Improving Accuracy of Inkjet Printed Core Body WRAP Temperature Sensor Using Random Forest Regression Implemented with an Android App

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***Abstract*—Inkjet printing (IJP) technology holds tremendous promise for the development of low cost, environment friendly and body-worn biomedical sensors. In this study, we have investigated the integration of a flexible body-worn disposable IJP Wireless Resistive Analog Passive (WRAP) temperature sensor with an android app for real-time monitoring of core body temperature with high accuracy using features extracted from the sensor response. Random Forest has been used for feature selection and regression. With 5-fold cross validation we have achieved an RMSE = 0.98, R-squared value = 0.99, and mean absolute error, MAE = 0.59 for temperature estimation. The model is applicable for the development of IJP body-worn sensors for various other physiological sensing e.g. breathing, heart rate.**

I. Introduction

Inkjet printing (IJP) is becoming popular as an additive manufacturing process because of many advantages, which include the ability to write the design directly to process structures or substrates, quick processing, minimal waste disposal, low cost, and low contamination [1]. Researchers have investigated the use of inkjet printing for biomedical applications [2-3]. However, the use of inkjet printing in the development of body-worn flexible sensors for advanced physiological sensing is yet to achieve. We have previously described a body-worn Wireless Resistive Analog Passive (WRAP) sensor which is battery-less (zero-power), low-cost, and printed on paper using IJP [4]. In this paper, we have report an IJP WRAP temperature sensor for core body temperature monitoring from armpit. The sensor transfers physiological data using inductive coupling (13.6 MHz) and use a machine learning algorithm to achieve high accuracy.

II. Materials And Methods

A. *IJP WRAP Temperature Sensor and Android App*

The IJP WRAP temperature sensor consists of a IJP traces with silver epoxy connected electronic components as shown in Fig. 1. The prototype is fully-passive (zero power consumption), flexible, body-worn, disposable, and suitable for wearing for multiple days. Dimatix Material Printer 2831 (Fujifilm Dimatix Inc.) with B40 Ag ink (Novacentrix Inc.) has been used to print the sensor on a paper substrate. The length of the sensor is 13 cm which is customizable and total thickness of the prototyped sensor is less than 1 mm. The temperature sensor has a negative temperature coefficient (NTC) type transducer, a coil for wireless power transfer and a circuitry for mapping the resistance change with temperature into a transition delay from high to low output. Details of the sensor can be found in [4].

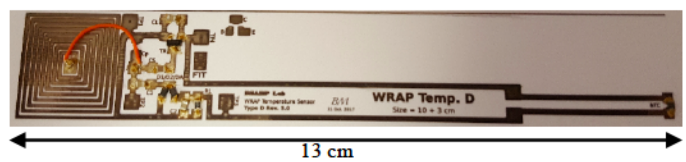

Fig. 1 Photograph of an IJP WRAP temperature sensor on paper substrate.

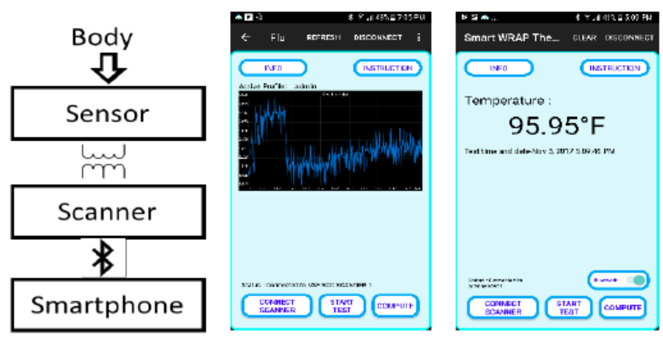

Fig. 2 Snapshots from the Android app depicting a) process for raw data collection, b) temperature sensor response, and c) computed tempirature.

As shown in Fig. 2(a), the data captured by the analog sensor is transferred to the scanner by inductive coupling. The scanner detects the signal envelope, digitizes the data (ADC sampling rate = 30 KHz), and sends the data to an Android app via Bluetooth. The smartphone app uses Android Studio 3.1.4 developed app that plays allows user interaction, data collection, data processing and visualization. It also has a SQLite database for storing the data with test date and time, and a plotting mechanism for monitoring the temporal trend of body temperature on a daily/weekly basis. Fig. 2(b) shows the app user interface for data collection, while Fig. 2(c) shows a computed temperature.

B. *Experimental Setup and Dataset*

The data has been collected in the laboratory setup. A controlled heat mat and digital controller thermostat have been

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used to generate different temperatures. The IJP WRAP temperature sensor was placed on the heat mat and output was monitored in the smartphone app. In total 67 samples (N = 67) were collected using eight sensors at different temperatures. Temperature was varied from 79°F to 107°F. A high precision fiber optic thermometer (Optocon FOTEMP) was used to measure the true value of the mat, and label the collected data samples. All the samples were saved in csv files with time stamp. Annotation record was maintained in a separate file.

