Low-Cost Tool for Measuring Magnetic Force in Large-Enrollment Courses

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Abstract

Measuring the force between permanent magnets is a fundamental and well-established experiment in teaching electromagnetism, essential for students to empirically validate physical models. However, the implementation of this classic setup in large undergraduate courses is systematically hampered by the high cost, fragility, and rigidity of commercial equipment. This work presents the redesign, manufacture, and validation of a low-cost, open-source experimental device, developed primarily through 3D printing with diamagnetic materials. The main objective is to overcome the logistical shortcomings of the traditional setup by integrating a screw-type mechanism for distance adjustment, a standardized support for force sensors, and an alignment structure that supports repeatable coaxial alignment during measurement. This open-source design approach supports instructors in iterative improvement of lab activities and local adaptation of the apparatus. The validation results demonstrate that the device is a robust, economical, and flexible solution with adequate precision for undergraduate laboratory use. The creation of a replicable and low-cost tool facilitates the successful implementation of this established experiment in large-enrollment courses, promoting active, self-directed learning and contributing to the democratization of teaching tools in university physics.

Keywords: Magnetic force measurement; 3D printing; low-cost apparatus; physics education research; experimental physics

Introduction

Electromagnetism courses in engineering often include experimental experiences for students to compare physical models with actual measurements. In undergraduate experimental physics, many activities focus on "typical" functional trends (linear, quadratic, exponential, or inverse square). However, incorporating phenomena with more pronounced nonlinear relationships can enrich experimental literacy: it forces students to pay attention to variable control, discuss uncertainty, and analyze data with more realistic criteria.

The force between permanent magnets as a function of distance offers precisely that educational value. Previous work has shown protocols and models for studying this interaction in educational settings, including experimental proposals and modeling discussions [1], [2]. However, transferring these experiences to large-enrollment courses is often problematic: small alignment errors, mechanical instability, and limitations in controlling the separation between magnets can distort measurements, especially when working with high-intensity magnets.

Practical gap (for large-enrollment courses). Although the experiment is conceptually valuable and well established, its adoption on a large scale is hampered by the need for costly or delicate setups and by the difficulty of standardizing the procedure for multiple groups in limited time. For reference, typical setups for this experiment are shown in the literature (Figure 1).

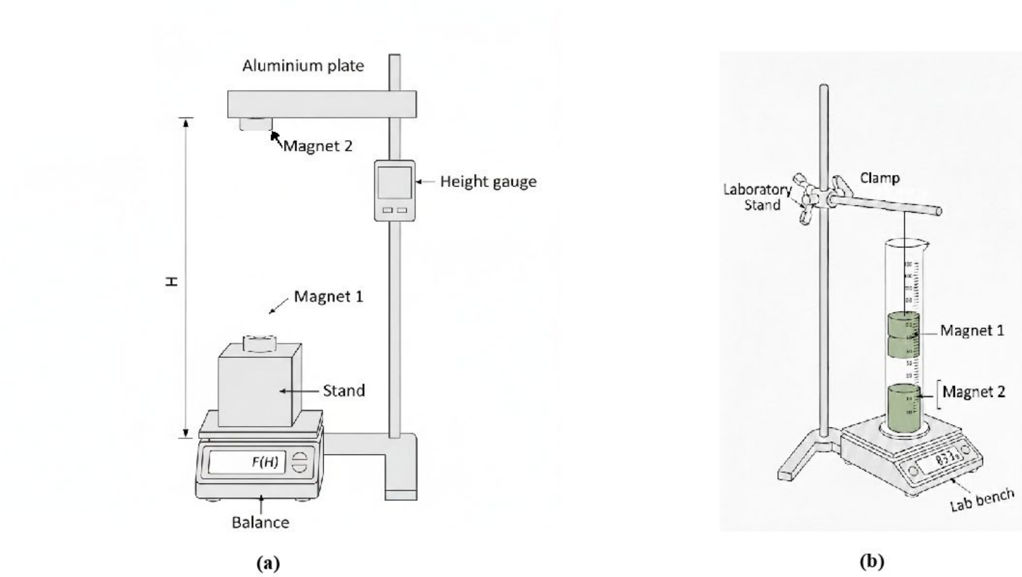

Figure 1. Schematic of representative setups reported in prior work for measuring magnet–magnet force as a function of separation distance: (a) digital scale with the movable magnet positioned using a height gauge/linear stage (based on [1]); (b) digital scale with the movable magnet guided by a graduated cylinder/syringe (based on [2]).

