

Low-cost magnetic levitation project kits for teaching feedback system design

Katie A. Lilienkamp
 Department of Mechanical Engineering
 Massachusetts Institute of Technology
 Cambridge, MA 02139
 email: gonzo@mit.edu

Kent H. Lundberg
 Department of Electrical Engineering
 and Computer Science
 Massachusetts Institute of Technology
 Cambridge, MA 02139
 email: klund@mit.edu

Abstract—Low-cost magnetic levitation project kits are used in teaching system design in an introductory undergraduate control systems course. Students receive individual kits along with assembly instructions for building a magnetic levitation device that is marginally stable, and they are then challenged to modify the system to improve performance. The magnetic levitation kits provide an open-ended design problem, a class memento, and on-campus advertising for future students.

I. INTRODUCTION

We have developed a new magnetic levitation project option for fulfilling the final laboratory assignment in a junior and senior-level control systems course (6.302 Feedback Systems) offered by the Department of Electrical Engineering and Computer Science at the Massachusetts Institute of Technology. In this new project, students analyze and redesign a dynamic system which suspends a magnetized object below an electromagnet. This system is similar to the classroom demonstration systems first described in [1] and [2]. Participating students assemble and modify individual kits to create their own desktop-sized systems with active control. Our main goal is to provide a challenging design problem which will capture student interest and will allow for open-ended solutions.

The unmodified basic system presented to the students is marginally stable. In this paper, we describe the basic magnetic levitation kit and outline some key design issues we expect students to explore in improving the performance of the device. We describe our efforts to keep the kits inexpensive, and we summarize some student experiences with the project.

II. THE BASIC SYSTEM

Figure 1 shows an assembled magnetic levitation system. The kit is relatively straightforward to assemble, however performance of the device is intentionally poor. When assembled as described, the system exhibits high sensitivity to initial conditions and considerable visible wobble of the object. This kit is based on a low-cost design developed by Guy Marsden [3] which uses simple proportional control and is only marginally stable. The parts kit includes all

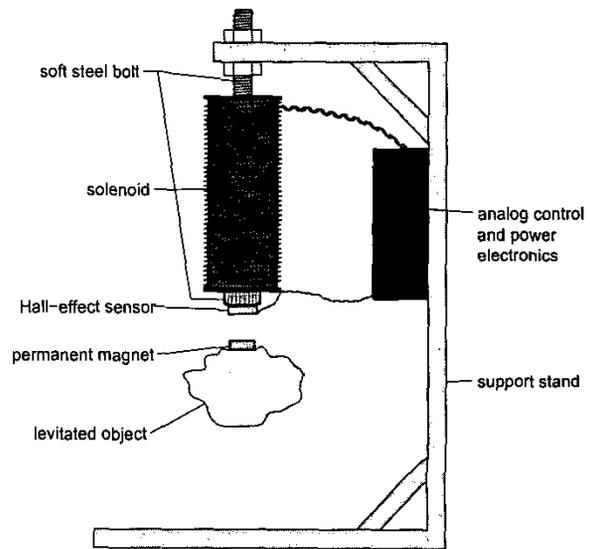


Fig. 1. An assembled magnetic levitation system. The controller senses the position of the object with the Hall-effect sensor and drives the current in the solenoid to maintain levitation.

U1	LM7805	voltage regulator
U2	MIC502	fan-management IC
U3	LMD18201	motor H-bridge IC
U4	SS495A	Hall-effect sensor
C1	470 μ F	electrolytic capacitor
C2	1 μ F	ceramic capacitor
C3	0.1 μ F	ceramic capacitor
C4	0.01 μ F	ceramic capacitor
prewound solenoid		
soft-steel carriage bolt		
neodymium magnets (2)		
heat sink for LMD18201		
small circuit board		

Fig. 2. List of kit contents. The labels refer to the schematic in Figure 3. The kit contains everything the students need except for a support stand and an object for levitation.

