A Technology Approach to Magnetic Levitation

Steven Barker, Ron Matusiak
Buffalo State College

Abstract

A magnetic levitation (maglev) project is described with two major goals in mind: (1) to describe the maglev design process using an engineering-technology approach, and (2) to compare the engineering-technology and engineering-design approaches. These descriptions are intended to yield working maglev systems which can be built by engineering technology students while simultaneously encouraging interest in the more abstract approaches to classical feedback control theory. A set of laboratory experiments derived from the maglev system are presented which can be used by engineering technology students. Circuit diagrams and equipment lists coupled with verbal descriptions are intended to yield inexpensive magnetic levitation systems. Both analog and digital control strategies are also included.

Introduction

A magnetic levitation demonstration can be a powerful motivation for the study of feedback control systems, perhaps because there is something very special about magnetic levitation. Middle school children have shown great interest in maglev design contests.[1,2] The transportation industry has acknowledged the real possibility of magnetically levitated trains in the near future.[3] Several excellent web sites have been devoted to the subject of magnetic levitation.[4,5,6] An inexpensive maglev science kit is commercially available.[7] Educational systems that allow students to investigate magnetic levitation are available but they are expensive.[8] Published descriptions using the classical-engineering approach are available, but they may be beyond the technical ability of many beginning engineering technology students.[9] Our description of magnetic levitation attempts to make magnetic levitation more accessible while simultaneously promoting an appreciation of the more abstract approaches to the subject.

A magnetic levitation demonstration has been used for several years in the Engineering Technology program at Buffalo State College. The hardware is inexpensive, and the analog proportional-derivative (PD) controller is easy to design and adjust using a "technology approach". Our paper focuses on inexpensive hardware with the purpose of encouraging those in budget-conscious schools to build maglev systems. The "technology approach" is described, not as a substitute for the "classical-engineering approach," but as one alternative for our readers who have not yet acquired the abstract engineering skills typically employed in the rigorous design of a feedback system. Digital control of the magnetic levitation system utilizing popular hardware and software is also discussed as an alternative to analog control. When a valid set of control gains is unknown, digital techniques can sometimes be used to quickly determine the feasibility of a particular combination of hardware components. We suggest several laboratory experiments, based on this magnetic levitation hardware, that are suitable for use in a control system course. The focus on experiments that require feedback for stability should be appealing to those who continually search for laboratory experiments that are motivational and inexpensive.

Our paper also compares the "classical engineering approach," and the "technology approach" to the design, fabrication, tuning, and testing of the magnetic levitation system. Often the implementation of engineering designs requires procedures that were not specified in the original design. Engineering technologists frequently make these types of contributions to their projects in ways that are not easily documented. The purpose for discussing two design methods is to promote an appreciation of both.

Those who have never thought about magnetic levitation and unstable systems may not appreciate the maglev experiment without some explanation or personal experience. We have found that the description of a fictitious "human-controlled magnetic-levitation system" can be an effective introduction. This fictitious system requires the "quick" human reaction time to move a magnet up and down for the purpose of keeping the magnet and the levitating ball separated. Anyone who attempts this experiment will quickly learn that human-controlled maglev is impossible because human reaction time is too slow. Most of us appreciate magnetic levitation - perhaps because the electrical control circuit can do something that we cannot do.

