Test Bench Construction for the Validation of Rotor Position Measurement in Magnetic Bearings

EPFL - LAI Microcity
Microtechnology Section

Jacopo Leo

Supervisors:
Yves Perriard
Juan Peralta

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1 Introduction

This project has been developed in the framework of the Essential Tech Center program which has the objective to reduce poverty through essential technology. One of their projects consists in developing a PPE (Personal Protective Equipment) as shown in Fig 1 to be used in areas with infection outbreaks to avoid contamination of health care workers. The existing PPEs are single use and can heat up very quickly in warm environments. The objective is to develop a PPE which is reusable, integrated and ventilated. The development of the ventilation system has been assigned to the EPFL Integrated Actuators Laboratory (LAI). The ventilation system uses an electromagnetic bearing to sustain the rotation of the fan. The project presented here has the aim to design, built and operate a test bench for the validation of rotor position measurements in magnetic bearings.

![Figure 1: New equipment used for medical intervention](image)

The requirements of this ventilation system are the following. First, the system needs to be robust and powerful enough to keep the worker at comfortable temperature without any maintenance. Secondly, The cleaning requirements for PPEs demands that all exposed parts shall be resistant to chlorine solution which is used for cleaning. The conventional ventilation systems are composed of electronics, motors and bearings to guide the rotor (and the fan). One solution to this stringent requirement consists of isolating the electronics and the active parts of the motor from the exposed parts and to use a magnetic bearing to couple the rotor (the fan) to the stator.

In this report, the ventilation system proposed by the LAI will be presented. Next, a literature review of some existing systems with all their advantages and disadvantages. Finally, the test bench built to validate the mathematical model which determines the position of the rotor will be presented.
2 Magnetic bearing

Magnetic bearing in motor uses magnetic forces to maintain the rotor aligned with the stator via a feedback loop. The principle of magnetic bearing is shown in Fig. 2. In the Fig. 2a, forces are applied to the rotor via a virtual magnet, this virtual magnet is created to maintained the rotor at the center via currents flowing into coils. In order to know which virtual magnet is needed, sensors are recording information of the rotor position and a virtual magnet is created in order to maintain the system aligned, this is the principle of a feedback loop (feedback loop of the system is shown in Fig. 2b). The main differences among magnetic bearings are the types of sensors used to determine the position of the rotor and the geometry of the magnetic fields used to impose a force on the rotor.

![Magnetic bearing principle.](image1)

![Feedback system to allow levitation.](image2)

3 Ventilation system from LAI

The drawing shown in Fig. 3, represents a system that satisfies all requirements that LAI is developing. The ventilation is guaranteed by an air flow forced by a fan integrated in the rotor. The air flow in constrained in an isolated tube which is separated from all the electronics and stator. The ventilation system being connected to the inside of the suit, needs to be cleaned with chlorine solution. The rotor being coated with Nickel, it’s cleanable with the said solution. All the electronic elements (PCB and sensors) with the stator are closed inside a sealed box. Thanks to the hermetic box, only the outside of the box can be cleaned. The sensors are the heart of the levitation system, as they allow to know the position of the rotor at any moment in time, which enable the levitation of the rotor. Six coils are wrapped around the stator and generate magnetic forces to control the position and the rotation of the rotor.

![Ventilation system.](image3)
4 Literature review

4.1 First article

The Institute of Electrical Drives and Power Electronics at Johannes Kepler University \[1\] has been developing a magnetic bearing shown in Fig. 4. The particularity of the system is the rotor shape and the sensor placement. The motor is composed of a rotor with a cavity. Inside the cavity, a ferrite core decreases the reluctance of the magnetic path passing through the rotor and core. Foucault current sensors are placed between the rotor and the ferrite core. Twelve coils are used in twelve different magnetic paths controlled via four LDC EVM. The sensors allow to determine the position of the rotor. A software with a feedback loop determines the current to be applied to the coil to generate the correct magnetic field to levitate the rotor. This system is incompatible with a ventilation system, because it is impossible to encapsulate all the electronic elements correctly (including Foucault sensors).