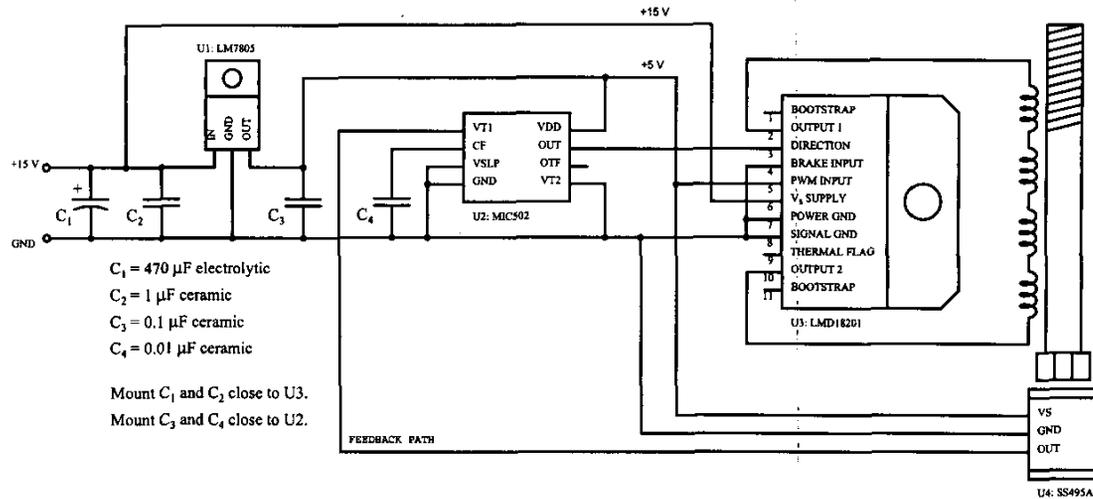


Fig. 3. Schematic of magnetic levitation system. The position of the levitated object is sensed by the SS495 Hall-effect sensor. The output voltage of the sensor drives the input of the MIC502 fan-management chip. The fan-management chip produces a PWM signal to the LMD18201 motor drive H-bridge chip. This PWM drive adjusts the average current in the solenoid, which controls the magnetic field.

of the parts listed in Figure 2, but it does not include the support stand or the object for levitation.

The schematic of the basic system is shown in Figure 3. In this system, the position of the levitated object is sensed by a Hall-effect sensor. The output voltage of the sensor drives the input of a low-cost fan-management chip, which produces a pulse-width modulated (PWM) drive signal to a motor drive chip. This PWM signal adjusts the average current in the solenoid, which controls the magnetic field.

Damping is provided by some washers attached to the levitated object. Losses and eddy currents in the ferrous material help to dampen the vertical wobble of the object [3]. The basic system exhibits unreasonable sensitivity to initial conditions and requires an extremely steady hand. Of course, the measurement of the magnetic field from the levitated object is corrupted by the field from the solenoid, so this measurement of position is far from ideal. However, for the basic system, the Hall-effect sensor is an inexpensive and adequate solution.

III. LAB PROJECT

After the basic system is demonstrated in lecture (as shown in Figure 4), students receive individual kits along with assembly instructions for building the magnetic levitation device. The laboratory assignment challenges the students to modify the system to improve system stability, transient performance, and disturbance rejection.

We intentionally present students with a device which is both badly instrumented and badly compensated, and we expect that two of the key issues students will analyze include sensor performance and compensator design. The project is open ended, however, and students are also encouraged to explore other areas of improvement. Their modifications can include the following: sensor selection

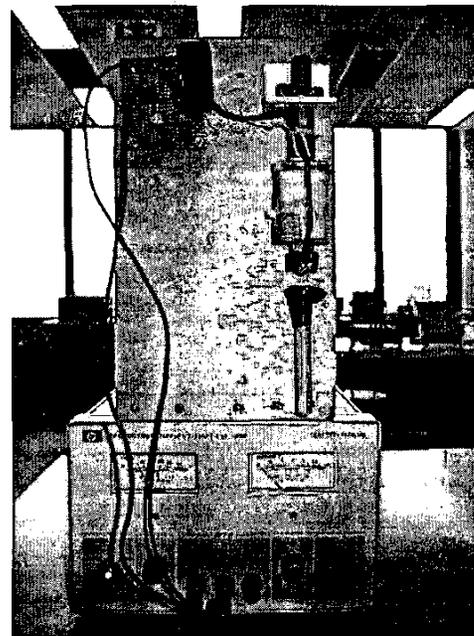


Fig. 4. The authors' lecture-demonstration system with a simple wooden stand. The system levitates a broken pencil attached the magnets with a glob of electrical tape. This solution is decidedly unattractive and low tech, and it demonstrates the marginal stability of the unmodified basic system.

and placement, the design of the coil actuator, the characteristics (magnetic, geometric or inertial) of the levitated object, power electronics, and the analog controller.

