W_i t_i^4}{4L_i^4} \]  

(14)

where $E_i$ is the elastic modulus of the high stiffness sensor, $L_i$ is the length of the high stiffness sensor, $W_i$ is the width of the high stiffness sensor, $t_i$ is the thickness of the high stiffness sensor $E_i$ is the elastic modulus of the low stiffness sensor, $L_i$ is the length of the low stiffness sensor, $W_i$ is the width of the low stiffness sensor and $t_i$ is the thickness of the low stiffness sensor. The dimensions of the cantilever beams were obtained by applying Equations (13) and (14). Since the elastic modulus $E$ is constant, the stiffness to be obtained is known (i.e $K_i$ and $K_l$), and the thickness of the material is selected to be 3 mm in this work due to its higher resistance to laser cutting. The length of each cantilever must be greater than or equal to 10 times the gauge length of the strain gauge for maximum sensing, where the gauge length of the strain gauge is 3 mm. Therefore, applying these criteria in Equation (14), the width of the cantilevers were obtained.

2.6. **Calibration of the sensor**

After the bonding of the strain gauge to the fixed end of each of the cantilever beam, the sensor was then calibrated. This was done by applying measured loads on the free end of each of the cantilever and then measuring the resulting output voltage at every loading and unloading of the cantilever beam. The high and low stiffness cantilever beams were calibrated separately by loading the free end of each of the cantilever beams with loads and then connecting the sensor to a quarter bridge measuring the change in the output voltage from an advanced Avometer, and this was done five times for each cantilever. A hole of 0.5 mm was drilled in the free end of the cantilever as shown in Figure (10) using the laser machine in order to allow the passage of strings that were used to carry the loads that were applied on the free end of the two cantilevers. Figures 11 and 12 illustrate the loading and unloading of masses on the high stiffness sensor, and the voltage–load relationship on the high stiffness sensor is linear, which implies that the high stiffness sensor is stable and reliable to give high repeatability of results. However, Figures 13 and 14 illustrate the loading and unloading of masses on the low stiffness sensor, and the voltage–load relationship on the low stiffness sensor is linear, which implies that the low stiffness sensor is stable and reliable to give high repeatability of results. Also, Figures 15 and 16 show load–voltage relationship of the average loading of masses on the high stiffness sensor and the low stiffness sensor, respectively. This load–voltage relationship is called the calibration factor. The calibration factor enables the proper conversion of measured voltage to the equivalent value of force. After the calibration of the sensors, the sensor tips were bonded to the free end of each of the cantilever beams.
The $R^2$ value for the high stiffness sensor as shown in Figure 15 is 0.9998 with a calibration equation of

$$Y = 0.0084x + 0.081$$  \hspace{1cm} (15)$$

while that of the low stiffness sensor as shown in Figure 16 is 0.9996 with a calibration equation of

$$Y = 0.0621x + 0.059.$$  \hspace{1cm} (16)$$

The strain gauge used in this work has a nominal resistance of 350Ω, gauge factor of 2.00–2.20, gauge length of 3 mm, modified phenolic resin backing, constantan alloy foil with temperature compensation and creep compensation; high accuracy and good stability. The working temperature range of the strain gauge is −30°C to +80°C. The strain gauges were connected to a quarter bridge which comprised of two resistors with nominal resistance of 330Ω each and a variable resistor of 500Ω. Figure (17) shows the quarter bridge circuit.
3. Experimental testing

3.1. Testing using test pieces representing mangoes

To prove the two-tip configuration concept of stiffness measurement, five test pieces with different known stiffness values to represent mangoes were fabricated. Test pieces were selected as cantilevers to avoid any non-linearity in mangoes and to explicate the concept of measurement, as shown in Figure 18. Each test piece consists of two cantilevers with the same width 5 mm and thickness 3 mm. However, changing the length of each test piece, gives variable stiffness. Table 1 illustrates the change in stiffness due to the change in cantilevers lengths.

The experimental setup is illustrated in Figure 19. It comprises of a special clamp which was designed and fabricated to hold the test piece; a displacement gauge was used measure the displacement moved between the sensor and the test piece, a handle to push the test piece towards the sensor. A data acquisition card was used to record the strain signals (two strain gauges, one on each cantilever). Each of these test pieces was tested with the sensor three times to ensure accuracy and repeatability.

Figures (20–24) present the force ratio versus the displacement between the sensor and the test pieces, along with their average values.

