Project-based learning approach for applying the principles of magnetism and movement in a magnetic linear motor

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This article describes the application of the principles of magnetism and motion by working with engineering students at Tecnológico de Monterrey to construct and simulate a Magnetic Linear Motor (MLM) through the Project-Based Learning (PjBL) methodology combined with STEM to facilitate experiential and collaborative learning. PjBL is a teaching methodology that applies learning to real-world problems. This approach is currently being adopted by various educational institutions, which face challenges in using pedagogical methods to foster positive relationships between students and mentors. Three phases can be distinguished in project-based methodology. *Commitment*: Students are motivated to participate in the importance of an MLM as a device capable of giving motion in one dimension. *Research*: Students engage in a research project where they design and model their ideas from different areas, such as electromagnetism, differential equations, and programming. *Action*: Assemble the prototype in the laboratory and evaluate its model. The differential equations of the magnetic force in the MLM prototype are used to determine its kinematic graphs and interpretation. As evidence of learning, students are required to submit two reports that are evaluated using rubrics.

Keywords: Project-based learning; magnetic linear motor; MATLAB simulation.

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1. Introduction

In an undergraduate electromagnetism physics course, we propose a project centered around a “magnetic linear motor” (MLM). This project-based learning (PjBL) initiative aligns with the science, technology, engineering, and mathematics (STEM) fields, enabling students to apply differential equations, numerical calculus, and electromagnetism to real-world situations. Additionally, students will collaborate with their peers and develop essential skills and competencies [1,2].

MLMs differ from traditional rotary electric motors as they directly convert electrical energy into straight-line motion. These motors have been used in various applications such as cross curtains, conveyor belts, solid waste separation, molten metal pumps, high-speed grinding, computer numerical control machining, rail transit, and even launching attempts [3,4]. Given the relevance of controlling and applying linear motion in our daily lives, a question arises: What approach could we employ that applies the concepts of magnetism and rectilinear motion, allowing basic engineering students at Tecnológico de Monterrey to learn through real and experiential problems?

Participating in this project enables students to apply their theoretical knowledge to real-life situations, which enhances their problem-solving skills. They also learn to collaborate effectively with their peers in a specific context, developing valuable competencies for their professional development [5].

For these reasons, our goal is to apply the principles of magnetism and movement by working with engineering students at Tecnológico de Monterrey to construct and simulate an MLM through PjBL methodology combined with STEM to facilitate experiential and collaborative learning. Teaching electromagnetism by building and modeling an MLM using the PjBL methodology poses some challenges. Introductory physics textbooks typically do not cover the topic [6,7]. Additionally, working with magnets and laboratory equipment requires great precision and patience from students, while managing time effectively can be challenging for both teachers and students, given the shift from traditional to multidisciplinary learning.

To achieve our goal, we have established specific objectives:

1. To plan a strategy for teaching basic sciences to first-year students at the Tecnológico de Monterrey based on PjBL to promote critical thinking in applying the principles of magnetism and the laws of motion.

2. To propose a solution to build, model, and simulate an MLM.

The purpose of presenting this prototype is not to suggest that it is the only way to achieve rectilinear movement but to inspire discussion and contemplation among the academic community. In Sec. 2, we outline the MLM project, which shows how to apply the PjBL methodology and evaluate the competencies of this challenge through a rubric. In Sec. 3, we propose a solution for the teacher of the MLM. Some data is included as an example. Results and discussions are given in Sec. 4. Finally, the conclusions are given in Sec. 5.

2. MLM project

We employ the Project-Based Learning (PjBL) methodology outlined in Ref. [1] in line with our first specific objective. Figure 1 illustrates the main steps of this methodology. PjBL enables students to learn by engaging in a specific project. Through a series of stages, students collaboratively address a problem, test a prototype, and find solutions related to a topic that interests them.

Under their teachers' guidance, students will work on a project that involves building an MLM, conducting literature reviews, taking measurements, modeling it numerically using `MATLAB`, and presenting their findings. This project follows an experiential learning approach, which means that students will gain practical experience and actively participate in actual or simulated situations instead of merely memorizing knowledge through traditional teaching methods. As a result, this project is intellectually demanding and conceptually relevant, making it an ideal project for collaborative work, which is a crucial component of the PjBL [8].

2.1. Proposed Methodology

Driving/challenging questions are the essence of PjBL, so it is essential to make them, along with the assessment criteria, clear and concise for students during the first class session. To incite PjBL, the following question is proposed to the students: *How would you describe, predict, and control the magnetic force and kinematics in a magnetic linear motor?*

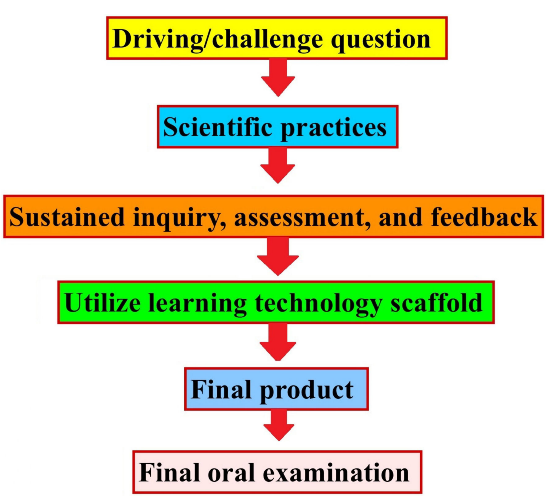

FIGURE 1. Main steps of the Project-Based Learning methodology used in this project.

Two progress deliveries and a final presentation are recommended to ensure students can manage their workload effectively.

The first task involves delivering a report that describes the diagrams and plans for the construction of the MLM. The report should include precise measurements, a list of materials, and a detailed description of the main problems encountered during the design and manufacturing of the MLM. The report should also include a model of the magnetic field of a single magnet. An evaluation rubric, which can be found in Appendix B, Table V, is suggested as a guide for students [9].

