Project Mihr: Enabling Gestural Interactions on a Keyboard using a Graphene-based Fabric

Citation: Luo, Yiyue, Barhudarian, Evelina and Seyed, Teddy. 2023. "Project Mihr: Enabling Gestural Interactions on a Keyboard using a Graphene-based Fabric."

As Published: https://doi.org/10.1145/3544549.3585873

Publisher: ACM|Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems

Persistent URL: https://hdl.handle.net/1721.1/150657

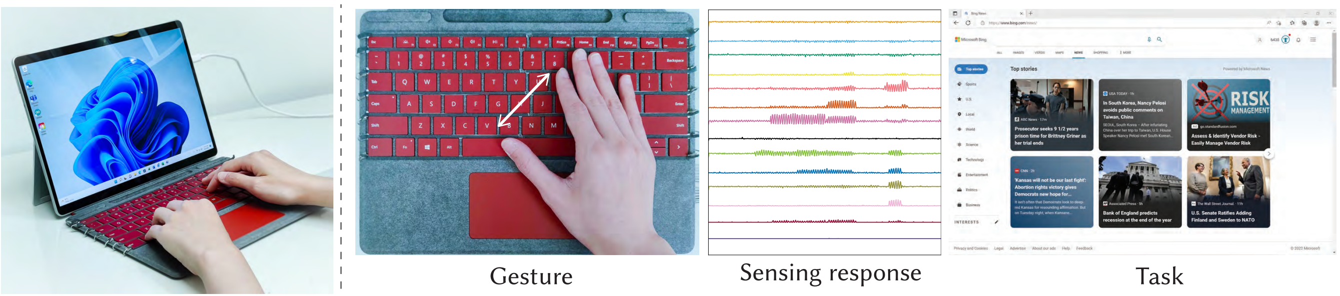
Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

Project Mihr: Enabling Gestural Interactions on a Keyboard using a Graphene-based Fabric

Yiyue Luo
yiyueluo@mit.edu
MIT CSAIL
Cambridge, Massachusetts, USA

Evelina Barhudarian
ebarhudar@gmail.com
Microsoft Research
Redmond, Washington, USA

Teddy Seyed
teddy@microsoft.com
Microsoft Research
Redmond, Washington, USA



Gesture

Sensing response

Task

Figure 1: The Project Mihr Keyboard : *Left:* Our touch-sensitive keyboard prototype using a graphene-based fabric; *Right:* the capturing and recognition of gestural interactions on keyboards with a smart textile is useful for everyday laptop applications, e.g. web browsing.

ABSTRACT

The physical keyboard has long been the *de facto* input mechanism for computers, despite advances in other input forms and modalities. Even with these advances, the augmentations of physical keyboards have still been limited to keystroke-based entry. We leverage the inevitable physical touch and motions over a keyboard during keystroke-based input to present Project Mihr, a physical keyboard that has been augmented to be touch-sensitive. We leveraged passive capacitive sensing with a graphene-based textile to detect and classify rich and expressive gestural interactions over a keyboard. We conclude this work by describing our characterization on the sensing performance and presenting several different application scenarios that are enabled by our technique over keyboards.

CCS CONCEPTS

• **Human-centered computing** → **Keyboards**; **Interaction devices**; **Keyboards**.

KEYWORDS

Smart textiles, keyboard interaction

ACM Reference Format:
Yiyue Luo, Evelina Barhudarian, and Teddy Seyed. 2023. Project Mihr: Enabling Gestural Interactions on a Keyboard using a Graphene-based Fabric. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems (CHI EA '23), April 23–28, 2023, Hamburg, Germany.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3544549.3585873

1 INTRODUCTION

Physical keyboards for text entry have long remained an important part of the user input interface for laptops, desktops and other devices. In addition to text entry through single keystrokes, the capabilities and expressiveness of physical keyboards have been enhanced by keyboard shortcuts. While keyboard shortcuts are widely used and efficient for issuing commands, they are sometimes difficult to learn, memorize, and execute. Recently, user interactions over physical keyboards have been further enriched with the integration of diverse sensing modalities, e.g. touch and vision. Despite the effectiveness, integrating sensing modalities into physical keyboard remains challenging because of two critical challenges. First, sensor integration with physical keyboards should be seamless and maintain the designed form factor of a physical keyboard. Secondly, the integrated sensors should be unobtrusive to traditional text input, thus allowing users to input text through the integrated sensing modalities or with regular keystrokes and shortcuts without manually transitioning from one modality to another.

With these challenges in mind, we integrated a graphene-based fabric into a commercially available keyboard, enabling sensing and gesture recognition to complement traditional text input. We chose a fabric based approach for sensing, because intelligent fabrics have already been used for a variety of sensing techniques [5, 10, 13, 24, 37]. Several commercially available input and output devices already use fabric (e.g. [1, 2, 4]), but primarily for aesthetic purposes. In this work, we explored a fabric-based sensing approach for gestural input on keyboards, to overcome the challenges of seamless and unobtrusive integration.

