

Método basado en inteligencia artificial para la calibración de sensores force sensitive resistor (FSR) orientado a la determinación de presiones plantares estáticas en la pisada

Nombres y apellidos

Edwin Leonel Álvarez Gutiérrez
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Tutor(es):

Silvia Carolina Moreno Trillos, PhD.

Leonel José Paredes Madrid, PhD.

RESUMEN

La investigación desarrolla una solución tecnológica innovadora para mejorar la precisión de los sensores piezorresistivos tipo FSR —Force Sensitive Resistor— en aplicaciones orientadas a la medición de presión plantar estática. Estos dispositivos, ampliamente utilizados por su bajo costo, asequibilidad, portabilidad y flexibilidad han sobresalido en los últimos años en comparación con tecnologías piezocapacitivas o piezoeléctricas. No obstante, presentan limitaciones significativas derivadas de fenómenos como la histéresis, el *creep* o deriva temporal, la no linealidad y la baja reproducibilidad, los cuales afectan de forma directa la exactitud y consistencia de las mediciones. Bajo el marco del paradigma positivista y mediante una metodología aplicada-experimental con enfoque cuantitativo, se diseñó un sistema híbrido que combina técnicas de medición multivoltaje y multisensor con modelos avanzados de inteligencia artificial, entre ellos redes neuronales artificiales (ANN), redes de memoria a largo y corto plazo (LSTM) y redes GRU. Estos modelos fueron integrados con métodos matemáticos clásicos para compensar los errores característicos de los sensores FSR. La validación del sistema se llevó a cabo en condiciones controladas, evaluando un total de 48 sensores pertenecientes a tres marcas comerciales: FlexiForce®, Interlink® y Peratech®. Para la experimentación se utilizó un sistema mecatrónico de ensayos mecánicos que permitió aplicar variaciones de carga y voltaje, reproduciendo así diferentes escenarios de operación conforme a la aplicación definida. Los datos adquiridos fueron procesados para desarrollar y entrenar los algoritmos de compensación de errores, abordando específicamente los efectos asociados al comportamiento viscoelástico del material conductor de este tipo de sensores. Los resultados evidenciaron que el sistema propuesto supera a los métodos tradicionales en precisión. Para la compensación de la histéresis, el modelo ANN mostró el mejor rendimiento, reduciendo el error desde valores iniciales entre el 6 % y el 9 % hasta menos del 1.5 % en algunos casos, con errores medios inferiores al 2.5 % en sensores FlexiForce® y Peratech®. Esto supone una mejora notable respecto a lo reportado por fabricantes y estudios previos. En el caso del *creep*, el modelo LSTM fue el más efectivo, alcanzando un error cuadrático medio (RMSE) de 0.0032 y un error porcentual medio de apenas 0.49 %. Su capacidad para modelar secuencias temporales lo convirtió en la opción más precisa para este tipo de error, ya que el *creep* se manifiesta como una variación lenta y dependiente del tiempo bajo carga constante. El modelo GRU, aunque con menor complejidad y exigencia computacional que LSTM, presentó un desempeño competitivo. Obtuvo un coeficiente de determinación R^2 de 0.9953 y errores medios en el rango del 3 % al 4 %. Esto lo posiciona como una alternativa viable para implementaciones en sistemas embebidos de bajo consumo energético, donde los recursos de hardware

son limitados. El análisis comparativo entre las diferentes tecnologías de sensores reveló comportamientos distintivos. FlexiForce® presentó una respuesta más estable y repetible en las mediciones, lo que facilitó la corrección de errores y la obtención de resultados consistentes. Interlink® mostró mayor susceptibilidad a la histéresis, pero esta fue significativamente mitigada mediante el uso de ANN. Peratech®, por su parte, ofreció una respuesta inicial favorable, la cual fue optimizada utilizando modelos multivoltaje que mejoraron su linealidad y precisión. En todos los casos evaluados, los modelos basados en inteligencia artificial superaron las técnicas convencionales para compensar errores estáticos de los sensores FSR bajo condiciones de operación variables. Esta mejora se tradujo en una estimación de fuerza más fiable y robusta, lo que representa un avance importante en aplicaciones como la medición de presiones plantares, donde la exactitud es crítica para la interpretación clínica y biomecánica. La investigación concluye proponiendo como línea futura el desarrollo de una implementación embebida de los algoritmos desarrollados, con el fin de evaluar su desempeño en condiciones reales de uso. Esto permitiría validar la viabilidad práctica del sistema y su potencial integración en dispositivos portátiles o de monitoreo continuo, beneficiando tanto la investigación biomédica como la instrumentación de bajo costo para el diagnóstico y seguimiento de la salud plantar.

