PHOTODIODE AND LED EMBEDDED TEXTILES FOR WEARABLE HEALTHCARE APPLICATIONS

Achala Satharasinghe[1], **Theodore Hughes-Riley**[1] **and Tilak Dias**[1]
[1] *Advanced Textiles Research Group, School of Art and Design, Nottingham Trent University, UK*
Achala.satharasinghe2016@my.ntu.ac.uk

ABSTRACT

This work presents a novel approach to embed miniature photodiodes (PDs) within the core of a textile yarn for wearable applications such as heart rate monitoring. These PD embedded E-yarns (PDEY) can be readily woven, knitted or embroidered into a comfortable, conformal, aesthetically pleasing, and washable fabric; this would overcome the challenges that many other electronic textiles currently face. The PDEYs exhibited an optoelectronic output comparative to free-standing PDs. PDEYs along with LED embedded yarns (LEDEY) were integrated into a knitted finger cuff to demonstrate a wearable PPG (photoplethysmography) heart rate monitoring device.

Key Words: electronic textiles, wearable sensors, photodiodes, photoplethysmography, heart rate

1. INTRODUCTION

Integration of electronics into textiles has opened-up numerous possibilities for wearable and mobile devices in the healthcare, entertainment and fashion industries. Despite the immense potential of electronic textiles (E-textiles), consumer acceptance has been slow, mainly owing to lack of normalcy (heavy, bulky, not soft and smooth, visibility of devices) and poor durability [1]–[3].

This work presents a novel approach to embed miniature photodiodes (PDs) within the core of a textile yarn for wearable applications such as heart rate (HR) monitoring. PDs generate an electric current and change in voltage, corresponding to the nature of light falling onto them, hence they are extensively used for optical sensing in various fields. Integration of photodiodes within textiles as an optical sensor will enable the non-obtrusive monitoring of body vital signs (e.g. heart rate, blood oxygen saturation, skin temperature) [4], [5] or environmental conditions (e.g. temperature, humidity, UV radiation level) [6].

To create the PD embedded yarns the Electronic yarn (E-yarn) technology [7] was employed. The technology has been previously demonstrated in developing textile devices for illumination [8], temperature sensing [9], vibration sensing and acoustic sensing [10] applications. PDs are first soldered onto fine copper wires, before being encapsulated within optically-clear resin micro-pods. The micro-pod-copper filament is then covered with a knit-braid to realize the complete yarn. The fine copper wires provide the electrical interconnection between the PD and the external circuitry, while the resin micro-pod protects the device and the solider joints from external mechanical stresses, as well as chemicals and liquids during use and washing. The knitted braid imparts the textile behaviour (soft, drapable, breathable, and moisture absorbent), and appearance as well as protects the interconnects form mechanical stresses during subsequent processing and use. Due to the integration of the PDs within the core of a yarn, it can be readily woven or knitted into a comfortable, conformal, aesthetically pleasing, and washable fabric; this overcomes the challenges that many other E-textiles currently face.

Previous study with PD embedded yarns (PDEYs) confirmed that PDEYs exhibited optoelectronic output comparative to non-encapsulated PDs [11]: The output was further enhanced by impregnating the surface fibres of the yarns with a clear resin. The PD yarns in woven fabric maintained above 90% of their original functionality after 15 machine wash and 25 hand wash cycles, confirming their washability, which would be crucial for a wearable product.

The PDEY along with an LED embedded yarn (LEDEY) were integrated into a knitted finger-cuff to demonstrate a wearable HR monitoring device. The device uses the photoplethysmograpy (PPG) technique where the change in the volume of arterial blood in the finger is estimated by measuring the intensity of the specific wavelength of light transmitted (Fig. 1a) or reflected (Fig. 1b) by the body tissue on that location [12]. The frequency of the measured pulsating signal (Fig. 1c) of the optical sensor (PD) corresponds to the HR of the subject. The most commonly utilized wavelengths are in the near-infrared region of the light spectrum. In this research a yarn embedded with an infrared (IR) LED for the light source, and a PDEY embedded with an IR PD as the sensing device were used. Using these E-yarns a transmission PPG device was prepared to be used on fingers.