CHI EA '23, April 23–28, 2023, Hamburg, Germany

ACM ISBN 978-1-4503-9422-2/23/04.
https://doi.org/10.1145/3544549.3585873

We differ from previous work, because our passive sensing modality is non-obtrusive and complementary to existing keyboard input modalities; it is enabled through the integration of semi-conductive graphene fabric in the spacing between keys. Such an implementation allows simultaneous input from traditional keystrokes and keyboard shortcuts, as well as gestural interactions over the keyboard, thus enriching expressiveness of a keyboard. Compared with trackpads, sensing over keyboards not only offers a larger space for gestural interactions but also enables more intuitive and convenient interactions during typing. To demonstrate the potential of interactions over keyboard, we prototyped a keyboard with gesture recognition and performed preliminary gesture recognition coupling with a random forest classifier. We then used this model to highlight different usage scenarios of gestural interactions over a keyboard.

2 RELATED WORK

We briefly discuss the literature on the different interaction techniques for physical keyboards and touch sensing using intelligent textiles.

2.1 Physical keyboard interaction

Leveraging the existing input functionalities of physical keyboard, hotkeys and keyboard shortcuts have been widely used to promote efficiency as well as to extend users' interactions over keyboard. Wobbrock et al. [35] presented a gesture-based text entry method by using four keys to mimic the writing of Roman letters. Gestkeyboard [38] allowed users to issue commands by performing a specific sequential keystrokes. Interactions over a keyboard can also be augmented by combining on-body sensing systems. Buschek et al. [7] proposed extending keyboard shortcuts with arm and wrist rotation gestures performed during keystrokes, leveraging data captured by an on-body smartwatch.

To further promote interaction resolution, reduced latency, and throughput, physical keyboards have also been augmented through the integration of additional diverse sensing modalities. Thanks to advances in computer vision and visual sensing systems, webcams have also been widely explored for on-keyboard and over-keyboard gestures input localization [26, 34] and identification [8, 40]. Other than visual systems, Taylor et al. [29] interspersed infrared (IR) proximity sensors within keycap spacing to sense and recognize the interaction over a mechanical keyboard. Furthermore, FlickBoard [30] integrated a capacitive sensing grid into a soft keyboard cover and combined a trackpad and keyboard into the same interaction area. Similarly, Gestakey [28] equipped capacitive sensing matrix to each keycap, which allowed the capturing of users' subtle gestures over each key. More recently, physical keyboards using capacitive sensing have also been presented for AR and VR text entry[20].

Physical keyboards have also been augmented and modified with smart textiles, which offer users comfort soft and comfortable feeling [18]. Wicaksono and Paradiso [33] presented a deformable keyboard interface based on a multi-modal fabric sensing surface. Wang et al. [32] touch-sensitive keyboards by implementing functional fabric and conductive electrodes above the keys as capacitive touch sensors. Jeon et al. [12] further demonstrated triboelectric nanogenerator-based wearable keyboard fabricated with commercial functional fabrics.

Inspired by previous works on fabric-based touch-sensitive augmented physical keyboard, we explored passive touch sensing and gesture recognition on the keyboard area by integrating graphene-based fabric with a physical keyboard. Different from previous work, our sensing capability is integrated in an unobtrusive and seamless manner; graphene-based fabric not only offers comfort and aesthetics but also enables touch-based interactions complementary to the conventional keystroke-based input.

2.2 Sensing Touch with Intelligent Textiles

Widely used textile-based touch sensors can be categorized into resistive and capacitive by their sensing mechanisms.

A typical resistive textile-based touch sensor converts pressure stimuli into electrical signals through the change of resistance. Diverse, soft textile-based interactive interfaces were enabled by integrating commercial conductive yarns in customized knitted fabric, where the resistance change was due to conductive yarn loops interactions [16, 17, 21]. Furthermore, matrix-like textile-based sensing arrays were presented by the integration of coaxial piezoresistive yarn in regular textiles [15, 23, 41], and the integration of conductive electrodes in customized piezoresistive textiles [6, 11] through digital textile manufacturing tools, e.g. machine knitting and embroidery. Such textile-based sensing arrays were widely used for wearable interactive interface [27] and everyday health monitoring [14, 22] because textiles are soft, conformal, and offer comfort during daily activities.

Similar to resistive sensing, capacitive sensing converts physical pressure stimuli into electrical signal through the change of capacitance. Capacitive sensing has shown enormous potential in human-computer interaction research because it is purely electrical, low power, and can be prototyped quickly using diverse materials for a wide variety of using scenarios [9]. Orth et al. [19] integrated capacitive touch sensing keypads into jackets through embroidery. Poupyrev et al. [25] presented touch sensing interface in garments by interlacing customized coaxial capacitive sensing yarn through weaving. Wu et al. [36] developed interactive textiles for object recognition by constructing a capacitive sensing matrix over textile substrate. Villar et al. [31] localized and identified tangible objects, as well as a users' touch and gestures by a capacitive-based touch-sensitive soft mat. Electrick [39] enables touch input on a wide variety of objects and surfaces by augmenting objects with conductive medium and transmitting and receiving electrodes.

In this work, we leveraged passive capacitive sensing by integrating a semi-conductive graphene-based textile.

