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A Study on

Model estimation for health monitoring and rehabilitation systems

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A thesis submitted in partial fulfilment of the requirements for the degree of

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Author's declaration

I, *Li Wang* declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the *School of Biomedical Engineering, Faculty of Engineering and Information Technology* at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Abstract

Electronic trainers (e-trainers) are fitness guidance systems consisting of motion signal sensor(s), a user interface, and a control system. Owing to the widespread popularity of fitness and personal training, e-trainers have found numerous applications across many fields. However, the design of e-trainers is challenging because of their requirement for miniaturisation and problems with discrepancies, drift, lack of data, and limited resources. The primary aim of this thesis is to design an improved e-trainer with a focus on the initial measurement unit calibration algorithm and the practical implementation of pattern recognition algorithms. Several problems in the field are considered, including kernel-based heart rate regulation, practical considerations for the calibration of efficient wearable devices, and model compression using the pruning method.

The first part of this thesis investigates several practical issues associated with calibrating the proposed low-cost wearable e-trainer in clinical settings, including poor repeatability and significant volatility. In field-based environments, the parameter variation of the low-cost triaxial gyroscope requires an effective and practical calibration process to reduce the errors due to unexpected variance. To this end, an efficient in-field calibration method is developed that can readily calibrate the triaxial gyroscope without additional equipment. This experimental scheme can be easily implemented by manually rotating the triaxial gyroscope over a certain angle as the calibration reference. A linearised calibration model is developed for the proposed experimental scheme, and G-optimality is achieved. Extensive numerical simulations demonstrate that the calibration error is relatively low and the estimation of model parameters is unbiased under mild experimental conditions. After a calibration process taking less than 30 s, the absolute error of the scale factors is always less than 2.5×10^{-2} for LSM9DS1 and that of the biases is less than 1×10^{-2} for ICM20948.

In the second part of this thesis, to overcome the lack of suitable training data for modelling the human cardiovascular response, the simulation and control of the human heart rate are investigated in detail using a kernel-based nonparametric model with model predictive control. This kernel-based method introduces a kernel regularisation term that provides prior information to the model estimation phase. By adding this prior information, the experimental protocol can be significantly simplified, with a model training time of only 10 min. Based on the identified model, a controller that uses model predictive control is designed to track a predefined reference heart rate profile. One

advantage of this approach is that the speed and acceleration of the treadmill can be maintained within a safe range for vulnerable exercisers. The entire model construction process takes 10 min, including an 80-s resting period. The protocol is relatively simple and consists of only two accelerations. In the heart rate tracking task, the heart rates of 12 experiment participants follow the target heart rate to within ±3 beats per second.

The third part of this thesis leverages the state-of-the-art neural network pruning method to compress the network model. This allows the computational complexity of the inference task to be reduced by 98% without significant performance degradation. It is therefore possible to use advanced deep learning models to estimate human motion states on embedded systems with limited resources. For the user, more neural network models operating on the device means that more functions can be provided. Experimental results verify the effectiveness and efficiency of the proposed method, with up to 60% of graph links and 98% of network weights pruned across different tasks with no significant drop in accuracy.

An application of the proposed e-trainer is introduced in the fourth part of this thesis. The purpose of this application is to estimate the gait parameters (i.e. contact time (CT) and flight time (FT)) of 40 rugby players associated with the Sydney Swans Football Club. This is important because the analysis of such gait parameters can help players increase their running performance and reduce the running-related injury risk. In addition to the CT and FT, a pre-processing system that detects the running period and identifies the 95% confidence interval is introduced to analyse and enhance the detection accuracy. We also investigate the compatibility of CT and FT estimation based on the data collected from a gyroscope and an accelerometer placed in a single location. The results show that the combined accelerometer–gyroscope system obtains the desired accuracy (absolute error <20 ms) in CT and FT detection. Moreover, after introducing the confidence interval, the two systems exhibit high consistency at lower running speeds (<20 km/h).

In conclusion, this thesis describes a comprehensive solution for the design of both hardware and software for electronic virtual trainers. The first part presents an efficient calibration method for gyroscopes. This method only requires simple external devices (or may not need any external device), and can be finished within 30 s. The gyroscope reading accuracy is significantly enhanced by the use of our method. The second part aims to overcome the problem of a lack of data using kernel-based modelling. For users, fewer experiments are needed during the model building period. For the issue of limited resources, the fourth part proposes a model compression method for complex neural networks operating on resource-limited embedded systems. Thereby, novel machine learning algorithms can provide additional guidance to the user.

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List of Publications

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2. **Wang, L.**, Zhang, T., Ye, L., Li, J. J., & Su, S. (2021). An Efficient Calibration Method for Triaxial Gyroscope. *IEEE Sensors Journal*. doi: 10.1109/JSEN.2021.3100589.

3. Yang, Y.[1], **Wang, L.**[1], Su, S., Watsford, M., Wood, L., & Duffield, R. Inertial Sensor Estimation of Initial and Terminal Contact during In-Field Running. *Sensors*.

Under Review :

3. **Wang, L.**, Fox, D., Duffield, R., Hammond, A., Zhang, A., & Su, S. An Infield Gyroscope Calibration Method In Wearable Health Monitoring. Submitted to *IEEE Transactions on Systems Man Cybernetics-Systems.*

4. **Wang, L.**[1], Huang, W.[1], Zhang, M, & Su, S. Pruning Graph Neural Network by Evaluating Edge Property. Submitted to *Knowledge-Based Systems*.

5. Zhang, M., **Wang, L.***, Campos, D., Huang, W., Guo, C., & Yang, B. Weighted Mutual Learning with Diversity-Driven Model Compression. Submitted to *NeurIPS 2022*.

6. Huang, W.[1], **Wang, L.**[1], Wang, S., & Zhang, M. Can Wide Variational Auto-encoder Generate? Submitted to *NeurIPS 2022*.

7. Liu, T., Zhang, W., **Wang, L.**, Ueland, M,. Forbes, S., Zheng, W., & Su, S. Numerical Differentiation from Noisy Signals: A Kernel Regularization Method to Improve Transient-State Features for the Electronic Nose. Submitted to *IEEE Transactions on Systems Man Cybernetics-Systems*.

UNDER PREPARATION :

9. **Wang, L.**, & Su, S. On the Influence of Rotation Speed and Noise Intensity of the Calibration Accuracy of Gyroscope. Prepare submit to *IEEE Transactions on Industrial Electronics*.

Table of Contents

List of Figures

List of Tables