Resistor-Capacitor Time Constant for Auto Ranging Capacitance Measurement

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Abstract. The study develops a low-cost, Arduino-based capacitance measurement system with auto-ranging capabilities, aiming to enhance the measurement accuracy and flexibility for soft robotics applications. This system utilizes the principle of resistor-capacitor (RC) time constant, where Arduino discharges and recharges a capacitor through a predefined resistor, determining the capacitance by measuring the time constant. The system's auto-ranging feature automatically adjusts resistor values, ensuring accurate measurement even with varying capacitance levels. The validation process compared the system's performance with an LCR meter, resulting in a minor 3.75 % error. The system also incorporates a custom-built soft material tester, where capacitance measurements were made alongside mechanical testing to evaluate stretchable conductive materials. Results from cyclic pressure tests showed stable performance and reliable data for material characterization. The system is designed to be scalable and easily integrated into electromechanical testing setups, providing an affordable alternative to expensive commercial equipment, especially in soft robotics and sensor testing. The study concludes that the Arduino-based system holds potential for advancing research in soft robotics, particularly in the development of soft, stretchable sensors for precise motion monitoring.

Keywords: Soft Robotics, Capacitance, Auto-Ranging, Time Constant.

1 Introduction

Soft robotics represents an emerging and advanced technology within the field of robotics. Recently, interest in soft robotics has increased significantly and has attracted considerable attention from researchers in specific fields such as healthcare [1], industry, aerospace, and the robotics sector itself [2]. Soft robotics consists of two main components, namely sensors and actuators [3]. Several popular soft actuators include pneumatic artificial muscles [4], soft manipulators [5], dielectric elastomer actuators, and soft pumps [6]. Soft robotics faces its own challenges in generating highly accurate

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movements [7]. When considering the practical applications of soft robotics, it is often necessary to integrate various sensors, such as force sensors, in certain cases. However, most commercially available sensors are composed of rigid components. If these commercially available sensors are integrated into soft robots, there is a risk that the advantages of soft robotics may be diminished. Therefore, these commercially available sensors are difficult to integrate into soft robots, and there is a need for sensors composed solely of soft materials.

Soft robotics integrates soft sensors and actuators, enabling flexible and precise movements. Among the key components in this technology, stretchable sensors play a significant role due to their ability to accurately monitor deformation in materials or robotic systems [8]. The quality of such sensors strongly depends on the linearity, reliability, and durability of their conductive materials during repeated stretch-release cycles. In this context, soft actuators combined with high-performance stretchable sensors offer a promising solution for high-precision motion monitoring in soft robotics. There are several types of stretchable sensors [9], including resistive-type and capacitive-type sensors. Each sensor has its own characteristics. For example, resistive sensors offer a higher gauge factor, lower fabrication cost, faster fabrication time, and simpler measurement methods compared to capacitive sensors [10]. On the other hand, the strengths of capacitive sensors include better linearity, less hysteresis at specific strain levels, and higher repeatability than resistive sensors [8]. To evaluate the performance of these sensors, electromechanical testing is commonly conducted, combining the measurement of both mechanical and electrical properties of the material [3]. Professional electromechanical testing equipment is generally expensive, with very high investment costs, which limits accessibility for researchers with limited resources. Therefore, there is a growing need to develop a low-cost, easily modifiable tensile testing device that can still provide accurate test results.

From a general perspective, the choice of sensor depends on the user's decision based on the end application. Although both resistive and capacitive sensors have their own characteristics, their performance largely depends on the quality of the stretchable electrodes. High-quality stretchable electrodes must be able to maintain material conductivity while withstanding large and repeated. strain-release cycles [1]. To understand the quality of stretchable electrodes, measurement equipment is required to simultaneously assess both mechanical and electrical properties. Through such measurements, the characteristics of a conductive soft material can be accurately determined.

In this study, the authors will perform capacitance measurements on conductive soft materials using a custom-built capacitance measurement device that can be integrated into an electromechanical tensile testing equipment. This measurement device utilizes an Arduino Nano, making it more affordable compared to conventional measurement instruments. The controller was selected because Arduino has its own built-in capacitance measurement capabilities. This device is expected to perform capacitance measurements of conductive materials using the electromechanical tensile testing system to evaluate the performance of the capacitance measurement setup.