3 IMPLEMENTATION

Based on the design implications described in the previous sections, we integrated a semi-conductive graphene-based fabric into a commodity keyboard (a Microsoft Surface Pro type cover) for gesture recognition over keyboard. In this section, we discuss our proposed sensing principle, characterization result, and implementation details.

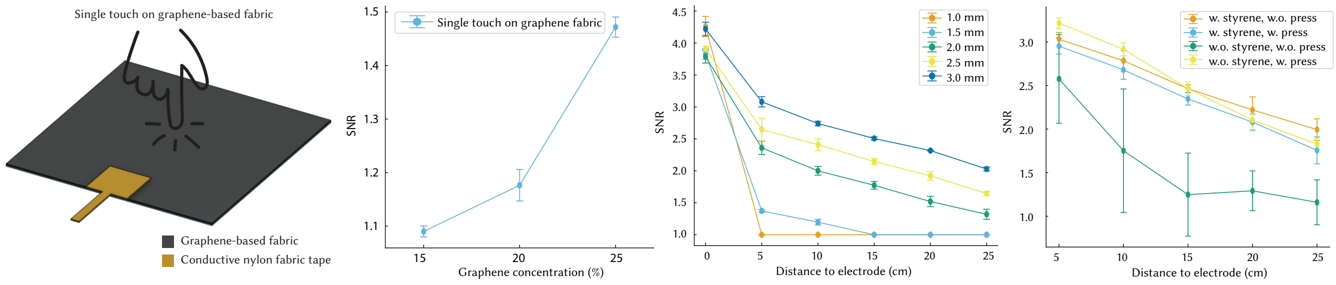


Figure 2: Project Mihr Sensing Principle and Characterization: *Left:* Characterization set-up with a 3mm x 3mm conductive nylon tape adhered to a 5cm x 5cm graphene fabric; *Middle left:* The signal to noise ratio (SNR) induced by a single touch increases with the increase of graphene composition of the sensing fabric and the decrease of sensing fabric resistance. *Middle right:* Signal-to-noise ratio from a touch on graphene-based fabric strip with different widths at different distances to the electrode and *Right:* on the graphene-based fabric strip mounted with and without elevated styrene spacing.

3.1 Sensing Principle

Our sensing is enabled by a custom semi-conductive graphene-based fabric. We used a commercially available fabric (Alcantara [3]) that is similar to soft, suede-like materials, which was impregnated with different concentrations of graphene (15%, 20% and 25%), each of which have different levels of resistance and capacitance. We measured the resistance of 15%, 20% and 25% concentrations of graphene in the fabric using a digital multimeter (Keysight 34450), and found resistances of > 1000 MΩ, 543 ± 143.4 MΩ and 7.3 ± 1 MΩ respectively.

Given the high resistance of the graphene-based fabric, we leveraged passive capacitive touch sensing. The human body obtains negligible electrical potential induced from biopotentials and the exposure to ambient electromagnetic wave. When the human body is in touch with the semi-conductive graphene fabric, voltage into a receiving electrode increases due to the potential leaking from the human body. Adhering a 5 mm x 5 mm conductive nylon fabric tape to a 5 cm x 5 cm graphene fabric, we validated the sensing principle by measuring the voltage at the electrode (Fig. 2 left) through a digital oscilloscope (Rigol DS1104). When there was no touch on the fabric, the signal to noise ratio (SNR) stayed at 1; however, when a human touch occurred on the fabric, the voltage increased dramatically and therefore the SNR increased. We characterized the sensing performance of fabric with different graphene composition. As demonstrated in Fig. 2 middle left, a larger SNR can be retrieved from a touch when tested with fabric with a higher graphene composition, which obtains lower resistance. Furthermore, we investigated the performance of the graphene-based fabric with different sensing areas. We measured the SNR from a single touch on a thin graphene fabric strip (30 cm in length) with conductive nylon taped on one side as a electrode. In general, the larger SNR was obtained with a wider strip because a larger contact area was obtained between the human body and the sensing fabric (Fig. 2 middle right). The SNR also dropped as the single touch moved away from the conductive nylon electrode. This agrees with our observation that a higher SNR can be extracted from sensing fabric with lower resistance and that the resistance increases with an increase in distance from the electrode on the side.

3.2 Keyboard Integration

To demonstrate the concept of a gesture based keyboard with fabric, we integrated the semi-conductive graphene-based fabric into a Microsoft Surface Pro Type Cover keyboard for gesture sensing and recognition.

As our approach used the space in between key caps, we observed a slight height difference between the surface of key caps and the in between spacing area, which blocked the direct contact between users' finger and the graphene fabric, therefore resulting in an unstable signal. To address this issue, and before being integrated into the keyboard, the graphene fabric was attached onto an additional styrene spacing layer (0.25 mm) to compensate the height difference between the spacing and the key caps. We compared the SNR from a single touch on the graphene-based fabric integrated directly to the key caps spacing area and on the graphene-based fabric mounted on a 0.25 mm styrene layer. As demonstrated in Fig. 2 right, with a strong press on the keyboard area (i.e. a key or keys are pressed), a reliable response can be extracted from the graphene-based fabric with or without the elevated styrene layer; however, for a normal touch on the keyboard area, which most users preferred (i.e. keys not pressed), a reliable response can only be extracted from the graphene-based fabric on top of the elevated styrene layer.

