Analogical Pedagogy for Control Systems: A Case Study on Controllability and Observability

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Abstract—**This study investigates the effectiveness of analogy-based pedagogy in enhancing the understanding of the abstract concepts of controllability and observability in a Control Systems course. Two analogies—one based on a car driving scenario and another on the teaching–learning process—were introduced sequentially to a cohort of 120 undergraduate electrical engineering students. Performance was assessed using a structured pre-test and two post-tests following each analogy session. Statistical analysis, including paired t-tests, F-tests for variance, and ANOVA, revealed significant improvements in student scores after each analogy intervention, with stable score variability, indicating genuine comprehension gains. Qualitative feedback further supported the positive impact of the analogies on student engagement and conceptual clarity. These results demonstrate that carefully crafted analogies serve as effective instructional tools to bridge the gap between abstract theory and intuitive understanding in engineering education.**

Keywords—**Analogy-based Pedagogy, Statistical Analysis, Controllability, Observability**

JEET Category—**Choose one: Practice**

I. INTRODUCTION

THE control system course is a cornerstone of engineering education, equipping students with the ability to design mechanisms that regulate and optimize processes in diverse fields such as electrical, mechanical, aerospace, and chemical engineering. It enables future engineers to ensure stability, accuracy, efficiency, and automation in real-world applications ranging from industrial machines to modern vehicles. A control system regulates a process to achieve desired outputs by using concepts like modeling, transient response, steady-state error, stability analysis and feedback control design [1]. Modern control theory is the next step in the control system course, where students are empowered to design a control system for various physical systems. This includes state feedback control, observer design, etc [2]. Among these, controllability and observability are pivotal in state-space analysis: controllability ensures that all system states can be driven to desired values, while observability allows internal states to be determined from outputs [3]. These concepts are critical for effective controller and estimator design but are often challenging to understand due to their abstract mathematical nature and limited physical visibility.

Various techniques can be employed to explain controllability and observability, including mathematical derivations, graphical interpretations, physical demonstrations, simulation-based visualization, and case studies [4]. Mathematical approaches, though precise, often feel abstract and disconnected from real-world intuition, while graphical plots and simulations help but may still lack relatable context. Physical demonstrations and case studies offer tangibility but are sometimes limited in scope or resources. Among these, analogy stands out as a powerful pedagogical tool because it bridges abstract theory with familiar, everyday experiences, enabling learners to intuitively grasp complex ideas [5]. By mapping the unfamiliar (system states, inputs, outputs) to the familiar (e.g., driving and navigation in a car), analogy not only aids retention and engagement but also supports conceptual transfer, allowing students to recall and apply these principles more effectively in diverse engineering contexts [6]. Analogy is a cognitive process in which knowledge or structure from a familiar domain (source) is mapped onto an unfamiliar domain (target) to aid understanding, problem solving, or communication [7]. Rather than focusing on superficial similarities, effective analogies rely on structural correspondence—matching the relationships between elements in the source and target domains [8]. In education, analogies serve as a bridge between prior knowledge and new concepts, enabling learners to visualize, reason about, and retain abstract or complex ideas. When carefully designed and explicitly mapped, analogies can reduce cognitive load, foster conceptual transfer, and make learning more engaging.

Analogy-based pedagogical approaches have been explored across diverse educational contexts for enhancing teaching and learning outcomes. In [9], an analogy-driven methodology was proposed to support artificial intelligence (AI) education in upper primary classes. A quasi-experimental study employing mixed methods revealed that students exposed to this approach significantly outperformed their peers taught through conventional direct instruction, demonstrating superior performance in AI knowledge, skills, and ethical awareness. Similarly, [10] investigated the application of analogy learning in primary Physical Education (PE) lessons. While the study reported positive effects, it also noted certain limitations and emphasized the need for greater awareness of analogy pedagogy in PE contexts. Both [9] and [10] primarily address school-level applications. Expanding this to higher education, [11] examined the spontaneous use of analogies and metaphors among electrical engineering undergraduates when

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discussing concepts such as current, voltage, and resistance in electric circuits, highlighting its role in conceptual understanding. Furthermore, [12] integrated analogy pedagogy into an engineering course on project-based learning, where it was employed for idea generation and enhancing creativity. In this context, "design by analogy" was used as a creative methodology for identifying novel ideas from distant domains beyond the immediate problem space.

