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ELECTRONIC PENDULUM

Bachelor’s thesis
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ABSTRACT

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The pendulum is one of the simplest physical devices. Due to its simplicity, it is often represented on robotics, control and machine learning courses by simulations. However, there are upcoming courses at Tampere University, where the difference between simulations and the real world needs to highlighted, and a hands-on project is deemed beneficiary for the students. Given the predominant focus on simulations, there are very few, if any, simple electronic pendulums. This thesis explores existing research and projects already done on the subject, outlines the process of designing and building an electronic pendulum from scratch, and offers general instructions and an in-depth look into the thought process essential for building an electronic pendulum regardless of the available components.

Various article and thesis databases were consulted for the background information on past pendulum projects. One particular project stood out and was picked as the backbone of this project. The main electronic components of the pendulum are a DC motor, angular encoder, a motor driver and a single-board microcontroller. The components were picked carefully and it was made sure that they would work with each other. This process is detailed in the thesis, along with some things one must consider when doing the wiring work and designing the structure. Regarding the components and structure, some ideas and suggestions based on the difficulties experienced in building the demo pendulum are also provided along with the most critical warnings for the wiring. Some basic structural and functional testing was conducted and documented. The final demo product is a functional electronic pendulum that meets the testing criteria.

Keywords: robotics, pendulum, mechatronics, Arduino, electronics

TIIVISTELMÄ

Arttu Lahti: Elektroninen heiluri
Kandidaatintyö
Tampereen yliopisto
Tieto- ja sähkötekniikan kandidaattiohjelma
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Heiluri on yksi yksinkertaisimmista fysikaalisista laitteista. Yksinkertaisuutensa vuoksi se saatetaan sivuuttaa robotiikan, säädön ja koneoppimisen kursseilla simulaatioiden tarjotessa lähes yhtä hyvän demonstraation. Tampereen yliopistolla on kuitenkin suunnitteilla kursseja, joissa oikean maailman ja simulaation ero on tarkoitus tuoda esille, ja mukaansatempaava fyysinen projekti olisi hyödyllinen opiskelijoille. Keskittyminen simulaatioihin on niin suurta, varsinkin tällä tasolla, että yksinkertaisia elektronisia heilureita on saatavilla erittäin heikosti, jos ollenkaan. Tässä työssä tutkitaan aiempia projekteja ja tutkimuksia, jotta saadaan käsitys saatavilla olevista heilureista ja työ käsittelee heilurin alusta asti suunnittelemisen ja rakentamisen vaiheet. Se myös tarjoaa yleisiä ohjeita ja syvemmän katsauksen siihen ajatusprosessiin, joka pitäisi olla perustana tällaista projektia toteuttavalla. Tarkoitus on, että tämän työn avulla henkilö pystyy suunnittelemaan ja rakentamaan elektronisen heilurin mistä vain saatavilla olevista osista.

Aluksi tutkittiin eri artikkeli- ja opinnäytetyötietokantoja taustatiedon keräämiseen aiemmista heiluriprojekteista. Yksi projekti valittiin tämän projektin perustaksi. Elektronisen heilurin tärkeimmät komponentit ovat tasavirtamoottori, kulmaenkooderi, moottoriohjain ja yhden levyn mikrokontrolleri. Komponentit valittiin huolella ja varmistettiin, että ne ovat toistensa kanssa yhteensopivia. Tämä prosessi on selitetty työssä johdotuksen ja rakenteen ohella. Työ tarjoaa myös yleisiä ohjeita ja ehdotuksia komponentteihin ja rakenteeseen liittyen perustuen demoheiluria rakennuksessa törmättyihin ongelmiin. Siinä on myös tämän kaltaiseen johdotukseen liittyviä varoituksia ja asioita, mitä ei kannata tehdä. Demoheilurille asetettiin ja tehtiin muutama perustesti liittyen rakenteeseen ja toimintaan. Valmis demoheiluri on toimiva elektroninen heiluri, joka täyttää testikriteerit.

Avainsanat: robotiikka, heiluri, mekatroniikka, Arduino, elektroniikka

PREFACE

This was my first ever proper project involving electronics. When I saw the topics offered to us, I decided to jump straight to the deep end, and here we are. I would like to extend my gratitude to Professor Joni Kämäräinen, my supervisor, for his support during every part of the project and always being ready to listen and easy to communicate with. I would also like to thank my friends and family for their support during the making of this project and thesis.