The second task requires students to document the simulation by including photos and videos, analyzing the results, and describing the effects of the design decisions made through a structured and substantiated argument. The report must include force and energy calculations, modeling graphs, and references. An evaluation rubric, which can be found in Appendix B, Table VI, is provided. Students should be specifically asked about the argument's characteristics according to the competencies.

In addition, students should be introduced to the basics of MLMs, including the motion of bars or coils in a magnetic field, electrical resistance, electro motive force (emf) of motion, equation of motion, and Runge-Kutta approach.

Finally, it is important to instruct students about the materials they have at their disposal and those they need to acquire for the project.

Scientific practices encourage students to formulate hypotheses, identify variables, generate ideas, and solve challenging questions. Teacher-designed scientific practices involve students constructing and simulating a MLM by measuring electric current and utilizing position and magnetic field sensors. This approach allows for the visualization and description of magnetic fields. Additionally, teachers should guide students in digitally constructing the system using `MATLAB`.

Sustained inquiry, assessment, and feedback. Students will conduct an exhaustive investigation on magnetic fields and their application to Newton's Laws. Using the measurements of the prototype, students must determine the differential equations of the kinematics of the MLM movement. Additionally, using `MATLAB` and the quiver command, students must model the magnetic field and obtain a color palette to represent the intensity of a series of magnets. At this point in the project, students should submit their first assignment for teacher feedback.

Utilize learning technology scaffolds. Model the dynamics of the MLM, which involves concepts such as magnetic forces, acceleration, and braking. Students are required to create graphs that illustrate the relationships between acceleration, velocity, and position over time. Additionally, using the knowledge acquired from the physics module on Ampère's Law, the student team must model a solenoid capable of braking the rod and predict its characteristics. This includes determining the magnetic field generated, the number of turns in the coil, and the type of core material used.

Note that the actual braking effect is not physically observed in this session, as it would require at least one additional four-hour session. If readers wish to extend the experiment, it is recommended not to forget that the braking effect can also be obtained simply by reversing the power source polarity, and appropriately adjusting the current intensity.

Final Product. Participants have completed their experimental work and can now either accept or reject the proposed hypotheses. The students will have to complete the second task: operate their MLM present in the laboratory. They are required to document their work with photographs and videos.

Final oral examination. It is recommended that all participating teachers and guests be present. Teachers should prepare a set of questions in advance to avoid having to create impromptu ones. The questions should be related to the fundamentals and functioning of the MLM, based on Newton's Laws and magnetic force principles, solutions to differential equations, and the main modeling commands in MATLAB.

Learning Issues. The project involves various challenges, such as determining the orientation and spacing of the magnets, the height of the rails, and the characteristics of the electromagnets. This will enable participants to discuss the impacts of these choices at the end of the challenge. Creating and modeling large matrices in MATLAB requires comprehensive support from an instructor. Throughout their experiments, students devise diverse solutions, ranging from the type of magnets and methods for generating current to the bases supporting the bars. The laboratory must provide various devices for generating current, from a simple battery to a current generator.

Some questions to consider include: Why are we concerned only with current directions perpendicular to the motion? Which current direction, along x or y, produces more force? What is the most convenient value for z? What effect does a ferromagnetic rod have? Does it alter the induction current? What occurs when the bar passes through the magnet zone? What are the signs of the flux, the change of the flux, and the magnetic field in the magnet zone, the free zone and the solenoid zone? Does the solenoid decelerate or accelerate during induction? What physical effects are disregarded and why?

2.2. Project evaluation

PjBL offers multiple opportunities for alternative and authentic assessment tools [5]. Students can work in teams or individually, creating products such as challenge proposal videos, research plans, and reflection videos, depending on their grade level and project length. Teachers and students should work together to define the products and determine how to assess them, including specific performance expectations and rubrics. Rubrics for the Assessment and Tutoring of Learning in the Forum (RETAF rubrics) [9,10] are proposed.

Two rubrics are proposed for students who receive two different assignments (see Appendix B and Tables V and VI). These rubrics aim to facilitate continuous evaluation without overwhelming students [10]. Rubrics are used to evaluate specific competencies:

1. Demonstrating the functioning of engineering systems and devices in controlled environments by applying theories and principles of physics, mathematics, and computing.

2. Investigating and identifying information from reliable sources related to engineering systems and devices. The proof demonstrates the use of recognized academic references (books, articles, patents) and references specific to the discipline to support the documentation.

3. Solving problems and questions of reality from objective, valid, and reliable methodologies.

Student learning results can be measured through numerical data, which allows for a quantitative evaluation of their performance against established criteria [11].

2.3. Participants

One hundred thirty basic engineering students enrolled in an electromagnetism course who are pursuing a professional career were divided into seven block models. The Tecnológico de Monterrey has developed a learning model called Tec21 Educativo [12], which introduces competency-based training through four main concepts: challenges, flexibility, enriching experiences, and inspiring teachers [13].

The Tec21 Educativo model includes an electromagnetism course based on PjBL, designed to deepen, integrate, and apply knowledge through various learning modules to resolve a specific challenge. This block spans five weeks, totaling 60 hours, and is structured into three theoretical modules and one experimental challenge. The experimental module accounts for 33% of the course and is designed to introduce students to PjBL and facilitate a discussion on MLM modeling.

The three theoretical modules constitute 77% of the block and primarily focus on introducing the laws of magnetism and their origins, including Ampère's Law and its applications, magnetic induction, higher-order differential equations using indeterminate coefficients, and their numerical solutions through the second- and fourth-order Runge-Kutta methods. Gauss's and Stokes's theorems are also covered in these modules.

