Sensor systems

Flexible and Ecofriendly Keypad Based on Paper and Pencil

Şahane Firdevs Er, Nurefşan Kalabey, and Dooyoung Hah

Department of Electrical & Electronics Engineering, Abdullah Gül University, Kayseri 38080, Türkiye

Manuscript received 7 August 2023; revised 14 September 2023; accepted 6 October 2023. Date of publication 11 October 2023; date of current version 20 October 2023.

Abstract—Pencil-on-paper electronics has gained growing interests as cost-effective, ecofriendly, flexible, and light-weight devices for various applications. In this letter, a flexible keypad employing pencil-on-paper capacitive touch sensors is presented. Spiral-type interdigitated sensors are interconnected via steel threads as well as graphite paths to constitute a ten-button keypad. Passivation of the sensors by means of acrylic paint coating works as protection against deterioration from bending, folding, and extended usage. Backing of the keypad with silicone provides extra durability. Sensor reading is administered by Arduino boards. The same manufacturing method is used to scale up the system to a 44-button keyboard. Functionalities of both systems are successfully demonstrated, and effectiveness of the passivation is verified.

Index Terms—Sensor systems, capacitive touch sensor, ecofriendly manufacturing, flexible electronics, paper-based electronics, pencil electrodes.

I. INTRODUCTION

Flexible electronics is a rapidly growing field with vast potential. Numerous application areas can benefit from flexible electronics, such as healthcare, defense, education, logistics, smart home, fashion, sports, and entertainment, to name a few. Various materials have been explored to be used in flexible electronics, including plastics, metal foils, cellulose, fabric, and so on. Among them, a cellulose paper is particularly interesting for flexible electronics with its compliant, ecofriendly, sturdy, printable, porous, and lightweight characteristics.

Sensors are one of the major components in flexible electronic systems as means to obtain inputs and data for the systems. Drawing sensors with pencils on papers has gained increasing attention recently as a low-cost and ecofriendly option for flexible electronics. The manufacturing method, in general, does not necessitate expensive equipment or hazardous chemicals, which makes it more attractive for commercialization. Design-to-fabrication cycles become incomparably shorter than conventional methods, making it ideal for prototyping. A broad range of pencil-on-paper-based sensors have been reported so far for measurement of various measurands, such as pressure [1], temperature [2], [3], body movement [3], humidity [4], gas [5], pH [6] and electrophysiological signals [7].

Touch sensors have been widely utilized for user interface, and a keypad is one of the representative examples. There have been reports of flexible touch sensors. Out of metalized papers, Maezzo et al. [8] produced touch pads for smart-packaging applications, employing either interdigitated capacitive sensors or parallel-plate capacitive sensors. Although the manufactured sensors demonstrated performances intended, a laser cutter was needed to create patterns on metalized papers, which increases the manufacturing cost. It should be also noted that typical metals have limited compliance. Ba et al. [9] developed flexible electronic circuits including a keyboard out of graphene-coated papers. In this approach, the pattern generation requires either precise control of the graphene deposition or laser cutting, in other words, usage of expensive equipment is needed. Zulfiqar et al. [10] reported on interdigitated capacitive touch sensors based on pencil and paper, and an array of them to form a five-button [10] and a 15-button [11] keypads. Although promising potential was demonstrated for the pencil-on-paper approach for the flexible keypad, the keypads were built as a straightforward extension of the sensors. It is imperative, therefore, that further development be made in order to move the concept forward to realize more sophisticated systems, which is the main objective of the current study.

In this letter, spiral-type interdigitated capacitive touch sensors were produced by drawing them with pencils on papers. Various passivation approaches were investigated to protect the sensors so that the system becomes more robust against extended usage and mechanical deformation. Interconnection methods were examined carefully, and as a result, ten-button keypads were successfully developed. Backing substrates were attached to the papers to provide extra durability to the system. The developed system was connected to a computer via a microcontroller board (Arduino) for testing. In addition, a keyboard was manufactured through the same process and tested with a computer.

