MAGNETIC LEVITATION SYSTEM
ENGR4220 SEMESTER PROJECT

In this semester project, you will design a magnetic levitation system. The goal is to have a relatively lightweight metallic object "hover" suspended at a small distance below the magnetic solenoid (Figure 1). The levitated object is attracted by an electromagnet that is placed above the sphere. The control problem consists of balancing the gravitational force against the electromagnetic force in such a way that small disturbances do not change the object's equilibrium position. Specifically, the magnetic force F, which is determined by the current I through the electromagnet, overcomes gravity (the mass of the object is m) and pulls the object upward. For this purpose of establishing feedback control, a distance sensor needs to be provided, and the current through the solenoid needs to be controlled in such a fashion that the distance of the levitated object to the solenoid is constant. The semester project is largely a design project, and the path to a viable solution is not prescribed. There are some mandatory components, however, and those are specifically highlighted.

To provide an overview, the design steps comprise:

1. Design and fabrication of the levitation *process* composed of the support frame, the solenoid and the levitated object

2. Design of a distance sensor

3. Mathematical description of the levitator process and the sensor

4. Design of a controller

5. Analysis of the closed-loop system (transient response, disturbance rejection, stability) with possible changes to the controller design to improve the quality of the control system

6. Demonstration of the working closed-loop system

The grading breakdown is described in Section 8. Please consider from the get-go that there will be bonus point awards for exceptionally good designs (see Section 8).

Grading milestone #1 (3 points): Identify your team members (4-5 members per team, points deducted for deviations from that number). Select a team leader. Prepare as the first page of your report the list of team members. Turn in that page.
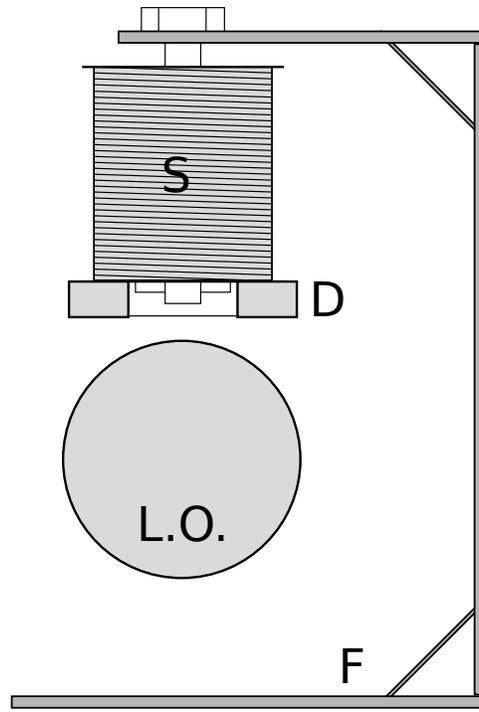
Figure 1: Sketch of the *process*, that is, the magnetic levitation system and its frame. A solenoid coil (S) is suspended from the frame (F). The levitated object (L.O.) is attracted by the magnetic force of the solenoid. The attractive (upward) force depends on the current through the solenoid. A distance sensor (D) provides a signal that depends on the distance of the levitated object from the solenoid.

1 Design of the Process

The first step in this semester project is the design of the process, which should be functionally similar to the one shown in Figure 1. It is suggested that you begin by selecting an object to levitate. This can be any ferromagnetic object, such as an iron bolt or a sheet metal world globe. You then need to design the solenoid. Remember that the magnetic field is determined by the solenoid current and the number of turns. The wire gauge limits the current, but a large wire diameter also limits the number of turns you can wrap. You may opt to make your own solenoid or obtain an off-the-shelf solenoid. In the latter case, very limited funds are available to purchase a solenoid. In general, the price should not exceed $10. A self-wound solenoid

may be constructed as follows: Use a long 1/4 inch iron bolt (approx. 3 in long) and cover it with some insulating material, such as thin PVC pipe: The length of the Pipe could be 2 in. Two 3-in diameter disks with a 1/4 inch hole are placed at the ends of the pipe, thereby creating a bobbin. Use approximately 170 meters of 22ga transformer wire and carefully wrap the wire around the core. You should be able to create a coil with approximately 500 turns. Note that such a long copper wire has a non-negligible resistance (approx. 5 Ohms), and a suitably high drive voltage is necessary. When designing a coil, consider your current needs, the coil resistance, the necessary voltage, and the power dissipation. Large coils can get very hot very easily (this is why today's MRI magnets are superconducting)! However, your magnetic force increases with n^2 (n=number of turns).

