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Enhancing Relative Motion Mastery through Strategic Instructional Design

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Enhancing Relative Motion Mastery through Strategic Instructional Design

Abstract

Mastery of relative motion concepts is critical for learning engineering dynamics. Despite its importance, a considerable number of students struggle to achieve proficiency. A key contributing factor is the suboptimal selection of practice problems and insufficient supportive information. The primary objective of this paper is to address this learning gap by utilizing the 4-Component Instructional Design (4C/ID) framework. This framework aims to improve both knowledge acquisition and skill development in solving relative motion problems.

The study addresses the research question: Can methodical problem selection and sequencing, guided by the 4C/ID framework, improve knowledge acquisition and retention in the area of relative motion? We use the 4C/ID framework to select and properly sequence practice problems, aiming to prevent cognitive overload in the majority of students. Assessment methods include formative assessments administered throughout the semester, a summative assessment via the final exam, and a retention assessment with a pre-test at the beginning of the subsequent course. These multiple data points offer a comprehensive perspective on student learning and retention, thus adding validity to our study.

We anticipate that the findings will have meaningful implications for mechanics instructors, urging a reevaluation of not just what is taught, but how it is taught. This paper contributes to the larger discourse on effective pedagogy by providing a well-structured methodology for problem selection and supportive information, which assists students in mastering complex engineering topics.

Finally, the paper will disseminate detailed formative assessments along with results from the final exam and retention pre-test in the subsequent course, serving as a valuable resource for educators in mechanics and related fields.

Introduction

The concept of relative motion remains a cornerstone in engineering dynamics, albeit a challenging one. Motion relative to a translating or rotating frame is not only fundamental to understanding the dynamics of various systems but also pivotal in applications spanning numerous engineering disciplines. However, its inherent complexity in its practical applications often poses significant learning challenges. Students frequently find themselves grappling with these concepts, struggling to move beyond rote memorization to a deeper, more intuitive understanding.

The challenges in teaching and learning relative motion are multifaceted. Firstly, students often enter these courses underprepared, lacking a robust foundation in the prerequisite physics and mathematics. This underpreparedness is compounded by prevalent misconceptions about motion, such as assuming the zero acceleration for a circular motion with constant speed, which are deeply rooted and resistant to change. The traditional teaching methods, often heavily reliant on lectures and standard problem sets, have been found inadequate in addressing these gaps. There is a growing recognition in the engineering education community of the need for more methodical and effective instructional designs that can tailor instruction to specifically address these learning deficiencies.

In this context, the significance of instructional design in engineering education, particularly in subjects like dynamics that pose great challenges to students, cannot be overstressed. Instructional design in engineering education is more than just a method for organizing course content; it is a strategic framework for creating an effective and efficient learning environment. It involves understanding the learners, defining learning objectives, designing activities and assessments, and implementing and evaluating the entire process. A well-crafted instructional design can make learning more engaging, intuitive, and relevant, thus enhancing student understanding and retention. Yet, engineering professors often lack formal instructional design training. Their advanced degrees focus heavily on domain-specific research and technical knowledge, with limited scope for pedagogical skill development. Mastering instructional design requires significant time and study, paralleling the commitment to engineering expertise. This gap in pedagogical expertise can lead to instructional approaches that are predominantly based on the instructors' personal experiences and academic backgrounds, rather than on the science of instruction or evidence-based practices. One of the critical issues with this approach is that it tends to focus more on what students need to learn (the content) rather than how they can best learn it (the process). This content-centric approach often overlooks the importance of optimizing the learning experience, which is crucial in complex subjects like engineering dynamics. Effective teaching in these areas requires not only a deep understanding of the subject matter but also an awareness of how students learn, the common misconceptions they might hold, and the cognitive load imposed by the material.

To better understand the challenges inherent in teaching relative motion, consider the following typical example, often encountered in introductory engineering dynamics courses. Students must not only grapple with abstract mathematical concepts, such as understanding how motion observed relative to a translating frame differs from that in a rotating frame, but also visualize the physical scenario, a task that can be daunting due to the complexity of considering multiple reference frames simultaneously.