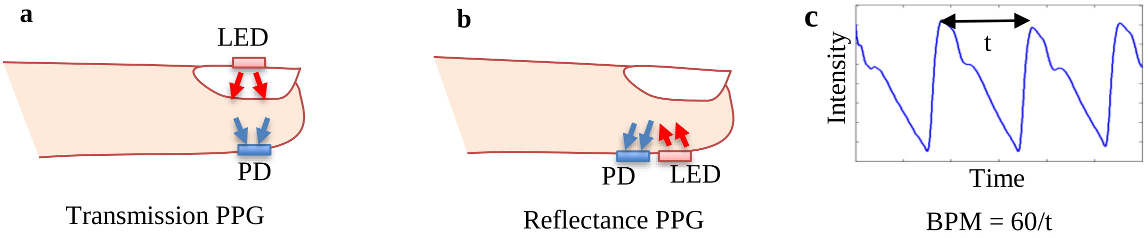

Figure 1. Basics of photoplethysmography (PPG). (a) Transmission PPG configuration. (b) Reflectance PPG configuration. (c) Output PPG signal with the pulse time period.

2. MATERIALS AND METHODS

2.1 Preparing the E-yarns

In this study, SMD (surface-mount device) type IR PDs (VEMD1160X01, Vishay Intertechnology, Inc., USA) and IR LEDs (TAN1111C, Stanley Electric, UK) were employed for the IR sensing and IR light source respectively. The devices were first soldered onto fine multi-strand copper wires (seven strand linear density = 120 mg/m, single strand diameter = 50 µm, Knight Wire, UK), using IR reflow spot soldering device (PDR IR-E3 Rework System, PDR- Design & Manufacturing Centre, UK). A Pb-free solder paste (SolderPlus® S965D500A6, Nordson EFD, UK) was employed for soldering. The length of copper wire between the solder pads of the device was removed after soldering using a scalpel.

The soldered device was then encapsulated inside a 1.5mm diameter clear resin micro-pod, using an ultraviolet (UV) curable resin (Dymax, 9001E-V3.5, Dymax Corporation, USA) and a silicone tube with a 1.5 mm inner diameter. The soldered device was positioned inside the silicone tube at extreme lower position along with a Vectran™ yarn (100 denier, Vectran™, Kuraray America Inc., USA). Then the silicone tube was injected with resin, before being exposed to a UV lamp (BlueWave™ 50, Dymax Corporation, USA). The cured micro-pod was forced out from the silicone tube by applying a tensile force on the Vectran™ yarn. The micro-pod strand was fed to a small diameter circular warp knitting machine (RIUS MC-Knit braiders with 2.0 mm inner diameter hollow cylinder and six needles; RIUS, Spain) where it was covered by two sets of textile fibres. First set of four texturized polyester yarns (48f/167 dtex) were directly delivered through the core of the hollow cylinder of the knitting machine without making loops. The second set of six texturized polyester yarns (48f/167 dtex) were fed to the six needles of the knitting machine making the tubular warp knitted structure, which consolidated the E-yarn. Finally, the photo-active sides of the E-yarns were impregnated with the resin used for making the micro-pods, by dispensing small amount (~10 µl) of resin to the surface of the knit-braid and curing using the UV lamp for 30s. This was to improve the light transmission from the LEDs and to the PDs.

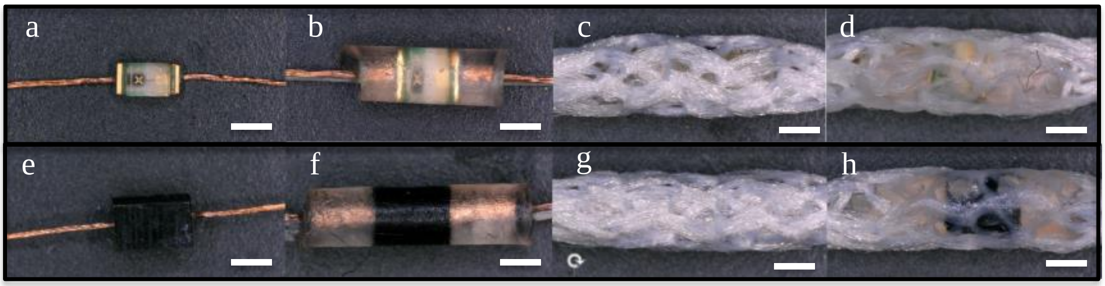

Figure 2. Microscopic images of the photodiode (PD) and LED embeded yarns at differnt stages of the fabrication process. LED after (a) soldering onto fine copper wire, (b) encapsulation inside resin micro-pod, (c) covering with fibre sheath and (d) resin impregnation. PD after (e) soldering onto fine copper wire, (f) encapsulation inside resin micro-pod, (g) covering with fibre sheath and (h) resin impregnation. Scale bar = 1 mm.