Figure (20) shows the force ratio versus displacement of the test piece of the stiffness of 1998.89 N/m. The corresponding force ratio of this test of the stiffness, 1998.89 N/m is 3.64. Figure (21) shows the force ratio versus displacement of the test piece of the stiffness of 1469.07 N/m. The corresponding force ratio of this test of the stiffness, 1469.07 N/m is 3.09. Figure (22) shows the force ratio versus displacement of the test piece of the stiffness of 975.22 N/m. The corresponding force ratio of this test of the stiffness, 975.22 N/m is 2.5. Figure (23) shows the force ratio versus displacement of the test piece of the stiffness of 810 N/m. The corresponding force ratio of this test of the stiffness, 810 N/m is 2.2. Similarly, Figure (24) shows the force ratio versus displacement of the test piece of the stiffness of 546.73 N/m. The corresponding force ratio of this test of the stiffness, 546.73 N/m is 1.9. It can be seen from Figures (20–24) that the displacement pushed was 5 mm, and the sensor’s readings started attaining stability and linearity from about 1 mm of displacement. This is because the sensor and the test piece had not made full contact at the initial point of displacement. Table 2 illustrates the comparison between the stiffness value for each test piece analytically, experimentally (average), simulation and their percentage error.

3.2. Testing of mangoes

Since the sensor has shown an acceptable level of accuracy and repeatability in the experimental testing of the five test pieces with known stiffness values, as shown in Table 2, five mangoes from the hardest (stiffest) to the softest as shown in Figure (25) were tested. The experimental setup for the test on mangoes is as shown in Figure 26.

Figures (27–31) show the three tests of the force ratio versus displacement of 3 mm of Mango A, B, C, D and E, respectively, with a corresponding force ratio of 3.37, 2.89, 2.49, 1.46 and 1.1, respectively. The results at the beginning is not stable because the mango surface is not flat as we assumed in the analytical and simulation, but after full contact it began to stabilize at around 1 mm of the displacement during the contact of the sensor and the mango.

Figure (32) shows the average of each force ratio of the mango tested versus the displacement pushed. It is seen in Figure 32 that the sensor distinguished clearly between the mangoes tested. Mango A is the mango with the highest stiffness, and it gave the highest force ratio which implies that during the contact between the sensor and Mango A, higher forces were generated due to its
stiffness, similarly Mango E was the softest of all the mangoes tested which means Mango E had the lowest stiffness, and it gave the lowest force ratio. Also, the matching values of the force ratios from the averages of each mango in Figures (27–31) are 3.37, 2.89, 2.49, 1.46 and 1.10 for mango A, mango B, mango C, mango D and mango E, respectively. In order to estimate the stiffness of these tested mangoes from their respective force ratios, Equation (4) was applied and the stiffness values for mango A, mango B, mango C, mango D, and mango E resulted to 1792.95 N/m, 1395.70 N/m, 1078.86 N/m, 317.15 N/m and 67.81 N/m respectively.

A relationship between the force ratio and the corresponding stiffness of the tested mangoes is shown in Figure 33. Figure (33) shows that there is a linear relationship between the force ratio and the corresponding stiffness value of the mangoes. This implies that, as stiffness increases, the force ratio increases i.e. stiffness is directly proportional to the force ratio. This is an indicator which proves an existing fact that as mangoes ripen, their stiffness reduces.

4. Conclusion
This paper presented a piezoresistive dual tip stiffness sensor for mango ripeness assessment. The sensor is designed, simulated, fabricated and tested with linear samples with different known stiffness and with real mangoes that have different stiffness based on its ripeness. The simulation results of the stiffness of the selected test pieces, which mimics mangoes as compared to the analytical results shows that the maximum error does not exceed 2.7%, while the experimental results of test pieces that mimics mangoes as compared to the analytical results shows that the maximum error does not exceed 7%. The experimental results of the mangoes proves that the sensor’s performance in determination of the ripeness levels of mangoes based on their stiffness is high. The stiffness values of the mangoes tested from the stiffest to the softest (Mango A—Mango E) is 1792.95 N/m, 1395.70 N/m, 1078.86 N/m, 317.15 N/m and 67.81 N/m, respectively. It is evident from this work that as ripeness increases in mangoes, stiffness reduces and vice versa. The comparison of the analytical force ratio with the simulation and experimental force ratio of the test pieces is an indicator of the accuracy and repeatability of the sensor. This approach of mango ripeness detection is unique and will be able to complement existing ripeness detection methods like image recognition and colour segmentation. Finally, during the entire process of the experiment, no bio-yield point appeared on the mangoes; therefore, this can be considered a non-destructive test in mango ripeness detection.

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