Development of a Mini Compression Test Machine using Arduino Microcontroller as Texture Analyzer Prototype

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Abstract

A texture analyzer is a standard device to measure food texture properties. This study aims to develop a mini compression test machine prototype that can function as a texture analyzer with simple operation and portability. The components and materials were chosen based on: low cost, manufacturability, and availability in the local Indonesian market. The prototype dimension was 375 × 215 × 450 mm, and used a linear ball screw slider for the translation movement with a 200 mm effective sliding distance. For obtaining the compression load, a 10 kg load cell was used, and it was replaceable by a load cell with a lower capacity if a higher measurement accuracy was required. After calibration, the linear vertical displacement and load cell had ±0.1 mm and ±1 g of accuracy, respectively. The prototype was tested to measure the texture properties of potato chops. As a result, the machine could successfully measure the load and displacement data and detect a crack phenomenon, verifying its usability as a food texture analyzer.

Keywords: texture analyzer; compression test, machine design and prototyping; Arduino.

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Introduction

In food engineering, human sensory analysis is typically used as the standard method to evaluate food properties [1]. The evaluation is done with the help of professional testers and consultants [2]. However, in many situations, some participants are chosen based on their qualifications for sensory capacity testing [2]. The human sensory evaluation standard has been improving since the 1900s in identifying the sensation of the food tested [3]. This method, however, only produces subjective qualitative data depending on the testers and experts. The texture analyzer was then introduced to replace the practice of sensory analysis [4]. The machine could perform various tests on the food by changing the probe. Commonly, the tests include compression, tension, extrusion, puncture, penetration, shear, and break [5,6]. The measured data are load, time, and displacement [7,8]. Based on the measurements, the analyzed food's mechanical properties include hardness, chewiness, gumminess, brittleness, viscosity, adhesiveness, elasticity, and cohesiveness [8, 9,10].

Texture analyzer is usually utilized in food material science studies. Food material science is a multidisciplinary field that focuses on the structure, properties, and processing of the materials used in food, their production, and their breakdown [5]. In Indonesia, the trend in the research and development of food engineering has increased significantly over the past few years [6]. The texture analyzer available in the market mostly has a 100 to 500 N maximum force capacity, 500 mm effective sliding distance, and 0.001 – 2032 mm/min speed range [11,12]. However, the machine's availability is rare in Indonesia. Most manufacturers are from Europe and the United States, which boosts the machine's price due to shipping and spare parts costs.

In the Indonesian market, a complete texture analyzer machine can range from around 300 to 400 million Rupiahs, excluding the shipping cost. Nevertheless, due to the increasing interest in food material science, the demand for this device is at an all-time high regardless of its price [7]. Therefore, this study aimed to develop a texture analyzer machine in Indonesia. In this study, a mini compression test machine was developed as an early-stage texture analyzer prototype produced with relatively low-cost components to achieve functional, simple operation and portable features. Furthermore, the device is designed for ease of build by anyone, so it is expected to help small and medium enterprises in Indonesia that need a texture analyzer for food product testing.

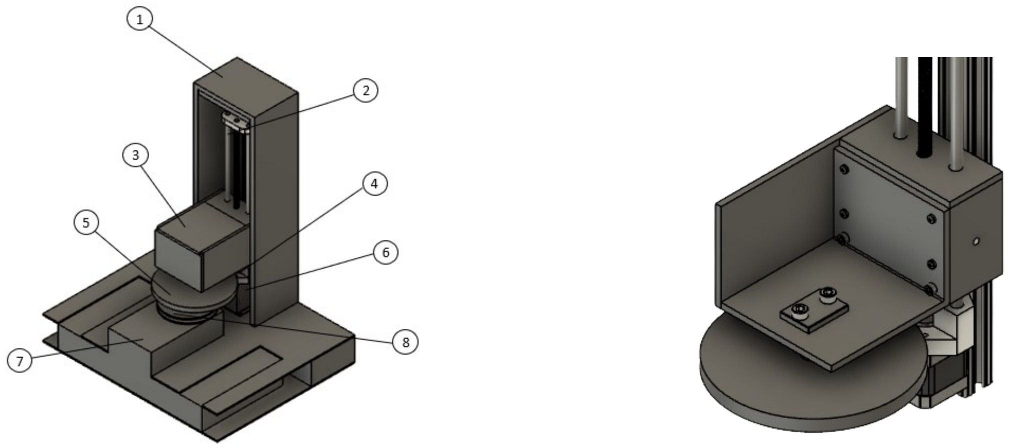
Methodology

1 Prototype Design & Manufacturing

In designing the device, Shigley's design methodology was applied [8]. The identification of need, problem definition, and synthesis processes were made by reviewing the texture analyzers available in the market. The proposed machine design also considered manufacturability, components availability, and production cost. The machine used a linear ball screw slider mechanism to move the probe in linear translational motion and a 10 kg load cell to measure the reaction force during food testing. Figure 1(a) shows the proposed machine with the part number; the detailed specification is given in Table 1. Figure 1(b) shows the inside view of part number 3, the load generator.

