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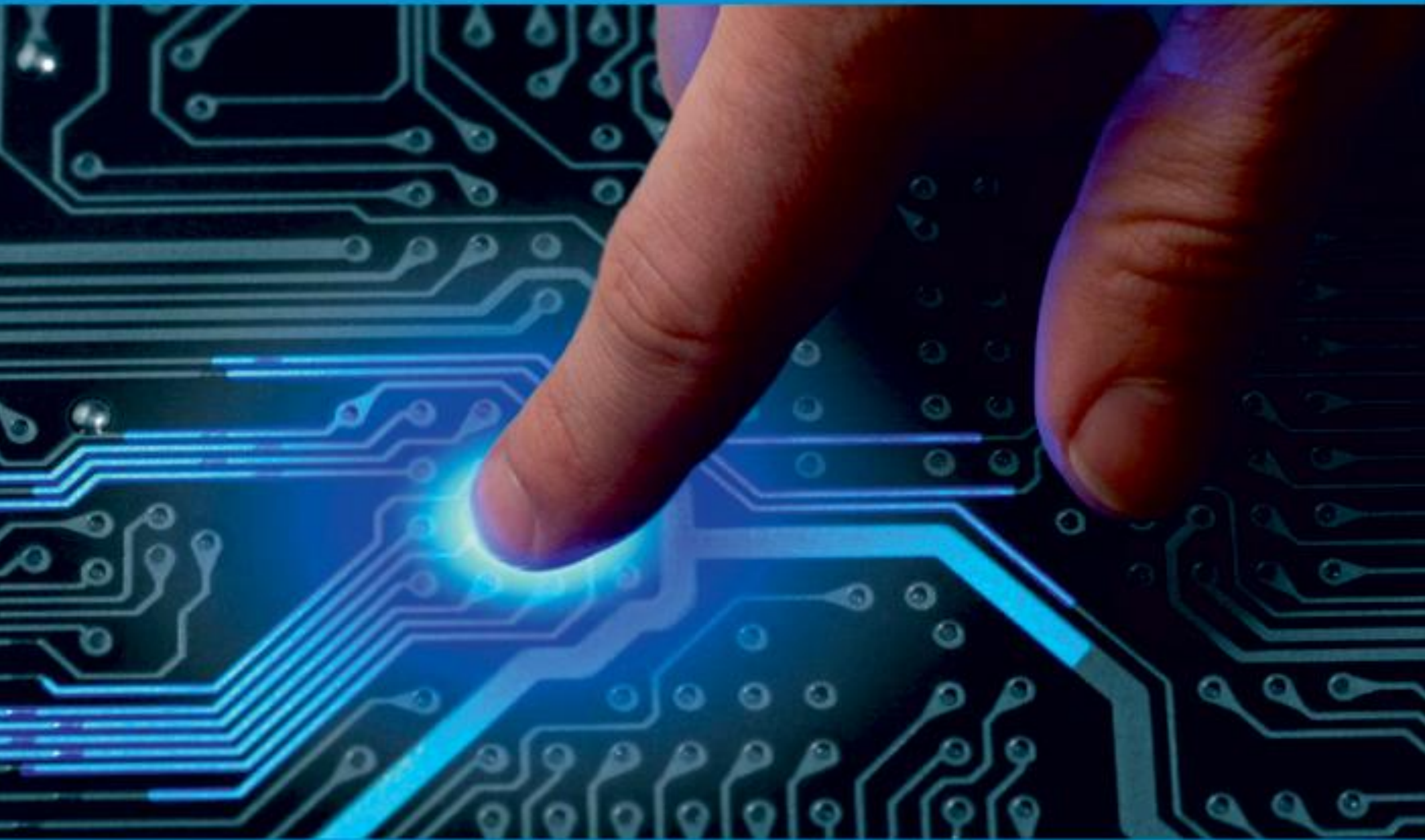

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A Review on Virtual Sensor Construction Based on AI Techniques

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ABSTRACT: Virtual sensors have emerged as pivotal tools in diverse applications, spanning robotics, automation, environmental monitoring, and smart home systems. This literature review explores the integration of Artificial Intelligence (AI) techniques, including Machine Learning (ML), Deep Learning (DL), and IoT technologies, in the design and deployment of virtual sensors. The review evaluates various methodologies and their effectiveness in replacing physical sensors, addressing challenges such as accuracy, scalability, and adaptability across different environments. Furthermore it concludes that AI-driven virtual sensors have the potential to revolutionize sensor technology, although further research is needed to address existing limitations and improve implementation strategies

I. INTRODUCTION

Physical sensors have been used extensively in many applications such as control systems, industrial automation, environmental monitoring, home automation, health care, aerospace and IoT, to measure and monitor attributes such as temperature, humidity, pressure, speed and so on. Physical sensors measures the physical quantity and converts it in to signals that is readable by an instrument. Physical sensors are often expensive and require a timely maintenance. Most of the applications that rely on the data of physical sensors for their proper operation will become inoperable when a physical sensor fail. Based on the requirement of the application, the virtual sensors also known as soft sensors trained through machine learning algorithms will ensure that the application can receive data through the soft sensor.