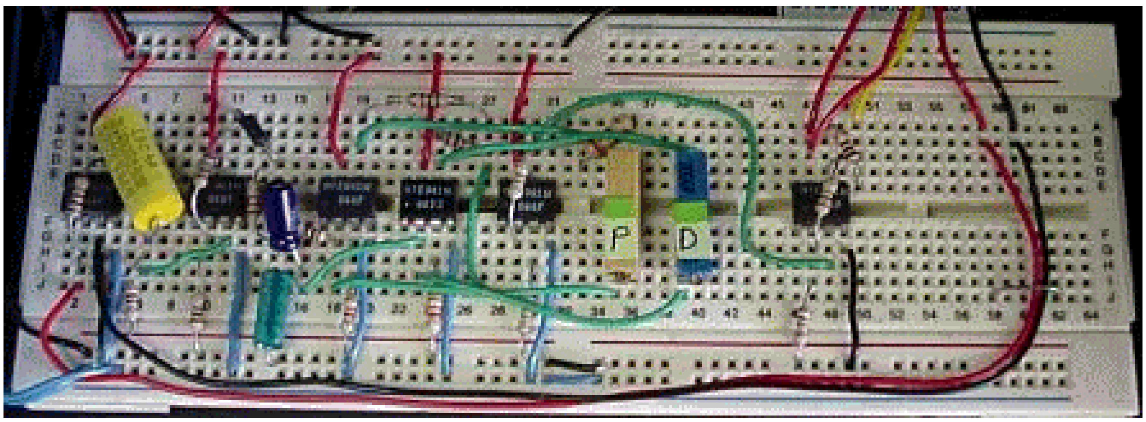


Figure 1. Magnetic Levitation Electronic Control Circuit.

Analog Controller Design

A complete magnetic levitation system has several major components: a metal tower that supports the electromagnet (although almost anything else would have been suitable) and an infrared (IR) light emitting diode (LED) and a photodetector; an electronic circuit that controls the current in the electromagnet; 30 volt power supply (with a 1 ampere capability) that provides current to the electromagnet; ±15 volt power supply required by the operational amplifiers; function generator that drives the IR LED; and a hollow metal ball that is levitated. Figure 1 shows an electronic control circuit. Figure 2 contains a close-up view of the levitating ball, IR LED and photodetector. Figure 3 contains a circuit diagram of the magnetic levitation controller along with numerous electrical test points. Each test point in Figure 3 is accompanied by a description of the corresponding test signal in Tables 2-3. The identifiers shown in parenthesis below refer to the electrical components and test points shown in Figure 3 and Tables 1-3. Table 1 contains a parts list of all electrical components, power supplies, and suggested test equipment. Table 2 contains a verbal description of each test signal when the IR light beam is not obstructed. Table 3 contains a verbal description of each test signal when the IR light beam is partially obstructed by the levitating ball.

Table 1. Electrical Components and Equipment List (See Fig. 3)

ID	Description	ID	Description
C1	CAP\MA20, 10 μF	C2	CAP\MA20, 1 μF
C3	CAP\MA20, 1 μF	C4	CAP\MA20, 10 μF
R1	R1/4 W, 1 kΩ	R2	R1/4 W, 1 MΩ
R3	R1/4 W, 1 k Ω	R4	R1/4 W, 18 kΩ [Note 1]
R5	R1/4 W, 10 kΩ	R6	R1/4 W, 10 kΩ
R7	R1/4 W, 10 kΩ	R8	R1/4 W, 330 Ω
R9	R1/4 W, 1 kΩ	R10	R1/4 W, 1 kΩ
R11	R1/4 W, 1 kΩ	R12	R1/4 W, 1 kΩ
R13	R1/4 W, 3.3 kΩ	R15	R1/4 W, 1 kΩ
R16	R1/4 W, 1.5 kΩ	R17	R1/4 W, 10 kΩ
R18	Pot, 1-turn, 10 kΩ	R19	Pot, 10-turn, 320 kΩ [Note 2]
R20	R1/4 W, 10 kΩ		
D1	LED, Infrared, T1-3/4 (Jameco #112168)		
D2	Photodiode,(Jameco #153269, Infrared Detector- $2.25)		
D3	Diode, 1N914		
D4	Diode, 1N914		
L1	Electromagnet, 91 mH, 24Ω		
Q2	2N3055 plus heat sink		
U1-7	DIP8, uA741		
Ball	Hollow metal globe, Diameter=4.5 cm, Mass=11.58 gm, StudentTools Pencil Sharpener, Globe Sharpener, Cue Craft, Made for Contima Company, New York, NY 10016, Made in China, Item #2851, $0.99, local store		
	IR LED/detector separation = 5 cm		
	Vectorboard breadboard		
	Apparatus stand (Can be made of wood or metal)		
S	Frequency generator, 10 kHz sine wave: 0 to -15 v. [Note 3]		
VCC	30 v, 1 a, DC Power Supply		
VDD VEE	±15 v, <20 ma DC power supply for all op amps except the one closest to the transistor		
	Dual-trace oscilloscope		
	Multimeter (electromagnet current monitor)		
	Total cost of components excluding electromagnet, circuit board, and test equipment: $12.49.		

Note 1: Doubling R4 will increase the DC voltage swing at (D) - probably desirable.
Note 2: Doubling R19 may promote increased damping capability - add a series resistor.
Note 3: A square wave at (S) may produce a larger DC voltage swing at (D).