Next, find a relationship between the solenoid current, the distance of the solenoid to the levitated object, and the force exerted on the object. Hint: The equations are nonlinear. Ideally, you should support this relationship with experimental data, because this will help your design later.

Grading milestone #2 (27 points): A completed assembly that consists of the support frame, the solenoid, and the levitated object (13 points). The solenoid must be strong enough that, when energized with DC current, the levitated object sticks to the solenoid (5 points). Equations that relate magnetic force to current and distance must accompany this milestone (10 points). Turn in your amended report.

2   Mathematical Description of the Process

Provide the Laplace-domain transfer function of the *process* with the distance $D(s)$ between solenoid and levitated object as the output variable and the solenoid current $I_S(s)$ as the input variable. Include a time-variable force $F(s)$, acting on the levitated object, as another input variable. It is recommended that you start with the balance of forces and develop the constituent differential equation. Note that it is allowable to cancel gravity against a constant component of the magnetic force (i.e, set the gravitational force to zero). Note also that the relationship of the magnetic force and the solenoid current is nonlinear. If you have quantitative data, for example, from an experiment, perform a formal linearization. Otherwise, simply use a real-valued proportionality α, whereby the magnetic force $F_m = \alpha \cdot I_S$. Add the mathematical description to your report.

Grading milestone #3 (10 points): Transfer function(s) of the process with the input variables $F(s)$ (disturbance) and $I_S(s)$ and with the output variable $D(s)$. Turn in your amended report.

3 Design of the Sensor

In this step, you need to design the distance sensor that measures the output variable $d(t)$ (or, in the Laplace domain, $D(s)$) and provides a proportional (or at least monotonically related) voltage $V_d(s)$. Several possible sensor solutions are available, including Hall sensors, ultrasonic distance sensors, optical sensors, and inductive sensors. This list is not exhaustive.

When you choose your sensor, consider several parameters, such as linear response, the dynamic range (i.e., distance between the maximum and minimum voltage output), noise and external influences (e.g., 60Hz EMI or 120Hz flicker), or the transfer function (e.g., any delay between input and output).

You need to determine the sensor characteristic curve, that is, the quantitative relationship between $d(t)$ (input) and $V_d(t)$ (output) by measurement. Add the description of the sensor principle and the measured sensor characteristic to your report. Sensors that increase the output voltage with the distance and those that decrease the output voltage with the distance are both acceptable, because a simple sign change in the controller can establish negative feedback.

Grading milestone #4 (20 points): A working distance sensor and a measured sensor transfer function with the input variable d and with the output variable V_d. Turn in your amended report.

4 Design of the Solenoid Driver

The solenoid driver deserves special consideration, because here you split paths between a pure analog solution and a semi-analog solution with digital option. A transistor, configured as emitter follower, serves as voltage-controlled current source. The nonlinear behavior of the B-E junction can be reduced with the help of an operational amplifier (Figure 2). In both cases, large heatsinks are required, because the variable coil current is associated with a variable voltage drop across the transistor. Note that we can introduce a nonlinearity (voltage drop across D1 is 0.7V) to reduce the gain for high currents. In its simplest form, the combination of R1 and D1

can somewhat alleviate the nonlinear relationship between magnetic force and distance. With a nonlinear element in the opamp's feedback path, a polynomial characteristic can be even more accurately realized.

The challenge of high heat dissipation does not arise with a transistor that is used as a switch (Figure 2C). Here, the current is controlled by the average on-time relative to the switching frequency (pulse-width modulation, PWM). Many microcontrollers have on-chip PWM capability. Analog ICs exist that provide a pulse-width modulated output signal. Moreover, complete integrated PWM feedback controllers exist, such as the UC3843 or the LM494.
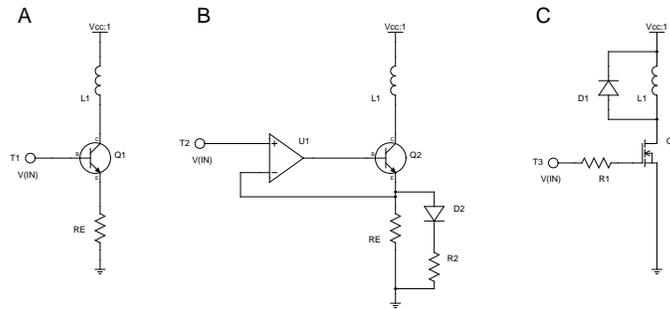