(a) CAD model showing a cross-sectional side view of the stator. The flux collector is made of a ferrite core to provide a non-conductive mounting surface for the sensing coils as well as the low-reluctance path for the actuator bias flux

(b) Sensing system integrated into a hysteresis slice bearing-less motor. The rotor is taken out in this view

Figure 4: Drawing and photo of the system
4.2 Second article

The Power Electronic Systems Laboratory at ETH Zurich [2] has been developing a magnetic bearing shown in Fig. 5. This system has the particularity to integrate a photonic sensor to determine the position of the rotor. Light is directed over the rotor, projecting the shadow of the rotor on the matrix of photonic sensors allowing to know the position of the rotor. Such a system is not usable for a ventilation in PPEs. As for the first system presented, it is impossible to isolate the electronic (ie photonic sensor). Additionally, the dust particles inside the ventilation will disturb the optical system, so the measurement of the rotor might be perturbed.

Figure 5: Topology of the presented high speed millimeter-scale slotless bearingless slice motor
5 Project overview

5.1 Theoretical model

The focus of the project is the sensing system of the bearingless motor of the PEE ventilation system. We have considered only the magnetic field generated by the magnet. All the magnetic fields generated by the coils to force the rotation and position of the rotor have been ignored, because we have made the assumption that we can predict them. In fact, the magnetic forces generated by coils are known and they can be substrate from hall sensor values. To understand the system, let’s look at the principal components of the system.

![Drawing of the principal components of system: rotor and stator](image)

Figure 6: Drawing of the principal components of system: rotor and stator (a) Representation of the magnetization of the rotor (b) Representation of hall sensors positions to get an optimized view of the magnetic field around the rotor.

As shown in Fig. 6, the core components are the stator and the rotor. The rotor has a diagonal magnetization and its position is determined by twelve sensors. The sensors used are hall sensors which are transducers that convert a perpendicular magnetic field (relative to the sensor) to a voltage. The measured magnetic field changes depending on the position of the rotor, as in the example shown in Fig. 7. To determine the position of the rotor with accuracy, the twelve hall sensors are split below and above the stator and are equally distributed (60 degrees between each sensor).

![Sensor sensing magnetic field changes depending on displacement](image)

Figure 7: Sensor sensing magnetic field changes depending on displacement (a) X displacement (b) Z displacement and (c) Tilting displacement
A mathematical model of the system has been developed to measure the rotor’s position from the sensors information. According to the calculation done by Peralta. The rotor’s position is a linear combination of the information of the twelve sensors (Eq. 1). However, the A matrix (linear combination) is not fully determined as the system is not perfectly know (size of stator, magnetization of the rotor $B_0$, etc...). The outputs of A are defined as the measured output multiplied by a constant. Additionally, it has to be considered that during the calculation of the matrix, some non-linear terms have been ignored because of the small significance. So, my job in this project is to show with a test bench that the mathematical model is good enough to provide enough precision about the rotor’s position in order to allow the rotor levitation.

$$\begin{bmatrix}
  C_{\alpha} \cdot \sin(\theta) \\
  C_{\alpha} \cdot \cos(\theta) \\
  C_x \cdot \text{POS}_x \\
  C_y \cdot \text{POS}_y \\
  C_z \cdot \text{POS}_z \\
  C_{\tilt{x}} \cdot \text{Tilt}_x \\
  C_{\tilt{y}} \cdot \text{Tilt}_y
\end{bmatrix} = A \cdot \begin{bmatrix}
  H_1 \\
  H_2 \\
  \vdots \\
  H_{12}
\end{bmatrix} \quad (1)$$

5.2 Axis of the system

To simplify the comprehension of the results obtained by the test bench, the definition of the axes is shown in Fig. 8.

Figure 8: Drawing of the principal elements of system: rotor and stator (a) Definition of the X,Y,Z and $\theta$ axes (b) Definition of $\tilt{x}$ and $\tilt{y}$