3. Proposal of MLM

3.1. Theoretical framework

In relation to our second specific objective, we have developed a solution for constructing, modeling, and simulating a MLM. This type of electric motor comprises a conductive but non-magnetic bar, such as aluminum or copper, which has a

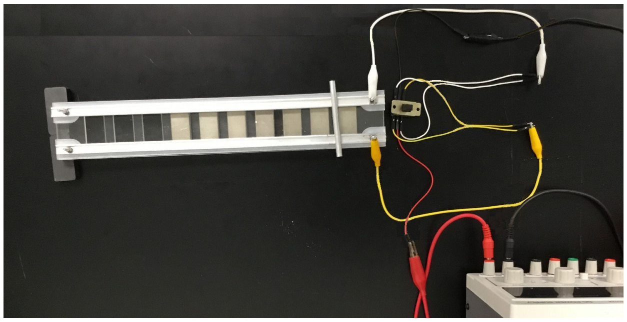

FIGURE 2. MLM with an arrangement of seven conventional magnets. The moving bar is observed on the rails. Appendix A shows the materials used in this experiment and the dimensions and characteristics of a neodymium block magnet.

mass m and a length ℓ. The bar moves perpendicular to a magnetic field generated by a series of magnets positioned between two horizontal, parallel rails. The moving bar and the rails are connected to a power source that supplies an electric current I, as illustrated in Fig. 2.

The intention of presenting this solution is not to imply that it is the only method for achieving an MLM; rather, it is meant to encourage discussion and reflection within the academic community. The student team will determine the length of the bar ℓ and measure its mass m, ensuring that the magnets are spaced adequately apart to prevent unwanted effects of attraction or repulsion between them. For this setup, it is recommended to mount the magnets on a wooden or plastic base to secure their positioning effectively. In this case, seven magnets have been used, with a separation of 8.0 mm between each magnet. This spacing will facilitate counting when modeling a large matrix that represents the MLM space, as well as the seven magnets and the modeling of a solenoid.

The magnetic force $\vec{F}$ acting on the moving rod is proportional to the electric current and the magnetic field, and can be expressed as

$$\vec{F} = I\vec{L} \times \vec{B}, \tag{1}$$

where $\vec{F}$ is measured in *newtons*, while I is measured in *amperes*. $\vec{L}$ is a displacement vector that points in the direction of the electric current flowing through the movable rod. The magnetic field $\vec{B}$ is measured in teslas and is oriented at a $90°$ angle to the direction of the current. The magnitude of $\vec{L}$, denoted as ℓ, represents the distance between the rails. This distance should be slightly larger than the longest side of the rectangular magnets to ensure that the movable part of the MLM is appropriately positioned and can effectively utilize the area with the strongest magnetic field. For this experiment, ℓ is set to 41 mm. Consequently, the magnitude of the force can be expressed as

$$F = I\ell B. \tag{2}$$

The magnetic field produced by the magnets, denoted as $B = B(x, y, z)$, varies depending on the distance between the rod and the center of the magnet, (x, y), and on the distance between the surface of interest and the rod, $z = h$. We assume $B = 0$ in the region between neighboring attractions due to the weak nature of the magnetic field in that area. The braking system involves a solenoid with a magnetic field B_s opposite to the magnets' array.

The magnetic field inside and near the edge of an ideal solenoid can be approximated from the magnetic field near its center [14]:

$$B_s = \frac{1}{2}\mu n i_s. \tag{3}$$

Here, μ is the permeability of the material in the solenoid's core, n is the number of turns per unit length, and i_s is the current flowing through the solenoid.

Our experiment involves regulating the current through a DC power supply with a constant voltage of 5.0 V along the rails. Physical effects such as resistance variation in rails, induced currents due to motion, and voltage source adjustments may alter the electric current. However, measuring the electric current with an ammeter shows that it has a constant value of 3.25 A, with the only variable being the magnitude of the magnetic field on the track.

We can choose a copper rod by applying Eq. (2) to Newton's Second Law. Since it is not as light as aluminum, it is expected to improve the rails' stability and electrical contact characteristics. An example could be a piece of thermocouple tubing from an LP gas boiler. In this solution, we have chosen a moving aluminum rod. We can obtain the rod's dynamics by considering a linear arrangement of magnets. The magnitude of the moving rod's acceleration along the rail can be obtained by

$$a = \frac{I\ell}{m}B, \tag{4}$$

where $m = 4\ g$ is the mass of the moving rod. Eq. (4) leads us to the differential equation

$$\frac{dV}{dt} = \frac{I\ell}{m}B, \tag{5}$$

being V the velocity of the moving rod along the rails. With Eq. (5), the equation of motion of the rod is obtained:

$$\frac{d^2x}{dt^2} = \frac{I\ell}{m}B. \tag{6}$$

3.2. Experimental design

Appendix A provides detailed information about the materials available in the school laboratory and those provided by the students. Also about the dimensions and characteristics of a neodymium block magnet, of which we used a set of seven to operate this MLM.

As a first step, we create a sample of magnetic field intensity measurements using a PASCO-type magnetic field sensor and a PASCO-type position sensor, both of which must be provided by the laboratory. Their specifications are detailed in Appendix A. Students will compile a table that represents the coordinates of each point along with the corresponding magnetic field measurements. The driving vertical magnetic

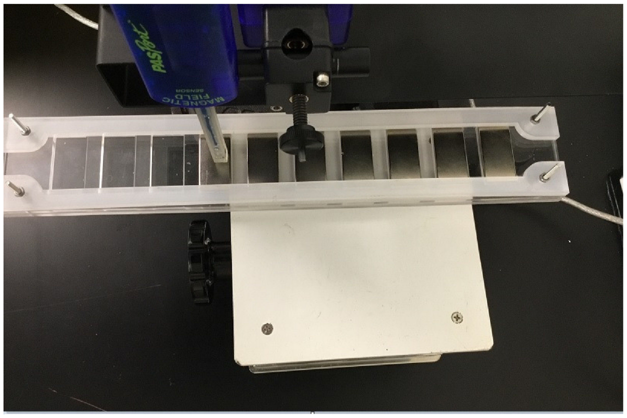

FIGURE 3. Tracking a neodymium block magnet with a PASCO-type sensor magnetic field and a PASCO-type sensor position. The North of the magnet is up.

field is obtained either with a magnet or through a solenoid. Obtaining magnetic field data through a solenoid is a difficult but not impossible task. It is a very complicated challenge that would take us more than a 4-hour laboratory session since it has to be connected and placed perpendicular, and its cross-sectional area must approximate the spacing between rails, which complicates building a solenoid or acquiring one on the market. In addition, at least 5 solenoids would be placed to generate the MLM. In contrast, measuring the magnetic field of a permanent magnet is much simpler. It only requires placing the magnet on a support that is perpendicular to the sensor, and it can be easily adjusted to fit the spacing between the rails. The sensors will cover an area defined by $x = (5, 25)$ mm and $y = (-20, 20)$ mm, with a step size $\Delta x = 1.11$ mm and $\Delta y = 2.16$ mm, as shown in Fig. 3.