Figure 2: Possible realizations of the coil driver. **A:** Transistor Q1 is configured as emitter follower, and the coil current is approximately $(V_{IN} - 0.7\text{V})/R_E$. **B:** More accurate version of the driver whereby an operational amplifier eliminates the nonlinear behavior of the B-E junction. The coil current is approximately V_{IN}/R_E. An optional nonlinear component (R2-D2) reduces the gain for high currents and thus alleviates the nonlinearity caused by $F_M \propto d^{-2}$. **C:** Switch-mode driver with a MOSFET. This driver requires a pulse-width modulated signal, and the coil current is determined by the pulse width and the maximum coil current. Note that a snubber diode D1 is required to discharge the magnetic energy safely when the transistor goes into the off-mode.

You need to decide at this point – at least tentatively – which of the following three options you prefer:

1. Purely analog solution: Transistor Q1 is a linear element. You need a powerful transistor, such as the TIP140. You can directly use the output of a controller op-amp to feed this transistor. With the general idea laid out in Figure 2B, some tweaking is possible.

2. Analog solution with PWM: You can still use a purely op-amp based solution, but you use the transistor as a switch (Figure 2C). This will

require you to use some form of oscillator and comparator to generate the PWM signal. It is possible to use discrete op-amps to build this unit, but integrated chips (e.g., LM494) are an interesting alternative, because you not only have the PWM generator integrated, but also a complete error amplifier around which you can build your controller.

3. Digital solution: This solution uses PWM and a microcontroller. You minimize the circuit efforts, but you need to realize the controller in software.

Irrespective of whether you use pure analog control or whether you prefer a digital option with PWM, the overall effort is not fundamentally different. In addition, you may change from PWM to purely analog (and *vice-versa*) at a later point if needed.

Grading milestone #5 (10 points): A working solenoid driver with a control voltage input and a voltage-proportional coil current.

5   Design of the Controller – Theory

You are now ready to build the controller and close the loop. Most likely, you'll have to switch back and forth between open-loop and closed-loop configurations to test the component's performance and to optimize the controller. For this reason, the following outline is merely a suggestion. Ideally, you begin the controller design with a good description of the process, and this will lead to the next two grading milestones (theory and working closed-loop model).

Analyze the components you built up to this point (i.e., the levitating object and the sensor). Where are the poles of the open loop components? What do you observe with respect to stability? What is the frequency response? What is the dynamic impulse or step response? Most importantly, where do you want to place the closed-loop poles to get the optimum dynamic response? Where would you introduce a control voltage that controls the nominal (setpoint) distance?

Based on these observations, propose a controller transfer function. How does your pole placement influence the loop gain and thus the suppression of disturbances? Sketch a circuit that realizes your transfer function (see Chapter 3.6).

Note: If you use a microcontroller-based system (i.e., a time-discrete controller), your analysis will have to use the z-domain. Any purely analog

solutions, and this includes integrated PWM controllers, may use Laplace-domain methods.

Provide an analysis of the behavior of the open-loop system, the controller, and the closed-loop system. Use equations, pole-zero diagrams, simulations, or any other tool you deem suitable. At this point at the latest, you need to know your process constants, such as the sensor gain in the operating point and your current-dependent magnetic force. Amend your report with the proposed controller, your controller circuit diagram, and the analysis of the controller behavior. As the absolute minimum, you need to address the following points:

- Location of the open-loop poles of the process and the sensor.

- Desired location of the closed-loop poles, justified by the desired dynamic response.

- How does the proposed controller transfer function lead to the desired closed-loop pole location? What coefficients does the controller have, and how do they influence the pole location?

- Stability analysis: What range of controller coefficients leads to a stable system? What range of controller coefficients leads to an unstable system?

- Robustness: Which process constants (e.g., levitated mass) reduce relative stability or lead to an unstable system? Moreover, how does the nonlinear behavior of the process and the sensor influence the loop gain and thus the dynamic response, the absolute or relative stability?

- Steady-state response: At equilibrium, what determines the object-magnet distance $d(t \to \infty)$?

Most of these questions can be answered with equations. A simulation could include additional nonlinear factors, such as saturation of the coil driver, and can even consider the nonlinearities. The overarching goal here is to demonstrate how the theory leads to a rational controller design.

Grading milestone #6 (20 points): Proposed controller and theoretical analysis of the expected closed-loop behavior. Acceptable closed-loop behavior of the physical system is not necessary for this grading milestone. Turn in your amended report.