As shown in Fig. 8a, a first axis is defined by passing through the first hall sensor and the stator center. Then a second axis is defined parallel to the first axis and passing through the rotor center. It allows to determine the magnetization angle ($\theta$) as the angle between the rotor’s magnetization and the second axis. For the x and y axes, the zeros are defined at the center of the stator. The X axis is aligned with the magnetic field of the rotor and the Y axis is defined perpendicular to this orientation. The $\tilt{x}$ and $\tilt{y}$ are rotating around the X and Y axis (Fig. 8b).
Some parameters are more important than others. If we consider the simplest system composed of a stator and a rotor, by moving the rotor (using simulation or with a test bench) some important features of the system can be observed. First, if the rotor is moved from its central position (rotor and stator correctly aligned), the magnetic forces will push the rotor to be realigned with the stator ($\theta_z = 0$, $tilt_y = 0$ and $POS_Z = 0$), so the minimum energy of those parameters are at the center of the system. However, for other parameters as $POS_X$ and $POS_Y$, an inverse spring effect can be observed. In other words, by placing the rotor at the position (0,0), no forces are applied to the rotor, but the more we move it from its central position, the more the forces applied to the rotor pointing to the exit will increase. So, the important parameters of the system to levitate the rotor correctly are $\theta$, $POS_X$ and $POS_Y$. Other parameters are nice to know but not essential.

5.3 3D printer

A lot of 3D printed pieces has been printed for the construction of the test bench. All pieces have been designed with Autocad Inventor, then exported to a program (called Cura) which converts the CAD file to a GCODE file. The GCODE file contains the information about the deposition of material for each layer in order to print it with FDM (Filament Deposition Modeling). The principal parameters of this converter are the layer size, the direction of printing and support structure. The process is shown in Fig. 9.

![Figure 9](image-url)

Figure 9: Printed piece with Ultimaker 2+ printer (a) CAD drawing from Inventor (b) CAD to GCODE file with Cura converter (c) Picture of printed part with support structure (d) Picture of the printed part after removal of support structure
6 Test bench

6.1 First test bench - XYZθ

The first test bench allowed to verify the correctness of the mathematical model on the parameters: X, Y, Z and θ. A CAD drawing of the system is shown Fig. 14. All 3D pieces of the system have been designed to be robust enough not to deflect because of the strength of magnetic forces. A complete explanation on how to build the system is shown in Appendix (Section 10) containing information about each piece (material, etc.). All pieces which are close to the stator and the rotor are made in plastic to avoid disturbing the magnetic field (3D printed plastic part and plastic screws/nuts).

![CAD drawing and pictures of the test bench with parameters: x,y,z θ](image)

Figure 10: CAD drawing and pictures of the test bench with parameters: x,y,z θ (a) Complete CAD drawing (b) CAD half-view drawing (c) Rotary stage (d) XYZ stage (linear stage).

The system is composed by two moving stages (shown in Fig. 10c and 10d). Unfortunately, I have not been able to find the original CAD files, so they have been modeled into the CAD software considering only critical parameters (positions of screw used, dimension of stage, etc...). In the drawing, the XYZ stage is shown in pink and the rotary stage in purple. The XYZ stage allows to move the stator in the x,y,z directions and the rotary stage allows to change the magnetization angle. By looking at the right side of the CAD drawing (Fig. 10b) and from bottom to top, the rotor’s tower is composed of a rotary stage attached to the optic table (via screws and a 3D printed piece in gray). The upper part of the rotary stage is linked to the magnet via another 3D printed piece. This plastic piece keeps the rotor in position and is screwed on the rotary stage at its base. By looking at the left side from bottom to top, the XYZ stage is screwed on the optical table, then a 3D printed piece (shown in blue) links the linear stage to the stator. This plastic piece is screwed on the xyz stage and tighten the stator. The
PCBs and sensors have been removed in the view. The PCBs are screwed above and under the yellow printed parts which are fixed to the stator. The yellow plastic pieces are used to establish an optimized distance between the sensors and the stator for an optimal view of the magnetic field considering the type of hall sensors used in this test bench.

During the test bench, two different rotors have been used. Because of the geometry of the rotors that are not the same, two different rotor’s towers have been designed. In order to avoid printing the top of rotor’s tower twice, it has been split into two different parts: the column and the crown. As the crowns are used to keep the rotor, we have two different crowns (shown in Fig. 11b and Fig. 11c). The column is the biggest part and remained unchanged during utilization of both rotors. It has been printed once and both crowns have been fixed on. In theory, each crown needed to be printed once (shown in Fig. 11). However, a lot of crowns weren’t tightening correctly the rotor. So, in total, more than five crowns have been printed for each rotor.

