上海交通大學

SHANGHAI JIAO TONG UNIVERSITY

学士学位论文

THESIS OF BACHELOR

Project Title: Controlled Rotation of Electromagnetically Suspended Object

Name1	Changqing Lu	ID1	515370910192	Major	ME
Name2	Hanqin Wang	ID2	5140809063	Major	ME
Name3	Junren Liao	ID3	5143709034	Major	ME
Name4	Yifu An	ID4	515370910152	Major	ME
Name5	Zilan Zhang	ID5	515370910198	Major	ME

Supervisor Chengbing Ma

School UM-SJTU Joint Institute

Semester 2018-2019-Summer

上海交通大学

毕业设计（论文）学术诚信声明

本人郑重声明：所呈交的毕业设计（论文），是本人在导师的指导下，独立进行研究工作所取得的成果。除文中已经注明引用的内容外，本论文不包含任何其他个人或集体已经发表或撰写过的作品成果。对本文的研究做出重要贡献的个人和集体，均已在文中以明确方式标明。本人完全意识到本声明的法律结果由本人承担。

作者签名：张清 张子岚 安一夫 廖俊人 王翰钦

日期：2019年8月5日

上海交通大学

毕业设计（论文）版权使用授权书

本毕业设计（论文）作者同意学校保留并向国家有关部门或机构送交论文的复印件和电子版，允许论文被查阅和借阅。本人授权上海交通大学可以将本毕业设计（论文）的全部或部分内容编入有关数据库进行检索，可以采用影印、缩印或扫描等复制手段保存和汇编本毕业设计（论文）。

保密□，在___年解密后适用本授权书。

本论文属于

不保密☑。

（请在以上方框内打“√”）

作者签名：张清 张子岚 安一夫
廖俊人 王翰钦

日期：2019年8月5日

指导教师签名：[illegible]

日期：2019年8月5日

2019 SUMMER

VM450 Design and Manufacture III
Final Report

Controlled Rotation of
Electromagnetically Suspended Object

Group 3

An, Yifu	安一夫	anyifu@sjtu.edu.cn
Liao, Junren	廖俊人	junren@berkeley.edu
Lu, Changqing	卢长清	luchangqing@sjtu.edu.cn
Wang, Hanqin	王翰钦	wanghanqin@outlook.com
Zhang, Zilan	张子岚	shilan0618@sjtu.edu.cn
	崔庆文 (Sponsor)	DeepMag 深磁科技

August 5, 2019

Abstract 摘要

The goal of the project is to achieve controlled rotation of electromagnetically suspended objects. We are required to include a rotary control system in the suspension control system, which is provided by our sponsors. Through controlled rotation, the electromagnetic suspended object should maintain vertical stability and a gap can be seen between the object and the suspension control base. The object should have a smooth rotation and can rotate at a constant specified angular velocity and can be rotated at a specified angle. We propose several solutions using system analysis and decision matrices. The final design concept is based on a gyroscope's rotary control system, in which the flywheel combines a DC motor, a rotary-controlled actuator and a PID control system with an angular velocity sensor (BMI160).We use acrylic plates, nuts and bolts as well as 3D printed battery cases. It has been verified that the final prototype will maintain vertical stability while the rotary control system is running. It can rotate at a constant angular speed specified by the customer. It is also possible to rotate the specified angle. Therefore, we conclude that the prototype basically validates the design concept and meets the customer's requirements. The limitations of this prototype include structural balance issues and uncontrollable scenarios can occur with extreme external disturbances. A further improvement to the prototype may be to build an integrated circuit board for the control system, replace the analog control circuit with a digital control circuit of the suspension system, and incorporate the wireless power system into the suspension portion.

该项目的目标是实现电磁悬浮物体的可控旋转。我们被要求在悬浮控制系统中加入一个旋转控制系统，该系统由我们的赞助商提供。通过可控旋转，电磁悬浮物体应保持垂直稳定性，物体与悬浮控制基座之间可见间隙。物体应具有平滑的旋转，并且可以以恒定的指定角速度旋转，并且可以以指定的角度旋转。我们使用系统分析和决策矩阵提出了几种解决方案。最终的设计理念是基于陀螺仪的旋转控制系统，其中飞轮结合了直流电动机，旋转控制的执行器和带有角速度传感器（BMI160）的PID控制系统。我们使用丙烯酸板，螺母和螺栓以及3D打印电池盒。经过验证，最终原型能够在旋转控制系统运行时保持垂直稳定性。它能够以客户指定的恒定角速度旋转。也可以旋转指定的角度。因此，我们得出结论，原型基本上验证了设计概念并满足了客户的要求。该原型的局限性包括结构平衡问题，并且在极大的外部干扰下可能发生无法控制的方案。对原型的进一步改进可以是为控制系统构建集成电路板，用悬浮系统的数字控制电路代替模拟控制电路，并将无线电源系统结合到悬浮部分。

Keywords 关键词

Electromagnetic suspension, Controllable rotation, digital control circuit, PID control, Dynamic balance

磁悬浮，可控制旋转，数字电路，PID 控制，动态平衡

Executive Summary

The project requires the design and manufacture of an electromagnetic suspension system with controllable rotation. Based on the available electromagnetic suspension system, provided by our sponsor, DeepMag, a rotation control system is designed to achieve accurate rotational speed control and rotation angle control. The system can be integrated into artistic or advertising mechanisms to achieve better display effects. In terms of the customer requirements, the suspended object should maintain its vertical stability while the rotation control system is in operation. There should be a visible gap between the suspended object and the suspension control base. The rotation motion should be smooth and without fluctuations. The rotation control system should be able to control the object to rotate at a specific rotation speed or rotate by a specific angle. In addition, the object should have no difficulty in rotating in different directions. Translating customer requirements into engineering specifications, we set the gap between the upper surface of the suspended object and the lower surface of the suspension control base to be 15 millimeters. The allowed weight of the suspended part is under 200 grams. The steady state angular speed at which the suspended object can be adjusted according to the requirements of the customers. The angular speed precision is set to ± 1 degree per second. The precision of the rotation angle is set to 3.6 degrees, which is one-hundredth of 360 degrees. The object should be able to rotate in both directions, clockwise and counter-clockwise.

To achieve the specified engineering specifications. We analyzed the system and subsystems, and provided several solutions to the subsystems. The system basically has two subsystems, the suspension system and the rotation control system. The rotation control system consists of the function of rotation motion, the function of rotation feedback which monitors the motion of the rotation, as well as the control system which modifies the motion of the rotation. For the function of rotating, we provided three concepts, the electromagnetic field control solution with a stepper motor concept, the air jet solution and the gyroscope solution. For the function of rotation feedback, the solutions were angular speed sensor, photoelectric gate and magnetic sensor. For the control system, we can use PID control theory, or simple remote control. The concept we chose for the rotation control system with the gyroscope concept as the rotation motion actuator, the angular speed sensor for motion monitoring, the PID control for control system. Because gyroscope actuator system does not require external torques to change the angular speed of the object and consequently eliminates the potential interference by the external control torques to the vertical suspension system. The gyro rotation can also inherently guarantee the smooth rotation of the object. With an angular speed sensor with good accuracy and PID control theory, changing the angular speed of the fly wheel would modify the angular speed of the object, which simplifies the control process. Also, an angular speed can monitor the rotation angle by integration during the control loop, which enables the object to rotate by a specified angle. Structurally, we assembled acrylic boards for fast prototyping and structural modification. For the power supply, we chose to integrate a battery system with the suspended part. Therefore, the final prototype is a gyro-based rotation control system which is integrated with permanent magnets for suspension purpose. The prototype is assembled with acrylic boards and powered by a 3.7 V battery.

The prototype was tested and it is able to rotate at a specified angular speed (30 degree per second during the test) and remain at zero angular speed if under small interference. It can also rotate by a specified angle (120 degrees during the test). The cost of the prototype is estimated to be around 220 RMB. With an integrated circuit for mass production, the cost is going to be decreased and the weight of the control system can be further reduced.

Therefore, the prototype we manufactured achieved the engineering specifications and realized the gyro-based rotation control concept successfully. Limitations of the system involve the weight balance problem as well as the fact that the PID control parameters should be modified according to the suspended object in practice. What's more, several improvements are recommended for more versatile applications on the system. Replacing the analog control circuit of the suspension system with a digital control circuit can simplify the adjustment on the suspension system. Replacing the battery system with wireless power supply can further reduce the weight of the suspended part.

Contents

1 Introduction

Currently electromagnetic suspension is applied not only in the industry but also can be applied in people's daily life. DeepMag Tech is the first company in the world that seeks innovative ideas of using electromagnetic suspension for advertisement, exhibition, and gifts. Figure 1.1 is an electromagnetic suspension lamp. A permanent magnet will appeal the lamp, while coils in the controller will reject it. Therefore, the lamp can be suspended vertically with a visible gap. However, for all designs the rotation of the suspension object is not controllable, i.e., now we are still not able to rotate the lamp using controlling system. It is a free body in the air subjected to all the turbulence such as air flow. In order for a better exhibition effect, a controllable rotation is required, which inspired this project.

Figure 1.1: Electromagnetic suspension lamp.[2]

The project "Controlled Rotation of Electromagnetically Suspended Object" is sponsored by DeepMag Tech. The project aims to achieve a controllable angular rotation of the suspension of fixed-point suspension equipment, including upper and lower suspension modes. The goal is expected to be achieved via mechanical and controller design of motor and electromagnetism.

The project seeks an approach to achieve controllable rotation at 15 mm suspension height. The term "controllable rotation" is defined as precise rotation angle as well as both clockwise and anti-clockwise rotation. More details will be provided in the following Engineering Specification section.

The major challenge of this project is that there is no directly relevant research or literature online. Based on the literature review, there are two relevant technologies. The first one is spin-stabilized magnetic levitation. The whole system consists of two parts - a magnetic base and a spinning magnetic top [1]. Magnetic force balances gravity and the angular momentum stabilizes the rotor. The second is stepper motor. The rotor is in the middle with several electromagnet around it. The electromagnet is activated one by one, attracting the nearest teeth to the alignment position. Thus the rotor moves step by step.

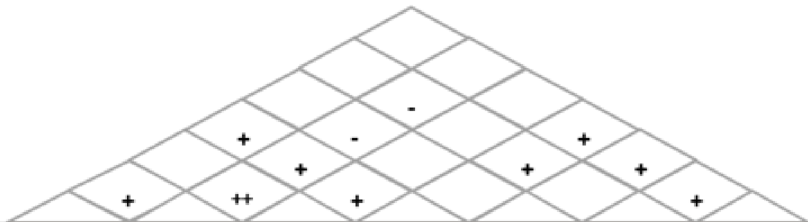
Two relevant produces are selected to be the standard for the benchmarking, electromagnetic suspension lamp and stepper motor. For electromagnetic lamp, it has a stable suspension with a noticeable gap (around 15 mm) and a low power supply [2]. However, there is no control of rotation and it has a poor disturbance resistance. Stepper motor provides a precise control of rotation up to 3.6 degrees [3]. The disadvantages are that there is no vertical electromagnetic suspension and the gap between rotor and stators is too small.

2 Customer Requirements and Engineering Specifications

2.1 Customer Requirements

With the rotation control system of the electromagnetically suspended object, the final prototype should be presented as the electromagnetic suspension lamp with controlled rotation. The customer requirements are specified as following.

1. **Steady Suspension and visible gap**. The object in suspension should remain its vertical stability. Since the rotational control system is an additional function of the electromagnetic suspension system, it is important for the additional control system not to disturb the suspension system itself. Therefore,



Weight	Engineering Specifications → / Customer Requirements ↓	suspension gap	particle weight	particle radial diameter	power	steady state angular speed	rotation angle precision	cost	Electromagnetic suspension lamp	Electromagnetic suspension globe tellurion
10	suspends particles	9	9	9	3			1	5	5
10	stablizes vertically	9	3	3	3	3	1		5	5
7	visible gap	9			3			1	5	5
7	rotates with commands		3	3	3	9	9	1	1	1
7	controllable rotating rate		3		1	9	9		1	1
4	resists to disturbance	3	9			9	9	3	3	2
7	rotates clockwise or counter-clockwise					9			2	2
7	defined rotation angle			3			9	3	1	2
3	look good	9		3		1	1		4	4
3	inexpensive							9	3	3
	Measurement units	mm	g	mm	w	rad/s	°	¥		
	Target value	**15**	**200**	**50**		**0.314**	**3.6**	**3000**		
	Benchmark values		200	50			3.6	100		
	Absolute importance	39	27	21	13	40	38	18		
	Relative importance %	19.90	13.78	10.71	6.63	20.41	19.39	9.18		
	Priorities rank	2	4	5	7	1	3	6		

Figure 1.2: Quality function Deployment for the Design Problem.

the object should remain vertically stable for all time. And for aesthetic purpose, there should be a visible gap between the suspension object and the suspension control panel.

2. **Smooth Rotation**. The suspended object should rotate smoothly, which means no obvious sudden movement due to control signals. This requirement is also for aesthetic purpose because this controlled rotation suspension system will be put into market first as a presentation tool for company logos.

3. **Constant angular speed**. The suspended object should maintain a constant rotation speed, which is specified by the customer.

4. **Specific rotation angle**. This is an additional requirement based on the previous one. As required by the customer, the suspended object should rotate from a stop, by a specified angle and stop. This is required because the system may be used for video recording.

5. **Clockwise/counterclockwise rotation**. The suspended object should be able to rotate at both directions.

2.2 Engineering Specifications

The product we are going to design should have a visible suspension gap, with a controllable rotational function. Therefore, we set up several major engineering specifications and target values to achieve these requirements.

1. **Suspension Gap**. In order to suspend the object, A suspension gap is required. The suspension gap has a fixed value of 15 millimeters, which is required by the sponsor. Such a distance is visible and enhances the aesthetic feeling. On the other hand, due to the existence of gap, the difficulty of electromagnetic rotational control will be greatly increased.

2. **Object Weight**. The weight of the object is under 200g. One clear point is that the magnetic force will balance with gravity. The higher the mass is, the greater magnetic force we will need. Therefore the object weight directly determines the scale of current in the coils during further design, which can generate magnetic forces.

3. **Steady-state angular speed and precision**. This is the most important element, which corresponds to most of the rotational requirements. Also, between different engineering specifications, the angular speed is the one correlated to every other specification. When setting the angular speed at a specified value, the measured angular speed of the object should be within $\pm 1^\circ$/s range of the reference value.

4. **Rotation angle precision**. For our design, we hope to control the rotational angle as precisely as possible. Since the background knowledge is about stepper motor, after searching for parameters of them, we set the precision angle as 3.6 degrees. Here with the suspension gap of 15 mm, It will not be easy to hold a very precise angle.

