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Integrating the Bisection Method into a STEM-Based Learning Model on Linear Programming for Robotics-Oriented Problem Solving and 21st-Century Skills Enhancement

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Abstract - This research aims to develop a STEM-based learning model on linear programming that integrates the bisection method to minimize modeling errors and enhance 21st-century skills among senior high school students. The study adopts a Research and Development (R&D) approach using the ADDIE model, encompassing analysis, design, development, implementation, and evaluation stages. The novelty of this model lies in embedding the bisection method not only as a numerical technique but also as a pedagogical strategy to support students in formulating more accurate mathematical models. Importantly, this study connects mathematical modeling in linear programming with real-world applications in robotics and automation, where optimization under constraints is critical. By engaging students in problem-solving scenarios inspired by robotics—such as task scheduling, energy management, and path planning—students learn to apply iterative logic similar to the reasoning used in robotic decision-making processes. The bisection method enables them to systematically refine solutions, reduce conceptual errors, and strengthen logical consistency. Data were collected through expert validation, pre- and post-tests, and observations of 21st-century skills, including critical thinking, creativity, collaboration, and communication. The findings reveal that the integration of the bisection method significantly reduces modeling errors and promotes interdisciplinary thinking relevant to robotic system design. This model offers a promising instructional innovation that bridges mathematical theory, STEM-based pedagogy, and the practical reasoning frameworks of intelligent robotic systems.

Keywords: STEM learning, bisection method, linear programming, modeling error, 21st-century skills, robotics, optimization

1. INTRODUCTION

In the era of rapid technological advancement and automation, education must evolve to prepare students with the knowledge and skills required for the 21st-century workforce, particularly in fields such as robotics, artificial intelligence, and control systems. These fields demand not only technical proficiency but also strong abilities in critical thinking, problem-solving, collaboration, and mathematical modeling.

One of the key mathematical tools applied extensively in robotics and automation is linear programming (LP). LP is used to solve optimization problems involving limited resources, path planning, task scheduling, and energy efficiency—all of which are essential in robotic system design and operation. Despite its importance, students often struggle with LP due to the abstract nature of the modeling process, which requires careful identification of variables, constraints, and objective functions. Errors in this modeling stage can lead to inaccurate solutions that are not viable for real-world applications.

To address this challenge, this study integrates the bisection method, a classical numerical approach used to find the root of a function, into a STEM-based learning model for LP. While the bisection method is traditionally introduced at the university level, it can be effectively adapted as a pedagogical strategy to help high school students refine their modeling logic and reduce conceptual errors. The method teaches students to iteratively narrow down solution ranges, which mirrors how autonomous robots make decisions based on step-by-step evaluations within defined constraints.

The application of STEM (Science, Technology, Engineering, and Mathematics) education provides an ideal framework for this integration. STEM-based learning emphasizes interdisciplinary approaches and real-world problem solving, making it highly relevant for preparing students to understand the mathematical and technological underpinnings of robotics. By embedding the bisection method within LP problems contextualized in robotics—such as optimizing a robot's movement through a grid, allocating battery power for multiple tasks, or minimizing time to complete delivery routes—students are exposed to the kind of iterative logic and decision-making processes used in robotic programming.

Moreover, STEM learning environments cultivate 21st-century skills, which are essential in the design, development, and operation of robotic systems. These include:

- Critical thinking, needed for debugging algorithms and analyzing robotic behavior,
- Creativity, for designing novel robotic solutions,
- Collaboration, often required in multidisciplinary robotics teams,
- Communication, which is key to documenting and presenting engineering solutions.

Thus, the integration of the bisection method into a STEM-based linear programming model not only supports mathematical comprehension but also bridges the gap between classroom learning and real-world robotic

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applications. It fosters the kind of analytical mindset and iterative thinking necessary for students to thrive in automation-driven industries.

This research aims to develop and evaluate such a learning model, measuring its impact on reducing students' modeling errors and enhancing their 21st-century skills, while also simulating the reasoning and logic used in real robotic decision-making systems.