II. CAPACITIVE TOUCH SENSOR

Implementation of touch sensors has been based on various transduction mechanisms, including piezoelectric [12], piezoresistive [13], capacitive [14], fluidic [15], triboelectric [16], optical [17], and so on. Among them, a capacitive type is deemed most suitable for the current purpose because of its high stability, low hysteresis, nonrequirement of exotic materials, and low-power consumption [18], [19]. Between the two most frequently used capacitive sensor configurations, i.e., a parallel-plate type and an interdigitated type, the latter was selected in this study for its better sensitivity in the current implementation scenario [8]. Different electrode configurations, including a comb finger type and a spiral type, were considered for the interdigitated capacitor, and the spiral type was chosen because it utilizes the footprint in an efficient manner.

First, the sensor geometry was outlined by using graphic software, and then printed on a paper to be used as a drawing guide. Next, the actual sensors were fabricated by copying the design on a tracing paper (thickness: 50–150 μm, dielectric constant: 2–3). The tracing paper serves as an insulating substrate for the sensors. For drawing of the sensors and paths, an 8B pencil was used—the higher the number in front of the letter "B", the more the pencil trace contains the graphite,

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Corresponding author: Dooyoung Hah (e-mail: dooyoung.hah@agu.edu.tr).
(Sahane Firdevs Er and Nurefşan Kalabey contributed equally to this work.)
Associate Editor: C. A. Zorman.
Digital Object Identifier 10.1109/LSENS.2023.3323898

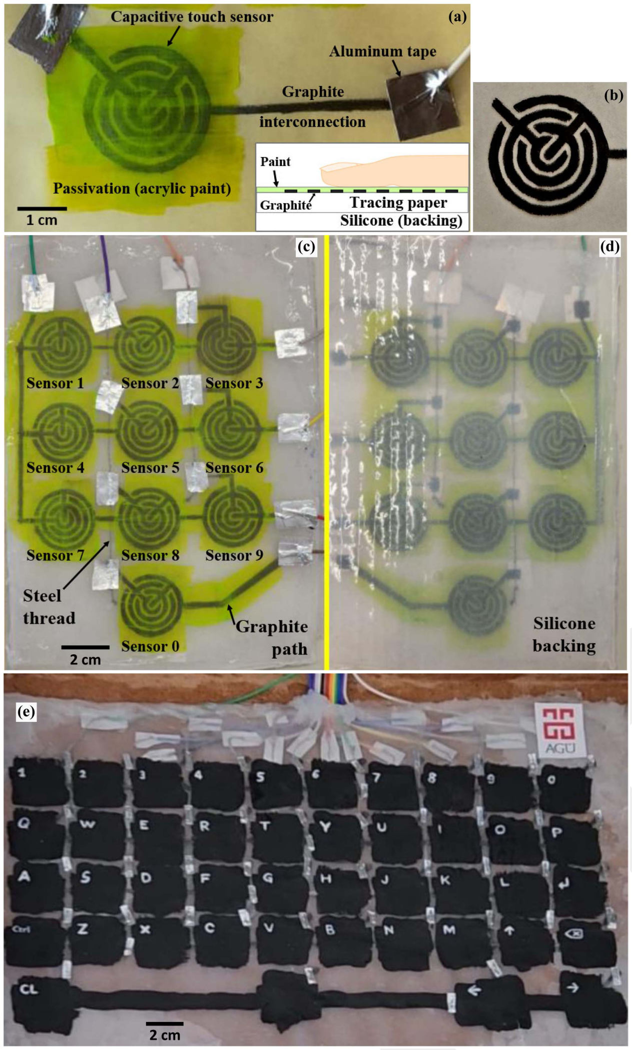

Fig. 1. Developed flexible keypad and keyboard systems with pencil-on-paper touch sensors. (a) Manufactured single sensor. Inset: Side-view sketch. (b) Sensor before passivation. (c)–(d) Manufactured keypad. (c) Front view. (d) Backside view. (e) Manufactured 44-button keyboard.

and hence, the higher the conductivity of the trace becomes [4], [7]. To increase the conductance of the drawn parts further, pencil stroke was repeated up to eight times—after eight strokes, the conductance increase was saturated [7]. The designed sensor [see Fig. 1(a)] has a diameter of 26 mm, composed of 2-mm-wide lines and 1-mm-wide spaces. For the sensor measurement, copper wires were made in contact with the pencil trace extension (graphite interconnection), and the contacts were secured by using an aluminum tape. The sensor was connected to an Arduino Uno board via copper wires, and the “capacitor” library was used to measure the capacitance value [20].