Tampere, 22nd May 2025

Arttu Lahti

The AI tools utilized in my thesis and their purposes are described below:

GPT-4o by OpenAI: GPT-4o was used to provide a massive help when figuring out the electronic components and wiring of the pendulum to make sure everything is compatible and safe. It was also a valuable and quick general assistant on different questions related to the thesis.

ScopusAI by Elsevier: ScopusAI was used to find useful sources from Elsevier's database and to generate search words to use in Andor's search function.

Apple Intelligence by Apple Inc.: Apple Intelligence provided fixes to the grammar and structure of the entire text to ensure it is easy to understand and follows academic style.

I am aware that I am totally responsible for the entire content of the thesis, including the parts generated by AI, and accept the responsibility for any violations of the ethical standards of publications.

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LIST OF SYMBOLS AND ABBREVIATIONS

b	viscous damping coefficient
c_f	Coulomb friction coefficient
DC	Direct Current
E	total mechanical energy
g	gravity
I	moment of inertia
I/O	Input/Output
IDE	Integrated Development Environment
K	kinetic energy
L	pendulum arm length
m	pendulum mass
PC	Peak Current
PLA	Polylactic Acid
RV	Rated Voltage
θ	angular position
$\dot{\theta}$	angular velocity
$\ddot{\theta}$	angular acceleration
TAU	Tampere University
τ	external torque from the motor
U	potential energy

1. INTRODUCTION

Pendulums are widely used in systems requiring control, mostly as benchmarking tools. The most well-known example is the inverted pendulum, which is used in various examples, particularly in robotics and human locomotion analysis (Myers et al. 2020).

Most of the simple beginner-level control theory is taught with simulations. This may lead students into thinking that physical real-world systems are as predictable as simulated environments, therefore, especially in robotics, learning with physical systems cannot be substituted (Jara et al. 2011). A basic electronic pendulum provides students with a connection to the real world that doubles as a physical, engaging, and dynamic system that can be used to experiment with control algorithms, reinforcement learning, and signal processing. Due to the focus on simulations in entry-level studies, where simple pendulums would be beneficial, simple electronic pendulums have been less explored and documented. There were no readily available simple pendulums online that met the criteria:

- reasonable tabletop size
- powered by a normal DC (Direct Current) motor
- able to follow programmed instructions to mimic realistic pendulum oscillation.

There are upcoming applications planned at TAU (Tampere University) for an electronic pendulum on courses in robotics, signal processing, and machine learning. The objective of this thesis is not to provide a detailed tutorial on building an electronic pendulum, but rather to offer insights into the thought process and the overall build and design process, as well as the author's considerations and reflections. Figure 1.1 depicts the 3D model of the demo pendulum, whose design and building process was used to write this thesis.

The resources, such as models and scripts, used in building and testing the demo pendulum freely available at `https://github.com/archulum/pendulum`.

Chapter 2 provides an overview of control theory simulations, the fundamental principles of a pendulum and various different designs for creating an electronic pendulum, and why they do not fit the aim of this project. The aim of chapter 2 is not to go far into detail on how a pendulum works, but highlight the phenomena that make a natural pendulum oscillate, aiming to provide further insight on how the motor could be controlled. Chapter