The material for the machine prototype was acrylic, wood, and 3D printed PLA for complex components' shapes. Moreover, the machine used metal elbow brackets for most joints and adhesive joints for exceptional parts. The detailed materials and common types for each component are tabulated in Table 1.

The fabrication and manufacturing process of the machine prototype was mainly done by sawing and drilling. First, a bent saw was used to cut off the acrylic material. Then, the drilling process was done using a semi-automatic drilling machine. The result of the prototyping is shown in Figure 2.



(a) (b)

Figure 1. The final model of the texture analyzer prototype (a) Isometric view (b) Inside look of part number 3 (box connector)

Table 1. List of components for the machine structure and frame

No.	Component's Name	Material	Joint
1.	Safety Closed Box	Acrylics	Metal Bracket and Screws
2.	Linear Ball Screw Slider Setup	Aluminum and Stainless Steel	Clamp and Screws
3.	Box Connector	Acrylics	Metal Bracket, Screws, and Adhesive Joint
4.	NEMA Stepper Motor	Plastic and Stainless Steel	Clamp and Screws
5.	Probe	PLA (3D Printed)	Metal Bracket and Screws
6.	Clamping for Motor	PLA (3D Printed)	Screws
7.	Base	Acrylics and Woods	Adhesive Joints
8.	Load Cell and Support	Acrylics and Woods	Adhesive Joints and Screws

(a) (b) (c)

Figure 2. Texture analyzer prototype (a) Front view (b) Isometric view (c) Inside view of box connector

2 Mechatronics Design

In this study, the mechatronics system of the prototype used Arduino Mega as the microcontroller due to its flexibility, components availability, user interface, and programming ease [13]. The detailed flowchart of the control program is shown in Figure 3.

