Project 1
Control of a ball in magnetic levitation

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1 Introduction of the project

Preliminary: this laboratory includes a few hours of test and trials with a real system in a lab room located in the Euler building. Due to fall season, the teams of students have to face and manage any disturbance in their planning induced by any sickness/quarantine period of one or several member(s) of the team.

For this project, students will deal with a magnetic levitation device (MagLev), in which a metallic ball can be maintained in levitation using a controlled magnetic field:

- The first introductory goal of this project is to use a basic discrete time PID controller which can drive the vertical position of the metallic ball around a set point.
- The second goal is to use and to enhance a switched discrete time PID controller to explore a range of setpoints as wide as possible.
- And the third goal is to program and use a controller (the structure is left free) to achieve the best tracking of the metallic ball on the widest range of setpoints as possible.

Students will have to build the controllers with the MATLAB/Simulink programming environment, where they will have the access to the input (the command) and the output (the measured vertical position of the ball) of the process.

2 General expectations

The students are expected to work autonomously on an experimental system in order to:

- Test several discrete controllers operating on a system that is unstable in open-loop.
- **Choose**, **build** and **test** some appropriate controllers to drive the ball.
- Justify quantitatively the choice of the controllers they use (so the students have to chose the structure/class of a controller, to enunciate the criterion they use, and to show why this controller is optimal for this criterion);
- Analyse and treat their data;
- Compare the differences between the theoretical data and these from the real process. Students also have to explain the origins of these differences;
- Write a report document summarizing all the work produced for this lab, with the decisions and the data recorded;
- Take whatever additional actions they believe is needed or relevant and draw conclusions from the results that they obtain. Design suitable experiments if needed.

The workload initially scheduled for this project is approximately 22 hours per student.

This project does not require any prior preparation. It is advised to have completed the point 5.1.1 before starting any other simulation. The students can schedule their session(s) as they want (just fill in the table on the valve in face of the office a.-122 (in the level -1 of the Euler building) to book a period).

More accurate details will be given in the fifth section of this document: 5 *Goal of the lab: details*.

3 Global overview of the system

During this project, the students will manipulate a MagLev system designed and hand-crafted by the Feedback group ™(see Fig. 1).

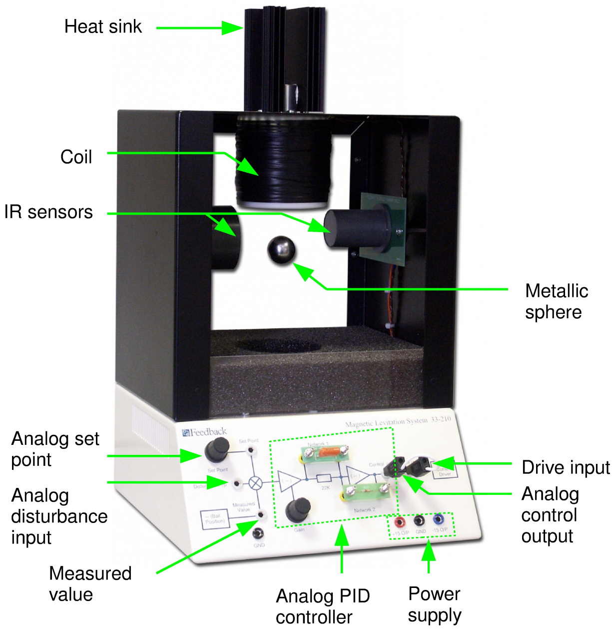

Figure 1: MagLev set description

This system can be controlled by a computer, via a PCI data acquisition board and an analog control interface board, or directly by an analog controller mounted on its front panel.

For this project, the students will only control this system from a computer, via MATLAB/Simulink and the related *Real-Time Windows target*, the *Simulink Coder* and the *Matlab Coder* toolboxes.

4 A few words about the MagLev model

The mechanical-electrical model is a DC voltage generator, connected to a $R - L$ circuit, and the associated DC current generates the magnetic force on the metallic sphere.