Example: The train on the circular track is traveling at a constant speed of 50 ft/s in the direction shown (Figure 1). The train on the straight track is traveling at 20 ft/s in the direction shown and is increasing its speed at 2 ft/s^2. (a) Determine the velocity and acceleration of passenger A that passenger B observes relative to the given coordinate system, which is fixed to the car in which B is riding. (b) Determine the velocity and acceleration of passenger B that passenger A observes relative to a coordinate system fixed to the car in which A is riding. [1]

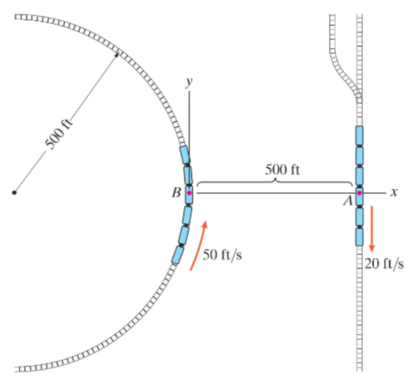

Figure 1 Relative Motion Problem Example

In traditional instructional settings, this concept is often taught through lectures and standard problem sets. While these methods may effectively convey the basic principles, they frequently fall short in helping students overcome common misconceptions and in developing a deep, intuitive understanding of the subject. This difficulty is exacerbated when instruction is primarily content-focused, with little attention given to the cognitive processes underlying learning. Without a structured instructional design, teaching methods can inadvertently increase the intrinsic cognitive load, making it more challenging for students to process and understand the information. Traditional methods might introduce multiple complex concepts simultaneously or use teaching materials that are not aligned with the students' prior knowledge and experiences. Such approaches can lead to confusion and a superficial understanding of the subject matter, hindering effective learning.

In contrast, Four Component Instructional Design (4C/ID) offers a strategic approach to instructional design that can significantly enhance the learning and understanding [2, 3]. The four components refer to four blueprint components of instruction, including (1) learning tasks, (2) supportive information, (3) procedural information, and (4) part-task practice. By breaking down the learning process into manageable tasks and providing supportive information, this model addresses the specific cognitive challenges faced by students, thereby facilitating a more thorough and intuitive grasp of the subject.

In this paper, we explore the application of the 4C/ID model in an introductory engineering dynamics course, with a focus on the teaching of relative motion. We hypothesize that this instructional design framework, with its strong foundation in cognitive theory, can effectively address the learning challenges faced by students in understanding and applying the concepts of relative motion. By demonstrating the effectiveness of a methodical instructional design framework rooted in cognitive theory, we hope to offer valuable insights and strategies for educators facing similar challenges in their teaching practices.

The paper is structured as follows: The Methods section details our instructional design approach, describing how we applied the 4C/ID model to the teaching of relative motion in engineering dynamics, including the design of formative assessments. The Results and Discussion section presents the outcomes of this approach, encompassing both formative and summative assessment results, and provides insights into the effectiveness of the 4C/ID model in enhancing student learning. Finally, the Conclusion summarizes our findings and discusses their implications for the teaching of complex topics in engineering education.

Methods

<u>Background</u>

This study was conducted in two sections of a sophomore-level “ES204 Dynamics” course at Embry-Riddle Aeronautical University (Daytona Beach campus) taught by the lead author during the Fall 2023 semester. The course is a required component for most engineering majors and typically enrolls approximately 35 students per section. The same instructor also taught the Spring 2023 sections, which served as the comparison group, using the same syllabus, textbook, and assessment structure. All instruction was delivered in person. The redesigned instructional approach based on the 4C/ID model was implemented for the first time in Fall 2023, while a traditional lecture-based approach was used in Spring 2023. Weekly formative assessments and a common final exam were administered to evaluate student learning outcomes. All assessments were graded by the instructor using consistent rubrics to ensure fairness and comparability across semesters.

At the beginning of each semester, students completed a diagnostic assessment covering prerequisite skills essential for solving dynamics problems. The results revealed that a substantial portion of students entered the course underprepared. Common deficiencies related to relative motion included difficulties in selecting proper trigonometric functions for resolving vectors, performing vector operations such as dot and cross products, and representing acceleration in circular motion with constant speed. These knowledge gaps likely contributed to cognitive overload when students attempted relative motion problems, highlighting the need for a structured instructional design. Insights from the diagnostic assessment directly informed the design of part-task practice activities and supportive materials used in the 4C/ID-based intervention.