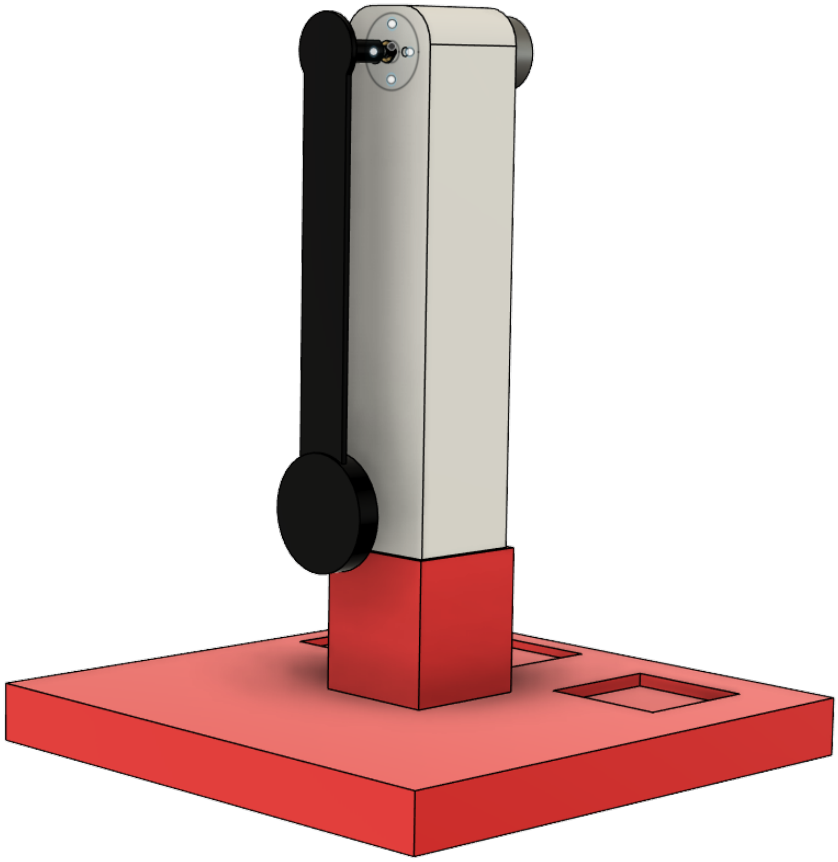

Figure 1.1. *3D model of the demo pendulum.*

3 focuses on the parts, structure, design, assembly and testing of the pendulum. Chapter 4 presents the finished and assembled pendulum, as well as results of the tests and how well it handles all of its criteria. Chapter 5 opens a discussion on limitations and future considerations, as well as gives the conclusion.

2. BACKGROUND

This chapter gives a brief overview on simulations, the fundamentals of a pendulum and other motorised pendulums identified during the research phase.

2.1 Simulations

Simulations, by definition, are models of a real activity, created for training purposes or to solve a problem (Cambridge University Press 2025). Generally, simulations are methods for analysing mechanisms using computers, as opposed to building the system or mechanism under investigation (Gardner 2001, p. 1). Simulations are especially good and efficient in situations, where it might be financially or physically impossible to build or setup a mechanism in real life. In general, simulations are easier to set up and they provide results instantly, whereas physical research might have to be conducted for a long time before any real and tangible results are received. A clear benefit of simulations is also that the data gathered is always clean, which helps students better understand the concept in question (De Jong et al. 2013). A study by Munoz Ubando et al. (2024) proposes that blurring the line between theory and practice, where the cycle of memorizing concepts and applying them to real-life problems is shortened, proved to more beneficial for students especially when the concept is complex and difficult.

When comparing simulations to physical tools, it is evident that using physical tools better prepares students to work more efficiently in real-life projects. They gain knowledge on the things that can go wrong, like measurement errors, otherwise unusable data or equipment malfunction (De Jong et al. 2013). While using simulations as laboratory exercise tools on courses has proven to be effective, allowing students to physically experiment with equipment hands-on generates more motivation for the students (De Jong et al. 2013).

There are various methods for simulating pendulums. It can be done using MATLAB with Simulink, LabVIEW, Python or various other methods. MATLAB and Simulink, created by The MathWorks, Inc., are widely used to aid computation and modelling of systems (Bolton 2015, p. 605). MATLAB offers different toolboxes for performing specific tasks in different areas of study, such as control systems or signal processing (De Silva 2010, p. 813). LabVIEW, by National Instruments, is a software development environment for

Figure 2.1. *Screenshot of the `gymnasium` pendulum simulation. The arrow describes the direction and amplitude of the pendulum's movement at the time of the screenshot.*

data acquisition and instrument and motion control. It enables the user to create programs graphically similar to creating a flowchart (De Silva 2010, p. 829). Individual LabVIEW programs mimic actual scientific instruments (Bolton 2015, p. 152), which makes it easier to understand especially to beginners. Additionally, the `gymnasium` library for Python, originally developed by OpenAI, includes a simulation of a pendulum (Towers et al. 2024), which can be initiated in a Python program with just a few lines of code (Farama Foundation 2025). Figure 2.1 depicts the pendulum from `gymnasium`.