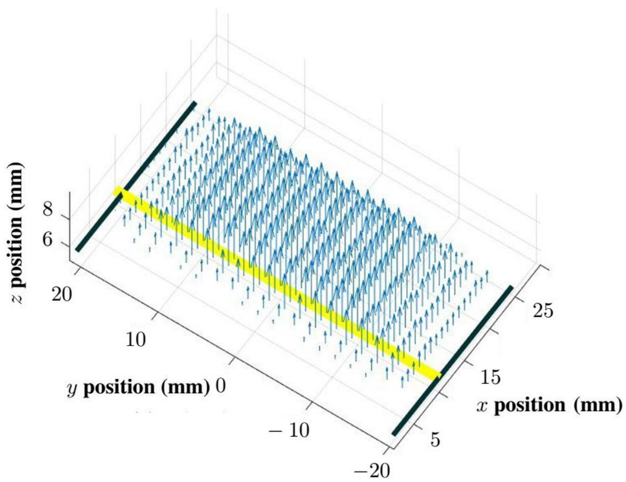

FIGURE 4. The vertical component (B_z) of the magnetic field vector $\vec{B}$ generated by the neodymium block magnet is illustrated in the plane at $z = 6$ mm. The field vectors point out of the page in Fig. 3, indicating that the magnet's North Pole is directed upwards. The yellow line represents the moving rod, while the solid black lines depict the rails. All measurements are in millimeters. It is important to note that the magnetic field is more intense at the center than it is at the edges.

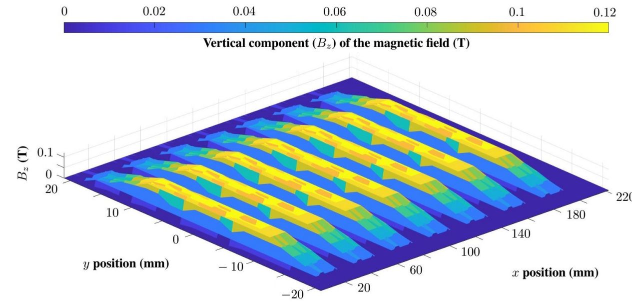

FIGURE 5. The color palette shows the intensity of the vertical component (B_z) of the magnetic field vector $\vec{B}$ of an array of seven neodymium block magnets spaced 8 mm.

A block magnet will be placed in the center of this area at a height of h. Once the MLM prototype is assembled, we will determine the closest approximation between the bar and the magnet. For this example, a 1/8" rod, which has a diameter of 3.175 mm, is used, and the height of the acrylic support is 3 mm. Therefore, we have selected $h = 6.0$ mm ($z = 6.0$ mm), which is approximately at the center of the rod. A data set consisting of 18×20 points will be collected, imported into Matlab as a matrix, and modeled using the 'quiver3' command to generate the magnetic field vector's vertical components (B_z), as shown in Fig. 4.

The student team is free to use any type of magnet geometry, but they must create a data matrix with the measurements collected at each point. If students choose to use circular magnets, they need to be careful to add zeros to complete their matrix. In contrast, if a rectangular magnet is used, the data matrix will be generated directly without the need for additional adjustments.

Using MATLAB, we create a mesh to visualize the intensity of the vertical component (B_z) of the magnetic field vector $\vec{B}$ generated by the seven neodymium block magnets. Figure 5 displays the magnitude through the dimensions of the rails, revealing intense magnetic fields in the center of the magnets and weak fields between adjoining magnets and on their sides. It is important to note that the observed magnetic field is not uniform; it is stronger at the center than at the edges, varying between 0.01 and 0.12 teslas.

3.3. Kinematics model

Students must model the kinematics of the MLM and obtain graphs of acceleration, velocity, and position over time. They must also model a solenoid that breaks the rod, specifying its characteristics, such as the number of turns and the core material. Braking is not physically observed, as it would take at least one more 4-hour session. If the reader wishes to extend the experiment, it is suggested to use a solenoid or reverse the polarity of the source, changing the current intensity if necessary.

Using data obtained in Sec. 3.2, we numerically solved Eq. (4) with the trapezoidal rule in MATLAB. We plotted acceleration vs. position in Fig. 6 using an array of seven magnets spaced 8.0 mm. The acceleration is maximum in the

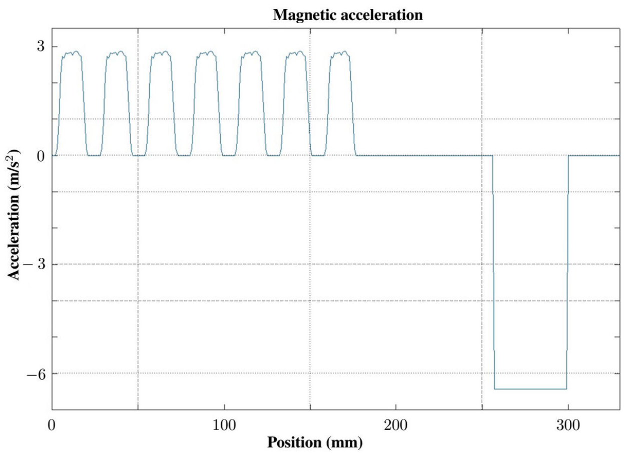

FIGURE 6. Accelerating the moving rod through the track in an MLM.

central zones of each magnet and falls to zero in the spacing zones. Once the moving rod leaves the magnets' array, the acceleration disappears until it reaches the model braking phase, dropping sharply until the rod slows down. In this example, braking is modeled using `MATLAB`. Once the student creates the kinematics, they must model the braking by varying the magnetic field until the rod comes to rest. The magnetic field obtained gives the characteristics of a solenoid that is assumed to be ideal, that is, very large compared to the diameter of its cross-sectional area. Obtaining the expression for a finite-dimensional solenoid is outside a basic science or engineering course that basic science books do not address [6,7].

