ME 429

MECHANICAL AND THERMAL DESIGN

A DYNAMOMETER DESIGN
FOR SMALL DC MOTORS

Group E

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Abstract

The main objective of this project is to design a tabletop absorption type dynamometer dedicated to measuring the power characteristics of a DC motor with a rated power range of 50-100 W and a torque range of 0.1-0.3 Nm. Another DC motor is chosen as the braking mechanism of the dynamometer. The dynamometer is designed by evaluating parameters such as cost, size, brake mechanism, working torque range, and manufacturability. In this report, detailed strength and fatigue analyses are made for the shafts, couplings, bearings, and torque arm used in the designed system, and these calculations are taken into account during the design process of the relevant parts. In addition, since the dynamometer design also aims to present the measurement values on the computer screen, the analysis and selection of the electronic parts to be used in the system are also carried out during the design process.

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1. Introduction

A dynamometer is a device that measures the torque and speed of a spinning prime mover (such as a motor) at the same time in order to compute the instantaneous power. Absorption dynamometers and transmission dynamometers are the two types of dynamometers. Transmission dynamometers use devices that measure torque by measuring the elastic twist of the shaft or by inserting a specific torque meter between shaft portions. Absorption dynamometers, on the other hand, generate the torque they measure by applying a constant constraint to the rotation of a shaft through mechanical friction, fluid friction, or electromagnetic induction. [1]

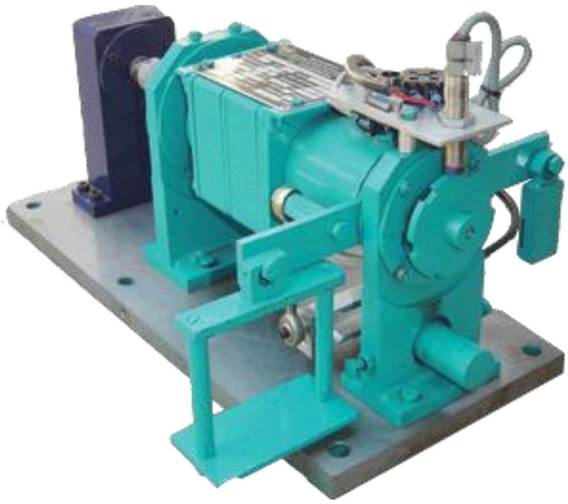


Figure 1. Example of absorption type dynamometer [2]

Dynamometers are widely used for measurement purposes in various industries from the automotive industry to manufacturing. Despite the fact that they are widely used, finding convenient dynamometers and appropriate systems to test small-scale motors constitutes a challenge as they are both expensive and rare. This challenge causes customers/designers to waste their time and/or money to find the motors with the correct specifications due to the lack of information on the power and torque characteristics of small-scale motors.

To address this problem, we have decided to design a tabletop absorption-type dynamometer dedicated to measuring the power characteristics of a DC motor with a rated power range of 50-100 W and a torque range of 0.1 – 0.3 Nm. In this design, we have determined four major goals to meet. Firstly, we aim to design a tabletop dynamometer, which will allow ease of installation and storage. Secondly, the design must allow easy mounting of testing motor, which will enable testing different motors with ease. Thirdly, the design must be compatible with a variety of shaft diameters, which will allow testing motors with different shaft diameters. Lastly, the design must be a low-cost dynamometer, which will allow the construction of a prototype.

During the design process, it was determined that the cost should be kept below 2000 ₺, the length of the dynamometer should be 120 cm and the width should be less than 65 cm, and the studies were carried out in this direction. The torque range of the test motors braked by the DC motor was determined as 0.1-0.3 Nm.

In the literature, several similar studies can be seen such as "*Design and Implementation of a Small Electric Motor Dynamometer for Mechanical Engineering Undergraduate Laboratory*" by Aaron Farley [3] and "*Design of a Small Electric Motor Dynamometer*" by William A. Black Jr [4], which are used as references throughout the project. Our approach differs from these studies in that it focuses on the use of another DC motor as a brake mechanism and data acquisition with the use of Arduino.

2. Overview of Possible Solutions

In this section, the possible solutions to the design problem are presented and discussed. Each configuration is designated with capital letters A, B, and, C respectively. Simple schematics are provided for each configuration to make them more comprehensible. Subsequently, each solution is explained and a comparison is carried out by means of a pros-and-cons table.

2.1 Option A

The block diagram of Option-A is provided in Appendix A. As shown in the diagram, there are two power units, each dedicated to supplying energy to the test and brake motor respectively. Apart from the motors, the energy required for the fan to work is also supplied by one of the power units which is Power Supply 1 due to the lesser power requirement of the test motor compared to the brake motor. The speeds of the motors are controlled via PWM dc motor speed controllers and the information about the electrical power applied to the motors is acquired with the help of power meters. There are two shafts, namely Shaft 1 and Shaft 2, extending from each motor. The shafts are connected with a coupler that works as an intermediary to transfer energy. The magnet that is attached to the coupler is utilized to measure the rotational speed of the test motor. The measurement is done by so using a linear hall effect sensor. The magnetic field originating from the magnet attached to the coupler is detected by the Hall effect sensor in a certain vicinity. Each time the magnet passes near the hall effect sensor, a signal is generated. Utilizing the time spanned between consecutive signals, the rotational speed is derived. The torque information of the test motor is obtained by utilizing a torque arm attached to the outer case of the brake motor. The force exerted at the tip of the torque arm is measured by a load cell and then the signals are transferred to the microcontroller. The signals acquired both from the hall effect sensor and the load cell are interpreted. Then, the measured rpm, torque, and power values of the test motor are displayed on the OLED panel. Also, the rpm vs. torque curve is plotted on pc.

The advantages and disadvantages of Option A are listed in Table 1 for a comparison. It should be noted that Option A is selected as the proposed solution.

Table 1: Pros and cons of the Option-A

PROS	CONS
Data acquisition via Arduino is viable.	The setup is harder to build.
Generating rpm/torque/power plots on PC is possible.	The measurement is less precise.
Power, rpm, and torque values are displayed all together on a single OLED screen.	
It takes up less space due to the sizes of the load cell and the Hall effect sensor	
It is cheaper due to the price of sensors	
The signals sent out by sensors are sufficiently clear.	

2.1 Option B

The simple schematic of Option B is provided in Appendix B. As shown in the schematic, what differs this setup from the previous one is the way how the torque and rpm are measured. In this setup, a tachometer is used to measure the rpm of the test motor. Each time the reflective tape attached to the coupler passes through a certain point, the infrared light originating from the tachometer is reflected and in turn, is detected by the tachometer. Utilizing the time spanned between consecutive detections, the rotational speed is derived and displayed. On the other hand, the torque of the test motor is measured by a torque meter connected to the shaft. In the presence of torque, the shaft is twisted so the strain gauges on the torque meter are deformed. The deformation of the strain gauges results in a change of resistance. Utilizing ohm's law to calculate the change in resistance, the deformation of the strain gauges and in turn, the torque applied by the test motor are measured.

The pros and cons of Option B are listed in Table 2 for a comparison.

Table 2: Pros and cons of the Option-B

PROS	CONS
The setup is easier to construct due to the ready-to-use nature of the industrial tachometer and torque meter.	It is expensive due to the price of the optical tachometer and torque meter.
There is less dependency on external power due to the built-in batteries of measuring instruments.	Displaying power value is unlikely since both measurement devices have different built-in software.
The measurement is more precise.	It takes up more space due to the sizes of the tachometer and torque meter.
It is capable to measure higher torque and rpm values, thus compatible with a wide range of motors.	

2.3 Option C

The block diagram, which shows the components and the process flow, of Option C is provided in Appendix C. In this setup, the IR optocoupler or IR reflective line tracking sensor is used for the purpose of measuring the rotational speed, instead of a Hall effect sensor. In the case of the implementation of the IR reflective line tracking sensor, the disc with a black strap attached is connected to the shaft. Utilizing the information about the thermal radiation emitting from an object, a signal is generated each time the black strap passes through a certain point where the infrared sensor points at. Then, the time spanned between consecutive signals is converted into rpm. On the other hand, the encoder disc is connected to the shaft in the implementation of the IR optocoupler sensor. Although the working principle of the IR optocoupler is very much the same as the IR reflective line tracking sensor, in this case, the holes in the encoder disc are detected instead of the black strap.

