International Journal of Electrical and Computer Engineering (IJECE)
Vol. 14, No. 5, October 2024, pp. 4987~4995
ISSN: 2088-8708, DOI: 10.11591/ijece.v14i5.pp4987-4995

Integrating hetero-core fiber optics sensor in intelligent technological textiles

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Article Info

Article history:

Received Apr 30, 2024
Revised Jul 5, 2024
Accepted Jul 9, 2024

Keywords:

DOIT ESP32 DevKit
Elastic textile
Macro-bending
Respiration detection
Smart textile

ABSTRACT

In the context of the emerging Industry 4.0 paradigm, smart fabric sensors have been representing a novel addition to the textile industry. The proposed sensors utilize macro-bending techniques with varying fiber optic core sizes. The study involved the construction and testing of macro-bending sensors using single-mode (9 μm) and hetero-core (50–9–50 μm) fibers, configured into seven sinusoidal loops. The experiment was further extended to different types of elastic textiles. Spandex demonstrated superior linearity compared with jersey and rubber bands. The integration with the DOIT ESP32 DevKit facilitated real-time monitoring of respiratory rates. The results from the experiment indicated that the macro-bending sensor, fabricated using hetero-core optical fiber, exhibited superior sensitivity in comparison to the sensor assembled from single-mode optical fiber, with respective sensitivity values of 1.72 and 1.30 dB/cm. The designed sensors displayed closely aligned behavior during forward and reverse loading, indicating the reversibility of the fiber optic sensor. Given its simplistic design and low fabrication cost, the proposed sensor holds significant potential for practical applications.

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1. INTRODUCTION

Fiber optic sensors (FOS) can be categorized into four distinct groups based on their operational principles: intensity modulation (including micro bending, transmission-based, reflection-based, and macro-bending FOS), phase modulation (comprising Mach–Zehnder interferometers, Michelson interferometers, Fabry–Perot interferometers, and Sagnac interferometers), wavelength modulation (incorporating Bragg gratings, fluorescent-based sensors, and blackbody sensors), and polarization modulation. The research community has been focusing on the development of cost-effective and easy-to-fabricate sensors. Among them, macro-bending sensors have emerged as viable alternatives with applications in various domains such as displacement, pressure, temperature, and liquid detection [1], [2]. Displacement sensors, in particular, hold promise for healthcare monitoring and structural health monitoring [3], [4]. Conventional methods for movement detection have also been extensively researched [5].

Recent years have witnessed a substantial increase in the enthusiasm for incorporating sensors into fabrics [6]. Shen *et al.* [7] have successfully created wearable macro-bending optical sensors that can detect small body vibrations resulting from heartbeat and breathing. These sensors can capture and document cardiac and respiratory activities, thus providing an all-encompassing health monitoring solution. Considerable progress has also been achieved in incorporating FOS into textiles, as propelled by a multitude of researchers [8]–[11].

The use of FOS is warranted due to its attributes, including prompt reactivity, heightened sensitivity, and inertness to chemical and biological substances. In addition, FOS do not produce thermal energy and are resistant to electrical discharge, unlike electrical devices [12], thus making them particularly suitable for incorporation into textiles, where paramount significance is placed on comfort and safety. FOS use silica optical fibers. Although these fibers exhibit reduced optical loss, they possess a fragile characteristic with limited tolerance to impact and strain. This attribute should be taken into account while designing and implementing FOS in wearable technologies. The intrinsic characteristics of FOS, such as their resilience to electromagnetic interference and their capacity to operate in challenging settings, make them well-suited for use in wearable electronics. Moreover, the compact dimensions and adaptability of FOS facilitate their incorporation into fabrics without sacrificing the comfort or visual appeal of garments [13].

