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Apnoea-Pi: Sleep disorder monitoring with open-source electronics and acoustics

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Abstract— **Apnoea is a sleep disorder that affects an increasing number of adults causing harm from fatigue to a growing chance of heart problems. Apnoea disorders can be treated but advanced monitoring and diagnosing tools are needed to identify its strand and offer adequate treatment. Therefore, Apnoea tracking is vital to help keep patients healthy. Sleep Apnoea can cause a number of conditions such as fatigue, high blood pressure, liver functionality and an increased risk of type 2 diabetes. These complications make it necessary to monitor as many potential patients as possible by designing an instrument that is accurate, comfortable to use, fit for purpose, cost effective and with embedded computation capabilities to store, process and transmit time series data. In this work we present Apnoea-Pi, an adaptation of our Acousto-Pi open source surface acoustic wave platform to monitor Apnoea in patients using ultrasonic humidity sensing.**

Keywords- Surface acoustic waves, sleep disorder, apnoea, open-source electronics, time series identification, pattern recognition, piezoelectric thin film.

I. INTRODUCTION

Apnoea is suffered by 2 to 4 percent of adult society [1]. There are two types of sleep Apnoea. The first one is obstructive sleep apnoea [2], which occurs when the muscles in the throat relax causing the airways to narrow while preventing enough air to keep adequate oxygen levels. The second one is less common and called central sleep apnoea [3], which happens when the brain fails to send signals to the muscles required for breathing causing shortness of breath. It is also possible to have both types of apnoea simultaneously. In apnoea monitoring, time series identification is of utmost importance to identify abnormal sleeping behaviours via the breathing patterns over sustained periods of time (hours during sleep).

Surface acoustic wave (SAW) devices are used to identify human breathing [4][5][6][7] as well as humidity on a flexible device, similar to exhaled breath aerosols [8]. SAWs are created by generating radio frequency (RF) signals and applying them to interdigitated transducer electrodes (IDTs) sitting on piezoelectric material. SAW technology is used in a many applications such as acoustofluidics, RF filters, , lab-on-a-chip (LoC), biomedical and sensing applications [9][10][11]. In this work we present a platform to be used for identification and storage of breath patterns using open-source electronics.

A. Background

Electronic open-source platforms offer new capabilities for customised applications in various fields including acoustofluidics and ultrasonics. For example, Ultraino [12] is an ultrasonic system that uses phased-array speakers system to levitate objects in 3D space control with applications in advanced particle handling and in holography. They use an Arduino Mega and an electric circuit board that interfaces with off-the-shelve speakers, used as ultrasonic transducers. Another open source acoustofluidic technique that functions with hearable frequency range devices interfaced via open-source Arduino board, which controls in-line liquids in micro channels whilst spinning molecules [13]. Handheld acoustofluidics [14] can be used to address integration issues. For example, eliminating bulky laboratory gear, shrinking and controlling systems powered with batteries; while being efficient in stirring liquids, particle manipulation and even droplet nebulization. A system employs a Raspberry Pi that controls actuators to place minute items [15] using, nonetheless, non-integrated feedback loop via an external MATLAB script. In addition, open source platforms in combination with rapid additive prototyping are also being employed to implement high-performing but low-cost scientific instruments [16]. Whilst a flexible SAW device has been used to monitor breathing using SAW humidity sensing [4], the design is still limited to in-lab use. It is becoming clear that Arduino, Raspberry Pi and other integrated and open-source microcontroller or PC based systems have the potential to bring acoustofluidic applications into portable devices, with interesting applications in life sciences.

Recently we have implemented an open-source interfacing setup for acousto-optic processing of fluids, named Acousto-Pi [17]. The Acousto-Pi platform uses ultrasound to manipulate the dispensing, position, speed, mixing and temperature of droplets as demanded by the application. The platform can be used in remote mode whilst storing measurements in safe databases. The platform presented in this paper employs Raspberry Pi for control and data analysis by monitoring frequency spectra of a SAW device. In this work, we present Apnoea-Pi, time