The benefits and the drawbacks of Option C are listed in Table 2 for a comparison.

Table 3: Pros and cons of Option C

PROS	CONS
Data acquisition via Arduino is viable.	The setup is harder to construct.
Generating rpm/torque/power plots on PC is possible.	The measurement is less precise.
Power, rpm, and torque values are displayed all together on a single OLED screen.	The signal is noisy if the digital output of IR optocoupler speed sensor module is used.
It takes up less space due to the sizes of the load cell and the Hall effect sensor	The desired rpm cannot be measured if the analog output of the IR optocoupler sensor is used.
It is cheaper due to the price of sensors.	The system is susceptible to daylight if IR reflective line tracking sensor is used.

3. Detailed Design and Analysis

In this section, detailed information about the system assembly, related parts, and calculations are presented. Free body diagrams and illustrations are also introduced to ensure clarification.

3.1 Overall Design

In Figure 2, the illustration of general system assembly is shown. The assembly consists of six general parts:

- The Frame
- Motors
- Motor Holder
- Torque Arm
- Bearings / Housings
- Coupling

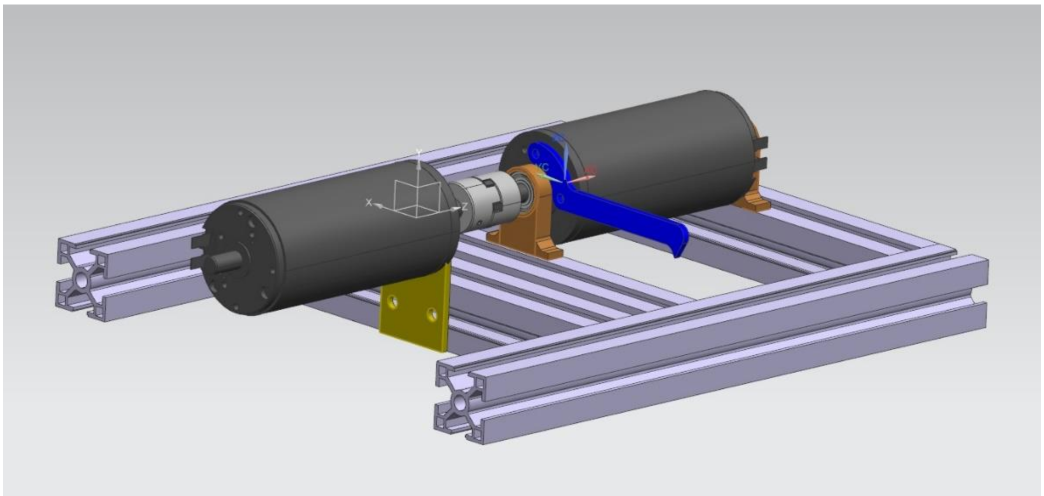


Figure 2: General system assembly

The frame consists of aluminum sigma profiles. Sigma profile is one most used profile types within the industry since the geometry of the profile provides slots for multipurpose operations and also less material is used to obtain desired mechanical properties. Therefore, sigma profiles appear as a lighter solution option along with cost-efficiency. The system contains five 30x30 mm sigma profiles. Three of the profiles are 200 mm in length and placed in the middle part of the assembly, where the remaining parts are fastened. Two of the profiles are 300 mm in length and placed at the left and right-hand sides of the assembly, providing structural integrity.

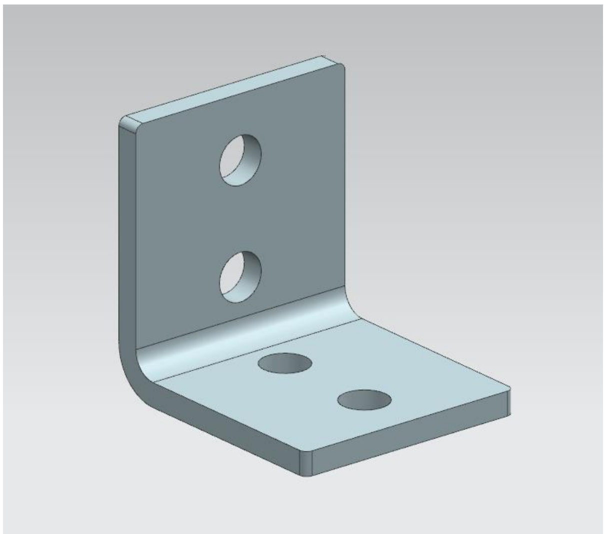


Figure 3: Bracket

The frames are fastened together with brackets, which are shown in Figure 3. Each one of the brackets has 4 holes for the M6 bolts, with a sheet metal thickness of 3 mm. The bolts connect the frames and since the operation is retrievable, the dimensions of the system can be easily changed, if necessary. One can loosen the bolts and retighten at the desired position. This provides the user to test different motors with different dimensions, just by rearranging the positions of the frames.

The motors are the main elements of the system. The system contains one brake and one test motor, with different fastening methods. The brake motor is connected to the frame via two bearings, the motor shaft is restrained for any motion except rotation. The housing of the motor is also free to rotate, which allows the torque arm to apply force on the load cell. The bearing is connected to the frame with bearing housings, which will be discussed in detail. The test motor is connected to the frame via a motor holder. The motor holder has also 3 mm's of sheet metal thickness and allows two M6 bolts to be fastened. The test motor is the changeable part of the system to allow different motors to be tested. The fastening method of the motor holder allows the user to change the motor with minimum effort and a modifiable frame system can accommodate motors with different dimensions.

There are three critical elements within the system: the torque arm, coupling, and the bearings, which will be presented in the same order.

3.2 Torque Arm

In Figure 4, the illustration of the torque arm is provided. The torque arm is assumed to be touching the load cell in a horizontal position and it is statically in equilibrium. The tip of the torque arm, which is designated as point A, is in contact with the surface. Point B and Point C are pinned.

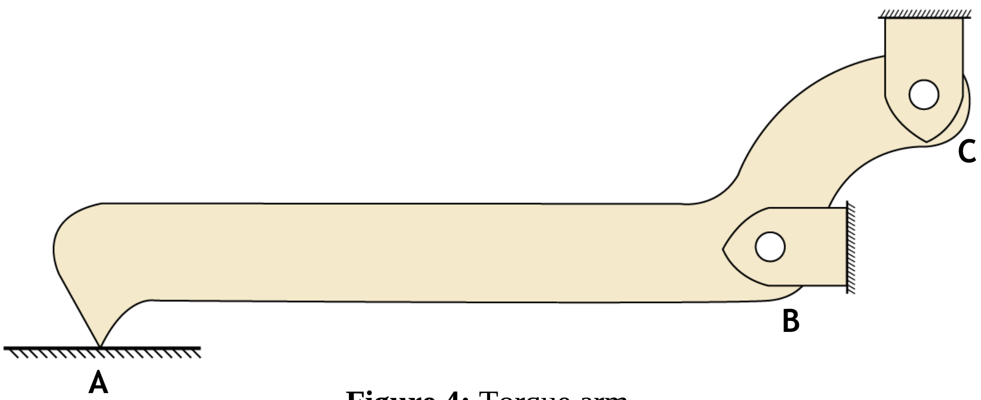


Figure 4: Torque arm

In Figure 5 below, free body diagrams of the torque arm and the motor case are sketched.