Our prototype has 14 separate sensing areas (7 on the left and 7 on the right), each of which is constructed with one horizontally aligned thin graphene-based fabric strip and one electrode at the outer edge. A strip runs from the left of the keyboard across to the end of the keyboard. The graphene-based fabric along with the connecting electrodes can be integrated within a Microsoft Surface Pro Type Cover keyboard with low-cost commercial materials, as shown in Fig. 3. First, we reshaped the 0.25 mm spacing styrene layer by laser-cutting and align it to the Type Cover keyboard area. We then cut the graphene-based fabric into the size of key caps spacing by hand and by using a CNC cutting machine. It is worth noting that we didn't lasercut the graphene-based fabric because it may change the conductivity and functionality of the fabric. We then attached a 5mm x 5mm conductive nylon tape to the end of each graphene-based fabric piece as sensing electrode. All graphene-based fabric pieces with electrodes were aligned and affixed on top of the styrene spacing among key caps using an

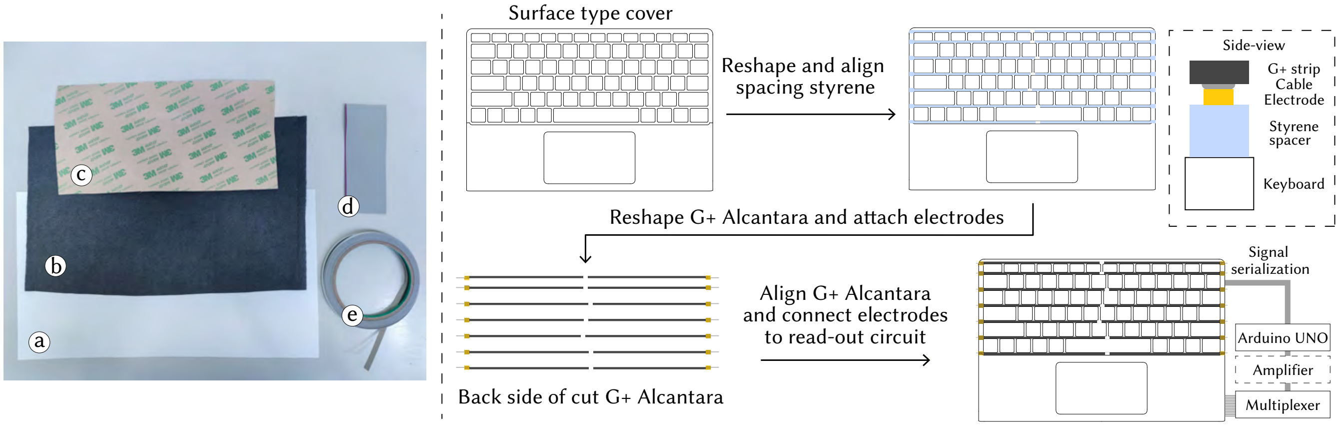


Figure 3: Fabrication procedures: *Left:* We prototype with (a) styrene sheet, (b) graphene fabric, (c) 3M adhesive, (d) IDC cables and (e) conductive nylon tape; *Right:* the general prototype implementation workflow. The side-view of the stack-up sensing structure is demonstrated at the top-right corner.

adhesive. All electrodes were further connected to a read-out circuit through routing cables. The signal from each of the 14 electrodes were multiplexed, optionally amplified, and serialized to a Surface tablet through an Arduino Uno at more than 200 Hz.

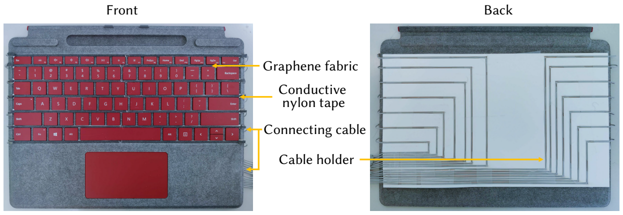


Figure 4: Integrating Sensing onto a Keyboard *Left:* The graphene fabric strips along with conductive nylon conductive tape on the side were integrated in the spacing between key caps; *Right:* The connecting cables were routed and arranged on the back and connected to the read out circuit.

4 GESTURE RECOGNITION

4.1 Data collection

The graphene-based fabric-integrated Surface Type Cover keyboard is shown in Fig. 4. As demonstrated in Figure 5, different response patterns can be retrieved from the 14 sensing areas when a user performs one of the elicited gestures over the keyboard area, such as taps, swipes, drawings, as well as two hand gestures. The sensing response characteristics depend on different temporal factors, e.g. the duration of a users' touch and the order of a users' touch at different sensing area, and spatial factors, e.g. touch distance from each electrode.

Signals extracted from each sensing strip contain information on the existence of a touch and the position of a touch. For example, as a user taps at a different location on the keyboard (Fig. 5 first row), the signal from the corresponding sensing strip can be extracted. Furthermore, based on the sequences and amplitude of signals extracted from each individual sensing strip, swiping directions (Fig. 5 second row) and different drawing patterns over the keyboard, e.g. cross and checkmark can be recognized (Fig. 5 third row). Since our prototype consists of 7 individual sensing areas on the left and right half of the keyboard respectively, different gestural interactions over the left and right keyboard can be extracted simultaneously. For example, in Fig. 5 (last row), the combination of holding on the left and tapping or swiping on the right are demonstrated. This type of design enriches the sensing capability of our prototype, thus allowing the of combinations of different gestural interactions.

