Article

Low-cost magnetic levitation system for education

Gisela Pujol-Vazquez [1,‡,*], Alessandro N. Vargas [2,‡], Saleh Mobayen[3,4,‡] and Leonardo Acho [1,‡]

[1] Department of Mathematics, Universitat Politecnica de Catalunya-BarcelonaTech (ESEIAAT), 08222 Terrassa, Spain; {gisela.pujol,leonardo.acho}@upc.edu.
[2] Electrotechnical Department, Universidade Tecnológica Federal do Paraná, UTFPR, CEP 86300-000 Cornélio Procópio, Brazil; avargas@utfpr.edu.br.
[3] Future Technology Research Center, National Yunlin University of Science and Technology, 123 University Road, Section 3, Douliou, Yunlin 64002, Taiwan; mobayens@yuntech.edu.tw
[4] Department of Electrical Engineering, University of Zanjan, Zanjan, Iran; mobayen@znu.ac.ir
* Correspondence: gisela.pujol@upc.edu
‡ These authors contributed equally to this work.

Abstract: This paper describes how to construct a low-cost magnetic levitation system (MagLev). The MagLev has been intensively used in the engineering education, allowing instructors and students to learn through hands-on experiments essential concepts, such as electronics, electromagnetism, and control systems. Built from scratch, the proposed MagLev depends only on simple, low-cost components readily available on the market. In addition to showing how to construct the MagLev, this paper presents a semi-active control strategy which seems novel when applied in the MagLev. Experiments performed in the laboratory have compared the proposed control scheme with the classical PID control. The corresponding real-time experiments illustrate both the effectiveness of the approach and the potential of the MagLev for education.

Keywords: Magnetic levitating system; Low-cost device; Semi-active control; Education for engineering.

1. Introduction

Being known in the literature simply as *MagLev*, the magnetic levitation system comprises an actuator, usually a coil, producing an electromagnetic force that actuates upon an object. The object, usually containing either metal or magnet, levitates according to the actuator's electromagnetic force. Magnetic levitation systems have been intensively studied due to their wide range of applications, such as in magnetically levitated vehicles [1,2], electrodynamic suspension devices [3,4], magnetic bearings levitating high-speed rotors [5–7], flywheel energy storage systems [8,9], among others [10]. Levitating an object through an electromagnetic force is usually accompanied by a feedback loop. In this case, a sensor measures the object's position and sends the position information to the controller, which is responsible for regulating the current passing through the coil. The regulated current then produces a corresponding electromagnet force that keeps the object levitating at the desired position. As largely documented in the literature, controlling the object's position is a difficult task, mainly because the MagLev shows a nonlinear, unstable behavior (e.g., [11,12]).

Many attempts have been made to control the MagLev system. For instance, some studies have checked the effectiveness of the classical PID control in levitating an object [13–15]. A subsequent study has shown that the sliding-mode control outperforms the classical PID control [16]. Another study has also improved the traditional PID by introducing the so-called fractional-order PID control with a soft computing approach [11]. Another study presents a comparison between the sliding-mode control and the fractional-order sliding mode control, emphasizing the benefits of the latter [17]. In another study, the authors have introduced the concept of generalized PI controller

[18], showing clear advantages with respect to the traditional PID. These investigations together indicate that controlling the MagLev is difficult, motivating the development of a plethora of control strategies. This paper contributes to this direction as well, as detailed next.

Promoting the study of the MagLev in an educational environment has been a practice of many instructors [19], motivated by the challenge associated with the students' learning on how to deal with electromagnetic forces to levitate an object [20]. A famous learning experiment was carried out with the participation of undergraduate students at the Massachusetts Institute of Technology, USA; the instructor asked students to construct their own magnetic levitation kit under the instructor's supervision. This experiment suggested a positive learning experience from the involved students [20,21]. It seems this educational experiment has motivated other researchers to pursue similar investigations, striving to construct their own low-cost magnetic levitation systems [22–24].

