Discussions on Integration of Automatic Detection Technology Course Knowledge and Mathematical Theory

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Abstract: Automatic detection technology is a key technology in modern engineering fields, involving sensor data processing, model development and optimization, feature extraction and analysis, all of which are closely related to mathematical theory. In teaching, a deep understanding and application of mathematical theory, such as solving equations, probability theory and statistics, numerical analysis, optimization theory are of great significance for cultivating students' analytical thinking and problem-solving abilities. This paper takes sensor calibration and electromagnetic detection device development as examples to explore teaching reform method of Automatic Detection Technology Course. By posing questions during the teaching process of automatic detection technology courses, it guides students to answer the questions and then reflect on the underlying reasons behind the questions, thereby understanding the mathematical principles behind the course topics. By employing the aforementioned approach, the integration of mathematical theory and detection technology course knowledge has been achieved, which enables students to not only fully digest the course knowledge but also deepen their understanding of mathematical theory.

Keywords: mathematical theory; automatic detection technology; equation solving; teaching reform

1. Introduction

Automatic detection technology is widely used in the development of intelligent sensor systems, industrial automation, aerospace, medical detection, and other fields [1, 2]. With the continuous development of technology, the complexity of automatic detection technology and the diversity of application scenarios are also increasing, such as monitoring of insect pests, diagnosis of COVID-19 infection, detection of defects in manufacturing [3-5].

In teaching, it is important to effectively cultivate students' professional skills and innovative thinking, enabling them to flexibly deal with various practical problems, many educators have made beneficial attempts. Some enhanced the connection with practical hands-on skills, such as practice-oriented education strategy [6] and project-based education [7], to cultivate the ability to solve practical problems. Some emphasized the use of modern tools [8], which enables education to keep pace with the times. Some integrate the craftsmanship spirit and focus on engineering applications in education [9, 10]. This paper attempts to explore the teaching reform of automatic detection technology course from the perspective of emphasizing the mathematical theories behind course knowledge. It requires students to grasp the mathematical theoretical foundation of detection technology in order to adapt to various changes and serve subsequent learning and practice.

2. Application of Mathematical Theory in Automatic Detection Technology

2.1. Application of Probability Theory and Statistics

Probability theory and statistics provide mathematical tools for modeling uncertainty and randomness. Measurement errors often have a random nature, meaning that the same quantity may have different measurement results in multiple measurements. Probability distribution is a mathematical tool for describing this randomness. Through probability distribution, we can understand the range of possible values of errors, probability density, and the probability of occurrence for each value.

For instance, many random errors follow a normal distribution, which is based on the probability density function in probability theory. The parameters of mean, variance, and standard deviation can describe the central position and dispersion of errors. The probability density function is a statistical regularity based on an infinite number of measurements. These parameters provide quantitative measures of error characteristics and can be used to evaluate the accuracy and precision of measurement methods.

In measurements, it is usually impossible to measure the entire population endlessly, so we need to sample a portion of the data to obtain a representative sample. The sampling theory provided by probability theory and mathematical statistics helps us understand the relationship between sample data and the population, enabling us to approximate the properties and distribution of the population based on sample data. In practice, we cannot perform an infinite number of measurements, but typically, making 10 measurements of the same value can approximate the distribution pattern of measurement random errors. It is an example of approximating from pure mathematical theory to engineering practice, and it demonstrates the application of mathematical theory to the field of automatic detection technology, sometimes requiring the use of approximation ideas. In course teaching, emphasis should be placed on the mathematical definitions of basic concepts and the approximation ideas in practical engineering applications.

2.2. Application of Numerical Analysis

Numerical analysis is a branch of mathematics that studies the methods and theories for solving mathematical computation problems using computers. In automatic detection technology, mathematical modeling of measurement parameters is often required, which involves solving differential equations. In practice, many differential equations are very difficult to solve. As one of the numerical analysis methods, finite difference methods can be used to approximate numerical solutions to differential equations or systems of differential equations.

A significant part of automatic detection technology is the introduction and application of sensor principles. If a sensor needs to be developed based on a certain physical effect, finite element numerical methods are often used to simulate and evaluate the performance of the sensor. For example, finite element numerical methods can be employed to analyze and evaluate the magnetic field of a sensor or analyze the modal properties of a sensor.

In course teaching, it is recommended to use specific examples of the permeation finite element method that are applicable.