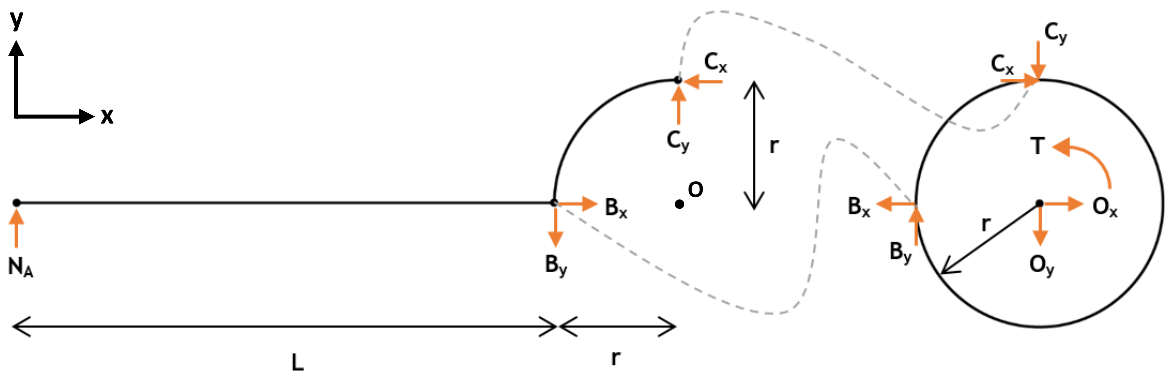


Figure 5: Free body diagram of torque arm and brake motor casing

The dimensions are design parameters and torque is a design criterion; thus, those are determined: L = 70 mm, r = 16 mm, T = 0.4 Nm.

The torque (T) is assumed to be distributed uniformly between pin C and B. ($C_x = B_y$)

Equations of equilibrium for the motor casing are

$$\sum M_O = 0 \quad \rightarrow \quad T - C_x r - B_y r = 0 \tag{1}$$

$$\sum F_x = 0 \quad \rightarrow \quad C_x + O_x - B_x = 0 \tag{2}$$

$$\sum F_y = 0 \quad \rightarrow \quad B_y - O_y - C_y = 0 \tag{3}$$

Equations of equilibrium for the torque arm are

$$\sum M_O = 0 \quad \rightarrow \quad C_x r + B_y r - N_A(L + r) = 0 \tag{4}$$

$$\sum F_x = 0 \quad \rightarrow \quad B_x - C_x = 0 \tag{5}$$

$$\sum F_y = 0 \quad \rightarrow \quad N_A + C_y - B_y = 0 \tag{6}$$

There are six equations and six unknowns. (C_x=B_y, O_x, O_y, B_x, C_y, N_A)

Solving equations (1) through (6), we get

$$C_x = B_y = \frac{T}{2r} = 12.5\ N \tag{1}$$

$$B_x = C_x = 12.5\ N \tag{5}$$

$$O_x = B_x - C_x = 0\ N \tag{2}$$

$$N_A = \frac{(C_x + B_y)r}{L + r} = 4.65\ N \tag{4}$$

$$C_y = B_y - N_A = 7.85\ N \tag{6}$$

$$O_y = B_y - C_y = 4.65\ N \tag{3}$$

Using these calculations, the torque arm was analyzed using Ansys software, which ables us to observe the load distribution and total deformation that will occur in the torque arm. The worst-case scenario was tried to be observed by performing the analysis at maximum operating values. Analysis was done using AISI 1040 material. As a result of the analysis, as can be observed in Figure 1, the maximum total deformation was observed as approximately 10^{-5} meters, and the maximum equivalent stress value was observed as approximately 1.5 x 10^{-7} Pascal, as can be observed in Figure 2. Since these values can be evaluated as negligible, the torque arm will be able to operate smoothly at the specified torque values.

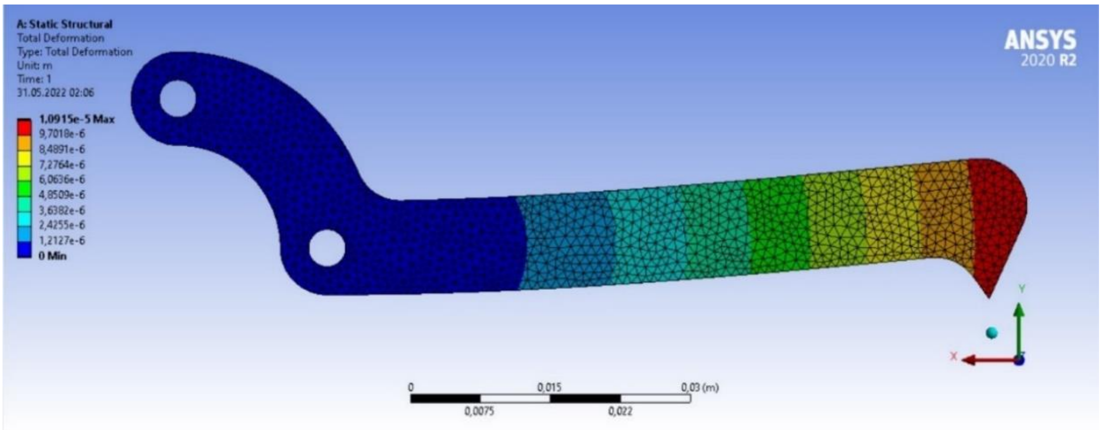


Figure 6. Total deformation analysis result of the torque arm

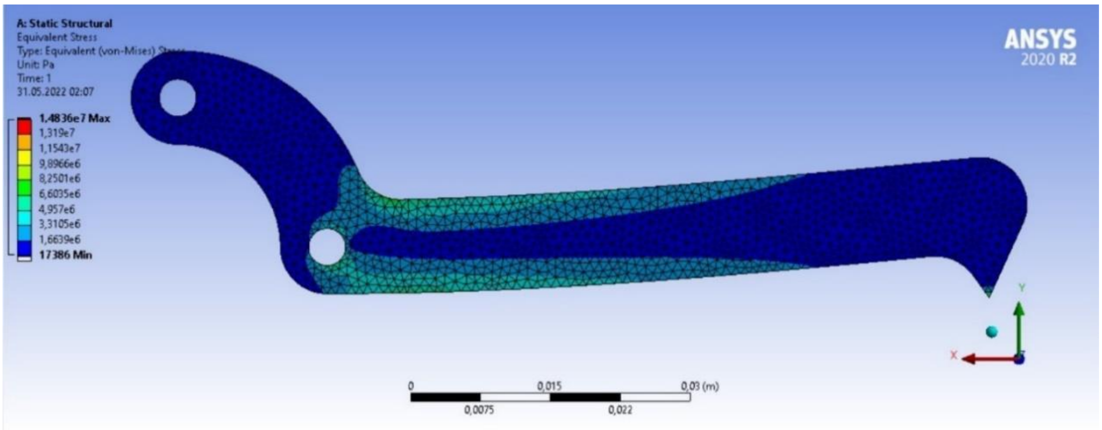


Figure 7. Stress distribution analysis result of the torque arm

3.3 Coupling

In Figure 5, the CAD model of the coupling assembly is shown. The coupling consists of two hubs and one spider. The motor shafts join the coupling assembly via hubs. Each hub has also set screw holes the ensure the motor shaft rotates with the coupling.

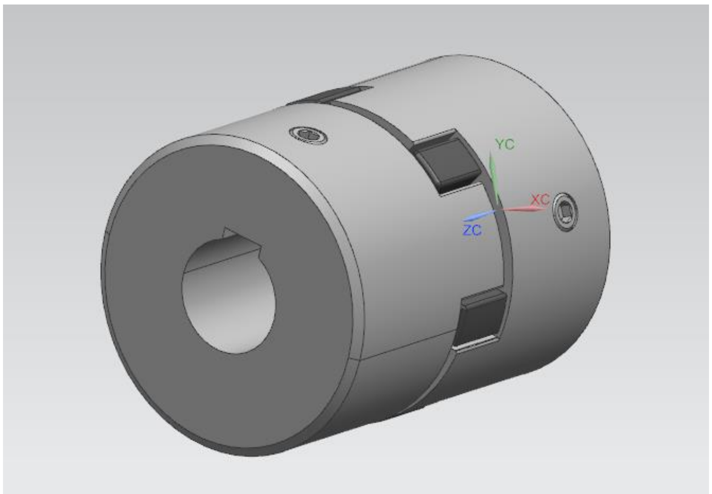


Figure 8: Coupling assembly

The hubs also contain keyways, which enable the usage of a wide range of motors. Depending on the shaft connection type of the motor, either keyway or set screw can be used. The jaw-like structure of the hubs transmits the power and torque to the counterpart. The spider is located between the two jaws and manufactured from an elastomer. The flexible material protects shock loads, which can be faced often in a dynamometer application.

