WaveLeNet: Transfer Neural Calibration for Embedded Sensing in Soft Robots

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INTRODUCTION

Soft robots have exhibited excellent compatibility with functional and physical requirements of intraluminal procedures such as bronchoscopy and cardiovascular intervention [1]. Despite their favourable mechanical compliance and scalable design, integrating miniature force and shape sensors on them is cumbersome [2]. Also, large mechanical deformation of such robots, i.e., flexures, may push traditional rigid sensors out of their linear range [3]. As an alternative approach, the authors have recently introduced a novel soft sensing method and soft embedded sensors for flexures that exhibited less than 10mN error in measuring external 3D tip forces on soft robots for bronchoscopy and cardiovascular applications [4], [5], [6]. Fig. 1(a –c) depict the conceptual design, the prototyped sensor developed in [5], and a representative interventional application. Their soft sensor was comprised of a gelatin-based matrix filled with graphite nano-particles that exhibited stable piezoresistivity under extremely large deformation. Despite its accuracy, the accuracy of the proposed sensor was adversely affected in noisy environments, e.g., operation rooms. The reason was that the rate-dependent features used in its neural calibration would amplify the peripheral noise which would diminish the accuracy. In this study, we have proposed and validated an alternative deep-learning-based method for calibration of the proposed soft sensor that is derivative-free thus does not amplify the peripheral noise and is versatile. Conceptually, the proposed calibration methods can be used to assemble an array of sensor readings for distributed sensing on soft robots. Our proposed method is based on generating a scalogram from the temporal-frequency content of the measured voltages using real-time wavelet transform and using transfer learning technique to infer rate-dependent and deformation-dependent features from the voltages' scalogram.

MATERIALS AND METHODS

As an alternative and derivative-free calibration method for the soft embedded sensor developed in [5], we investigated the utilization of a deep-learning-based calibration schema. Fig. 2(a) depicts the proposed calibration framework. To this end, first the scalograms Continuous Wavelet Transform (CWT) of two voltages V_1 and V_2 recorded during the sensor calibration were obtained

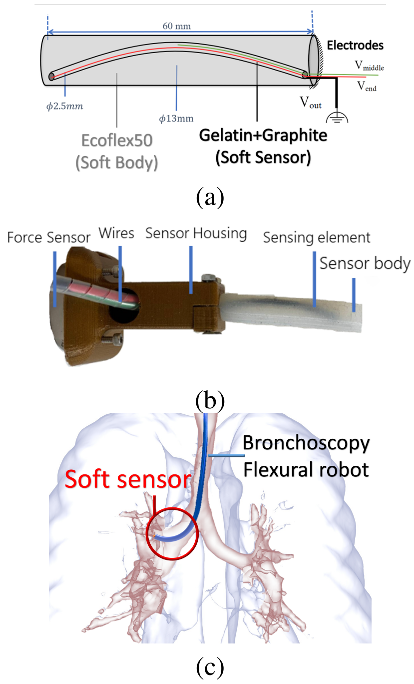
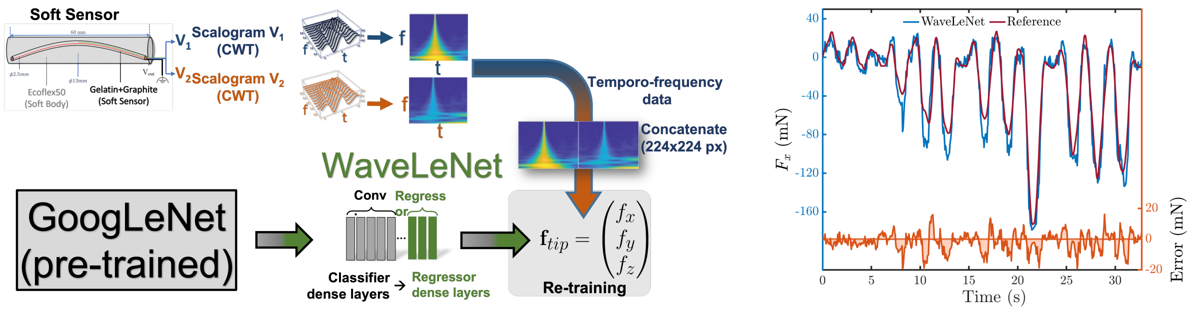