2.2 Characterization of the E-yarns

The opto-electronic performance of the PDEYs were characterized under a bespoke test rig comprised of a tungsten halogen lamp (QTH10, Thorlabs Inc., UK) as the light source (Fig. 3a). The short-circuit current of the PDEYs were measured using a high precision digital multimeter (34410A 6 ½, Agilent Technologies LDA UK Limited, UK). For characterizing the LEDEY, a test apparatus with an IR PD (VEMD6110X01, Vishay Intertechnology, Inc., USA) as the IR sensor was used (Fig. 3b). The IR LEDEYs were powered with 1.2V (~20 mA) and short circuit-current of the IR PD was measured using the high precision multimeter. Five samples were tested at each stage of the E-yarn making process for both PDYs and LEDEYs.

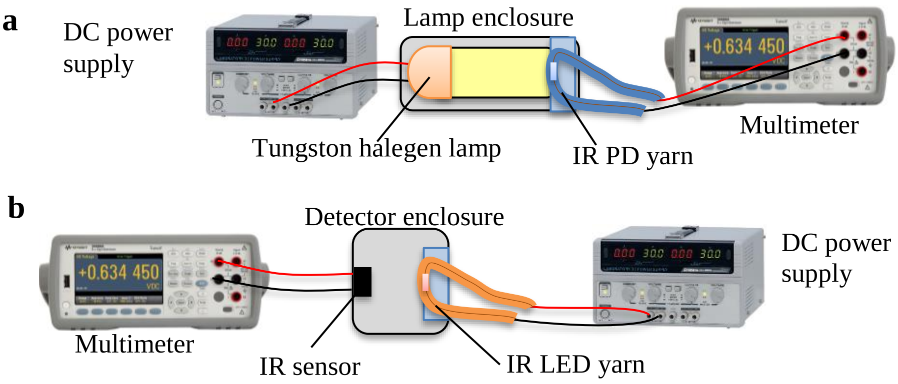

Figure 3. Apparatus for characterisation of (a) IR LED devices and yarns , (b) PD devices and yarns.

2.3 Development of the heart-rate monitoring device

For the proof-of-concept, a knitted finger-cuff was prepared with one PDEY and two IR LEDEYs attached to the inner side of the finger-cuff by hand stitching (Fig. 4a). The photoactive sides of the PDEY and LEDEYs were positioned to directly face each other ~8mm from the tip of the cuff. The two LEDEYs were connected in parallel and were powered by continuous 1.25V supply provided through the USB data acquisition (DAQ) unit (NI USB-6008, National Instruments, USA). The IR PDY was connected to a two-stage signal amplifier circuit. The amplified analog signal was acquired through the USB DAQ and directed to a computer based LabVIEW® program at a rate of 100 samples per second. The signal was simultaneously observed through a digital oscilloscope to verify the signal captured by the computer (Fig. 4b). The LabVIEW® program was employed to smoothen the received signal using a ten-point moving average method. The frequency of the smoothened signal was estimated using the LabVIEW® built-in frequency detection algorithm to realize the HR in beats per minute (BPM).