The coupling is chosen from SKF and denoted as PHE L050HUB. While selecting the coupling, the manual which is provided by the SKF is used. The first step was the selection of the coupling type. Couplings are classified and rated by the manufacturer based on the different properties that the couplings demonstrate such as Temperature Range, Shock Load Capability, Speed Capability, Torsional Stiffness, Ease of Installation, Chemical Resistance, and Adaptability in Design. Jaw-type couplings that the manufacturer offer have a temperature range of -40 to 100 ℃, shock load capacity of 3 out of 5, medium speed capability, medium torsional stiffness, easiest to install, high chemical resistance, and adaptable with using spacers in the design. Based on these criteria, jaw-type couplings are the best option.

After the coupling type selection, to select the most convenient product for our application the manufacturer offers several steps:

1. Determining Required Service Factor
2. Calculating Design Power
3. Selecting the coupling size
4. Checking the bore size

Required service factor is provided by the manufacturer for different types of applications. For dynamometer applications, the suggested service factor is given as 1.5. Design power is the multiplication of the normal running power with the service factor. Since our system has a maximum power of 200 W, which is restricted by the brake motor, Design power equals 1.5x200 W = 300 W. In the coupling size selection, both the RPM and power are considered. The key point is to select a size with a greater power rating greater than the design power for an appropriate RPM. The size of 50 meets the requirements of our system with a power rating of 1.323 kW, which is much higher than the design power of our system. The last step is the selection of the model while checking whether the bore size is available for chosen coupling size. 50 size jaw couplings offer a bore diameter range from 6.35 mm to 14 mm, which is convenient considering the shaft diameters of our motors [5]. Furthermore, PHE L050HUB coupling can transmit torques up to 3.51 Nm, which is above our design selection of 0.4 Nm.

3.4 Bearings

In Figure 9, the illustration of the sub-system, which is composed of shaft 2, bearings, and brake motor, is provided. The bearings attached to the shaft at points B and C are fastened to the frame through the housings. Thus, the shaft is fixed in space and the translational motion of the shaft is restrained in all directions. Since the shaft is fixed through bearings, it is free to rotate.

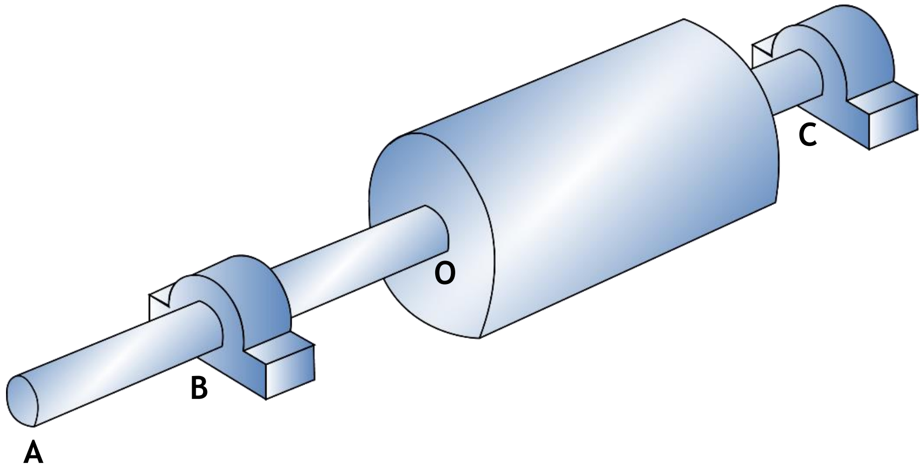


Figure 9: Illustration of the sub-system including shaft 2, brake motor, and bearings

In Figure 10 below, the free body diagram of the sub-system is sketched.

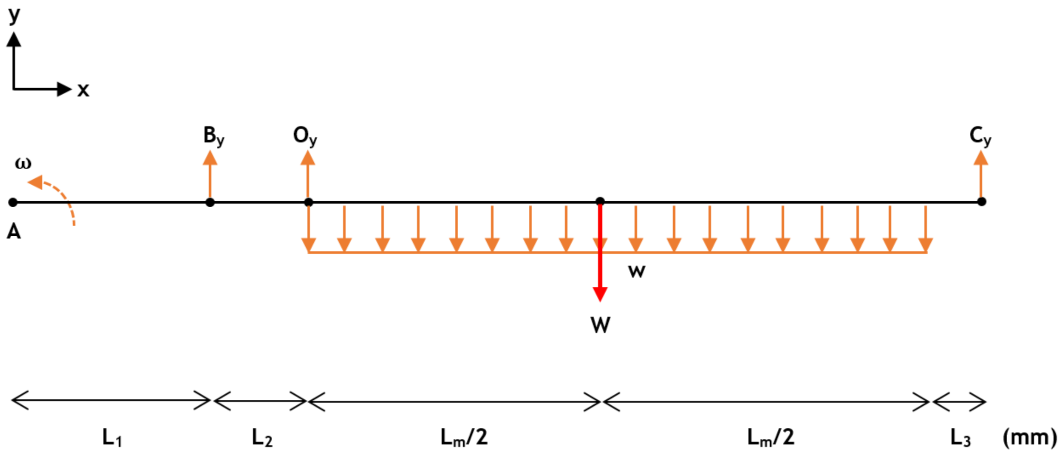


Figure 10: Free body diagram of the sub-system including shaft 2, brake motor, and bearings

The dimensions are design parameters; thus, those are determined: L_1 = 22.2 mm, L_2 = 10 mm, L_m = 108 mm, L_3 = 7.5 mm. O_y is found to be 4.65 N from the torque-arm and motor-casing equilibrium. ω is taken as 5680 rpm which is the nominal speed of the brake motor. The mass of the shaft and the bearings are neglected; whereas, the mass of the brake motor is assumed to be uniformly distributed.

The mass of the brake motor is 1.1 kg. Hence, w and W are found to be

$$W = mg = 1.1\,x\,9.81 = 10.8\,N \qquad w = \frac{W}{L_m} = 100\,N/m \tag{7}$$

Equations of equilibrium for the sub-system are

$$\sum M_B = 0 \quad \rightarrow \quad O_y L_2 + C_y(L_2 + L_3 + L_m) - W\left(\frac{L_m}{2} + L_2\right) = 0 \tag{8}$$

$$\sum F_x = 0 \quad \rightarrow \quad 0 = 0 \tag{9}$$

$$\sum F_y = 0 \quad \rightarrow \quad B_y + O_y + C_y - W = 0 \tag{10}$$

There are three equations from 2-D equilibrium and two unknowns. (B_y and C_y)

Solving equations (8) through (10), we get

$$C_y = \frac{W\left(\frac{L_m}{2} + L_2\right) - O_y L_2}{(L_2 + L_3 + L_m)} = 5.14\,N \tag{8}$$

$$B_y = W - C_y - O_y = 1.01\,N \tag{10}$$

Thus, the forces, that the bearings B and C are to accommodate, are found. Calculating the radial and tangential bearing loads for bearing B and bearing C, we get

$$(F_r)_B = \sqrt{B_x^2 + B_y^2} = 1.01\,N \qquad (F_t)_B = 0\,N \tag{11}$$

$$(F_r)_C = \sqrt{C_x^2 + C_y^2} = 5.14\,N \qquad (F_t)_C = 0\,N \tag{12}$$

Then using the information about the tangential and radial bearing loads, the equivalent dynamic bearing load, F_e, is calculated as [6]

$$For\ 0 < \frac{F_t}{F_r} < 0.35, \quad F_e = F_r \tag{13}$$

$$(F_e)_B = 1.01\,N \quad (F_e)_C = 5.14\,N \tag{14}$$

From the manufacturers' catalog, it is found that the commercially used deep-groove ball bearings with an inner diameter of 8 mm have a 3.15 kN basic dynamic load rating (C) and 26 000 rpm limit, on average. Since C >> $(F_e)_B$, $(F_e)_A$ and RPM_{limit} >> ω, any commercially used bearing is expected to accommodate the applied loads and execute the desired task without a failure. In order to support this proposition, the design life of the bearings are calculated.