Sensors are indispensable in modern technology, playing a crucial role in monitoring and controlling processes across diverse sectors, including manufacturing, healthcare, and environmental management. Traditional physical sensors, while effective, face limitations such as high costs, maintenance challenges, and restrictions in deployment environments. In response to these limitations, the concept of virtual sensors has emerged. Virtual sensors are software based systems that estimate desired measurements by integrating data from multiple sources and applying computational models.

The integration of artificial intelligence (AI) in virtual sensor construction has opened new possibilities, enabling the development of systems that are not only more cost-effective but also capable of providing higher accuracy and reliability. AI techniques, including machine learning and deep learning, allow for the analysis of complex datasets, identification of patterns, and real-time predictions, making them well-suited for virtual sensor applications.

II. RELATED WORK

The purpose of this literature review is to explore the various AI techniques used in the design of virtual sensors, evaluate their effectiveness, and identify existing gaps in research. It aims to provide an in-depth analysis of Artificial Intelligence, Machine Learning, Deep Learning, and IoT-based virtual sensors. Over time, virtual sensing has been applied across various fields, such as robotics, automation, anomaly and leak detection, air quality management, active noise control, wireless communication, as well as in the automotive and transportation sectors [1–3].

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The study presented in [5] includes temperature monitoring in an open space office, where a set of physical sensors is deployed at uneven locations. The primary goal is to develop a black-box virtual sensing framework that is independent of the physical characteristics of the scenario and can be adapted to any indoor environment. Initially, a systematic analysis of various distance metrics is conducted to identify the best sensors for temperature monitoring. Subsequently, a novel metric developed using a genetic programming approach combines and summarizes information of the considered distance metrics. Finally, an automated method is proposed to determine the best subset of sensors for effective monitoring in any given room. Further the distance metrics guide the selection of relevant physical sensors, ensuring that only the most informative sensors are used as inputs for the virtual sensor model.

By utilizing the Borda count voting method and distance metrics, relevant physical sensors are selected which are the most informative, leading to accurate and efficient virtual sensor predictions. The black-box approach then leverages this data to create accurate and reliable virtual sensors without the need for extensive domain-specific knowledge. To evaluate the performance of the sensor and feature selection phases with respect to the task of temperature virtual sensing, and to identify the most effective prediction methodology, we conducted experiments comparing the following approaches:

- Baseline: simple and Inverse Distance Weighted (IDW) average of the temperatures;
- Particle filters;
- LinearRegression – Python's package Scikit-learn [9];
- XGBoostRegressor – Python's package xgboost [8];
- An LSTM recurrent neural network, trained by means of the PyTorch Deep Learning library [10].

Both XGBoost and LinearRegression demonstrate superior performance compared to baseline methods. LSTM-based model demonstrates competitive performance with XGBoostRegressor.

The proposed solution [5] covers essential aspects of virtual sensing, including sensor selection, determining the necessary amount of training data, selecting predictive models, and evaluating their performance. Importantly, the approach operates as a black-box system, completely independent to the specific physical characteristics of the environment, such as elements that can influence internal temperature (e.g., windows, radiators).Thus, in principle, it can be applied to any generic indoor environment with an arbitrary set of pre-located sensors.

The paper [4] compares fourteen different machine learning (ML) models to determine which one most accurately replaces physical sensors (like temperature and humidity sensors) in a smart home environment. The setup involves deploying both virtual and physical sensors on a custom, lightweight IoT platform running on a Raspberry Pi. To maximize cost efficiency, the proposed solution retains only one physical sensor, with the rest replaced by ML models acting as virtual sensors. These virtual sensors run on the same IoT device as the physical sensor. This methodology allows a single physical sensor to monitor the data of one room and, through the ML models, provide accurate temperature and humidity readings for all rooms in the smart home. This approach aims to maintain high accuracy while reducing the number of physical sensors needed. To examine the applicability of the proposed methodology, a platform has been developed that monitors temperature and humidity in a central room using a DHT11 sensor connected to a Raspberry Pi (RPi). This platform visualizes the time series metrics from one physical sensor and five virtual sensors through a web graphical user interface.