The lab assignment requires that at a minimum the students design an analog compensator to improve the stability and disturbance rejection of the basic system. Students need to modify the system to enable basic transient measurements

LM7805	\$ 0.48
MIC502	\$ 1.91
LMD18201	\$ 8.13
SS495A	\$ 2.02
470 μ F	\$ 0.42
1 μ F	\$ 0.34
0.1 μ F	\$ 0.09
0.01 μ F	\$ 0.11
Solenoid	\$ 3.50
Carriage Bolt	\$ 0.40
Magnets	\$ 0.45
Heat sink	\$ 0.93
Total	\$ 18.78

Fig. 5. Cost of kit parts, for quantities of 100. Capacitors are all 50-volt rated. Keeping the cost under twenty dollars enabled the students to keep their systems at the conclusion of the class.

of the system (by adding an electrical drive input). Once the desired loop transfer function is determined, the circuit must be modified to include the compensator circuitry. Most students found this requirement easy to satisfy with a simple *op-amp circuit implementing a lead compensator*.

IV. COST OF KIT COMPONENTS

Magnetic levitation project systems have long been used in control systems laboratories [4], [5], textbook examples [6], [7], and hobbyist construction articles [8], [9]. These projects are appropriate for lab stations and hobbyists, but they require custom construction of the electromagnet and dissipate considerable power (needing large heat sinks).

In this effort, the kit we give each student is their own to keep, and we anticipate that several dozen students will elect to complete this project each year. *Minimizing the cost of the kits is therefore a key issue.*

The total cost of the laboratory kits provided to the students was under twenty dollars. Meeting this goal made it possible to let the students keep their systems at the conclusion of the class. Several factors are worth mentioning in keeping the cost so low. In particular, the system is designed with commodity integrated-circuit power electronics and an inexpensive prewound solenoid. Also, a prebuilt stand was not provided to the students. The cost of the parts included in the kits is listed in Figure 5. Further cost savings was made possible by a generous donation of motor H-bridge chips (the most expensive item in the kit) by National Semiconductor Corporation.

V. END-OF-TERM CONTEST

Beyond the basic modifications required by the laboratory assignment, we encouraged additional improvements to the system through an end-of-term contest. Students were challenged to improve specific performance measures and to compete against other students. There were five categories of competition.

- 1) **Widest Dynamic Range** defined as the largest periodic movement of the levitated object, measured with a ruler, for a square-wave or sine-wave input.
- 2) **Best Disturbance Rejection** defined as the largest ratio between heaviest object levitated to lightest object levitated, using the same system settings and number of magnets (no tweaking allowed).
- 3) **Heaviest Object Lifted** measured by weighing the levitated object on a scale, with a design maximum of one magnet.
- 4) **Lowest Power Consumption** measured with an ammeter on the single 15V supply (no other supplies allowed).
- 5) **Most Artistic System** as appreciated by the teaching staff (beauty is in the eye of the beholder).

Winning students in the first four categories were awarded significant extra credit on the lab, while the prize for the final category was a gift certificate for a local ice cream shop. Pictures of some of the winning systems are shown in Figures 6, 7, and 8.

VI. STUDENT EXPERIENCES

MIT 6.302 Feedback Systems includes class coverage of a wide variety of electronic applications and physical systems. For the final laboratory assignment in the course, students were given a choice of four laboratory assignments: compensation of a thermal system, construction of a ball-balancing system, experimental work with phase-lock loops, or the magnetic levitator system. Over 40% of the class choose to construct the magnetic levitator system.

Overall, student reactions were very positive. Below are some of the responses students gave when surveyed about the class.

- "It's fun and you can take it home. Unlike other EE labs, you can actually see what your circuit is doing with your eyes; you don't have to take the scope's word for it."
- "It was a cool problem and satisfying to complete."
- "[The best part was] the 'cool' factor."
- "I got to keep it."

Follow-up discussions indicate many student have their systems on display in their dorm rooms, and some have even featured their completed system on their personal web sites.