2.2 Fundamental principle of a pendulum

A pendulum is a fundamental, simple mechanical system comprising a weight (bob) connected to a fixed point by an arm (rod or string) of length L. When the weight is displaced from its equilibrium position and released, it moves periodically around the equilibrium position. This repeating motion is called oscillation, occurring along a segment of a circle of radius L. The amplitude of the oscillation is influenced by gravity and L (Young 2016, p. 474). In the context of a motor driven pendulum, an equation of motion is defined (Wiebe et al. 2022)

$$I\ddot{\theta} + b\dot{\theta} + c_f \mathrm{sign}(\dot{\theta}) + mgL\sin(\theta) = \tau, \tag{2.1}$$

where $I\ddot{\theta}$ represents the rotational inertia as per Newton's 2nd Law for Rotation, i.e. the pendulum's resistance to changes in its motion. $b\dot{\theta}$ represents viscous damping, where the resistance force increases with the speed of the pendulum. $c_f \mathrm{sign}(\dot{\theta})$ accounts for

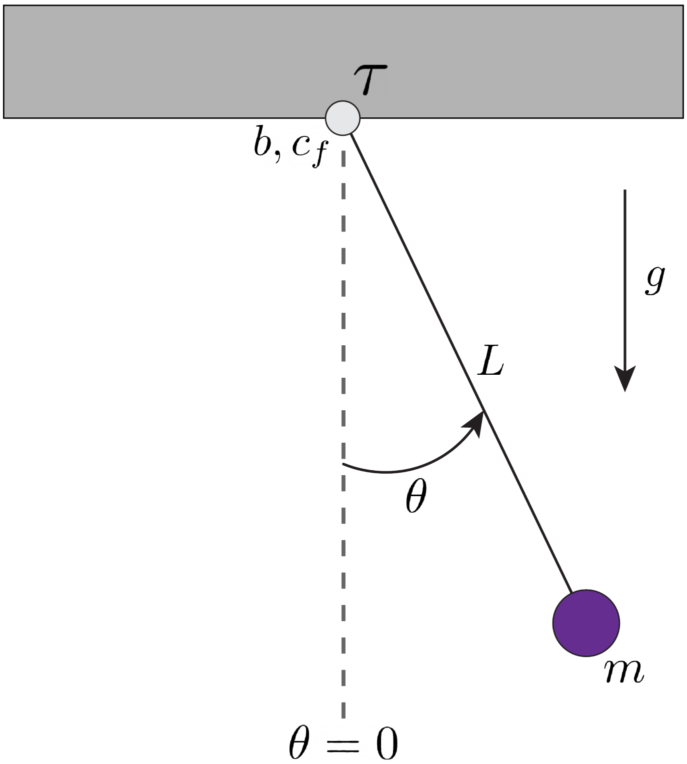

Figure 2.2. *Drawing of a pendulum's physical attributes according to the equation of motion in Equation 2.1. Reproduced and modified from (Wiebe et al. 2022).*

dry friction, with $\mathrm{sign}(\dot{\theta})$ determining the direction of the friction force using the signum function, which returns the sign of a value submitted to it (Venetis 2024). $mgL\sin(\theta)$ models the effect of gravity on the pendulum. τ denotes the torque applied by the motor. The relations between the different terms are depicted in Figure 2.2.

When a pendulum bob is lifted from the equilibrium position, it gains potential energy. When released, the bob goes back down to the equilibrium position and the potential energy is converted into kinetic energy. If it is not stopped at the equilibrium position, it goes up to the opposite side and the kinetic energy converts back to potential energy as the angular velocity decreases and the bob reaches its maximum amplitude (Baker 2006).

The equations for the potential (U), kinetic (K) and total mechanical (E) energies of the pendulum are as follows (Wiebe et al. 2022; Young 2016)

$$U = -mgL\cos(\theta) \tag{2.2}$$

$$K = \frac{1}{2}mL^2\dot{\theta}^2 \tag{2.3}$$

$$E = K + U. \tag{2.4}$$

In an ideal scenario, a pendulum would oscillate indefinitely without the need for a motor driving it. However, natural pendulums tend to dampen over time, per each oscillation, as shown on the left side of Equation 2.1. Potential, kinetic and mechanical energies in Equations 2.2 – 2.4 diminish over time and eventually, when there is no energy left to transfer, the pendulum stops. As displayed in Equation 2.1, the torque τ the motor periodically applies is there to add energy back into the system, preventing it from stopping naturally.

2.3 Related works

Pendulums are one of the classic problems in control theory (Farama Foundation 2025), which means there are many various ways to construct one for education or research purposes. They are fundamentally the same in that they are powered by an electronic actuator and are controlled by a microcontroller, usually an Arduino or a similar device. The largest difference between these versions is their method of generating the oscillation motion.

The aeropendulum differs from the others in that the bob is also the provider of the oscillation force. It has been done previously with a propeller connected to a brushless DC motor at the end of the arm (Neto et al. 2023; Vargová et al. 2023). Due to this, the arm and bob must be as light as possible and to also achieve rigidity, are made of carbon fibre (Vargová et al. 2023).