The empirical equation that is used to calculate the design life of a bearing is given as [6]

$$L = L_{10}(C/K_aF_e)^p \tag{15}$$

where L_{10} is basic rating life with 90% reliability, C is basic dynamic load rating, K_a is application factor, F_e is equivalent dynamic bearing load and p is the exponent of the life equation. C and F_e are already known. Application factor, K_a, is taken as 2 – assuming moderate impact. The exponent of the life equation, p, is equal to 3 for ball bearings and the basic rating life, L_{10}, is accepted as 10^6 according to ISO 281 standard. So the design life of the bearings are calculated to be

$$L_B = 3.8\ x\ 10^{15}\ rev \qquad L_C = 2.9\ x\ 10^{13}\ rev \tag{16}$$

3.5 Electronic Parts

3.5.1 PWM DC Motor Speed Controller

In order to measure the power of the motor at a given RPM, the rotational speed of the motor is required to be controlled. Although there are several ways of controlling the rotational speed of a dc motor, the most effective and precise way to do this is by using the PWM method. PWM, pulse-width modulation, is a technique of breaking an electrical signal effectively into discrete parts to reduce the average power delivered by the signal. Turning the switch between supply and load on and off at a steady rate, the average value of voltage fed to the load is controlled. As shown in Figure 11, the shorter the switch is on compared to the off periods, the lower the total power supplied to the load and vice versa [7].

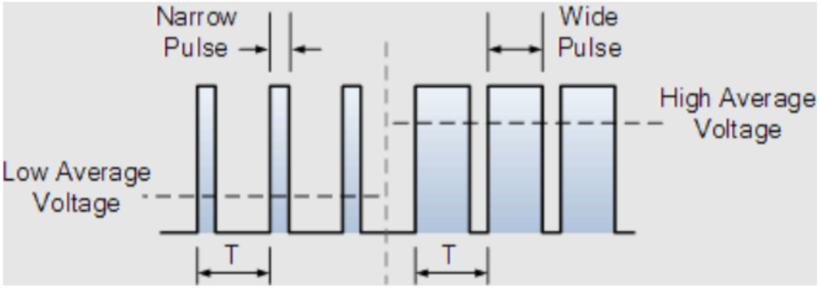


Figure 11: Pulse-width modulation technique [8]

In Figure 12, the image of the PWM dc motor governor module to be implemented in this project is provided. The module has an operating voltage of 12-40 V and an output current up to 10 A, which is sufficient for the motors to be used in the project.

Figure 12: PWM dc motor governor module [9]

3.5.2 Linear Hall Effect Sensor

Two parameters, one of which is rotational speed, are required to be measured simultaneously for the calculation of the power of the test motor. Although there are several ways of measuring the rotational speed of a shaft such as using an IR optocoupler, IR line tracking sensor, and industrial tachometer, the Hall effect sensor is the most optimum way due to budget concerns and minimum signal noise. A Hall effect sensor is a type of sensor that utilizes the Hall effect to detect the presence and magnitude of a magnetic field. The Hall sensor's output voltage is proportional to the intensity of the field. The phenomenon is named after an American scientist, Edwin Hall. The working principle is the following: A current is applied to a thin strip of metal in a Hall sensor. In the presence of a magnetic field perpendicular to the direction of the current, the charge carriers are deflected by the Lorentz force – resulting in a difference in voltage between the two sides of the strip [10].

In Figure 13, the image of the Hall effect sensor module to be implemented in the project is provided.

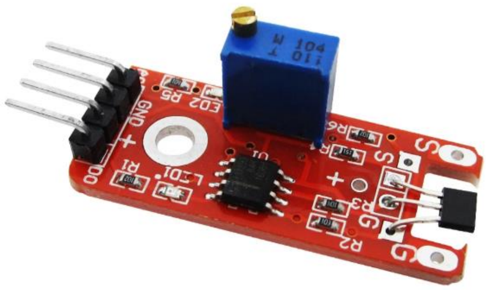


Figure 13: Magnetic hall effect sensor module [11]

3.5.3 Load Cell

The other parameter that is required to be measured for the calculation of the power of the test motor is torque. Although there are several ways of measuring the torque of a shaft such as using a torque meter, due to budget concerns and high compatibility with Arduino, the load cell is selected as the instrument to measure the torque. A load cell is a force transducer that converts a force such as tension, compression, pressure, or torque into an electrical signal that can be measured and standardized. As the force applied to the load cell increases, the electrical signal changes proportionally [12].

In Figure 14, the image of the load cell weight sensor to be implemented in the project is provided. The load cell has a maximum load capacity of 5 kg. The maximum load capacity of the cell is sufficient since the maximum force exerted on the cell is equal to 4.65 N which corresponds to 0.474 kg. In addition, the cell has a percentage accuracy of 0.5. The load cell is integrated with a signal amplifier, HX711, so that signals can be read from Arduino.

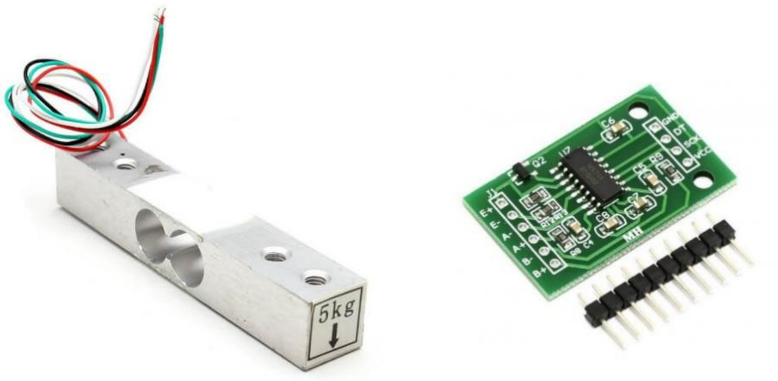


Figure 14: Load cell and HX711 load cell amplifier module [13]

3.5.4 OLED Display

In Figure 15, the image of the OLED display panel to be implemented in the project is provided. The panel is utilized to display the rpm, torque, and power values of the test motor. The reason why the OLED panel is selected is due to the higher refresh rate and customizability.

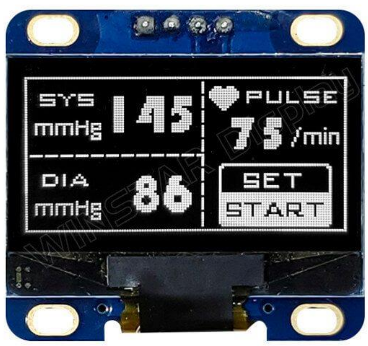


Figure 15: OLED display I2C 128x64 [14]

3.5.5 Powermeter

In Figure 16, the image of the digital DC power multimeter to be implemented in the project is provided. The multimeters are connected to the output of the PWM controllers to measure the current, voltage, and electrical power supplied to the motors.

Figure 16: Digital DC power multimeter [15]

3.5.6 Microcontroller

In Figure 17, the image of the microcontroller to be implemented in the project is provided. The reason why Arduino is selected is due to its high compatibility with sensors, user-friendly interface, and programming language.

Figure 17: Arduino UNO [16]

3.6 Cost

Since a dynamometer is a system containing many components, the cost is one of our most critical design constraints evaluated during the process. Two approaches were considered while assessing the total cost. First, a market analysis was made for the parts that are currently on sale and to be used, and the most cost-effective parts that meet the design criteria were tried to be selected. Secondly, the cost calculation for the torque arm and motor holder, which will be produced, was made by considering the price of the chosen material to meet our design criteria and the manufacturing prices selected as the production method.

The brake motor to be used has been determined as the 0.4 Nm DC motor we already have. After this selection, it was decided to purchase two test engines, one 0.27 Nm and the other 0.1 Nm. Coupling, bearings, aluminum sigma profiles, scale-load cell, PWM dc motor governor module, potentiometer, magnetic hall effect sensor, and 12C OLED display are commercially available products. Therefore, it is decided to purchase these parts. The torque arm and the motor holder will be produced with a laser-cut process to be made from sheet metal using AISI 1040 alloy within the framework of our own designs. Finally, besides the brake motor, the power supply, AC-DC power meters, microcontroller, and fan have helped us to reduce the total cost since they are the components that we have now and that we have decided to use in the future.