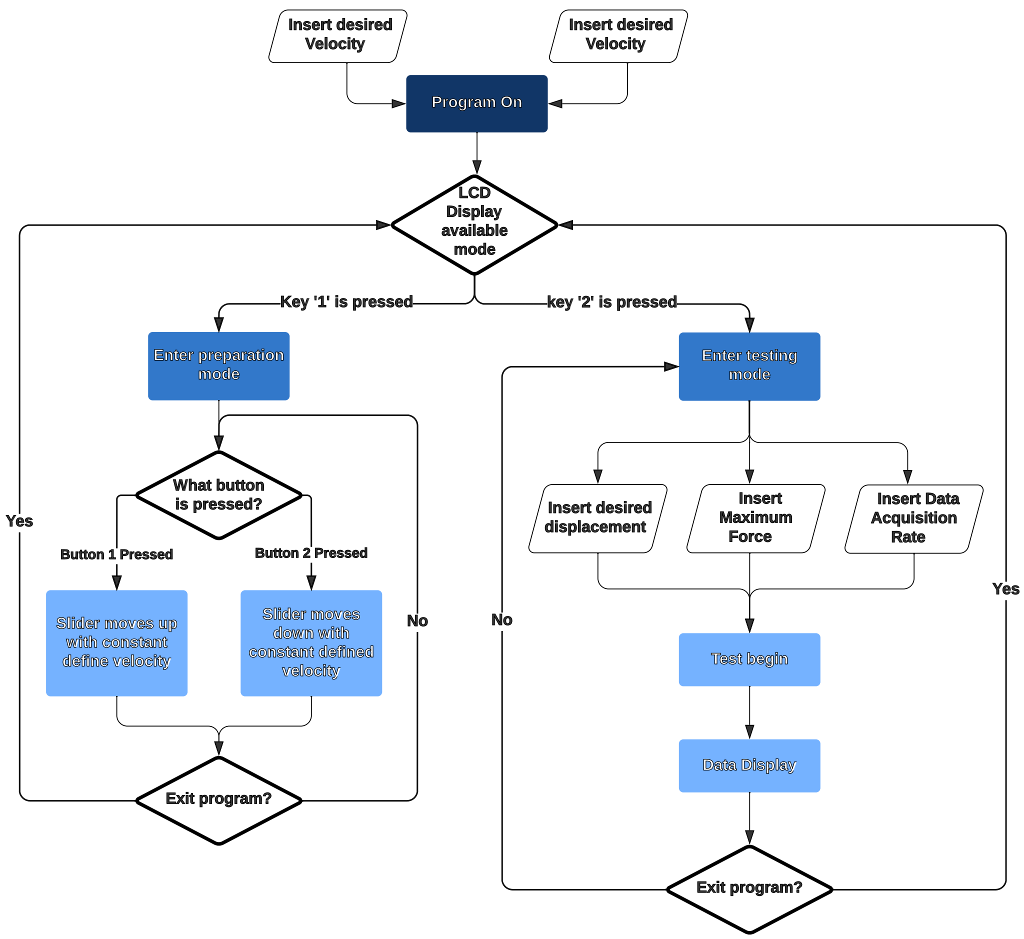


Figure 3. Prototype process flowchart

The control program consisted of three modes, namely Modes 0, 1, and 2. Mode 0 was the initial condition that informed the user what modes were available and asked for input before moving into either Mode 1 or Mode 2. For example, if the user pressed key '1' on the keypad, the machine showed the preparation mode and activated the control button for linear movement. Next, the user adjusted the probe's vertical position based on the specimen height. After completing the preparation mode, the user moved into Mode 2 to input the required testing variable. Then the machine ran the test based on the adjusted variables. The user could skip the preparation mode by pressing the key '2' when Mode 0 runs. Before the program starts, the Arduino must be connected to Excel Data Streamer, the automatic data recorder. Thus, the data were recorded directly in the excel file format, live-plotted, and exported through a data storage card, such as a hard disk or USB memory stick [9,14].

To control the stepper motor movement, the TB6560 driver was used. This driver required additional power input to run a stepper motor with 5V DC power input with a 2-3 A current. An LCD of 20 x 4 mm and I2C backpack modules were utilized as the user interface for inputting parameters and displaying the Mode status. A 10 kg load cell was installed in the machine, along with an HX711 amplifier. The 10 kg load cell was chosen referring to the availability in the market, and it was replaceable by another load cell with a different capacity following the application. In addition, the buttons and keypads were also installed to operate and control the program. In the display, the input-output and control system codes using an open-source library were applied with modification in the process flow. Figure 4 shows the wiring circuit of the machine. Since all the components, spare parts, and control system programs were readily accessible from the local resource; anyone could easily build the prototype.