In 2009, researchers in Japan began producing a respiratory detection system using optical fibers attached to elastic textiles [14]. This study garnered the attention of researchers due to its importance to human health. Since then, several studies on smart textiles have been conducted. To date, the smart textiles studied by researchers use Bragg grating structures, micro-bending, and macro-bending FOS [15]. Smart textiles using optical fibers structured with Bragg gratings [16]–[19] have also been developed but their operating process is complex and involves high costs [20]. Therefore, smarter and more effective textiles are designed based on macro-bending and micro-bending structures [3]. In 2012, Witt *et al.* [21] successfully conducted a study using single-mode structure and structures with more than 7 bends. Subsequently, Alemdar *et al.* [22] developed sensors that are structured with macro-bending and hetero-core structures to improve their sensitivity performance. The operation of hetero-core optical fiber sensors (62.5-50-62.5 μm) typically involves an evanescent field mechanism to enhance sensor sensitivity. Other studies show that sensitivity increases due to the number of bends (as much as seven) and the influence of bending radius. In 2018, Dhia *et al.* [23] and Purnamaningsih *et al.* [24] developed sensors using single-mode optical fiber with a wavelength of 1550 nm. These studies were successfully conducted with as many as seven bends without using a hetero-core structure. Based on these studies, macro-bending structured optical fiber sensors have been used by researchers to detect respiratory system movement. However, having a large number of bends may affect the wearability of sensors and increases the risk of breaking the optical fiber.

Researchers have also explored the integration of macro-bending structures with hetero-core fiber optics to create reliable sensors with superior performance. These sensors can be integrated with elastic textiles to create wearable devices for respiratory monitoring. However, the integration of FOS with different elastic textiles requires further investigation and the effects of using various elastic textiles with FOS have not been thoroughly investigated. This research gap must be addressed to understand the capabilities and limitations of integrated sensing systems. The present study thus combines macro-bending and hetero-core fiber optics to evaluate the performance of the constructed FOS. Another novelty of this study lies in its integration of FOS with an ESP32 microcontroller for the real-time and accurate monitoring of respiratory rates (RR).

2. FUNDAMENTAL THEORY

The operation of the proposed FOS is fundamentally governed by the principle of light propagation along the fiber optic and the impact of the evanescent field which results from the combination of single-mode and multimode fiber optics. Theory of macro-bending is closely related to mode theory. As light travels along the fiber, guided modes couple with radiation modes when bending occurs [25]. Higher-order modes, being less tightly bound to the fiber core, radiate out of the fiber before lower-order modes. Consequently, a curved fiber supports fewer total modes than a straight fiber.

Macro-bending losses are observed when an optical fiber is bent to a radius of several centimeters [26]. Significant bending loss is incurred when the bend radius falls below the critical bending radius [27]. Losses attributed to the evanescent field are observed when a hetero-core structure is incorporated into the sensor. The evanescent field is generated when light traverses the interface between the core and the cladding medium, and penetrates into the cladding medium (where the core medium possesses a higher refractive index than the cladding medium). This condition creates of an electromagnetic field that decays exponentially [28].

The evanescent field can also be observed when two fiber optics, possessing different core sizes but similar cladding sizes, are connected. In this configuration, the light traversing the transmission line partially expands into the cladding region of the hetero-core segment. As the transmission line terminates, light seeps into the cladding layer, which forms part of the hetero-core splicing interfaces. The excitation of cladding modes in the hetero-core segment is triggered by the light leakage at the spliced interfaces. Changes in the environment at the outer cladding boundary can affect the leakage wave in the cladding layer influenced by surrounding physical and mechanical properties. These waves can be re-coupled into the core of the downstream transmission line. The combination of macro-bending and hetero-core fiber optics enhances the sensitivity of sensors [29].

3. SENSOR DESIGN

The proposed FOS, which can be embedded in textiles and feature a macro-bending structure, are depicted in Figure 1. The sensor region comprises an elastic fabric with an optical fiber embedded via knitting in a sinusoidal-shaped configuration. The structure of FOS, which incorporates a macro-bending structure, consists of a rail system designed to adjust displacement. This setup is arranged such that one plate on the rail system remains stationary, while the other is movable. The system employs a 4–6 V stepper motor integrated board (2-phase 4-wire speed adjustable) and a Globedealwin linear guide actuator with a 200 mm range computer numerical control slide for adjusting the displacement of the impression. Experimental measurements were conducted by shifting the movable plate on the rail system from 0–4 cm displacement (forward direction) and recording the output light intensity at each interval. This particular range of strain corresponds to the magnitude of chest expansion observed during human respiration [30]. Data were also collected in the reverse direction by reducing the displacement and measuring the output light intensity at each interval. The movement was operated in automatic mode. A light source with 1 mW power at a wavelength of 1,550 nm was utilized at one end of the fiber optic, with the other end connected to a power meter. The experiment continued using parameters optimized via the Taguchi method at bending dimensions of 2.5×1.5 cm [31].