VII. PUBLICITY

Several MIT courses allow students to build and keep small mechanical systems. These classes include 2.670 Mechanical Engineering Tools, in which students build a functional Stirling engine, and 8.02 Physics II, in which students compete to build small electric motors. Given the choice between another math class and a class that builds something cool, many students will opt for the latter. These student-completed projects then become conversation pieces in the student dorms and living groups and provide publicity for future students.

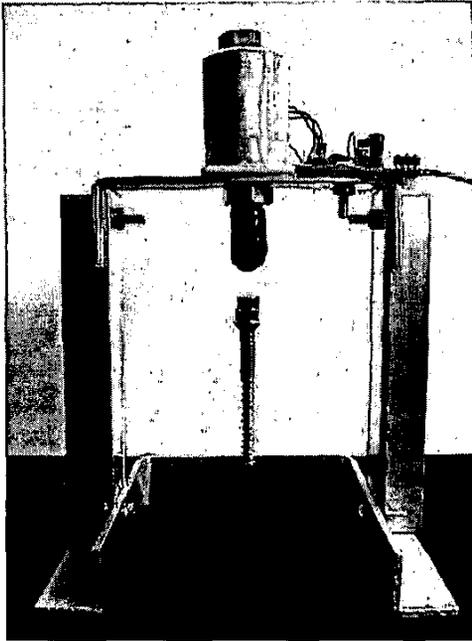


Fig. 6. Student-built system with aluminum stand. The system levitates a large metal screw. This industrial-looking system won the award for lowest power consumption.

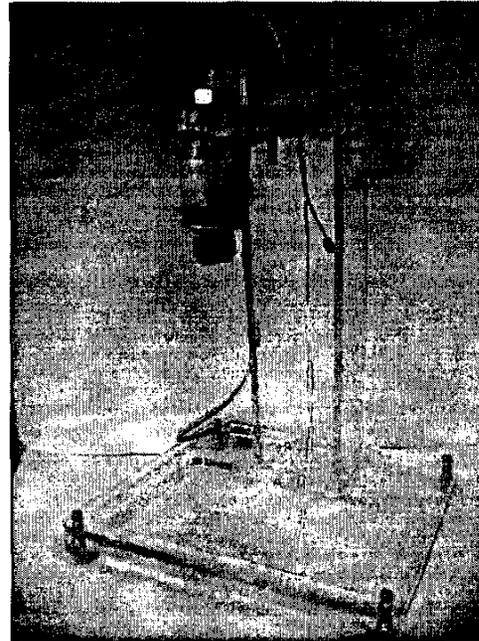


Fig. 8. Student-built system with laser-cut acrylic stand. This impressive stand placed first in the "Most Artistic" category.

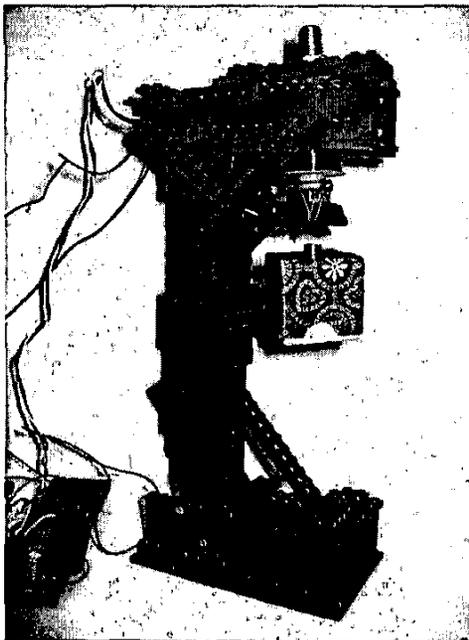


Fig. 7. Student-built system with LEGO stand. The system levitates an attractive paper box. This creative support system placed second in the "Most Artistic" category.

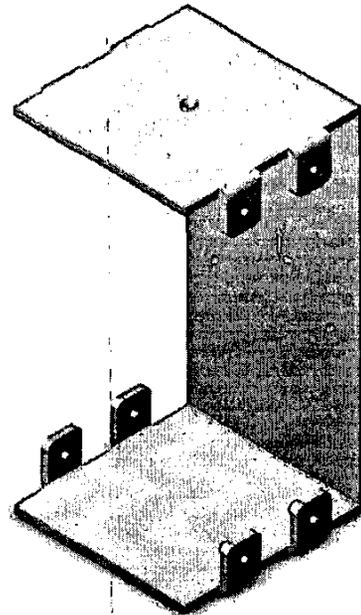


Fig. 9. Model of student-designed aluminum stand. This potentially low-cost stand is to be manufactured out of a single piece of aluminum. Several sets of mounting holes and tabs are provided for additional sensor placement.