Passivation of the sensors is an important issue for the pencil-based ones because pencil traces are prone to be removed, degraded, and modified by touches during usage and handling. A proper passivation method can improve reliability and lifetime of the sensors. Various materials, which satisfy low cost, flexibility, good adhesion, and easy handleability, were tried, including tracing papers, plastic wraps, transparent tapes, sodium carboxymethyl cellulose (CMC), polystyrene, poly(methyl methacrylate) (PMMA), and silicone. All of these attempts failed because those materials modified the sensors during touches (e.g., smudging, spreading, and detachment) or compromised the functionality of the sensors. On the other hand, acrylic paint (see Fig. 1), a natural choice for drawing on a paper, turned out to satisfy all of the requirements while maintaining the sensor performances over extended usage. Passivation with acrylic paint (typical dielectric constant: 5–8) did not incur noticeable changes in the sensor idle capacitance values.

III. FLEXIBLE KEYPAD IMPLEMENTATION

A keypad system is one of the most widely used interface devices. In this study, a keypad system was designed by arranging and connecting multiple touch sensors. Scalability of the sensor array was one of the main design considerations, and the developed configuration was further extended to a keyboard system in the following stage.

Interconnection is one of the most important design considerations for a keypad (and for a keyboard) implementation. Following objectives were set for the interconnection design:

1) reduction in the number of interconnection lines;
2) short conductive paths, and
3) minimized parasitic capacitance, which is mainly caused by crossings of interconnections.

The final design (row–column addressing scheme) can be seen from Fig. 1(c) and (d), which contains three column and four row addressing lines, and hence requires, in total, seven external cables for connection to the Arduino board. Although most of the interconnections were made with pencil drawings, it was not possible to complete it on a single level in the addressing scheme adopted, and hence, another level of interconnection was needed. At first, copper cables were tried as the second level, however, they were not compliant enough for the purpose. In the end, steel threads were adopted for the second level [see Fig. 1(c) and (d)], which was mainly placed on the backside of the tracing paper. Connections between the two interconnection levels (i.e., graphite and steel thread) were rendered via holes made through the paper. Experimentally, it was learned that the quality of electrical contact makes a huge impact to the sensor reliability. After trials of several different combinations, the best option was found to be direct contact between the graphite and the steel thread, which was secured by aluminum tape on them.

A keypad system described to this point was sufficient from the functional point of view. However, for extended usage of the device, it is essential to make it more robust against mechanical deformation, such as bending, rolling, and folding. For this purpose, silicone was used as a backing substrate. RTV-3040, a clear silicone rubber compound, was used for this purpose. It came as a highly viscous solution. First, it was mixed with catalyst, and the mixture was poured onto a mold with the size of a keypad. Then, the keypad was placed on the silicone. It took, typically, one day to cure the silicone completely at room temperature. Finally, the silicone-back-coated keypad was removed from the mold. The manufactured keypad with the silicone backing is shown in Fig. 1(c) and (d).

After the successful development of the keypad system, it was scaled up to a keyboard system, consisting of 44 sensors (36 keys for alphanumeric characters and eight keys for special characters and functions). The same manufacturing method was followed. Fig. 1(e) shows the developed keyboard system. In case of the keyboard, black acrylic paint was used as the passivation, on which letters and numbers were scribed in white acrylic paint. For connection between the keyboard and a computer, an Arduino Leonardo board was used to utilize its built-in “Keyboard” library [21] and USB communication. Communication

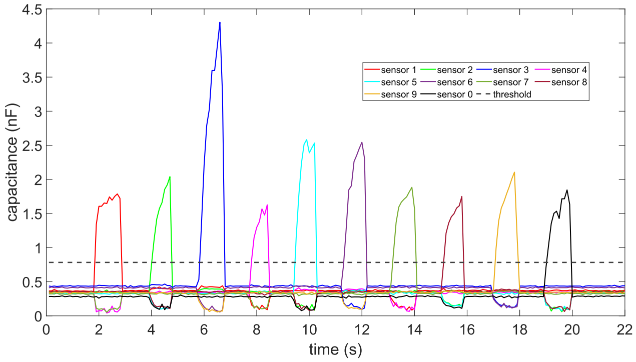

Fig. 2. Example of sensor responses from a keypad. A threshold capacitance value (mean) is indicated as a dashed line.

between the manufactured keyboard and a computer was handled by the ATmega32U4 microcontroller on it.