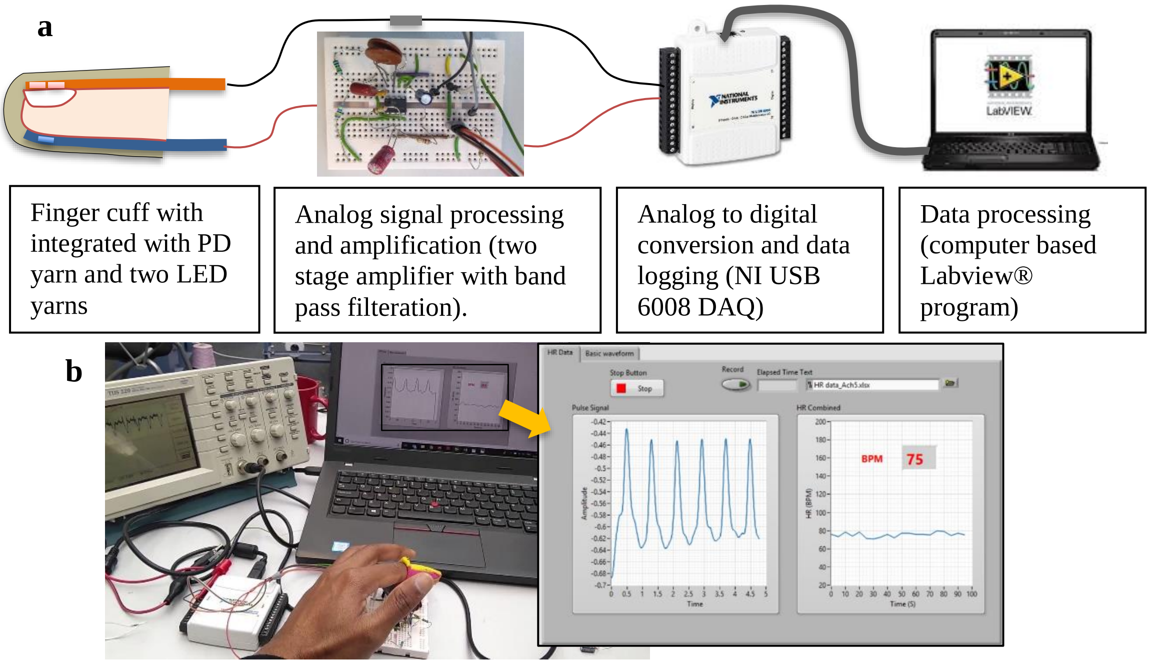

Figure 4. (a) Schematic illustration of the PD and LED yarn based heart rate detection system, for the proof-of-concept. (b) Image of the heart rate detection system and Labview® program interface during a test.

2.4 Validation of the E-yarn based heart-rate monitoring system

To validate the performance of the E-yarn based HR monitor developed, HR of five healthy subjects were recorded for 5 minutes at 5s intervals (n=60). HR was recorded in the computer simultaneously for two fingers of the same hand using the E-yarn based system developed and a commercially available finger-based HR monitor (CMS 50D+ OLED USB Finger Pulse Oximeter & Heart Rate Monitor, BLYL, China) (Fig. 5).

Figure 5. Simultaneous comparison study of finger based HR using the E-yarn based device and the commercial HR monitoring device on the same hand.

3. RESULTS AND DISCUSSION

3.1 Characterization of the E-yarns

Based on the results (Fig. 6), the combined effect of the resin micro-pod and the fibre sheath of the E-yarns had resulted an insignificant change in the performance of the device. This may be due to the balancing effect of the light enhancement by the resin micro-pod (lensing effect) and the shading effect of the fibre coverage, which was investigated in a previous study on PDEYs made with visible-spectrum PDs [11]. In comparison to the E-yarns made with visible-spectrum PDs, IR PDEY and IR LEDEYs appear to have improved performance. This may be due to the higher transmission of IR radiation through the fibre sheath in comparison of visible light. When the E-yarns were impregnated with the resin a 15% and 21% increase in measured current was observed for LEDEYs and PDEYs respectively. This increase is caused by the reduced light scattering by the fibre sheath due to the presence of resin between the fibres [13]. The results confirmed the viability of E-yarn technology to create optoelectronic devices for optical sensor applications.

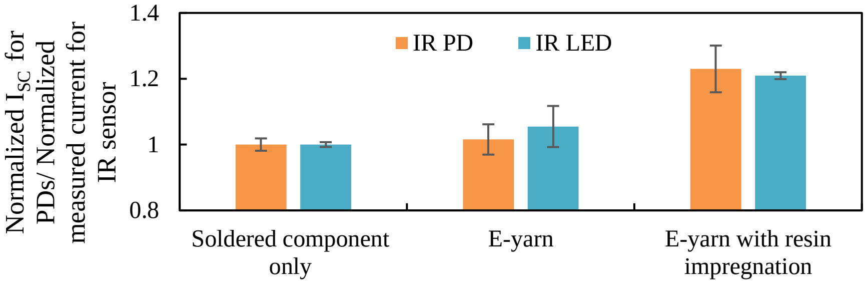

Figure 6. Normalızed Short-circuit current of the IR PD yarns and current measurements corresponding to the intensity of IR LED yarns in comparison with the soldered components. Values given are normalized to the measurements for the soldered components. Error bars show standard deviation of five measurements.