2 Experimental Methode

A step-by-step approach is carried out in a structured manner to ensure that both mechanical and electrical measurements can be performed to characterize the electrodes. This section describes the methodology to be employed, including the working principle of the capacitance measurement module and the conductive material to be used.

2.1 Electrical Tester Module

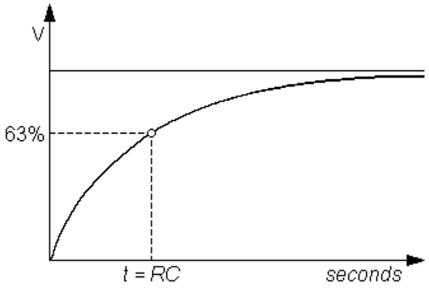


Fig. 1. Graph of voltage percentage versus capacitor charging time

In this paper, capacitance measurement is performed using a custom-built device, where the measurement is conducted through an Arduino microcontroller. The principle relies on changes in capacitance resulting from variations in the physical dimensions or the surrounding environment of the sensor. [1]. Capacitance (C) is defined as the ability of a system to store electrical charge, which depends on the geometry of the sensor and the dielectric properties of the material located between the two electrodes. Capacitance can be calculated using the equation (1):

$$C = \frac{\lambda_0 \cdot \lambda_r \cdot A}{d} \tag{1}$$

Arduino operates based on its own working principle to determine the value of an electrode. Using its RC timing method, Arduino measures capacitance by discharging the capacitor and then recharging it, allowing the system to determine the capacitance value of the stretchable sensor. Each Arduino-based capacitance measurement relies on the properties of the resistor-capacitor (RC) circuit—specifically, the time constant. In Fig. 1 the RC time constant is defined as the time required for the voltage across the capacitor to reach 63.2 % of its full charge voltage [11]. By determining the time *t* at which the voltage *V(t)* reaches exactly 63.2 %[12].

For example, when V has a voltage of 10 V and the resistor used has a resistance of 100 $k\Omega$, at time $t = 7$ seconds, V (7 s) = 3.54 V. As a result, the capacitance *C* is calculated to be 160 μF. The time at which the voltage across the capacitor reaches 63.2 % of 10 V (i.e., 6.3 V) is found to be 16 seconds. This value is then substituted into the equation (2):

$$t = R \cdot C \tag{2}$$

$$16 = 10.000 \cdot C$$

This results in a capacitance of 160 μF. Thus, capacitance can be determined using Arduino by charging a capacitor through a known resistor R with a 5V supply and measuring the time it takes for the voltage across the capacitor to reach 63.2 % of 5V, which is 3.16 V. For the Arduino's analog-to-digital converter, 5V corresponds to a value of 1023. Therefore, it is only necessary to wait until the analog input value reaches:

$$1023 \cdot \frac{3{,}16}{5} = 647$$

With this time, the capacitance (*C*) can be calculated. To enable the measurement of capacitors with significantly different capacitance values, we used five different charging resistors. Initially, a low resistance is used to determine the charging time up to a value of 647. The auto-ranging method is implemented through multi-level resistor selection (100kΩ–1MΩ) based on RC time constants, with conditional logic for real-time optimal range selection. If this time is too short, indicating that the capacitor's capacitance is too low, the next higher charging resistance is selected logarithmically. Capacitance in an RC circuit is related to the time constant by the equation (3):

$$C = \frac{TC}{R} \tag{3}$$

where TC is the time constant in seconds, R is the resistance in ohms, and C is the capacitance in farads. Thus, using Arduino, the capacitance of soft materials can be measured, as they exhibit capacitive behavior.