The linear pendulum is easily the most common pendulum setup, and it is used in without a doubt the most popular control problem and illustration: the pendulum on a cart (Choukchou-Braham 2014, p. 28). It can be done literally with a cart or a linear actuator run with a belt. However, this results in the system usually being quite large, or at least requiring space to move around, and therefore is not feasible as a base for this project.

The vibration pendulum creates oscillation by vibrating the other end of the arm either horizontally, vertically or both. They are rare especially in single-arm applications since it is very difficult to make it oscillate normally, and they are mostly used with two arms in demonstrating chaotic properties since a double-arm vibration pendulum is the simplest way to demonstrate it (Gitterman 2008, pp. 53–60, 80–84).

The magnetic pendulum differs from the others in that it is the only one that fully allows for completely natural pendulum movement since the arm is not attached to the source of oscillation. It is driven by a coil magnet excited by a voltage source, usually located at the apex of the bob's trajectory (Nyiembui et al. 2024). This setup has its good sides, but the negatives outweigh the positives. It is not possible to stop a magnetic pendulum at any location, nor is it possible to accelerate or decelerate it at will since it must always pass by the apex point's coil to adjust the movement.

A torque-driven inertia wheel pendulum, like the aeropendulum, is another pendulum that is actuated by the bob itself. It is a mechanism that consists of a symmetric disc (a wheel), which is attached to the distal tip of the arm and is connected to an actuator capable of spinning parallel to the axis of rotation of the pendulum arm (Sandoval et al. 2021).

The simple pendulum, by Wiebe et al. (2022), with a rigid arm directly connected to the actuator, is the one this project will focus on, scaled down and reduced in cost.

3. METHODS

3.1 Parts and structure

This section provides an overview and details on picking the electrical components and the structural design. It also provides insight on what different things need to be considered to make the project safe for the user and equipment.

3.1.1 Electrical components

The *electrical components* as per the project's backbone, Wiebe et al. (2022), suggests are an angular encoder, DC motor, motor driver, power supply and a single-board microcontroller. Some basic wiring is necessary to connect everything together. The table of electrical components for the demo pendulum is presented in Table 3.1.

Selecting the components for the project is a step that always requires careful attention. Different electrical components have varying specifications regarding their rated and operational voltages and currents. Every component connected to each other must not exceed each other's requirements, because doing so will result in unexpected behaviour or even component failure. If unsure or if the project is complex, one should make a table to make sure all the components and their requirements and abilities work together. The full parts list of the demo pendulum is available on the GitHub page.

Table 3.2 should serve as the starting point, when considering the wide array of electri-

Table 3.1. *Electrical components of the demo pendulum.*

Item	Price (Quantity)
DC motor with encoder (6 – 24 V, 0.25 A)	36.08 € (1)
L298N motor driver	8.17 € (1)
Switching DC power supply (12 V, 1.6 A)	20.40 € (1)
Arduino Uno R3	26.40 € (1)
1.5 mm^2 diameter wire	– (2 m)
Different jumper wires	–
Total	91.05€

Table 3.2. *Input and output specifications of each component of the demo pendulum.*

Component	Input	Output	Notes
DC motor with encoder	RV: 12 V, PC: 250 mA	N/A	Output is sensor output, which is low enough for the Arduino and jumper wires.
L298N motor driver	RV: 7 – 30 V, PC: 2 A (1 A/channel)	N/A	The motor driver also has pins for wires coming from the Arduino. These are always rated for jumper wires.
DC power supply	Mains power	12 V, 1.6 A	–
Arduino Uno R3	6 – 20 V*	Depends on pin: either 20 mA or 50 mA (Arduino Documentation 2025).	*The Arduino can also be powered with USB power, especially when the motor driver handles the motor's power needs.

cal components to select from. In simple terms, voltage represents the "pressure" that pushes current through a circuit, while the used current is determined by the load of the component. Consequently, the voltage must not exceed the RV (Rated Voltage) and the PC (Peak Current) drawn by the ultimate component must be lower than the main power supply current.

Using Table 3.2, the demo pendulum was designed in such a way that everything works well with each other. The selected DC power supply provides 12 V at 1.6 A, which means it has lower current capabilities than the PC of the motor driver. The motor draws a PC of 250 mA, so the selected power supply is more than enough in the case of the demo pendulum.