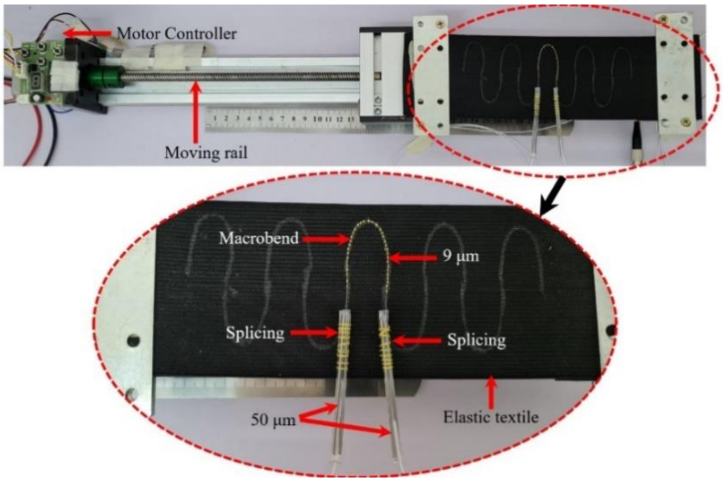


Figure 1. Experimental setup of fiber optic sensor for displacement detection

The fusion splicer of Sumitomo Electric Group was employed to join two optical fibers. The single-mode fiber had a core diameter of 9 μm, the multimode fiber had a core diameter of 50 μm and both types of fibers have a cladding diameter of 125 μm. Table 1 presents the comprehensive specifications of the optical structure's parameters.

Figure 2 presents a concise module of the displacement sensor, which shows that changes in displacement alter the bending size of the optical fiber. The experiments were conducted using optical fibers comprising an exterior that functioned as sensor transmission lines, constructed using 50/125 μm-mode fibers, and an interior with macro-bending sections, constructed using 9/125 μm mode fibers. The initial interval is denoted by x0. If a displacement of Δx is applied to one end of the elastic textile-linked metal handle, then the curvature of the sinusoidal-shaped optical fiber will increase. In this mechanism, the curvature of the Δr optical fiber can be adjusted by selecting the appropriate initial x0 interval and the amount of displacement Δx. The strain displacement examined in this study ranged from 0–4 cm.

These optical fiber sensors operate based on the change in light loss due to the integration of optical fiber bending into the elastic textile. This integration was achieved by sewing optical fibers onto the surface of the elastic textile in a sinusoidal form. When the sensor was subjected to power, the optical fiber sensor experienced a change in light loss from the lateral and tangential directions. In these sensors, the sinusoidal fiber optic altered the duration of the bent fibers when force is applied. This variation in curvature translates into an amplitude change for optical fibers. Therefore, the study of displacement commenced by using a single-mode optical fiber sensor with different elastic textiles. Comparisons were then made between 9 μm and 50-9-50 μm sensors. After examining of the mechanical properties of various elastic textiles and their impact on sensor accuracy, the integration of FOS with an ESP32 microcontroller was studied for the real-time and accurate monitoring of respiratory rates.

Table 1. Parameters of fiber optic sensor with macro-bending structure

	Type of experiment	Elastic textiles	Core size (µm)
1	Impact of textile utilization on strain detection	Spandex Jersey Elastic Band	9
2	Intensity output	Spandex	9 50-9-50
3	Usability of web application	Spandex	9 50-9-50