4.2 Modeling

We demonstrated a preliminary gesture recognition by coupling our prototype with a Random Forest machine learning technique, which is robust, efficient in computation, and suitable for real-time applications with low-power consumption. We captured data on one user performing 12 of the elicited gestures, including swipe right, swipe left, swipe up, swipe down, tap single, tap double, draw check, draw cross, draw spiral, hold, pinch in and pinch out. Each gestures was performed 30 times. Each individual gesture was captured in 4 seconds with 900 data points. We deployed a random forest classifier from Scikit-Learn module and used 80% of the captured data from training and the rest for testing. The model used 500 trees and the criterion of 'entropy'. Across these 12 classes, our system achieved an overall accuracy of 91.7%. The confusion matrix for the model is shown in Fig. 6 (left). We further projected the high dimensional data into 2D space using t-SNE. The 12 classes form separate clusters, which indicate the discrimination of the signal.

4.3 Usage Scenarios

As shown in Fig. 7, we demonstrated a number of different usage scenarios of our fabric-based gesture sensing keyboard. Inspired and grounded by our elicitation study, we use gestural interactions over keyboard as a complementary input technique with traditional text input. For example, when a user is performing text editing in Word, our prototype senses and recognizes different gestures, such as pinch out, drawing, and swiping along different directions, to trigger specified text editing commands, such as enlarge font size, accept changes, subscript, superscript, and delete. Our prototype also allows users to call supportive commands in a more efficient