Table 2. Signal Descriptions with Light Beam Unobstructed.

Signal	**Signal Description (Full Light) See Fig. 3**
A	0 to 1.5 v *
B	±0.8 v *
C	±12 v *
D	2 v DC ±0.1 v noise
E	-7.5 v DC ±0.1 v noise and *
F	±3 v *
G	7 v DC ±0.5 v *
H	17 v DC ±1 v *
I	17 v DC ±1 v *
J	±0.06 v (high frequency noise)
S	Frequency Generator, 10 kHz sine wave: zero to 15 v, Note the 7.5 DC offset.
air gap	Ball not present, Full light beam
misc.	R18=3.75 kΩ, R19=198 kΩ, L1 current=520 ma
	* a noisy 10 kHz signal

Table 3. Signal Descriptions with Levitating Ball.

Signal	**Signal Description (Partial Light) See Fig. 3**
A	0 to 1.2 v *
B	±0.6 v *
C	±10 v *
D	1.6 v DC ±0.05 v noise
E	-6 v DC ±0.1 v noise
F	±0.4 v *
G	6 v DC ±0.3 v *
H	15 v DC ±1 v *
I	10 v DC ±1 v *
J	±0.05 v (high frequency noise)
S	Frequency Generator, 10 kHz sine wave: zero to -15 v
air gap	7 mm
misc.	R18=3.75 kΩ, R19=198 kΩ, L1 current=470 ma
	* a noisy 10 kHz signal

The following descriptions of the major signals in the control circuit are provided to permit a systematic evaluation of the control circuit, but they assume some familiarity with operational amplifiers (op amps) and electrical concepts in general. We will begin with the 10 kHz function generator and end with the electromagnet voltage (I). We suggest that the electromagnet current be monitored at all times so that all the signals can be correlated with it. A significant feature of this design is the simple demodulation of the 10 kHz control signal. The position of the ball is detected by the infrared light beam that begins at the IR LED (D1) and ends at the IR photodetector (D2). An advantage of the IR light beam over a visible light beam is that disturbances from ambient light are reduced. The 10 kHz sine wave of the function generator stimulates the IR LED to produce 10,000 IR light pulses per second. The IR photodetector is a photodiode whose current is modulated by the intensity of the infrared light beam. The 10,000 IR light pulses per second stimulate the IR photodetector to conduct 10,000 times per second which generates a 10 kHz one volt signal at (A). The amplitude of the signal at (A) is proportional to the position of the ball as it controls the amount of light that reaches the detector. The signal at (B) is the same as (A) except the DC component has been removed by the high-pass RC filter (R3 & C3). Ideal op amp theory predicts that the signal at (C) will be 19 times the signal at (B) by using (R1 & R4). The signal at (D) is mostly DC with a small noise component due to the rectification and low-pass filtering by (D3, R12, & C1). The proportional part of the controller produces the signal at (E) by multiplying the gain (-1 * R18 / R11) by the signal at (D). The gain of this stage is controlled by the adjustable potentiometer (R18). The derivative part of the controller produces the signal at (F). The signal (J) should be approximately zero but may contain a small noise component. The signal at (F) is harder to explain using ideal op amp theory, but in practice it may contain a small amount of noise centered about zero volts when the ball is not moving. Ideally, (F) should be zero when the ball is not moving. The signal at (F) should have some negative DC value when the ball moves up and some positive DC value when the ball moves down. The signal at (G) is the inverted sum of (E) and (F). The signal (H) is the control signal that drives the power transistor and theoretically should be 2.5 times the signal at (G) according to (R15 & R16). The range of (H) is zero volts to 30 volts (VCC) due to the different way of connecting the power supply to the op amp. An easy test of the entire control circuit should observe (H) swing between 5 and 30 as the light beam swings from maximum intensity to zero intensity. The signal at (I) is the voltage across the electromagnet and is proportional to the controlling signal (H). The signal at (I) is also proportional to the resulting current in the electromagnet and the corresponding magnetic field that attracts the ball. The electromagnet voltage (I) may have a noise component but it should be mostly a DC signal that is proportional to the ball position.