This paper's main contribution is to show how to construct a novel low-cost magnetic levitation system for educational purposes. Although recognizing a large number of MagLev models in the literature, we present a novel design that employs easily found, low-cost spare parts. Using the components and source code described here, instructors and students can construct their own low-cost MagLev devices. By doing so, instructors and students not only can enrich the learning experience, but also can practice hands-on training on relevant electronic topics, such as sensors, actuators, electronic circuit building, microcontroller programming, electromagnetism, and control systems. This paper describes the step-by-step necessary to construct a MagLev from scratch—all the diagrams and source code are freely available (see Remark 1). Understanding how the electromagnetic force works under feedback control is an important component in the electrical engineering curriculum, as quoted in [20,21]. The main implication of this paper is facilitating instructors' and students' access to that knowledge, thus improving the learning experience. As a byproduct, this paper discusses some of the difficulties researchers may face when handling electromagnetic forces. For instance, we bring the reader's attention to the fact that the hysteresis in the electromagnet complicates the task of controlling the MagLev—experimental data illustrate this assertion. Also supported by experimental data, we show how ineffective the classical PID control is, thus confirming other investigations [11,16,18]. To overcome such difficulties, we present an anti-windup control. Even though the anti-windup control is not novel in the literature, its application in the MagLev seems useful, as the experimental data suggest.

The remaining of this paper is as follows. Section 2 describes the devices used to assemble the MagLev. Section 3 presents some of the device's limitations, highlighting the pros and cons. The control strategy implemented in the Maglev is detailed in Section 4. The corresponding experimental data, as well as discussions, are shown in Section 5.

2. Material and methods

Before presenting the details about the implementation of the magnetic levitation system (MagLev), we recall how a MagLev prototype should work [20,21]. The MagLev contains a coil, which is assembled as an electromagnet. The electromagnet represents the MagLev control system's actuator. By regulating the current passing through the coil, the MagLev controls the electromagnetic force the electromagnet generates. The MagLev employs algorithm to control the current in the coil. The algorithm is responsible for regulating the induced electromagnetic force, which in turn counteracts the effect of the gravitational force acting on the object. The algorithm requires real-time measurements from the position of the object being levitated. This task is accomplished through a Hall-effect sensor, as detailed next. From the practical viewpoint, the low-cost magnetic levitation prototype consists of an electromagnet, a Hall-effect sensor model A1324 from Allegro(c), an Arduino-Uno microcontroller, and a power amplifier, as depicted in Figure

1. It is necessary a computer to program the algorithm into the Arduino-Uno; in this project, we use a small single-board computer known as Raspberry-Pi (see Figure 2).

Figure 3 presents an schematic that governs the construction of the prototype. The Hall-Effect sensor monitors the position of the object being levitated. This sensor's analog voltage signal is measured by the Arduino Uno microcontroller (MC) through an analog-to-digital converter (ADC). The control algorithm running into the microcontroller, then calculates the necessary control value which will be supplied to the electromagnet by using a pulsed-width-modulated output pin. This process is accomplished in the discrete-time domain with a sampling rate fixed at ten milliseconds.

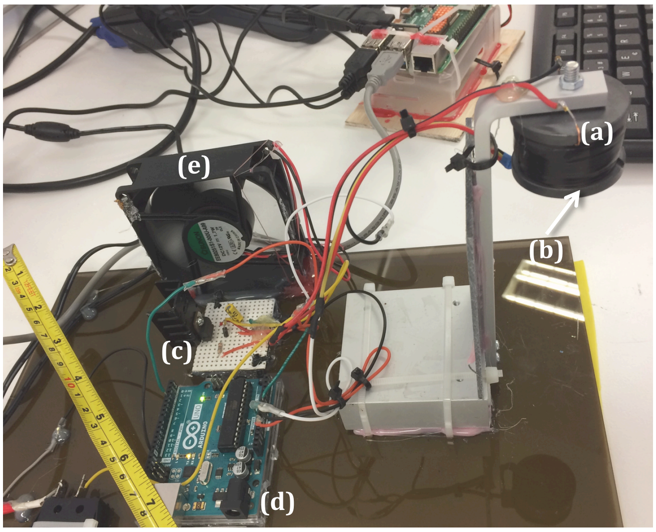

Figure 1. A low-cost experimental platform for electromagnetic levitation control design. Main parts: (a) Actuator coil; (b) Hall-effect sensor; (c) Power amplifier; (d) Arduino Uno microcontroller; and (e) a Fan to dissipate heat from the power amplifier.

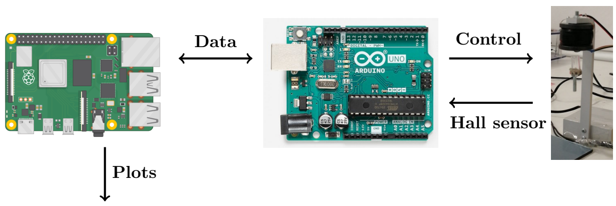

Figure 2. Communication scheme. The leftmost board represents a Raspberry-Pi, used to collect and store measurements from the control system. The control system is implemented in the Arduino Uno board (middle), which communicates in real-time with the MagLev (right).