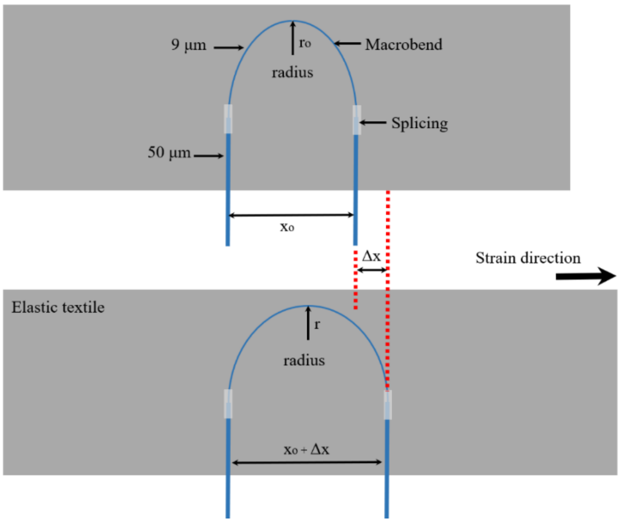


Figure 2. Detection optical fiber sensor structure and displacement sensor module

Figure 3 delineates the architecture of the FOS system designed for RR detection, which is a structured process comprising four stages. The initial stage, called data acquisition, commenced with the transmission of a laser with a wavelength of 1,550 nm into a hetero-core fiber optic. This laser was processed by a photodiode and an operational amplifier, before being read by the DOIT ESP32 DevKit. This DevKit converted the analog signal into a digital format, to facilitate real-time processing and enable the concurrent execution of data collection and transmission. The second stage, called data processing, involved the server receiving the raw data from the ESP32, followed by its validation and caching. Upon the receipt of a request, the server employed the fast Fourier transform method to transform the data, eliminate noise, and subsequently retransform the data into filtered data. The third stage, called data analysis, involved the server scrutinizing the data from the preceding 30 seconds by enumerating the number of peaks and ascertaining the RR status. The final stage, called output, involved the presentation of the readings and bpm status on a web application that is accessible via any device equipped with an internet browser and an internet connection.

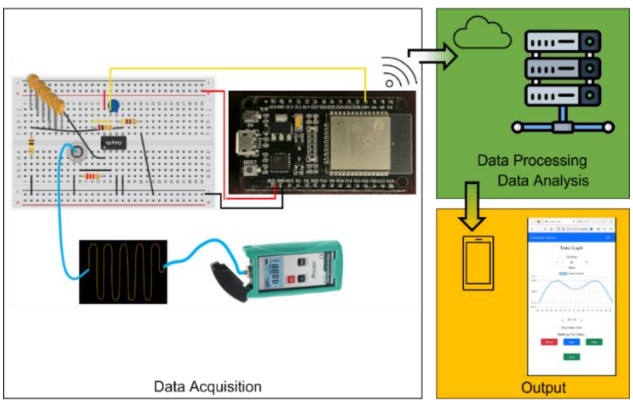
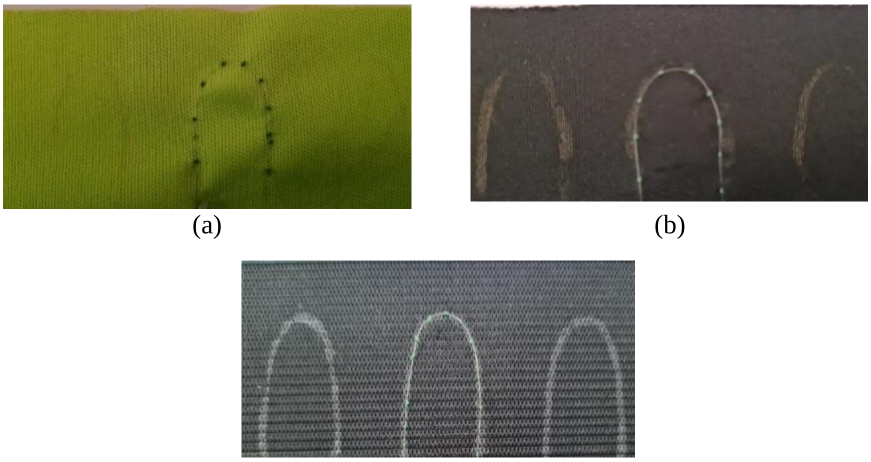


Figure 3. Architecture of fiber optic sensor system in detecting respiratory rate