The Electromagnet and Levitated Ball

The size, weight, and location of the ball relative to the electromagnet and IR sensor are all important and are stated in Tables 1-3. The size of the ball must be large enough to block the light beam. The weight of the ball must be small enough to be lifted by the electromagnet and the associated power supply. The levitated position of the ball (air gap) can be arbitrarily selected; we found that an air gap of one centimeter or less worked well for our hardware. The major effect of the air gap is on the amount of continuous current in the electromagnet. A smaller current can be achieved when the air gap is small. The air gap is easy to adjust if one designs the IR LED and detector supports that can rotate or translate vertically.

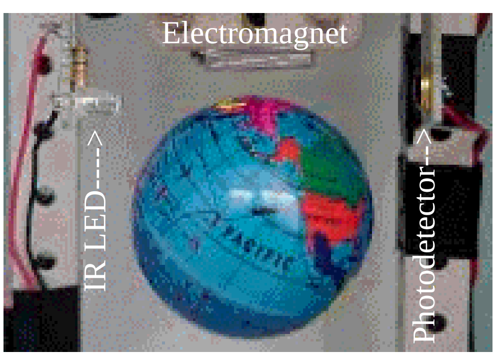


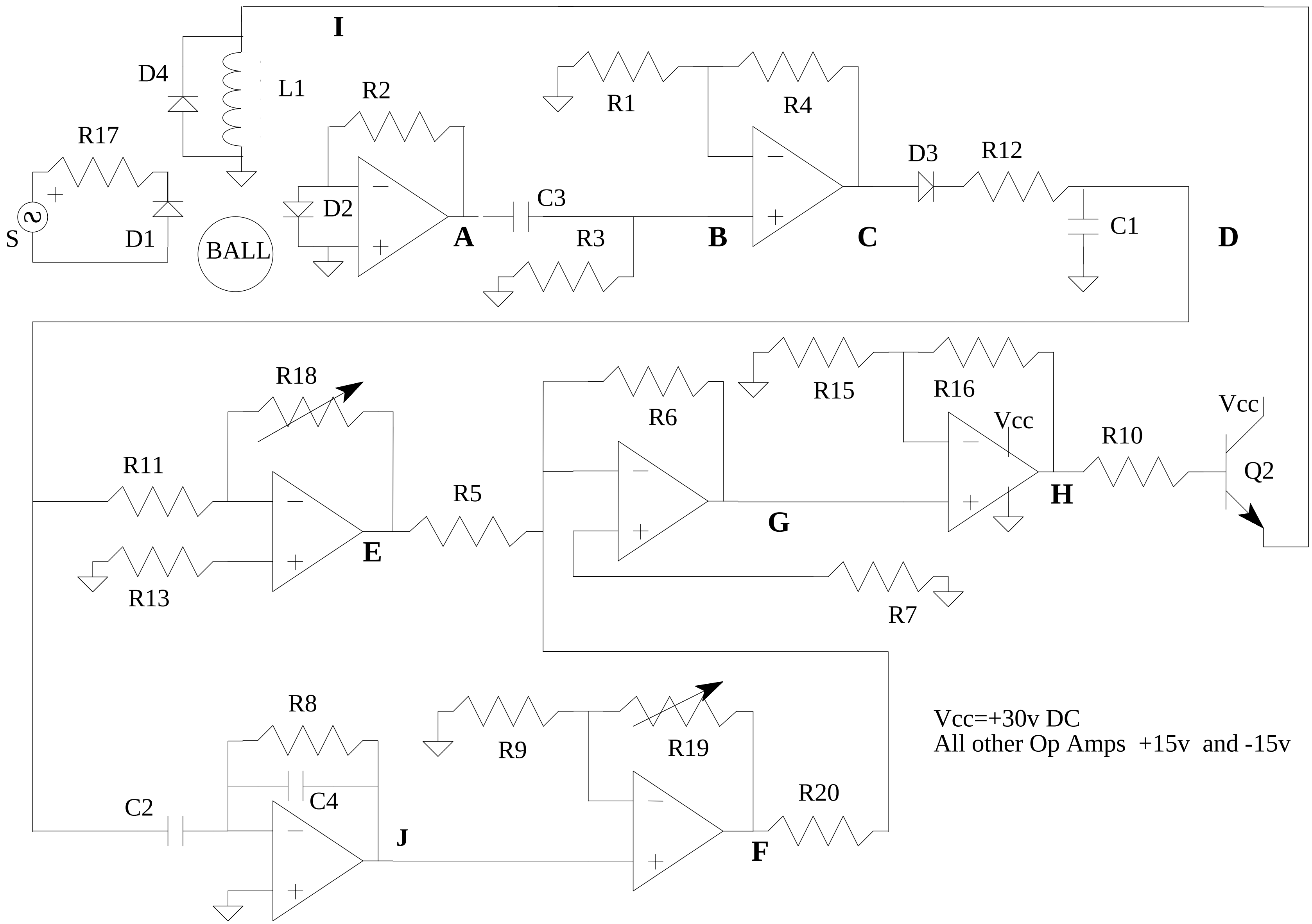
Figure 2. Maglev Close-up

The electromagnet requires special consideration. It may be one from a science project, a solenoid, a modified choke, or a modified transformer. The electromagnet that we preferred was one from an old science kit. It has a laminated core which is 114 mm long with a square cross section of 18 mm on each edge. An electrical choke or transformer with a metal band that supports a two-piece iron core may also be used. Removing the metal band may permit one side of the iron core to be removed. Some iron cores have been glued together and cannot be separated easily. In this case, a section of the iron loop can be removed with a metal hacksaw. The magnetic field will then exist in the air gap where the ball is to be levitated. If a small power supply is used, the electromagnets should have an iron core (probably laminated) to increase the magnetic field at the ball's location. Ampere-turns is a parameter frequently used to describe an electromagnet, but since this parameter is typically unknown for inexpensive electromagnets that have been previously constructed, we will use inductance and resistance instead to describe electromagnets. A digital storage oscilloscope can be used to measure the electromagnet time constant that leads to a calculation of the inductance through the equation: tau=L/R. If the inductance is too small, the electromagnet will not be capable