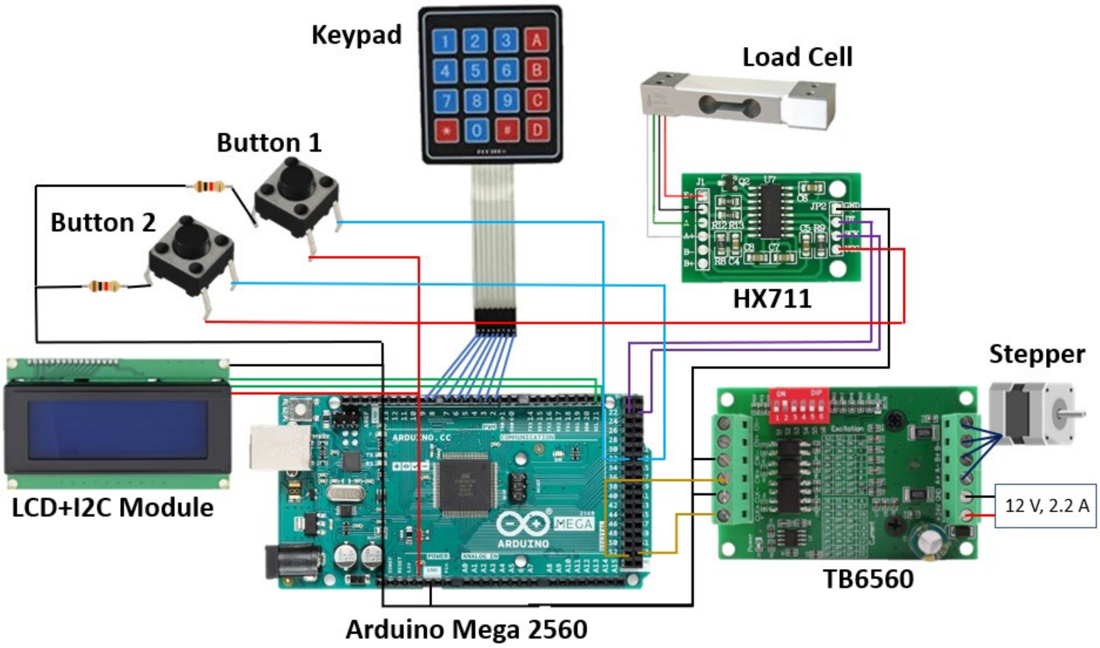


Figure 4. Wiring schematics of the program

3 Load Cell Calibration

The 10 kg load cell consisted of several components that must be assembled before calibrating. The components included acrylic plates, screws, beam load cells, and pin support, as shown in Figure 5. The load cell was assembled in between the acrylic backing. Therefore, placing an acrylic spacer was vital to ensure a proper space between the support and the load cell. After the components were assembled, then the load cell was calibrated. Several calibrated weights, i.e., 100, 500, and 1000 g, were used for the calibration process, as shown in Figure 5. The calibration process must be repeated if the load cell types and capacity change.

In the calibration process, the load cell was connected to the Arduino. The calibration program code was first uploaded to initiate the process, and the weights range was selected. Then the load cell measured the weight, and the serial monitor displayed the value. The calibration factor might need adjustment to show the correct 233.75 mV/mg value. Calibration and adjustment were also required when the load cell was changed or re-installed. This process produced the load cell error value of ±1 g or equal to 0.005% accuracy, as shown in Table 2.

Table 2 shows the comparison between the actual weight and the read values from the load cell as a result of the calibration process. As seen from the table, the machine prototype demonstrated reasonably good accuracy but might not be as precise as the commercial products in the market. Therefore, the mini-compression test machine was considered adequate to function as a simple Texture Analyzer prototype. In addition, the loading measurement precision could be improved by replacing the load cell with a better-quality product and improving the machine structure with stiffer and stronger materials.

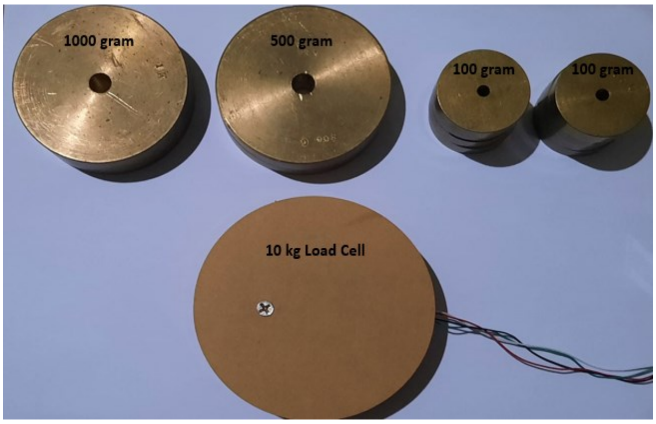


Figure 5. Load cell calibration equipment

Table 2. Load cell calibration result

No.	Actual Mass (in g)	Read Value (in g)	No.	Actual Mass (in g)	Read Value (in g)
1.	100	100	6.	600	599
2.	200	201	7.	700	700
3.	300	301	8.	800	800
4.	400	401	9.	900	901
5.	500	499	10.	1000	1000

4 Linear Ball Screw Calibration

The machine used a linear bar screw slider to generate a translational movement for the compression test. Therefore, a calibration process was also required to obtain the relationship between the stepper motor's rotation and final linear displacement. This process was conducted by operating the stepper motor using the Arduino code and then measuring the generated linear motion by a vernier caliper. Figure 6 shows the measurement process of the linear translation motion using the vernier caliper as a result of linear ball screw motion.

The experiment for obtaining the relationship between the motor rotation and the linear displacement was performed six times with various speeds and accelerations, as tabulated in Table 3. The speeds were 100, 200, 300, and 400 in step/s, while the acceleration was set to be 0, 50, and 100 in step/s^2. These experiments were performed in a different initial position, with the displacement being measured for every 400-step increment. During calibration, the controller was restarted to calculate at each increment. Accordingly, the code was run separately for each measurement. Finally, the equation relating the ball screw rotation and the final linear displacement was extracted using the linear curve fitting technique.