Application of the 4C/ID Model

In applying the 4C/ID model to the teaching of relative motion in engineering dynamics, we used the example introduced in the Introduction as a foundation. This example, which involves calculating the relative velocities and accelerations of passengers in different reference frames, encapsulates the typical challenges students face. The 4C/ID model's application was structured to demonstrate how the four components are constructed in developing instructional materials for teaching relative motion.

Learning Tasks: The design of learning tasks in our application of the 4C/ID model begins with skill decomposition. This process entailed dissecting the skill of solving relative motion problems into its constituent knowledge and skills, along with the requirements for mastering each component. Skill decomposition is pivotal from various perspectives:

Firstly, it aids in the effective selection and sequencing of learning tasks. By dissecting the skills and knowledge required for mastering relative motion, we could meticulously design and sequence the learning tasks. This sequencing ensures each task builds upon the previous, facilitating an effective and efficient progression of knowledge. Secondly, skill decomposition informed the development of our formative assessments. Understanding the specific skills and knowledge targeted by each task enabled us to craft assessments that precisely measured students' understanding and progression at each stage.

Furthermore, a notable feature of 4C/ID was the structured increase in the complexity of tasks. Unlike traditional instruction, which often lacks a systematic progression in task difficulty, our learning tasks were designed to gradually escalate in complexity. This gradual escalation is essential to prevent cognitive overload by introducing complex tasks too early, ensure solidification of foundational skills and knowledge before advancing to complex concepts, and foster student confidence and motivation.

Additionally, variations in learning tasks were a key component of our design. Variations serve critical functions in learning. They prevent rote learning by encouraging students to apply concepts in diverse contexts, thereby fostering deeper understanding. They prepare students for the unpredictable nature of real-world engineering problems, necessitating the application of skills in varied scenarios. Moreover, variations are instrumental in identifying and rectifying any persistent misconceptions, which might not be evident in uniform problem sets.

Figure 2 shows an example of skill decomposition for teaching relative motion. As shown in the diagram, the problem solving process starts with categorizing the reference frame as a translating frame or a rotating frame, followed by the same constituent skills including setting up equations, representing vectors, and identifying unknowns. To set up equations, students need to determine whether the reference frame is translating or rotating. Furthermore, when set up the equations, students need to understand the meaning of each term, especially which term represents the velocity and acceleration of the origin of the reference frame; after equations are set up, students will represent each vector and identify unknowns to determine whether sufficient equations are set up to solve the given problem. Through the skill decomposition process, challenges faced by students could be identified. For example, students often miss the normal acceleration of an object moving along a circular path or use incorrect trigonometry functions to represent vector components.

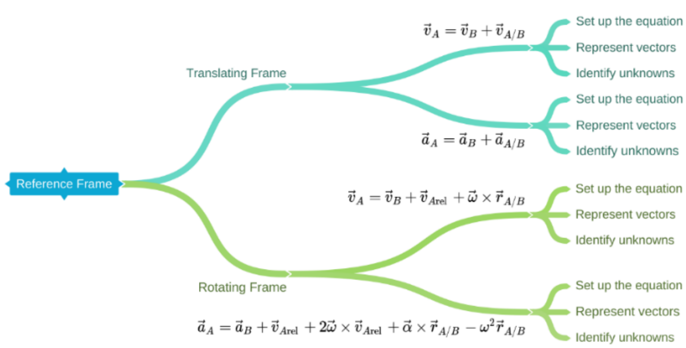

Figure 2 Skill Decomposition in Solving Relative Motion Problems

After the skill decomposition is completed, a series of learning classes can be developed to facilitate the progression of knowledge along with the timeline as shown in Table 1. The concepts of relative motion are usually introduced in Week 6 and Week 8, respectively. Task Class 1 is assigned before the concepts are introduced to help students develop the required knowledge. When the concepts are introduced, students will focus on how to categorize the reference frame and understanding the difference. When all the constituent skills are developed, students will use the rest of the semester to practice on a variety of problems to consolidate their understanding.