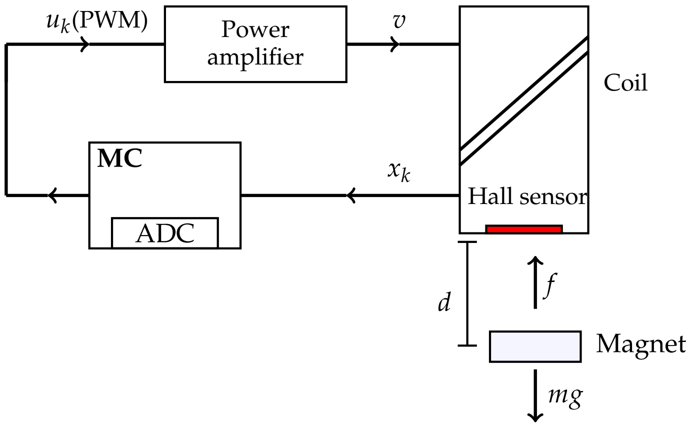

Figure 3. MagLev block diagram. The power amplifier receives the command u_k and generates the corresponding voltage v supplied to the actuator (solenoid coil). The actuator then generates the electromagnetic force f. The levitated object, possibly a magnet with mass m, remains at a distance d from the actuator's bottom. The microcontroller (MC) reads the position x_k, computes the control algorithm, and issues the control command u_k in the format of a PWM signal.

2.1. Actuator

The MagLev's actuator is an electromagnet (i.e., solenoid coil). The electromagnet is handmade, as now detailed. A bolt with dimension M20 x 250mm (hexagon head) is used as the core of the solenoid coil, as suggested in [21,24]. The wire is closely wound around the bolt—the wire used is the enameled copper wire with a diameter of 1mm (110 meters of wire). After built, the electromagnet has both the inductance of 15mH and the resistance of 2.4Ω. The circuit which drove the electromagnet in the experiments is depicted in Figure 4. As can be seen, the Arduino Uno generates the PWM signal which controls the current flow through the coil.

The object being levitated is a neodymium disc magnet N42 with a weight of 5.02 grams and dimension 1/2"x1/8". The Neodymium disc is attached to a transparent plastic for the sake of a better visual appreciation of the controlled levitation experiment (see Remark 1).

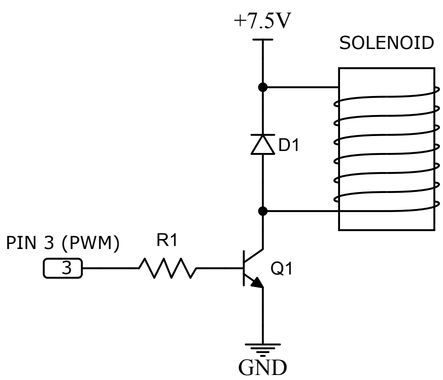

Figure 4. Power amplifier circuit. The PIN 3 of the Arduino Uno generates a PWM signal that drives the transistor Q1 into either 'on' or 'off', like a switch, thus controlling the current that flows through the solenoid coil accordingly. The components used are a resistance of R1=580Ω, a diode D1 with a forward voltage drop of 450mV and a forward current of 1A; and transistor Q1 (code NTD4858N 25V 73A).

2.2. Sensor

The MagLev's sensor chosen to measure the levitated object's position is a Hall-effect sensor, see Figure 5. The motivation for using this kind of sensor stems from

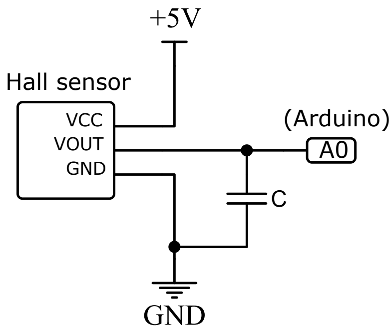

Figure 5. Hall-effect sensor circuit. The sensor is connected to the analog input of the Arduino Uno through PIN A0. The capacitor $C = 10\,\mu F$ was included to filter noise.

the fact that it gives analog measurements, not to mention its low-cost acquisition. An option would be using an optic sensor [25] since it has a higher measurement accuracy; however, this sensor seems to be not only more sensitive to disturbances from either light or dust [19, p. 198], but also more expensive than the Hall-effect sensor [26].