Overall, the literature suggests that analogy pedagogy fosters deeper understanding, supports knowledge transfer, and stimulates creativity across educational levels and disciplines. Its versatility in both conceptual learning and innovative thinking underscores its significance as a powerful instructional strategy in contemporary pedagogy. In this paper, analogy is employed as a pedagogical tool to enhance the understanding of controllability and observability. Two carefully designed analogies are presented: the first relates to driving a car, and the second to the teaching–learning process. To evaluate the effectiveness of these analogies, a classroom-based case study was conducted. Initially, the topic was taught using the conventional approach without analogy, followed by a pre-test. Subsequently, Analogy 1 was introduced to reinforce the concept, and Post-Test 1 was administered. Thereafter, Analogy 2 was discussed, and Post-Test 2 was conducted. The comparative analysis of test results demonstrates the progressive improvement in students' conceptual understanding, highlighting the potential of analogy as an effective instructional strategy in control systems education.

The remainder of this paper is organized as follows: Section II presents the mathematical formulation of controllability and observability. Section III describes Analogy 1 and Analogy 2 in detail. Section IV discusses the results and provides an analysis of the findings. Finally, Section V concludes the paper.

II. CONTROLLABILITY AND OBSERVABILITY

System Description

Consider an nth order linear time-invariant (LTI) single-input single-output system in state-space form:

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

where x is a state, u is the control input, **A** is the system matrix of order (n x n), **B** is the input matrix of order (n x 1), y is the output, C is the output matrix of order (1 x n), and D is the direct transmission matrix of order (1 x 1).

Controllability

Now, as per the standard definition of controllability, the system is said to be completely state controllable if, for any initial state $x(t_0)$ and any desired final state $x(t)$, there exists an input u(t) that transfers the system from $x(t_0)$ to $x(t)$ in finite time [2]. Mathematically, it is proved by calculating the controllability matrix as follows. The system is controllable if and only if the controllability matrix

$$Q_c = [B \quad AB \quad A^2B \quad ... \quad A^{n-1}B]$$

has full rank, i.e., rank(**Q$_c$**)=n.

Observability

Further, as per the standard definition of observability, the system is said to be completely state observable if, for any initial state $x(t_0)$, knowledge of the output y(t) over a finite time interval $t_0 \leq t \leq t_1$ and the input u(t) is sufficient to uniquely determine $x(t_0)$ [2]. Mathematically, it is proved by calculating the observability matrix as follows. The system is completely observable if and only if the observability matrix

$$Q_o = [C \quad CA \quad CA^2 \quad ... \quad CA^{n-1}]^T$$

has full rank, i.e., rank(**Q$_o$**)=n.

Mathematically, calculating the controllability matrix and determining its rank is straightforward, and the same applies to the observability matrix. However, grasping the true meaning behind these definitions is more challenging. As a result, students often memorize the definitions and follow the numerical procedures demonstrated by the teacher without fully understanding the underlying concepts. Even for instructors, conveying the essence of these definitions intuitively can be difficult. By introducing analogies, these concepts can be linked to familiar situations, making it easier for students to relate elements such as the initial state, desired state, control input, and knowledge of outputs, thereby fostering deeper conceptual understanding.

III. ANALOGY FOR EXPLAINING THE CONCEPTS OF CONTROLLABILITY AND OBSERVABILITY

Analogy 1 Car Driving System

Consider a driver moving a car with some initial speed. As the driver approaches a square with no traffic signal, another vehicle is about to cross the road from a perpendicular direction. The driver must decide whether to cross before the other vehicle. If, based on the initial speed and location (position), the driver can apply the appropriate acceleration (control input) and reach the other side (desired state) safely within a finite time, the system is controllable. Otherwise, the system is uncontrollable, and an accident will occur. This has been given in Table 1 below.