3.1.2 Structural components

The *structural components* of a tabletop electronic pendulum, as mentioned earlier, include the base, mast, arm and bob. All of these have various ways of implementing. One approach is to make the pendulum using random pieces of wood or leftover metals. The demo pendulum, however, aims for a 3D printed approach to maintain cleanliness and so that students would not have to do 3D designing as part of the project. 3D printing is also easy and quick, and revisions to the design can be done with ease. It also provides the simplest way of creating a structure that is reasonably straightforward to assemble and disassemble. Figure 3.1 illustrates the 3D printed parts used in the demo pendulum. The 3D models used for the demo pendulum were created using Fusion 360 by Autodesk, Inc.

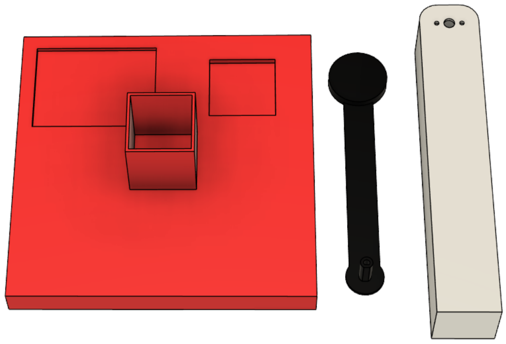

Figure 3.1. *The 3D models of the demo pendulum's structural components.*

and are available to download on the GitHub page.

3.2 Assembly

This section will detail the wiring process and give some attention to important details that must be noted when doing the wiring.

3.2.1 Wiring

The wiring for the demo pendulum is done as presented in Figure 3.2. The power supply is connected to a 2.1 mm adapter with 1.5 mm^2 wires leading to the L298N motor driver. The thick wire is used for the connection to power the motor, as it is safer for higher voltage and current wires to be thicker, especially when the pendulum might be swinging for longer durations of time, resulting in continuous loads on the wires. All other wires are jumper wires (0.2 mm^2 with DuPont style connectors), since they are able to handle the voltage and current requirements of every other function of the pendulum.

The author of this thesis does not provide any safety warranties on the wiring. When assembling the pendulum, several safety related issues should be kept in mind.

1. Under **no** circumstances should one work with *mains power*. Always use a certified power supply to plug into the mains.
2. When working on the electronics and handling wires, the power supply should *always* be disconnected from the outlet.
3. The Arduino pins can only handle 20 mA or 50 mA currents. Motors should *never* be powered directly from the Arduino pins. Use a suitable motor driver.

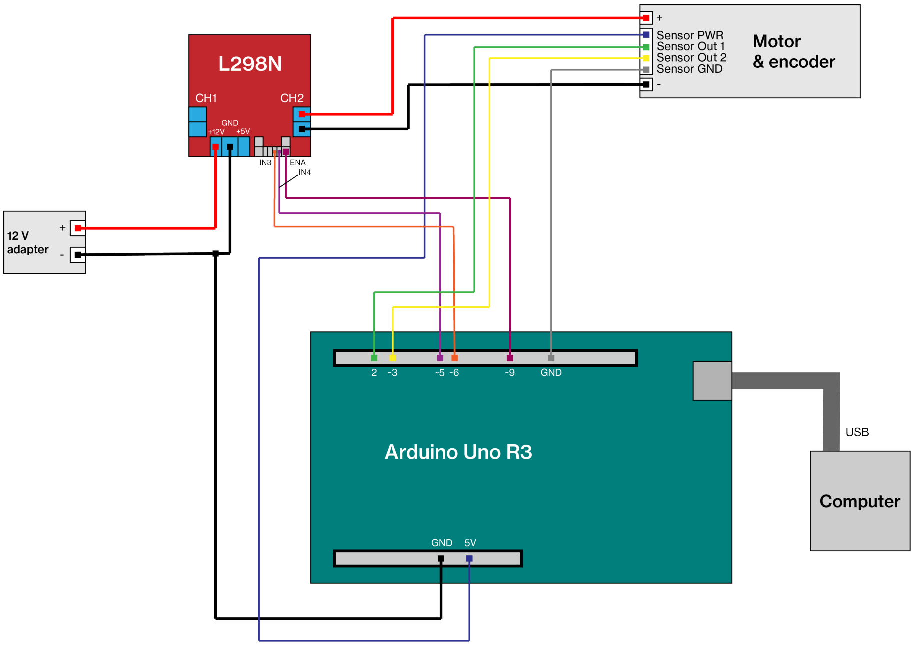

Figure 3.2. *The wiring diagram of the demo pendulum.*

3.2.2 Structure

The 3D printed base of the pendulum is of $200 \times 200 \times 20$ mm in size. It includes small cutouts to accommodate the Arduino Uno R3 and the L298N motor driver, so they do not freely roam about the table. A mast-shaped protrusion is also present on the baseplate, providing support for the mast without compromising its overall height, while also minimizing the need for extra screws. The mast is 230 mm tall and at the top it has a housing for the motor with a 7 mm central hole for the axle and two 3 mm holes for screws to secure the motor in place. The arm is 150 mm long. The components described above are shown in Figure 3.1.