To be viable in large-enrollment courses, the apparatus should: (i) be low-cost and easy to replicate, (ii) provide repeatable distance control, (iii) maintain coaxial alignment under stronger magnets, (iv) be robust to frequent handling, and (v) support quick reconfiguration for different magnet geometries.

Purpose and contribution. This work seeks to close that gap through an open-source, low-cost redesign based on 3D printing, which makes the experiment more stable, repeatable, and easier to implement [3], [4]. The main contribution is not to "reinvent" the experiment, but to rethink its educational engineering: to design a device conceived from the outset for scalability, robustness, and rapid adaptation to different types of magnets in order to democratize access to experimental experiences and reduce implementation barriers.

This paper makes four contributions:

(1) defines design requirements for implementing the magnet force–distance experiment in large-enrollment labs;

(2) presents an open, 3D-printed apparatus with screw-based distance control and coaxial guidance;

(3) documents key design iterations required to prevent deformation when using stronger magnets (e.g., neodymium); and

(4) provides validation data showing an expected force–distance trend with increased sampling density (24 points), enabling richer modeling and data-analysis activities in the classroom.

Methodology

Design and Iteration Approach

An iterative design process (prototyping–testing–adjustment) was followed, motivated by failures observed in initial implementations. In the first stage, we attempted to replicate experimental setups reported in the literature, but we identified high sensitivity to setup variables (alignment, structural rigidity, and distance control).

To reduce these sources of variation, we designed our own setup in CAD (Autodesk Fusion360) and manufactured prototypes using FDM 3D printing. The initial CAD design is shown in Figure 2, and its implementation with encapsulated ceramic magnets is shown in Figure 3.

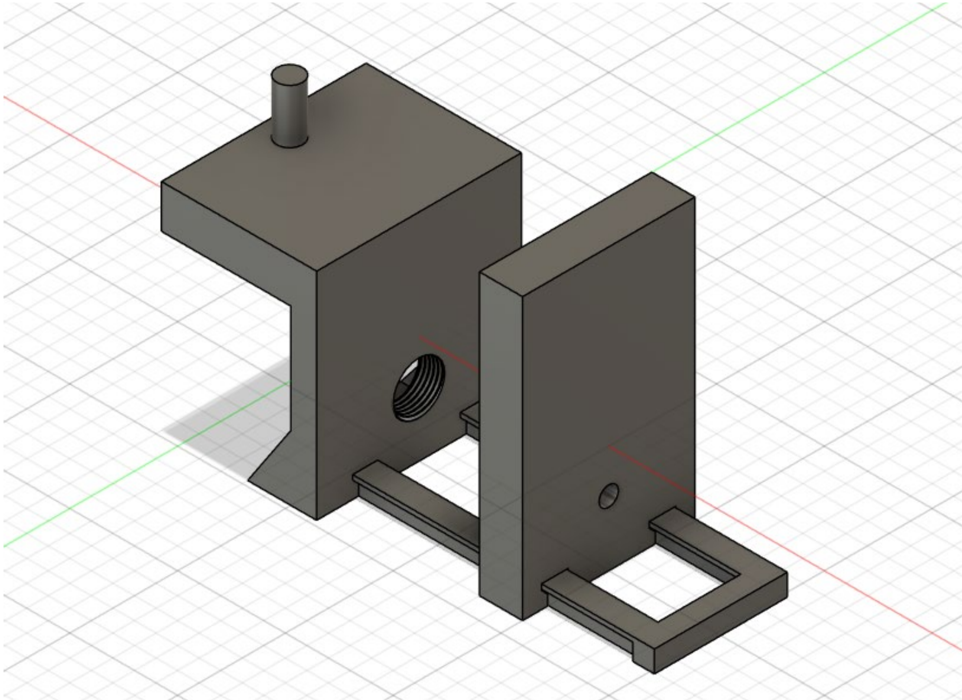

Figure 2. CAD model of the initial apparatus, featuring bottom-mounted screw-based distance adjustment (authors' work).