The first rotor is a cylinder (as shown in Fig. 11b) and the second one is a cylinder with cavity at the middle (as shown in Fig. 11c). The tightening of the first rotor is done via 3 flexible elements holding the rotor by its sides. Because of the precision of the 3D printer which is not perfect, the CAD’s dimensions weren’t respected during 3D printing (+/- 0.1 [mm] for this specific piece). Because of this imperfection, the tightening induced a lot of stress into the structure in the radial direction. However, it has to be considered that the Z direction of a 3D printed piece is very weak, because the inter-layer links are weaker than the intra-layer links. So, the crown has been printed in the way that the direction of weakness of printing (Z direction) was different than the radial direction. Additionally, a lot of different crowns have been printed to optimize parameters for a good tightening. The parameters which have been changed are the dimension and shape of the flexible elements, the 3D printing direction and the support structures (a part of this process is shown in Fig. 12). The second rotor has a hole inside (shown in Fig. 11c), the tightening is done via a tall cylinder able to tighten the piece via the hole. However, the second rotor wasn’t perfectly fixed onto the crown and a new design will be beneficial when a new test bench will be built.
(a) Broken pieces because of stress induced by rotor tightening

(b) Intermediate design with wrong printing direction, screenshot of Cura program

(c) Weakness of 3D printer depending on printing direction

(d) Final design using correct printing direction with support structure to avoid lowering, screenshot of Cura program

Figure 12: Design optimization of crown

A picture of the XYZ set up is shown in Fig. 13.

Figure 13: Picture of the XYZθ test bench.
6.2 Second test bench - tilt<sub>x</sub> and tilt<sub>y</sub>

The second test bench allowed to verify the correctness of the mathematical model on the parameters: tilt<sub>x</sub> and tilt<sub>y</sub>. A CAD drawing is shown Fig. 14. As for the first test bench, all 3D pieces of the system have been designed to be robust enough not to deflect because of the strength of magnetic forces. A complete explanation on how to build the system is shown in appendix (Section 10) containing information about each piece (the material, etc.).

The system is composed of two moving stages (shown in Fig. 14c and 10d). As for the first test bench, I have not been able to find the original CAD files of those stages, so they have been modeled into the CAD software considering only critical parameters (positions of screw used, dimension of stage, etc...). In the CAD drawing, the XYZ stage is shown in pink and the tilting stage in green. The XYZ stage allows to move the stator in the x,y,z directions and the tilting stage allows to change the tilting angle (tilt<sub>x</sub> or tilt<sub>y</sub>). By looking at the right side of the drawing and from bottom to top, the rotor’s tower is composed of a tilting stage attached to the optic table (with screws and a 3D printed piece in gray). The upper part of the rotary stage is linked to the magnet via another 3D printed piece, this plastic piece is tightened into the tilting stage and the rotor is tightened via flexible elements. By looking at the left side, the XYZ stages and its elements are the same of the first test bench. The PCBs are screwed above and below the stator above via 3D printed parts shown in yellow. The PCBs are shown in green and the sensors as dark boxes.

Figure 14: CAD drawing and pictures of the test bench with parameters: tilt<sub>x</sub> and tilt<sub>y</sub> (a) CAD half-view drawing (b) Complete CAD drawing (c) Tilting stage (d) Picture of the tilt<sub>x</sub> and tilt<sub>y</sub> test bench.
The plastic tower (plastic piece connecting the rotor and the tilting stage) needs to be long because the tilting stage is made of metal and influences too much the magnetic field around. As for the first test bench, two magnets have been used. The tightening of the rotor by the crown is the same, (Fig. 11b and Fig. 11c) but the positions and number of screws have been changed. Therefore, two new crowns have been designed.

The tilting stage (shown in Fig. 24) allows tilting in two directions through screws. A representation of the system is shown in Fig. 15a. A screw with a flat end allows to change the distance between the two planes, where on the other side a sphere gives enough DOF to the system to let the upper plane move during screwing. A spring holds together the upper and bottom plane. However, when the rotor is tilted, the center of mass of the rotor is changing as shown in Fig. 15b. Since we are interested in the tilting only and we don’t want to change other parameters, the center of mass of the rotor need to be at the center of the stator. Therefore, for every tilt, an adjustment of the XYZ stage is required. Calculation to determine the XYZ compensation is presented in the Appendix (Section 10).