TABLE I
COMPARISON OF TERMS WITH THE CAR DRIVING SYSTEM

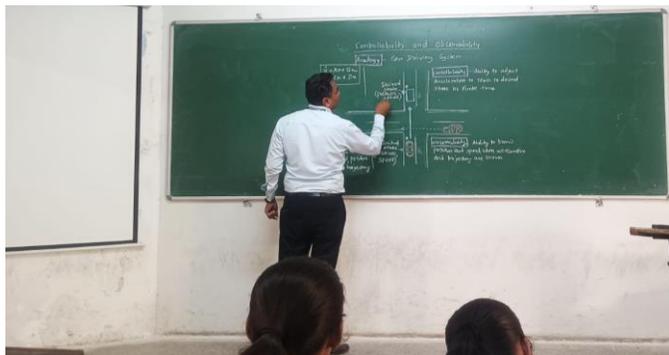| Control System Term	Car Driving Analogy
Initial State	Car's current position and speed before reaching the square
Desired State	Safely reaching the other side of the square before the other vehicle
Control Input	The acceleration applied by the driver
Controllability	Ability to adjust acceleration to reach the desired state in a finite time
Uncontrollable System	Inability to reach the desired state in a finite time, leading to an accident
Observability	The driver's ability to perceive the other vehicle's position, speed, and trajectory
Unobservable System	The driver is unable to see or sense the approaching vehicle, leading to wrong decisions.

Fig. 1. Graphical representation of a car driving system on a green board

Analogy 2 Teaching Learning Process

In this analogy, the control system is represented by a teaching–learning process. The teacher acts as the input, aiming to take students from their initial knowledge level at the start of the course (initial state) to a target level where they can achieve more than 75% marks (desired state). The inputs provided by the teacher include lecture notes, classroom discussions, assignments, videos, and PowerPoint presentations. If, through these inputs, all students can achieve the desired performance level within the duration of the course, the overall system is said to be controllable. If some students fail to reach this level despite the teaching efforts, those individual cases are considered uncontrollable states.

From the observability perspective, the teacher can only assess and guide students effectively if their learning progress is visible through tests, quizzes, assignments, and interactions. If the teacher can clearly determine each student's level of understanding and identify their knowledge gaps, the system is observable. However, if the learning progress remains hidden (e.g., students do not attempt assignments, avoid participation, or assessment tools are inadequate), then the system is unobservable for those students, making it harder to take corrective action.

TABLE II
COMPARISON OF TERMS WITH THE TEACHING LEARNING PROCESS ANALOGY

Control System Term	Teaching–Learning Process Analogy
System	Classroom with students
Initial State	Students' knowledge level at the start of the course
Desired State	Students achieving >75% marks (high competency level)
Inputs	Lecture notes, classroom discussions, assignments, videos, and PowerPoint presentations by the teacher
Output	Students' performance in exams, assignments, and projects
Controllable System	All students reach the desired state within the course duration.
Uncontrollable System	Some students fail to reach the desired state despite teaching efforts.
Observability	Teachers can assess learning progress through tests, quizzes, interactions, and assignments.
Unobservable System	The teacher cannot clearly determine progress due to a lack of participation or inadequate assessment.

IV. RESEARCH DESIGN

The objective of this study is to investigate the effectiveness of using analogies, specifically the Car Driving System analogy and the Teaching-Learning Process analogy, to enhance the understanding of controllability and observability concepts in a Control Systems Engineering course. The research is conducted with a sample of 120 undergraduate students enrolled in the third year of the Electrical Engineering program. The research design is given in Figure 2.
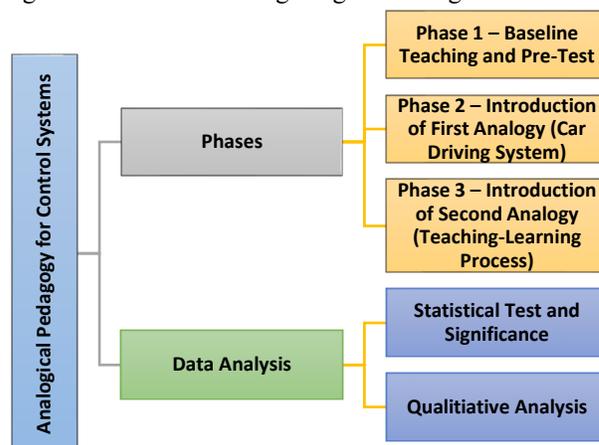

Fig. 2. Research Design

Phase 1 – Baseline Teaching and Pre-Test
Initially, the concepts of controllability and observability are taught using the regular instructional method in a two-hour classroom session without introducing any analogy. Following this session, a pre-test of 20 marks is conducted to assess baseline understanding. The test is structured as follows:
4 marks: Multiple Choice Questions (MCQs)
4 marks: True/False questions
4 marks: Short answer questions
8 marks: Long answer questions
Peer assessment is employed for evaluating the answer sheets to encourage student involvement and critical review. The question-wise marks for each student are recorded for further analysis.