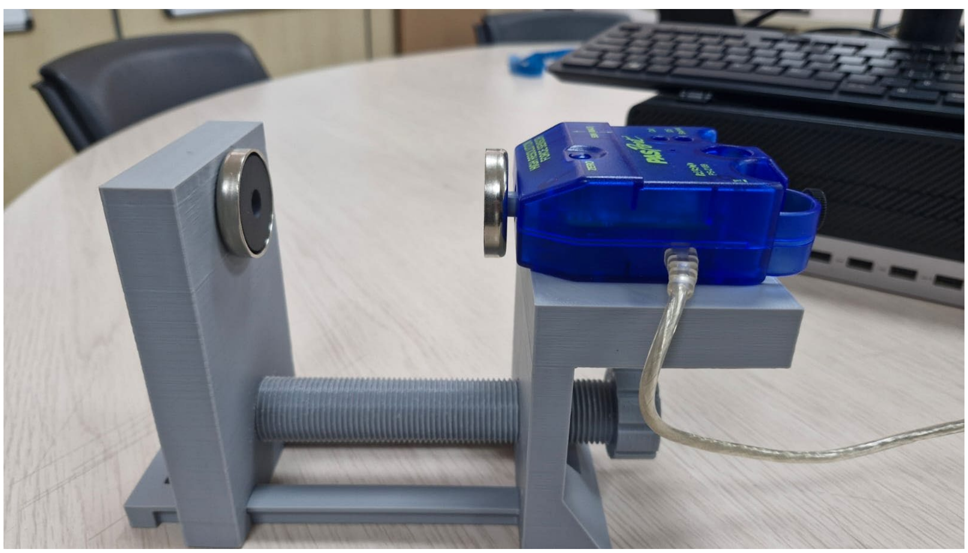

Figure 3. Initial apparatus setup with encapsulated magnets and bottom-mounted screw-based distance adjustment (authors' work).

The device evolved through successive versions: initially, it worked acceptably with encapsulated ceramic magnets, but when these were replaced with neodymium magnets, structural deformation/yielding was observed at short distances, compromising the measurement. This prompted redesign iterations (Figure 4), including changes to the mobile-magnet support, screw location, and structural reinforcements, until a stable final configuration was achieved.