5. **Cost** The cost is estimated at 3000 RMB for the entire prototype-developing process. We consider that some magnetic materials may be expensive. Also, the project is research-related. We will try our best to achieve the goal with the least cost.

6. **Object Radial Diameter**. The diameter of the object will determine the dimension of the controller for aesthetic reason. The diameter is about 50 millimeters, close to that of the electromagnetic suspension lamp. This value is not strictly constrained. As long as the suspension control is not affected, it can be increased or decreased to a certain extent.

According to the customer requirements and engineering specifications, we made the qualification function deployment. There are two main functions, suspension and rotation. The former one is more represented by the specification of suspension gap, and the later one is more related to the important parameter, steady-state angular speed. After ranking the importance of each engineering specification, we found that the steady-state angular speed is the most significant, since it directly determines the rotational function we are going to design, and there are very limited existing related products for us to refer to. Meanwhile, all the rotational control functions are based on the 15mm suspension gap, which has the second priority.

Functions	Options		
Steady rotation	EM field control	Aerodynamic force	Gyroscope
Rotation feedback	Angular speed sensor	Photoelectric gate	Magnetic sensor
Control scheme	PID control	Open loop control	Remote control
Structure	Boards assembly	3D-printing	Milling and drilling
Power supply	Battery	Wireless power supply	

Table 3.1: Morphological chart

3 Concept Generation

Our design is base on an existing product - electromagnetically suspended lamp. The lamp is upper suspended, subject to three major forces: magnetic force from permanent magnet, magnetic force from electromagnet, and self gravity. Figure 3.1 shows concept diagram of the design.

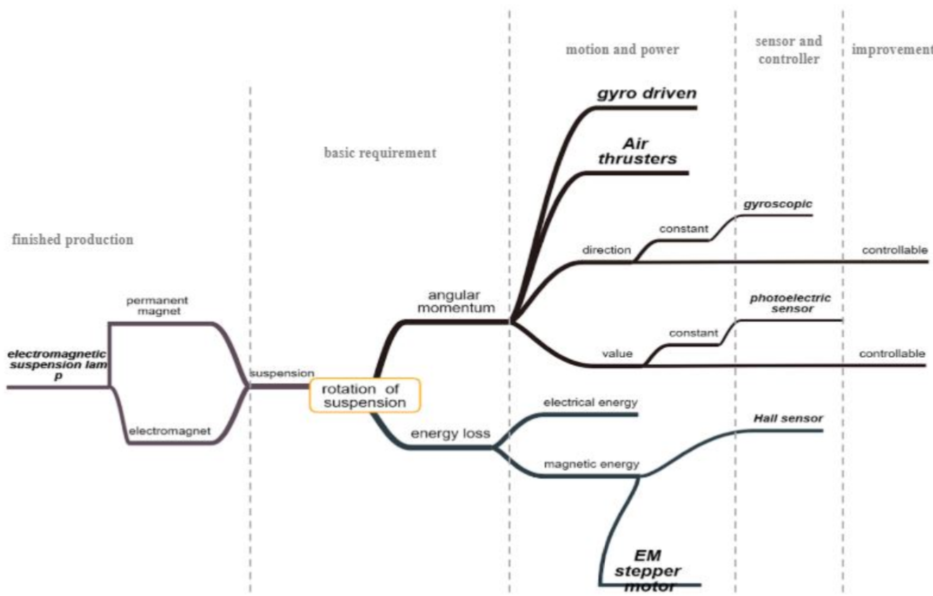


Figure 3.1: Concept diagram of the electromagnetic suspension lamp

The basic requirement of this project is to add a rotation control module to the suspended lamp so that the rotation can be controlled. There are two major challenges: changing the angular momentum of the suspended object and preventing energy loss due to air friction.

One solution for angular momentum control is to use a gyro to drive the system. As the object is suspended and there is no vertical torque, the angular momentum converges. The gyro is controlled by a motor and its rotation in one direction will cause the rest of the system to rotates in the opposite direction. By controlling the angular velocity and acceleration of the gyro, the suspended object can achieve controllable rotation. The other potential solution is using air thrusters. Two thrusters can be attached to the suspended object, generating a force couple which provides the torque. The angular acceleration is controlled by two thrusters. Furthermore, a gyroscope can be used to detects the direction of the angular momentum and a photoelectric sensor can be applied to monitor the angular velocity. With the sensors, the system performance data can be collected so that we can improve the system by modifying parameters.

There are five major sub-functions in our design: steady rotation, rotation feedback, control scheme, structure, and power supply. The options for each function realization are listed in Table 3.1. To achieve steady rotation, three potential solutions are selected. Aerodynamic force corresponds to the air thrusters and gyroscope corresponds to gyro driven. Another solution is electromagnetic field control, by activating the electromagnet step by step, attracting the rotor to move step by step, similar to the step motor. To monitor the state of the object, a feedback system is required. Angular speed sensor and photoelectric gate can be used to record the object rotation while magnetic sensor can be applied to keep track of the suspension state of the object. PID control, open loop control, and remote control are potential options for the control scheme. As for the rotation module structure, it is built under the combination of acrylic board assembly, 3D-printing and milling/drilling. Finally, there are two options for power supply, simply use a battery or use wireless power supply.

4 Concept Selection Process

In this section, we will first analyze the project description, engineering specification as well as the customer requirement to determine the system and subsystems that are involved in the design problem. Then for each subsystem, we will provide several solutions and assess the advantages and disadvantages of the solutions qualitatively and quantitatively using the scoring matrices. Finally, we will give a justification of the final choice of the design concept.

4.1 System and Subsystem Analysis

To realize the overall system of the controlled rotation of electromagnetically suspended object, two major subsystems are required. The first one is the **suspension system** and the second one is the **rotation control system**.

The suspension system controls the vertical stability of the suspended object. Since the suspension control system is an analog circuit module that is provided by the sponsor, we only need to adjust the potentiometer in the analog circuit so that the suspension system can provide an adequate amount of force to lift the object within a certain mass range.

The rotation control system is the major design problem. Dynamically, it is a system that transfers electric power into the rotational kinetic energy of the suspended object. In order to change the rotational kinetic energy, the system should be able to generate torque and change the angular momentum of the suspended object. Since the rotation is not free but controlled, an microcontroller and sensors are involved to provide accurate control signal to the system.

In addition to the two major systems, we also need to consider the energy supply method. Since the object is suspended and needs to rotate, the suspended part should be "self-sufficient" in the perspective of energy supply.

After separately defining the functions and identifying certain limitations of the subsystems, we also considered the potential interference between the subsystems. For example, how will the rotation control system interfere with the suspension system? Will the structure design of the rotation control system affect the stability of the suspension system? Will the weight of the rotation control system cause failure to the suspension system?

4.2 Subsystems and Solutions

4.2.1 Suspension System

As mentioned in Section 4.1, the suspension control system is an analog circuit provided by our sponsor DeepMag. It utilizes a Hall sensor to detect the strength of the magnetic field of the permanent magnet that will be integrated within the suspended object and correspondingly provide a varying electric current to generate a magnetic field that will counterpart the gravity of the object so that the object can be suspended. Also, in order to protect the object, once the power is off, the object will be attracted to the suspension panel instead of falling down.

In order to be compatible with the suspended object, we need to adjust the potentiometer configuration in the analog circuit accordingly to support the suspended object within a certain mass range. In order to maintain the stability of the suspended object, the current in the analog circuit should be at minimum to protect the electronics as well as to provide maximum supportable mass range.

4.2.2 Rotation Control System

In order to transfer electric power into rotational kinetic energy of the suspended object, we need a system that can generate torque or change the angular momentum of the suspended object. Three solutions are generated based on different principles.

1. **Electromagnetic Force with Stepper Motor Model**

   The first concept is based on generating a direct torque on the suspended object to change its angular speed (Figure 4.1). The rotation control system and the suspension system are both located in the stationary part.

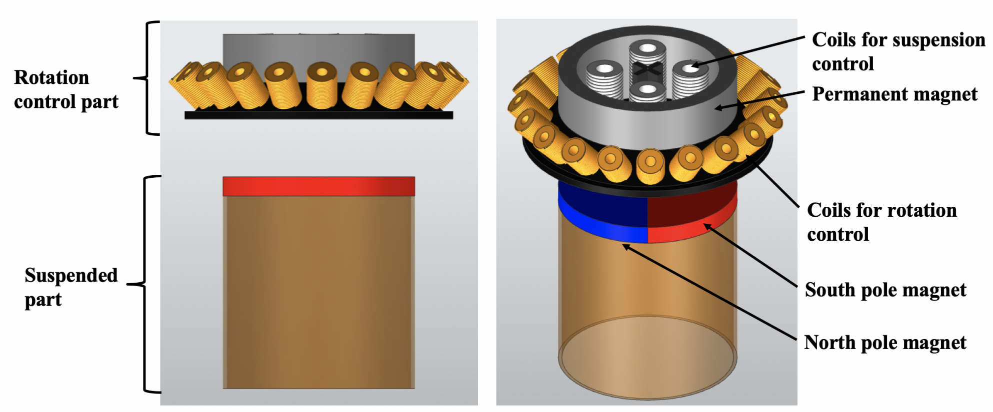


Figure 4.1: Rotation control system concept: electromagnetic force integrated with the model of a stepper motor

   On the top of the suspended part, a magnet with clear N and S polar difference is integrated. The coils for rotation control are located around the upper stationary part. When the currents in the rotation control coils change, the generated magnetic field can attract the magnet on the suspended part. The multiple small coils are designed so that they can attract the suspended magnet step by step, similar to a common stepper motor.

   Advantage: Simple rotation angle control

   By locating multiple solenoids on the upper stationary part, it is easy to control the absolute rotation angle of the suspended object. By maximizing the magnetic field generated by the corresponding solenoid, the suspended object can be attracted to the precise position.

   Disadvantage: Interference with vertical magnetic field

   Since the rotation control solenoids generate additional electromagnetic field during operation, it is likely that the magnetic field generated by rotation control solenoids interferes with the magnetic field generated by the suspension control system. Since the superposition principle applies to the magnetic field, it is therefore likely that the new magnetic field cannot support the suspended object steadily.

   Disadvantage: Rotation discontinuity

   Since the torque is generated by varying the current in the rotation control coids one by one, this control method is analogous to a stepper motor. Due to the constrained diameter of the suspended object as well as the manufacturing ability, we cannot reduce the size of the solenoids and consequently increase the number of the single solenoids to a great extent because it can contribute to too complicated control-related electronics and programming. For example, the wiring of the circuits can take up too much weight. Or there can be inadequate signal pins to control on the microcontroller. Therefore, the number of solenoids are constrained as well, which can contribute to the discontinuity of the attractive force to the magnet on the suspended part, resulting in discontinuous rotation.

2. **Gyro-based Rotation Control**

   The second concept is based on angular momentum conservation principle. The rotation control part is integrated with the suspended part. For the upper stationary part and the suspended part, both are integrated with permanent magnets, which are for the suspension control system. In the suspension part, there are a high speed motor and a flying wheel (Figure 4.2).

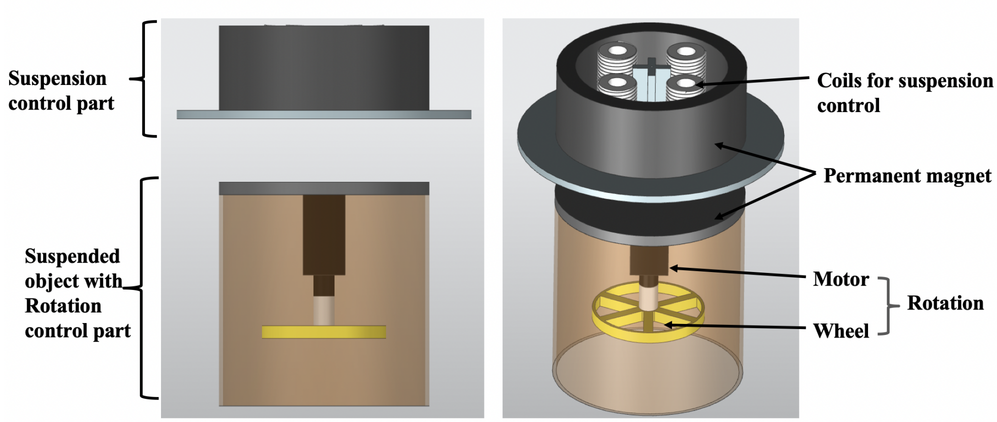


Figure 4.2: Rotation control system concept: gyro control based on angular momentum conservation principle.

   Consider the suspended object as a whole, without external strong interference which can generate significant torque, we can consider the angular momentum of the whole system conserved. Therefore, when we adjust the angular momentum of the flying wheel, the angular momentum of the upper suspended part can be changed as well. Therefore, the rotation speed of the suspended object can be changed by adjusting the rotation speed of the flying wheel. Instead of providing external torque, the angular momentum of the suspended part, excluding the flying wheel, is changed based on the conservation principle.

   <u>Advantage: Smooth rotation</u>

   Since the concept is based on angular momentum principle, once the flying wheel begins to rotate at certain speed, the suspended part, excluding the flying wheel, can naturally rotate at a corresponding speed. Since the rotation of the flying wheel is stable and smooth due to the high speed motor, the rotation of the suspended object can be smooth as well, provided that the suspended object has gained proper balance vertically.

   <u>Advantage: Relatively simple control</u>

   Referring to one of the customer requirements that the suspended object can rotate at specified angular speed, the rotation control system should be able to adjust the rotation speed of the suspended object by changing the motor speed. Theoretically, with an angular speed sensor, we can use a "bump test" to estimate the parameters for the PID control loop. Once with the PID control parameters, it would be relatively simple to maintain the specified rotation speed.

   <u>Disadvantage: Long time integration error</u>

   When using PID control, calculations on the differential term as well as the integration term would have errors once the operation time is long, which can contribute to an decrease in the accuracy of the rotation speed. More importantly, one of the customer requirement is specified rotation angle. Integration on the angular speed data to calculate the rotated angle can have errors as well.

Disadvantage: Friction torque causing angular momentum loss

During operation, small interference such as air friction as well as external small disturbances from surroundings can all cause angular momentum change of the whole suspended system. Although the integral term of the PID control can compensate the angular momentum loss to a certain extent, the motor has a maximum rotation speed. Once the required rotation speed can not be achieved physically by the motor, the specified rotation angular speed cannot be achieved consequently.

3. **Air Jet Torque Generation**

   The third concept is also based on the direct generation of torque. Similar to the second concept, the rotation control part is integrated with the suspended object, which means that the weight of the rotation control part is constrained by the suspension weight range of the suspension control system (Figure 4.3).

