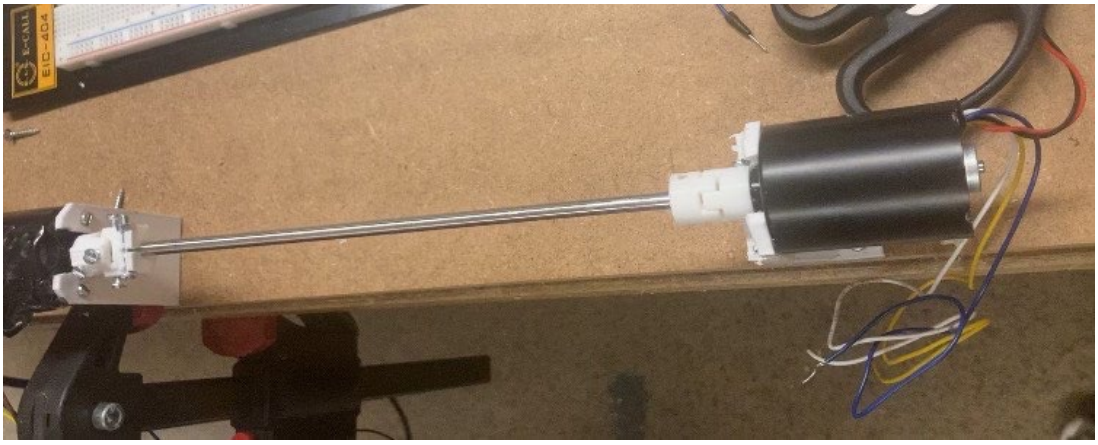
Building a Motor Test Bench Prototype



Examensarbete inom högskoleingenjörsprogrammet maskinteknik

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Abstract

In modern production machines, numerous electrical motors are used, and failures are common. To reduce downtime and improve reliability, anomaly detection by sensors can be used. The anomaly detection algorithms can discover abnormal patterns in the motor's performance and thus, give an early indication when failure is underway.

An issue with this, however, is that the subject is complicated to study, as real-life production machines are difficult to test with different failure scenarios.

The purpose of this project was to set up a test bench with two DC motors and sensors that could be used for studying anomaly detection algorithms.

A test bench was built with an MDF board as the base. On the board, two 3D-printed motor holders for the DC motors were attached along with two axis holders to mount an axis between the motors. An Arduino Mega was connected to control the motors and adjust the speed with a potentiometer. Additionally, a temperature sensor and a 3-axis accelerometer sensor were applied to the motor and connected to the Arduino Mega.

In conclusion, a prototype of a test bench for further development was created.

Keywords: Test bench, Arduino, DC motors, 3D printing, Prototype building

Acknowledgements

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1 Introduction

This chapter contains the problem statement, aim, and limitations of this project.

1.1 Background

The background to this project comes from an earlier test bench (see figure 1.1). That setup used a microcontroller to measure vibration changes in a DC motor when a servo motor drives a metal rod horizontally on the motor shaft while it rotates. This earlier test bench served as inspiration for a new design, where two DC motors were positioned opposite each other to simulate resistance from one motor while the other rotated. Consideration was also given to scaling the test bench to operate multiple motors simultaneously for comparative measurements.

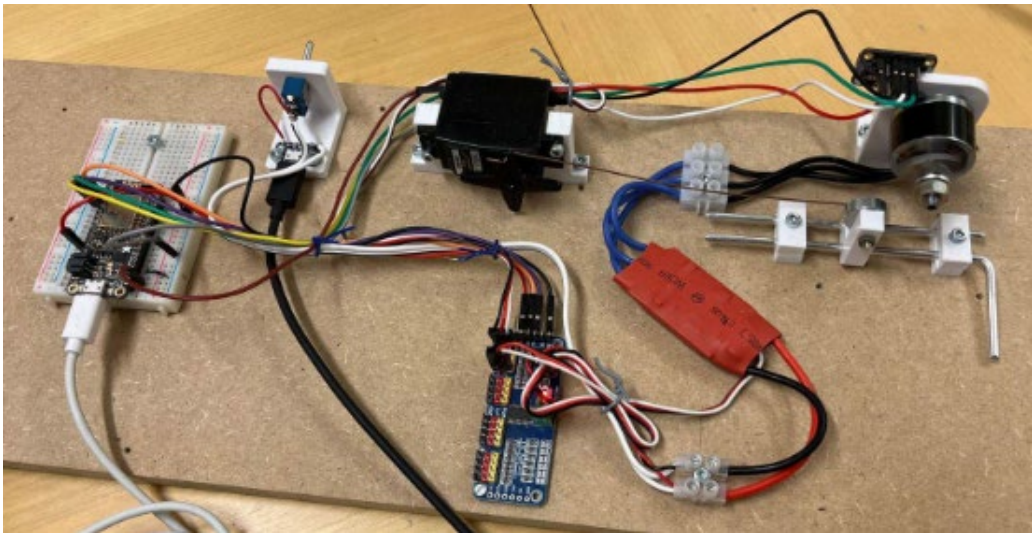

Figure 1.1: *Prototype Test Bench with DC motors built by Göran Stigler at Chalmers.*