Figure 15: Drawing of the tilting system (a) Tilting system schematics (b) XYZ compensation displacement for different tilting angles.
# Measurement system

The measurement system is composed by twelve Hall sensors fixed on two PCBs. A CAD drawing and a picture are shown in Fig. 16. Half of the sensors are fixed above the stator and the other half below. They are equally distributed to obtain an optimized view of the system (60 degrees between each sensor). Hall sensors are transducers that convert a perpendicular magnetic field (relative to the sensor) to a voltage. The PCBs being connected to a microcontroller, the microcontroller converts those voltages into digital information encoded on twelve bits. Then, the microcontroller sends the information to a computer via USB. The information is saved into matlab files. Those files are then read by a matlab program which will measure the displacement of the rotor with the information of the twelve sensors using the mathematical model presented previously. In this way, it is possible to determine the exactitude of the mathematical model by looking at the difference between the measured displacement and the imposed displacement (real displacement done by the test bench).

![Image](image1.png)

(a) [Image](image2.png) (b) [Image](image3.png) (c) Imperfection of the stator

Figure 16: Measurement system (a) Picture (b) CAD drawing (c) Imperfection of the stator

The Hall sensor gives an output between 0 and 4096 encoded on 12 bits. By looking at the datasheet of Hall sensor used, the range of the sensor is \(+/-21\text{[mT]}\). So, by applying a simple equation we can convert the bits to mT. The equation is shown in Eq. 2, with \(\text{bit}_{\text{Range}}\) equal to 4096 and \(\text{mT}_{\text{Range}}\) equal to 42:

\[
\text{Hall\_sensor\[mT\]} = (\text{Hall\_sensor\[bits\]} - \frac{\text{bit}_{\text{Range}}}{2}) \times \frac{\text{mT}_{\text{Range}}}{\text{bit}_{\text{Range}}} \tag{2}
\]

However, the system is not perfect. Several imperfections are shown in Fig. 16. First of all, the elements used are not perfectly symmetric. As an example, the stator is curved because of the fabrication method used. Secondly, the Hall sensors are not perfectly perpendicular to the PCB, a mold has been designed to help us during soldering to align them correctly. Despite the use of the mold, the Hall sensors are not aligned because of the flexibility of the PCB. During the soldering, the PCB was deflecting because of its flexibility. This flexibility is due to the small thickness of the PCB. Finally, because the stages are done in metal, the magnetic field is affected. To lower the impact of metallic components, all screws and elements near the rotor and the stator are made in plastic (because plastic does not influence the magnetic field). Other imperfections come from the Hall sensors, the zero bit value (which is in theory equal \(\frac{\text{bit}_{\text{Range}}}{2}\)) is changing from sensor to sensor. A simple way to overcome this problem is to determine the zero value of each sensor by placing the sensor to a zero input magnetic field and read the real zero value.
8 Results

To simplify future explanations, the real displacement (applied via the test bench) is called imposed displacement. The displacement measured using a linear combination of the information of the twelve sensors is called measured displacement. Every result is presented in two plots. An example of those plots is shown in Fig. 17. The plot on the left shows the Hall sensor responses depending on the imposed displacement. The X axis represents the imposed displacement and the Y axis represents the response of the six Hall sensors in \([mT]\). The plot is composed of two subplots, the upper plot shows the response of the six top sensors and the bottom plot for the six bottom sensors. The first sensor has been defined arbitrary and the following sensors are defined in clockwise direction by looking at the system from a top view (Fig. 16b). The second plot on the right shows the measured displacement multiplied by a constant depending on the imposed displacement. In fact, as said before, the A matrix is not perfectly known, so every output of the linear combination is equal to the measured displacement multiplied by a constant (one constant for every parameter). In theory, this constant is not changing over time. So, once it has been defined for a specific system it is possible to get the measured displacement easily by dividing the result by the constant.

Figure 17: (a) Hall sensor responses depending on the imposed displacement (b) Measured displacement depending on the imposed displacement.
8.1 XY parameters

X and Y displacements for a magnetization angle of zero are shown in Fig. 18.