Table 1 Learning Classes and Tasks

Task Class 1: Represent vectors (Weeks 2-5) **Goal:** Be able to represent the velocity and acceleration vectors in given relative motion problems. **Learning Task 1.1**: Draw the velocity and acceleration vector of each object. **Goal:** Be able to represent the normal and tangential acceleration. **Learning Task 1.2**: Represent the velocity and acceleration vector of each object. **Goal:** Be able to use proper trigonometry functions to represent vector components. **Learning Task 1.3**: Represent the relative motion. **Goal:** Be able to use proper notations to represent the relative velocity and acceleration.
Task Class 2: Categorize the reference frame (Weeks 6-7) **Goal:** Be able to categorize the reference frame as a translating or rotating frame. **Learning Task 2.1**: Categorize the reference frame **Goal:** Be able to categorize the reference frame as a translating or rotating frame.

Learning Task 2.2: Represent $\vec{\omega}$ and $\vec{\alpha}$ of the rotating frame **Goal:** Be able to represent $\vec{\omega}$ and $\vec{\alpha}$. **Learning Task 2.3**: Choose the correct equations **Goal:** Be able to choose the proper equations to solve given relative motion problems.
Task Class 3: Solve the relative motion problems (Weeks 8-14) **Goal:** Be able to solve relative motion problems. **Learning Task 3.1**: Set up the equations and identify the unknowns. **Goal:** Be able to solve the complete problems.

Supportive Information: The second design component in the 4C/ID model is supportive information, which is integral to connecting students' existing knowledge with the skills required for solving relative motion problems. Supportive information encompasses problem-solving guidance, illustrative examples, and cognitive feedback. Incorporating these elements in the development of supportive information for teaching relative motion not only imparts theoretical knowledge but also effectively guides the problem-solving process.

In teaching relative motion within the framework of the 4C/ID model, problem-solving guidance is provided through a Systematic Approach to Problem Solving (SAPS) and mental models. SAPS offers students a structured methodology for tackling relative motion problems, which can often be complex and counterintuitive. The flowchart in Figure 3 serves as a visual guide to the SAPS. It commences with the categorization of the reference frame—distinguishing between translating and rotating frames—which is a critical first step in solving any relative motion problem. From there, the flowchart guides students through the next stages of problem-solving: applying the correct kinematic equations for the identified frame, representing vectors appropriately, and identifying unknown variables. This systematic progression ensures students approach the problem in a logical, step-by-step manner, reducing cognitive overload and clarifying the path to the solution. It is this level of structured guidance that can transform the student experience from one of confusion to clarity, laying down a solid foundation for mastering relative motion.

After outlining the structured problem-solving steps, we now turn to mental models, which provide the underlying concepts critical for understanding relative motion in engineering dynamics. When teaching relative motion, two types of mental models, conceptual models and causal models, offer a scaffold for solving relative motion problems. Conceptual models are fundamental to grasping basic dynamics concepts, such as differentiating between inertial and non-inertial reference frames or understanding the distinction between translating and rotating frames. These models help students form an initial understanding of the context in which relative motion occurs. Causal models, on the other hand, are crucial for linking theories or principles to observable outcomes. In solving relative motion problems, a causal model can illustrate how a rotating frame influences the observed motion, such as the centripetal and Coriolis acceleration of moving objects. These models enable students to predict and explain the behavior of objects in different reference frames, providing a deeper understanding of the dynamics involved.

The SAPS and mental models are effectively illustrated through carefully chosen examples and case studies. As an illustration, let us refer to the example introduced in Introduction section. This example can be transformed into a worked example, demonstrating the application of each step in the solution process in accordance with the SAPS. Concurrently, it illustrates the utilization of mental models throughout the problem-solving process. Refer to Figure 9 in the Appendix for a detailed presentation of this illustrative example.