2. RESEARCH METHODOLOGY

2.1 Research Design

This research employed a **Research and Development (R&D)** approach, guided by the **ADDIE model** (Analysis, Design, Development, Implementation, and Evaluation). The study aimed to produce a STEM-based learning model that integrates the **bisection method** as a tool to minimize modeling errors in linear programming and to prepare students for real-world applications—especially in fields such as **robotics and automation**.

The rationale behind choosing the R&D method is rooted in the need to not only investigate theoretical understanding but also to **design, implement, and evaluate a practical instructional model** that mirrors engineering processes commonly used in robotic system design—such as model iteration, feedback-based refinement, and constraint-based optimization.

2.2 Subjects and Setting

The research involved 34 students from a senior high school (Class XI) in the Mathematics and Science program and three experts in mathematics education and educational technology. The study was conducted in a classroom setting equipped with computers and simulation tools, allowing students to engage in tasks related to optimization problems inspired by robotic systems, such as automated path planning and resource allocation.

2.3 Development Process

Each phase of the ADDIE model was adapted to incorporate robotic concepts within the linear programming context:

- Analysis: Identified students' common misconceptions in LP and explored how robotics-related scenarios (e.g., robot route optimization, task scheduling) can be embedded to improve engagement and contextual relevance.
- Design: Created lesson plans and student worksheets involving STEM challenges that required LP formulation and step-by-step error reduction using the bisection method—similar to how robotic systems iteratively calibrate sensors or adjust control parameters.
- Development: Produced learning materials, simulations, and interactive modules. Example problems included minimizing a robot's travel distance given certain constraints, resembling path-planning algorithms in robotics.
- Implementation: The model was implemented over 4 sessions in a real classroom setting. Students worked in groups to solve robotics-inspired LP problems using the bisection method to refine their model accuracy, mimicking the trial-and-error process in robotic programming.
- Evaluation: Data were collected using pre- and post-tests, observation sheets, performance rubrics, and expert validation. The results measured both the reduction of modeling errors and the improvement of 21st-century skills, particularly those relevant to collaborative engineering tasks in robotics.

2.4 Instruments and Data Collection

The instruments used included:

- Validation sheets (assessing content quality, STEM integration, and feasibility),
- Student worksheets featuring LP problems inspired by robotic scenarios,
- Pre- and post-tests measuring modeling accuracy,
- Observation sheets focusing on indicators of critical thinking, communication, collaboration, and creativity.

Qualitative data were also collected through student interviews and group discussions to analyze how the learning process simulated robotic system design logic, such as feedback loops and adaptive decision-making.

2.5 Data Analysis

Data were analyzed using both quantitative and qualitative techniques:

- Quantitative data from pre- and post-tests were analyzed using descriptive statistics (mean, percentage improvement) to evaluate the effectiveness of the bisection method in reducing modeling errors.
- Qualitative data from observations and student reflections were categorized into themes related to engineering thinking, problem-solving in robotic systems, and STEM integration.

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Through this methodology, the study not only assesses academic outcomes but also demonstrates how structured mathematical thinking, when taught through STEM-based LP modules, can reflect the cognitive processes involved in real robotic systems—such as constraint-based control, iterative optimization, and feedback learning.

3. RESULT AND DISCUSSION

3.1 Model Development and Validation

The STEM-based learning model was developed by integrating the bisection method within linear programming modules designed for senior high school students. Expert validation showed a high level of feasibility and relevance, with an average score of 92% across indicators of content quality, instructional design, and innovation. The model consisted of five phases:

1. Contextual engagement through real-world robotic problem scenarios,
2. STEM concept exploration,
3. Application of the bisection method to refine mathematical modeling,
4. Collaboration and communication of solutions, and
5. Reflection and iteration.

This structured learning design enabled students to iteratively model and verify optimization problems, such as resource allocation or shortest path selection, which are also fundamental in robotic systems.

3.2 Reduction of Modeling Errors

The integration of the bisection method significantly reduced errors in students' formulation of linear programming models. The average error rate decreased from 31% in the pre-test to 9% in the post-test. Students developed a better understanding of constraints, variables, and feasible regions in LP problems.