of providing the magnetic force required to lift the ball without overheating. If inductance is too large, several problems can occur using our design. The first problem is that the power supply and power transistor may not be able to provide the required current. The second problem is that the time constant may be too large. Since the time constant is directly proportional to the inductance and inversely proportional to the resistance, the electromagnet speed (i.e. the rate at which control signal can change the magnetic field in the air gap) is directly affected by these parameters. Smaller electromagnets (physical size and inductance) are expected to be faster and more likely to lead to successful maglev systems using our design. The transient performance of the electromagnet can be improved by using a feedback loop to control the current in the electromagnet, although we did not use this method. We also constructed a home-made electromagnet that worked well. Table 5 summarizes our experience with various electromagnets.

Table 5. Various Electromagnets (L Measured Without the Ball)

Electromagnet	**Experience**
L=180 mH, R=24 Ω	Science kit. Works great even with a pure differentiator. First prototype.
L=85 mH, R=22 Ω I=407 mA air gap=7 mm	Science kit. Works great. Initially set R19=0 and increase the R18 to 3.75 kΩ until on the threshold of levitation. Then increase R19 to 198 kΩ. Then fine tune both if necessary. Laminated square core.
L=85 mH, R=22 Ω I=640 mA air gap=1 cm	Science kit. Works great. Initially set R19=0 and increase the R18 to 5.12 kΩ until on the threshold of levitation. Then increase R19 to 425 kΩ. Then fine tune both if necessary. Laminated square core.
L=503 mH R=67.7 Ω I=300 mA air gap=1 cm	Disassembled Choke. Works ok, but jittery. R18=4.06 kΩ, R19=329 kΩ. L=2.9 H (measured value for the assembled choke). E-shaped laminated core.
L=437 mH R=31 Ω I=330 mA air gap=6 mm	Home-made. Works great. Initially set R19=0 and increase the R18 to 3.03 kΩ until on the threshold of levitation. Then increase R19 to 96.4 kΩ. Then fine tune both if necessary. 2.5" by 0.25" steel-bolt core. 3000 turns of 25 AWG copper wire. S is a square wave.

Figure 3. Magnetic Levittation Control Circuit with Test Signals (A,B,C,...)