Numerical solutions for Eqs. (5)-(6) are computed using the Runge-Kutta method. Graphs of position and velocity versus time are plotted in Fig. 7. The position versus time graph shows the moving bar's increasing position until it approaches a constant line due to magnetic force opposing its motion. The velocity versus time graph displays a series of steps representing the intervals between magnets where the bar's speed remains constant. As the bar exits the magnet array, its speed decreases until it almost stops due to the solenoid's brake.

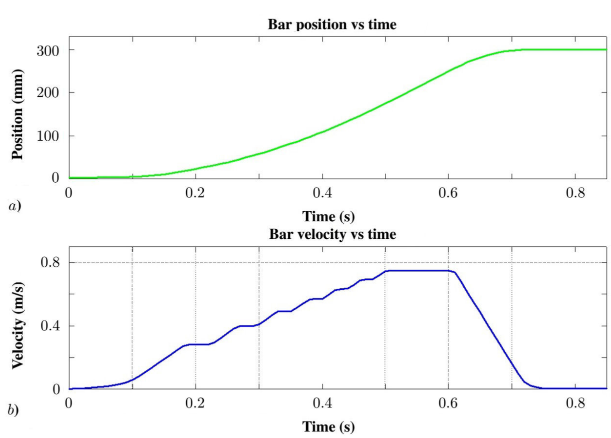

FIGURE 7. a) Rod position across the track as a function of time. b) Moving rod velocity through the track as a function of time in an MLM.

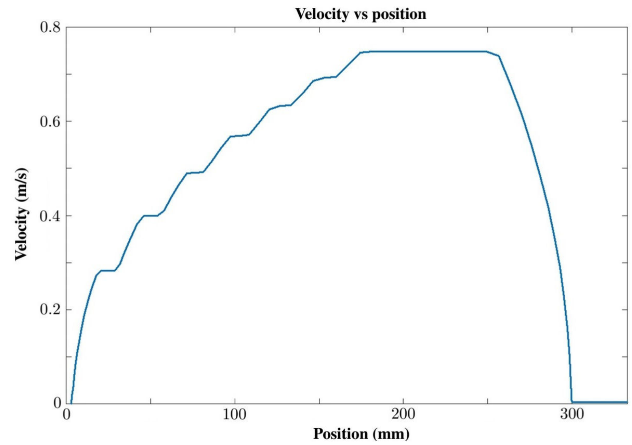

FIGURE 8. Moving rod velocity across the track as a function of position in an MLM. A series of steps represents the space between adjacent magnets. Then a constant speed is reached as the rod leaves the magnets' array. Outside the magnets, the speed decreases sharply due to a uniform magnetic field.

TABLE I. Aluminum rod kinematics in an MLM.

Speed (m/s)	Position (mm)	Time (s)
0	0	0
0.16	9.00	0.14
0.28	26.1	0.21
0.40	50.0	0.28
0.49	76.4	0.34
0.57	103	0.39
0.63	127	0.43
0.69	153	0.47
0.75	182	0.51
0.75	197	0.55
0.75	241	0.60
0.55	276	0.64
0.29	293	0.68
0	302	0.76
0	330	0.81

Table I shows the relationship between speed, position, and elapsed time. Speed increases as the magnets' array position changes, remains constant when the moving rod leaves the magnets and decreases towards rest when the rod passes through an electromagnetic brake with a uniform magnetic field.

The speed of the rod moving along the track in the MLM is illustrated in Fig. 8. The rod speed is reduced by an electromagnetic brake, which is created by a uniform magnetic field generated by a solenoid. For this prototype, the magnetic field necessary for modeling the solenoid is 0.18 T, opposing the magnetic field produced by the magnets. This solenoid can be modeled, for instance, with annealed iron

($\mu = 1.76 \times 10^{-3}$ Tm/A [6]) in its core. Considering Eq. (3), the required current and number density of turns for this solenoid would be such that $n\, i_s = 204$ turns A/m.

4. Results and discussions

The students who participated in the project, implementing the PjBL methodology [1], were able to apply, in an effective way to promote critical thinking, the principles of magnetism and movement with the construction and simulation of an MLM. They used cheap and accessible materials found in any basic science laboratory, which differs from other references that use expensive and inaccessible materials [3,4]. MLMs are typically not covered in introductory physics courses, which presents challenges for students [6,7]. In Sec. 3, we propose a solution that includes detailed measurements to guide the construction, modeling, and simulation of the forces and kinematics involved with the MLMs. A significant limitation of our approach is the time constraint; we only had 16 hours in the laboratory over a span of five weeks. As a result, we could not take into account factors such as friction force, the moment of inertia of the bar due to rolling, current control, rail stability, and the induced electromotive force (emf) caused by the bar's motion. Another important limitation of this work, which influences the reported measurements, is the freedom to place the magnets closer together or further apart without measuring and considering the magnetic field entering those areas.

To investigate the achievements derived from applying PjBL as a teaching strategy to stimulate critical thinking, we conducted a student satisfaction survey template [15] from April to May 2023[i]. This survey assessed students' satisfaction levels regarding theoretical modules, projects, course content, teaching methodology, team competency, course duration, and organization to measure learning outcomes. See Table VII in Appendix C for detailed satisfaction and learning levels associated with the block model.