2.3. Microcontroller

Arduino Uno is a low-cost, open-source microcontroller board, widely accepted by the research community [27]. In the MagLev, the Arduino Uno implements the control algorithm. Its additional task is to send the corresponding experimental data to a Raspberry Pi board (see [28] for further details about the Raspberry Pi board). Note that any computer can be used in place of the Raspberry Pi board, yet we opt for the Raspberry Pi board because it represents the cheapest solution.

2.4. Implementation cost

Table 1 details the cost of the MagLev, excluding the computer, monitor, keyboard, and mouse, these being necessary to program the source code into the Arduino Uno. It is worthy mentioning that the total cost seems compatible with a low-cost device, since its assemblage depends only on open-source technology.

Table 1. Component list and cost calculation in € (Euro).

Element	Specification	Price
Arduino Uno		20.07
Hall sensor	A1321	0.57
Object	Neodymium disc	0.10
Capacitator	10μF	0.25
Resistor	580Ω	0.10
Diode	1N5817	0.32
Transistor	NTD4858N	0.70
Solenoid	15mH-2.4Ω	9.13
Total		31.24

2.5. Control algorithm

Considering that the Arduino Uno works with voltage ranging from 0 to +5V, we introduce the expression

$$v = \min(\max(u_k, 0), 5). \tag{1}$$

By recalling that x_k represents the distance, and considering that the control strategy requires the speed of the object, we can use the Euler approximation method to compute the object's speed, say δx_k, as

$$\delta x_k = \frac{x_k - x_{k-1}}{h}, \tag{2}$$

where $h > 0$ denotes the board sampling time. In the equipment, it is used $h = 0.01$ seconds. The integral term reads as

$$I_k = aI_{k-1} + h(x_k - x_{ref}). \tag{3}$$

To avoid the drift of the element I_k when the controller becomes saturated (i.e., integrator windup), we impose that

$$\text{If } I_k > T, \quad \text{then } I_k = 0, \tag{4}$$

where $T > 0$ represents a threshold value to be chosen. Additionally, we consider $T < 5$, since the Arduino Uno converts the voltage representation of 0–5V into a PWM signal of 0–255 units (8 bits).

The control algorithm which we suggest to the MagLev is a straightforward adaptation of the well-known anti-windup PID control [29], which, in our case, reads as

$$u_k = K_p(x_k - x_{ref})\text{sign}(\delta x_k) + K_d\delta x_k + K_i I_k + D, \quad \text{subject to (4)}. \tag{5}$$

The positive constants K_p, K_d, K_i, and x_{ref} are given. The term $D > 0$ has a practical motivation. That is, it comes from trial and error experiments: what was observed in the laboratory is that taking a constant $D > 0$ in (5) diminished the hysteresis produced by the electromagnet. Since the MagLev's goal is to enhance the learning experience, the constant $D > 0$ can be adjusted in the laboratory to either increase or decrease the hysteresis effect upon the electromagnet. Note that D value is added to mitigate the variability of the residual magnetic flux due to the semi-active magnetic control scheme.

We now recall the classical PID control for the sake of experimental comparisons, with hysteresis compensation factor D:

$$u_k^{PDI} = K_p(x_k - x_{ref}) + K_d\delta x_k + K_i I_k + D. \tag{6}$$

2.6. Limitations

The designed prototype faces some limitations. Some of them are due to the low-cost solution, while others are due to the difficulties posed by handling the electromagnetic forces, as detailed next.

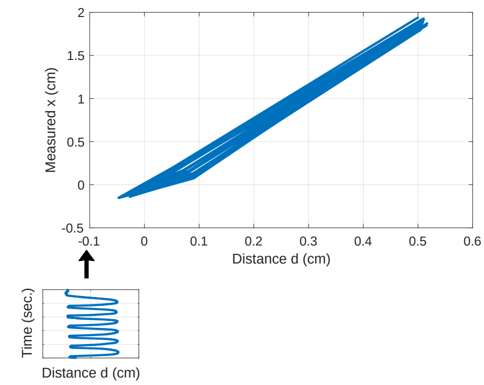

Figure 6. Hall-effect sensor showing hysteresis. The real-time distance, measured by the Hall-effect sensor, differs from the distance d measured by other calibrated measurement device. Even when the object is fixed at a certain position, the Hall-effect sensor measures a kind of sinusoidal signal (lower box).