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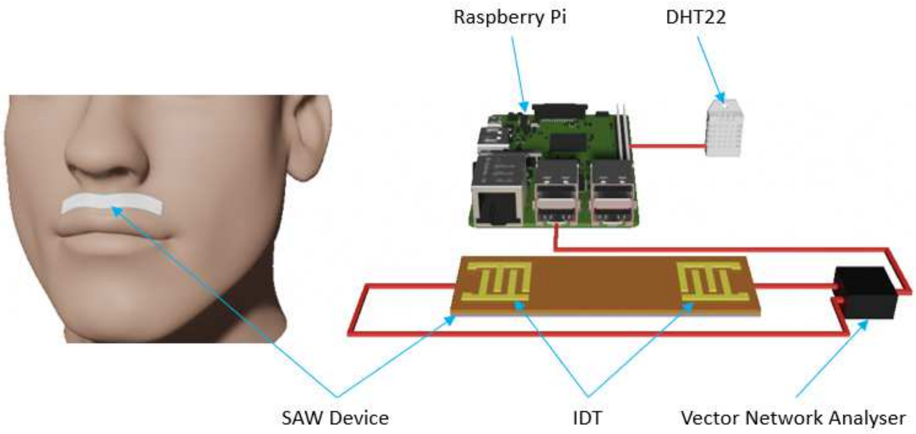

Figure 1. Illustration of the proposed Apnoea-Pi Platform

domain breath monitoring using flexible thin film SAW devices operated at MHz frequencies. We consider that the platform is well suited to store, process and identify time series overnight.

B. Apnoea-Pi overview

In this work, we combine potentially flexible SAW devices mounted under a patient's nose into a platform that can notify patient or carer via an app, as illustrated in Figure 1 The platform is integrated with a Raspberry Pi and a temperature sensor (DHT22) combined humidity and temperature sensor. The system is characterised via vector network analyser (VNA) measurements. The Raspberry Pi monitors the change in the frequency at the SAW device, which is placed on the patient. The DHT22 is used to monitor the environment and filter out any possible interference causing a frequency shift. The resultant wave form is converted into a digital signal where 1 is when the user has exhaled. And 0 when the device resets during inhaling. The frequency of this signal can determine the breathing rate of the patient.

We envisage a system to continuously monitor patents' conditions, recording, analysing and transmitting breathing information. By designing a system that is comfortable to use, patient's adherence increases along with the clinical effectiveness.

II. Design Methodology and Prcedures

A. Hardware description

In this section we describe the electronic platform developed for experimental data obtention and its corresponding analysis. The system uses a Raspberry Pi, model 4, as embedded processor. The choice is made due to the relative low-cost, versatility, high-performance and open-source characteristics. Raspberry Pi presents a Linux-based operational system with a standard desktop visual graphic interface, topped up with its own peripheral hardware range with General Purpose Input Output (GPIO) ports for external component interface. A combined humidity and temperature sensor is integrated with a GPIO pin for serial communication to monitor ambient changes. A vector network analyser (Keysight FieldFox Handheld RF and Microwave Network Analyzer) is connected via the ethernet port. This is used to obtain the frequency spectrum, monitoring and storing the change. Then, Raspberry Pi sets the frequency spectrum range and tracks the peak automatically as illustrated in Figure 1. To be a user centred design, The SAW device can be flexible mounted on the upper lip of the patient, ready to monitor the breathing and comfortable to wear during sleep (see illustrated in Figure 1). The device conforms to the upper lip just below the nose