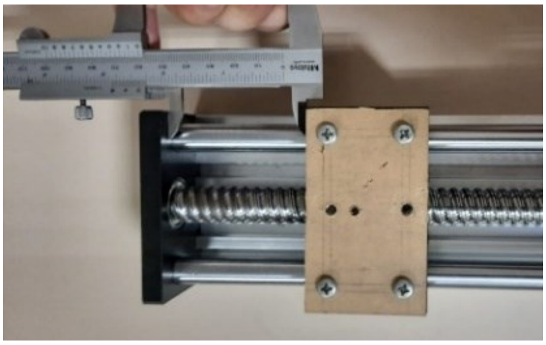


Figure 6. Linear ball screw calibration process using a vernier caliper

Table 3. Calibration results of linear bar screw slider from each experiment

No.	Parameter	Weight Equation	No.	Parameter	Weight Equation
1.	Velocity: 100 step/s Acceleration: 0 step/s^2	$y = 3199.5x$	4.	Velocity: 200 step/s Acceleration: 100 step/s^2	$y = 3199.9x$
2.	Velocity: 100 step/s Acceleration: 50 step/s^2	$y = 3198.0x$	5.	Velocity: 300 step/s Acceleration: 100 step/s^2	$y = 3204.3x$
3.	Velocity: 100 step/s Acceleration: 100 step/s^2	$y = 3204.9x$	6.	Velocity: 400 step/s Acceleration: 100 step/s^2	$y = 3194.1x$

Table 3 provides the weight equations as the results from each calibration experiment. The x variable defines the desired linear displacement in cm, while y defines the motor rotation in step number. The average slope was calculated from the equations to give the final equation, $y = 3200.1x$. The accuracy of this equation was verified by inputting several desired displacements and measuring the actual displacement using a vernier caliper. The desired displacement was 10, 5, 2, 1.5, 1, 0.5, 0.1, and 0.05 cm, resulting in error values between ±0.005 to ±0.01 cm. These errors were due to the tolerance limit of the vernier caliper. Thus, the equation required further evaluation with a higher-resolution measurement device. Nevertheless, the equation has accommodated the required accuracy for the machine to function as a simple Texture Analyzer for current applications.

Result & Discussion : Food Testing Experiment

After the calibration processes, the Texture Analyzer prototype was ready for the food testing experiment. Pringles® potato chips were chosen as the specimen considering their uniform shape and slight deviance from one sample to another [15]. The sample was taken from the type of Original 107 g package. During the testing process, the specimen should be freshly taken from the package, intact, and have no damage in the body.

Table 4 shows the parameters set in the machine during the food texture testing by compression load on a single Pringles® potato chip specimen. The table shows that the desired linear displacement was set at 15 mm. Therefore, when starting the test, it was vital to take caution in the distance between the probe and the load cell. For obtaining the measurement data, Excel Data Streamer was utilized to process the raw experimental data containing two different parameters: the load (gram) and the displacement (mm). The load-displacement live plot was also constructed in Excel Data Streamer. After obtaining the load and displacement data, a post-experiment data analysis was needed to build the proper load vs. displacement graph.

Table 4. Food testing parameter

Parameter	Value
Velocity	1 mm/min
Acceleration	0 mm/min^2
Desired Displacement	15 mm
Interval Data Rate	150 ms