![Figure 18: (a) X Displacement (b) Y Displacement](image)

For an x displacement and a magnetization angle of zero, the result is shown in Fig. 19. The magnetic field response is very linear and changing slowly over time. However, it can be observed on the right plot that the imposed zero is different than the measured zero. This offset can be caused by a lot of factors, it can be due to the asymmetry of the elements used in this set up, or because of the reference method used (the imposed zero reference between the rotor and the stator has been done by sight). To overcome this problem, a software solution can be considered.

![Figure 19: (a) Hall sensor responses depending on the imposed X displacement (b) Measured X displacement depending on the imposed X displacement.](image)

By looking at the simulation for an X displacement shown in Fig. 20a, if we ignore the fact that simulation is noisy. It can be observed that all Hall sensors values are crossing another sensor value at displacement zero. This is not the case for the real Hall sensor responses (Fig. 19a), top and bottom values are complementary increasing and decreasing but not crossing at zero. If the crossing is forced by adding some offset to the real Hall sensor responses, it will result in a shift in the measured x displacement in Fig. 20c. Now, the measured zero is equal to the imposed zero. One more reason to proceed with this test bench is because of the noisiness of the simulation. This noisiness can be explained...
by the approximation done by the program during computing. The simulation being very noisy, it’s
difficult to determine if the position of the rotor is a linear combination of the information given by
the twelve Hall sensors. So, the utility of the test bench is to validate the hypothesis of linearity. In
reality, all systems are not perfect, so there is a need of software compensation for imperfections. The
test bench allows to test some software compensation method.

For a y displacement and a magnetization angle of zero, the result is shown in Fig. 21. The magnetic field
responses and the measured y displacement are very linear. It has been observed that if the referencing
of the x axis is applied using the offset method, this will induce a referencing for y axis too. However,
the constant for an x displacement is different from the constant for a y displacement, \( C_y = 1.19 \times 10^{-4} \)
and \( C_x = 7.69 \times 10^{-5} \). Because of the asymmetry of the system, it has been observed that by changing
the magnetization angle, the constants \( C_x, C_y \) and the offsets (to correct the referencing) are slowly
changing. Therefore, if we know every constants and offsets correction for every magnetization angle,
the position of the rotor can be determined with precision if and only if the magnetization angle is
measured with accuracy. The measured angle becomes critical. A non-exhaustive table of different \( C \)
constants for different magnetization angles is shown in Tab. 1.

![Figure 20: (a) Sensor responses depending on imposed X parameter obtained via simulation (b) Sensor
responses obtained via the bench test with added offsets (c) Measured X depending on the imposed X
after adding offsets.](image)

![Figure 21: (a) Hall sensor responses depending on the imposed Y displacement (b) Measured Y dis-
placement depending on the imposed Y displacement.](image)
8.2 Magnetization angle

The result is shown in Fig. 22. On the left plot, a sinus response can be observed, which is expected for a change of the magnetization angle. On the right plot, the result is linear with $C_\alpha = 1$. This result is critical, because it allows to know the exact value of the magnetization angle, which is primordial for the software compensation presented previously.

<table>
<thead>
<tr>
<th>Magnetization angle</th>
<th>$0 \text{[rad]}$</th>
<th>$\frac{\pi}{2} \text{[rad]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_x$</td>
<td>$7.69 \cdot 10^{-5}$</td>
<td>$6.48 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$C_y$</td>
<td>$1.19 \cdot 10^{-4}$</td>
<td>$1.23 \cdot 10^{-4}$</td>
</tr>
</tbody>
</table>

Table 1: Constant of A matrix depending on the magnetization angle

![Figure 22](image1.png)

Figure 22: (a) Hall sensor responses depending on the imposed magnetization angle (b) Measured magnetization angle depending on the imposed magnetization angle.