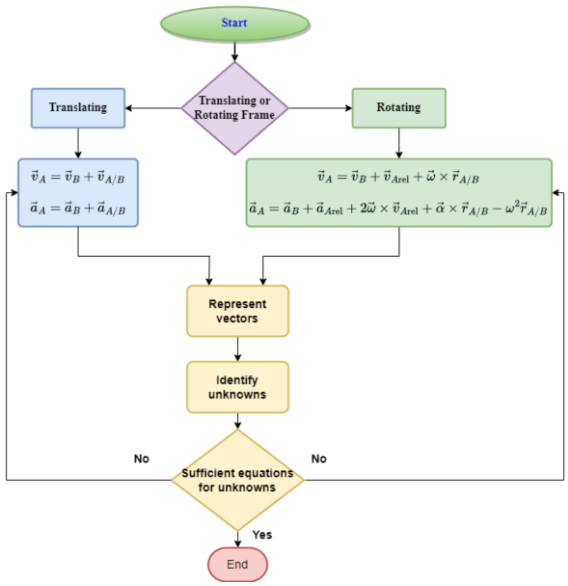

Figure 3 SAPS for Solving Relative Motion Problems.

Procedural Information: In the 4C/ID model, procedural information typically applies to recurrent learning tasks, where rigid procedural steps are to be followed. However, in the context of solving relative motion problems, the nature of the tasks is predominantly non-recurrent. These problems involve a high degree of decision-making and adaptability, as opposed to following predefined steps.

Part-task Practice: Part-task practice forms the final key element in our instructional design, focusing on mastering specific skills essential for solving relative motion problems. For example, to reinforce the skill of accurately representing vectors, students engage in targeted exercises, such as choosing the correct trigonometry functions or representing normal accelerations. These exercises are intentionally designed to concentrate on individual components rather than solving complete relative motion problems, enabling students to develop mastery over these crucial skills. The tasks outlined in Table 1 for Weeks 2-7 predominantly constitute part-task practice, crafted to aid students in consolidating the necessary component skills for effectively solving relative motion problems (see Figure 10 in the Appendix for homework examples).

Most of these tasks are assigned as homework, taking the form of either auto-graded online quizzes or traditional paper-and-pencil assignments that students can self-check against provided solutions. This method of daily practice immerses students in specific component skills, facilitating mastery through repetition. By consistently engaging with these tasks, students incrementally build their proficiency, ensuring a solid foundation in each skill set that contributes to their overall understanding and ability to tackle relative motion problems.

Formative Assessment Design

To ensure that students developed mastery of the prerequisite knowledge necessary to solve the example problem, we implemented a series of formative weekly assessments. These assessments were designed to evaluate students' understanding at various stages of the learning process as outlined in Table 2.

Table 2 Formative Assessment Topics and Schedule

<table>
<tr><th>Learning Tasks</th><th colspan="2">Formative Assessment</th></tr>
<tr><td rowspan="2">Task Class 1: Represent vectors (Weeks 2-5)
Learning Task 1.1: Draw the velocity and acceleration vector of each object.
Learning Task 1.2: Represent the velocity and acceleration vector of each object.
Learning Task 1.3: Represent the relative motion.</td><td>Week 3</td><td>Graphical representations of the acceleration components on a figure</td></tr>
<tr><td>Weeks 4-6</td><td>• Graphical representations of the acceleration components on a figure
• Algebraic representation of the velocity/acceleration components</td></tr>
<tr><td rowspan="2">Task Class 2: Categorize the reference frame (Weeks 6-7)
Learning Task 2.1: Categorize the reference frame
Learning Task 2.2: Represent $\vec{\boldsymbol{\omega}}$ and $\vec{\boldsymbol{\alpha}}$ of the rotating frame
Learning Task 2.3: Choose the correct equations</td><td>Week 8</td><td>• Graphical representations of $\vec{\omega}$ and $\vec{\alpha}$ on a figure
• Algebraic representations of $\vec{\omega}$ and $\vec{\alpha}$</td></tr>
<tr><td>Week 10</td><td>Choose the equations to solve a relative motion problem</td></tr>
<tr><td>Task Class 3: Solve the relative motion problems (Weeks 8-14)
Learning Task 3.1: Set up the equations and identify the unknowns</td><td>Weeks 11-14</td><td>Solve the relative motion problems</td></tr>
</table>