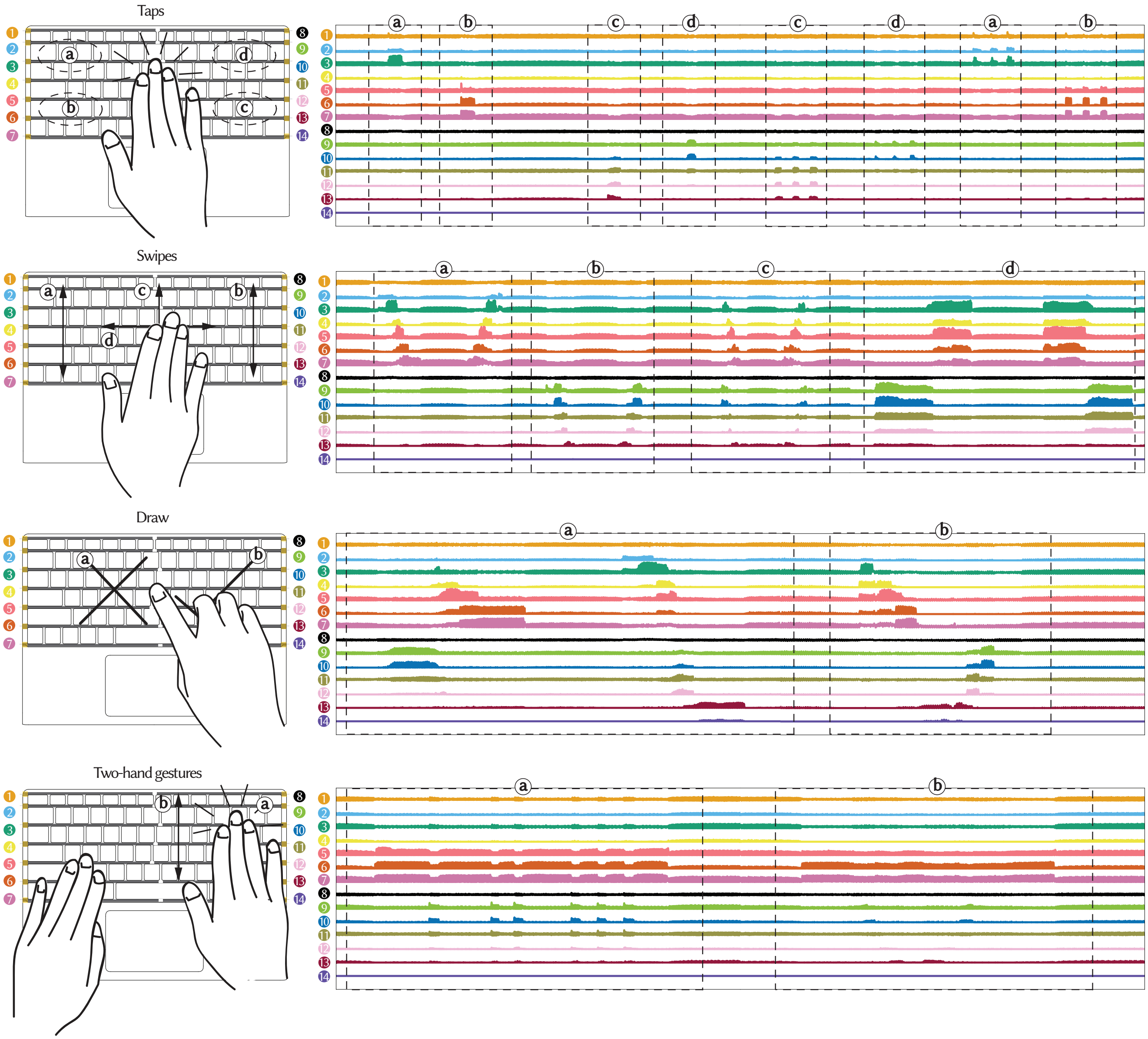


Figure 5: Example sensor responses from the 14 sensing areas on the prototyped gesture sensing keyboard: The existence of touch, the position, the duration, as well as the pattern of a gestural interactions can be captured by the multiplexed signal from our prototype with graphene-based fabric sensing strips placed in between key caps on a keyboard.

manner on different platforms, e.g. using a swipe gesture to autocomplete an email and use a hold hand gesture to hand raise for attention in a video conferencing application (e.g. Zoom or Microsoft Teams). Following participants' feedback from the elicitation study, we also made use of gestures that are already well-established on other electronic devices. For example, users can tap or double tap on the keyboard area for the next video or next song, similar to the gestures used on headsets; users can also pinch in or pinch out on the keyboard to zoom out or zoom in on a web page, similar to the gestures used on trackpads. A real-time demonstration can be found in our supplementary video.

5 LIMITATIONS AND FUTURE WORK

In this section, we discuss the limitations of our work and propose several potential directions for future research.

Passive sensing. Our sensing scheme is passive, which relies on ambient electric field and human body potentials. While it operates with minimal power consumption and a straightforward read-out circuit, it tends to be less precise and more susceptible to changes in the environment. Also, the SNR needs to be further improved for stable and reliable performance in real-life applications. Investigations into active capacitive sensing for future work, may overcome these changes and prove to be more acceptable for a fully integrated graphene-based fabric keyboard.

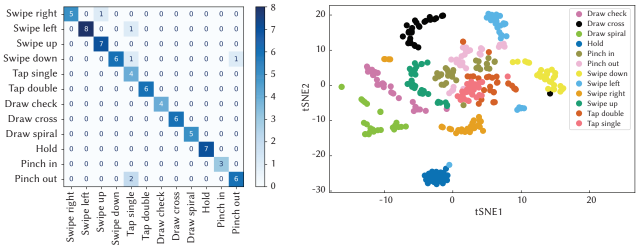


Figure 6: Gestural interaction recognition result: *Left:* Confusion matrix for gesture classification; *Right:* clusters of different gesture sets formed in the projected 2D space by t-SNE.

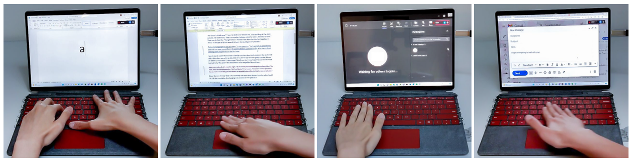


Figure 7: Usage Scenarios of Gestural Interaction over a Keyboard: *From left to right:* Increasing font size during text editing, accepting changes in a text document, raising a hand during a video conference all, and auto-completing an email.

Ambiguity on multi touch. Each sensing area currently is composed of only one electrode at the outer edge. Multi touch on one individual sensing area (the individual graphene fabric stripe) creates ambiguous signalS. This problem can be addressed by adding more electrodes or adding more separated graphene-based fabric sensing areas.

Sensing area extension. The sensing graphene-based fabric is only integrated in between the keys in the current prototype. Going forward, the sensing graphene-based fabric can be fully integrated over the entirety of the keyboard in a seamless manner, which will extend the sensing area to the side and bottom of the type cover, and potentially provide a more enriched user experience.

Gesture classification. Currently, our preliminary gesture recognition model is based on data of one single user and a relatively simple modeling method. Going forward, we will expand our dataset on diverse users and apply more advanced machine learning technique, e.g. convolutional neural network (CNN), for generalized recognition.

6 CONCLUSION

In this work, we presented Project Mihr, a passive capacitive sensing physical keyboard using a graphene-based fabric for gestural interaction over keyboard recognition. We implemented a prototype touch-sensitive physical keyboard for gesture recognition. We characterize the sensing performance of our design and demonstrate over-keyboard gestural interaction recognition coupled with machine learning algorithm for a number of different usage scenarios.

ACKNOWLEDGMENTS

We thank Lex Story, John Romualdez, and Teresa LaScala for their help and insightful discussions in the development process of Project Mihr. We also thank Wojciech Matusik for providing us with the necessary testing facilities.