Analog Tuning

We recommend a systematical approached to the analog tuning process. If each signal in Figure 3 and the corresponding descriptions in Tables 2 and 3 are compared sequentially from the IR sensor to the electromagnet, then any wiring errors can be located. An oscilloscope is required to observe these signals. We also found that if the electromagnet current is monitored at the same time that each test signal is observed, then a strong sense of the proper adjustment levels can be learned quickly. Each signal should be understandable based on the gain of the preceding op amp. The AC sine wave of the frequency generator should have sufficient amplitude and DC bias as indicated in Table 2 to produce the signals; some variations from our values are probably acceptable. After all the signals in Tables 2 and 3 are confirmed, the two potentiometers (R18 and R19) become the most critical final adjustments.

The approximate proportional gain (adjusted by R18) is set first and then the derivative gain (adjusted by R19) is set next. The final adjustments include slight changes of both (R18) and (R19). If (R19) is set to a low value initially, then the derivative part of the controller will not interfere with the initial setting of the proportional gain. The proportional signal (E) reacts to the position of the ball. The derivative signal (F) reacts to the speed of the ball. As the position error increases, the size of signal (E) increases. As the velocity error increases, the size of signal (F) increases. When the ball is stationary with the desired air gap, the derivative signal should be zero and the proportional signal (E) should be about -6 v. If (R18) is increased slowly while holding the ball at the desired location, then the approximate initial value of (R18) can be set. Our levitating current was 470 ma for an air gap of 7 mm. When (R18) is too small (small proportional gain), the magnetic force will not be large enough to lift the ball. As (R18) is increased to the correct value, the magnetic force will be just enough to lift the ball. It is also important that the current in the electromagnet becomes low (about 150 ma assuming that the levitating current is approximately 470 ma) as the ball is manually moved up to block the IR light beam. As (R18) increases, the proportional gain increases and the electromagnet current increases. The size of the air gap directly affects the electromagnet current. Smaller air gaps will yield smaller currents and lower temperatures in the electromagnet and power transistor. When the proportional gain (controlled by the value of R18) is sufficiently large to attract the ball, but the derivative gain (controlled by the value of R19) is too small, the ball may fly into the electromagnet and perhaps bounce off. At this time, increasing the value of (R19) should prevent the ball from flying upward so quickly. The value of (R18) may need some readjustment. The final step involves a continuous adjustment of (R19) and perhaps only a slight adjustment of (R18). If the ball is levitating but it is vibrating, increasing (R19) should eliminate the vibrations. Once the ball is levitating, minor adjustments of both (R18) and (R19) should achieve a more robust feedback control system. If the correct values of (R18) and (R19) are found quickly before the electromagnet and power transistor warm up to their steady state temperatures, then the value of (R18) may need a slight final adjustment.

Implementation problems can be expected, but we believe that they are all surmountable. Assuming that the control circuit is constructed properly, which requires some technical expertise, and that the test signals are close to the values in Figure 3 and Tables 1-3 , then other problems can occur. Electrical noise can be a big problem. Keeping all wires as short as possible and twisting long wires (such as those connecting R18 and R19) will help to reduce noise. A sufficiently small electromagnet appears to be important. The voltage swing at (D) is important and should be at least 2 v and possibly even more. The first students who built maglev systems using this design found that it was desirable to increase the voltage swing at (D) by doubling R4. We will continue to document our improved designs on our WebPage.[11]

Digital Controller Design

Digital control can be used in the "technology approach" to determine the feasibility of an analog design. When the stabilizing proportional and derivative gains are unknown; or worse, if it is unknown whether any stabilizing gains exist, a digital controller can replace the proportional and derivative parts of the control circuit and the gains can be selected quickly in the software of the digital controller. The analog alternative is to swap electrical components to achieve different control strategies. An excellent paper on magnetic levitation using the engineering approach to digital control was published recently.[10]

To use the digital controller instead of the analog controller, the four operational amplifiers between (D) and (G) in Figure 3 are disconnected and the digital controller is inserted. To be conservative, the sample rate should be selected as high as possible. All other programs and windows should be closed, especially if MS Windows is the operating system. The selection of gains in the digital controller uses the same strategy that was suggested for the analog controller. When the magnetic levitation system is working for the first time, the electromagnet current can be measured and the heating of the coil and transistor can be monitored. The steady-state temperature of both should be sufficiently low. If the electromagnet overheats, reducing the air gap will reduce the electromagnet current and the steady-state temperature. If the power transistor overheats, reducing the air gap, increasing the size of the heat sink, and adding a fan to the heat sink will all reduce the steady-state temperature of the power transistor.