Phase 2 – Introduction of First Analogy (Car Driving System)
In the second phase, the Car Driving System analogy is introduced and explained in a one-hour interactive session, mapping car control mechanisms to controllability and observability principles. After this, Post-Test 1 (20 marks) is conducted using the same format as the pre-test but with an increased difficulty level to evaluate knowledge gains and the ability to apply concepts. Peer assessment is again carried out, and question-wise marks are documented.

Phase 3 – Introduction of Second Analogy (Teaching-Learning Process)
In the third phase, the Teaching-Learning Process analogy is presented in a one-hour session, focusing on mapping teacher-student interactions, feedback, and instructional strategies to controllability and observability concepts. Following this, Post-Test 2 (20 marks) is conducted, maintaining the same structure but with a further increased difficulty level to test deeper conceptual understanding and application skills. Peer assessment is performed, and marks are noted question-wise.

Data Analysis
The performance of students in the Pre-Test, Post-Test 1, and Post-Test 2 is compared on a question-by-question basis for all 120 students. The analysis aims to identify improvement trends, the effect of each analogy, and the overall enhancement in comprehension. It is observed that student understanding improves progressively after each analogy, with

notable gains in both conceptual clarity and problem-solving ability.

V. RESULTS AND DISCUSSIONS

The analysis of students' performance across the three assessment stages—Pre Test, Post Test 1, and Post Test 2—demonstrates a clear and progressive improvement in understanding the concepts of controllability and observability, attributable to the instructional analogies introduced. This is shown in Figure 3.
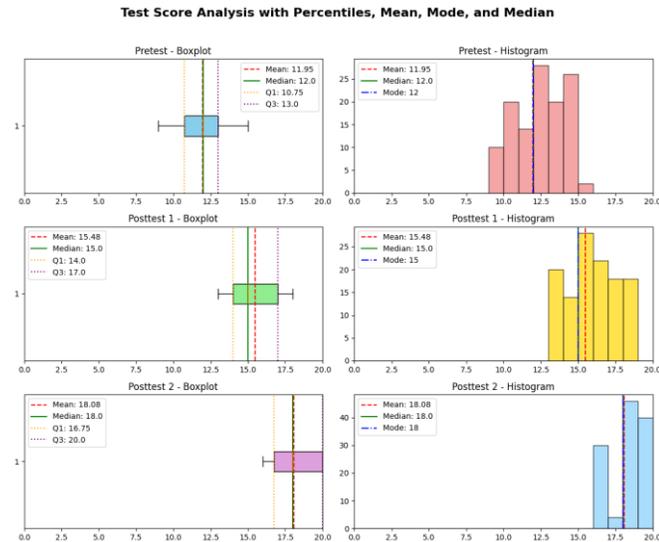

Fig. 3. Test-wise Distribution boxplot and Histogram

Performance Metrics

- *Pre Test* The baseline mean score was 11.95 out of 20, with a median of 12 and a mode of 12. The interquartile range (IQR) spans from 10.75 (Q1) to 13.0 (Q3), indicating a moderate level of initial comprehension with some variability among students.

- *Post Test 1 (After Car Driving Analogy)* The mean score increased significantly to 15.48, with a median and mode both at 15. The IQR widened slightly (14.00 to 17.0), showing not only an improvement in average understanding but also that a majority of students gained a deeper conceptual grasp following the introduction of the car driving analogy. This suggests that mapping abstract control system concepts to a familiar real-world scenario enhanced students' engagement and cognitive connection.

- *Post Test 2 (After Teaching–Learning Analogy)* The highest mean score of 18.08, with a median and mode of 18, and an expanded IQR from 16.75 to 20.0, reflects continued and substantial improvement in student learning. The teaching-learning analogy likely reinforced and expanded their conceptual framework by relating system dynamics to their own educational experience, further solidifying their understanding.

The incremental increases in mean, median, and mode scores between the Pre Test and successive Post Tests strongly indicate that the use of analogy-based teaching was effective in improving students' comprehension of challenging abstract concepts. The narrowing of the gap between median and mode scores in later tests also reflects a more consistent understanding among the students.

The analogies worked as cognitive bridges, transforming theoretical ideas into relatable scenarios, which reduced cognitive load and promoted active learning. The car driving analogy provided a tangible mental model of system controllability and observability, while the teaching-learning analogy personalized the concepts, fostering higher-order thinking about control systems in an educational context.