IV. RESULTS

Fig. 2 shows an example of the responses of the ten sensors in the manufactured keypad system. Sensors were touched in a sequence—a touch of Sensor 1 for one second, a pause for one second, a touch of Sensor 2, and continued. A typical value of idle capacitance of a sensor was a fraction of nF. A typical value of capacitance change by touch was a few nF. Among the sensors in a keypad system, slight variations in idle capacitance values and considerable differences in capacitance change by touch were observed due to manufacturing nonuniformity, pressing location changes, touch pressure variations, and so on. However, these variations did not pose a serious problem for the system operation because the capacitance change by touch was substantial (see Fig. 2) and because it could be overcome by defining adequate threshold values (to be recognized as "pressed") and by a proper calibration method. A tradeoff exists with respect to the threshold capacitance value. A relatively high threshold value can avoid incorrect recognition of unpressed events. However, high threshold value also results in longer delay between the actual pressing moment and its recognition by the system. Considering this, the threshold value was set as twice of the idle capacitance value for each sensor. The threshold value indicated in Fig. 2 is the average of those threshold values for all sensors. From Fig. 2, negative capacitance changes can be also observed from some of the unpressed sensors, more specifically from the ones that share the same column address line with the pressed one. For example, Sensor 4 and Sensor 7 exhibit negative capacitance change when Sensor 1 is pressed (between 2 and 3 s). It is considered that this negative capacitance change is probably due to the specific capacitance reading method used in the study. However, this does not result in incorrect reading, thanks to the threshold-based detection algorithm. In addition, if needed, the system operation can be further reinforced by using separate address lines and multiplexers.

Experiments were also carried out to understand the effectiveness of the paint passivation. First, changes in resistance values of graphite paths, incurred by bending (around a diameter of 1 cm) and harsh folding (to the degree sufficient to leave a permanent folding mark on the paper), were measured and compared (see Table 1 and Fig. 3). Without passivation, bending increased the resistance by 24%, and harsh folding made it an open circuit. With the paint passivation, the resistance was increased by 8.7% after bending, and by 520% after harsh folding, still maintaining conductivity. Painting itself increased the resistance by 28%. These results indicate the effectiveness of the passivation method used. The effect of passivation was examined on the sensors as well. Without passivation, idle capacitance values were decreased to less than a half by bending and harsh folding, whereas such a change was not seen in the passivated sensors. Bending and folding also resulted in substantial drops in capacitance change by touch for the sensors without passivation. The drops were smaller for the passivated sensors. Although the magnitude of capacitance change by touch after bending and folding is still higher for the without passivation case than the passivated one, it needs to be considered that these magnitudes drop dramatically over usage for the sensors without passivation (see Fig. 4).

Table 1. Effects of Paint Passivation

Passivation	Without			With		
Test condition	AM	AB	AHF	AM	AB	AHF
Path resistance [kΩ]	7.5	9.3	∞	9.2	10	56
Idle capacitance [nF]	0.5	0.2	0.2	0.5	0.5	0.5
Capacitance change by touch [nF]	60	40	20	3.3	2.3	2.4

AM: As manufactured, AB: After bending (ϕ: 1 cm), AHF: After harsh folding. Average values are reported for capacitance values.

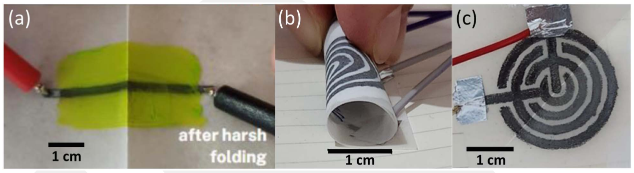

Fig. 3. Bending and folding tests of (a) graphite paths and (b), (c) sensors on paper. (a) After harsh folding, with passivation. (b) After bending (ϕ: 1 cm). (c) After harsh folding. (b), (c) Without passivation.