Results and Discussion

This section will present the outcomes of both formative and summative assessments to evaluate the effectiveness of the 4C/ID model in teaching relative motion. Over the course of the Fall 2023 semester, we administered nine weekly formative assessments to a cohort of 63 students, each featuring a problem covering various aspects of relative motion problems. These assessments served as a continual measure of student understanding and progression under the newly implemented instructional design. For an example representative of the types of problems used in the formative assessment, refer to Figure 1. To maintain the integrity and ongoing utility of the assessments, the actual assessment item is not shown. Additionally, we conducted a summative assessment at the end of the semester to gauge the overall learning outcome on relative motion. The results of this assessment are particularly significant when compared to the Spring 2023 semester, where the same course was conducted without the implementation of our instructional design and yielded less than satisfactory results. This comparison allows us to critically analyze the impact of the 4C/ID model on student learning performance in relative motion concepts.

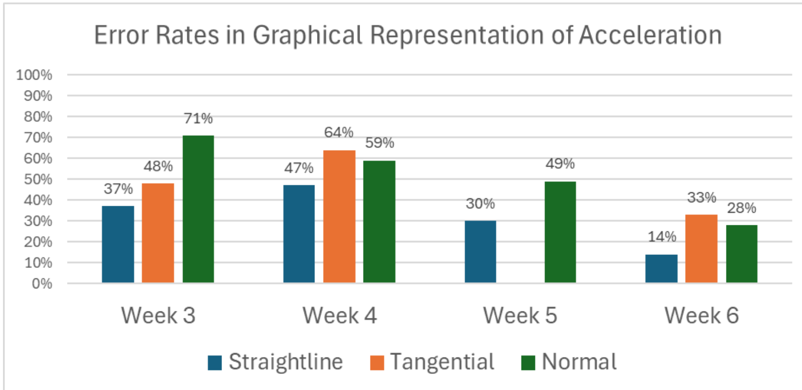

Figure 4 Progression of Error Rates in Graphical Representation of Acceleration

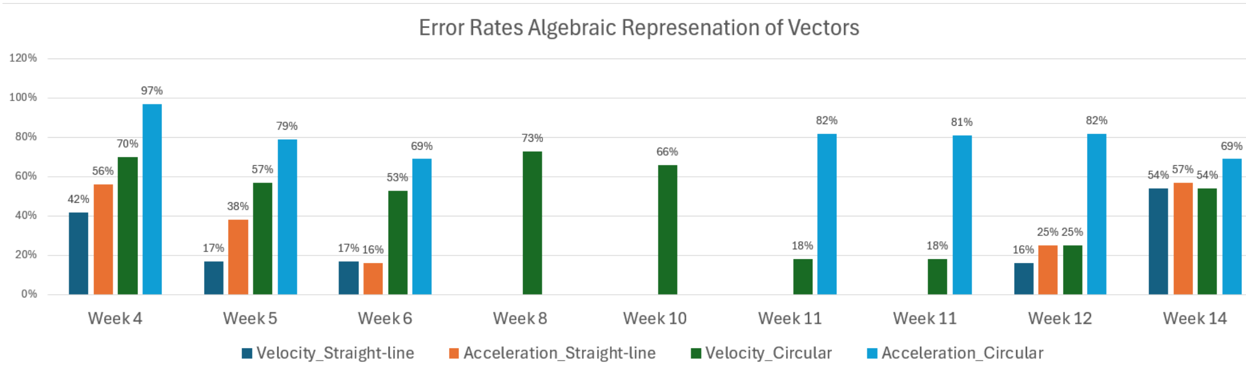

Figure 5 Progression of Error Rates in Algebraic Representation of Vectors

Figure 4 displays the error rates in the graphical representation of acceleration for both straight-line and circular motion, where 'error rates' refer to the percentage of students who incorrectly depicted these concepts. The graph indicates a decrease in error rates when representing accelerations. Figure 5 illustrates the error rates in the algebraic representation of velocity and acceleration vectors. Initially, there is a high error rate for both velocity and acceleration in straight-line motion, with a notable improvement by Week 12. While an improving trend is observed for velocity in circular motion, the error rates for acceleration remain high, suggesting this concept poses significant challenges for students. The elevated error rates in Week 14 might be attributable to a change in problem format, where students misinterpreted the requirement and represented magnitudes only, rather than vectors. Figure 6 details error rates in the application of equations to solve relative motion problems. The trend generally shows improvement; however, the error rates spike in Week 14, potentially due to the problems transitioning from a rotating to a translating frame reference, which may have introduced new complexities for the students.