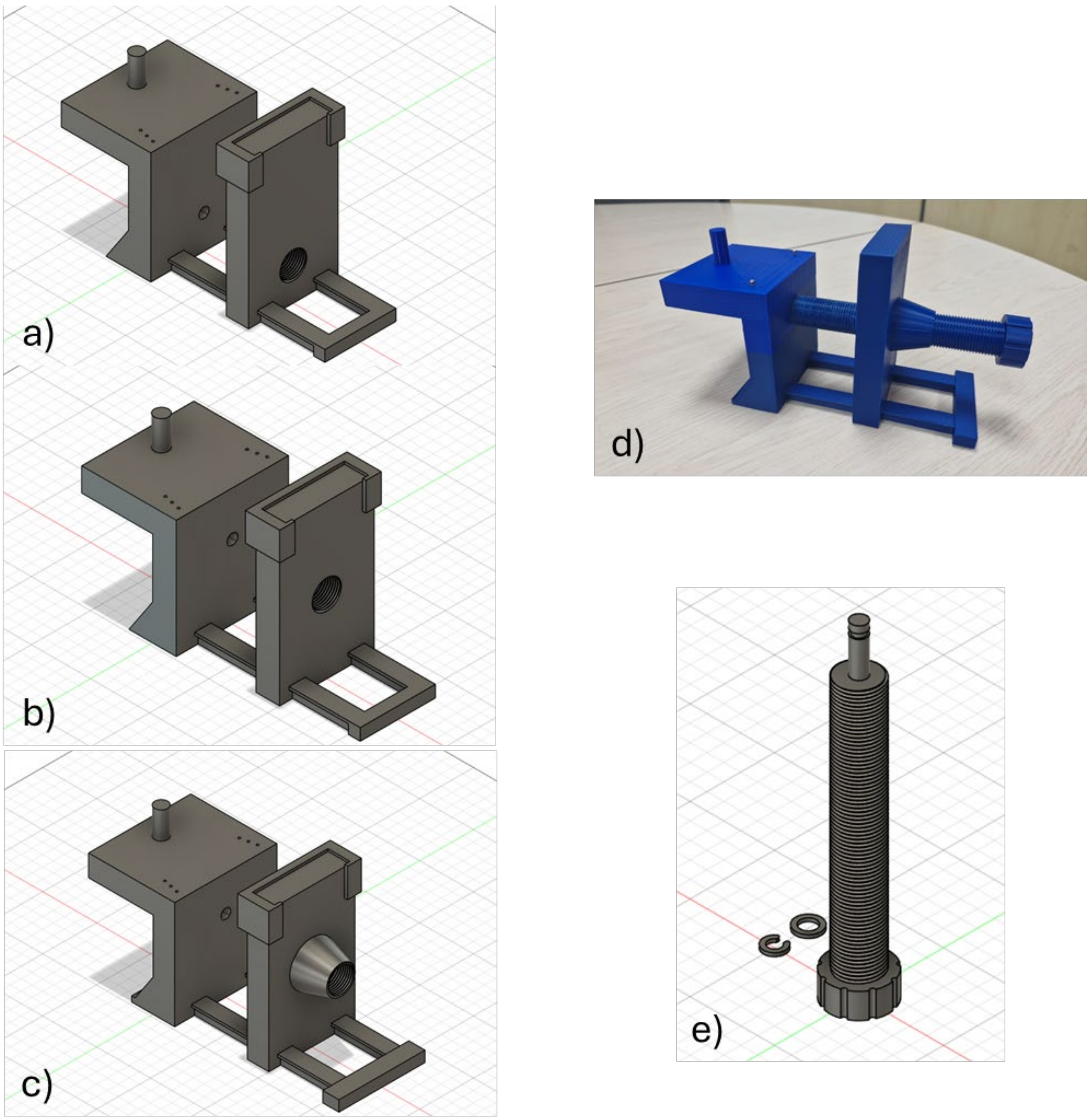

Figure 4. Apparatus design iterations: (a) bottom-screw layout; (b) top-screw layout; (c) reinforced top-screw layout; (d) refined top-screw layout; (e) detail view of the screw-and-support mechanism (authors' work).

Description of the Final Setup

The final setup (Figure 5 and available in printables) incorporates three design decisions aimed at large-enrollment courses:

1. Distance control by screw: a screw-type mechanism allows fine and repeatable adjustment of the separation between magnets, reducing the dependence on "manual adjustments" and favoring a standardizable procedure between groups.

2. Coaxial alignment and rigidity: the structure guides the trajectory of the moving magnet to maintain coaxiality, avoiding angled configurations that introduce lateral components and noise in the reading.

3. Modularity of supports: the magnet support is interchangeable; to study magnets of different geometries, simply change this part, without redesigning the entire system. Examples of magnets we used are a ceramic magnet in the shape of a ring encapsulated in a nickel coating, with approximate dimensions of 35 x 5 x 7 mm, and a cylindrical neodymium magnet measuring 13 x 5 mm.