Actually, the analog design approach is as easy as the digital design approach provided that one knows that the PD control strategy will work. As an academic exercise, one may attempt to correlate the digital and analog gains of the PD controller. This process falls into the "engineering approach," and is taught in a digital control systems course. We could not correlate our digital and analog gains, perhaps because the real sample time was unknown due to the Windows 95 operating system that time shares the data acquisition process with other "necessary" functions of the operating system. National Instruments has subsequently provided an optional data acquisition system that, when running, is virtually independent of the Windows operating system. Such a system should allow a successful comparison of the digital and analog gains. A successful digital design implies that a successful analog design is probable.

Laboratory Experiments

Many laboratory experiments are possible with the magnetic levitation apparatus. Since most control-system students are highly motivated by the maglev demonstration, experiments using the maglev apparatus could be interesting to those students. It may be possible that control-system laboratories for an entire semester could be derived from the magnetic levitation apparatus. Table 4 summarizes several possible laboratory experiments associated with the maglev apparatus. At the time of this writing (spring semester 2000), four senior engineering technology students in the second control systems course have individually built maglev systems using this design. Preliminary results are so good, that another paper describing the experience is likely.

Classical and Technology Design Approaches

The following comparison of two design methods for the magnetic levitation system attempts to promote an appreciation of both methods. This paper has focused on the "engineering technology approach" which, if successful, should lead to a working magnetic levitation system without

Table 4. Laboratory Experiments Using the Magnetic Levitation Apparatus

Experiment	**Experiment Description**
Fabrication	Build the maglev system using this paper
Electromagnet	Measure the resistance and inductance of the electromagnet. Predict and measure the time constant of an electromagnet step response.
Power Transistor	Determine the transfer function of the power transistor (current output / current input)
IR Sensor with Op-Amp	Determine the transfer function of the IR LED and photo-detector with the op-amp detector (output voltage / input voltage)
Basic Op-Amp Amplifiers	Construct and measure the basic op-amp gains: inverting, non-inverting, and summing amplifiers
Bode Gain and Phase Plots for the Op-Amp Differentiator	Develop a theoretical Bode plot for the differentiator with high-frequency attenuation. Construct the circuit using the two op-amps and confirm the Bode gain and phase at three frequencies: the corner, one decade above, and one decade below.
Op-Amp Supply Voltages	Explain the difference between the two non-inverting amplifiers based on the different supply voltages.
Ball Transfer Function	Develop the differential equation that describes the dynamics of the ball (ball position / magnetic force)
Electromagnet Transfer Function	Develop the transfer function of the electromagnet (magnetic force / input current)
Gain-Bandwidth Product of the Op-Amps	Investigate the gain-bandwidth product of the op-amps.
DC Rectification	Redesign the DC rectification part of the circuit that reduces the noise component (ripple).
Function of diode D4 or "How to protect the last op amp"	Simulate, using PSpice, the voltage across a switch in a series circuit containing a battery, inductor, resistor, and switch - with and without a diode in parallel with the inductor.

having to use the advanced mathematical techniques that are initially beyond the capabilities of young engineering technology students. The other approach is the "classical engineering approach." This approach requires more abstract analytical skills that are typically acquired by engineering students and some engineering technology students after taking a senior-level course in classical feedback control systems. Engineering students are skillful at mathematical analysis and design that utilizes Laplace transforms, linear transfer functions, differential equations, and computer design tools such as MATLAB. Most engineering students and some engineering technology students develop expert algebra skills. Generally, the engineer focuses on the design while the engineering technician constructs the system that the engineer has designed. The engineering technologist fills the gap between the engineer and the technician. The engineering technologist should be able to understand the engineering design sufficiently to make modifications to it when necessary. The engineering technologist should be able to understand the requirements of the technician sufficiently to do some of those tasks when necessary. Large engineering projects require the engineer to work on the initial design; the engineering technician to fabricate the system; and the engineering technologist to translate the engineering design into the language that the technician understands. The engineering technologist must sometimes do the work of an engineer and sometimes do the work of a technician. Senior electrical engineering technology students at Buffalo State College are taught the classical engineering approach to control system design and are also given extensive laboratory applications of the theory.