Fig.2 and Fig. 3 presents the schematic of the capacitance measurement system based on the Arduino Nano, which is used to measure the capacitance of soft conductive materials. The system includes multiple resistors functioning as an auto-ranging feature that adjusts the measurement based on the deformation of the soft material. The resistor values and the corresponding Arduino pins used are detailed in Table 1. In soft material testing, when the material is stretched, the distance between the electrodes or the involved surface area changes, thereby altering the measured capacitance. Capacitive sensors are superior in terms of linearity and resistance to hysteresis compared to resistive sensors, making them preferable for applications that require high accuracy in strain measurements. In soft material testing, when the material is stretched, the distance between electrodes or the active area changes, thereby altering the measured capacitance [6]. Capacitive sensors are superior in terms of linearity and resistance to hysteresis compared to resistive sensors, making them more suitable for applications that require high accuracy in strain measurement.

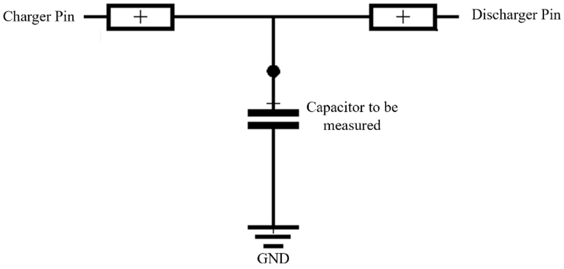


Fig. 2. Simple circuit diagram of capacitor capacitance measurement

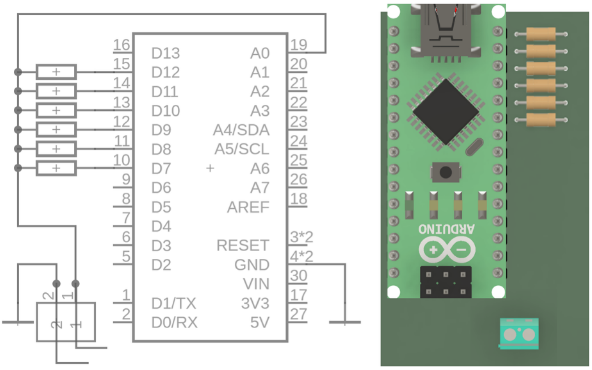


Fig. 3. Capacitance measurement circuit using Arduino

Table 1. Connection Arduino Pin to Other Part

Arduino Nano Pin	Part	Value
D12	Resistor 1	220 Ω
D11	Resistor 2	10 kΩ
D10	Resistor 3	100 kΩ
D9	Resistor 4	1 MΩ
D8	Resistor 5	100 MΩ
D7	Resistor 6	1 GΩ
A0	Probe	+
GND	Probe	-

2.2 Soft Material Conductive Preparation

The material to be tested must possess stretchable properties and exhibit high linearity [13]. Therefore, the material was fabricated using double-sided permanent tape (Fig. 4a), which has stretchable characteristics, with an initial diameter of 60 mm (Fig. 4b), and was stretched using a stretcher device to a diameter of 110 mm, as shown in Fig.

4c. Subsequently, the specimen was mounted onto a fixed frame that was fabricated using a 3D printer with PLA PETG (Fig. 4d). Following this, paper was utilized to shape the mold, which was then coated with conductive grease with a diameter of 30 mm. Copper tape was affixed at both ends (Fig. 4e), serving as connectors between the material and the capacitance measurement device. The paper is then affixed onto double-sided permanent tape to serve as a mold prior to the application of conductive grease (Fig. 4f). After applying conductive grease to both sides of the permanent tape to impart electrical properties (Fig. 4g), the paper mold was removed (Fig. 4h). As shown in Fig. 4i, the specimen was completed and ready for compression testing.