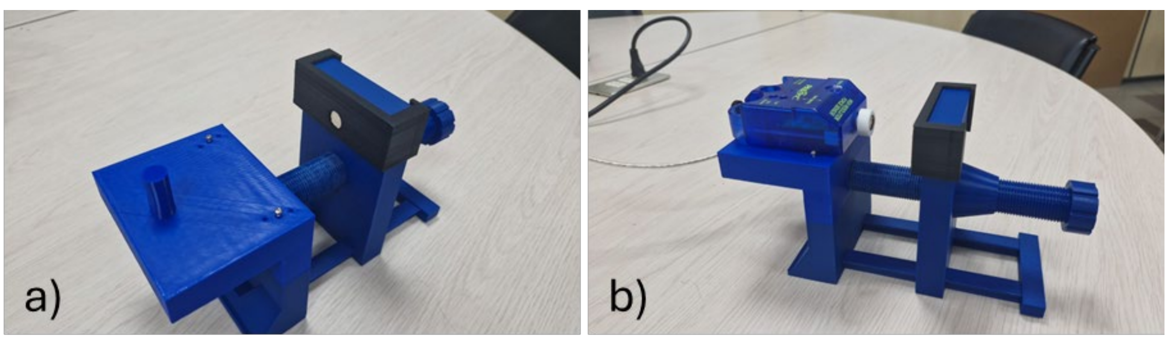

Figure 5. Final apparatus: (a) without force sensor; (b) integrated with the force sensor for data acquisition (authors' work).

With this latter configuration, we can collect experimental data for different magnet configurations by simply modifying the corresponding support (Figure 6). In addition, deformation due to interaction between magnets at short distances is avoided.

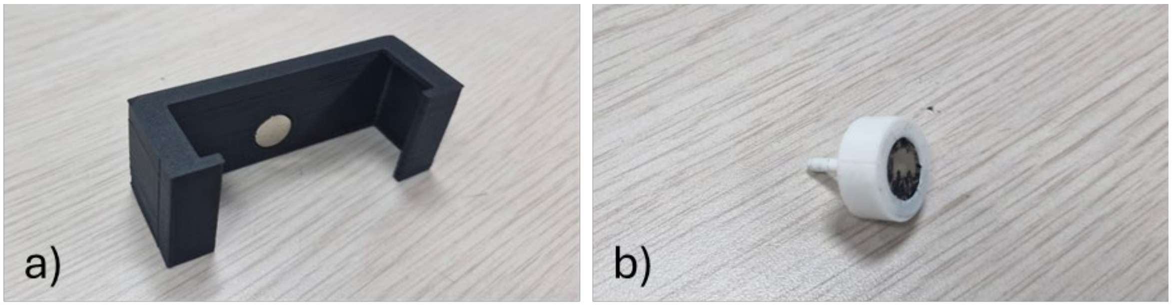

Figure 6. Modular magnet mounts: (a) interchangeable mobile-magnet holder; (b) mount for positioning the fixed magnet on the force sensor (authors' work).

Instrumentation and Measurement Protocol

The force is recorded with a force sensor mounted on the device (depending on laboratory availability). Distance is measured in millimeters and force in newtons. During development, a significant difficulty was detected: the use of a metal vernier caliper interfered with distance measurement due to the magnetic field; this was resolved by replacing it with a plastic caliper.

Suggested protocol (standardizable for large classes):

1. Mount the fixed magnet on the force sensor and the movable magnet on the interchangeable support.

2. Define a safe initial distance (to avoid "jumps" due to attraction) and record the force reading.

3. Adjust the separation with the screw in predefined increments, measuring the distance with the plastic caliper.

4. Record pairs (distance, force) to construct the force-distance curve.

5. (Optional for report robustness) Repeat each point 2-3 times to estimate instrumental variability.

Results

Mechanical Performance and Setup Stability

The most relevant result of the iteration process is that the final configuration avoids the deformation observed when working with stronger magnets (e.g., neodymium) at short distances. Consequently, the device allows data to be collected consistently "for any magnet configuration" by changing the support, while maintaining structural integrity.

Data Quality: Resolution and Qualitative Comparison with Literature

The device produces the expected force-distance curve shape, with pronounced nonlinear behavior (Figure 7). When qualitatively compared with results reported in the literature [2], similarities in overall behavior are observed.