PALABRAS CLAVES: Inteligencia Artificial, Calibración, Creep, Resistencias de detección de fuerza FSR, Histéresis.

ABSTRACT

This doctoral dissertation presents an innovative technological solution aimed at improving the accuracy of piezoresistive sensors of the FSR —Force Sensitive Resistor— type in applications focused on static plantar pressure measurement. These devices, widely used for their low cost, affordability, portability, and flexibility, have stood out in recent years compared to piezocapacitive and piezoelectric technologies. Nevertheless, they exhibit significant limitations arising from phenomena such as hysteresis, creep (or temporal drift), non-linearity, and low reproducibility, all of which directly affect the accuracy and consistency of measurements. Within the framework of the positivist paradigm, and following an applied–experimental methodology with a quantitative approach, a hybrid system was designed that combines multi-voltage and multi-sensor measurement techniques with advanced artificial intelligence models, including artificial neural networks (ANN), long short-term memory networks (LSTM), and gated recurrent units (GRU). These models were integrated with classical mathematical methods to

compensate for the characteristic errors of FSR sensors. System validation was carried out under controlled conditions, evaluating a total of 48 sensors from three commercial brands: FlexiForce[®], Interlink[®], and Peratech[®]. For the experiments, a mechatronic mechanical testing system was used to apply variations in load and voltage, thus reproducing different operational scenarios according to the defined application. The acquired data were processed to develop and train error-compensation algorithms, specifically addressing the effects associated with the viscoelastic behavior of the conductive material in this type of sensor. The results showed that the proposed system outperformed traditional methods in terms of accuracy. For hysteresis compensation, the ANN model achieved the best performance, reducing error from initial values between 6% and 9% to less than 1.5% in some cases, with mean errors below 2.5% for FlexiForce[®] and Peratech[®] sensors. This represents a significant improvement over the figures reported by manufacturers and previous studies. In the case of creep, the LSTM model proved to be the most effective, reaching a root mean square error (RMSE) of 0.0032 and an average percentage error of only 0.49%. Its ability to model temporal sequences made it the most accurate option for this type of error, given that creep manifests as a slow, time-dependent variation under constant load. The GRU model, while less complex and computationally demanding than LSTM, demonstrated competitive performance. It achieved a coefficient of determination (R^2) of 0.9953 and mean errors ranging from 3% to 4%, positioning it as a viable alternative for implementation in low-power embedded systems where hardware resources are limited. The comparative analysis of the different sensor technologies revealed distinctive behaviors. FlexiForce[®] exhibited a more stable and repeatable measurement response, facilitating error correction and the achievement of consistent results. Interlink[®] showed greater susceptibility to hysteresis, but this was significantly mitigated through the use of ANN. Peratech[®], on the other hand, delivered a favorable initial response, which was further optimized using multi-voltage models that improved its linearity and accuracy. In all cases evaluated, AI-based models outperformed conventional techniques in compensating for the static errors of FSR sensors under variable operating conditions. This improvement translated into a more reliable and robust force estimation, representing a significant advancement in applications such as plantar pressure measurement, where accuracy is critical for both clinical and biomechanical interpretation. As a future line of work, this dissertation proposes the development of an embedded implementation of the developed algorithms to evaluate their performance under real operating conditions. This would make it possible to validate the practical feasibility of the system and its potential integration into portable or continuous

monitoring devices, benefiting both biomedical research and low-cost instrumentation for the diagnosis and monitoring of plantar health.

Keywords: Artificial Intelligence, Calibration, Creep, Force Sensing Resistors FSRs, Hysteresis.

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