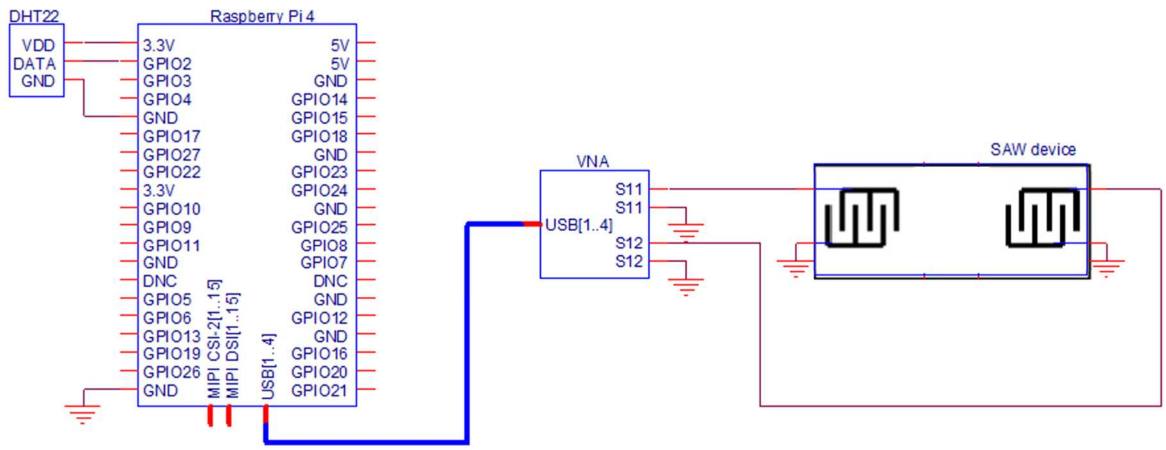

Figure 2 Circuit diagram of Raspberry Pi pinout and SAW control

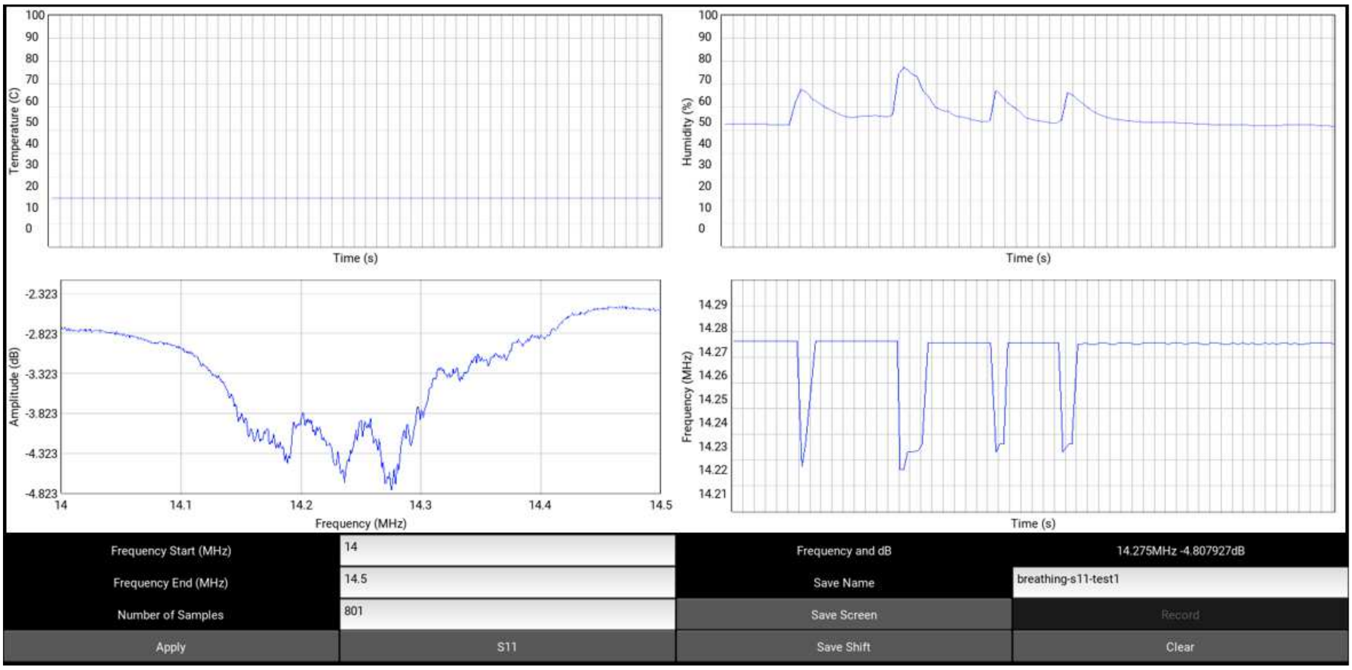

Figure 3 GUI used to monitor SAW device and DHT22

and is connected wirelessly to the nearby electronics and Raspberry Pi.

B. Software description

In this section, we show the development of our graphical user interface (GUI), written using Python. The humidity sensor DHT22 is connected to the Raspberry Pi and the network analyser to monitor both in real time displaying graphs and performing calculations. An Open source, cross platform Python framework for GUI and app development Kivy [19] are used to develop a visually pleasing and ergonomic user environment (3). Whilst the current GUI is focused on the development and prototyping, a similar style can be used with patient usability in minimum displayed data. This will be useful to help understand the events that happened during monitoring. With the multiple data recorded it is possible to present the current frequency spectrum of the SAW device and the fundamental resonant frequency and any changes as they happen in real time. The GUI also records humidity and temperature, all in separate plots on screen (see Figure 3). The data is stored in the Raspberry Pi, and Python algorithms are used to process time-domain signal for pattern identification. Using Raspberry Pi embedded computation power signal processing techniques can be used to identify apnoea patterns. For instance, with off-shelve Python libraries on machine learning, it is possible to match this with apnoea records. This allows to identify the type of apnoea that the patient suffers along with its severity, as well as its progression over time when receiving treatment.