1. Arduino Uno microcontroller. Yet being a low-cost solution, the Arduino Uno limits the speed of numerical evaluations. In addition, it works only with positive voltage (i.e., $u_k \geq 0$). To handle this situation, we develop a semi-active control law to compensate the gravitational force, as described in the sequel.
2. The electromagnet can produce hysteresis, a phenomenon documented in the literature [30, Ch. 1.6]. Also, the Hall-effect sensor may become inaccurate due to the corresponding hysteresis [31]. In this case, what happens with the sensor is that it measures an unreal distance d, depending on whether the object moves in the sensor's direction or not—Figure 6 illustrates this phenomenon through experimental data. Besides, the Hall-effect sensor is sensitive to the magnetic field generated by nearby electrical wires.
3. There is no proof of stability for the control algorithm in (5). In practice, it means that either the instructor or student should tune the parameters of (5) via trial and error, a tedious procedure.
4. The PWM signal driving the electromagnet creates a certain level of noise in the circuit, which could lead to instability. The capacitor attached to the output of the Hall-effect sensor diminishes the amplitude of that noise.

3. Results and discussion

Experiments are carried out in the laboratory to check the effectiveness of the proposed MagLev. The experimental data are measured and recorded (see Remark 1 in connection). The goal is to levitate an object at the position $x_{ref} = 1.32$ cm. For a comparison between the anti-windup control (5) and the classical PID control (6), we consider the statistical mean-value error as $C_N = \frac{1}{N}\sum_{k=0}^{N} |x_k - x_{ref}|$, where N represents the quantity of steps used in the experiment. The data yields the values shown in Table 2. As can be seen, the proposed control strategy in (5) outperforms the classical PID control.

The data are also illustrated in Figure 7. A visual inspection confirms that the control (5) greatly diminishes the error of the object's position when compared to the error produced by the classical PID control. This finding represents a contribution of (5) for controlling the MagLev.

Table 2. Statistical mean-square error corresponding to the control in the MagLev.

C_N (Error)	Value
Classical PID	0.071
Control in (5)	0.033

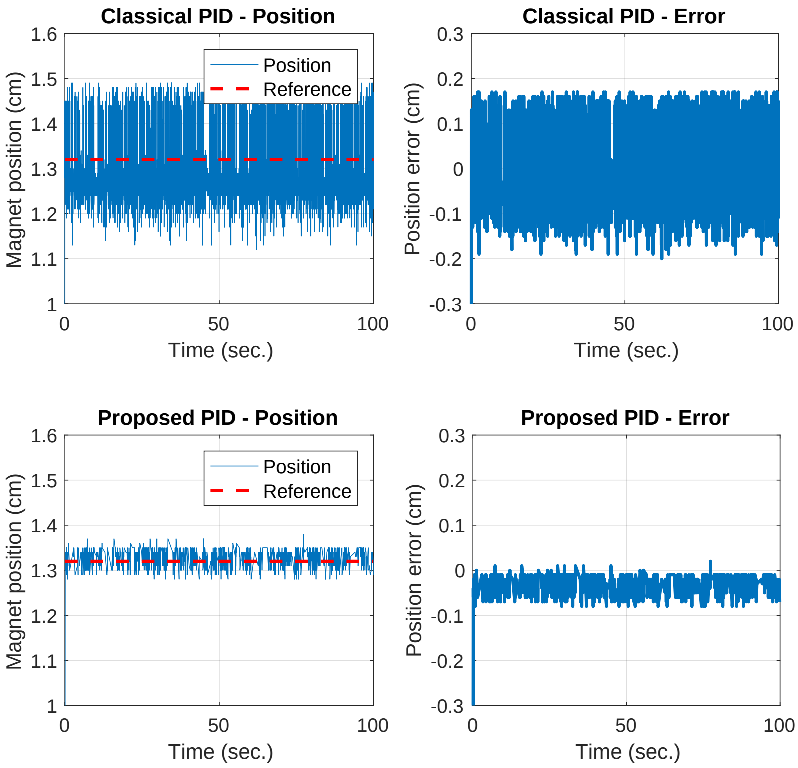

Figure 7. Experimental data from the MagLev. The upper figures show data from the classical PID control (6), and the lower figures show data from the anti-windup control (5) under parameters $K_p = 300$, $K_p = -70$, $K_i = 70$, $D = 100$, $a = -0.8$, and $T = 2.35$ (see Remark 1 for further details).