Fig. 10. This photograph ran on the front page of the MIT student newspaper with the caption "Students crowd the electronics lab in 38-500 the night before projects are due for many classes. Ricky Muller (left) demonstrates her 6.302 final lab project, a magnetically levitated miniature toilet complete with real toilet paper, to Katherine Lilienkamp." The authors did not expect (but were very pleased) to receive this much publicity for the projects!

A secondary goal of this project is to create this kind of publicity for courses in control systems. In this regard, we succeeded beyond our wildest dreams when the picture in Figure 10 was published on the front page of the student newspaper [10].

VIII. CONCLUSIONS

These low-cost magnetic suspension kits provide students with an open-ended design problem. The performance of the basic system is inadequate in several ways, but students are able to apply their knowledge to improvements in sensors, magnetics, power electronics, and compensation electronics.

Student reaction to this project was very positive. The low cost of the kits allowed each student to personalize their kit and keep the finished product at the end of the term. This laboratory assignment was successful in providing an open-ended design challenge, providing the students with real hardware experience, and in providing publicity for the class.

IX. ACKNOWLEDGEMENTS

Thanks to our prize-winning students, Adam Kumpf (Figure 6), Alex Crumlin (Figure 7), and Matthew Malcolm (Figure 8). The low-cost stand in Figure 9 was designed by

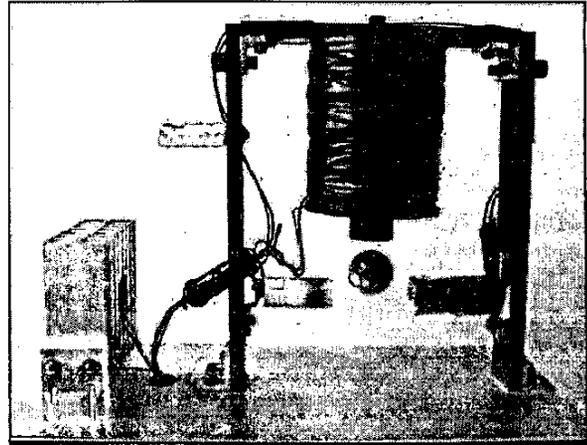


Fig. 11. Magnetic levitation system described in [2]. Even after thirty years of use, this system is still a beloved lecture demonstration in MIT courses "Signal and Systems," "Fields, Forces, and Motion," and, of course, "Feedback Systems." The large heat sink at left houses the output power transistor.

Joaquin Ruiz with Steven Leeb. Thanks to Lourenco Pires for construction assistance with the lecture demo system.

Photograph in Figure 10 courtesy of Brian Hemond and The Tech. Author One would like it known that Author Two insisted on the inclusion of Figure 10.

Special thanks to Guy Marsden for encouragement and to National Semiconductor for a generous donation of LMD18201 chips.

APPENDIX PRIORITY OF REFERENCES

A general history of the field and applications of magnetic levitation can be found in [11] (precision machines), [12] (gyroscope suspension), [13] (transportation), and [14] (transportation). The earliest references to lecture-demonstration or undergraduate-laboratory magnetic levitation systems we have found are [1] and [2]. A picture of a system in operation can be found in [1].

The actual system discussed in [2] is shown in Figure 11. The complete schematic for this system shown in Figure 12. (Note that a linear current amplifier topology was rejected for the present project because of the power dissipation, heat-sink requirements, and necessary construction effort. The large heat sink visible in Figure 11 would cost nearly \$10 alone.)

A battery operated version of this system was built and presented to Gordon Brown [15] on the occasion of his retirement in 1973 [16].

These works predate [17] by at least ten years.

REFERENCES

- [1] H.H. Woodson and J.R. Melcher. *Electromechanical Dynamics Part I*. New York: Wiley, 1968. pp. 193-200.
- [2] J.K. Roberge. *Operational Amplifiers: Theory and Practice*. New York: Wiley, 1975. pp. 214-217.