8.3 Z parameter

The result is shown in Fig. 23. On the left plot, it can be observed that all the sensors from the bottom are increasing (getting away from 0) and the top sensors are linearly decreasing. Normally, the top and bottoms sensors should give the same output voltages for a zero imposed displacement. However, it may be observed an offset (top sensor three is not equal in magnitude to bottom sensor three) due to the imperfection of the system as said before. On the right plot, a linear response can be observed. So, the offset does not have any influence for this parameter. No software has been used. The Z parameter is not primordial because it is stable, but it is always nice to know if the rotor is correctly aligned with the stator.
8.4 Tilt parameters

To maintain the stator and the rotor aligned during the tilting, a xyz compensation is needed. So, for each tilting angle, a compensation via the XYZ stage is required. The needed compensation for each tilting angle has been calculated via matlab, a complete explanation on how the matlab program works is shown in Appendix (Section 10). However, because of the low range of the XYZ stage, the maximum compensated tilting angle is one degree. The result is shown in Fig. 24. A non-linear response has been observed in the two right plots in a range of one degree. It will be interesting to change the XYZ stage to increase the maximum compensated tilting angle to see if it’s linear for higher degree. I have not been able to create a new test bench with a new XYZ stage because of lack of time.
8.5 Discussion of result

Some results have been omitted to simplify the explanation. Every parameter has been tested with the two rotors. However, the result which are shown are the results obtained using the second rotor except for tilting measurement. The magnetization of the first rotor (with cylinder shape) is weaker. The results obtained using the first rotor were linear but with a higher SNR. So, the results obtained weren’t interesting. For the tilting test bench, the tilting stage was not adapted for the second magnet, because its magnetization generates so much forces that the spring used to hold the two planes together was not strong enough to hold the two planes, and the screw wasn’t touching the below plane (a drawing of the situation is shown in Fig. 25a).

The most important parameters of the system are the parameters which are not stable and have been correctly determined: $POS_x$, $POS_y$ and $\theta$. $\theta$ is determined without any compensation software and $POS_x$ and $POS_y$ are corrected via software compensation, the compensation is depending on $\theta$. The $Z$ parameter is linear without any software compensation and $tilt_x$ and $tilt_y$ are not linear.

Further possible work would be to create a software for automatic compensation for imperfections. The imperfections are present in real system and a calibration software is mandatory. Another possible work would be to design a new test bench for tilting parameters with a new tilting stage to allow the use of a stronger magnet and a new XYZ stage to be able to compensate tilting of more than one degree. Finally, a reference method needs to be developed using optical or other systems to know the exact position of the zero imposed position.

Figure 25: (a) Magnetic forces applied to the tilting stage by the second magnet (rotor) (b) Tilting stage

9 Conclusion

The aim of this project was to design a test bench that can validate the mathematical model for the determination of the position of the rotor via hall sensor values. The test bench has confirmed a good fit between the expected values and the measured ones for important parameters $POS_x$, $POS_y$ and $\theta$. A measurement software compensation has been proposed to overcome the imperfections of the system. Future developments may consist in the addition of other types of sensors to increase the precision of the measurement. In addition, a more capable calibration method needs to be developed to try to compensate the imperfections of the system.
10 Appendix

10.1 Assembly manual

10.1.1 XYZ Stage

Figure 26: The XYZ stage is fixed to the optic table with screws M6x16 (2x). The static part of the XYZ stage is shown in purple and the moving part of the XYZ stage (called XYZ plate) is colored in green.

Figure 27: The stator is tightened into a plastic piece (called stator holder). The stator is colored in red and the stator holder in blue.
Figure 28: The PCBs are fixed to the stator holder (blue plastic piece) with long screws M3x25 (5x) and nuts M3 (5x). Screws and nuts are in plastic in order to avoid disturbing the magnetic field generated by the rotor. Two 3D printed pieces (colored in yellow) allow to have the correct distance between the sensors (which are on the PCBs) and the stator to have an optimal view of the magnetic field around the rotor. The stator is colored in red, 3D printed plastic pieces in blue and yellow. PCBs are in green.

Figure 29: A CAD drawing after the assembly of the stator and the PCBs.
Figure 30: The stator holder (blue piece) is fixed to an intermediate 3D printed piece (in yellow) with screws M4x20 (6x) and nuts M4 (6x). Then, the intermediate piece is fixed to the XYZ plate (in green) with screws M4x8 (6x). So, by moving the green plate, the stator and sensors are moving in XYZ directions compared to the optic table.