3.3 Oscillation with Arduino

The Arduino is an open-source electronics platform by Arduino ®, which focuses on ease-of-use and breaking the barrier between the electronics design and rest of the world (Arduino 2025). Arduino provides both hardware and software in the form of microcontroller development boards and an IDE (Integrated Development Environment) that allows users to program the boards in Arduino Programming Language, a slightly altered version of C++ (Wikipedia contributors 2025). Arduino boards are used widely in education, prototyping, professional and hobbyist projects due to their strong community support, affordability, and flexibility (Arduino 2025). For this project, the Arduino was chosen because of its beginner-friendly nature.

The specific microcontroller used in the demo pendulum is the Arduino Uno R3. It offers sufficient digital and analog I/O (Input/Output) pins to interface with the angular encoder and the L298N motor driver. It also provides a stable USB link with the host computer for monitoring and debugging purposes, and for uploading the scripts. In this project, the Arduino acts as the main controller for the pendulum system. It reads angular position data from the motor encoder and sends control signals to the L298N motor driver, which adjusts the motor's torque accordingly. Depending on the control algorithm, the Arduino is capable of maintaining the pendulum in a passive swing state or be programmed to stabilize it in an inverted position with a motor capable of handling it. The Arduino was programmed using the Arduino IDE, which is available to download for free on the official Arduino website. Basic motor control and data acquisition routines were implemented with serial communication used for debugging and to visualize data on the host computer during testing.

3.4 Testing criteria

The testing of this project revolves around analysing the structural and functional capabilities of the pendulum. It must be

- able to oscillate using the motor
- stay intact and upright, preferably on its own but if needed, different fastening methods shall be explored
- relatively easy to assemble and disassemble.

The functional capabilities can be assessed without the structural components, since it only means the wiring is done correctly and every component in the circuit works as intended. The structural integrity must wait until the physical components are created or otherwise procured. The ease of assembly, if using the provided 3D structure, should be guaranteed.

4. RESULTS

4.1 Assembled pendulum

The 3D printed structural components of the pendulum fit together very tightly, as was intended. The mast needed to be inserted into the holder with some force, but eventually it was a good fit and the tightness ensures that the mast does not shake with the motor's movements and high torque. Figure 4.1 depicts the fully assembled and connected pendulum.

The pendulum was printed using PLA (polylactic acid), which is a strong and eco-friendly bioplastic and a very popular filament for 3D printing. The base and arm were printed with 15% infill and the mast with 5% infill, keeping the centre of gravity as low as possible. PLA is known for its strength, making it suitable for indoor use. It is, however, brittle, which calls for attention when inserting the mast into the holder as well as screwing in the motor. If these are done with care, the material will endure the stress by the pendulum itself easily.

4.2 Testing

If the project is replicated using the provided 3D models, the ease of assembly has already been confirmed in previous chapters, and it was taken into account in every step of the design process.

The motor was attached to the housing of the mast using screws, and the pendulum arm was connected to its axle. An Arduino script mimicking normal pendulum oscillation was acquired using OpenAI GPT-4o and it was edited to fit this purpose, and also to not have abrupt torque changes. With this script, the pendulum oscillates as expected, the motor goes from forward to reverse and follows the instructions sent over by the Arduino. The encoder values also work correctly, which was confirmed using serial print-ins in the Arduino IDE and supported by the fact that the pendulum always keeps the same trajectory and does not, for example, rotate the "equilibrium" position (i.e. the apex point of the trajectory) around. When oscillating, the pendulum stays intact, upright and it is noticeably stable, removing the need for any fastening to the platform it stands on. Two scripts, one for normal, continuous oscillation and one for normal, damped oscillation, are