Overall, these results support the hypothesis that analogy-based pedagogy enhances conceptual understanding, engagement, and application skills in engineering education. The significant improvement from Pre Test to Post Test 2 highlights the potential for integrating well-designed analogies into control systems curricula to address learning difficulties commonly encountered with abstract mathematical topics. In doing all these experiments, it must be noted that all student-related data is collected as per the institutional guidelines, and students were voluntarily encouraged to participate in the process. Ethical guidelines are followed for the student data.

VI. STATISTICAL ANALYSIS AND INTERPRETATION

To quantitatively assess the effectiveness of the analogy-based teaching interventions, statistical tests were conducted comparing student performance across the three assessments: Pre-test 1, Post-test 1, and Post-test 2 and as shown in Figure 4 and Table 3.

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| Test Type          | Comparison                | Statistic  | p-value      |
|--------------------|---------------------------|------------|--------------|
| Paired t-test      | Pre-test 1 vs Post-test 1 | -68.615    | 1.5297e-97   |
| Paired t-test      | Pre-test 1 vs Post-test 2 | -113.273   | 4.7936e-123  |
| F-test (variance)  | Pre-test 1 vs Post-test 1 | 1.012      | 0.94997      |
| F-test (variance)  | Pre-test 1 vs Post-test 2 | 1.228      | 0.26349      |
| ANOVA              | All three tests           | 444.765    | 1.1704e-97   |
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Fig. 4. Statistical Test Results

TABLE III
STATISTICAL TEST RESULTS

Test Type	Comparison	Statistic	p-value
Paired t-test	Pre-Test vs Post-Test 1	-68.615	1.53×10^{-97}
Paired t-test	Pre-Test vs Post-Test 2	-113.273	4.79×10^{-123}
F-test (variance)	Pre-Test vs Post-Test 1	1.012	0.95
F-test (variance)	Pre-Test vs Post-Test 2	1.228	0.263
ANOVA	All three tests	444.765	1.17×10^{-97}

Paired t-tests comparing Pre-Test with Post-test 1 and Post-test 2 yielded highly significant results ($p \ll 0.001$), indicating that the improvements in student scores after introducing each analogy are statistically significant. The large negative t-statistics confirm that the mean scores in the post-tests were significantly higher than in the pre-test.

F-tests for variance show no significant difference in the variability of scores between Pre-Test and either Post-test 1 or Post-test 2 ($p > 0.05$). This suggests that the variance among student scores remained stable, implying consistent

performance improvements across the group rather than outliers driving the changes.

The **ANOVA test** across all three tests confirms a highly significant difference in means ($p \ll 0.001$), further supporting the conclusion that the analogies have a positive and measurable effect on student learning outcomes.

The statistical analysis validates the effectiveness of analogy-based instruction. Students exhibited substantial and statistically significant gains in understanding controllability and observability concepts after each pedagogical intervention, without significant changes in score variability. This demonstrates that the analogies facilitated a broad-based improvement in conceptual grasp among the student cohort.
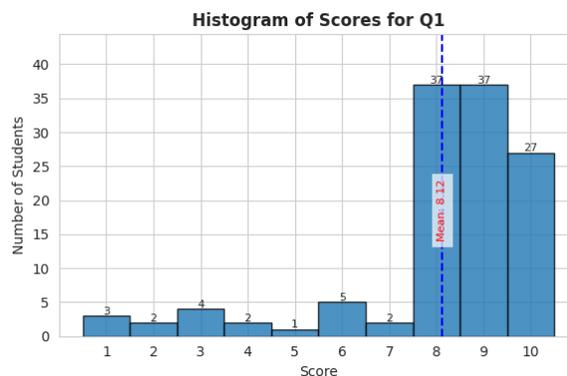
TABLE IV
HYPOTHESIS TESTING