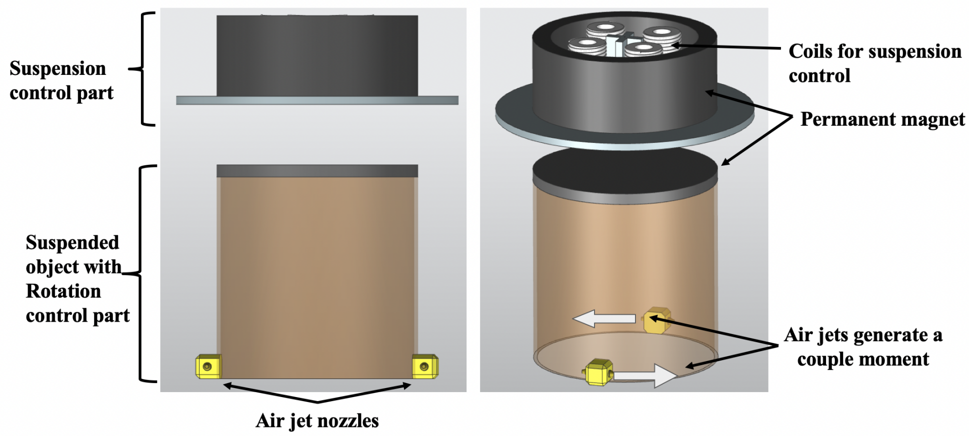


Figure 4.3: Rotation control system concept: air jets torque generation.

Two small air jets are located on the opposite side of each other and together they can generate a torque to change the angular speed of the object. In order to control the rotational speed, the propulsion of the air jets should be changed accordingly.

Advantage: Smooth rotation

Compared to the concept based on the stepper model, the air jet concept can maintain rather smooth rotation of the suspended object if the jet propulsion directions are aligned with each other and positioned accurately.

Disadvantage: Air jets positioning difficulty

Although theoretically, air jets that are positioned perfectly opposite of each other and aligned in the propulsion direction can provide torque in the desired direction, the positioning of the air jets during manufacturing process can be difficult. If the propulsion directions of both air jets are not aligned, a permanent biased torque direction can cause instability to the vertical stability as well as the rotational stability.

Disadvantage: Clockwise and counterclockwise direction rotation

Using two air jets in the configuration shown in Figure 4.3, without extra mechanism, it is difficult to change the propulsion direction if the specified rotation direction suddenly changes.

4.3 Decision Matrix

4.3.1 Engineering Specifications vs. Criteria

In order to construct the decision matrix to select the most feasible concept for the rotation control system, we first determine five criteria on the rotation control system and relate these criteria to the previously determined engineering specifications. The relevance is shown in Table 4.1.

Specifications	**Criteria**
Steady-state angular speed	**Smooth Rotation**
Suspension gap Object weight	**Interference with vertical suspension**
Electric power Maximum cost	**Control System Simplicity**
Steady-state angular speed Suspension gap Object radial diameter	**Appearance**
Rotation angle precision	**Control Accuracy**

Table 4.1: Engineering Specifications vs. Criteria

4.3.2 Weight Factor

The weight factor of the five criteria determined in Table 4.1 is determined in Table 4.2.

As we can see from Table 4.2, the weight factor for each criterion is determined by weighting over two criteria at a time. By comparing their importance, the more important criterion is given a point of 1. The weight factor can then be determined after weighing all the criteria.

The most important criteria for the rotation control system is ***Interference with vertical suspension***, followed by ***smooth rotation***. This ranking of criteria is rational because since the rotation control system is an "additional" function of the suspension system. It is important that the control of rotation does not disturb or dysfunction the original suspension control system. After the realization of no or small interference with vertical suspension, smooth rotation is the fundamental requirement of the rotation control system.

4.3.3 Decision Matrix

After deciding the weight factors of the criteria, we can evaluate each solution for the rotation control system referring to the criteria (Table 4.3). Since the criteria are qualitative descriptions of the rotation control system, we use experience value such as "High", "Medium" and "Low" to assess the system.

Criteria	Rotation	Interference with vertical suspension	Control System Simplicity	Appearance	Control Accuracy	Row Total	Weight Factor
Smooth Rotation	-	0	1	1	1	3	**0.27**
Interference with vertical suspension	1	-	1	1	1	4	**0.36**
Control System Simplicity	0	0	-	1	0	1	**0.09**
Appearance	0	0	0	-	1	1	**0.09**
Control Accuracy	0	0	1	0	-	1	**0.09**
						11	**1**

Table 4.2: Determining weight factor of the five criteria for the rotation control system.

Design Criterion	Weight Factor	Unit	EM Stepper Motor			Gyro Control			Air Jets		
			Value	Score	Rating	Value	Score	Rating	Value	Score	Rating
Smooth rotation	0.27	Exp	Medium	4	1.08	High	9	2.43	Medium	7	1.89
Vertical Interference	0.36	Exp	High	1	0.36	Low	8	2.88	Low	7	2.52
Control system simplicity	0.09	Exp	Low	2	0.18	High	6	0.54	Medium	4	0.36
Appearance	0.09	Exp	High	8	0.72	Medium	6	0.54	Low	4	0.36
Control accuracy	0.09	Exp	Medium	5	0.45	High	8	0.72	Low	4	0.36
Total					2.79			**7.11**			5.49

Table 4.3: Rotation Control System Design Matrix

From Table 4.3, the ***gyro-based control system*** has the highest score. Therefore, we decided to use the gyro-based concept for the rotation control system.

4.4 Final Choice and Justification

After relating the engineering specifications to criteria specific to the rotation control system, evaluating the weight factor of the criteria and completing the decision matrix, our final choice is the ***gyro-based rotation control system***.

The rationalization through the method of decision matrix generate the five criteria from the perspective of engineering specifications. Next we will further justify the decision by explaining the advantages of the concept, referring to the **customer requirements**:

1. Steady suspension and visible gap:

   This requirement requires the rotation control system only generates minimum disturbance to the vertical suspension control system. For the gyro-based rotation control, no external torques are required to change the angular speed of the suspended object. Therefore, potential interference by the external control torques to the vertical suspension system is eliminated.

   In order to stabilize the suspension, we only need to consider the structure design as well as the electronics placement to balance the suspension object so that the center of mass is still inline with the center of the suspension control panel.

2. Smooth rotation:

   Since the angular speed of the suspended object (excluding the flying wheel) is changed indirectly by changing the angular momentum, which is changed by the angular speed of the flying wheel. Based on the angular momentum conservation principle, the relation between the angular speed of the suspended object (excluding the flying wheel) and the angular speed of the flying wheel is determined by the rotational inertial of the two object, which stay constant during operation. Therefore, as long as the angular speed of the flying wheel is stable, the stability of the angular speed of the suspended object is intrinsically stable. Therefore, the rotation of the object can be smooth.

   That is to say, based on this concept, we do not need to consider the execution stability of the torque to change the angular speed of the suspended object, which simplifies the control process as well as the manufacturing process significantly.

3. Specific and constant angular speed:

   In addition to the previous requirement, the suspended object is required to maintain a specified angular speed. This can be achieved using an angular speed sensor and the PID control theory. In short, we treat the angular speed sensor data as the output of the system, which will be compared to an input reference angular speed (the specified rotation speed). Then we will use PID control theory to calculate the desired motor rotation speed to maintain the constant rotation speed. This is further illustrated in Section 5.5.

4. Specific rotation angle:

   In order to control the suspended object to rotate by a specified angle, we can implement the PID control once again to maintain the suspended object's stability at angular speed of zero. Apart from that, since we can control the object to rotate at a rather small but constant speed, the integration of the angular speed data can be used to keep track of the rotation angle.

   Compared to the other two torque generation concept, in order to stop the rotation, a reverse torque should be provided, which can easily cause fluctuation at the angular speed zero position.

5. Clockwise/counterclockwise rotation direction:

   The suspended object is expected to be able to rotates in both clockwise and counterclockwise directions. The rotating direction of the object is always opposite to the flying wheel. Therefore, we only need to change the rotation direction of the flying wheel to reverse the rotation of the object.

In conclusion, the choice of ***gyro-based concept*** for rotation control system is justified because the concept simplifies the realization process of customer requirements and is achievable based on our current manufacturing ability and resources.

5 Selected Concept Description

5.1 Engineering Design Analysis

Our final choice is to use gyro-control. The physical principle is conservation of angular momentum. Since the objective of the design is to rotate about the vertical axis, we only need a flying wheel which can rotate around the same axis. Next we will provide the theoretic calculation.

Assume the whole body is rotating at a constant angular speed ω_1 with respect to the ground, and the moment of inertia of it is I_1. The flying wheel, together with the coupler, is rotating at the speed ω_2 with respect to the ground, and its moment of inertia is I_2.

From the conservation of angular momentum, which is calculated as $H = I\omega$, when there is no external torque, the system's total angular momentum should be constant, i.e.

$$\sum H_i = \sum I_i \omega_i = \text{const}$$

where i indicates the ith part of the system. In this project, therefore, we have

$$I_1 \boldsymbol{\omega_1} + I_2 \boldsymbol{\omega_2} = \text{const} \tag{5.1}$$

or if we only consider the angular speed.

$$I_1 \omega_1 = I_2 \omega_2$$

The second equation comes from relative motion. Since the motor is also fixed on the suspended object, itself is having an angular speed ω_1. Using relative motion, we are able to calculate the RPM of the motor:

$$\omega_2 - \omega_1 = RPM \tag{5.2}$$

This relative motion will be important if the speed is not large.

5.2 Final Design

Here, the detailed CAD drawings will be shown to the readers. Figure 5.1 gives the whole 3D CAD model. The upper part is the control system for suspension, this part will generate magnetic field that will suspend the object. The permanent magnet appeals the object, while the coils reject the object so that it will be stabilized. We use this control system from the electromagnetic suspension lamp, which is provided by our sponsor.

What we have designed is the lower part, which is the suspended part, where the rotational control system is included. Figure 5.2 is the three view diagram of the suspended part, with the overall dimensions. The greatest diameter occurs at the top, which is 60mm. The total height is about 61mm.

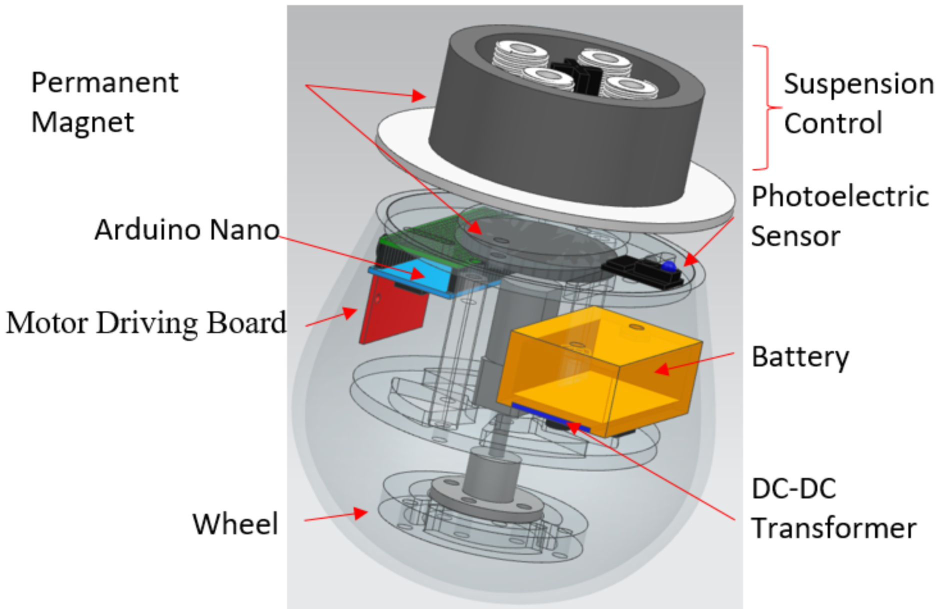


Figure 5.1: CAD model for the whole system.

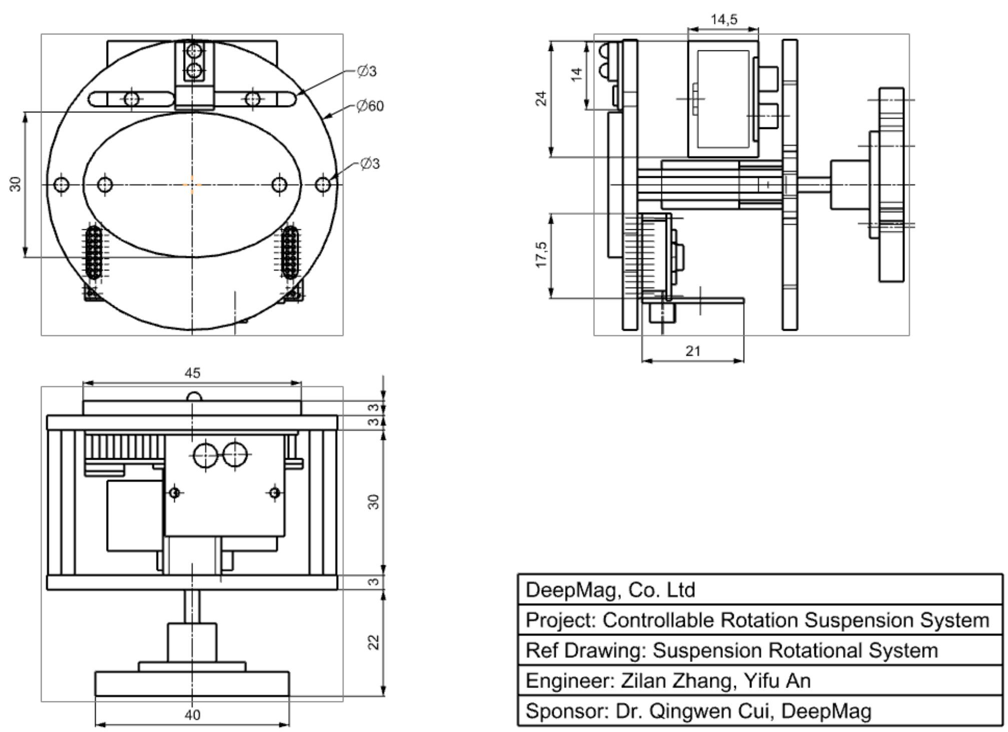


Figure 5.2: Three-view drawing for the rotational system.

Next, we will introduce the components of the rotational system. Since the suspension control system is already provided by the sponsor, we will not talk too much detail about it.

5.2.1 Two horizontal layers

There are two layers in the structure. The upper layer made of acrylic locates the magnet, which is used to suspend the object. Figure 5.3 is the drawing of it. The holes with diameter of 3mm are used for screws. The two horizontal sliders are used for locate the Arduino Nano and the motor driving board. The two vertical sliders are for battery adjustment. The mass distribution can be balanced by moving along the sliders.