3.2 Validation of the E-yarn based heart rate monitoring system

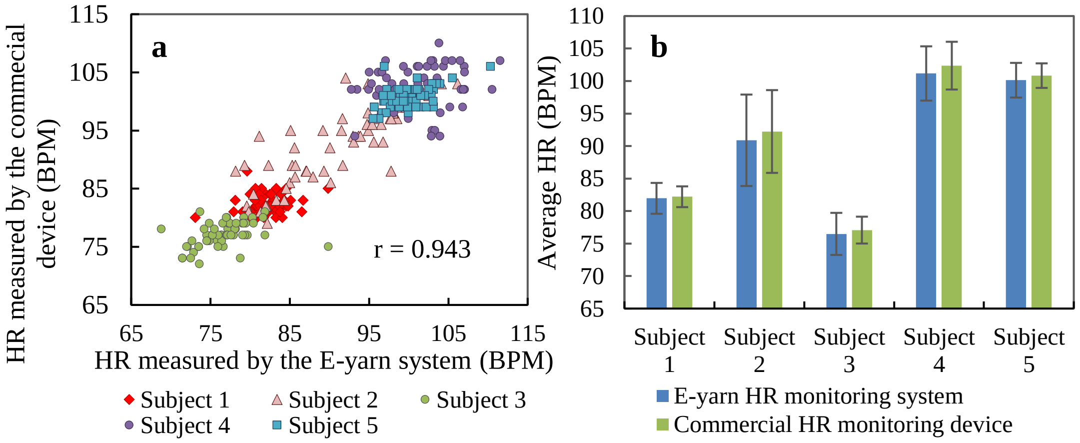

Figure 7. (a) Heart rate data for five minutes in 5s intervals collected using the E-yarn system developed and the commercial HR monitor. (b) Average and standard divation (error bars) of heart rate data within five minutes for five subjects.

The data captured by the E-yarn based HR monitoring system showed a close agreement with the commercial HR monitor. When, data from all five healthy subjects were considered (n = 300) a correlation coefficient of 0.943 was observed (Fig. 7a). No significant difference in average HR was observed by the two measurement systems for five subjects evaluated (Fig.

7b). Also, the distribution of HR data for each test subject (given by standard deviation) gathered by two systems exhibited similar values. The results confirmed that the E-yarn based PPG HR monitoring system performance was equivalent to the commercial PPG HR monitor.

4. CONCLUSIONS

This work investigates the viability of textile yarn embedded with miniature photodiodes (PDs) and light-emitting diodes (LEDs), fabricated using the university's proprietary E-yarn technology, for wearable healthcare applications such as heart rate (HR) monitoring. The infrared (IR) PD and IR-LED embedded textile yarns exhibited similar opto-electronic performance to the PDs and LEDs before processing. Proof-of-concept of textile based photopleysmography (PPG) system for measuring HR from fingers was demonstrated using the developed IR-PD and IR-LED embedded textile yarns. The HR data generated by developed textile-based system exhibited an equivalence to a commercially available PPG based HR monitoring system confirming the validity of developed the textile-based system for PPG based HR monitoring.

5. REFERENCES

[1] K. Cherenack and L. Van Pieterson, "Smart textiles: Challenges and opportunities," *J. Appl. Phys.*, vol. 112, no. 9, 2012.
[2] M. Stoppa and A. Chiolerio, "Wearable Electronics and Smart Textiles: A Critical Review," pp. 11957–11992, 2014.
[3] T. Hughes-Riley, T. Dias, and C. Cork, "A Historical Review of the Development of Electronic Textiles," *Fibers*, vol. 6, no. 2, p. 34, May 2018.
[4] C. M. Lochner, Y. Khan, A. Pierre, and A. C. Arias, "All-organic optoelectronic sensor for pulse oximetry," *Nat. Commun.*, vol. 5, p. 5745, 2014.
[5] M. Kano *et al.*, "Fabrication of Reflectance Pulse Oximeter with Ring-Shaped Photodiode," *2013 IEEE International Conference on Systems, Man, and Cybernetics*. pp. 3771–3774, 2013.
[6] I. Christopher *et al.*, "Optical proximity sensor with ambient light and temperature compensation," 2015.
[7] T. K. Dias and A. Rathnayake, "Electronically functional yarns," GB259900B, 2017.
[8] D. Hardy, A. Moneta, V. Sakalyte, L. Connolly, A. Shahidi, and T. Hughes-Riley, "Engineering a Costume for Performance Using Illuminated LED-Yarns," *Fibers*, vol. 6, no. 2, p. 35, 2018.
[9] P. Lugoda, T. Hughes-Riley, R. Morris, and T. Dias, "A Wearable Textile Thermograph," *Sensors*, vol. 18, no. 7, p. 2369, Jul. 2018.
[10] T. Hughes-Riley and T. Dias, "The development of acoustic and vibration sensing yarns for health surveillance," in *25th International Congress on Sound and Vibration (ICSV25)*, 2018, pp. 1–7.
[11] A. Satharasinghe, T. Hughes-Riley, and T. Dias, "Photodiodes embedded within electronic textiles," *Sci. Rep.*, vol. 8, no. 1, p. 16205, Dec. 2018.
[12] J. Allen, "Photoplethysmography and its application in clinical physiological measurement," *Physiol. Meas.*, vol. 28, no. 3, pp. R1–R39, Mar. 2007.
[13] W. E. Morton, J. W. S. Hearle, W. E. Morton, and J. W. S. Hearle, "Optical properties," in *Physical Properties of Textile Fibres*, Woodhead Publishing, 2008, pp. 690–708.