To investigate the effect of passivation to the sensor performance in long-term usage, first, the sensors in both conditions (with and without passivation) were pressed over 1000 times, while their capacitance changes were being monitored. In the passivated sensor, both the idle capacitance and the capacitance change by touch did not show remarkable differences over time. The sensor without passivation, however, showed significant drop (from about 60 nF to about 2 nF) in capacitance change by touch over the same period. Fig. 4 shows the capacitance outputs of the sensors for 100 s (50 presses; repeat of a 1-s-press and 1-s-release cycle) after being pressed over 1000 times. The capacitance curve of the passivated sensor is quite clear without much noise, and the capacitance returned to the idle value consistently during release. Although the peak capacitance values varied among different presses, it does not pose a problem to the operation as explained earlier. In case without passivation, the capacitance graph became significantly noisy. Moreover, return to the idle value was noticeably inconsistent. These results substantiate the necessity of decent passivation.

The manufactured keyboard was connected to a computer via an Arduino Leonardo board to be tested. Fig. 5 shows an example of typing a sentence, "hello world" on a computer with the developed keyboard. Other functions, such as movement by arrow keys, shortcut keys (e.g., Ctrl+X and Ctrl+C), etc., were successfully performed as well.

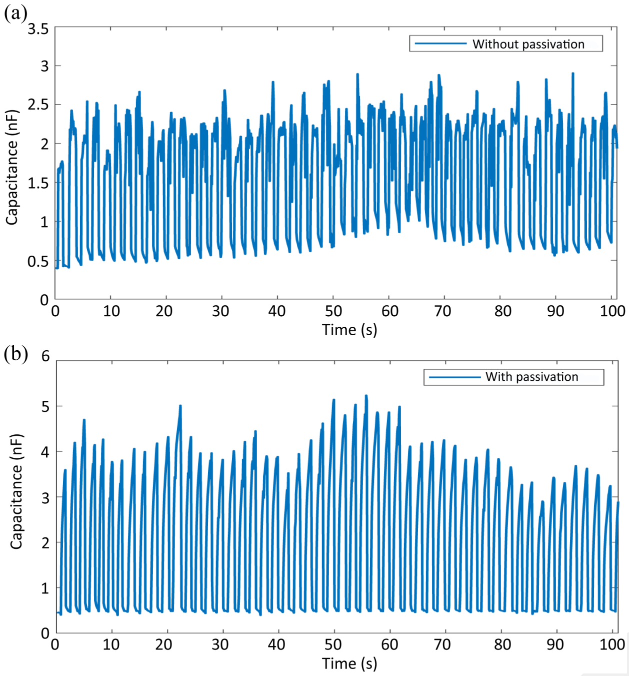

Fig. 4. Sensor performances in repeated usage. (a) Without and (b) with passivation. The graphs show responses for 50 presses after being pressed 1000 times beforehand.

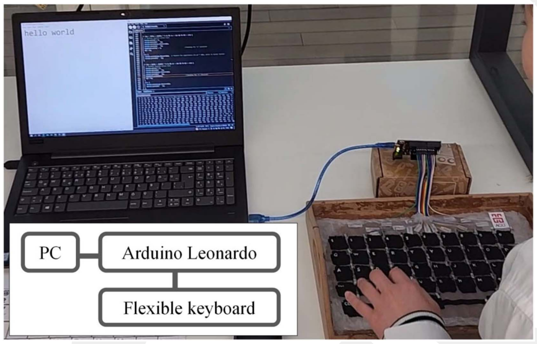

Fig. 5. Testing of the manufactured flexible keyboard with a PC.

V. CONCLUSION

This letter has presented the process of designing and manufacturing a flexible, ecofriendly, and cost-effective keypad and keyboard systems based on pencil-on-paper capacitive touch sensors. Both systems were connected to a computer, and successfully demonstrated the functions intended. Pencil-on-paper electronics has shown its potential for a range of applications, including wearable systems, health monitoring, smart homes, sensor networks, and so on. This work furthers the development in the field, providing engineering solutions for flexible peripheral devices. It is envisaged that more devices will be developed in the similar manner for a wide range of applications.

ACKNOWLEDGMENT

This work was supported by TÜBITAK under University Students Research Project Support Program 2209-A under Grant 1919B012206356. The authors would like to thank Dr. Kutay Icoz, Müzeyyen Savaş, and Aykut Coşkun.

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