The simplest model of the magnetic levitation system relating the ball position and the coil current is the following:

$$m\ddot{x} = mg - k\frac{i^2}{(x+a)^2}$$

where x is the ball position, i is the current in the coil and k is a constant depending on the coil (electromagnet) parameters. To present the full phenomenological model as a relation between the control voltage u and the coil current, the entire MagLev system circuitry should be analysed. However the MagLev system is equipped with an inner control loop providing a current proportional to the control voltage that is generated for control purpose:

$$i = k_1 u$$

where u is the control signal, which has to remain in $[-5V, +5V]$.

You can note that the mass of the metallic ball is 20, 7 g. For two set points, there exists a linear controller that stabilizes the metallic ball with the following command values (measured a few years ago):

$$\left.\begin{array}{c} r = 0 \\ x = 0 \end{array}\right\} \to u = 1.5$$

$$\left.\begin{array}{c} r = 1 \\ x = 1 \end{array}\right\} \to u = 1.85$$

5 Goal of the lab : details

5.1 Part I: PID control

In this first part, students are free to select their tuning method. Students can select model-free heuristic techniques and/or model-based techniques. The most important is to use a scientific method and to explain qualitatively and quantitatively all the experiences and the choices made accordingly.

5.1.1 Getting familiar with the process and a basic PD controller

Preliminary : Open and explore the `MagLev_Control_Basic.mdl` file and try to run it. On several test of 60 seconds, try changing:

- the sampling period;
- the parameters of the controller by manual tuning;
- the structure of the controller (students can, for example, add an integral action);
- and the function of the setpoint (for example, add some sine wave, a combination of ramps and steps ...).

Goal : The goal of this first point is, by manual tuning, to obtain a stable controller that converge as fast as possible to an error equal to zero, with the lowest sampling frequency.
Of course, the students are asked to explain how they conduct their trials and what strategy they used to tune the parameters.
If you encounter any problem to set the ball in levitation, do not hesitate to contact F. Wielant.

Quantitative objective : The controller will be considered reasonably good if it satisfies the following criterion: cancel the error as quickly as possible (i.e. in a few seconds) on a setpoint range of at least 1 V.

5.1.2 PID with switched integral action

Preliminary : Open, explore and test the Simulink diagram `MagLev_PIDswitch.mdl`. You can find that the controller shows a time switched integral gain. Try to understand the advantages of this action.

Goal : The goal of this point is to design a controller, based on one or several linear PID to enhance the range of setpoints reachable with the ball (MATLAB and Simulink enable you to program whatever you want). One way to proceed is, for example, to apply a periodic setpoint with a growing amplitude. In a second time, try increasing the frequency of the periodic setpoint.

Quantitative objective : The controller will be considered reasonably good if it allows the ball to cover the entire range of the position sensor with a triangle wave as setpoint. In parallel, investigate the robustness of the controller you propose.

5.2 Part II: Advanced controller

Preliminary : For this last part, students will have to chose and program a controller (PID-based or not) to allow the best tracking (without error and with the fastest response) of the ball position on the widest range of setpoint, and with the highest frequency (only for sine trajectory) as possible. Ideas can for example come from robust control, minimum variance control, or iterative feedback tuning.

Goal : The goal of this point differs from the point 5.1.2 above: it is asked to implement a model free technique or a technique that handles/treats model uncertainty. As a benchmark, the file *MagLev_Benchmark.mdl* contains a trajectory of 60 seconds. Integrate this source of setpoint in your Simulink working file to illustrate the performance of your controller (of course increase the values of amplitude and frequency (for the sine setpoint) as high as possible).

Quantitative objective : The controller will be considered reasonably good if it satisfies at least one of the followings criterion:

- Be different and as performant as (but advised to be better than) the controller of the point 5.1.2;
- In case of IFT, do at least 4 consecutive iterations where the cost function decreases.

6 What you have to know before testing

In this project, students will be completely free about the method to design their experiments and to reach the goal.