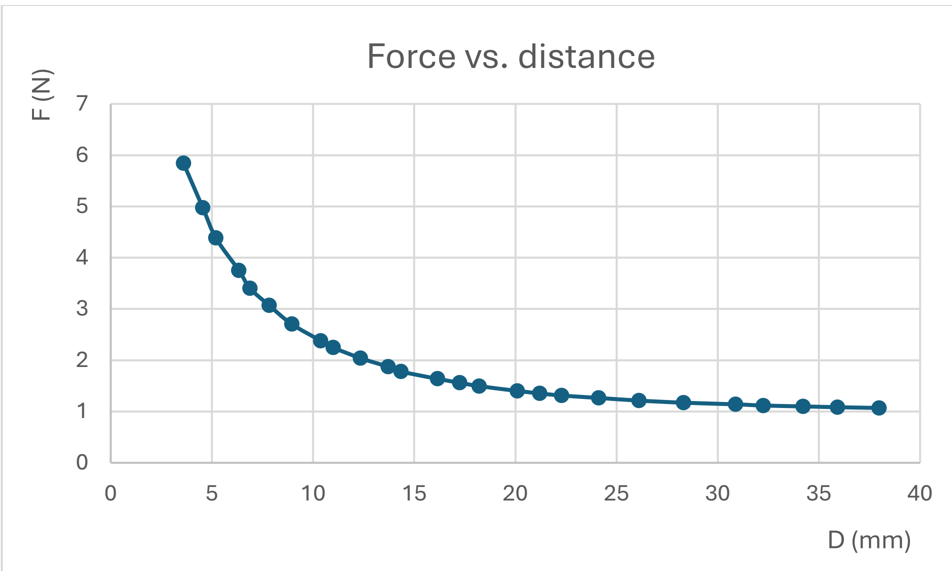

Figure 7. Measured magnetic force as a function of separation distance using the final apparatus (distance in mm; force in N) (authors' work).

The repeatability of measurements was mainly evident in the stability of the graphical forms obtained by repeating the procedure with an encapsulated ceramic magnet and then (after adapting the assembly) with a neodymium magnet. Graphical stability favors instrument reliability, as the results reproduce similar patterns under equivalent conditions.

A practical contribution to teaching is the increase in sampling density: while a reference setup reports 8 points, 24 measurements were recorded with the proposed device. This higher resolution facilitates discussion of (i) global trends, (ii) sensitivity to distance in the near regime, and (iii) noise/variability effects, without the curve depending on a few points.

Discussion

From an implementation perspective, the innovation lies in designing for the large-enrollment courses: the screw mechanism and coaxial guide reduce the instructor expertise required to operate the experiment; interchangeable supports allow the same device body to be reused for different magnets; and the use of 3D printing facilitates rapid replacement of parts in case of wear or loss, reducing the logistical fragility associated with commercial equipment.

In addition, the open approach enables instructors to adopt a continuous-improvement mindset by documenting modifications, sharing updated versions, and adapting the apparatus to local constraints (e.g., available sensors, magnet types, and safety requirements). This positions the work as a practical contribution to expanding access to hands-on experimentation: rather than offering a one-off “device,” it provides a replicable, adaptable design that lowers common barriers to implementation and scaling in undergraduate laboratories.

Conclusions

This work presents an open, low-cost redesign for measuring force between permanent magnets, explicitly aimed at use in large-enrollment courses. The final device integrates fine distance control via a screw, coaxial alignment, and modularity of supports, solving problems of instability and deformation observed in initial prototypes when working with high-intensity magnets. Validation shows force-distance curves with expected behavior and allows for an increase in experimental data density (24 measurements), which improves experimental discussion in the classroom.

Educational Implications

From a large-scale implementation perspective, the main pedagogical value of the device is that it reduces the operational burden of the experiment (alignment, distance control, and repeatability), making it easier for multiple teams to work with a standardized procedure in limited time. This allows the focus to shift from "making the setup work" to analysis: data interpretation, discussion of assumptions, and experimental decision-making. In other words, the redesign not only makes the experiment cheaper, but also improves its implementation conditions so that the activity contributes more consistently to the learning objectives in electromagnetism.

In terms of learning, the force-distance curve between magnets offers an opportunity to work on scientific and engineering practices: hypothesis formulation, parameter adjustment (e.g., power law models), distance sensitivity analysis, and discussion of uncertainty and systematic error. The higher data density enabled by the proposed setup (Figure 7) favors the contrast between model and evidence and opens up space for guided inquiry or project-based learning activities, for example: comparing different magnet geometries/materials, evaluating the influence of alignment, or proposing design improvements as part of an iteration cycle similar to the one followed in this work.

Acknowledgments

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