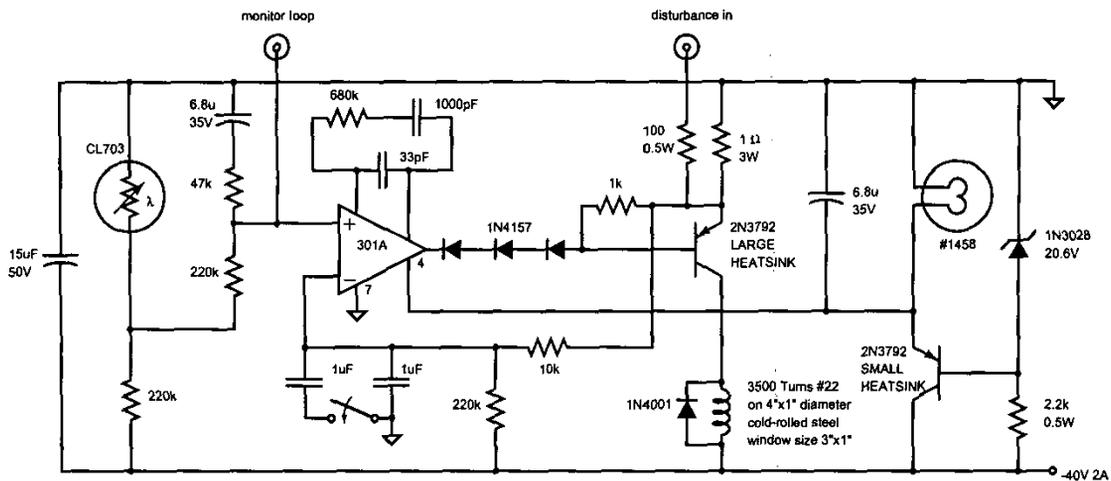


Fig. 12. Schematic of magnetic levitator described in [2] and shown in Figure 11. This schematic is dated March 30, 1974.

- [3] Guy Marsden, *Levitation! Nuts and Volts Magazine*, vol. 24, no. 9, September 2003, pp. 58–61. Available online at <http://www.arttec.net/Press/N&V/Levitation.html>
- [4] S.A. Green, R.S. Hirsch, and K.C. Craig, Magnetic levitation device as teaching aid for mechatronics at Rensselaer, in *Proc. ASME Dynamic Systems and Control Division*, vol. 57-2, 1995, pp. 1047–1052.
- [5] K. Craig, T. Kurfess, and M. Nagurka, Magnetic levitation testbed for controls education, in *Proc. ASME Dynamic Systems and Control Division*, vol. 64, 1998, pp. 83–88.
- [6] G.F. Franklin and J.D. Powell. *Digital Control of Dynamic Systems*. Reading, MA: Addison-Wesley, 1980.
- [7] B. Shahian and M. Hassul. *Control System Design Using MATLAB*. Englewood Cliffs: Prentice Hall, 1993. pp. 455–465.
- [8] D. Williams, Electromagnetic levitator, *Electronics Now*, February 1996, pp. 33–34, 67–70.
- [9] J. Cicon, Building a magnetic ball levitator, *Popular Electronics*, May 1996, pp. 48–52, 78.
- [10] *The Tech*, vol. 123, no. 61, pg. 1, December 5, 2003.
- [11] D.L. Trumper, Magnetic suspension techniques for precision motion control, PhD Thesis, MIT, 1990.
- [12] R.H. Frazier, P.J. Gilinson, and G.A. Oberbeck. *Magnetic and Electric Suspensions*. Cambridge: MIT Press, 1974.
- [13] B.V. Jayawant. *Electromagnetic Levitation and Suspension Techniques*. London: Edward Arnold, 1981.
- [14] P.K. Sinha. *Electromagnetic Suspension – Dynamics and Control*. London: Peter Peregrinus, 1987.
- [15] G.S. Brown and D.P. Campbell. *Principles of Servomechanisms*. New York: Wiley, 1948.
- [16] J.K. Roberge, private communication, 2003.
- [17] T.H. Wong, Design of a magnetic levitation control system – an undergraduate project, *IEEE Transactions on Education*, vol. 29, November 1986, pp. 196–200.