REFERENCES

[1] 2013. Logitech FabricSkin Keyboard Folio for iPad (review) | ZDNET. [Online]. Available from: https://www.zdnet.com/article/logitech-fabricskin-keyboard-folio-for-ipad-review/.
[2] 2019. Alcantara fabric on Microsoft Surface PCs: Everything you need to know | Windows Central. [Online]. Available from: https://www.windowscentral.com/what-is-alcantara-microsoft-surface.
[3] 2019. Alcantara fabric: What is it and is it worth it? | carwow. [Online]. Available from: https://www.carwow.co.uk/guides/glossary/what-is-alcantara-0518.
[4] 2022. Amazon.com: Echo (2nd Generation) International Version – Charcoal Fabric : Amazon Devices & Accessories. [Online]. Available from: https://www.amazon.com/Echo-2nd-Generation-International-Version/dp/B075RSCZHD.
[5] Roland Aigner, Andreas Pointner, Thomas Preindl, Rainer Danner, and Michael Haller. 2021. TexYZ: Embroidering Enameled Wires for Three Degree-of-Freedom Mutual Capacitive Sensing. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 499, 12 pages. https://doi.org/10.1145/3411764.3445479
[6] Roland Aigner, Andreas Pointner, Thomas Preindl, Patrick Parzer, and Michael Haller. 2020. Embroidered resistive pressure sensors: A novel approach for textile interfaces. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–13.
[7] Daniel Buschek, Bianka Roppelt, and Florian Alt. 2018. Extending keyboard shortcuts with arm and wrist rotation gestures. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–12.
[8] Nalin Chhibber, Hemant Bhaskar Surale, Fabrice Matulic, and Daniel Vogel. 2021. Typealike: Near-Keyboard Hand Postures for Expanded Laptop Interaction. *Proceedings of the ACM on Human-Computer Interaction* 5, ISS (2021), 1–20.
[9] Tobias Grosse-Puppendahl, Christian Holz, Gabe Cohn, Raphael Wimmer, Oskar Bechtold, Steve Hodges, Matthew S Reynolds, and Joshua R Smith. 2017. Finding common ground: A survey of capacitive sensing in human-computer interaction. In *Proceedings of the 2017 CHI conference on human factors in computing systems*. 3293–3315.
[10] Nur Al-huda Hamdan, Simon Voelker, and Jan Borchers. 2018. Sketch&Stitch: Interactive Embroidery for E-Textiles. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3173656
[11] Cedric Honnet, Hannah Perner-Wilson, Marc Teyssier, Bruno Fruchard, Jürgen Steimle, Ana C. Baptista, and Paul Strohmeier. 2020. PolySense: Augmenting Textiles with Electrical Functionality Using In-Situ Polymerization. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13.
[12] Seung-Bae Jeon, Sang-Jae Park, Weon-Guk Kim, Il-Woong Tcho, Ik-Kyeong Jin, Joon-Kyu Han, Daewon Kim, and Yang-Kyu Choi. 2018. Self-powered wearable keyboard with fabric based triboelectric nanogenerator. *Nano energy* 53 (2018), 596–603.
[13] Hye Ran Koo, Young-Jae Lee, Sunok Gi, Seonah Khang, Joo Hyeon Lee, Jae-Ho Lee, Min-Gyu Lim, Hee-Jung Park, and Jeong-Whan Lee. 2014. The Effect of Textile-Based Inductive Coil Sensor Positions for Heart Rate Monitoring. *J. Med. Syst.* 38, 2 (feb 2014), 1–12. https://doi.org/10.1007/s10916-013-0002-0
[14] Joanne Leong, Patrick Parzer, Florian Perteneder, Teo Babic, Christian Rendl, Anita Vogl, Hubert Egger, Alex Olwal, and Michael Haller. 2016. proCover: sensory augmentation of prosthetic limbs using smart textile covers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. 335–346.
[15] Yiyue Luo, Yunzhu Li, Pratyusha Sharma, Wan Shou, Kui Wu, Michael Foshey, Beichen Li, Tomás Palacios, Antonio Torralba, and Wojciech Matusik. 2021. Learning human–environment interactions using conformal tactile textiles. *Nature Electronics* 4, 3 (2021), 193–201.
[16] Yiyue Luo, Kui Wu, Tomás Palacios, and Wojciech Matusik. 2021. KnitUI: Fabricating interactive and sensing textiles with machine knitting. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 1–12.
[17] Yiyue Luo, Kui Wu, Andrew Spielberg, Michael Foshey, Daniela Rus, Tomás Palacios, and Wojciech Matusik. 2022. Digital Fabrication of Pneumatic Actuators with Integrated Sensing by Machine Knitting. In *CHI Conference on Human Factors in Computing Systems*. 1–13.
[18] Charles McLellan. 2012. Eleksen Wireless Fabric Keyboard: a first look. *Retrieved from: on May* 7 (2012).

[19] Maggie Orth, Joshua R Smith, E Rehmi Post, JA Strickon, and Emily B Cooper. 1998. Musical jacket. In *ACM SIGGRAPH 98 Electronic art and animation catalog*. 38.

[20] Alexander Otte, Tim Menzner, Travis Gesslein, Philipp Gagel, Daniel Schneider, and Jens Grubert. 2019. Towards utilizing touch-sensitive physical keyboards for text entry in virtual reality. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 1729–1732.

[21] Jifei Ou, Daniel Oran, Don Derek Haddad, Joseph Paradiso, and Hiroshi Ishii. 2019. SensorKnit: Architecting textile sensors with machine knitting. *3D Printing and Additive Manufacturing* 6, 1 (2019), 1–11.