The "classical engineering approach" to the design of the magnetic levitation demonstration is very different from the experimental approach presented in this paper.[9,10] The "classical engineering approach" to magnetic levitation would have developed differential equations of the levitating ball and the magnetic force produced by the electromagnet. Linear transfer functions of each component would also have been developed for the ball, electromagnet, and analog controller. The operational amplifier stages that implement the control system could have been specified by the design engineer or left up to the engineering technologist. Performance specifications such as settle time and percent overshoot to a step input would have been selected that make sense for the magnetic levitation system. For example, a settle time of one second or longer would have been too long and a settle time of less than a millisecond probably would have been too fast. The weight of the levitating ball, the current capability of the electromagnet and power transistor, are all critical to the success of the project. A computer design tool such as MATLAB with the control system tool box would have been used to select proportional and integral gains. The engineer’s design process would have led him/her to reject controllers such as proportional (P), proportional plus integral (PI), and proportional plus integral plus derivative (PID).

For those readers interested in the different characteristics of people that attempt to explain why some people are attracted to engineering while others are attracted to engineering technology, we suggest that the MBTI personality model may be an excellent starting point.[12,13] Intuitive people tend to be attracted to the abstract concepts found in the engineering approach, while sensing people tend to be attracted to hands-on experiences found in the engineering technology approach. This may be the most significant difference between engineers and engineering technologists.

Conclusions

A magnetic-levitation project was described using detailed circuit diagrams and equipment lists coupled with design, fabrication, tuning, and testing descriptions. We have focused on the magnetic-levitation design using an engineering-technology method, but a discussion of a classical engineering-design method was also included in order to permit a comparison of the two methods. Digital control of the magnetic-levitation system was discussed as an alternative to analog control. Several laboratory experiments suitable for a control system course were derived from the magnetic levitation hardware. Preliminary experience with senior engineering technology students building magnetic-levitation systems is very encouraging.

Bibliography
1. Burghardt, D. "Engineering and K-12 Education--A Two-Way Street," 1996 ASEE Annual Conference Proceedings, Session 3553
2. Burghardt, D. "Hofstra's Center for Technology Education A Model for Engineering Involvement in K-12 Edution," 1996 ASEE Annual Conference Proceedings, Session 2266
3. Bragdon, C. & Berkowitz, C. "Transportation Technology Careers: 2005," 1996 ASEE Annual Conference Proceedings, Session 1625
4. URL: http://www.teslev.com/links.htm; Maglev reference resources.
5. URL: http://www.geocities.com/Area51/Shire/3075/maglev.html; Maglev reference resources.
6. URL: http://www.eskimo.com/~billb/maglev/maglev.html; Maglev reference resources.
7. URL: http://www.ccnet.com/~lnstech/#lev; Magnetic levitation science kit.
8. URL: http://www.fbk.com; Educational magnetic levitation systems
9. Hurley, W.G. & Wolfle, W.H. "Electromagnet Design of a Magnetic Suspension System," IEEE Transactions on Education, Vol. 40, No. 2, May 1997, pp. 124-130.
10. Oliveira, V.A., Costa, E.F., & Vargas, J. B. "Digital Implementation of a Magnetic Suspension Control System for Laboratory Experiments," IEEE Transactions on Education, Vol. 42, No. 4, November 1999, pp. 315-322.
11. URL: http://tech.buffalostate.edu/~barker/publications/maglev/index.html; Author's homepage contains additional maglev information.
12. URL: http://tech.buffalostate.edu/~barker/publications/diversity_erie_pa.html, "Diversity and Effective Teaching/Learning in Electrical Engineering Technology."
13. URL: http://keirsey.com/, David Keirsey is also the author of the classic book: Please Understand Me

D. STEVEN BARKER
Steven Barker received a Ph.D. in Electrical Engineering from the University of Wyoming in 1984. He is an associate professor of Electrical Engineering Technology at Buffalo State College where he has been teaching control systems since 1995. He has ten years of industrial experience in the aerospace industry. His interests include industrial automation, the use of Linux, PLC's, and fuzzy logic.

RONALD C. MATUSIAK
Ron Matusiak received a B.S. in Electrical Engineering from State University of New York at Buffalo in 1978. He has been an Instructional Support Technician in the Technology Department at Buffalo State College since 1994. He has prior industrial experience in the aerospace industry. He currently maintains all electrical and electronic equipment for the department and designs special-purpose laboratory equipment used by the students and faculty.