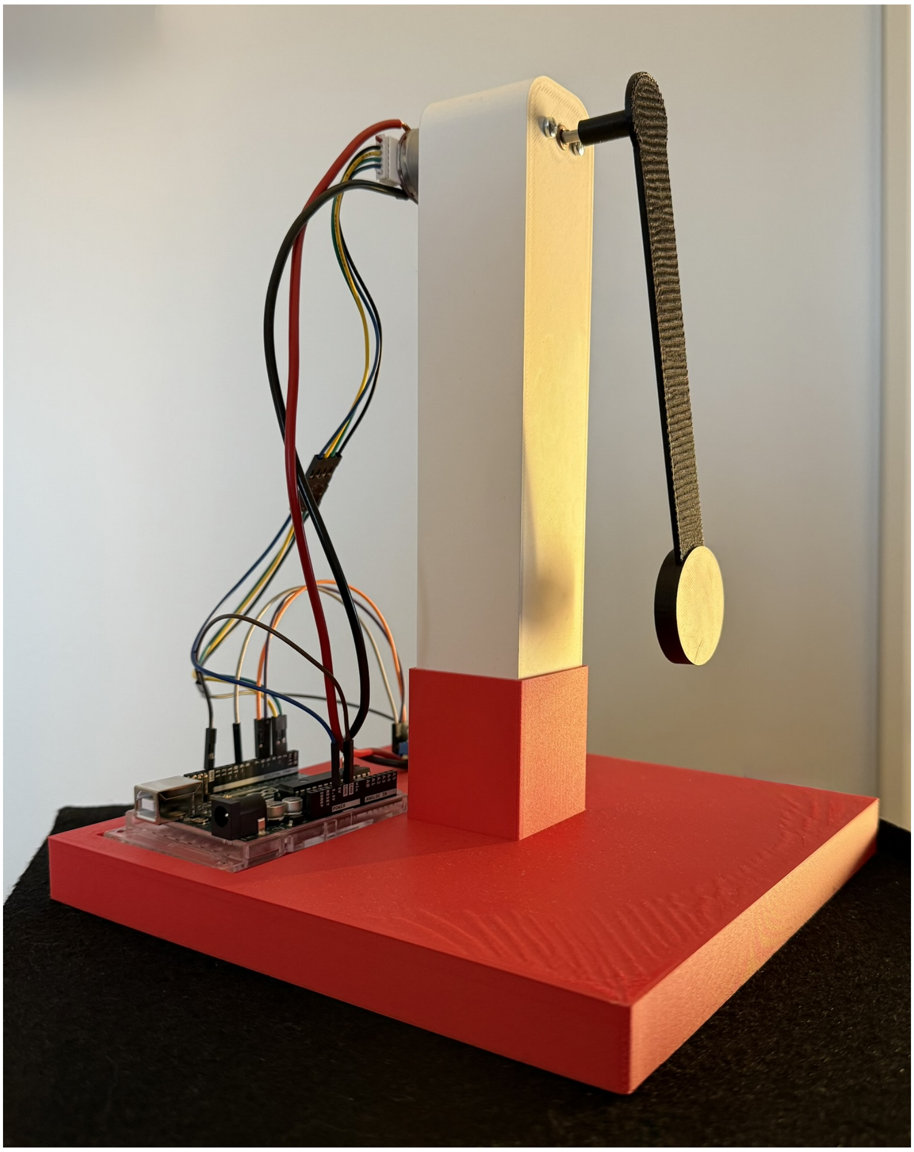

Figure 4.1. *Finished and fully assembled demo pendulum.*

available on the GitHub page.

5. DISCUSSION AND CONCLUSION

The finished pendulum meets the main criteria that were set in the introduction. However, there are several of limitations and future considerations to address. Firstly, the motor used in the demo pendulum was too stiff. This problem appears if one wants to use the pendulum in a free-swinging state. This is quite difficult to overcome without sacrificing other requirements. It would need a motor with a lower ratio gearbox or no gearbox at all, both of which would compromise the accuracy of the movements the motor is able to make but also would most likely increase costs. The motor used in the project by Wiebe et al. (2022) is priced at over 500€, which is impractical for this kind of project.

Additionally, a motor with a higher maximum rotation speed than the motor used in the demo is recommended. The demo's motor had a no-load speed of 128 rpm, which introduced uncertainty during the design process, and the arm and bob of the pendulum had to be made into a pseudo weight. In the demo, the arm and bob were a single 3D printed object, which weighed only about 13 g. This ensured that the motor would handle it with no issues, as the schedule of the project did not allow for a redesign with a new motor, motor driver and structure. Depending on the motor available, a real weight could be used, which would also open opportunities for writing scripts for more complex systems, such as an inverted pendulum.

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