Indicator	Pre-Test (%)	Post-Test (%)	Improvement
Accurate problem formulation	62%	89%	+27%
Logical estimation	55%	91%	+36%
Error detection ability	61%	88%	+27%

This reduction in modeling errors is not only an academic achievement but also reflects an essential capability in robotics engineering, where precision in mathematical modeling and constraint definition directly affects robotic performance. For example, robotic arm motion planning, obstacle avoidance, and task scheduling often rely on linear programming and numerical methods to reach optimized, real-time decisions.

By practicing these methods in an educational setting, students begin to simulate the cognitive processes of a robot—iteratively narrowing solution spaces, refining actions based on constraints, and selecting optimal outcomes. The bisection method, while simple, introduces them to the logic of divide-and-conquer algorithms, which are frequently used in robotic pathfinding and root-solving applications in real-time control systems.

3.3 Development of 21st-Century Skills

Observational and qualitative analysis revealed substantial improvements in the four core 21st-century skill domains:

- Critical Thinking: Developed through iterative evaluation of LP models using the bisection method. Students learned to question initial assumptions, test their models, and adjust strategies based on results—similar to robotic calibration.
- Creativity: Evident when students formulated their own real-world optimization problems, often inspired by automation or robotic contexts (e.g., minimizing energy consumption in a delivery robot).
- Collaboration: Fostered through group discussions and peer model verification. Students mirrored collaborative debugging processes commonly used in robotics project teams.
- Communication: Improved through the presentation of model outcomes and reflection sessions. Students had to articulate their mathematical reasoning and explain their iteration logic clearly.

These skills mirror the soft and technical competencies required in robotics development—where design thinking, teamwork, and clear documentation are crucial components of system success.

3.4 Discussion and Robotic Relevance

This study confirms that the bisection method can be more than a mathematical technique—it becomes a didactic tool that mimics the operational logic of robotic systems. In robotics, especially autonomous systems, decisions are often made based on iterative computations that seek optimal results within constraint boundaries. The student learning experience in this research closely aligns with such decision-making architectures.

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Moreover, introducing the concept of error reduction through logical iteration builds a foundation for students to later grasp more complex optimization algorithms used in robotics, such as genetic algorithms, PID tuning, or gradient descent.

In educational robotics—such as robot line-followers or automated warehouse prototypes—students can apply the same LP principles used in this study to determine path efficiency, load distribution, or energy management. Therefore, the learning model developed here is not only academically sound but bridges abstract mathematical learning with tangible, real-world robotic applications.

4. CONCLUSION

This study has established that integrating the bisection method into a STEM-based learning model in linear programming can effectively reduce modeling errors and enhance 21st-century competencies among senior high school students. Beyond its success in improving mathematical accuracy and cognitive skills, this model also holds promising implications for real-world applications—particularly in the field of robotics.

The learning model encourages students to engage with real-life problem-solving scenarios that mirror the types of optimization challenges commonly found in robotic systems, such as path planning, motion control, and resource allocation. By learning how to use the bisection method to iteratively narrow down feasible solutions within defined constraints, students indirectly practice the same logic-driven processes applied in robotic programming and control algorithms.

Furthermore, linear programming itself is a foundational tool in robotics for optimizing movements, minimizing energy consumption, or scheduling multiple tasks simultaneously. The reduction of modeling errors through the bisection-based approach ensures that students not only construct more accurate mathematical models but also understand how these models can be embedded in autonomous systems to make precise, data-driven decisions.

This connection is vital as robotics becomes increasingly integrated into educational and industrial settings. Students who are trained using STEM frameworks enriched with numerical reasoning methods are better prepared to design or interact with intelligent robotic systems. They learn not only how to model constraints and objectives mathematically but also how to iterate, verify, and refine those models in dynamic environments—skills that mirror the core of robotics programming and AI system development.

In conclusion, the integration of the bisection method within a STEM-based learning model does not merely serve academic purposes but also builds a bridge toward applied technologies like robotics. This positions students to become future contributors in interdisciplinary fields where mathematics, engineering, and technology converge to solve complex, real-world challenges. Future research may expand this model by applying it directly to robotics-based projects in the classroom, fostering hands-on learning experiences that align even more closely with industry demands.

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