When all these are evaluated, detailed cost analysis has been made and the prices obtained are presented in Table 4, together with the total cost. The total cost has been calculated as approximately 2236₺. Considering that our predetermined cost constraint is to try to keep the total cost under 2000₺, this total cost is slightly over the budget. However, by examining local markets, these components can be supplied at lower costs.

Table 4. Cost Analysis

Part List	Approximated Cost	
	Number (#)	Cost (₺)
Brake Motor	1	none
Test Motor	1	1000
Coupling	1	75
Torque Arm	1	100
Bearings	2	80
Aluminum Sigma Profile	2 (m)	80
Power Supply	2	none
DC Power Meter	2	200
Scale-Load Cell	1	50
HX711 Signal Amplifier	1	20
PWM DC Motor Governor Module	2	118
Magnetic Hall Effect Sensor	1	18
Microcontroller	1	none
I2C OLED Display	1	85
Fan	1	none
Motor Holder	1	50
	Total Cost	**1876**

4. Conclusions

In conclusion, although there are many dynamometer examples in the industry, each of these solution options offers limited areas of usage. Especially to test the small DC motors with low torque outputs, it is hard to find a convenient dynamometer system and the appropriate systems are both expensive and rare. Three different solution options are investigated with different torque and RPM measurement methods. The selected design presents torque arm implementation for torque measurement via a loadcell and Magnetic Hall Effect Sensor for RPM measurement. Data acquisition is provided with a microcontroller, which also collects data from the load cell and Magnetic Hall Effect Sensor. It was also necessary to design a torque arm to be used in this system. The designed torque arm is analyzed on ANSYS and it has been seen that the design meets the requirements. Coupling selection was another important criterion, since the coupling is one of the key elements of the system, it must not fail under the operating range of the system. Also, it must be resistant to shock loads, since the testing procedures include sudden load applications, especially when the brake motor is actuated from an idle state. As a result of the analysis, it has been determined that the selected coupling has these properties. In addition, cost analysis was made for the project. After the analysis, the determined maximum budget has been slightly exceeded, but the cost will be kept at a minimum during the project construction process.

References

[1] J. B. Winther, Dynamometer Handbook of Basic Theory Applications, Cleveland, Ohio: Eaton Corporation, 1975.

[2] Elektrodyne, "Elektrodyne," Associated Elektrodyne Industries Pvt. Ltd., [Online]. Available: http://www.elektrodyne.com/fhp_low_speed_dyn.html. [Accessed 2 June 2022].

[3] A. Farley, "Design and Implementation of a Small Electric Motor Dynamometer for Mechanical Engineering Undergraduate Laboratory," University of Arkansas, North Carolina, 2012.

[4] W. A. B. Jr., "Design of a Small Electric Motor Dynamometer," Massachusetts Institute of Technology, Cambridge, 1951.

[5] S. Group, "SKF Group Coupling Catalogue," 2018.

[6] R. C. Juvinall, Juvinall's Fundamentals of Machine Component Design, WILEY, 2017.

[7] Wikipedia, "Pulse-width modulation," 2009.

[8] "Pulse-width Modulation," [Online]. Available: https://www.electronics-tutorials.ws/blog/pulse-width-modulation.html. [Accessed 07 06 2022].

[9] "Arduino Pwm Dc 12V/24V/30V/40V Motor Governor Module With 10A Speed Control Switch," [Online]. Available: https://www.hepsiburada.com/pwm-dc-motor-hiz-kontrol-devresi-motor-hiz-kontrol-12v-40v-10a-pm-HB000004QHG0. [Accessed 07 06 2022].

[10] "The Guide to Hall Effect Sensors," [Online]. Available: https://ie.rs-online.com/web/generalDisplay.html?id=ideas-and-advice/hall-effect-sensors-guide. [Accessed 07 06 2022].

[11] "Digital Temperature Sensor Module AVR PIC DIY," [Online]. Available: https://tr.aliexpress.com/item/32843310520.html. [Accessed 07 06 2022].

[12] "Load Cell and Strain Gauge Basics | Load Cell Central," [Online]. Available: www.800loadcel.com. [Accessed 29 07 2019].

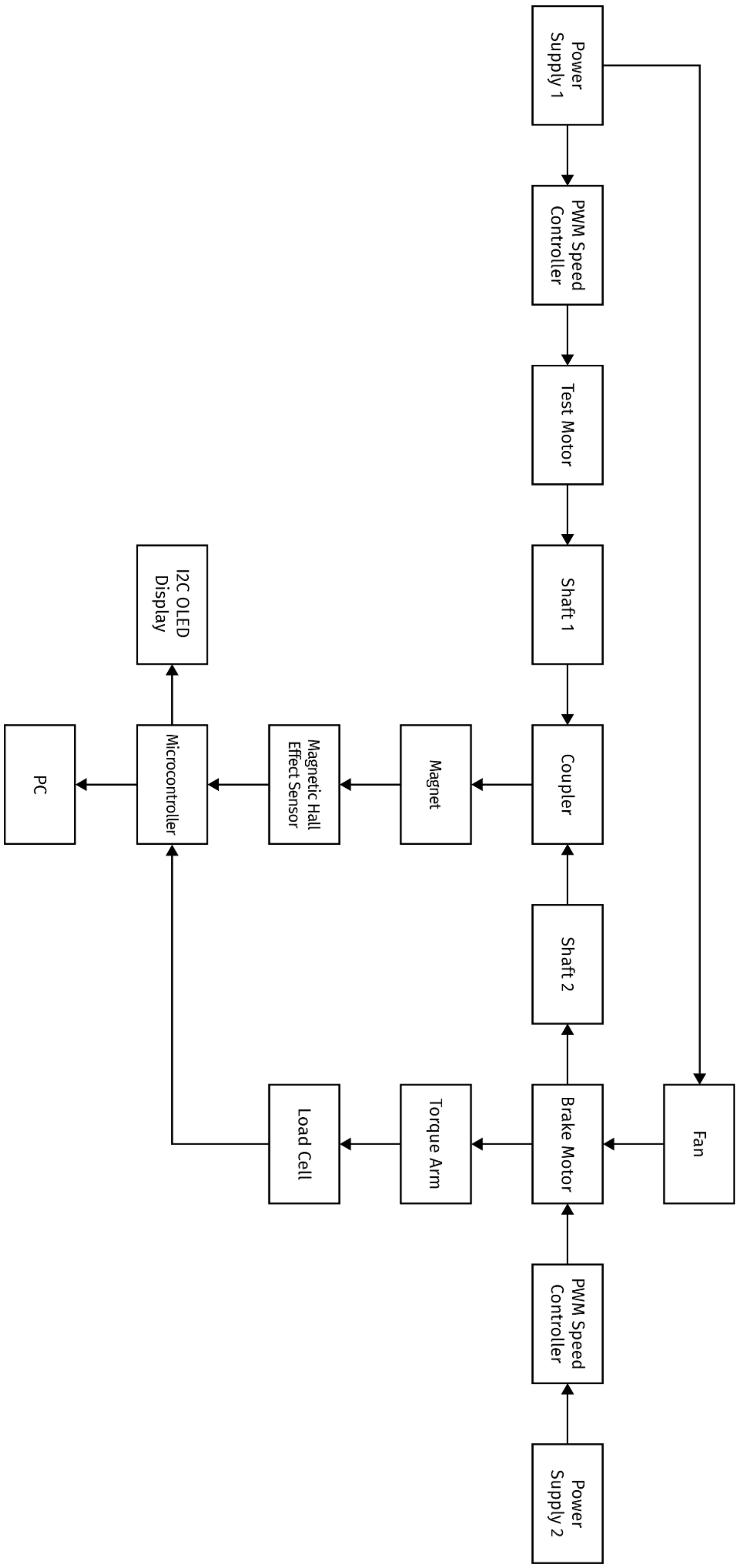
[13] "Loadcell Weight Sensor - 5 Kg," [Online]. Available: https://www.robitshop.com/urun/loadcell-agirlik-sensoru-5-kg. [Accessed 07 06 2022].

[14] "0.96 inch, 128x64 COG+PCB Graphic OLED Display," [Online]. Available: https://www.winstar.com.tw/tr/products/oled-module/graphic-oled-display/4-pin-oled.html. [Accessed 07 06 2022].