Fig. 1. (a) Conceptual design and (b) the prototyped soft flexure with embedded soft sensor [4], and (c) conceptual application of the proposed soft sensor.

using Matlab Signal Processing Toolbox. As shown in Fig. 2(a) scalograms were 2D images in red-green-blue (RGB) colorspace. More specifically, the Morse wavelet was employed to generate the CWTs. The CWT images were of 224×112 px size and were horizontally concatenated in the form of $[V_1\ V_2]$ to form a 224×224 px input image for the transferred neural network. Also, we applied synchro-squeezing to the wavelet to improve the temporal resolution of the scalogram. A total of 70 pairs of CWT scalograms were obtained from the calibration dataset obtained in [5]. Considering the small size of the dataset and to perform accurate feature extraction on scalogram images, GoogLeNet (Alphabet Inc.) pre-trained network was used. It had a total of 22 layers (including convolutional and max-pooling. To perform force estimation (regression), the last layer of GoogLeNet (classifier) was replaced with eight fully-connected layers with 250,200,150,100,50,25,10, and 3 neurons with the rectified linear unit (ReLU) activation function. The restructured convolutional calibration model was denoted



(a) (b)

Fig. 2. (a) Dataflow-gram of the proposed transfer-learning-based calibration method, (b) representative performance of the proposed calibration.

as `WaveLeNet` in this study. For better accuracy, the training forces were normalized. In training, `'adam'` optimizer with 20 epochs and goal function of mean-absolute error was used. The training was performed in Matlab Deep Learning Tool Box (Mathworks, MA, USA). The dataset was split (70:15:15 for train:validate:test).

RESULTS AND DISCUSSION

Fig. 2(b) shows a representative performance of the proposed calibration for unseen data for predicting tip force in $x-$direction, i.e. F_x. To assess the accuracy, maximum and mean absolute errors between predicted force and ground truth (reference) were analyzed and compared with the previous rate-dependent calibration proposed in [5]. In addition, the minimum detectable force observed with `WaveLeNet` and that of [5] were compared. Table I summarizes the performance of `WaveLeNet` with the rate-dependent calibration proposed in [5]. The results showed that the MAE of the proposed network was less than 5% of full range (i.e., 160mN). Although the MAE over full range was larger than the previous rate-dependent calibration it was still below the 5% error level. Most importantly, we analyzed the error for small force ranges, where our previous rate-dependent calibration was most erroneous (due to noise amplification). The results showed that not only the proposed WaveLeNet calibration was more accurate than the rate-dependent calibration, but it was also more accurate compared to itself at full range. We believe the derivative-free nature of the WaveLeNet method has contributed to its superiority compared to rate-dependent calibration. Also, the more in-depth analysis showed that at force ranges > 100mN, the scalograms become quite bright and the temporal gradient of WaveLet scalograms diminishes. This might have contributed to lower accuracy in high forces.

CONCLUSION

In this study, we proposed a transfer learning-based calibration schema inherited from GoogLeNet for soft embedded sensing in soft robots. The proposed method was derivative-free and would capture temporal changes in electrical signals from the soft sensors by capturing image features in scalograms of wavelet transform. WaveLeNet, our derivative-free deep convolutional calibration

TABLE I

PERFORMANCE OF WAVELENET IN COMPARISON WITH REF. [5].

Force	MAE WaveLeNet (mN)	MAE [5] (mN)	MDF WaveLeNet (mN)	MDF [5] (mN)
F_x (full-range)	7.5	3.3	< 1	< 1
F_y (full-range)	7.1	2.6	< 1	< 1
F_z (full-range)	12	8.0	< 1	< 1
F_x < 20mN	3.3	12.0	< 1	< 1
F_y < 20mN	3.7	13.1	< 1	< 1
F_z < 20mN	5.4	14.4	< 1	< 1

MAE: Mean Absolute Error
MDF: Minimum Detectable Force

model, had comparable accuracy over the full range of our soft flexural sensor compared to a previously validated rate-dependent calibration. However, thanks to its derivative-free features, it improved the accuracy for small forces, i.e., < 20mN. The proposed sensor and derivative-free calibration facilitates utilization of the proposed sensor in soft robotic applications especially tactile grasping (with force feedback) and interventional soft robots (for intraluminal applications). The authors have demonstrated the applicability of the proposed sensor for bronchoscopy applications in [5].

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