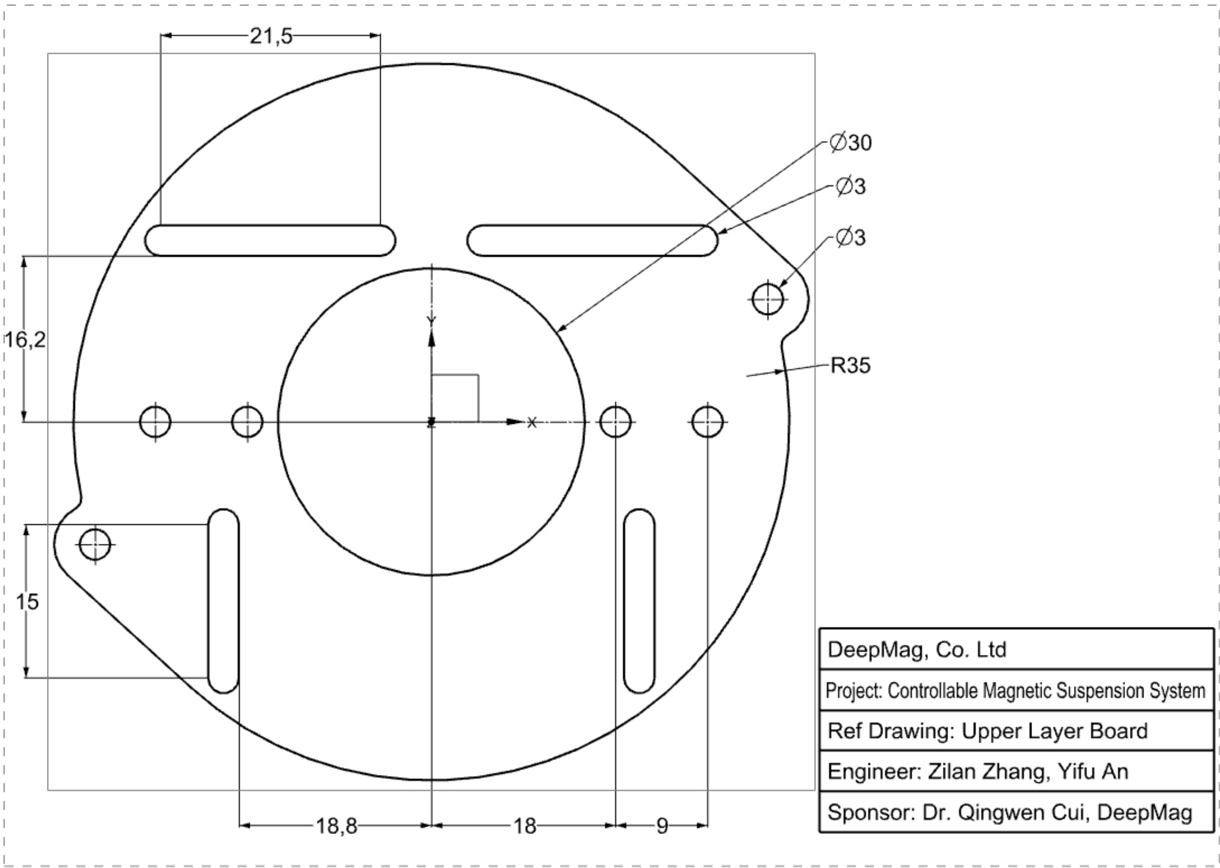


Figure 5.3: Drawing for the upper layer board.

The lower layer is also an acrylic board, shown as Figure 5.4. It is used to locate the motor. Again, the holes with diameter of 3mm are used for screws. Those with 1.6mm are for motor screws. To reduce the mass, some useless space are also cut.

The connection between the two layer boards are nylon hexagonal columns of 30mm. These three components, the upper and lower boards, and the columns, construct the basic structure of the suspended object.

5.2.2 Motor and coupler

In order to save space and mass, we choose the GM12-N20 micro motor to rotate the wheel. We can see the three-view diagram from Figure 5.5. The coupler connects the motor with the wheel, with an axis of 3mm diameter. We also give its two-view diagram.

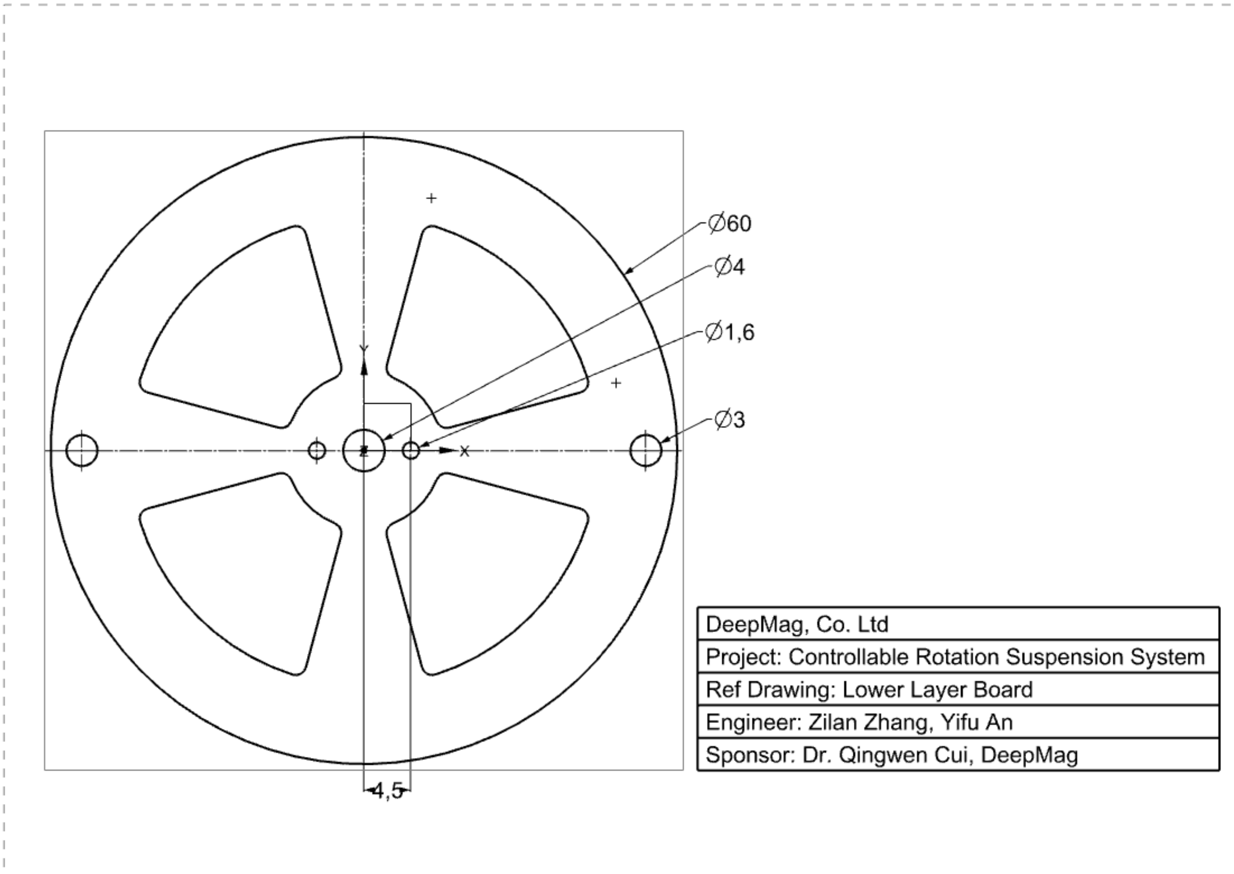


Figure 5.4: Drawing for the lower layer board.

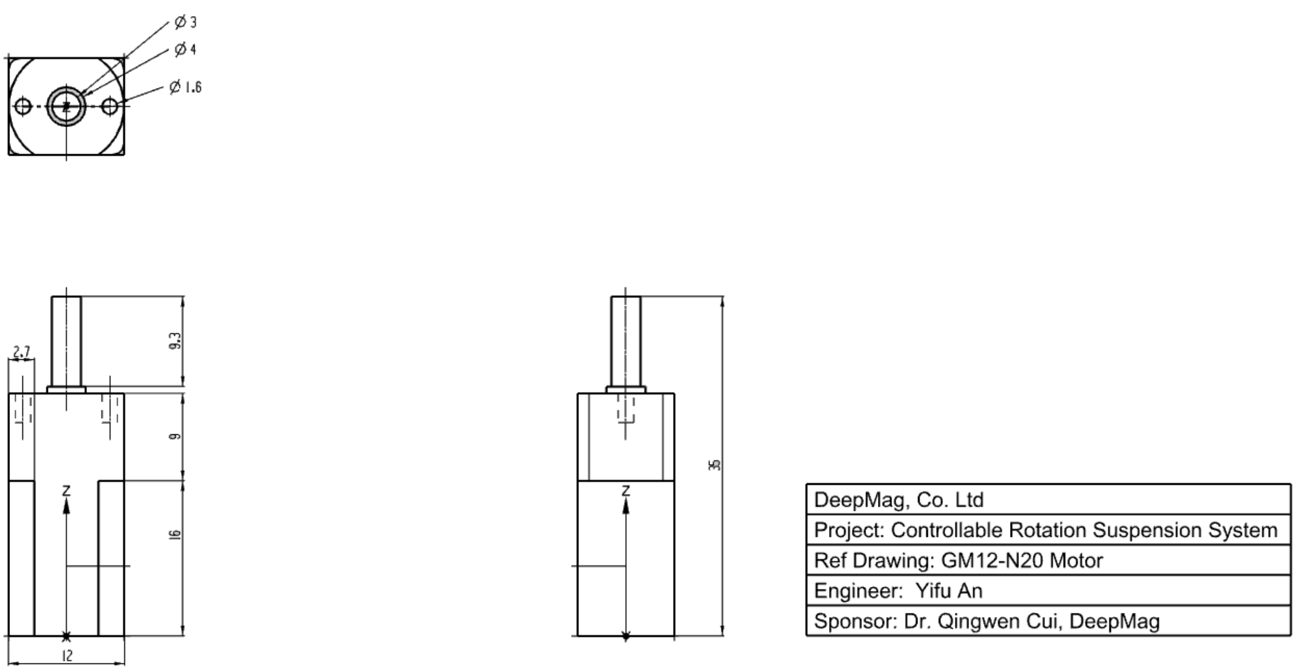


Figure 5.5: Three-view drawing for the motor.

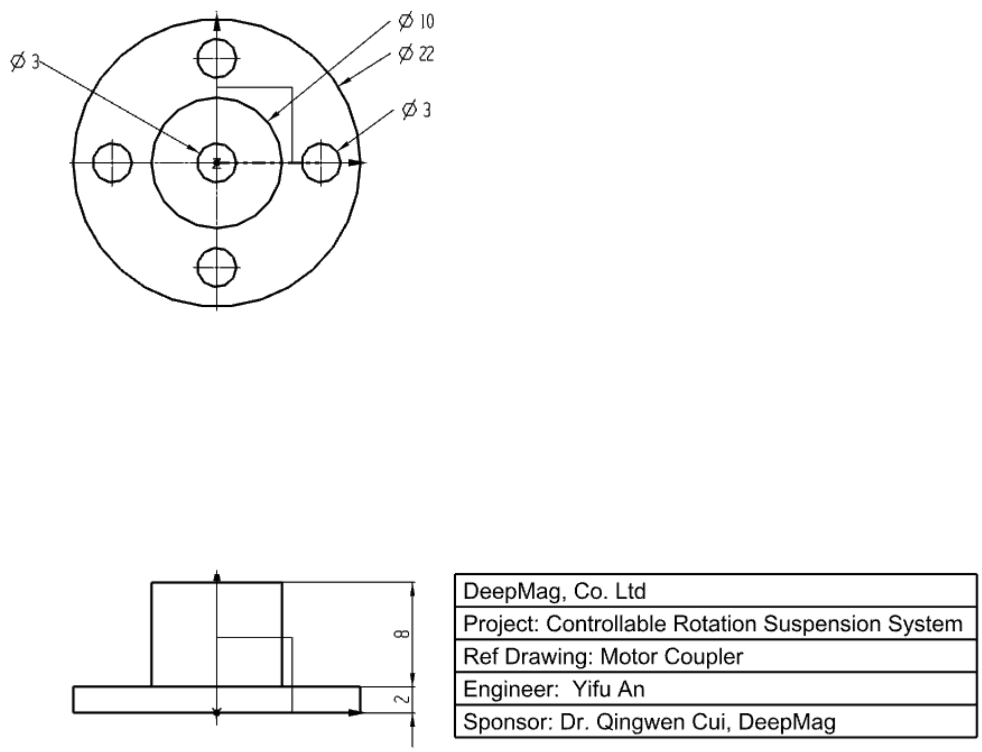


Figure 5.6: Two-view drawing for the coupler.

5.2.3 Flying wheel

The flying rotating wheel can generate a angular momentum to the whole object, so we hope to make it a little heavier. The acrylic board for the wheel is 5mm in width. The layout drawing is also shown in Figure 5.7.

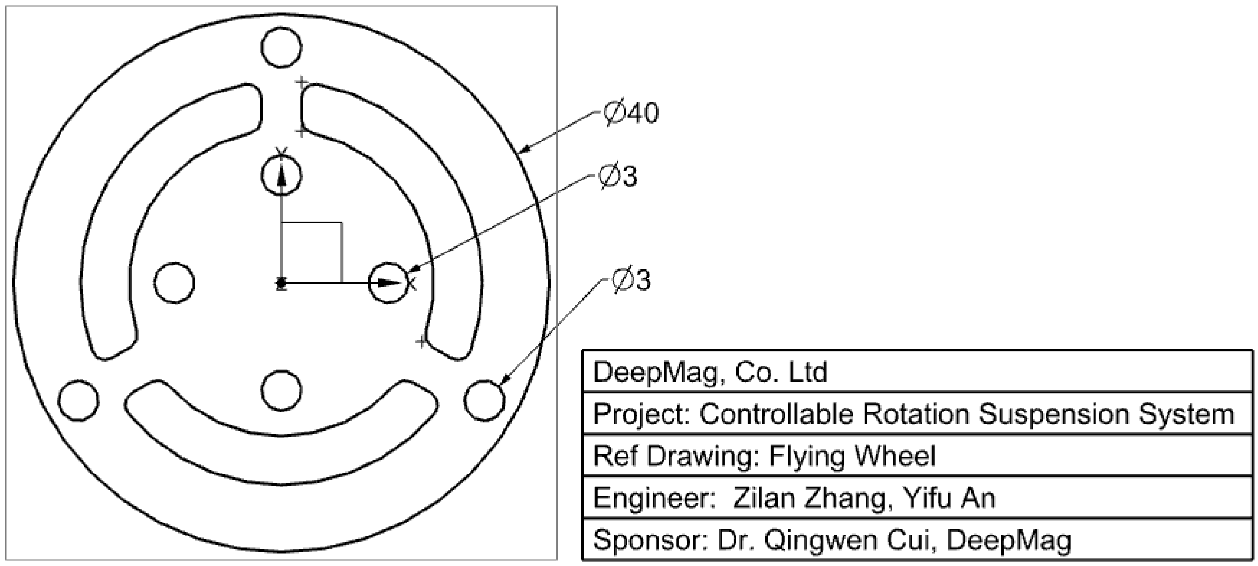


Figure 5.7: Drawing for the flying wheel.