C. Feature Extraction, Feature Selection, and Regression

The raw data (sensor output signal) received at the app has been filtered using a moving average filter to remove noises. Then, four features were extracted from the filtered signal. These features are: i) signal maxima, ii) signal minima, iii) signal average, and iv) time delay of signal transition. For feature selection, we used the caret Package in R [5]. To get the optimal number of features for maximizing the model performance, we used Random Forest model in R. The algorithm for temperature estimation was tested using different regression models such as KNN, Linear regression, K-nearest neighborhood. Random Forest has been selected based on performance. For model evaluation, five-fold repeated cross validation has been used with the number of repeats = 3.

III. Results

IJP WRAP temperature sensor produces an analog response which changes with temperature. Since the temperature transducer is NTC type, the resistance and hence delay of signal transition decreases with an increase in temperature. Fig. 3 shows the sensor response received inductively at the scanner after envelope detector. The IJP WRAP temperature sensor output can get affected by sensor variability, position, and alignment. Fig. 4 compares the output filtered at app of a misaligned sensor with that of a properly positioned sensor. It is evident that misalignment impacts the transition delay, signal average, maxima etc. The random forest algorithm suggests that best accuracy can be obtained with two features (Fig. 5). The top two features, delay and average are used in the final regression model. Fig. 6 shows the signal transition (high to low) and delay (mean ± 95% confidence interval) among various temperatures.

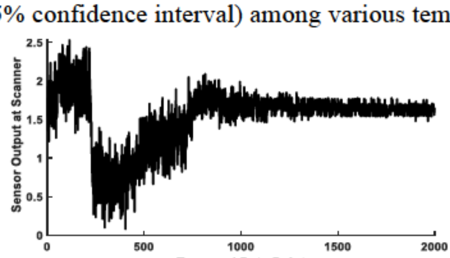

Fig. 3. Sensor output of inductively received at the scanner.

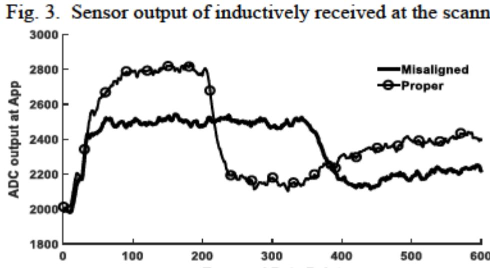

Fig. 4. Comparison of properly positioned sensor output with misaligned sensor output at app (sampling rate = 30 KHz).

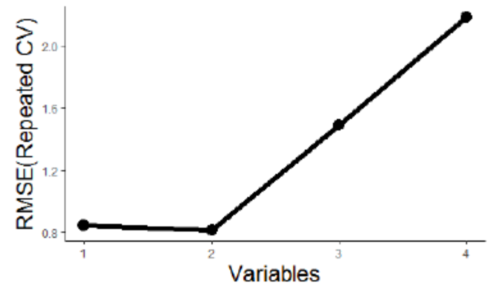

Fig. 5 Feature selection by Random Forest showing the optimal outcome.

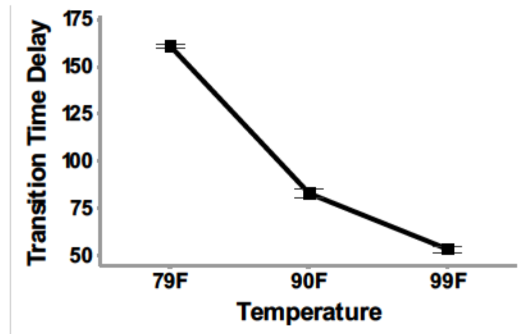

Fig. 6 Sensor characterization- change in time delay with temperatures

TABLE I. Evaluation of Regression Models

	Model	Performance Metrics		
		RMSE	*R Squared*	*MAE*
1	Random Forest	0.98	0.99	0.59
2	Linear Regression	1.35	0.98	1.07
3	k-Nearest Neighbor	1.38	0.94	1.03

The results of five-fold cross validation with different algorithms have been shown in Table I. Results indicate that random forest is the best performer with an RMSE = 0.98, R-squared value = 0.99 and mean absolute error, MAE = 0.59.

IV. Conclusion

IJP WRAP temperature sensor has the potential to be used in the monitoring of disease severity. In addition, it serves as a basis for the development of other IJP body sensors, which may include airflow, electrocardiogram and pulse oximetry sensors. Successful use of IJP in the development of biomedical sensors will lower wearables cost significantly.

References

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