Figure 31: A CAD drawing after the assembly of the stator and the XYZ stage
10.1.2 Rotary stage

Figure 32: The rotor is tightened on the crown (plastic piece shown in gray) then the crown is fixed on the column (plastic piece shown in gray) via four threads inside the crown. Screws M4x12 (4x) and nuts M4 (4x) are in plastic.

Figure 33: The column (in gray) is fixed through an intermediate plastic piece (square piece shown in gray) with screws M6x16 (4x), screws M3x10 (4x) and nuts M6 (4x) to the rotary stage (shown in purple). Then the rotary stage is fixed to the optical table through another intermediate plastic piece (rectangle piece shown in gray) with screws M6x16 (4x) and screws M4x10 (4x). The screws are in metal in order to be solid enough to resist to any deformation. The crown and the rotor are not shown to facilitate the comprehension of the system. (a) Top view (b) Side view
Figure 34: A CAD drawing after the assembly of the column and the rotary stage

Figure 35: A CAD drawing of the first test bench - XYZ
10.1.3 Tilting stage

Figure 36: The rotor (in blue) is tightened on the crown (plastic piece in yellow). Then, the crown is fixed to the intermediate plastic piece (in gray) with a screw M4x25 and nut M4. The screw and the nut are in plastic. Then the intermediate piece is tightened into the tilting stage. A screw can be used on the side of the titling stage to tighten it with more force. The base of the tilting stage is tightened to another intermediate plastic piece, another screw can be used to tighten it. Finally, the intermediate piece is fixed to the optic table via oblong holes and screws M6x12 (2x) in order to move it in one direction if needed.
10.2 xyz compensation for tilting stage

A drawing of the tilting mechanism is shown in Fig. 37. A matlab program called XYZ_Compensation_for_tilting.m calculates the xyz compensation for different angles.

When we screw the screw, the distance $h_d$ is changed. The tilting angle ($\alpha$) can be determined by Eq. 3 and 4. The XYZ compensation is defined by Eq. 5 and 6.

\[
\sin^2(\alpha) + \cos^2(\alpha) = 1 \rightarrow \left(\frac{h_t}{d}\right)^2 + \left(\frac{ht}{hd}\right)^2 = 1
\] (3)

\[
\frac{d \cdot h_d}{\sqrt{h_d^2 + d^2}} = h_t \rightarrow \alpha = \arccos \left(\frac{h_t}{d}\right)
\] (4)

\[
\Delta y = \frac{d}{2} \cdot \sin(\alpha) - h(1 - \cos(\alpha))
\] (5)

\[
\Delta x = \frac{d}{2} \cdot (1 - \cos(\alpha)) - h \cdot \sin(\alpha)
\] (6)
10.3 Mathematical model - Matlab program

The axis used in matlab are defined differently than in the report. The X and Y axis are not moving with the magnetization angle. They have been defined as shown Fig. 38.

![Figure 38: Definition of matlab axis](image)

A matlab program have been developed in order to read the files that contain information of sensors values and convert this information in rotor displacement (measured displacement).

In order to read the files correctly, the filenames are defined as shown in Fig. 39. Normally, the file names give info on the magnetization angle used during the measurement. FA1 means fixed magnetization angle one and is equal to $\frac{\pi}{4}[\text{rad}]$. FA2 means fixed magnetization angle two and is equal to 0[rad].

![Figure 39: Filename definition](image)

All the functions with the explanation of each parameters are shown in Fig. 41 and 42. First, the program read the files with hall sensor values via the function Read_file.m. Then, the measured displacements are determined with the function Position_measured_via_Linear_combination.m using the information of hall sensor values. Two different plots have been developed to visualise the outputs. The function plot_Sensor_response_with_LR.m plots hall sensor responses depending on the imposed displacement and the function plot_result_with_LR.m plots the measured displacement multiplied by
a constant that depends on the imposed displacement. An example of those plots is presented in Fig. 40.

Figure 40: An example of an imposed displacement changing in Z (a) Plot result of plot_Sensor_response_with_LR.m (b) Plot result of plot_result_with_LR.m

Figure 41: Matlab functions (a) Read_file.m (b) Position_measured_via_Linear_combination.m
Figure 42: Matlab functions (a) plot_Sensor_response_with_LR.m (b) plot_result_with_LR.m
11 References