[22] Patrick Parzer, Adwait Sharma, Anita Vogl, Jürgen Steimle, Alex Olwal, and Michael Haller. 2017. SmartSleeve: real-time sensing of surface and deformation gestures on flexible, interactive textiles, using a hybrid gesture detection pipeline. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*. 565–577.

[23] Andreas Pointner, Thomas Preindl, Sara Mlakar, Roland Aigner, and Michael Haller. 2020. Knitted RESi: A Highly Flexible, Force-Sensitive Knitted Textile Based on Resistive Yarns. In *ACM SIGGRAPH 2020 Emerging Technologies* (Virtual Event, USA) *(SIGGRAPH '20)*. Association for Computing Machinery, New York, NY, USA, Article 21, 2 pages.

[24] Ivan Poupyrev, Nan-Wei Gong, Shiho Fukuhara, Mustafa Emre Karagozler, Carsten Schwesig, and Karen E. Robinson. 2016. Project Jacquard: Interactive Digital Textiles at Scale. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 4216–4227. https://doi.org/10.1145/2858036.2858176

[25] Ivan Poupyrev, Nan-Wei Gong, Shiho Fukuhara, Mustafa Emre Karagozler, Carsten Schwesig, and Karen E. Robinson. 2016. Project Jacquard: Interactive Digital Textiles at Scale. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 4216–4227.

[26] Julian Ramos, Zhen Li, Johana Rosas, Nikola Banovic, Jennifer Mankoff, and Anind Dey. 2016. Keyboard surface interaction: Making the keyboard into a pointing device. *arXiv preprint arXiv:1601.04029* (2016).

[27] Stefan Schneegass and Alexandra Voit. 2016. GestureSleeve: Using Touch Sensitive Fabrics for Gestural Input on the Forearm for Controlling Smartwatches. In *Proceedings of the 2016 ACM International Symposium on Wearable Computers* (Heidelberg, Germany) *(ISWC '16)*. Association for Computing Machinery, New York, NY, USA, 108–115.

[28] Yilei Shi, Haimo Zhang, Hasitha Rajapakse, Nuwan Tharaka Perera, Tomás Vega Gálvez, and Suranga Nanayakkara. 2018. Gestakey: Touch interaction on individual keycaps. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–12.

[29] Stuart Taylor, Cem Keskin, Otmar Hilliges, Shahram Izadi, and John Helmes. 2014. Type-hover-swipe in 96 bytes: A motion sensing mechanical keyboard. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 1695–1704.

[30] Ying-Chao Tung, Ta Yang Cheng, Neng-Hao Yu, Chiuan Wang, and Mike Y Chen. 2015. FlickBoard: enabling trackpad interaction with automatic mode switching on a capacitive-sensing keyboard. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 1847–1850.

[31] Nicolas Villar, Daniel Cletheroe, Greg Saul, Christian Holz, Tim Regan, Oscar Salandin, Misha Sra, Hui-Shyong Yeo, William Field, and Haiyan Zhang. 2018. Project Zanzibar: A Portable and Flexible Tangible Interaction Platform. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, Article 515, 13 pages.

[32] Paul X Wang, Chia Chi Wu, Qiliang Xu, Zheng Gao, Daniel D Sunshine, and Aidan N Zimmerman. 2019. Keyboard with touch sensor illumination. US Patent 10,514,772.

[33] Irmandy Wicaksono and Joseph A Paradiso. 2017. Fabrickeyboard: multimodal textile sensate media as an expressive and deformable musical interface.. In *NIME*, Vol. 17. 348–353.

[34] Andrew D Wilson. 2006. Robust computer vision-based detection of pinching for one and two-handed gesture input. In *Proceedings of the 19th annual ACM symposium on User interface software and technology*. 255–258.

[35] Jacob Wobbrock, Brad Myers, and Brandon Rothrock. 2006. Few-key text entry revisited: mnemonic gestures on four keys. In *Proceedings of the SIGCHI conference on Human Factors in computing systems*. 489–492.

[36] Te-Yen Wu, Lu Tan, Yuji Zhang, Teddy Seyed, and Xing-Dong Yang. 2020. Capacitivo: Contact-based object recognition on interactive fabrics using capacitive sensing. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. 649–661.

[37] Te-Yen Wu, Zheer Xu, Xing-Dong Yang, Steve Hodges, and Teddy Seyed. 2021. Project Tasca: Enabling Touch and Contextual Interactions with a Pocket-Based Textile Sensor. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 4, 13 pages. https://doi.org/10.1145/3411764.3445712

[38] Haimo Zhang and Yang Li. 2014. Gestkeyboard: enabling gesture-based interaction on ordinary physical keyboard. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 1675–1684.

[39] Yang Zhang, Robert Xiao, and Chris Harrison. 2016. Advancing hand gesture recognition with high resolution electrical impedance tomography. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. 843–850.

[40] Jingjie Zheng and Daniel Vogel. 2016. Finger-aware shortcuts. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. 4274–4285.

[41] Lara Zlokapa, Yiyue Luo, Jie Xu, Michael Foshey, Kui Wu, Pulkit Agrawal, and Wojciech Matusik. 2022. An Integrated Design Pipeline for Tactile Sensing Robotic Manipulators. In *2022 International Conference on Robotics and Automation (ICRA)*. IEEE, 3136–3142.