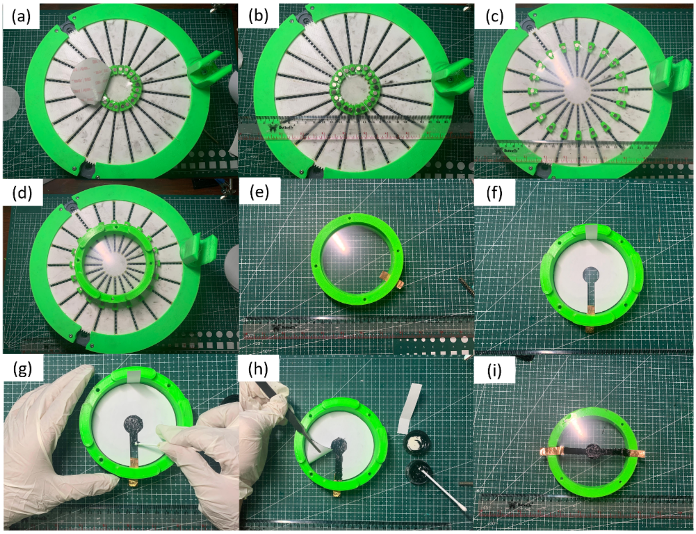
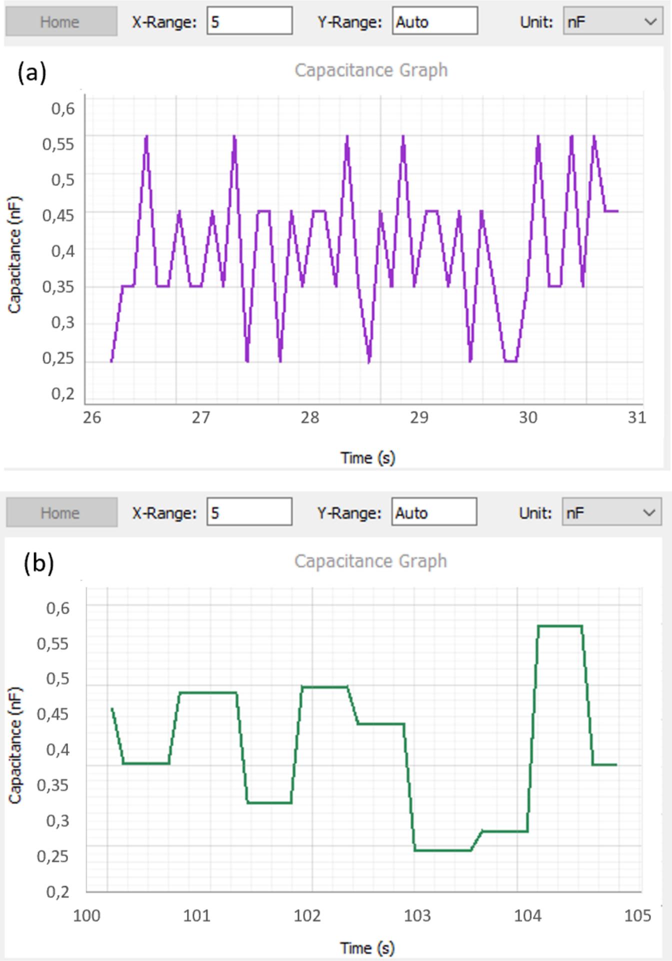


Fig. 4. Stretchable material was fabricated using double-sided permanent tape (a–c), mounted on a 3D-printed PLA PETG frame (d), and shaped with a paper mold coated in conductive grease (e–g). After mold removal (h), the specimen was ready for compression testing (i).

2.3 Electrical Conductivity Test

Capacitance measurements can be validated using an LCR meter, specifically the East Tester ET 4410. This validation was performed by comparing the results from the custom-built capacitance measurement device with those obtained from the LCR meter. Prior to testing, the specimen was measured using both the LCR meter and the Arduino-based capacitance measurement system. The LCR meter displayed a capacitance value of 385 pF (Fig. 5b), while the Arduino-based system showed a value of 400 pF (Fig. 5a) 3.75 % error compared to an LCR meter. The discrepancy between the two measurements arises because the capacitance measurement frequency can be adjusted in the LCR meter, whereas in the Arduino-based system, frequency cannot be changed without adding additional components [14].