5.2.4 Battery box

We have designed a box to place the battery. If you look at Figure 5.1, the orange one is the box. Currently the box is made by 3D printing. As is mentioned previously, the two holes on the box will connect the two horizontal sliders on the upper layer board. The groove on the other side of the box, with a small depth, is used to place the DC-DC voltage transformer. The Three-view diagram of the battery box is shown in Figure 5.8.

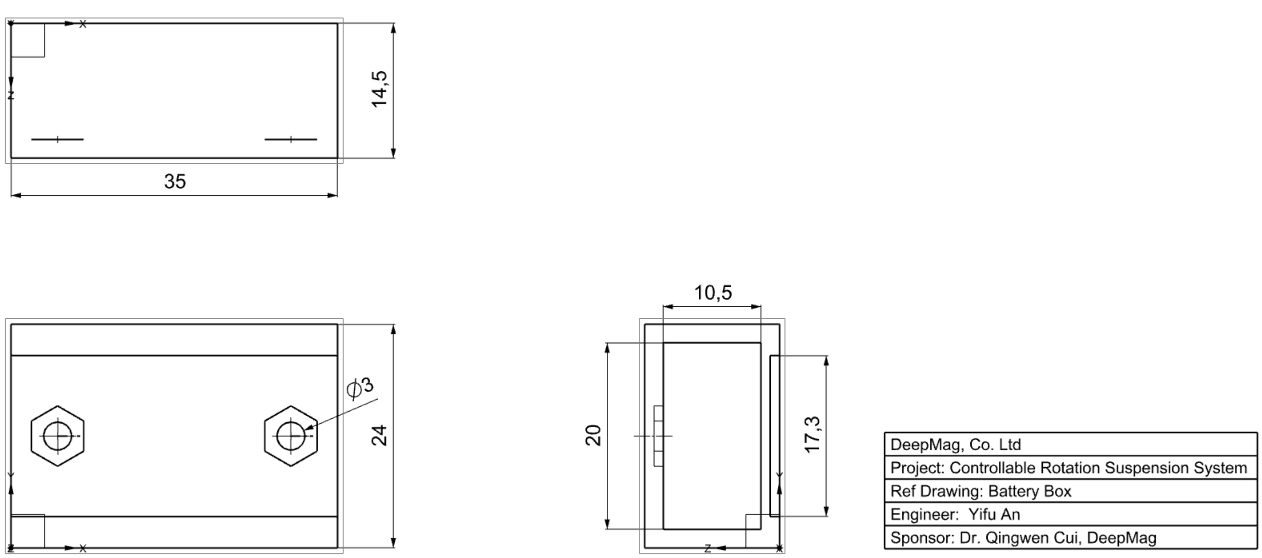


Figure 5.8: Three-view drawing for the battery box.

5.2.5 Arduino Nano and the chip board

By soldering wires on the chip board, which is the green part in Figure 5.1, we are able to connect the Arduino Nano, the blue one in the same figure, to the chip board. The chip board is then connect to the upper layer board using hexagonal columns, by digging two 3mm holes on it, shown in Figure 5.9. Also, we have the dimension of the Arduino Nano, shown in Figure 5.10

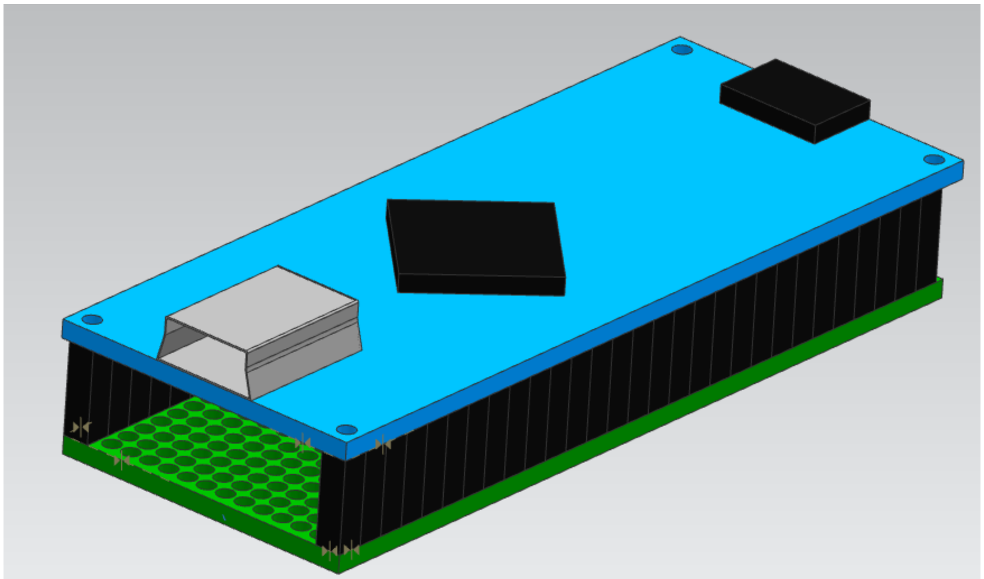


Figure 5.9: Arduino Nano and the chip board.

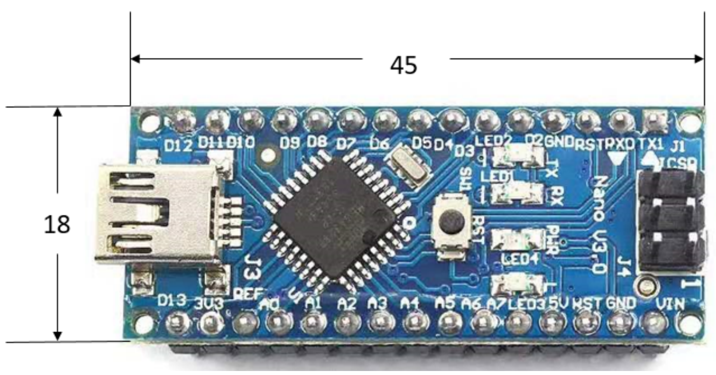


Figure 5.10: Arduino Nano.

5.2.6 Motor driving board

We need to save space, so the motor driving board is L298N micro board. In Figure 5.1, it is shown as the red part, which is located vertically sticking on the chip board, the dimension of it is given in Figure 5.11

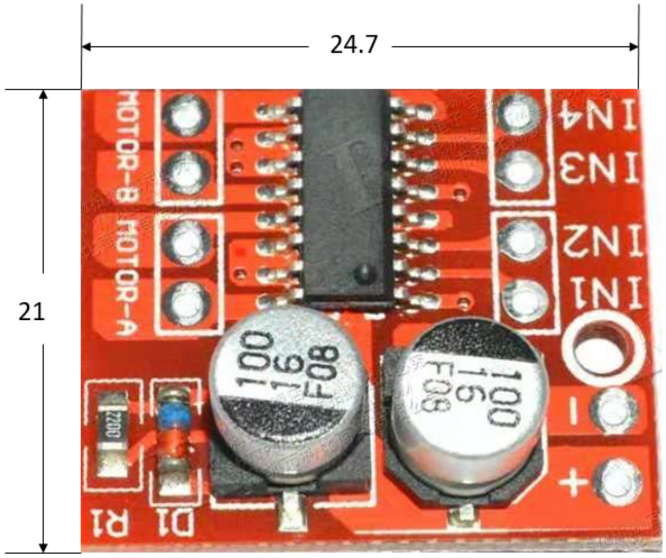


Figure 5.11: Motor driving board.

5.2.7 Outer shell

For a good aesthetic sense, we are going to design an outer shell for the whole system. This component has not been designed. It is expected to be as light as possible. 3D printing may be used.

5.2.8 Rb magnet

The Rb magnet is used to suspend the object. It is stuck in the 30mm diameter hole of the upper layer board. The magnet should be as horizontal as possible.

5.2.9 Decorating Shell

The outer decorating shell is only used for EXPO display, shown in Figure 5.12. It is connected to the upper layer board, with the two screws through the holes. For future products design, the shape can be changed.

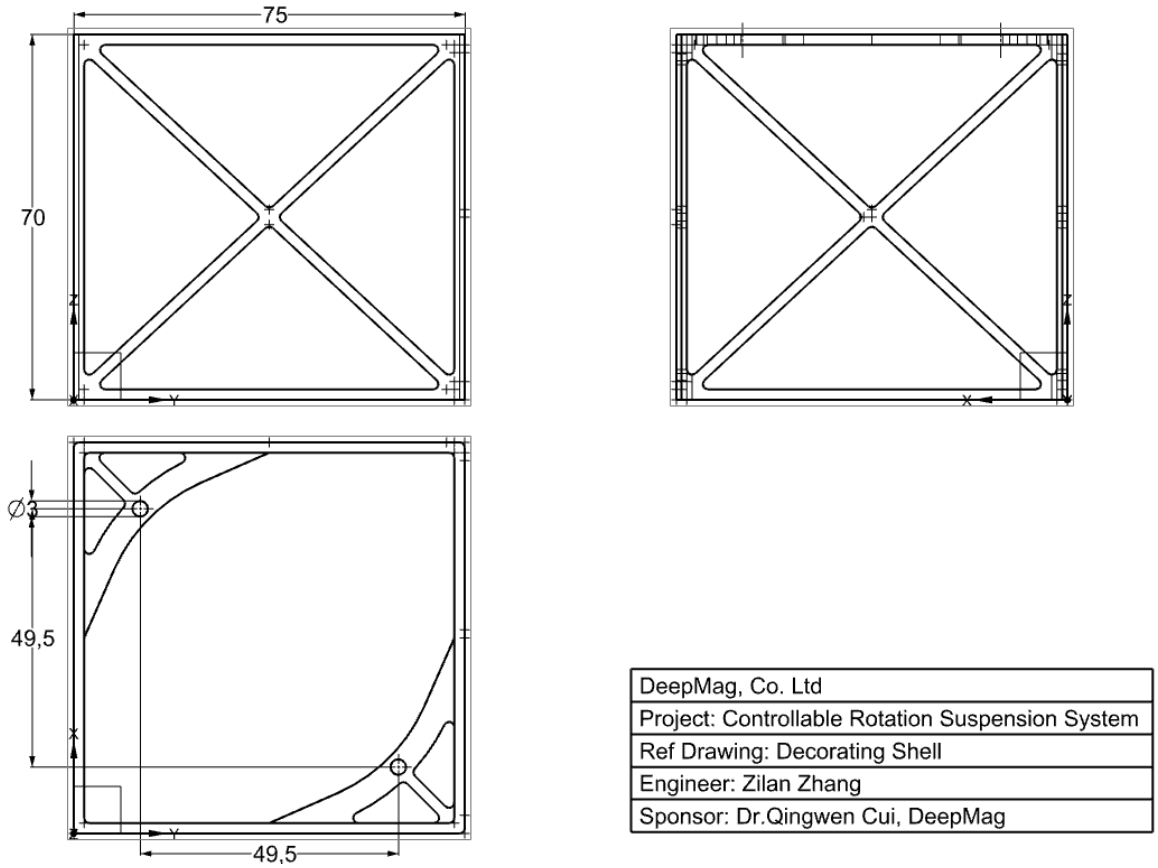


Figure 5.12: Decorating board.

5.3 Manufacturing Plan

5.3.1 Material and Manufacturing Method

To manufacture the components introduced in section 5.2, we will mainly use laser-cut acrylic boards and utilize the 3D-printers in the design and manufacturing lab. The printed material is polylactic acid. The components, their material and the manufacturing techniques are listed in table 5.1. Note that the components that have to be purchased are listed simply to correspond to the components discussed in section 5.2. We expect insubstantial errors in the dimensions of the components as a result of the manufacturing techniques. Laser cutting usually result in a 0.1-0.2 mm loss of material at the cutting edges due to the width of the laser beam; Errors in 3D-printing are unknown. However, tolerance is unimportant throughout the prototype. This is because we expect the mechanical loading on the structure to be minimal. Errors

Component	Material	Manufacturing technique
Horizontal layers	Acrylic	Laser cutting
Motor and coupler	N/A	Purchase
Flying wheel	Acrylic	Laser cutting
Battery box	Polylactic acid	3D-printing
Decorative Shell	Polylactic acid	3D-printing
Circuits	N/A	Purchase

Table 5.1: Manufacturing plan.

in dimensions will be compensated for by tightening the bolts, so the major source of manufacturing error, namely the material loss at the cutting edges, can simply be neglected.

5.3.2 PID Control System Realization

Although this project will eventually result in a manufactured prototype, one should realize that programming of the PID control is equally important. Figure 5.13 shows the block diagram for our control scheme of the angular position. The input is a specified angle, which is compared with the angular position feedback (as an integral of the angular speed) from the plant to obtain the error. The error is passed to an integrator and differentiator respectively and multiplied by the gains. The resulting values are added to the error multiplied by the proportional gain. The sum is then passed to the motor control board to determine the angular speed of the flying wheel in the next duty cycle. Thus, by carefully tuning the proportional, integral and derivative gains, we expect to achieve an elaborate dynamic balance. In order to get the PID control

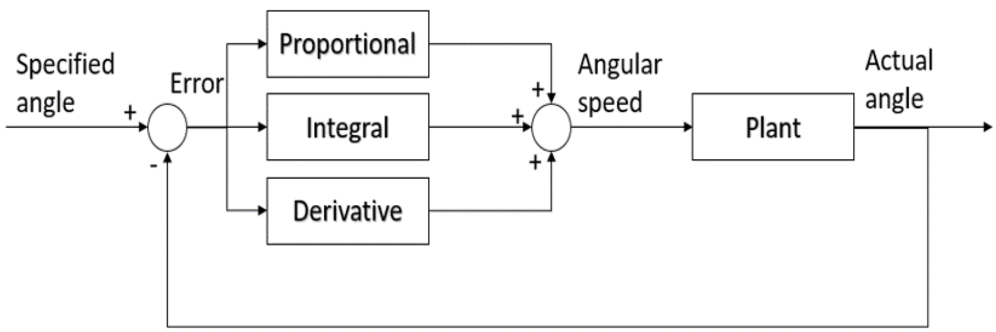


Figure 5.13: Block diagram for PID control.

parameters, we will implement a simple bump test. By changing the angular speed of the motor from zero to a certain value u, the suspended system will respond to the change. By recording the angular speed variation of the suspended object using an angular speed sensor and an SD module for data recording, we can get a $\omega - t$ diagram, where ω is the angular speed of the suspended object. Then by analyzing the diagram, we can get an estimation of the PID control parameters. Then by further fine adjustment of the parameters, we can maintain the suspended object to rotate at a constant and specified angular speed. The bump test code is shown in Appendix D.