C. SAW device fabrication and surface treatment

The concept of this system is for SAW devices regardless of their fabrication structure. Our group is well-known for thin-film SAW device research, hence we use these to demonstrate the concept.

These are particularly advantageous as they can be fabricated in flexible substrates, ideal to be installed in a breathing mask [19, 20, 22]. Moreover, thin-film SAW can be scaled industrially and integrated into microelectronic fabrication process, to achieve low cost. Also, these devices have been reported to be good humidity sensors for human breathing tracking [20]. Thus, here ZnO thin film on Al substrates are employed as SAW devices [21][22].

Piezoelectric ZnO thin films were deposited onto Al plate (1.6 mm thick) using direct-current. The same process can be used to fabricate SAW devices with 50µm Al foil with similar performance [19]. Magnetron sputter coater, Direct Current mode, was used for thin film depositions using Ar/O2 flow ration of 10/15 sccm and 99.99% pure Zn target. Direct current power was set to 400 W, with gas pressure of 4 × 10-4 mbar. A rotating sample holder was employed while thin film deposition in order to realise uniform films. The rate obtained was 5.6 nm/min, which after 18h of deposition led to a film thickness of~6 µm.

The IDT electrodes were patterned using photolithography with standard lift-off. Metallisation was made via sputtering Al target with a thickness of 200nm.

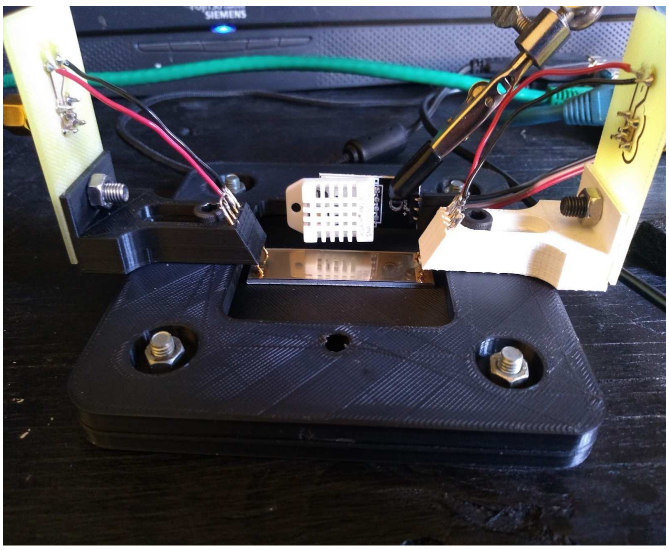
Figure 4 SAW device and DHT22 setup

The IDT design was set at 200 µm, with an aperture of 5 mm and 50 finger pairs. Resonance was reported at ~14.3MHz (Rayleigh wave). S parameters were measured with a network analyser, model (Keysight Fieldfox portable vector network analyser, N9913A 4GHz) for the characterisation of the fabricated devices (with one example shown in Figure 3). Figure 4 shows the assembled SAWW platform with different components. Figure 4 shows a ZnO on aluminium plate SAW device in a 3d printed device test holder. A DHT22 combined humidity and temperature sensor is held near the SAW device as sensing zone.. The electrodes are connected to a network analyser via spring loaded pins fixed in the plastic structure at both ends of the device

III. Results And Discussion

Figure 5 shows data recorded using a Raspberry Pi. A network analyser is connected to record resonant changes. A DHT22 is also connected the Raspberry Pi to record relative humidity and temperature. The exhaled breathing pattern was kept fairly consistent. Both the humidity and the frequency spikes can be correlated to when breathing took place with more intensity (exhaled breathing, especially in sleep). The DHT22 is used to verify that humidity is currently causing the largest frequency shift. For breath duration, condensation from water vapor affects the device and evaporates then this repeats with each breath. During the breathing cycles the exhales are not long enough for the temperature to change significantly or to affect the device. The current change in temperature and the resultant small change in baseline frequency is caused by existing room temperature changing over the cause of the tests. Using the change in the SAW device, a breathing frequency can be calculated specifically for the user (patient) and changes or breathing completely stopping can be highlighted. For the latter case, sudden stop of breathing, the system could send a message alarm to a stored contact or carer, or even emergency services.