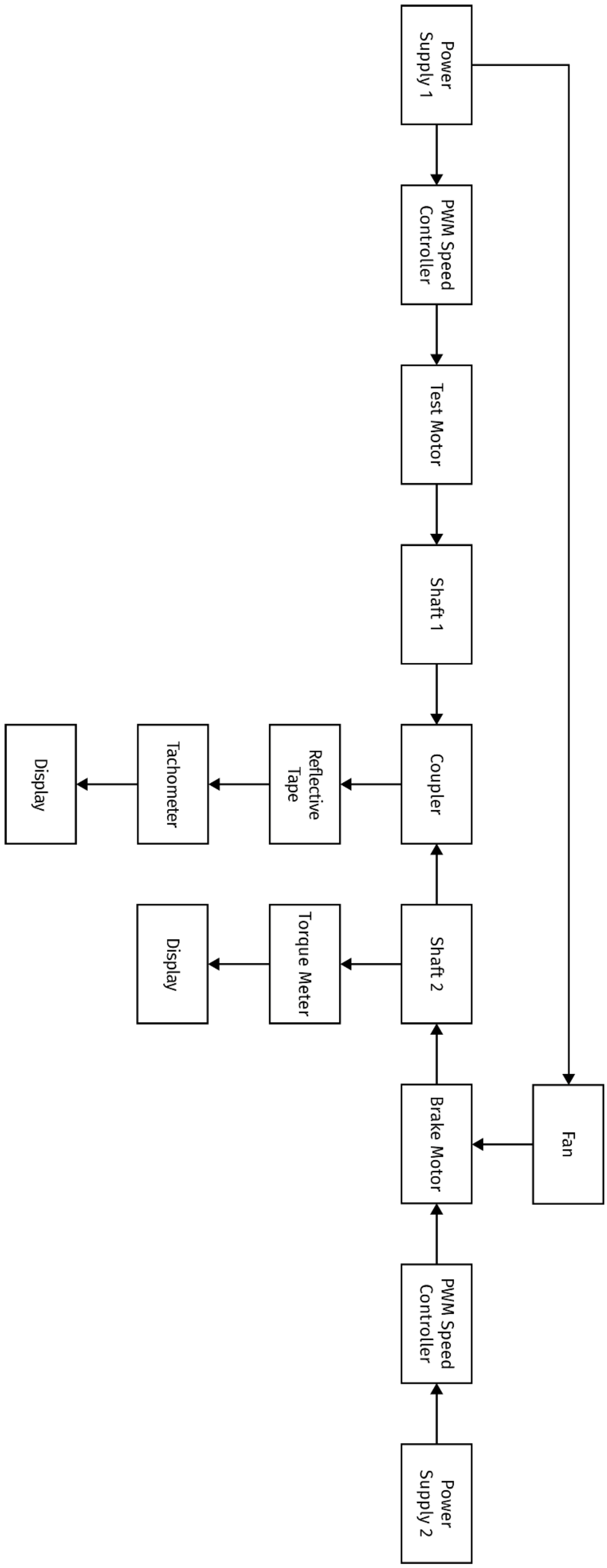
[15] "New DC 6.5-100V 0-20A LCD display digital current voltage power energy meter multimeter ammeter voltmeter with 20A current shunt," [Online]. Available: https://tr.aliexpress.com/i/32565861001.html. [Accessed 07 06 2022].

[16] "Original Arduino UNO R3," [Online]. Available: https://www.robotistan.com/orjinal-arduino-uno-r3-yeni-versiyon. [Accessed 07 06 2022].

Appendix A

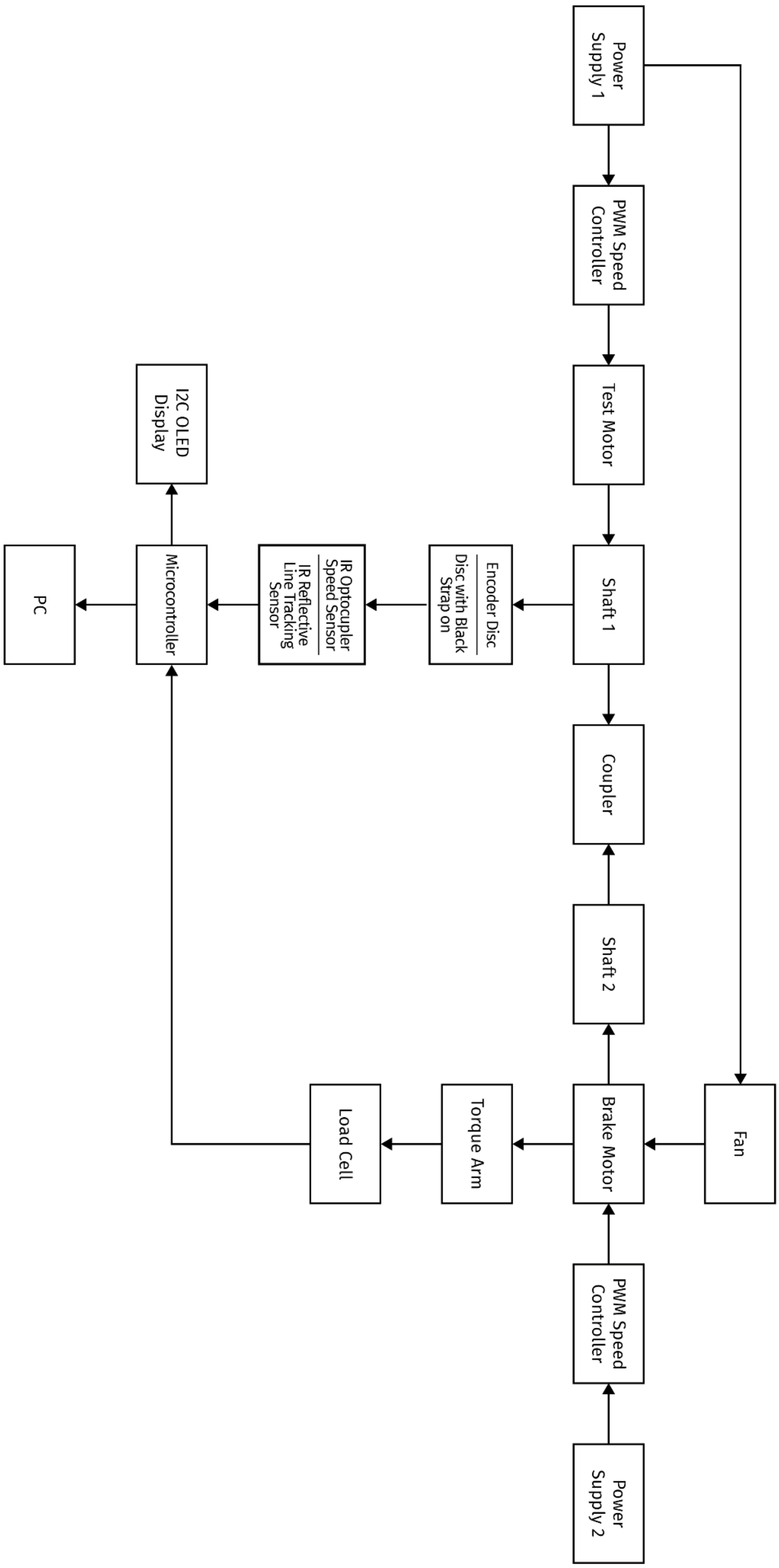

Power Supply 1
PWM Speed Controller
Test Motor
Shaft 1
Coupler
Shaft 2
Brake Motor
PWM Speed Controller
Power Supply 2
Fan
Torque Arm
Load Cell
Magnet
Magnetic Hall Effect Sensor
Microcontroller
I2C OLED Display
PC

