METHODS OF MACHINE LEARNING IN MODERN METROLOGY

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Abstract. In the modern world of scientific and technological progress, the requirements for the accuracy and reliability of measurements are becoming increasingly stringent. The rapid development of machine learning (ML) methods opens up perspectives for improving metrological processes and enhancing the quality of measurements. This article explores the potential application of ML methods in metrology, outlining the main types of ML models in automatic instrument calibration, analysis, and prediction of data. Attention is paid to the development of hybrid approaches that combine ML methods with traditional metrological methods for the optimal solution of complex measurement tasks.

Key words: Machine learning, metrology, measurement accuracy, instrument calibration, data analysis, forecasting.

1. Introduction

Currently, increasing demands for accuracy and reliability in measurements are becoming increasingly important in various fields, including industry, science, and technology. Metrology, as the science of measurement, plays a key role in ensuring standards of accuracy and reproducibility in these areas [1]. With the development of modern technologies, especially ML methods, perspectives emerge for improving metrological processes and enhancing the quality of measurements.

ML, which includes a set of algorithms and methods that enable a computer system to learn from data and make predictions or decisions based on this experience, is recognized as an important tool in the field of metrology. One of the key advantages of applying ML methods is the capability to automate and optimize metrological processes. This facilitates the reduction of the time required for measurements and enhances the efficiency of their execution. Furthermore, ML contributes to improving data analysis and detecting anomalies in metrological data. By processing large volumes of information, models can identify abnormal situations or deviations from standard behavior. This ensures prompt response to potential problems and increases the reliability of measurements, which is crucial for ensuring the quality and accuracy of the obtained results.

2. Challenges of Implementing ML

When implementing ML methods in metrological practice, several key problems arise, relating to both technical and organizational aspects of this process.

Firstly, one of the main challenges remains ensuring quality data. Effective functioning of ML algorithms requires a large, diverse, and sufficiently representative dataset for training. Insufficient volume or low quality of data can lead to distorted results and unreliable conclusions.

Secondly, the complexity of interpreting results is also a significant factor. Some ML methods, such as deep neural networks, can be extremely complex and poorly interpretable by humans. This complicates the explanation and understanding of the decisions made by the model, which is crucial in the context of metrological activity requiring a high level of transparency and comprehensibility of results.

Thirdly, updating and maintaining the relevance of ML models is a continuous process. Technologies in this field are rapidly evolving, and periodic updates and adaptation to new conditions and requirements are necessary to maintain the effectiveness of the models.

Finally, integrating machine learning methods with existing metrological systems requires both technical and organizational efforts. This includes technical aspects such as compatibility with existing equipment and software, as well as cultural and organizational changes in work processes and decision-making.

3. Goal

The purpose of this scientific article is to study the effectiveness of using various types of ML models to ensure the accuracy and reliability of measurements.

4. Types of machine learning models and classification of machine learning models by task type in metrology

In the field of ML, several basic types of models are distinguished, each of which has its applications and characteristics in the context of metrology.

Supervised learning – this approach involves training a model based on labeled data, where each example corresponds to a known response. In metrology, this type of learning can make a significant contribution to various tasks, including classification and regression. For example, a model can classify measuring instruments based on their characteristics or predict measurement accuracy based on device parameters.

Unsupervised learning is employed to analyze unlabeled data in order to detect hidden patterns or structures within the dataset. These methods can assist in clustering measurement data or identifying anomalies, thereby enhancing the quality and reliability of measurements.

Semi-Supervised learning - this is a combination of supervised and unsupervised learning, which can be beneficial when only limited labeled data is available. In metrology, this could be applied, for example, for more accurate prediction of measurements based on a restricted dataset, thereby enhancing the efficiency and accuracy of measurement processes.

Reinforcement learning based on interacting with the environment and receiving feedback in the form of rewards or punishments. In metrology, this approach could be applied, for instance, to optimize measurement processes or develop systems for automatic instrument calibration. The model interacts with the measuring equipment, making decisions that lead to the best measurement quality, and receiving feedback on the accuracy and reliability of the results.

Additionally, in metrology, alternate ML methodologies can be utilized, such as deep learning, multi-layer neural networks, and hybrid models integrating diverse techniques to achieve optimal outcomes. These methodologies can be applied to address specific metrological challenges, including signal processing, pattern recognition, or real-time analysis of measurement data [2].

Each type of model serves as a tool for solving specific tasks and can be classified into the following types:

• Regression in ML is employed to predict numerical values based on given data. In the context of metrology, regression methods such as linear regression find wide application in creating mathematical models that describe complex dependencies between measured quantities. These models serve as valuable tools for analyzing and forecasting measurement results in situations where real measurements are unavailable or impractical due to experimental constraints. For example, linear regression models can predict changes in the characteristics of materials or objects based on their properties or the influence of external factors. This helps optimize manufacturing processes or make decisions based on forecasts. Consider a scenario where it's necessary to assess changes in temperature or pressure over time or other factors. A linear regression model can approximate this data and forecast future values based on previous measurements. This approach allows making forecasts necessary for planning and decision-making in various fields, including manufacturing, science, and technology.

Classification in ML is a method that allows dividing data into predefined categories or classes. This approach can be useful for addressing various tasks in metrology. For example, automatic identification of types of measuring instruments based on their technical characteristics. Suppose the dataset contains information about various devices such as thermometers, pressure gauges, and scales, including their technical specifications such as accuracy, measurement range, and sensor type. Models such as support vector machines or random forests, trained on this data, can automatically distinguish between types of instruments based on these characteristics [2]. Additionally, classification can help categorize measurement objects based on their characteristics. For example, if the data consists of measurements of physical parameters of objects, such as size, shape, color, and texture, classification models will automatically classify objects into different categories based on their characteristics.