A key clarification is that if an error rate is zero in a given week, it does not necessarily indicate that every student answered correctly; rather, it means that the topic was not explicitly assessed during that week. Additionally, fluctuations in error rates over the semester provide insight into students' learning progress and highlight areas where instructional adjustments may be necessary. In particular, we observe a persistent challenge in representing normal acceleration and correctly applying equations for acceleration in circular motion. These areas may require additional instructional emphasis in future iterations of the course.

Figure 7 presents a comparison of error rates from the summative assessments between Spring 2023 and Fall 2023 for various components of the problem about the motion relative to a rotating frame. The data reveals that the instructional design implemented in Fall 2023 resulted in a marked improvement in student performance in understanding and solving problems involving rotating frames. However, challenges persist in specific areas, particularly in the representation of vectors in circular motion, which may necessitate additional instructional refinement.

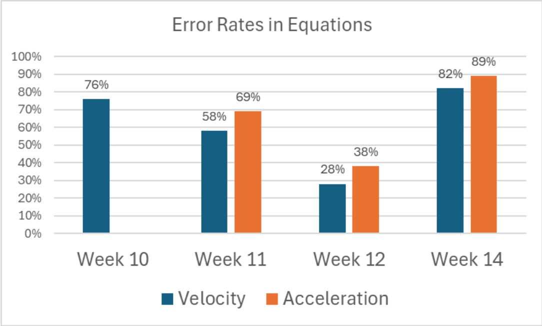

Figure 6 Progression of Error Rates in Equations

It should be noted that in Spring 2023, students were not exposed to the same variety of relative motion problems. Instead, their practice was limited to similar problems as illustrated in Figure 8. While some concepts from these problems are transferable to the types of problems introduced in the Introduction section, it is evident that such transfer does not occur naturally for most students without dedicated instructional support.

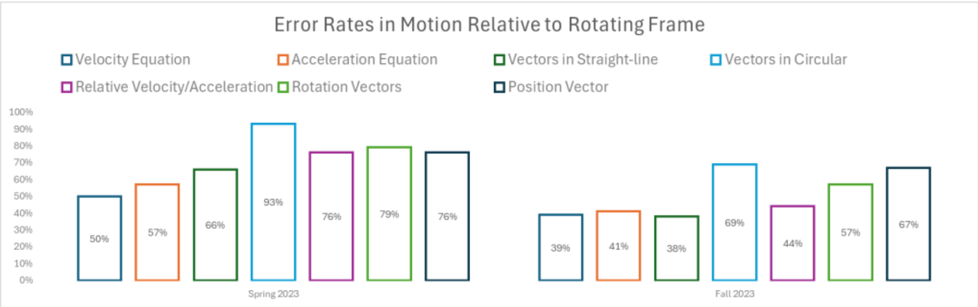

Figure 7 Error Rates in Solving Relative Motion Problem with a Rotating Frame

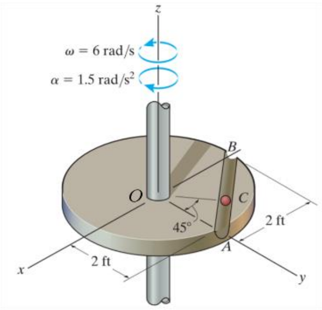

Figure 8 Rotating Frame Example in Spring 2023

Conclusion

This study examined the application of the 4C/ID instructional design model to the teaching of relative motion in engineering dynamics. Through a systematic instructional design that included the selection of learning tasks, development of supportive information, and creation of part-task practice, we observed enhanced student understanding and mastery of this complex subject.

Our formative and summative assessments reveal a clear trend of improvement. Through the implementation of the 4C/ID model in Fall 2023, we observed a significant decrease in error rates across various components of motion relative to a rotating frame, compared to the previous Spring semester. This indicates that our instructional design improved students' ability to solve relevant problems.