After several try-outs, we decided to neglect the differential term in the PID control loop because the PI controller has already given good results and controls over the rotation speed of the object as well as the rotation angle. The detailed implementation code are shown in Appendix C. Note that the control parameters, $k_p,\ k_d,\ k_i$, are subject to change for different suspended objects.

5.3.3 Electronics Wiring

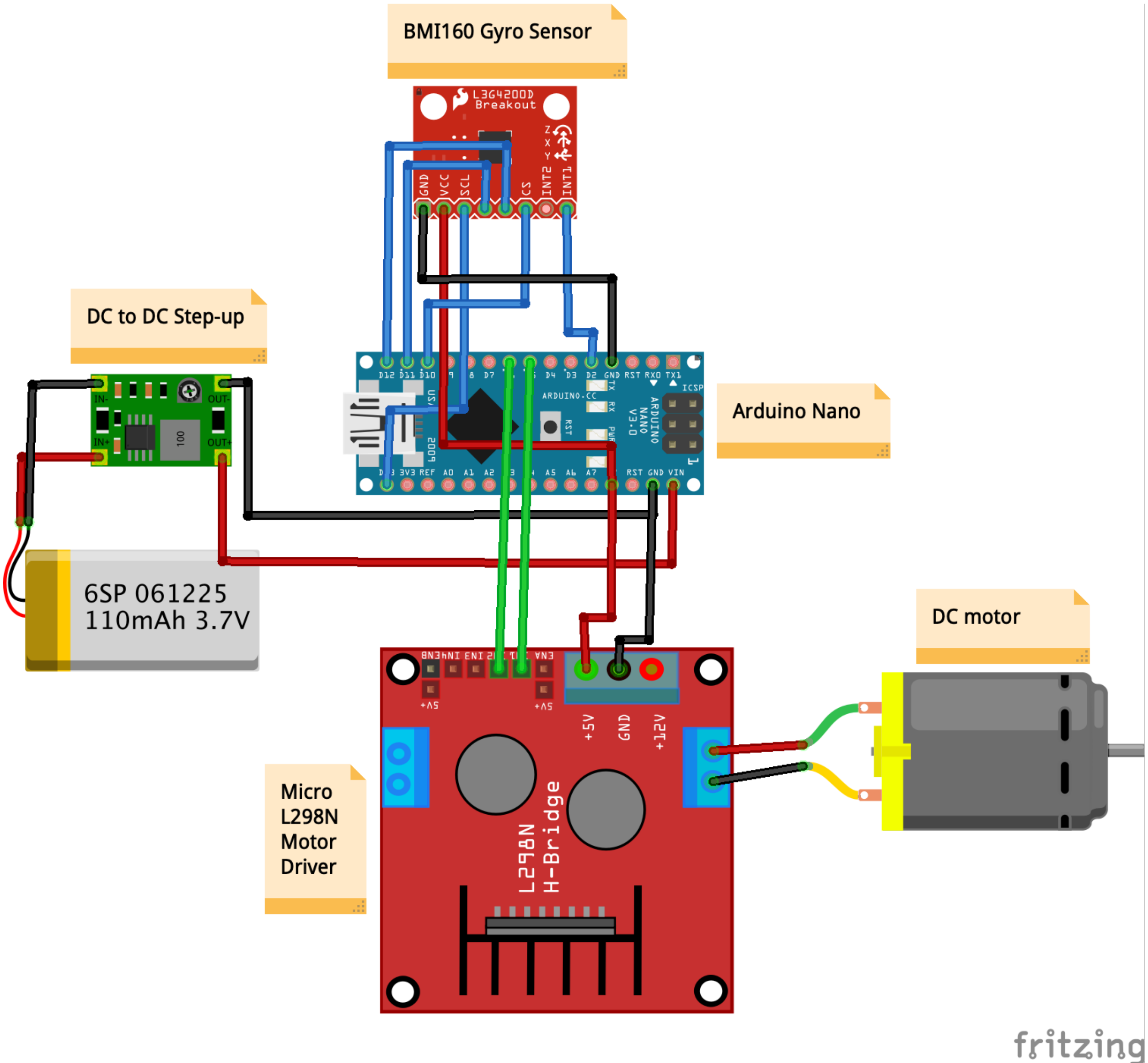
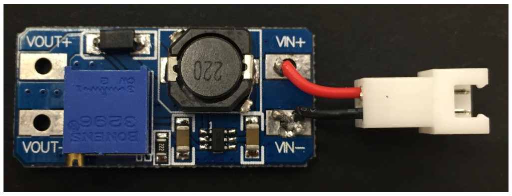


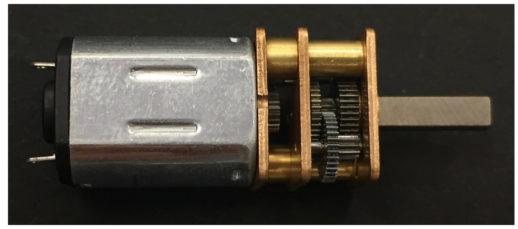
Figure 5.14: Electronic Wiring Diagram

Figure 5.14 describes the electronic wiring for the control system. We use a 3.7 V battery because we need to minimize the weight of the suspended part. Therefore, a DC to DC step-up voltage converter is needed to provide a steady 6V input for the Arduino Nano. The Arduino Nano powers both the motor driver as well as the BM160 gyro sensor. The sensor communicates with Nano in SPI mode.

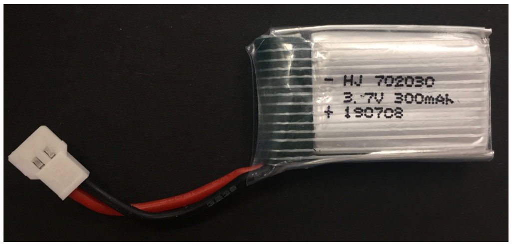
Note that the icons for electronics shown in Figure 5.14 are not identical to the real ones, which are shown in Figure 5.15. Also, note that the motor driver L298N is a version of smaller size because we need to reduce the overall weight of the rotation control system.



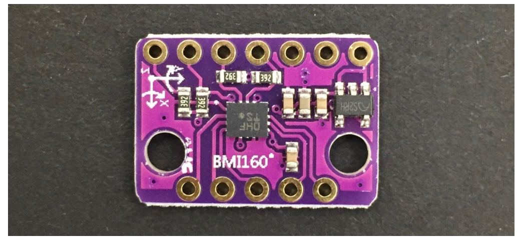
(a) DC to DC step-up voltage converter



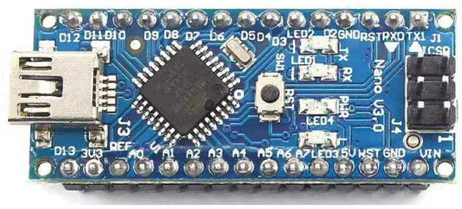
(b) Motor



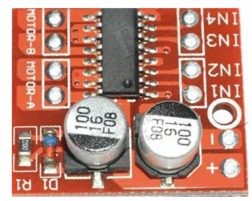
(c) 3.7V battery



(d) Angular speed sensor BM160



(e) Arduino Nano Microcontroller



(f) L298N Micro Motor Driver

Figure 5.15: Electronics for the prototype

We prototyped the suspension rotation control system using the electronics shown above as well as some 3D-printed structures, such as the battery box, for positioning and fastening.

5.4 Assembly

The assembly procedures are straight-forward since the structure part and the electronics part are explained in the previous sections. The acrylic boards are assembled using nuts and bolts. The prototype is shown in Figure 5.16.

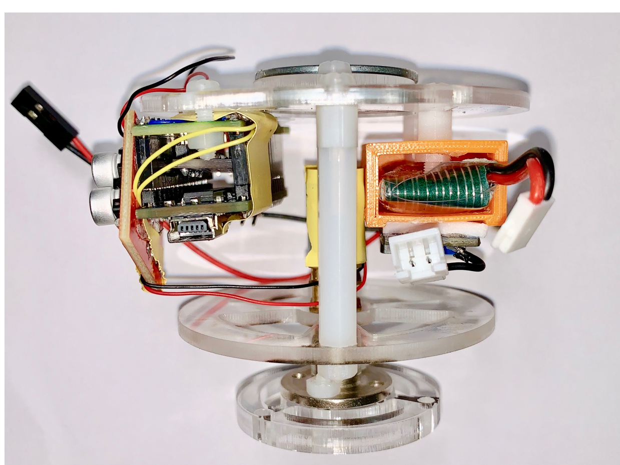


Figure 5.16: Prototype Assembly Example

5.4.1 Monetary Considerations

Table 5.2 shows the manufacturing budget. The total budget for manufacturing a prototype is ¥220 (subject to change), which is far lower than the initially proposed ¥3000. Meanwhile, one should keep in mind that this low amount is in part due to the free access of 3D-printers in the design and manufacturing lab, and in part due to the fact that some of the components have to be purchased by large numbers, yet only a few items are used on the prototype, thus decreasing the price per item. The more detailed bill of materials are shown in Appendix B.

Category	Component	Actual cost [¥]
Structural	Raw acrylic boards	40
	Coupler, nuts and bolts	5
	Battery box and decorative shell	Free
Electronics	Motor	20
	Battery	50
	DC-DC transformer	2
	Motor driving board	6
	Arduino nano	35
	Sensors	15
Magnets	Permanent magnets	12
Testing	SD card adapter	5
	SD card	30
Total		220

Table 5.2: Monetary consideration for the manufacturing plan.

5.5 Validation Plan

Requirement	Specification
Steady angular speed accuracy	$\pm 1°/s$
Angular position accuracy	3.6°
Total R&D budget	3000 RMB

Table 5.3: Finalized engineering specifications.

For reference, we restate the finalized engineering specifications in table 5.3. We will verify the first two specifications using two simple experiments, and verify the last one at the end of the R&D process.

- **Steady angular speed accuracy.** We will verify steady angular speed accuracy by setting the reference angular speed at different values and measure the time it takes for the object to rotate a full circle. Then we can calculate the actual angular speed of the object and compare them with the reference value. The test results are shown in Table 6.1.
- **Angular position accuracy.** We will verify the rotation angle by setting the rotation angle at different values and then measure the differences when the object rotate by a full circle. For example, when the rotation angle is set at 90°, the object should rotate four times to rotate by a full circle. After four 90-degree-rotations, we compare the angle difference with 360° and then calculate the average rotation angle of the four rotations. Similar procedures are conducted when the reference rotation angle is set at 120°. The test results are shown in Table 6.2.

- **Total R&D budget.** We will evaluate the total expenditure at the end of semester. This includes costs on unused/spare components and all previous prototypes.

6 Test Results

6.1 Validation for Constant Rotation Speed

ω_{ref} (deg/s)	Time (s)	ω (deg/s)	ω_{ref} (deg/s)	Time (s)	ω (deg/s)
30	12.33	29.20	60	6.05	59.50
30	12.01	29.98	60	6.11	58.92
30	11.89	30.28	60	5.93	60.71
30	12.26	29.36	60	5.99	60.10
30	12.09	29.78	60	6.12	58.82
Average	12.12	29.72		6.04	59.61

Table 6.1: Validation for Constant Rotation Speed

As we can see, the measured angular speed of the object is within the tolerance we set for the engineering specifications ($\pm 1°/s$). Therefore, the requirement for constant angular speed is satisfied.

6.2 Validation for Rotation Angle

θ_{ref} (deg)	$\Delta\theta$ (deg)	θ (deg)	θ_{ref} (deg)	$\Delta\theta$ (deg)	θ (deg)
90	5	88.8	120	-5	121.7
90	-4	91.0	120	7	117.7
90	7	88.3	120	-8	122.7
90	3	89.3	120	-3	121.0
90	-6	91.5	120	3	119.0
Average	1.0	89.8		-1.2	120.4

Table 6.2: Validation for Rotation Angle

Again, the rotation angles measured experimentally are within the accuracy requirements. Therefore, the prototype is able to rotate by a specified angle.

7 Engineering Changes Notices

In Design Review 3, we have made the diameter of the upper layer board to be 60mm. However, in our final prototype, we made some changes, as is shown in Figure 7.1.

The new diameter is 70mm. We increase it to make a further connection with an outer frame, which is only used for EXPO display. Also the length of the slider is increased for better mass balancing.

8 Discussion

In this section, several limitations of the current prototypes are discussed and the related recommendations are in Section 9.

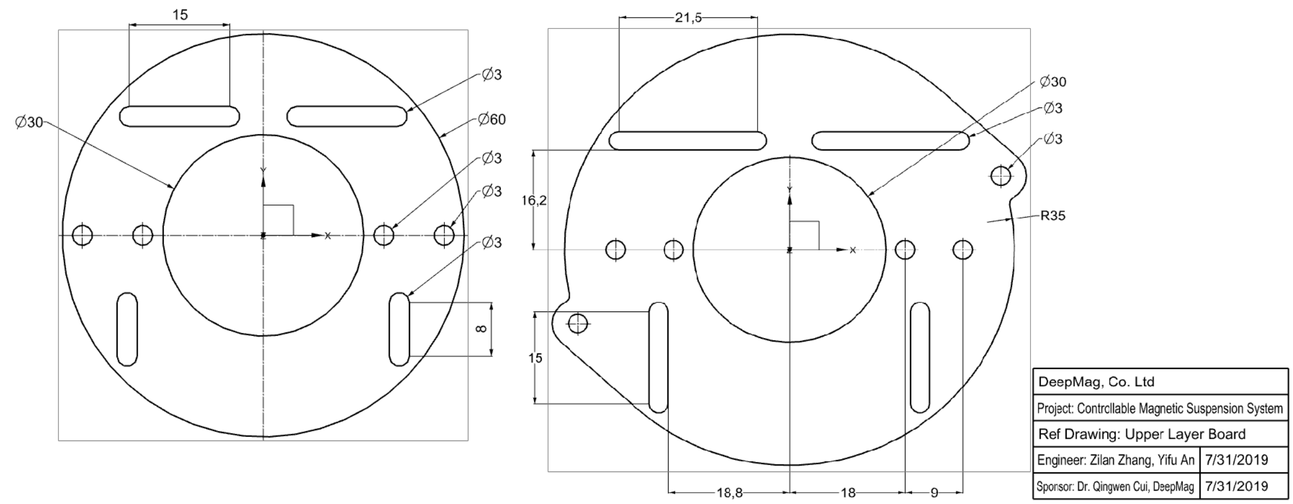


Figure 7.1: Changed upper layer board

8.1 Structure Balance

One of the major difficulties that we encountered during the manufacturing of the prototype lies in that it is difficult to balance the suspended part so that its center of gravity is in the center of the circular shape. However, it is a very important procedure during manufacture since the consequent rotation control depends on whether the suspended object is properly balanced. For our prototype design, we have added sliding slots to the main acrylic boards so that the balancing procedure is simplified. However, the positioning and adjustment still consumes time and efforts in an inefficient way.