4. RESULTS AND DISCUSSION

4.1. Impact of textile utilization on strain detection

Textiles with elastic properties conform to Hooke's Law. This investigation began by utilizing three distinct types of elastic textiles to observe the resulting output pattern. The optical fiber employed in this segment had a core dimension of 9 µm. The experiment maintained the optimized parameters determined via the Taguchi method at bending dimensions of 2.5×1.5 cm. The findings identify the optimal type of textiles for further study by using a hetero-core optical fiber. Figure 4(a)-(c) illustrates the schematic of the optical fibers stitched onto different elastic textiles including Malaysia grade A jersey/interlock fabric, spandex 95% polyester, and a 4' elastic rubber band with dimensions of 14×8 cm. Sinusoidal shapes were drawn on these textiles to aid the stitching of the optical fibers.



(a) (b) (c)

Figure 4. Optical fibers are sewn on the elastic textiles surface using (a) jersey (b) spandex and (c) rubber bands

Figure 5 illustrates the correlation between optical power loss and strain distance across all types of elastic textiles. Each of the six lines represents the average reading for the respective textile utilized. The optical power exhibited an almost linear increase in response to changes in displacement. Despite the absence of a perfect straight line in Figure 6, the observed properties aligned with the expected pattern of optical loss. Spandex demonstrated superior linearity compared with jersey and rubber bands. Although the use of rubber band textiles resulted in higher loss, they also produced significant hysteresis. This difference in hysteresis is primarily attributed to the integration of optical fibers and elastic textiles, which is a consequence of the elastic properties of the textile. This phenomenon is distinctly observable on the F and R lines for each type of elastic textile.

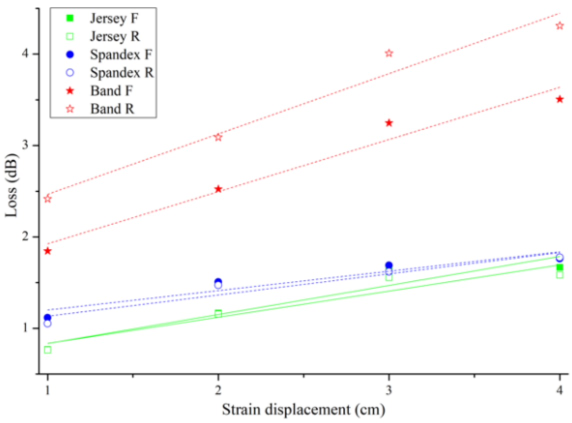


Figure 5. Relationship of optical power loss to the displacement of the elastic textiles used

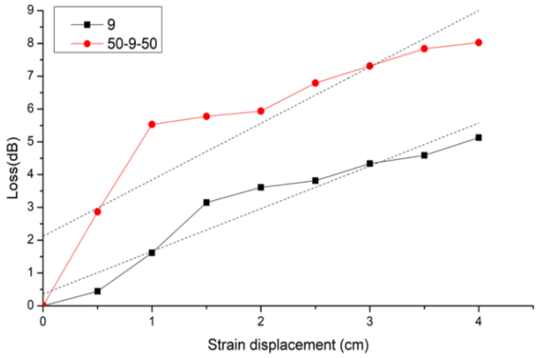


Figure 6. Loss variation with the distance function for 9 µm and 50-9-50 µm

4.2. Intensity output

The investigation focused on the application of elastic textiles exhibiting minimal hysteresis. Optical fiber sensors of two distinct types, namely single-mode (9 µm) and hetero-core (50-9-50 µm) sensors, were integrated into spandex-type elastic textiles. The performance of these sensors was evaluated by examining their output in response to varying power levels ranging from 0–4 cm. Figure 3 presents the operational mechanism and schematic representation of the study while Figure 6 presents a comparative analysis of optical loss as a function of displacement between 0 and 4 cm for the two categories of FOS. Figure 6 highlight the superiority of the hetero-core-based macro-optical fiber sensors over their counterparts.

The gradient values derived from each combination type were considered in assessing the resultant sensitivity. Sensitivity is characterized as linear propensity, with the Pearson value (R) parameter functioning as a linear function. Table 2 presents the outcomes of data interpretation, inclusive of the sensitivity and R values using the Origin software. The sensitivities of the single-mode and hetero-core optical fiber structures were 1.30 dB/cm and 1.72 dB/cm, respectively. Thus, macro-bending structures incorporating hetero-core optical fibers exhibit enhanced sensitivity compared with single-mode fibers.