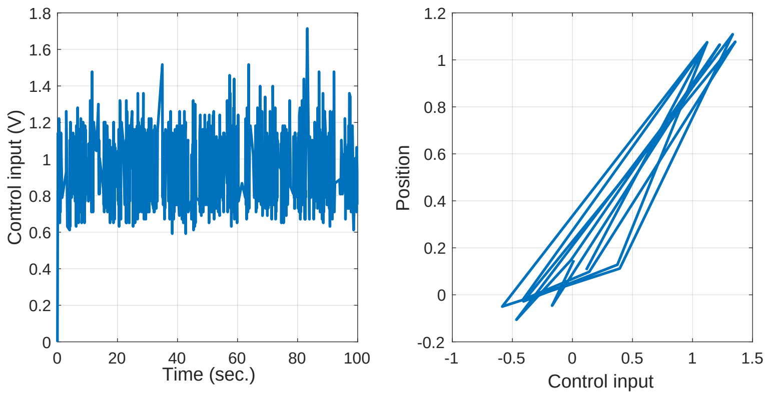

Figure 8. Control effort and the corresponding hysteresis for the anti-windup control (5). : $K_p = 300$, $K_p = -70$, $K_i = 70$, $a = -0.8$, $x_{ref} = 1.32$, $D = 100$.

Remark 1. *A video showing the experiment was recorded, and it is freely available at https://youtu.be/etz8mvdPHXs. All the data and source code used in this manuscript are also freely available on GitHub at github.com/labcontrol-data/MagLev and archived in Zenodo [32].*

3.1. Discussion

From the educational viewpoint, learning how to deal with electromagnet forces represents an exciting challenge. In particular, constructing a MagLev device from scratch is an enriching experience [21].

The experimental data lead us to some conclusions. First, building a low-cost MagLev requires specific skills developed during the assemblage process. Unavoidably, the trial and error attempts push the designer's learning process forward. Undoubtedly, hands-on help to improve his or her learning curve [21]. Second, designing a control strategy working upon an electromagnet may instigate even more the designer's curiosity. As an illustration, we have developed the control (5), which seems to be novel, even though being a direct adaptation of the anti-windup PID control [29].

Certain project limitations are observed, such as the presence of noise, oscillations, and hysteresis (see a discussion in Section 2.6). Some of those limitations come as a side effect of the low-cost strategy, yet overcoming them encourages creativity, a benefit from the educational viewpoint.

4. Concluding remarks

This paper has shown how to build a prototype of a magnetic levitation system (MagLev). All the steps necessary to build the MagLev from scratch were detailed. Constructing the MagLev from scratch can be an enriching learning experience, helping instructors and students learn essential components covered in the curriculum of electrical engineering [21]. Thus, this paper presents a contribution to education, covering a wide range of topics, such as electronics, electromagnetism, and control systems.

The experimental data suggest, in particular, that the MagLev is a tool in which instructors and students can use to learn control systems in practice. Even novel control strategies can be checked in practice, observing the pros and cons, as documented in Section 3. These features, associated with the low-cost solution, represent an essential step towards facilitating engineering education.

Author Contributions: Conceptualization, L.A., A.-N.V. and G.P.; methodology, L.A., A.-N.V., S.M. and G.P.; software, L.A. and G.P.; validation, L.A: and G.P.; formal analysis, S.M. and A.-N. V.; writing-original draft preparation, G.P., A.-N.V. and L.A:; writing-review S.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded in part by the Ministry of Economy, Industry and Competitiveness, State Research Agency of the Spanish Government through grant DPI2016-77407-P (MINECO/AEI/FEDER, UE), and in part by the Brazilian agency CNPq under Grant 305998/2020-0; 421486/2016-3.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Data supporting reported results can be supplied by the authors.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

PID	Proportional Integral Derivative controller
MC	Microcontroller
PWM	Pulse-Width Modulation
ADC	Analog-to-Digital Converter
MagLev	Magnetic Levitation
GND	Voltage reference Ground