One hundred thirty students from the Seven Blocks model program at Tecnológico de Monterrey participated in the survey, which consisted of 15 questions. The results revealed high satisfaction with the block model but lower satisfaction with certain mathematics subjects and integration activities. Table VII lists the 15 questions posed to participants, while Fig. 9 displays the evaluation results.

The first three questions focused on the block model and yielded satisfactory results overall. Nevertheless, students expressed dissatisfaction with specific mathematical subjects. Questions Q4.1 to Q4.5, which pertained to the project, indicated intense satisfaction, although Q4.3 and Q4.5, which addressed interactions among colleagues, received less favorable responses. Satisfaction scores ranged from 80% to 95% for questions Q5.1 to Q5.4, which dealt with the teachers' support for the project. Question Q6 garnered 80% satisfaction, while question Q7, framed negatively, had a 65% satisfaction rate, suggesting that some students felt overwhelmed or experienced communication issues with their teachers.

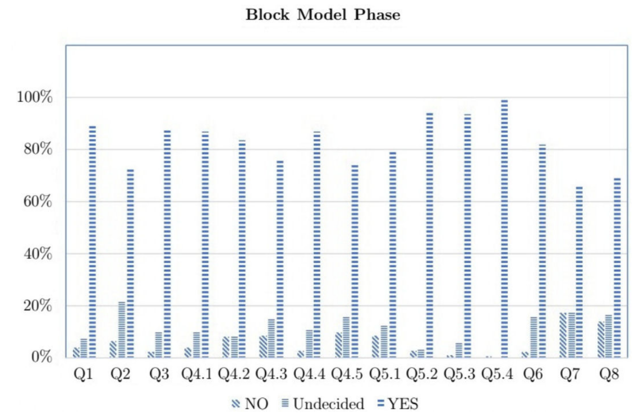

FIGURE 9. Satisfaction level to the questions in the block model phase. Table VII shows questions.

Question Q8 highlighted a need for improved integration activities among students [16].

The students, guided by their teachers and working as a team, were able to solve the question/challenge by creatively debating and collaborating on decisions about the size and type of materials for their MLM. They summarized information related to the concepts of magnetic force and laws of motion, discussed modeling in MATLAB, and presented the final project. One challenge encountered when implementing this approach is the time management issue for teachers transitioning from traditional to multidisciplinary learning. As a result, students felt overwhelmed when connecting physics concepts with solving differential equations using exact and numerical methods, so it is recommended that students not be left alone and that their progress be monitored.

The achievement was made possible through a scientific laboratory practice created by the teachers. This practice involved students in observing and measuring the magnetic force. The learning issues questions helped guide student teams in understanding how the magnetic force is connected to the movement of a bar through a magnetic field and in describing and modeling the motor's movement numerically.

Students were able to learn using the technology scaffolds by measuring the magnetic field using PASCO-type sensors, obtaining a 20 by 18 data matrix, and then the magnetic field intensity was modeled in MATLAB using a color palette. The students also modeled motor kinematics using a large matrix containing data for seven magnets and a braking solenoid. They applied magnetic force and solved it numerically using the trapezoid method, Newton's Second Law of motion, and the Runge-Kutta method. This helped them solve the differential equation of motion, obtaining acceleration, velocity, and position graphs. The students were animated to see their graphs in response to a real-world problem. One limitation is that modeling large matrices requires teacher support and teamwork. One of the limitations encountered was that five four-hour sessions were insufficient to fully assemble the motor. As a result, the braking component that uses a solenoid had to be predicted through a model of an ideal solenoid in

MATLAB. Another limitation is that modeling large matrices proved challenging and required support from the instructor and collaboration within the team.

Students submitted a pair of documents with their progress as a final learning product, one after week three and the other as a final report. These reports were then summarized for the final team presentation, during which students discussed their achievements, limitations, and conclusions. The professor in charge of the project evaluated the reports, and a pair of rubrics is provided in Appendix B as a suggestion. In the past, students had to submit three assignments, videos, and exam assignments, which we found to be overwhelming based on our experiences with similar courses.

The final presentation formed the basis of a final oral exam, which was graded by all the teachers who participated in this block. A significant achievement is that the students covered all the topics of magnetic force and Newton's Second Law, as well as explaining and presenting graphs and conclusions from their projects.

Project-based learning (PjBL) management promotes theoretical and experiential education by leveraging students interests and developing competencies such as collaboration, decision-making, advanced communication, ethics, and leadership [2,17]. This project aims to encourage students at Tecnológico de Monterrey to actively engage with the PjBL methodology, specifically focusing on improving collaboration. It involves constructing and modeling a lesser-known electromagnetic phenomenon, offering real-world, experiential learning that sets it apart from traditional teaching methods. PjBL enables students to gain a deeper understanding of core subjects and develop life and career skills while allowing them the freedom to be self-directed, creative, and inspired. Physics teachers demonstrate positive mental habits and new ways of thinking and learning, helping students acquire profound knowledge and understanding in core subject areas as well as 21st-century content, learning and innovation skills, and life and career skills.

5. Conclusions

The engineering students at Tecnológico de Monterrey applied the principles of magnetism and motion by creating and simulating an MLM using the collaborative PjBL methodology [1]. This approach facilitated experiential and collaborative learning by exploring topics from diverse perspectives and across multiple disciplines, such as differential equations, numerical calculus, and electromagnetism (numerical analysis, programming, and the assembly of magnets, rods, and connectors). A solution to the project was proposed, including detailed measurements that act as a guide to building an MLM with inexpensive and accessible materials. In turn, the forces and kinematics of the movement were modeled and simulated using MATLAB.

The evidence showed that students were very satisfied with the block model. However, they indicated lower satisfaction levels with specific mathematics topics and integration activities. It is important to showcase the development and acquisition of the content students learn, illustrating the transition from rote memorization to genuine understanding and recognizing the complex relationship between traditional evaluation methods and competence assessment [18].