As elucidated in the Fundamental Theory section, hetero-core FOS were designed to exhibit greater sensitivity compared with single-mode optical fiber sensors. The outcomes derived from the study involving hetero-core FOS can be ascribed to the phenomena associated with the designed FOS. The core optical fiber sensor demonstrates superior sensitivity relative to the single-mode fiber sensors, a characteristic attributable to the mode coupling in the connection area. The propagation of light within optical fibers is confined to discrete modes, and is determined by the wavelength sources, physical properties of the optical fiber, and refractive indices. Owing to the significant difference in core diameter, light can predominantly leak into the cladding post mode connection. The majority of the light waves are integrated into the cladding mode in a single-mode area, a process heavily dependent on the geometric shape of the hetero-core fiber optics components. Following deceleration in the single-mode section, the light wave traverses the single-mode fiber interface and enters the second multimode. At this interface, the propagation mode energy is reintegrated from the cladding and core modes in a single-mode optical fiber. The mode structure transporting light energy to the output terminal is contingent on the alteration in the shape of the optical fiber.

Table 2. Analytical data for optical fiber combinations with core sizes 9 and 50-9-50 µm using origin

Combination of Fiber optics (µm)	Slope (dB/cm)	Intercept (dB)	Standard Error	Pearson value, R
9	1.30	0.36	0.135	0.96
50-9-50	1.72	2.12	0.305	0.90

4.3. Usability of web application

Figures 7(a) to (c) present the web application interface at different RR ranges for spandex. Each peak represents a complete breathing cycle where the lower point indicates that the subject has completed the exhale process and began to exhale right afterward while the highest point in the graph indicates that the subject has completed the inhale process before the exhale process repeats its next cycle. The line graph in each of these figures were plotted near real-time. Thus, the plot can represent the actual breathing cycle if the right combination of textile and fiber optics sensor is deployed. The graphs were plotted within a 30-second plotting window and the RR value represents the number of completed breathing cycles within one minute. Figures 7(a) and 7(c) depict slow RR and fast RR, respectively with a warning message displayed at the lower part of the interface. Figure 7(b) shows the normal RR without any warning message. The results displayed in the interface match the actual RR counted manually by eye observation of the subject's abdominal movement. Similar testing was conducted for two other elastic textiles namely jersey and elastic band. These fabrics were also combined with the exact same type of FOS that is weaved with the same geometry during the testing. However, these products fail to display accurate RR values when compared with the actual abdominal movement. Jersey tends to display a smaller number of RR, while elastic band displays a higher number of RR when compared with the actual abdominal movement. Therefore, spandex is by far the textile that can accurately represent the RR of human subjects.