Appendix B

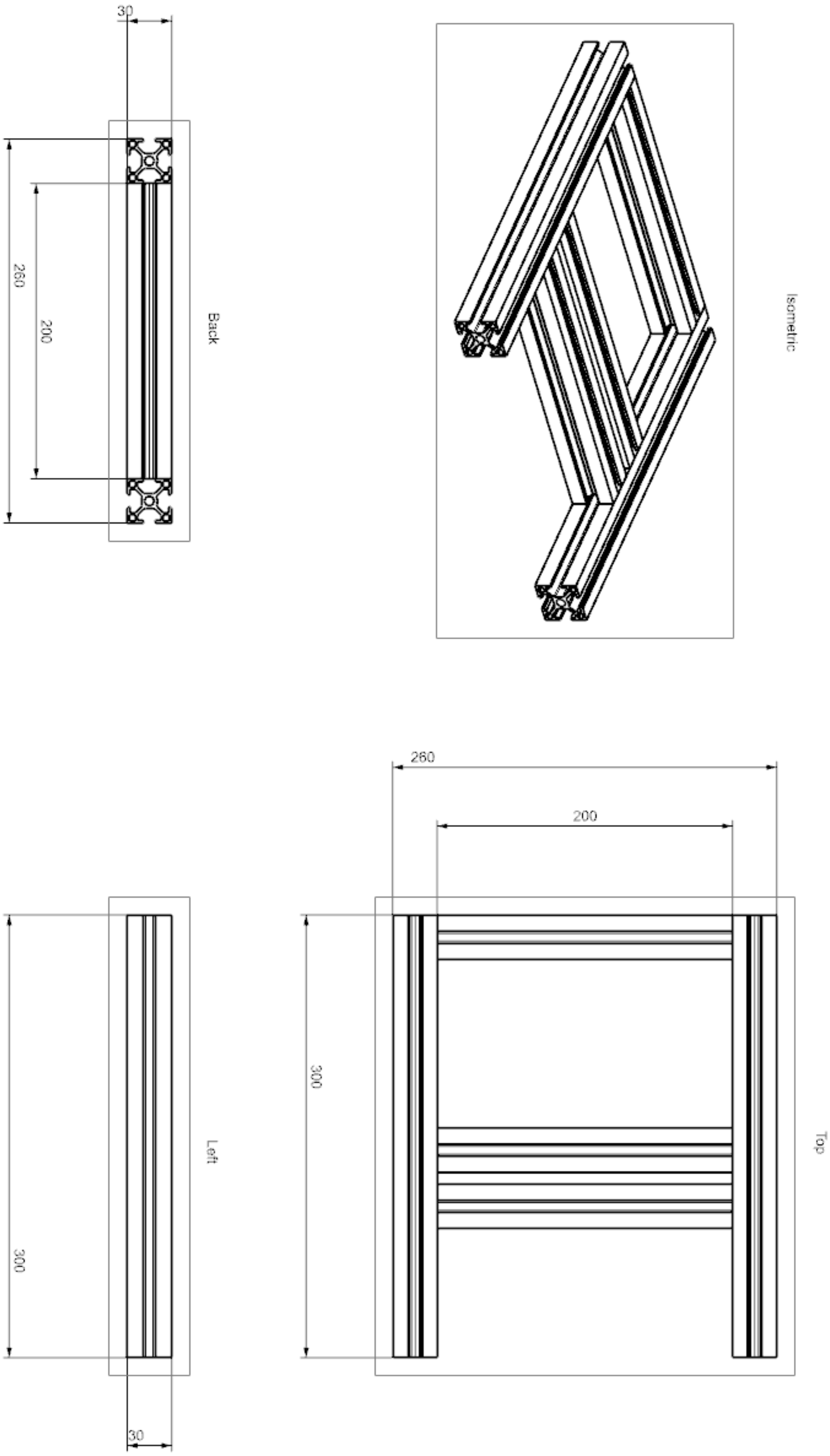


Power Supply 1
PWM Speed Controller
Test Motor
Shaft 1
Coupler
Reflective Tape
Tachometer
Display
Shaft 2
Torque Meter
Display
Fan
Brake Motor
PWM Speed Controller
Power Supply 2

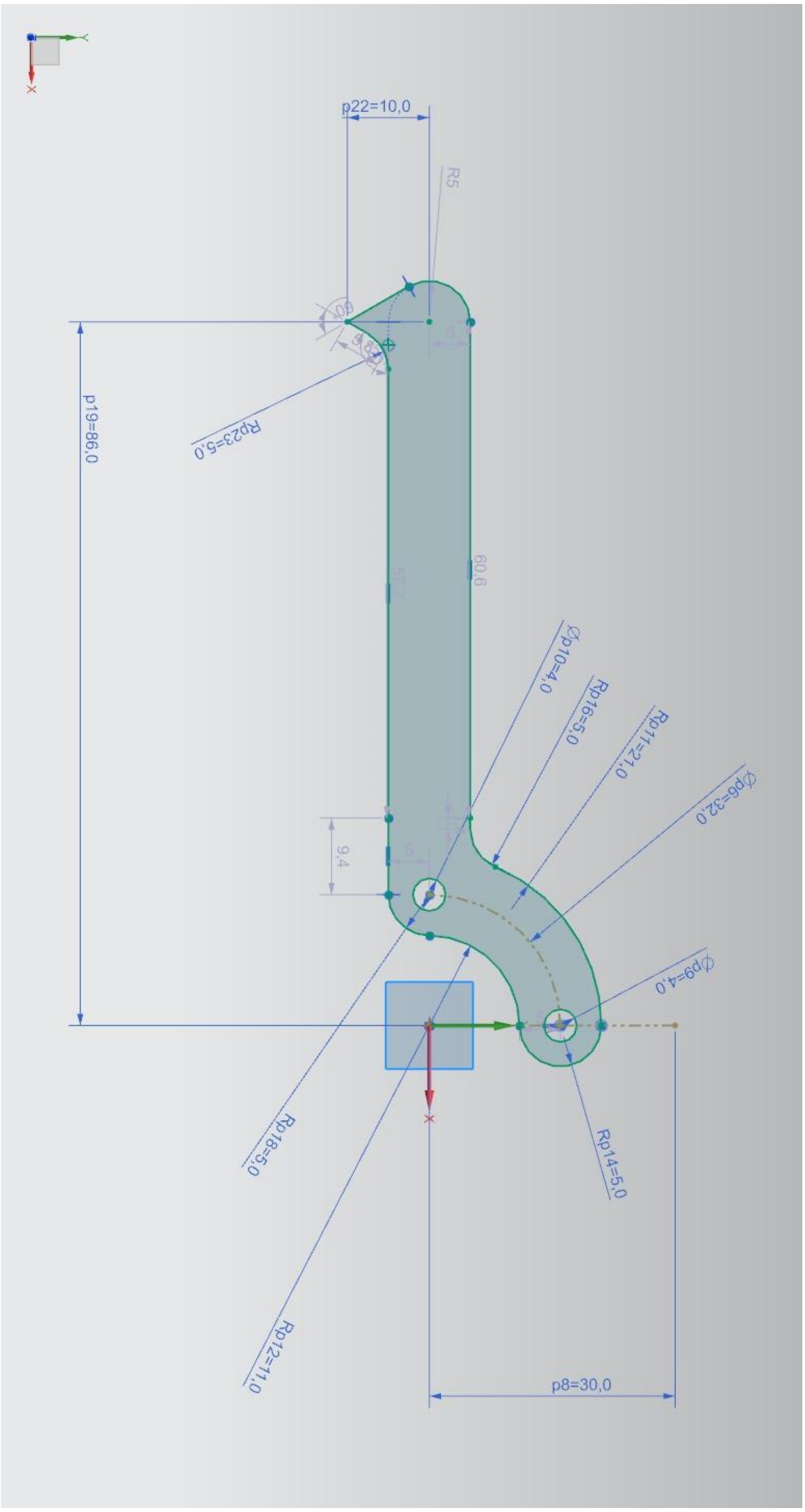
Appendix C


Power Supply 1
PWM Speed Controller
Test Motor
Shaft 1
Coupler
Shaft 2
Brake Motor
PWM Speed Controller
Power Supply 2
Fan
Encoder Disc Disc with Black Strap on
IR Optocupler Speed Sensor
IR Reflective Line Tracking Sensor
Microcontroller
I2C OLED Display
PC
Torque Arm
Load Cell

Appendix D



Appendix E



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R5
p19=86,0
Rp23=5,0
60,6
∅p10=4,0
Rp16=5,0
Rp11=21,0
∅p6=32,0
9,4
∅p9=4,0
Rp18=5,0
Rp14=5,0
Rp12=11,0
p8=30,0