PjBL is a hands-on STEM learning experience that combines active learning and collaboration. This paper described the PjBL methodology in three phases: commitment, research, and action [2]. During the commitment phase, stu-

TABLE II. Material provided by the students.

1. Aluminum Rod, 6.32 mm, large 44.32 mm, 4.0 g
2. Acrylic template 5 mm thick to attach magnets
3. Screws
4. Alligator Clips (at least 5)
5. Rails 1 m, L-Type aluminum gutter 5 mm
6. Magnets
7. Reverse polarity switch
8. Thermocouple tubing from an LP gas boiler

TABLE III. Material supplied by the laboratory.

1. Magnets. Technical Information in Table IV
2. Linear Programmable DC power supply
3. PASCO PS-2120A Rotary Motion Sensor
4. PASCO CI-6520A Magnetic Field Sensor
5. Mechanical support of two racks coupled in x and y
6. Multimeter

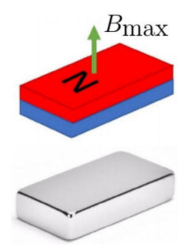

FIGURE 10. The neodymium block magnet used in this MLM.

TABLE IV. Technical information on the Neodymium Block Magnet used in this challenge and shown in Fig. 10.

Material	NdFe
Coating	NiCuNi
Length	38.10 mm
Width	19.05 mm
Thickness	6.35 mm
Magnetization Direction	$Axial$
Weight	35 g
Pull	$\pm$ 6 kg
$Br_{\max}$	11700 a 12100 Gauss
Surface power	5,900 Gauss
Maximum operating temperature	80°C (176°F)

TABLE V. Suggested criteria to evaluate students' first assignment. Students can receive a maximum of 10 points on each criterion. It is important to note that each criterion is weighted deferentially. Thus, the final grade is obtained by multiplying the scores for each criterion by the percentage suggested in the last column of the table.

10 pts *Advanced mastery of this criterion*	8 pts *Solid command of the topic*	6 pts *Basic command of the topic*	4 pts *Some areas to improve*	2 pts *A lot of areas to improve*	0 pts *This criterion is not observed*	%
Explains the operation and use of the MLM.	Explains the operation but not the use of the MLM.	Explains, very simply, the operation of the MLM.	Explains, incompletely, the operation of the MLM.	Explanation of operation or use of the MLM should improve.	Does not explain the operation or the use of the MLM.	20%
Presents a plan with all the dimensions of the prototype in detail.	Only presents the measurements of the magnets, but not their distribution and orientation.	Only presents the orientation of the magnets but not their measurements. the rails.	Measurements of the magnets are included, but not the sizes of	The use of plans and drawings should be improved.	Does not use plans.	20%
Describes the components of the MLM in detail.	Lists the types of materials and their dimensions that will be used, but does not describe their use.	Lists the types of materials but does not give dimensions or their use.	The list of materials to be used is incomplete.	Very few measurements match the model.	Average and theoretical data do not match.	15%
Their theoretical model includes all the equations involved in the system.	Only presents some of the equations involved in the system.	Presents a basic description of each process. each process.	Shows some details of description of	The description of the process is not completely.	The description of the process is not clear.	15%
Presents simulation under `MATLAB` of the measurement of a magnet with variable magnetic field and simulation with all the magnets.	Only presents simulation under `MATLAB` with all the magnets.	Presents simulations under `MATLAB` but with a constant magnitude of the magnet's magnetic field.	Only presents one simulation with constant magnitude of the magnet's magnetic field.	The simulation is not complete or clear.	Does not apply correctly simulation in `MATLAB`.	30%

dents set a goal to build and model a prototype MLM. The research phase involved defining the values for the components of the MLM, and the action phase required students to assemble the prototype, record its electrical behavior, and model the data obtained with theoretical values for the MLM. Teachers who implemented PjBL in teams reported that collaboration with other teachers is a beneficial and enjoyable aspect of the educational approach.

Appendix

A. Materials

This material may vary depending on the measurements the students and the teacher decided; for example, instead of Rails 1 m, L-type aluminum gutter 5 mm, you can get 10 gauge copper wires.

B. Rubrics

Tables V and VI show the rubrics to evaluate students' submissions for assignments one and two, respectively.

C. Survey

Table VII shows the satisfaction poll posed to the participant students.

TABLE VI. Suggested criteria to evaluate students' second assignment. Grading criteria are similar to the first assignment.

10 pts *Advanced mastery of this criterion*	8 pts *Solid command of the topic*	6 pts *Basic command of the topic*	4 pts *Some areas to improve*	2 pts *A lot of areas to improve*	0 pts *This criterion is not observed*	%
Presents his calculations with essential steps to arrive at the differential equation of motion.	Presents his calculations with some steps to arrive at the differential equation of motion.	Presents incomplete calculations to arrive at the differential equation of motion.	Presents very few calculations, and the differential equations of motion are incomplete.	Does not present his calculations clearly to arrive at the differential equation of motion.	Does not apply the equations of the motion correctly.	15%
Calculates stored energy.	Presents stored energy.	Presents a basic description of stored energy.	Shows some details of stored energy. is not completely.	The description of the stored energy	Does not calculate stored energy.	10%
Accomplishes finding the value of a solenoid's magnetic field to stop the moving rod.	Only accomplishes to reduce the speed of the rod without stopping but associates it with a solenoid.	Accomplishes finding the magnetic field's value to stop the moving rod, but he does not relate it to a solenoid.	Accomplishes finding the value of the magnetic field of a solenoid, but he cannot stop the rod of an MLM.	Fails to find the value of a solenoid's magnetic field to stop the moving rod.	Fails to slow down the moving rod.	25%
Uses and explain graphs and tables.	Uses graphs and tables.	Uses some graphs and tables.	Just uses some graphs.	Just uses some tables.	Does not use graphs and tables.	20%
Analyzes the results and synthesize the information.	Analyzes but do not synthesizes information.	Only synthesizes information.	Incompletely analyzes the information.	Must improve the information.	Does not analyze and synthesize information.	20%
All references consulted are reliable and in APA format.	Some references consulted are reliable and in APA format.	All references consulted are reliable but not in APA format.	The references consulted are incomplete.	Should improve the references consulted.	The references consulted are not displayed.	10%

TABLE VII. Survey of the block model.