Despite these advances, the persistence of certain challenges, particularly in the algebraic representation of vectors in circular motion and the use of equations, suggests areas that require further instructional refinement. It is evident that while the 4C/ID model provides a strong foundation for learning, continuous adaptation and nuanced approaches are crucial for addressing all facets of learning in relative motion.

In light of these findings, future research should consider longitudinal studies to evaluate the long-term retention of knowledge and skills taught via the 4C/ID model. Additionally, further investigation into alternative instructional strategies to target the specific challenges identified may prove beneficial.

In conclusion, the adoption of the 4C/ID instructional design model represents a positive step forward in the teaching of engineering dynamics. By providing a structured and comprehensive approach to learning, we are better positioned to equip students with the skills and knowledge necessary to excel in this critical field of engineering.

Appendix:

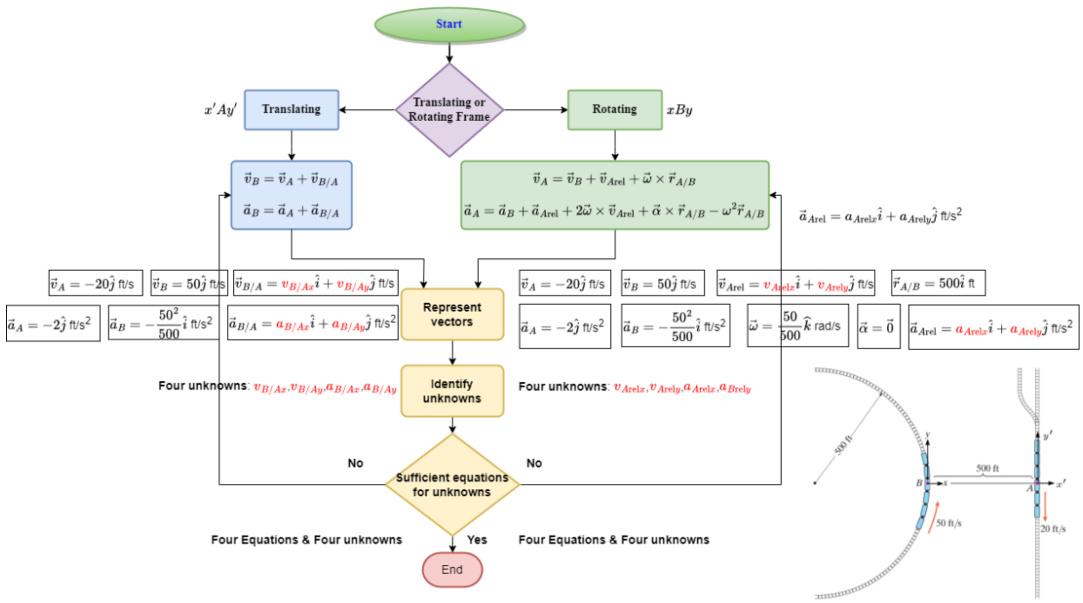

Figure 9 An Illustrative Example of Applying SAPS for Solving Relative Motion

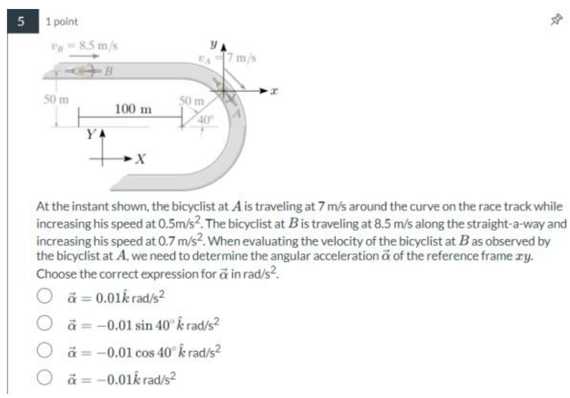

Figure 10 Homework Example of Part-task Practice

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[2] J. J. Van Merriënboer and P. A. Kirschner, *Ten Steps to Complex Learning: A Systematic Approach to Four-Component Instructional Design.* Routledge, 2017.

[3] Y. Tang, H. Bai and R. Catrambone, "Applying deliberate practice to facilitate schema acquisition in learning introductory mechanics," in *ASEE Annual Conference Proceedings,* 2021.