2.3. Application of Optimization Theory

Many problems in automatic detection technology cannot be solved linearly, and in such cases, the mathematical framework and methods provided by optimization theory are needed. For example, optimization methods such as gradient descent and genetic algorithms are used to train models or optimize the coefficients of digital filters within a detection system. Additionally, neural network methods can be utilized to train detection systems for classification and recognition. These mathematical theories change the way we think and essentially involve trial and error based on certain rules, relying on the powerful computing capabilities of computers to solve problems. The three important aspects of the solution process are the objective function, driving mechanism, and receiving mechanism. In teaching, the mindset shift in problem-solving methods should be emphasized from the above perspectives, laying a foundation for students' knowledge transferability skills.

3. Mathematical theories in sensor calibration and analysis of its results

In automatic detection technology, polynomial functions can be used to establish models, fit curves, optimize parameters, and more. In sensor calibration, polynomial equations can be used to describe the nonlinear relationship between sensor output and input.

Taking an accelerometer sensor as an example, the output voltage can be expressed as a polynomial function of acceleration, where the constant term represents the bias, the linear term represents the scale factor, and the quadratic term represents the nonlinearity factor. We can ask the question: What series in advanced mathematics is this similar to? The answer is that it is essentially the Taylor expansion of the input-output curve. In teaching, we often mention that smaller quadratic terms are better, but why is that? It is because higher-order terms can lead to harmonic distortion. However, we can guide students to question why the resistance value of a thermistor temperature sensor is a cubic function of temperature, with all three terms present. It can lead students to think that a polynomial expression might better reflect the actual situation than a linear expression.

In fact, we are solving the equation by knowing the system output and calculating the input, which is equivalent to solving a polynomial equation. Here, we can further guide students to think about why the presence of a fourth or fifth-order term is not observed. It can be considered from the perspectives of model complexity and practical application. Adding higher-order terms would make the mathematical model more complex, requiring more parameters for fitting. It increases the complexity and computational cost of the model and may require more experimental data to accurately determine the coefficients of higher-order terms. In typical temperature measurement applications, there is usually no need to consider very large temperature ranges or extreme temperature changes. For applications within the normal temperature range, the cubic term is usually sufficient to accurately describe the nonlinear characteristics of a thermistor. The influence of higher-order terms is relatively small and can be neglected.

However, a more crucial explanation requires the use of foundational data theory. From a mathematical perspective, the measurement problem is a problem of solving a polynomial equation. In general, the higher the order of the polynomial, the more complex the solution becomes. Solving equations of the third degree or higher is relatively easy. For a cubic equation, we can use Cardano's formula or Vieta's formula to solve it. For a quartic equation (a fourth-degree polynomial), we can use methods like Ferrari's formula. However, for a polynomial of the fifth degree or higher, there is currently no general algebraic solution available. It is because the complexity of higher-order polynomial equations makes it impossible to find a general analytical solution. In such cases, we usually need to use numerical methods (such as iteration, numerical approximation, etc.) to approximate the solution. Understanding the aforementioned mathematical theory helps us understand why the cubic term is typically the highest order in general nonlinear expressions. It is because equation solving is required when using sensors for measurement.

By addressing these interconnected questions, students not only learn what is being discussed but also understand why it is the case. And both are achieved through a precise understanding of mathematical theory.

Typically, we need to analyze the results of sensor calibration, and a crucial related knowledge in detection techniques is the theory of error synthesis and decomposition.

By decomposing the total error, we can determine the contributions of different error sources to the system output. It helps identify the main sources of errors and take appropriate measures to reduce their impact. It also assists in optimizing system design, reducing the cumulative effects of errors, and improving the accuracy and reliability of the system. Error synthesis and decomposition can reveal potential issues and limitations in measurement methods. Additionally, by decomposing the total error, we can determine the impact of different error sources on measurement results. It helps improve measurement methods by reducing the influence of various error sources and enhancing measurement accuracy and repeatability.

Differential equations play a role in the application of error synthesis and decomposition. Error synthesis and decomposition is a method used to analyze and deal with the contributions of multiple sources of errors to the measurement errors of a system. Differential equations provide a mathematical framework for modeling the propagation and transmission of errors, describing the laws and effects of error propagation.

In error synthesis, differential equations can be used to describe the interaction and influence between different sources of errors. They can describe various sources of errors in the system through the form of differential equations and derive the error expression of the system output. By synthesizing and combining these error terms, the overall error expression of the system can be obtained, enabling analysis and evaluation of the total system error.

In error decomposition, by establishing the differential equations of the system model, the differential expression of the system output can be derived. By solving and analyzing the differential equations, the effect weight of each error source to the system output can be determined, facilitating error decomposition and quantitative assessment.

Differential equations provides a mathematical framework for modeling and analyzing the process of error propagation and transmission, assisting in optimizing system design, improving measurement methods, and enhancing measurement accuracy and reliability.