Block Model Phase
Q1 The physics module gave me the knowledge to reach the analysis and modeling required to solve the project. YES ☐ NO ☐ Undecided ☐
Q2 The mathematics module reinforced my necessary knowledge to analyze and delve into the course's physics and the project's solution. YES ☐ NO ☐ Undecided ☐
Q3 The computing module gave me the necessary knowledge for the algorithmic development of the solution to the project. YES ☐ NO ☐ Undecided ☐
Q4.1 Working on a project's solution has helped me reinforce my understanding of the topics I saw in the modules. YES ☐ NO ☐ Undecided ☐
Q4.2 Working on the solution of a project has helped me to understand more clearly and deeply the theoretical concepts in an authentic context. YES ☐ NO ☐ Undecided ☐

Q4.3 Working on a project's solution has helped me interact with my colleagues in a proactive and committed way.
YES ☐ NO ☐ Undecided ☐

Q4.4 Working on a project solution has helped me to develop subject-specific skills for my professional training.
YES ☐ NO ☐ Undecided ☐

Q4.5 Working on a solution to a project has helped me to develop adequate social skills.
YES ☐ NO ☐ Undecided ☐

Q5.1 All the teachers in the block are coordinated with each other.
YES ☐ NO ☐ Undecided ☐

Q5.2 All the teachers in the block know the project I worked on.
YES ☐ NO ☐ Undecided ☐

Q5.3 All the teachers in the block maintain communication with me.
YES ☐ NO ☐ Undecided ☐

Q5.4 All the teachers in the block are willing to help me.
YES ☐ NO ☐ Undecided ☐

Q6 I understood the theoretical concepts involved in the modules.
YES ☐ NO ☐ Undecided ☐

Q7 The scientific content was presented out of order.
YES ☐ NO ☐ Undecided ☐

Q8 There needed to be more appropriate activities to assess my performance.
YES ☐ NO ☐ Undecided ☐

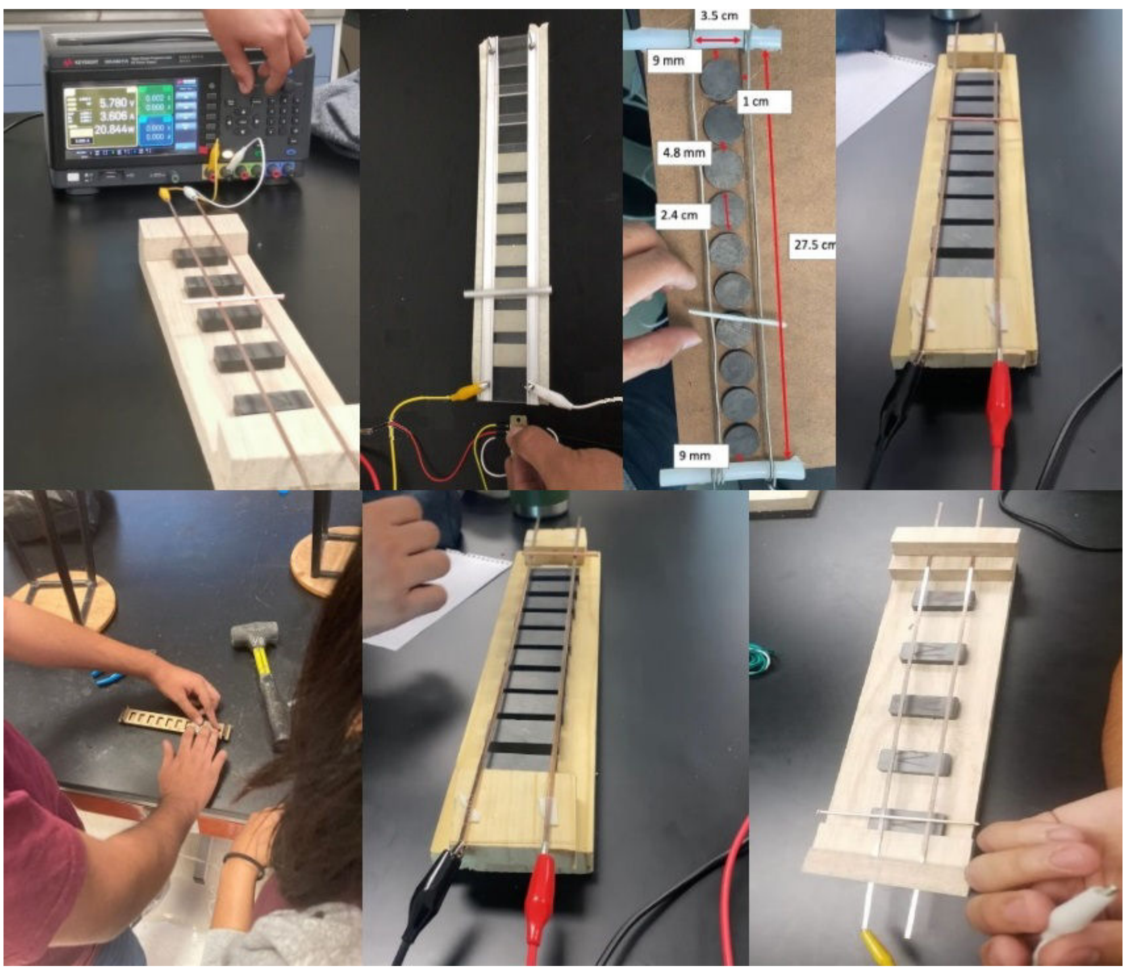

FIGURE 11. Photographic record of the experiment.

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i. All subjects gave their written informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Tecnológico de Monterrey Institutional Research Ethics Committee.

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