Test Type	Hypothesis	Paragraph Explanation
Paired t-test	Null Hypothesis (H0): There is no significant difference in the mean scores between the compared tests.	The null hypothesis for the paired t-test assumes that the average student scores before and after the introduction of analogies are statistically the same. This means that the analogies did not produce any real improvement in student performance, and any difference is due to chance.
	Alternative Hypothesis (H1): There is a significant difference in the mean scores between the compared tests.	The alternative hypothesis states that there is a significant improvement in mean scores after introducing analogies, showing that the analogies had a positive effect on students' understanding and learning outcomes.
F-test for Variance	Null Hypothesis (H0): The variances of the two compared groups are equal.	The null hypothesis for the F-test assumes that the variability or spread in student scores remains consistent between the compared tests. This means any observed change in average scores is not due to increased or decreased variability among students' performances.
	Alternative Hypothesis (H1): The variances of the two compared groups are not equal.	The alternative hypothesis suggests a significant difference in the variability of scores between the tests, which could indicate that the consistency of student performance changed, potentially affecting the interpretation of improvements in average scores.
One-way ANOVA	Null Hypothesis (H0): The mean scores of all three groups are equal.	The null hypothesis in the ANOVA test assumes that there are no differences in the average scores across all three test phases, before and after introducing the analogies. This implies that student performance did not change meaningfully during the study.
	Alternative Hypothesis (H1): At least one group has a significantly different mean score.	The alternative hypothesis posits that at least one test phase differs significantly in average score, indicating that student performance changed over time, which could be attributed to the teaching interventions, like analogy-based instruction.

Test Type	Comparison	Statistic	p-value	Hypothesis Result
Paired t-test	Pre-test 1 vs Post-test 1	t = -68.615	1.53E-97	Reject H0: Significant improvement in scores after the first analogy introduction.
Paired t-test	Pre-test 1 vs Post-test 2	t = -113.273	4.79E-123	Reject H0: Significant improvement in scores after the second analogy introduction.
F-test (variance)	Pre-test 1 vs Post-test 1	F = 1.012	9.50E-01	Fail to reject H0: Variances are statistically similar; no significant difference.
F-test (variance)	Pre-test 1 vs Post-test 2	F = 1.228	2.63E-01	Fail to reject H0: Variances are statistically similar; no significant difference.
ANOVA	All three tests	F = 444.765	1.17E-97	Reject H0: Significant differences exist among the three test groups.

The introduction of analogies as teaching tools significantly enhanced student understanding and performance in the control systems course. The consistent increase in mean scores from Pre-test to Post-test 1 and further to Post-test 2, supported by statistically significant paired t-tests and ANOVA results, confirms that analogies effectively improve learning outcomes. Moreover, since the variances remained stable across tests, the improvements are reliable and reflect genuine gains in student knowledge rather than random fluctuations. This validates the use of analogy-based teaching as a powerful strategy to facilitate conceptual understanding in engineering education. Student feedback was collected at the end to understand the impact of the Analogy discussed to enhance understanding of Controllability and Observability. The Feedback questions are given in Table 6.

Qualitative Analysis

a)

TABLE V
RESULTS OF STATISTICAL AND HYPOTHESIS TESTING

Histogram of Scores for Q2

b)

Histogram of Scores for Q3

c)

Histogram of Scores for Q4
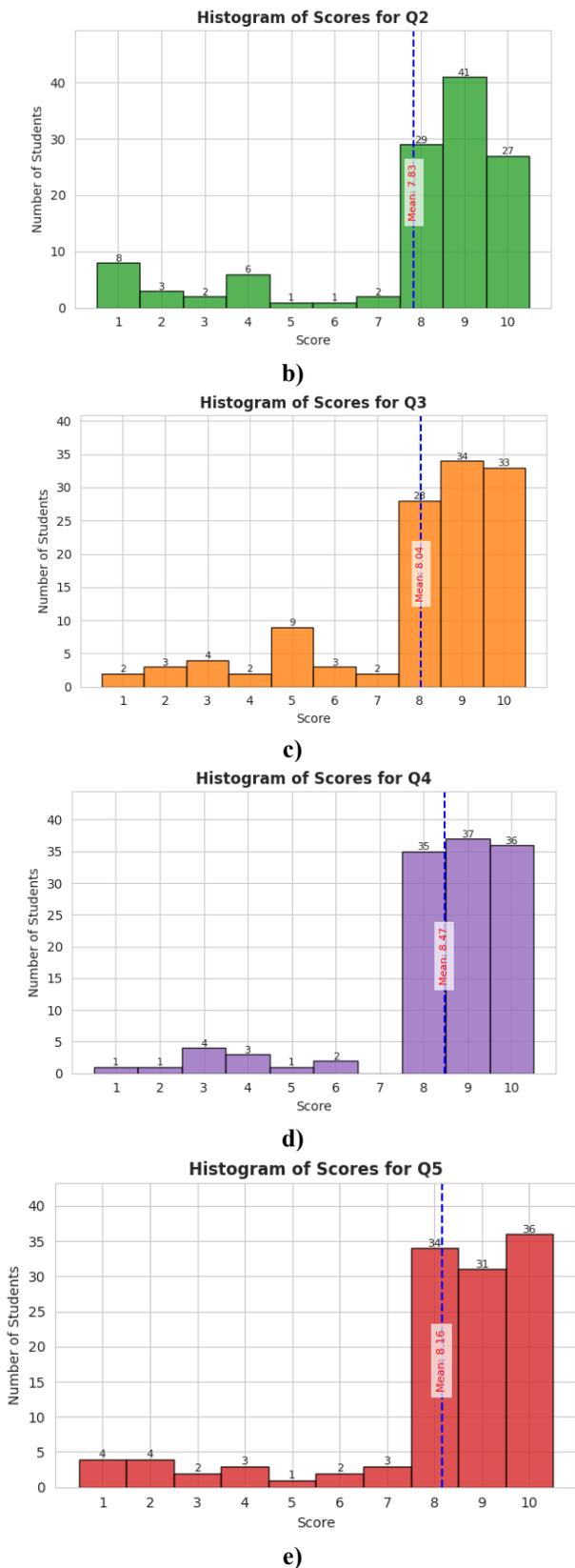
d)