4. Mathematical theories in the Development of Magnetic-Electrical Detection Devices

The development of electromagnetic detectors involves the use of mathematical theories, such as a moving-coil detector that utilizes electromagnetic induction to detect ground vibrations. According to Faraday's law of electromagnetic induction, when the magnetic field changes due to ground vibrations, the coil in the detector cuts through the magnetic field lines, generating an induced electromotive force. By measuring the variation in the induced electromotive force, the intensity and frequency of the ground vibration signal can be indirectly detected.

The moving-coil detector consists of a spring-mass system and a magnetic circuit system. The spring-mass system is a typical second-order system that receives the ground vibration signal and converts it into relative motion between the mass and the magnet. The magnetic circuit system includes permanent magnet steel, soft magnetic pole pieces, and a soft magnetic material housing. These components form a closed loop, with the coil-magnet assembly placed in the air gap between the pole pieces. External vibrations cause the mass to cut through the magnetic field lines, converting the external vibration signal into an electrical signal.

Mathematical theories play a guiding role in various stages of the development of moving-coil detectors:

A: Modeling. Differential equations are mathematical tools used to describe the vibration and electromagnetic induction processes in moving-coil detectors. By establishing the differential equations for the second-order system of the moving-coil detector, one can analyze the system's dynamic behavior and response characteristics. By transforming the differential equations into frequency domain transfer functions using complex transforms, transfer function models can be established to analyze the system's frequency response characteristics and frequency selectivity.

B: Simulation and Evaluation. In the simulation and evaluation stage, finite element methods can be used to model and analyze the magnetic circuit system, solving equations for magnetic field distribution and evaluating the characteristics of the magnetic circuit system. The spring-mass system of the moving-coil detector can be modeled as a second-order system. By using finite element methods to establish the mechanical model of the spring-mass system and conducting simulation analysis, one can predict and evaluate parameters such as spring stress distribution and system vibration characteristics.

C: Mechanical Manufacturing. In the mechanical manufacturing stage, mathematical global optimization methods can be utilized to optimize the structure of the moving-coil detector. By considering factors such as the mechanical properties of materials, stress analysis, and structural stability, structural design and optimization can be performed.

D: Experimental Testing. In experimental testing, mathematical fitting algorithms can be used to analyze and process experimental data. By fitting the experimental data, key system parameters can be obtained.

In conclusion, mathematical theories play an important role in various stages of detector device development. It is helpful to present this information using visual aids to create a clear and intuitive understanding.

5. Conclusion

The core of automatic detection technology is based on mathematical principles. Probability theory, statistics, numerical analysis, and other mathematical foundations form the basis of automatic detection technology, providing us with the mathematical framework for detection techniques. The innovation of detection technology often requires a shift in mathematical thinking.

For example, by integrating concepts from mathematics such as state space, linear systems, and Bayesian estimation, Kalman filtering provides an effective method for system state estimation. This shift in thinking has made Kalman filtering an important tool for solving estimation problems.

In the field of object detection, traditional methods are often based on manually designed features and classifiers. However, with the rise of deep learning, people have begun to adopt end-to-end detection methods based on neural networks. This shift represents a transition from traditional models and features to multi-layer neural network model representations.

Incorporating mathematical methods and thinking into the education of automatic detection technology has several benefits:

A: Deepened understanding. Mathematics is the foundation of automatic detection technology. Incorporating mathematical methods and thinking into education can help students gain a deeper understanding of the principles and algorithms of detection technology.

B: Technological innovation. The introduction of mathematical methods and thinking can inspire students' creativity and innovative thinking. They can approach problems from a mathematical perspective, explore new algorithms and technical solutions. It helps cultivate students' problem-solving and innovation abilities, enabling them to propose new ideas and methods in practical applications.

C: Enhanced comprehensive abilities. Learning mathematical methods requires students to possess comprehensive abilities such as problem analysis, model building, and deductive reasoning. Incorporating mathematical methods and thinking into education can promote the enhancement of students' comprehensive abilities, cultivate their logical thinking, abstract thinking, and reasoning abilities.

D: Practical applications. The application of mathematical methods and thinking is not limited to the theoretical level. It can also help students apply their knowledge to practical problems. Through real-world cases and project practices, students can apply mathematical methods to tasks such as data processing, model building, and algorithm optimization, fostering their practical skills and problem-solving abilities.

As technology continues to evolve and application domains change, new mathematical methods and thinking will be explored to solve new problems. By incorporating mathematical methods and thinking into the education of automatic detection technology, not only can a deeper understanding of automatic detection technology be achieved, but also students can be motivated to engage in technological innovation, making their learning meaningful, applicable, and fruitful.

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