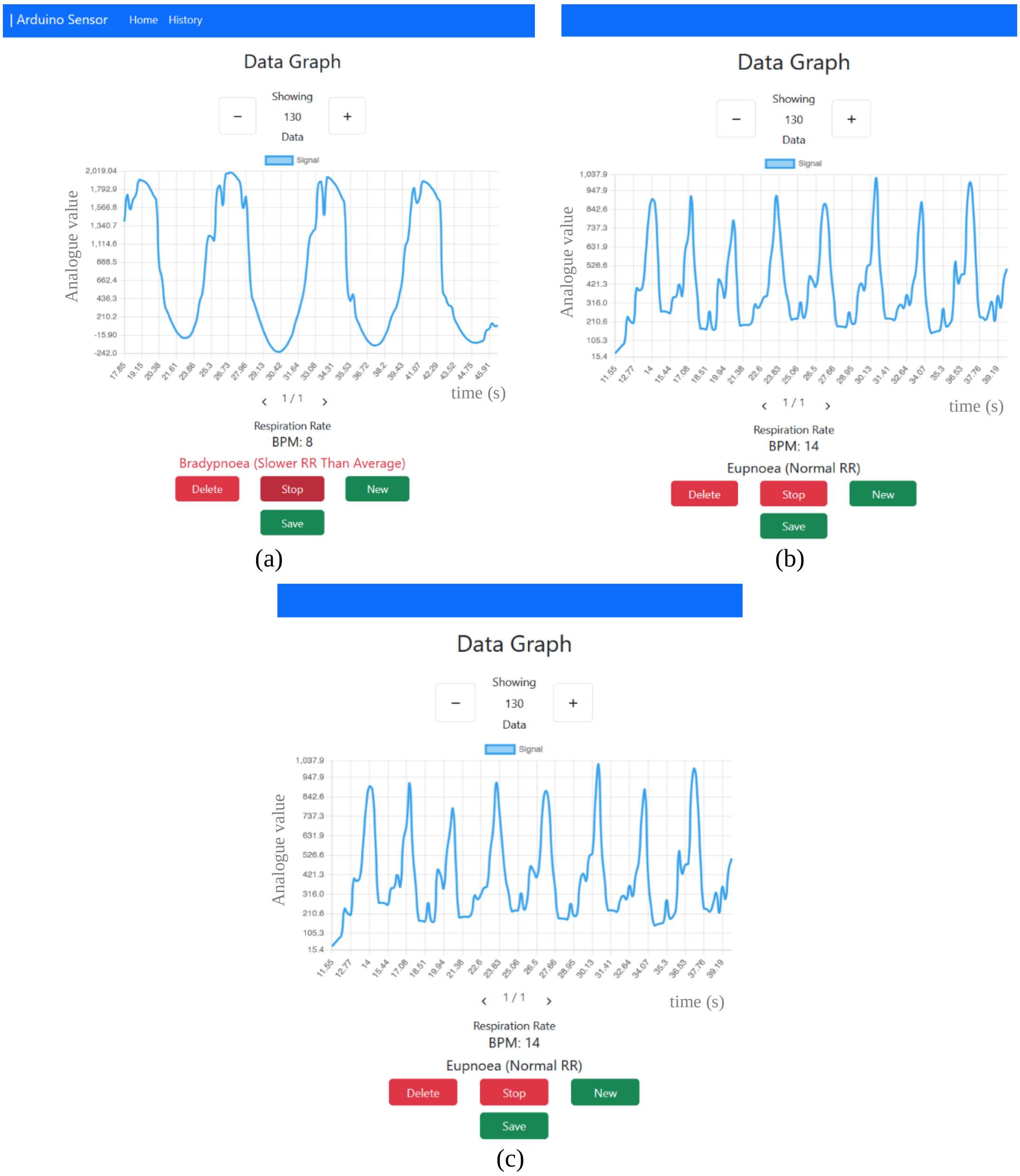


Figure 7. Interface of the web application when RR is (a) below 12 (b) within 12 and 20 and (c) beyond 20

5. CONCLUSION

The proposed strain sensors, which incorporate a hetero-core macro-bending structure within an elastic fabric, were evaluated on various elastic textiles. Spandex demonstrated superior linearity compared with jersey and rubber bands. A series of experiments was conducted on macro-bending sensors utilizing single-mode and hetero-core fibers. The hetero-core FOS demonstrated superior sensitivity relative to the single-mode FOS. Preliminary data suggest that the proposed hetero-core FOS is a promising candidate for application in personal healthcare monitoring, potentially advancing the current research in this domain. The integration of FOS into smart textiles also facilitates a precise, non-invasive, and real-time monitoring of vital signs. Currently, this system is tailored for adults for monitoring their respiration rates, with the potential for future programmatic adaptations to cater to the elderly and children. This pioneering approach promises to improve user well-being by providing an accurate and non-intrusive monitoring of vital signs in real-time.

ACKNOWLEDGEMENTS

The authors express their gratitude to the Nanophotonics Laboratory at the Institute of Microengineering and Nanoelectronics, Universiti Kebangsaan Malaysia, and the Physics Laboratory at the Centre for Pre-University Studies, Universiti Malaysia Sarawak for providing the necessary facilities. This research was funded by the Ministry of Higher Education Malaysia, Universiti Malaysia Sarawak and the Research, Innovation and Enterprise Centre, Universiti Malaysia Sarawak.

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BIOGRAPHIES OF AUTHORS

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