A virtual sensor is a software component based on a machine learning (ML) model that provides indirect temperature and humidity measurements.

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Training Mode:

- Pairs of time series measurements are retrieved by the DBMS to train the ML model.
- A regression ML model learns the relationships between the reference room and each virtually monitored room.
- The goal is to minimize the errors in the forecasted values.
- Each target room has a unique relationship with the reference room influenced by factors like geographic

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orientation, wall insulation type, and exposure to sun and wind.
- The relationship may involve non-linear and complex patterns, making simple linear regression insufficient.

Inference Mode:

- Once training is complete, the IoT platform switches to inference mode.
- Virtual sensors use real measurements from the physical sensor in the reference room as input.
- They estimate the temperature and humidity in other rooms based on these inputs.

The fourteen machine learning models such as AdaBoost, BayesianRidge, CatBoost, ElasticNet, GradientBoosting, HistGradientBoosting, KernelRidge, LinearRegression, LGBM (LightGBM), RandomForest, SGD (Stochastic Gradient Descent), SVR (Support Vector Regression), XGB (XGBoost), RANN (Recurrent Artificial Neural Network) are compared to identify the most accurate one for replacing physical sensors in the smart home setup. The first best model in terms of Mean Absolute Error (MAE) across the target rooms is the Random Forest (RF) model.

In the paper [6], to train the virtual sensors, the data from faulty sensors and the neighboring sensors that are highly correlated are chosen. The virtual sensor is able to predict the output of a solar power plant by either using a close by sunlight sensor or other nearby solar power plants. Virtual sensor are created by using similar type of sensors and different types of sensors. To create a virtual sensor of same type, ANN, LR, Bayesian ridge regression algorithms are used. 67% of the dataset from various solar power plants within the city of Aarhus (Denmark) is used to train these algorithms. 33% of the dataset is separated for the test data. To create a virtual sensor of different sensor types say temperature, humidity, wind speed, battery level, ANN, LR is used. The framework proposed in the paper [6] automates the creation of Virtual Sensors using historical data from faulty sensors and correlated nearby sources. This automation is crucial in environments with a large number of IoT sensors where manual intervention for each Virtual Sensor creation is impractical. To automate the virtual sensor creation process autosk-learn & grid search is used.

In the paper [7], the main task in the sensor cloud environment is the provisioning of virtual sensor. It chooses physical sensors to create virtual sensors in response to user requests. The physical sensors are grouped into several categories using historical data. K-means clustering algorithm is used to cluster the physical sensors. One representative physical sensor is chosen from each cluster to create the corresponding virtual sensors. Firstly linear regression model is used to classify all the physical sensors into several classes as per the historical data, then k- mean clustering algorithm is used to optimize the selection.50 physical sensors are classified into 11 clusters. Only 11 physical sensors are activated to provide service which achieves almost 75.50% decrease in energy consumption compared to leach & aggregation scheme.

III. CONCLUSION

Brunello et al. demonstrates the effectiveness of a black-box virtual sensing framework for temperature monitoring in open office spaces. By utilizing various distance metrics and a genetic programming approach, the study develops an automated method to select the most informative physical sensors for creating accurate virtual sensors. The use of advanced ML models like XGBoost and LSTM ensures high performance, making the approach adaptable to any indoor environment without extensive domain-specific knowledge.

In the context of smart homes, Georgios Stavropoulos et al. compares fourteen ML models to determine the most accurate virtual sensors for temperature and humidity monitoring. The proposed solution significantly reduces the number of physical sensors needed by deploying virtual sensors on a custom IoT platform. The Random Forest model emerges as the most accurate, demonstrating the potential of ML models to maintain high accuracy while minimizing costs in smart home environments.

Eushay Bin Ilyas et al. focuses on automating the creation of virtual sensors using historical data from faulty sensors and highly correlated nearby sources. By employing ANN, LR, and Bayesian ridge regression algorithms, the framework efficiently predicts the output of solar power plants. The automation process, supported by autosk-learn and grid search,

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is crucial in environments with a large number of IoT sensors, where manual intervention is impractical.

Addressing the sensor cloud environment, this paper by Ming-Zheng Zhang et al. introduces a methodology for provisioning virtual sensors by grouping physical sensors using historical data and K-means clustering. The approach achieves significant energy savings by selecting representative physical sensors from each cluster. This method demonstrates the potential for optimizing sensor deployment, reducing energy consumption, and maintaining service quality.

In summary, the reviewed papers provide a solid foundation for the ongoing development and deployment of virtual sensors, demonstrating their potential to revolutionize various fields by offering accurate, cost-effective, and adaptable solutions.

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