8.2 Vertical Suspension Stability

In order to integrate with the suspension system provided by the sponsor, the weight and dimensions of the suspended object are limited. In addition to that, the suspension system need to be adjusted according to the weight of the suspended object by manually turning the potentiometer embedded within the analog circuit so that the current in the suspension control circuit is minimized for circuit protection.

8.3 Rotation Angle Integration

In order to control the object to rotate by a specified angle, the angular speed measured by the sensor are integrated to monitor the motion. However, since there are noises in the signal and the integration is done discretely, it means that there are long time errors of angle integration, which would reduce the accuracy of the angle. It may depend on the actual application that how accurate the rotation angle should be and in what range the rotation angle is allowed. Regardless, long time integration error is present and should be taken into consideration.

8.4 Power Supply

Currently, the prototype is powered by a 3.7V battery with a DC-to-DC voltage step-up converter to 6V to the micro-controller. This is due to the weight limitation on the suspended part. The power of the entire rotation control system for the current prototype is considerably low, so for the current weight and dimension of the suspended object, using battery is sufficient. However, if the suspended object is heavier and has a larger rotational inertia, a corresponding more robust motor will be used as well as a heavier fly wheel. Therefore, the choice of power supply might favour the wireless power supply system.

8.5 Uncontrollable Schemes

The PID control system that we use for the prototype treats the angular speed value measured by the sensor as the output y, and the input of the system is the PMW value of the motor ($0 \sim 255$) calculated based on the control parameters as well as the states, for example, the angular speed, of the system. However, external interference is unavoidable (Figure 8.1).

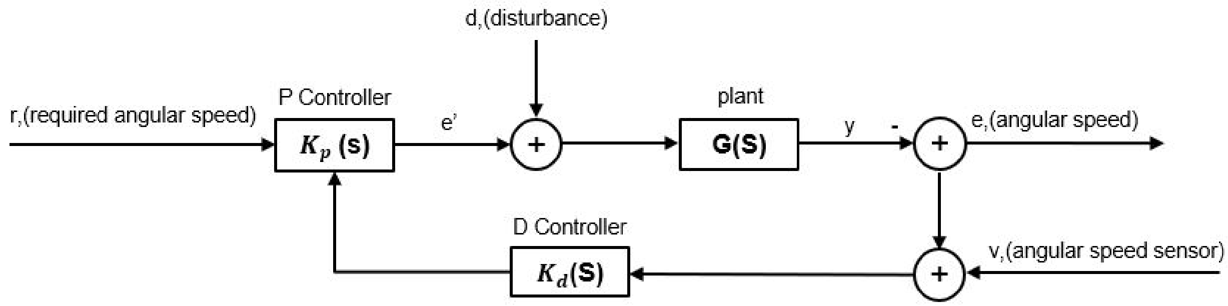


Figure 8.1: Block diagram for PD control with disturbance.

External interference introduces angular momentum change to the system. Since our control-and-actuate process is based on the angular momentum conservation principle, if the external interference introduces a large angular momentum change to the system, the rotating fly wheel at maximum speed, which corresponds to PMW value set at 255 for the motor, still does not compensate the external angular momentum change. Therefore, for the current prototype, it is susceptible to external interference. However, it is proved that the system can remain stable under a small interference scheme.

9 Recommendations

Related to the limitations that discussed in the previous section, we provide several recommendations on the further improvement of the prototype.

9.1 Suspension Control System

The analog circuit that controls the suspension could be improved to **digital circuit**. Similar to the PD controller we used for the rotation control, we can integrate a PID controller to maintain the stability of the suspended object so that the electromagnetic force that supports the weight of the object can be adjusted by the circuit itself and does not need manual adjustment, which greatly simplifies suspension control process. And with a greater allowable range of the weight, the suspension control system can be more versatile in terms that the customers can "DIY" their displaying object and do not need to worry about the suspension control.

9.2 Suspension Weight Balance

Regarding the balance problem, we recommend that the electronics in the prototype to be made into an integrated circuit so that the center of mass of the integrated circuit board is fixed and labeled on the board. This can simplify the weight balance procedure.

Another solution is that instead of a single solenoid in the suspension base, we can use four or more solenoids placed equally on the circle and the permanent magnets are placed accordingly on the suspended part. By individually controlling the currents within the solenoids, incorporated with PID controllers, the suspension system can balance the weight automatically so that a little weight imbalance of the structure would not affect the suspension effect.

9.3 Power Supply

We recommend that a wireless power supply system should incorporate with the rotation control system. This can simplify the control circuit design by reducing the battery and the DC-to-DC step-up voltage converter. The wireless power supply system can also power other electronics if needed.

10 Conclusion

The objective of this project is to achieve the controllable rotation of an electromagnetically suspended object. We were required to incorporate a rotation control system to the suspension control system, which was provided by our sponsor. With controllable rotation, the electromagnetically suspended object should maintain vertical stability with a visible gap between the object and the suspension control base. The object should have smooth rotation and can rotate at a constant specified angular speed as well as rotate by a certain specified angle. We came up with several solutions using system analyses and decision matrices. The final design concept is the gyro-based rotation control system with a fly wheel incorporated with a DC motor as the actuator of the rotation control and the PID control system with an angular speed sensor (BMI160). We manufactured the prototype using acrylic boards, nuts and bolts as well as 3D-printed battery box. After the validations, the final prototype is able to maintain vertical stability when the rotation control system is in operation. It is able to rotate at a constant angular speed specified by the customer. It is able to rotate by a specified angle as well. Therefore, we conclude that the prototype basically validates the design concept and satisfies the customer requirements. Limitations of this prototype includes the structural balance problem and that uncontrollable schemes may happen under great external interference. Further improvements on the prototype may be building an integrated circuit board for the control system, replacing the analog control circuit with a digital one for the suspension system and incorporating a wireless power supply system to the suspended part.

11 Acknowledgements

When the project comes to a conclusion, we would like to thank the following individuals for their help. Prof. Chengbin Ma, our instructor, gave us lots of valuable suggestions and encouragements during our weekly meetings. It was him that ignited the spark in brainstorming – He inspired us to think outside the box, leading to this simple, elegant solution. Mr. Jinpeng Yu, who is counseling DeepMag Co. Ltd. while working for his Ph.D. degree, was always there to answer our technical questions. We thank Dr. Qingwen Cui, CTO of Deepmag Co. Ltd., and Mr. Chuyao Peng, Founder and CEO of the company, as it was them that came up with this interesting project and delivered it to the Joint Institute. Their supportive attitude has been an inspiration as well. We shall also thank Ruowen Tu, one of our colleagues. His diligence has been our example; Thanks to his expertise, he helped us a lot in accessing the 3D-printers. Without them, we would miss so much fun and encounter much more twists and turns in the semester. Finally, we shall thank our group member, Changqing Lu. She has made the greatest contribution to this project, including calling out the idea of angular momentum conservation, programming for the control sequence, and actively taking up responsibilities in recording this project.

References

[1] Simon, Martin D. et al. 1997. "*Spin stabilized magnetic levitation.*" *Am. J. Phys.* 65: 286-292.

[2] 9GAG. 2019. *Magnetic Suspension Lamp.* https://9gag.com/gag/a83G9b6. 8 Jun 2019.

[3] "*Motor Stepper Motor - 42mm Hybrid Stepper Motor 70oz-in 48mm 2.5A For - 1x Stepper Motor.*" Amazon, Amazon, www.amazon.com/Motor-Stepper-42mm-Hybrid-70oz/dp/B07FLPBSHZ.

Appendix A Engineering change notice

From Design Review 3, the only change occurs in the upper layer board.

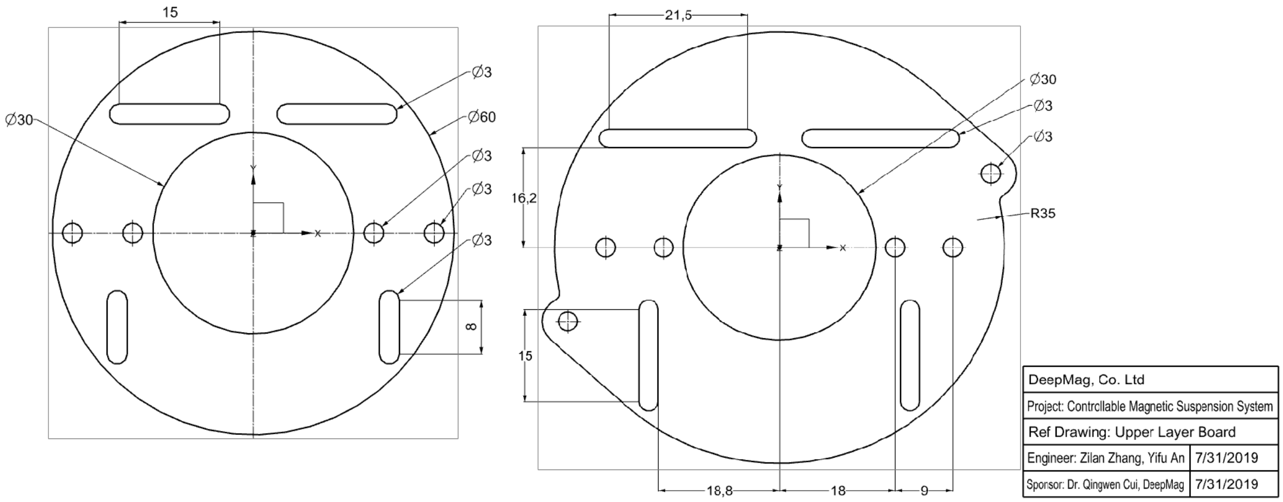


Figure A.1: ECN for upper layer board

Appendix B Bill of materials

Here we list the materials as well as special tools that were required to manufacture the prototype.

Quantity	Part Description	Purchased From	Part Number	Unit Price (RMB)	Price
1	Arduino Nano	taobao.com	v3.0	35.06	35.06
1	Motor Driver	taobao.com	L298N (micro)	6.07	6.07
1	Angular speed sensor	taobao.com	BM160	12.68	12.68
1	DC to DC step-up converter	taobao.com		1.93	1.93
4	3.7V Battery	taobao.com		12.5	50
1	DC motor	taobao.com		20	20
1	SD module	taobao.com		2.76	2.76
1	16 GB micro SD card	taobao.com		29.9	29.9
3	Raw Acrylic boards	taobao.com			40
1	Battery box	UMJI lab	3D printed		0
5	Permanent magnets	taobao.com		2.4	12
several	nuts and bolts	taobao.com			5
				Total	215.4

Appendix C Demonstration Code

This code will make the suspended object rotate at -30 deg/sec (upwards positive) for 30 seconds. Then the object will remain still for 10 seconds before it rotates by 120 degrees for three times, during which the object will start at a relatively high angular speed and then slow down as it approaches to the desired rotation angle.

```
#include <BMI160Gen.h>

const int select_pin = 10; // pin for sensor (SPI mode)
const int IN1 = 5; // pin for motor
const int IN2 = 6; // pin for motor

unsigned long lastTime, nowTime, iniTime;
double timeChange, totalTimeChange;
// control variables
float kp = 0.1;
float ki = 1;
float kd = 0;
float epsilon = 0;
float errSum, lastErr;
float w_new, w_old; // input - measured angular speed
int u; // motorValue
double w_ref; // const rotation speed 30 deg/sec
float theta; // for angle integration
int motorRef = 41;
int theta_ok = 0;
int rot_angle = 120;

void setup() {
  // set up motor
  pinMode(IN1,OUTPUT);
  pinMode(IN2,OUTPUT);
  // let motor stay constant when setting up
  digitalWrite(IN1, LOW);
  digitalWrite(IN2, LOW);
  Serial.begin(9600);
  while (!Serial);
  //initialize device
  //Serial.print("BMI160 initializing...\n");
  if (!BMI160.begin(BMI160GenClass::SPI_MODE, select_pin)){
  //Serial.print("BMI 160 initialization failed.\n");
  }
  BMI160.setGyroRange(250);
  delay(180000);
  iniTime = millis();
}

void loop() {
  nowTime = millis();
  timeChange = (double) (nowTime - lastTime)/1000;
  totalTimeChange = (double)(nowTime-iniTime)/1000;
  if (totalTimeChange<=30){
    w_ref = -30;
    ctr_rot_spd();
```

```
  }
  if (totalTimeChange>30 && totalTimeChange <=40){
    w_ref = 0;
    ctr_rot_spd();
  }
  if (totalTimeChange > 40 && totalTimeChange <= 50){
    if (theta_ok == 0){ w_ref = 10+50*abs(rot_angle-theta)/rot_angle; }
    if (theta_ok == 1){ w_ref = 0; }
    ctr_rot_spd();
    if (theta_ok == 0){
    theta += (w_new+w_old)/2*timeChange;
    }
    if (theta > rot_angle && theta_ok == 0){
      theta_ok = 1;
      theta = 0;
    }
  }
  if (totalTimeChange > 50 && totalTimeChange <= 60){
    if (theta_ok == 1){ w_ref = 10+50*abs(rot_angle-theta)/rot_angle; }
    if (theta_ok == 2){ w_ref = 0; }
    ctr_rot_spd();
    if (theta_ok == 1){
    theta += (w_new+w_old)/2*timeChange;}
    if (theta > rot_angle && theta_ok == 1){
      theta_ok = 2;
      theta = 0;
    }
  }
  if (totalTimeChange > 60 && totalTimeChange <= 70){
    if (theta_ok == 2){ w_ref = 10+50*abs(rot_angle-theta)/rot_angle; }
    if (theta_ok == 3){ w_ref = 0; }
    ctr_rot_spd();
    if (theta_ok == 2){
    theta += (w_new+w_old)/2*timeChange;}
    if (theta > rot_angle && theta_ok == 2){
      theta_ok = 3;
      theta = 0;
    }
  }
  if (totalTimeChange > 70){
    iniTime = nowTime;
    theta = 0;
    theta_ok = 0;
  }
  lastTime = nowTime;
  w_old = w_new;
  delay(10);
}

// convert Raw angular speed data into deg/sec unit
float convertRawGyro(int gRaw) {
  float g = (gRaw * 250.0) / 32768.0;
  return g;
}
```

```
void motorValue() {
  double error = w_new - w_ref;
  errSum += (error * timeChange);
  double dErr = (error - lastErr) / timeChange;
  u = kp * error + ki * errSum + kd * dErr;
  lastErr = error;

  if (u >= 0){
    u = u + motorRef;
  } else {u = u - motorRef;}

}

void wmeasure() {
  int wxRaw, wyRaw, wzRaw;
  float sumwx, sumwy, sumwz;
  float wx, wy, wz;
  sumwx = 0;
  sumwy = 0;
  sumwz = 0;
  for (int i=0; i<2;i++){
     BMI160.readGyro(wxRaw, wyRaw, wzRaw);
     sumwx = sumwx + convertRawGyro(wxRaw);
     sumwy = sumwy + convertRawGyro(wyRaw);
     sumwz = sumwz + convertRawGyro(wzRaw);
  }
  wx = sumwx/2+0.11;
  wy = sumwy/2-0.35;
  wz = sumwz/2+0.36;
  w_new = sqrt(wx*wx+wy*wy+wz*wz);
  if (wz<0){
    w_new = -w_new;
  }
}

//void motorActuate1() {
//  if (w_new < w_ref-epsilon){
//    analogWrite(IN1, abs(u));
//    digitalWrite(IN2, LOW);
//  }
//  if (w_new > w_ref+epsilon){
//    digitalWrite(IN1,LOW);
//    analogWrite(IN2, u);
//  }
//  if (abs(w_new-w_ref)<= epsilon){
//    digitalWrite(IN1,LOW);
//    digitalWrite(IN2,LOW);
//  }
//}

void motorActuate() {
  if (u<0){
```

```
    if (abs(u)>255){u = -255;}
    analogWrite(IN1, abs(u));
    digitalWrite(IN2, LOW);
  }
  if (u>=0){
    if (abs(u)>255){u = 255;}
    digitalWrite(IN1,LOW);
    analogWrite(IN2, u);
  }
}

void ctr_rot_spd() {
    wmeasure();
    motorValue(); // calculate motor speed
    motorActuate();
}
```