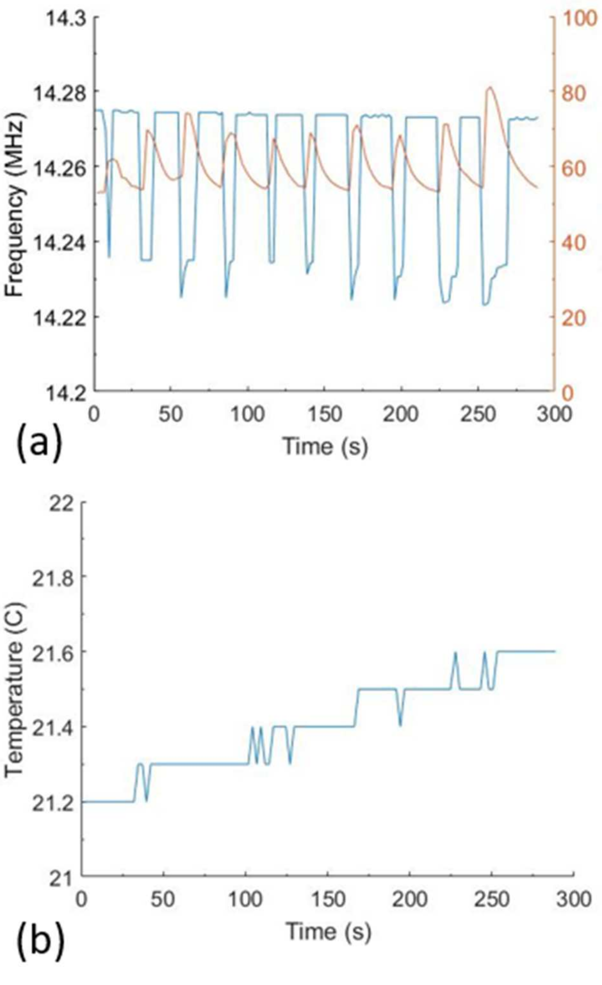

Figure 5 (a) breath tracking and humidity sensor (b) temperature over time during breath tracking

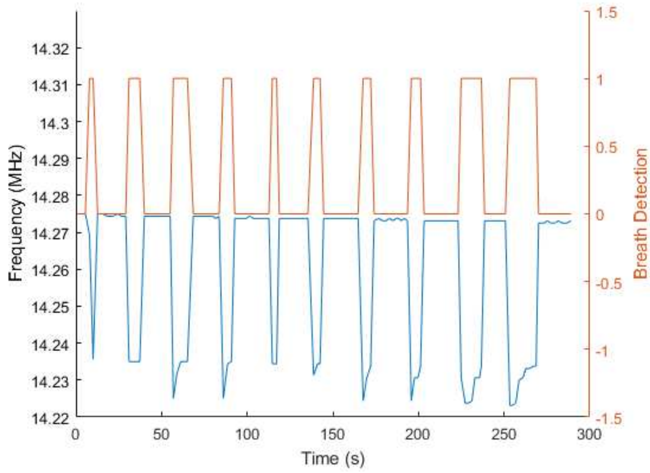

Figure 6 Frequency shift of device converted to digital signal

IV. Conclusions

In this paper we describe Apnoea-Pi, an ultrasonic open-source system for sleep disorder monitoring and identification. The platform is suitable for all SAW gadgets, including thin film SAW fabricated in 50µm Al foils. We show all the steps that the system needs to achieve for breath tracking. The system is suitable for different variations in size and frequency of SAW devices including the potential for flexible substrates. Using the open-source electronics in combination with design thinking practices, further functionalities can be achieved.. The system gives embedded computing characteristics for signal processing, data storage, and transmission.. For more advanced data processing and pattern recognition, machine learning algorithms could be implemented such as TensorFlow open-source library. This would give the product the possibility to learn and match the time-domain signals of both healthy and apnoea patients, detect breathing abnormalities, diagnose apnoea type and monitoring apnoea progress under treatment.

References

[1] T. Young, M. Palta, J. Dempsey, J. Skatrud, S. Weber, and S. Badr, "The Occurrence of Sleep-Disordered Breathing among Middle-Aged Adults," *N. Engl. J. Med.*, vol. 328, no. 17, pp. 1230–1235, Apr. 1993.

[2] P. J. Strollo and R. M. Rogers, "Obstructive Sleep Apnea," *N. Engl. J. Med.*, vol. 334, no. 2, pp. 99–104, Jan. 1996.