Histogram of Scores for Q5

e)

Fig. 5. Feedback Analysis

The feedback focused on the clarity of the analogy used, its relevance to the concept taught, and its effectiveness in simplifying complex ideas. Students responded to a set of

targeted questions designed to evaluate how well the analogy aided their comprehension, retention, and engagement during the lesson.

TABLE VI
QUESTIONNAIRE FOR FEEDBACK

Q. N.	Question
Q1	Did the case study help you clearly understand the concept of controllability?
Q2	Did the case study help you clearly understand the concept of observability?
Q3	Was the step-by-step explanation in the case study easy to follow?
Q4	Did the examples used in the case study make the concepts more understandable?
Q5	Was the case study more effective than a regular lecture for learning these topics?

The interpretation of the answers to the questions given in Table 6 is given in Table 7. Question-wise feedback rating (histogram) is given in Figure 5.

TABLE VII
QUESTION-WISE FEEDBACK ANALYSIS AND INTERPRETATION

Question	Mean Score	Interpretation
Q1	8.12	Strong positive feedback: This score indicates that most students responded favorably to Q1. The concept or aspect evaluated by this question was well-received and understood by the majority. It suggests that the teaching method or content related to Q1 was effective.
Q2	7.83	Moderate positive feedback: Slightly lower than Q1, this score still reflects a generally positive perception but indicates room for improvement. Students may have found Q2 a bit more challenging or less engaging compared to Q1. Targeted enhancements or clarifications could help improve this aspect.
Q3	8.04	Good positive feedback: This score is solidly positive, indicating that students mostly found the topic clear and satisfactory. Minor improvements could further elevate understanding or engagement related to Q3.
Q4	8.48	Highest positive feedback: Among all questions, Q4 received the most favorable response. This suggests that the material or teaching approach linked to Q4 resonated very well with students, possibly due to clearer explanations, better examples, or interactive methods. It could be considered a model for improving other areas.
Q5	8.16	Strong positive feedback: Similar to Q1, Q5 shows that students felt positively about this topic or teaching approach. It reflects effective communication and good comprehension.

CONCLUSIONS

The incorporation of analogical teaching strategies in explaining controllability and observability significantly improved student learning outcomes in the Control Systems course. The progressive increase in test scores from the baseline pre-test to the post-tests following each analogy demonstrates the pedagogical value of mapping complex theoretical constructs to relatable real-world contexts. Statistical evidence from paired t-tests and ANOVA confirms that these improvements are both significant and consistent across the student population, while stable variances highlight that the gains reflect true conceptual understanding rather than random performance fluctuations. Qualitative feedback

indicates strong student appreciation and engagement with the analogy-based approach, particularly the car driving and teaching–learning process analogies, which made abstract concepts more accessible and meaningful. Overall, this study validates analogy as a powerful educational tool in engineering curricula to foster deeper learning, enhance cognitive connections, and promote active engagement with challenging subject matter.

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