Ranking models in ML enable the arrangement of elements based on a specified criterion. In metrology, where precision and dependability in measurements are paramount, ranking serves as a valuable tool for evaluating measurement accuracy and arranging outcomes. For instance, suppose we possess a dataset containing measurements of diverse physical attributes like temperature, pressure, humidity, etc. Leveraging ranking models allows us to evaluate the precision and dependability of each measurement and structure the outcomes based on their trustworthiness. This facilitates the identification of the most trustworthy measurements, which can be prioritized in decision-making processes reliant on this data. Moreover, ranking models are instrumental in identifying anomalies or outliers within measurement data. By contrasting measurement results with anticipated values or accuracy standards, we can pinpoint measurements that deviate from the overarching trend, necessitating further analysis or rectification.

Clustering in ML is a method of grouping data based on their similarity. This approach helps identify internal structures and patterns in data without the need for a prior definition of categories or classes. In the context of metrology, clustering can be a useful tool for analyzing similar measurement characteristics or devices. Examples of clustering applications in metrology include grouping measurements or devices based on their technical characteristics or operational features. For instance, in datasets containing information about various types of measuring equipment and their technical specifications, clustering methods such as k-means or hierarchical clustering can group devices with similar characteristics into one cluster. Additionally, clustering can be useful for data analysis and discovering hidden patterns that may be valuable for optimizing measurement processes or improving data quality. For example, clustering can help identify groups of measurements with similar anomalous values, which may indicate equipment issues or anomalies in the measurement process that require attention.

Anomaly detection, also known as outlier detection, is a technique used in ML to identify data points that significantly deviate from the typical or expected behavior in a dataset. In metrology, anomaly detection can enhance the quality and reliability of measurements by identifying unusual or unexpected observations. One approach to anomaly detection involves using statistical methods, such as Z-score analysis or the interquartile range method. These methods involve computing statistical parameters based on the distribution of data points and identifying observations that fall outside a certain threshold deviation from the mean or median [3].

Another approach involves utilizing ML algorithms such as isolation forests, one-class support vector machines, or autoencoders. These algorithms are capable of learning patterns from normal data and can subsequently detect anomalies by identifying deviations from these learned patterns. In the field of metrology, these algorithms can be employed to identify unusual measurement readings that may signify equipment malfunction, measurement errors, or other anomalies. Detecting anomalies in metrology is crucial for upholding the accuracy and reliability of measurements, as it enables the early detection of disruptions that could potentially affect measurement quality or data integrity. By promptly identifying anomalies, appropriate corrective actions can be initiated to investigate and address underlying issues, thereby ensuring overall measurement quality and reliability [4].

5. Prospects of applying ML methods.

The application of ML methods in metrology offers a wide range of potential applications covering various areas:

- Automatic instrument calibration - supervised learning methods can enable automatic calibration of measuring equipment [5,6]. By using historical data on instrument readings and known reference values, these models can learn to correct instrument errors and improve the accuracy and reliability of measurements.
- Measurement data analysis - unsupervised learning methods are well-suited for analyzing large volumes of measurement data to identify underlying patterns, highlight characteristic features, and detect anomalies. By revealing hidden structures in the data, these methods can enhance the understanding of measurement processes, improve data quality, and identify equipment malfunctions or measurement errors.
- Prediction of measurement outcomes - supervised learning methods are suitable for this task. They are capable of building predictive models that forecast expected measurement outcomes based on input parameters and experimental conditions. Thanks to these models, it is possible to predict the results in advance, allowing metrologists to optimize measurement processes and prevent potential issues before they arise.
- Image classification and recognition - ML classification methods enable the identification and categorization of different types of objects or patterns in measurement data. For example, these methods can be applied to classify defects on material surfaces or differentiate between different types of measuring equipment based on their characteristic features.
- Enhanced metrological workflow - ML algorithms can optimize and automate various aspects of the metrological workflow, including data preprocessing, feature selection, model training, and result interpretation. By automating repetitive tasks and augmenting human decision-making processes, ML can accelerate metrological procedures, reduce manual errors, and enhance overall efficiency.
- Quality control and assurance - ML methods can improve quality control processes by detecting outliers, deviations, or inconsistencies in measurement data. By identifying abnormal observations and highlighting potential issues, these methods enable metrologists to ensure consistency, reliability, and traceability of measurement results.
- Optimization of measurement processes - ML models can optimize measurement procedures by determining optimal settings, configurations, or conditions for conducting measurements. By analyzing historical data and experimental parameters, these models can recommend the most effective approaches for achieving desired measurement outcomes.
- Data-driven decision-making - leveraging information derived from ML models, metrologists can make informed decisions regarding measurement strategies, instrument selection, calibration intervals, and process improvements. By integrating data-driven insights into decision-making processes, metrology methods can become more adaptive, responsive, and aligned with organizational goals.

The implementation of ML methods in various tasks is thoroughly described in the works [5-10] from the literature list.

6. Conclusions

The implementation of ML methods in metrology enables significant improvement in the quality and efficiency of measurements, opening opportunities for innovation and enhancement. It is necessary to develop adaptive ML models capable of effectively operating in various scenarios and conditions. One important direction of development is the design of methods capable of ensuring the interpretability of ML model results. This en- hances trust in the decisions made and understanding of measurement processes. Hybrid models, combining the advantages of both ML methods and traditional metrological approaches, can provide optimal results when addressing complex measurement tasks.

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