6 Design of the Controller – Practice

Build the controller you proposed in the previous section. Complete your system by feeding the sensor signal into the controller and using the controller's output voltage to drive the solenoid. Perform any fine-tuning of the controller that may be necessary to obtain stable, non-oscillatory behavior.

Note: Individual help will be provided for this step. Try to make some coefficients of the controller adjustable, for example, the placement of pole(s) and zero(s), and the controller gain. Use either a sine-wave frequency sweep (Bode diagram) or a square-wave signal (step response) to verify your controller's transfer function.

Voltmeters, a frequency generator and – most importantly – an oscilloscope are valuable tools for this step.

This step is successful if you can keep the levitated object at a constant (and nontrivial) distance from the magnet, without any additional support and for a prolonged period of time (at least one minute). You need to demonstrate the operational closed-loop system *before* the presentations to obtain the score of 40 points for this grading milestone. If the control system is not operating, a partial credit of no more than 10 points (for a valiant attempt) will be awarded for this section.

Grading milestone #7 (40 points): The operational feedback control system, demonstrated to the instructor. In addition, turn in your report, now amended by any design changes you have made.

7 Presentation, Demonstration, Finalized Report

Each group has 15 minutes for the presentation, which should be approximately split into 10 minutes for the presentation of the design and realization of the controller, followed by 5 minutes of practical demonstration. Any group wishing to achieve an award should prepare the presentation accordingly. For example, a group who wishes to demonstrate a high dynamic range should have a function generator and oscilloscope, as well as a ruler, prepared. A group who wishes to demonstrate disturbance rejection should have a scale and the levitated objects of different weight present.

At this time, the report should be completed with any new findings, and the design and realization updated. Award-winning performance should be recorded. You may include photographs of your system if you wish. The report *must contain* all circuit diagrams with component values and, for

digital systems, the full source code.

Each student will be handed out a score sheet so that the audience can award each presentation up to 20 points. A good presentation can earn points even when the control system is not functional. The audience will also record any awards (and award votes) on the score sheet.

Grading milestone #8 (20 points): Score awarded by the audience for the presentations.

Grading milestone #9 (10 points): Turn in your finalized report.

8   Grading

A summary of the grade points (maximum achievable score is 160 points) is below:

- Grading milestone 1 (team nomination): 3 points

- Grading milestone 2 (design and assembly of the process): 27 points

- Grading milestone 3 (transfer function of the process): 10 points

- Grading milestone 4 (design of the sensor): 20 points

- Grading milestone 5 (solenoid driver): 10 points

- Grading milestone 6 (theory of the controller): 20 points

- Grading milestone 7 (practical realization of the control system): 40 points

- Grading milestone 8 (presentation and demonstration): 20 points

- Grading milestone 9 (complete typewritten report): 10 points

Score points for grading milestone #8 will be awarded by the audience, i.e., the students. Points awarded are the average score from all grade sheets. On top of the regular score points, each project *with a fully functional control system* [1] eligible for the awards listed below. Each award comes with a bonus score of 10 points or more as specified below. One team can receive multiple awards.

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[1]Stability requirement is met when the object remains levitated for 10 seconds or more

1. An automatic 5-point award is given to any team that uses LaTeXfor their report (Milestone 9)

2. Award for the design with the highest load lifting capacity (the object will be weighed on a scale. A maximum of one auxiliary magnet is allowed): 10 points. Competing: All levitator projects.

3. Award for the design with the widest dynamic range (the largest periodic movement, measured by a ruler and a laser pointer, for a sinusoidal or square-wave setpoint input): 15 points. Competing: All levitator projects.

4. Award for the design with the best disturbance rejection (defined as the ratio of weights of the heaviest object levitated to the lightest object levitated, with unchanged controller settings. No auxiliary magnets are allowed): 15 points. Competing: All levitator projects.

5. Award for the design with the highest compatibility to any of the other levitated objects (objects from other groups will be used with the device under examination. Levitated objects may not be modified, but controller settings may be changed. Tied projects share award points): 10 points. Competing: All levitator projects.

6. Award for the best feature above and beyond this assignment – any demonstrated, useful and justified feature that is not part of the project assignment qualifies. Voted by the audience. Each student has one vote. You cannot vote for your own team. The majority of votes determines the team that gets this award: 10 points. Competing: All projects.

7. Award for the most artistic design (voted by the audience. Each student has one vote. You cannot vote for your own team. The majority of votes determines the team that gets this award): 10 points. Competing: All projects.