To ease the firsts tests, a basic example code has been developed. On this code, the position of the metallic ball is controlled around a given set point by a linear discrete P+D controller (this one is not tuned to control the ball's position). To run it, follow all these steps:

1. Of course switch on the PC and the MagLev system (with the green switch on its rear face). The PCs for the two MagLev systems available for this project run Win 64 bits. You can login on the following session:
   - login session: **labo-user**
   - password: **BLAbla123**
2. Open MATLAB and Simulink.
3. Download the file `LINMA2671_MagLev_2023.zip` from *Moodle UCL* and extract it on the `Z:\` (network directory). Or if not online, use the directory `C:\LINMA2671_MagLev_2023` from the lab computer and copy-paste it on your `Z:\` directory (**do not work/modify on the original files**).
4. Place the current folder of MATLAB on `Z:\LINMA2671_MagLev_2023`.
5. With the *Simulink Library Browser*, select and open the `MagLev_Basic.mdl` file. The controller included in this example is set manually (i.e. just stabilising the ball). **Students must program their own controller**.
6. When the Simulink model is ready to run, build the real time code by doing *DESKTOP REAL-TIME > Run in Real-Time* (left click on the button illustrated with a big green triangular arrow).
7. If the real-time code runs, the time is counted and the button `Stop` enables. The system is controlled and the data are plotted in real time on the scopes (use the foam strut to place the ball in levitation).

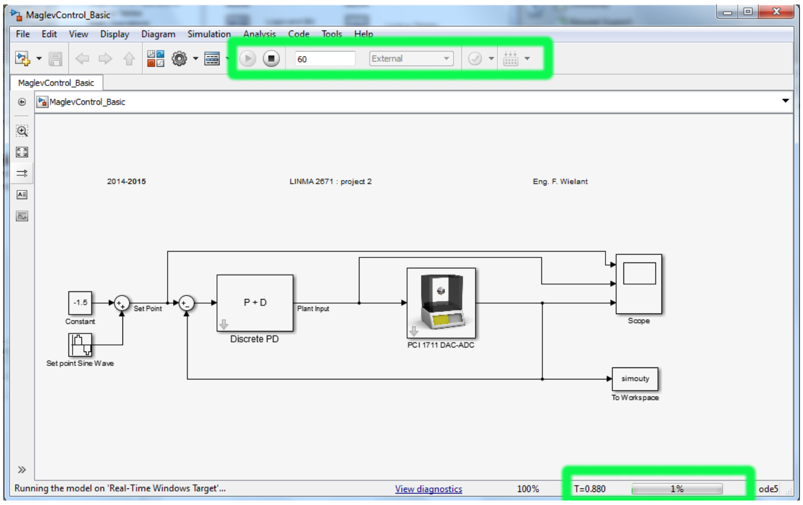

Figure 2: *Real-Time Windows Target* - real time code running

The students can customize this example code for all their tests.
The first thing students could do is to stabilize the metallic ball around the setpoint defined in the Simulink program (the sinusoid can be removed) by "manual" tuning. After that, it will be possible to compute some parameters to test the controllers originally scheduled.

For more informations about Simulink and the *real-time windows target toolbox*, visit real-time windows target documentation.

Remark: Simulink and the associated toolboxes contain (a lot of) bugs (for example student will see that they have to stop the trial before the scheduled period to keep their experimental data). Be careful and work accordingly (defensive programming).

7 Report and discussion

The report should reflect the work of the students, describe the results obtained, the motivations for the decisions made, the conclusions and any other relevant observations (possibly about things that the students have learned during the project).

We kindly remind that reports from master students in engineering are expected to meet the following basic requirements:

- The ideas are clearly explained with correct sentences and appropriate vocabulary;
- The sections of the report ease the reading and the understanding of the work accomplished for the project.
- The graphics are clear and show readily the desired item;
- The graphics come with a title, axes, units, a legend and a caption;
- Each figure or graph is linked with the text;
- Each relative unit (like %, *per unit*, *ppm*) is described.

Explicitly declare any collaboration with other group of students and/or any source of idea (book, article, past lab report, ...).

Any plagiarism will be reported and punished.

On the first page of your report, explicitly mention if you do not want that your report could anonymously be used for this course during the next years (as a report to be reviewed by students).

8 Practical information

- The code to enter the local a.-115, to type on the door handle, is **14231**;
- Do not modify any electrical contact or tuning;
- Please keep clean the work environment, including the PC (*i.e.* do not leave any trace of your working data/folder!);
- Before leaving the lab, do not forget to close the session on the lab computer AND to **Switch OFF** the lab system;
- Do not hesitate to contact François Wielant for any question (Euler building, offices a.-120 and a.-122) regarding the laboratory.