Appendix A. Arduino Uno code

This section presents the Arduino Uno code used to implement the proposed controller. Remark that on the Aduino floating point mathematical operations are slow, so variable must be carefully defined as float, double or integer, as needed. An interesting test, specially for graduate students, is to change the storage of the variables and observe the behaviour dynamic of the closed-loop system. Also, note that Arduino only supports 32bit IEEE754 floats with (7 significant digits aprox.).

```
int PinS=A0,s,k=0,u,un=0,sg,x,xn=0;
```

```
double vel,xr,xref=1.32,g,gn=0,h=0.01;
 void setup() {
  pinMode(3,OUTPUT);
  TCCR2B = TCCR2B & B11111000 | B00000001; // for PWM frequency of
  Serial.begin(9600);
 }
 void loop() {
  // First clear the channel
  if (k==0){
     u=0;
     analogWrite(3,u);
     delay(100);
     u=255;
     analogWrite(3,u);
     delay(100);
     u=0;
     analogWrite(3,u);
     k=1;
  }
  // Read the position from PIN A0
  xr=analogRead(0);
  delayMicroseconds(20);
  // Convert (0,1024) bites to measured position.
  double x=5-xr*(5.0/1023);
  // Velocity sign function
  vel=x-xn;
  if (vel>0){
    s=1;
    }
  if (vel<=0){
    s=-1;
    }
  // Integral part (discrete evaluation and reset)
  g=-0.8*gn+h*(x-xref);
  if (abs(g)>120){
      g=0;
      }
  // Satured control input
  u=min(max(300*(x-xref)*s-70*vel+70*g+100,0),255);
  // Send to Arduino Uno through PIN 3
  analogWrite(3,u);
  // Store last valued variables, needed to
  // evaluate the velocity and integral factor
  xn=x;
  gn=g;
 }
```

References

1. Ding, J.; Yang, X.; Long, Z. Structure and control design of levitation electromagnet for electromagnetic suspension medium-speed maglev train. *Journal of Vibration and Control* **2019**, *25*, 1179–1193.
2. Jeong, J.; Ha, C.; Lim, J.; Choi, J. Analysis and Control of the Electromagnetic Coupling Effect of the Levitation and Guidance Systems for a Semi-High-Speed MAGLEV Using a Magnetic Equivalent Circuit. *IEEE Transactions on Magnetics* **2016**, *52*, 1–4.