X-Range: 5
Y-Range: Auto
Unit: nF

X-Range: 5
Y-Range: Auto
Unit: nF

Fig. 5. Comparison of measurement results GUI python: (a) Arduino-Based capacitance measurement and (b) LCR Meter

3 Result and Discussion

To observe the behavior of the soft material, compression testing was carried out using an available tensile testing machine, with the system configuration shown in Fig.6. This quipment is simlar to our previous equipment [1]. TB6560 stepper motor was used to drive the pressing end, which has a diameter of 5 mm. LVDTs (Linear Variable Differential Transformers sensor) functioned as a displacement sensor. A load cell sensor was used to measure the applied force during testing. A custom-built capacitance measurement with arduino was employed to evaluate the electrical properties, and its results were compared with measurements from the East Tester ET 4410 LCR meter. The purpose of this test setup was to examine the force–displacement curve of the conductive soft material and to assess how effectively the custom capacitance measurement system can characterize the material's properties.

In this test, a speed of 200 mm/min was used to perform electromechanical compression testing 21 cycles on the stretchable conductive material. The measurement process was stable and presents data obtained from actual measurements. Fig.7 shows the result pressure tests of the stretchable conductive material conducted. The first graph (Fig. 7a) presents the load-cell sensor measurements in Newtons. Fig. 7b shows the displacement readings from the LVDTs. Fig. 7c reports the capacitance measured with the East Tester instrument, and Fig. 7d reports the capacitance measured using the Arduino. Finally, these two capacitance datasets are compared to examine differences in measurement results (Fig. 7e).

Initially, the material was compressed at a speed of 200 mm·min^{-1} to a depth of 50 mm and held for one minute. Afterward, the pressure was gradually released to compare the capacitance measurements obtained from the Arduino and the LCR meter on the soft conductive material (Fig. 8). Fig. 8 shows the differences in characteristics between capacitance measuring instruments, where measurements using Arduino exhibit an 3.75 % error compared to those taken with an LCR meter. This test aims to demonstrate changes in mechanical properties during deformation and the electrical properties of the material, particularly the capacitance of soft materials.

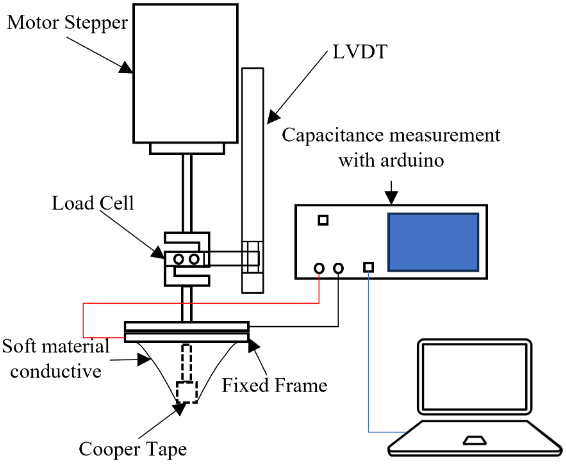
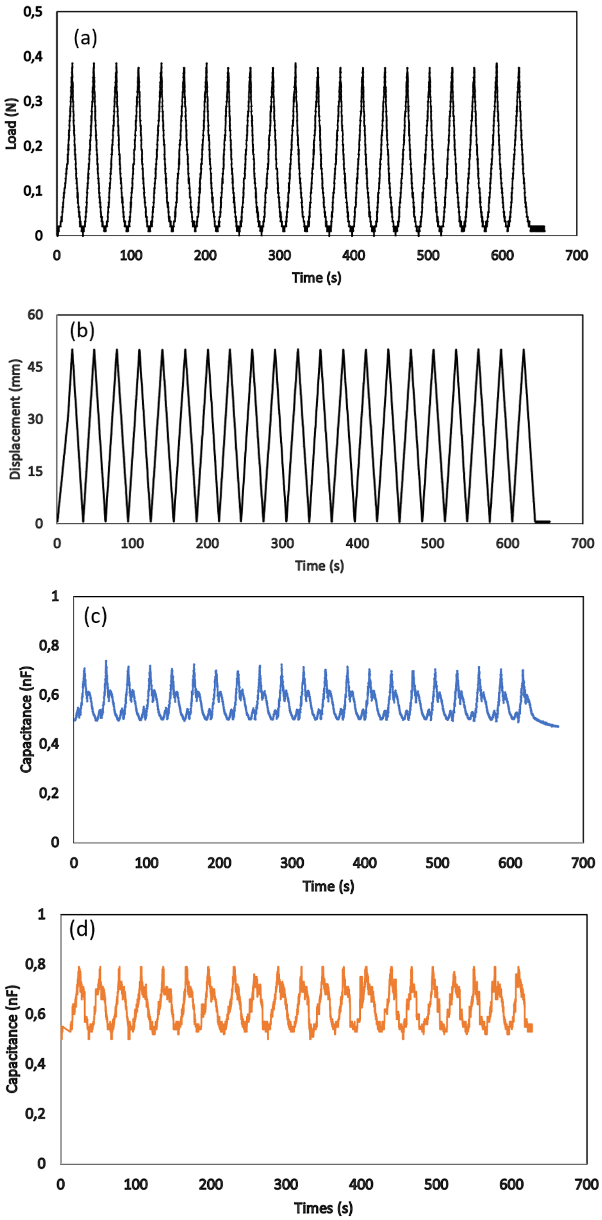