[3] D. J. Eckert, A. S. Jordan, P. Merchia, and A. Malhotra, "Central sleep apnea: Pathophysiology and treatment,"

Chest, vol. 131, no. 2, pp. 595–607, 2007.
[4] H. Jin *et al.*, "Flexible surface acoustic wave respiration sensor for monitoring obstructive sleep apnea syndrome," *J. Micromechanics Microengineering*, vol. 27, no. 11, p. 115006, Oct. 2017.
[5] Y. Q. Fu *et al.*, "Recent developments on ZnO films for acoustic wave based bio-sensing and microfluidic applications: a review," *Sensors Actuators, B Chem.*, vol. 143, no. 2, pp. 606–619, 2010.
[6] Y. Q. Fu *et al.*, "Advances in piezoelectric thin films for acoustic biosensors, acoustofluidics and lab-on-chip applications," *Prog. Mater. Sci.*, vol. 89, pp. 31–91, 2017.
[7] X. Tao *et al.*, "Three-Dimensional Tetrapodal ZnO Microstructured Network Based Flexible Surface Acoustic Wave Device for Ultraviolet and Respiration Monitoring Applications," *ACS Appl. Nano Mater.*, vol. 3, no. 2, pp. 1468–1478, 2020.
[8] R. Tao *et al.*, "Flexible and Integrated Sensing Platform of Acoustic Waves and Metamaterials based on Polyimide-Coated Woven Carbon Fibers," *ACS sensors*, vol. 5, no. 8, pp. 2563–2569, 2020.
[9] J. Zhang *et al.*, "Surface acoustic waves enable rotational manipulation of Caenorhabditis elegans," *Lab Chip*, vol. 19, no. 6, pp. 984–992, Mar. 2019.
[10] K. Wang *et al.*, "Sorting of tumour cells in a microfluidic device by multi-stage surface acoustic waves," *Sensors Actuators, B Chem.*, vol. 258, pp. 1174–1183, Apr. 2018.
[11] M. Rotter, A. V. Kalameitsev, A. O. Govorov, W. Ruile, and A. Wixforth, "Charge conveyance and nonlinear acoustoelectric phenomena for intense surface acoustic waves on a semiconductor quantum well," *Phys. Rev. Lett.*, vol. 82, no. 10, pp. 2171–2174, 1999.
[12] A. Marzo, T. Corkett, and B. W. Drinkwater, "Ultraino: An Open Phased-Array System for Narrowband Airborne Ultrasound Transmission," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 65, no. 1, pp. 102–111, Jan. 2018.
[13] H. Bachman *et al.*, "Open source acoustofluidics," *Lab Chip*, vol. 19, no. 14, pp. 2404–2414, 2019.
[14] A. Huang *et al.*, "Practical microcircuits for handheld acoustofluidics," *Lab Chip*, pp. 1352–1363, 2021.
[15] J. Matouš, A. Kollarčik, M. Gurtner, T. Michálek, and Z. Hurák, "Optimization-based feedback manipulation through an array of ultrasonic transducers," in *IFAC-PapersOnLine*, 2019, vol. 52, no. 15, pp. 483–488.
[16] J. M. Pearce, *Open-Source Lab: How to Build Your Own Hardware and Reduce Research Costs*. 2013.
[17] J. Vernon *et al.*, "Acousto-Pi: An Opto-Acoustofluidic System using Surface Acoustic Waves controlled with Open Source Electronics for Integrated In-Field Diagnostics," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, pp. 1–1, 2021.
[18] "MIPI Overview." [Online]. Available: https://www.mipi.org/about-us. [Accessed: 06-Sep-2019].
[19] Www.kivy.org, "Kivy Documentation," 2012. [Online]. Available: https://kivy.org/doc/stable/.
[20] H. Dong, D. Li, J. Pang, Q. Zhang, and J. Xie, "Highly Sensitive and Fast-Response Humidity Sensor Based on Saw Resonator and MoS for Human Activity Detection," *Proc. IEEE Int. Conf. Micro Electro Mech. Syst.*, vol. 2021-January, pp. 322–325, Jan. 2021.
[21] R. Tao *et al.*, "Hierarchical nanotexturing enables acoustofluidics on slippery yet sticky, flexible surfaces," *Nano Lett.*, vol. 20, no. 5, pp. 3263–3270, May 2020.
[22] Y. Wang *et al.*, "Flexible/Bendable Acoustofluidics Based on Thin-Film Surface Acoustic Waves on Thin Aluminum Sheets," *ACS Appl. Mater. Interfaces*, p. acsami.0c22576, Apr. 2021.