3. Duan, J.; Xiao, S.; Zhang, K.; Rotaru, M.; Sykulski, J.K. Analysis and Optimization of Asymmetrical Double-Sided Electrodynamic Suspension Devices. *IEEE Transactions on Magnetics* **2019**, *55*, 1–5.
4. Chen, A.; Zhang, M.; Zhu, Y.; Huai, Z.; Yang, K.; Hu, C. A Whole Space Harmonic Force Model for the Disk Electrodynamic Suspension Device Utilizing Magnetic Vector Potential. *IEEE Transactions on Magnetics* **2017**, *53*, 1–10.
5. Fonseca, C.A.; Santos, I.; Weber, H.I. An experimental and theoretical approach of a pinned and a conventional ball bearing for active magnetic bearings. *Mechanical Systems and Signal Processing* **2020**, *138*, 106541.
6. Sheh Zad, H.; Khan, T.I.; Lazoglu, I. Design and Adaptive Sliding-Mode Control of Hybrid Magnetic Bearings. *IEEE Transactions on Industrial Electronics* **2018**, *65*, 2537–2547.
7. Zhang, W.; Zhu, H. Radial magnetic bearings: An overview. *Results in Physics* **2017**, *7*, 3756–3766. doi:10.1016/j.rinp.2017.08.043.
8. Filatov, A.V.; Maslen, E.H. Passive magnetic bearing for flywheel energy storage systems. *IEEE Transactions on Magnetics* **2001**, *37*, 3913–3924.
9. Li, X.; Anvari, B.; Palazzolo, A.; Wang, Z.; Toliyat, H. A Utility-Scale Flywheel Energy Storage System with a Shaftless, Hubless, High-Strength Steel Rotor. *IEEE Transactions on Industrial Electronics* **2018**, *65*, 6667–6675.
10. Yaghoubi, H. The most important maglev applications. *Journal of Engineering*, *2013*, 1–19. doi:10.1155/2013/537986.
11. Mughees, A.; Mohsin, S.A. Design and Control of Magnetic Levitation System by Optimizing Fractional Order PID Controller Using Ant Colony Optimization Algorithm. *IEEE Access* **2020**, *8*, 116704–116723. doi:10.1109/ACCESS.2020.3004025.
12. Qin, Y.; Peng, H.; Ruan, W.; Wu, J.; Gao, J. A modeling and control approach to magnetic levitation system based on state-dependent ARX model. *Journal of Process Control* **2014**, *24*, 93–112.
13. Molina, L.M.C.; Galluzzi, R.; Bonfitto, A.; Tonoli, A.; Amati, N. Magnetic Levitation Control Based on Flux Density and Current Measurement. *Applied Sciences* **2018**, *8*, 1–13.
14. Kishore, S.; Laxmi, V. Modeling, analysis and experimental evaluation of boundary threshold limits for Maglev system. *International Journal of Dynamics and Control* **2020**, *8*, 707–716.
15. Yaseen, M.H.; Abd, H.J. Modeling and control for a magnetic levitation system based on SIMLAB platform in real time. *Results in Physics* **2018**, *8*, 153–159.
16. A., V.S.; S., S. Design of sliding mode controller for magnetic levitation system. *Computers & Electrical Engineering* **2019**, *78*, 184–203.
17. Roy, P.; Roy, B.K. Sliding Mode Control Versus Fractional-Order Sliding Mode Control: Applied to a Magnetic Levitation System. *Journal of Control, Automation and Electrical System* **2020**, *31*, 597–606. doi:10.1007/s40313-020-00587-8.
18. Morales, R.; Sira-Ramírez, H. Trajectory tracking for the magnetic ball levitation system via exact feedforward linearisation and GPI control. *International Journal of Control* **2010**, *83*, 1155–1166. doi:10.1080/00207171003642196.
19. Wong, T.H. Design of a Magnetic Levitation Control System—An Undergraduate Project. *IEEE Transactions on Education* **1986**, *E-29*, 196–200.
20. Lundberg, K.H.; Lilienkamp, K.A.; Marsden, G. Low-cost magnetic levitation project kits. *IEEE Control Systems Magazine* **2004**, *24*, 65–69.
21. Lilienkamp, K.A. Low-cost magnetic levitation project kits for teaching feedback system design. Proceedings of the 2004 American Control Conference, 2004, Vol. 2, pp. 1308–1313. doi:10.23919/ACC.2004.1386755.
22. Gergely Takács, Jakub Mihalík, E.M.; Gulan, M. MagnetoShield: Prototype of a Low-Cost Magnetic Levitation Device for Control Education. IEEE Global Engineering Education Conference (EDUCON), 2020, pp. 1516–1525.
23. Zhang, Z.; Gao, T.; Qin, Y.; Yang, J.; Zhou, F. Numerical Study for Zero-Power Maglev System Inspired by Undergraduate Project Kits. *IEEE Access* **2020**, *8*, 90316–90323. doi: 10.1109/ACCESS.2020.2994128.
24. Artigas, J.I.; Barragán, L.A.; Llorente, S.; Marco, A.; Lucía, O. Low-cost magnetic levitation system for electronics learning. 2010 4th IEEE International Conference on E-Learning in Industrial Electronics, 2010, pp. 55–60. doi:10.1109/ICELIE.2010.5669845.
25. Wang J., Zhao L., Y.L. Adaptive Terminal Sliding Mode Control for Magnetic Levitation Systems With Enhanced Disturbance Compensation. *IEEE Transactions on industrial electronics* **2021**, *68*, 756–766. doi:10.1109/TIE.2020.2975487.

26. Zubia, J.; Casado, L.; Aldabaldetreku, G.; Montero, A.; Zubia, E.; Durana, G. Design and Development of a Low-Cost Optical Current Sensor. *Sensors* **2013**, *13*, 13584–13595.
27. Galadima, A.A. Arduino as a learning tool. 2014 11th International Conference on Electronics, Computer and Computation (ICECCO), 2014, pp. 1–4. doi:10.1109/ICECCO.2014.6997577.
28. Johnston, S.J.; Cox, S.J. The Raspberry Pi: A Technology Disrupter, and the Enabler of Dreams. *Electronics* **2017**, *6*.
29. Bohn, C.; Atherton, D.P. An analysis package comparing PID anti-windup strategies. *IEEE Control Systems Magazine* **1995**, *15*, 34–40.
30. Chikazumi, S. *Physics of ferromagnetism*, 2nd ed.; Vol. 94, *International series of monographs on physics*, Oxford Univ. Press: Oxford, UK, 2010.
31. Gryś, S.; Najgebauer, M. An attempt of accuracy assesment of the hysteresis loop and power loss in magnetic materials during control measurements. *Measurement* **2021**, *174*, 1–7. doi: 10.1016/j.measurement.2021.108962.
32. Pujol-Vazquez, G.; Vargas, A.N.; Mobayen, S.; Acho, L. Data, source code, and documents for the MagLev **2021**. doi:10.5281/zenodo.4678928.