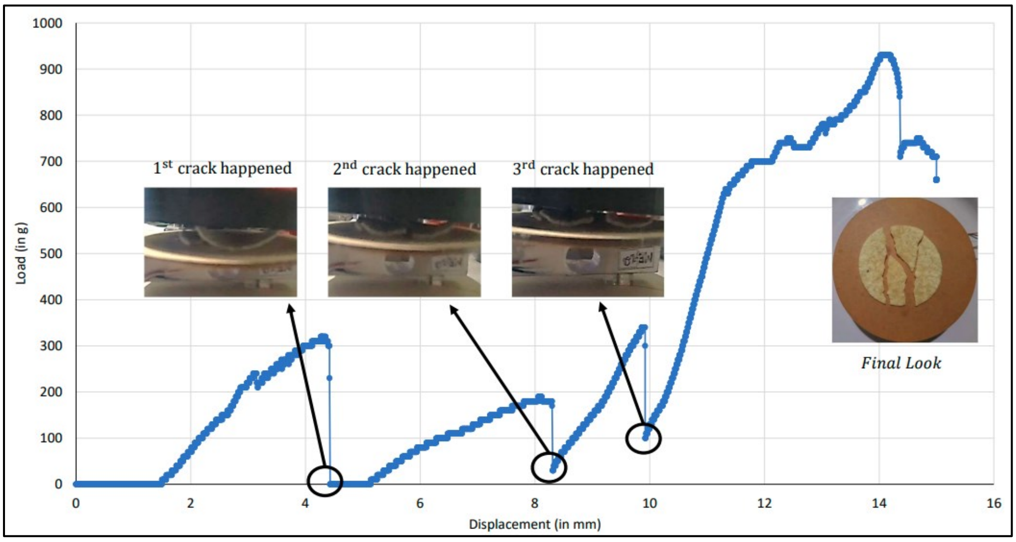


Figure 7. Load vs. displacement plot result

The result of the Pringles® potato chips compression test is shown in Figure 7. The figure shows that the load increased during the compression of the chips for the first time. Then, when the specimen experienced sudden cracking, the load value dropped dramatically, and the specimens broke into smaller chunks. Accordingly, the probe lost contact with the specimen and showed a zero force point in the graph. A similar force drop occurred again in the second and third cracks. However, even though the sample turned into smaller chunks, the probe was still in contact with the specimen. Therefore, the load still dropped suddenly but did not reach zero load value. After the third crack, the load increased rapidly as the probe touched the bottom support. The graph ended after reaching 15 mm displacement as set earlier. In addition, if the user wants to remove the specimen by adjusting the probe, the machine's program should be reset, then go back to Mode 1. The measured load and displacement curve showed that the machine successfully functioned as a texture analyzer by its ability to produce the load and displacement data from the compression test and detect the cracking phenomenon of specimens during the trial.

From the cost perspective, the machine prototype had a relatively low cost for fabricating and purchasing components and spare parts. The detailed cost breakdown is presented in Table 5. The price number was obtained from the local online shop. Therefore, the machine can be produced for less than 3 million rupiahs. This price was considered affordable for the SMEs to create their texture food analyzer. Moreover, the machine was portable because it was small and lightweight.

For further development, several improvements are required in this study. It included a feature that allows the user to change the speed and acceleration during the operation and a mechanism to stop the machine during the trial and allows the user to change modes immediately. Changing the structure and frame with stainless steel is also needed to improve the structural integrity of the machine. In addition, calibration with a standard device is also required.

Table 5. Cost Breakdown of Texture Analyzer Prototype

No.	Material	Price	No.	Material	Price
1.	TB6560 Nema Driver	IDR 72,400	8.	Linear Ball Screw kit + NEMA Stepper motor	IDR 1,320,025
2.	2 Buttons	IDR 63,800	9.	Small Keypad	IDR 16,800
3.	Blue LCD 20x4 Screen + I2C Module	IDR 70,500	10.	Acrylic Sheet Frame	IDR 232,000
4.	Jumper Cable	IDR 13,200	11.	Screw & L Steel Joint	IDR 164,800
5.	Breadboard	IDR 28,000	12.	Wood Beam 5x10x100 cm	IDR 60,000
6.	Arduino Mega 2560 + USB Cable	IDR 703,000	13.	Power Supply	IDR 32,000
7.	20kg Load Cell kit + HX711	IDR 99,000			
Total			**IDR 2,875,525**		

Conclusion

There are many commercial texture analyzers available in the market. However, the machines were imported, and the associated price was high. This work successfully demonstrated the design, fabrication procedures, calibration, and performance tests of a mini compression test machine prototype that functioned as a food texture analyzer. The machine was designed for easy and low-cost production and portable handling. The result was that a machine prototype with a final size of 375 × 215 × 450 mm and a vertical translational distance of 200 mm was produced with a spending of less than 3 million rupiahs. A load cell with a capacity of 10 kg was installed to measure the applied load during food testing. The load could be replaced when a different capacity was measured. The machine structure primarily uses wood, acrylics, and 3D print PLA materials. For controlling the machine, an Arduino Mega microcontroller was utilized, in which an open-source program was developed to acquire the load and displacement data from the load cell and linear ball screw slider. In addition, the machine was equipped with other components, such as a TB6560 driver, LCD 1602 and I2C module, buttons, and a keypad. According to the calibration and performance test results, the machine performed a compression test of the potato chips specimen with an error value of ± 1 g for the load and ± 0.1 mm of the linear displacement. Moreover, the measurement data also effectively detected the crack phenomenon during the test, which served as one of the primary functions of a food texture analyzer. Further development was required to improve the machine's appearance, measurement performance, and control system program modules to achieve a commercial standard.

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