Appendix D Bump Test

Here we show the bump test code for the acquisition of the PID control parameters. Also, this is an example of the acquisition of the sensor data.

```
#include <BMI160Gen.h>
#include <SPI.h>
#include <SD.h>

const int select_pin = 10; // pin for sensor (SPI mode)
const int SD_pin = 4;
const int IN1 = 5; // pin for motor
const int IN2 = 6; // pin for motor

int u = 80; // set bump motor value at 80 0~255)
float w_new, w_old;
float w_int = 0;
unsigned long iniTime;
unsigned long preTime;
unsigned long timeChange, totaltimeChange;
int firstloop = 1;
int lastloop = 0;

File w_record;

void setup() {
  // set up motor
  pinMode(IN1,OUTPUT);
  pinMode(IN2,OUTPUT);
  // let motor stay constant when setting up (motorValue = 0)
  digitalWrite(IN1, LOW);
  digitalWrite(IN2, LOW);

  Serial.begin(9600);
  while (!Serial);

  //initialize device or check sensor and SD function
```

```
  if (!BMI160.begin(BMI160GenClass::SPI_MODE, select_pin)){
    Serial.print("BMI160 initialization failed.\n");
  }

  // file setup
  if (!SD.begin(4)){
    Serial.print("SD initialization failed.\n");
  }

  delay(5000);
  iniTime = millis();
  preTime = iniTime;
}

void loop() {
  unsigned long nowTime = millis();
  totaltimeChange = nowTime-iniTime;
  timeChange = nowTime-preTime;

  // record data for 10s
  if (totaltimeChange < 10000){
  // set motor
  analogWrite(IN2, u);
  analogWrite(IN1, 0);

  // read gyro measurements
  wmeasure();
  if (firstloop!=1){
    w_int = w_int + (w_new + w_old) / 2 * timeChange / 1000;
  }
  // serial output recording system response
  w_record = SD.open("w.txt",FILE_WRITE);
  w_record.print(nowTime);
  w_record.print("\t");
  w_record.print(w_new);
  w_record.print("\t");
  w_record.print(w_int);
  w_record.print("\n");
  w_record.close();

  w_old = w_new;
  }

  if (totaltimeChange >= 10000){
    if (lastloop==0){
      w_record = SD.open("w.txt",FILE_WRITE);
      w_record.println("------------------------------------");
      w_record.close();
      slow_down();
    }
    lastloop = 1;
  }

  firstloop = 0;
```

```
  preTime = nowTime;
  delay(100);
}

float convertRawGyro(int gRaw) {
  float g = (gRaw * 250.0) / 32768.0;
  return g;
}

void slow_down(){
  int N = u;
  while (N>=1){
    N = N-1;
    analogWrite(IN2,N);
    digitalWrite(IN1,LOW);
    delay(100);
  }
  if (N==0){
    digitalWrite(IN2,LOW);
    digitalWrite(IN1,LOW);
    u = 0;
    delay(3000);
  }
}

void wmeasure(){
  int wxRaw, wyRaw, wzRaw;
  float sumwx, sumwy, sumwz;
  float wx, wy, wz;
  sumwx = 0;
  sumwy = 0;
  sumwz = 0;
  for (int i=0; i<5;i++){
     BMI160.readGyro(wxRaw, wyRaw, wzRaw);
     sumwx = sumwx + convertRawGyro(wxRaw);
     sumwy = sumwy + convertRawGyro(wyRaw);
     sumwz = sumwz + convertRawGyro(wzRaw);
  }
  wx = sumwx/5+0.11;
  wy = sumwy/5-0.35;
  wz = sumwz/5+0.36;
  w_new = sqrt(wx*wx+wy*wy+wz*wz);
  if (wz<0){
    w_new = -w_new;
  }
}
```

In order to use the bump test, an additional SD module as well as an SD micro card is needed. The connection for the circuit is shown in Figure D.1.

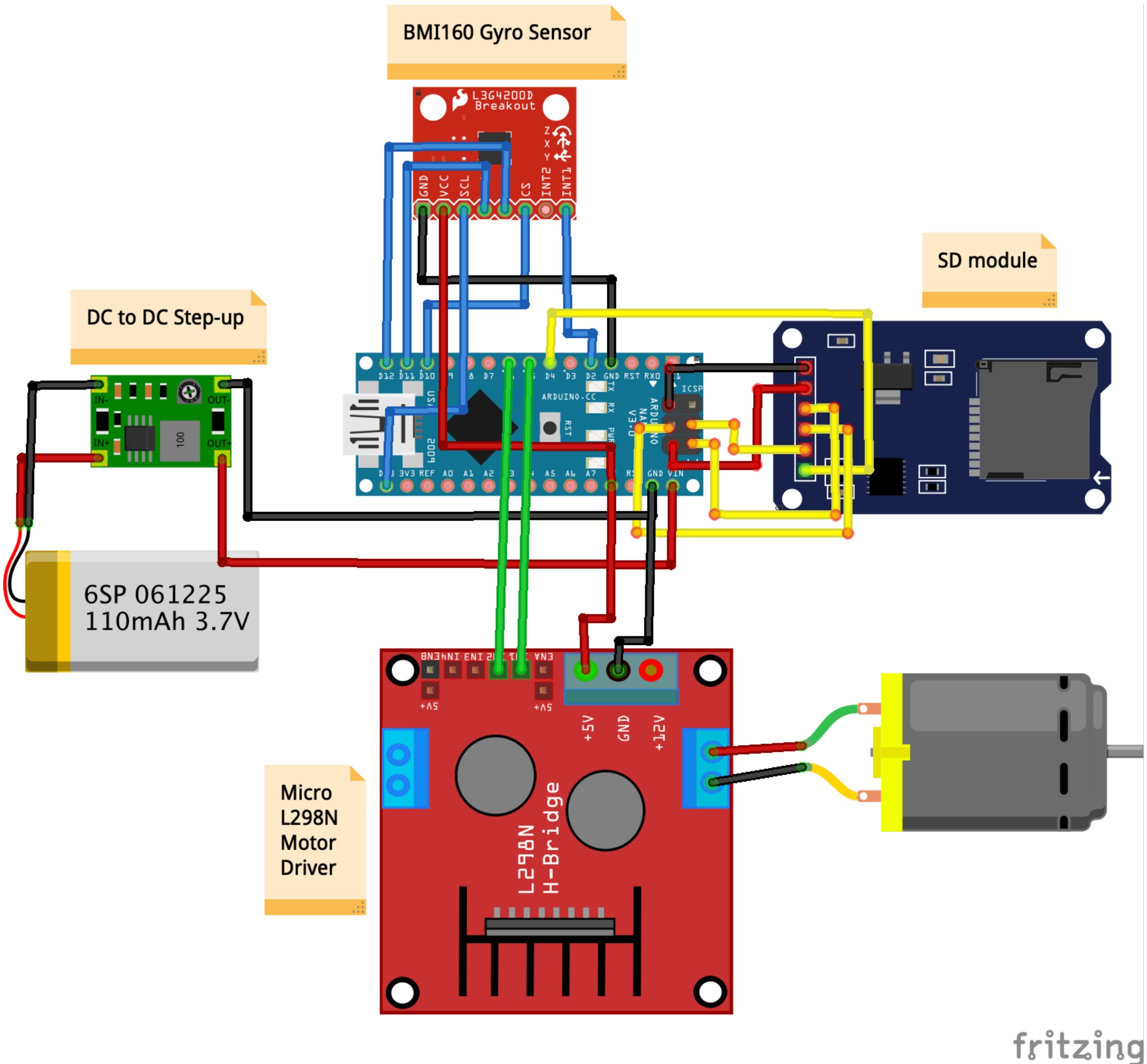
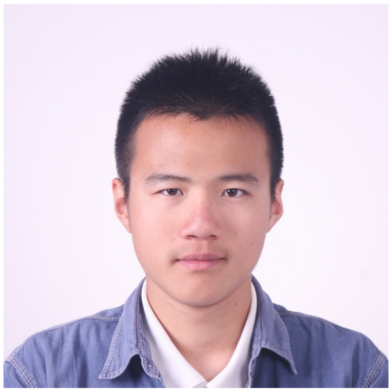


Figure D.1: Electronic Wiring Diagram for Bump Test

Appendix E Biographies



An, Yifu was admitted to Shanghai Jiao Tong University (SJTU) in 2015 and to the University of Michigan (UM) in 2017. He majored in Mechanical Engineering at SJTU and Aerospace Engineering at UM. He has just gradutated from UM and is now working for his second B.S.E. degree.

At the University of Michigan, he became interested in fluid dynamics. While the theoretical models for fluid fascinated him for their simplicity and elegance, we was also aware of the fact that many problems, especially those realistic ones, can only be effectively solved using numerical tools. He then conducted a directed study project related to numerically solving the shock tube problem. He also took a few graduate courses in the last semester at UM, to understand numerical engineering methods in depth.

He has been admitted to the M.S.E. in Aerospace Engineering program at the University of Michigan, and planned to further study numerical methods. For this project, he could use his knowledge in computational methods to model the electromagnetic field, or to combine aerodynamics with electromagnetics to generate some novel designs.

Liao, Junren was admitted to Shanghai Jiao Tong University (SJTU) in the year 2014, majoring in Mechanical Engineering in the Joint Institute (JI). In the year 2016, he was admitted to a Dual Degree program between SJTU JI and University of Michigan (UM). My major in UM was Civil Engineering. He graduated from UM in 2018 and went to University of California, Berkeley (UCB) for Master of Science education. For some reason I'm still working on the SJTU ME degree now and I'm planning to graduate in fall, 2019.

He already spent a year in UCB and He is going to graduate in fall, 2019. His major there is Transportation Engineering, which he decide to choose as his career. Back in UM, he was involved in a project about mode choice analysis of a low income area. He also did an internship at the University of Michigan Transportation Research Institute, working on autonomous vehicle detectors (radar, lidar, and camera) simulation. In UCB, He is now working on airport capacity prediction in New York area. His research interest is Urban Air Mobility (UAM), which is about flying taxi. Uber already launched a project about UAM, which is called Uber Elevate. Hisy future plan is either working for Uber on this project or pursuing a PhD with a topic about UAM.

Lu, Changqing was admitted to University of Michigan - Shanghai Jiaotong University Joint Institute in 2015, major in Mechanical Engineering. In the summer of 2017, she was admitted to the Aerospace Engineering department of University of Michigan - Ann Arbor. In April 2019, she graduated from University of Michigan and went back to Shanghai to continue my Bachelor's degree in SJTU. In September 2019, she will go to Stanford University and begin my Master of Science degree in Mechanical Engineering.

Due to her strong interest in physics, during her two year study under the Aerospace Engineering department, she became rather interested in fluid mechanics. She did a research project on the application of machine learning on the prediction of transition locations on airfoils. She plans to focus on the field of fluid mechanics or new energy during her Master of Science education and she plans to work in industries related to new energy or environment after graduation. For this project, her previous study about the control of the spacecraft and aircraft can be rather helpful.

Wang, Hanqin was admitted to University of Michigan - Shanghai Jiao Tong University Joint Institute in 2015, majoring in Mechanical Engineering. He will be graduated in August 2019 and go to a stock index futures company as a quant assistant. During the undergraduate period, Wang was interested in auto-control and financial model analysis. He did two researching projects. One is related to autophaqy gene function model analysis and another one is the trajectory control of the double cutters shield machine. Currently, he is intern in Vehicle Group of Tian Fen Security Researching Center after a half year OEM factory model analysis project cooperating with the Dupont Researching Center (China).

Zhang, Zilan is now a senior student in the SJTU-UM Joint Institute majoring in Mechanical Engineering. In September 2017, he was enrolled in the Dual Degree program and major in Aerospace Engineering at UM. During undergraduate study, he had great interest in solid mechanics. In summer 2018, he made a small research on stress and strain field in a cylindrical system. The method of calculating field, together with the computer aided simulation, is developed, helpful in almost all the cylindrical stress and field solid layer systems. He has been admitted to University of California, Berkeley for the Master degree in science of mechanical engineering. Currently, He has located his study direction on the field of materials, combining with thermal energy study. Therefore, in this project, the related study on magnetic materials will be a very good start.