Fig. 6. Testing Device System


(a)
Load (N)
0
0,1
0,2
0,3
0,4
0,5
0
100
200
300
400
500
600
700
Time (s)
(b)
Displacement (mm)
0
15
30
45
60
0
100
200
300
400
500
600
700
Time (s)
(c)
Capacitance (nF)
0
0,2
0,4
0,6
0,8
1
0
100
200
300
400
500
600
700
Time (s)
(d)
Capacitance (nF)
0
0,2
0,4
0,6
0,8
1
0
100
200
300
400
500
600
700
Times (s)

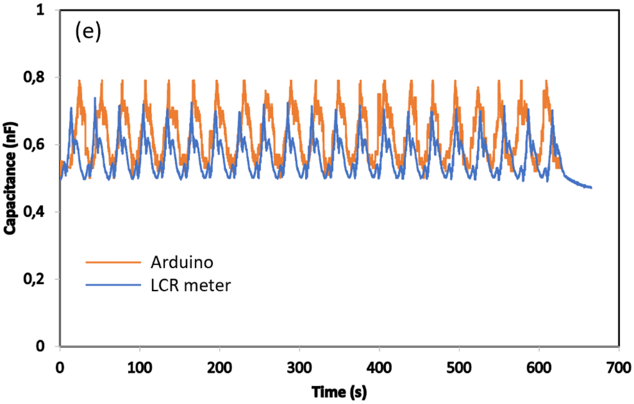


Fig.7. Compression testing results were obtained simultaneously over time for (a) Load, (b) Displacement, (c) Arduino Capacitance, (d) LCR meter Capacitance, (e) Arduino and East Tester Comparation

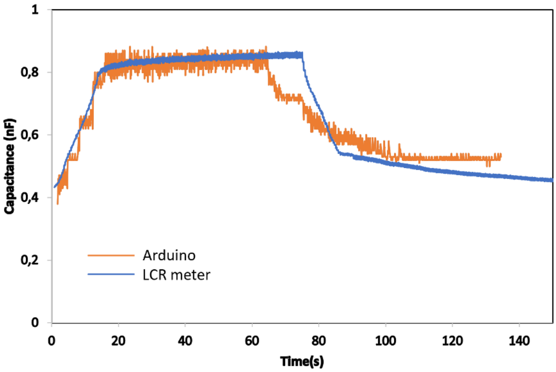


Fig.8. The data of relationship between the Arduino and LCR meter measurements prior to the cyclic testing

4 Conclusion

This paper presents the development of a device for testing both electrical and mechanical properties. Simultaneous testing of mechanical and electrical characteristics provides valuable insights into the key properties of stretchable conductive materials. Although the capacitance measurement equipment was specifically designed for soft materials, it can also be applied to rigid materials such as PVC, carbon composites, or nylon, as long as the material exhibits capacitive behavior. We hope that this Arduino-based capacitance measurement system will contribute to the advancement of soft robotics, particularly in the development of soft and stretchable sensors.

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