1.2 Aim

This project aims to design and prototype a modular motor test bench that is both scalable and cost-effective. The new test bench should be capable of operating a pair of DC motors, with the option to expand to multiple DC motors. To achieve this, the design will employ low-cost components and materials, while also prioritizing ease of assembly and maintenance. The resulting prototype serves as a proof of

concept, demonstrating how inexpensive consumer hardware can be used to create a flexible platform for motor testing.

1.3 Limitations

The scope of the project was limited to testing a pair of DC motors, with only an evaluation of the potential for expansion. Sensor use was restricted, as implementing a larger number of sensors would have required additional time and resources. The test bench was constructed using wood and 3D-printed components, without the use of an aluminum frame or other time-intensive manufacturing processes. The primary focus of the project was on developing the physical test bench rather than software or electronics. No digital simulations of components were conducted, as the project group lacked sufficient experience with such tools.

2. Theory

2.1 Use of physical setups as a test bench

The use of a physical test bench enables the ability to try out different scenarios that a product may experience during its lifetime. It provides the possibility to measure performance under controlled conditions and ensures repeatability when conducting experiments (Keyence, n.d.).

2.2 Anomaly detection concept

Anomaly detection is a concept intended to analyze a system, such as a motor with sensors to monitor vibration, temperature, and current, and send data to the algorithm. The algorithm is then intended to identify outliers and anomalies from the data that can indicate an unintended change in the system. The anomaly can be a gear in the motor starting to fail and create anomalies for the algorithm to pick up, and can be detected with software that uses data from sensors to form patterns that are formed over time (Avalon, 2024).

2.3 Hall sensor

A hall sensor operates by sending a constant current through the sensor. When a magnetic field comes near the sensor, it will push the electrons in the sensor slightly to one side, causing a voltage difference in the sensor. These changes in voltage can be read to determine the speed of the DC motor by the rotating magnets in the rotor turning on and off the hall sensors as they rotate. Depending on how fast the sensors are switched on and off, the speed of the rotor can be calculated (Electronics Tutorials, n.d.).

2.4 NTC: Negative Temperature Coefficient thermometer

An NTC thermistor is a resistor where the resistance decreases as the temperature increases, typically following a nonlinear relationship (Dwyeromega, n.d.). Using this property, the Arduino measures the change in current through the sensor and calculates the corresponding temperature (see Appendix C).

2.5 Accelerometer

An accelerometer is a sensor that measures the small changes in motion; these small changes can be from vibration of the object on which the accelerometer is mounted.

It works by having a small mass that can move back and forth in one direction. This mass has small “fins” that go out from it that are situated between 2 other “fins” as seen in figure 2.1. This creates a small change in voltage depending on the distance between the fin from the mass and the two fins that are on either side of it. For an accelerometer to be able to read motions in x/y/z directions, it simply needs to have these small sensors oriented in each direction (Dwyeromega, n.d.).

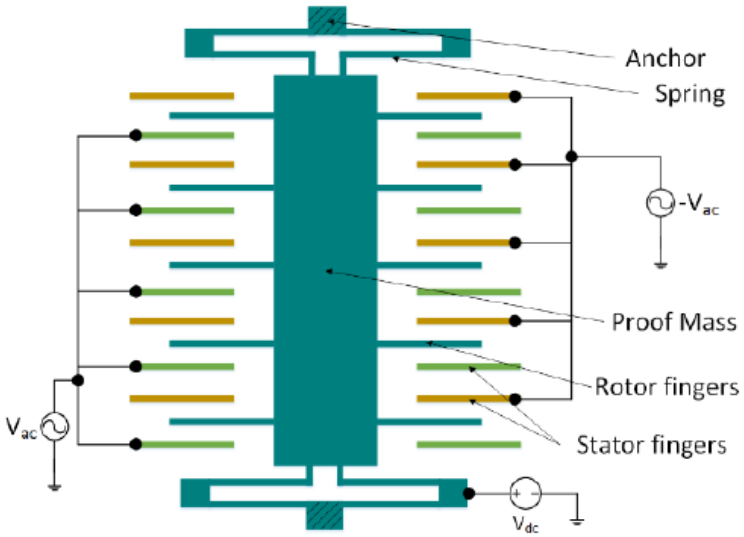

Figure 2.1: *Visual presentation of an accelerometer.*

Adapted from *Spring-design-for-the-accelerometer* by S. Sinha, S. Shakya, R. Mukhiya, & B. D. Pant, n.d., Openverse. Licensed under CC BY-SA 4.0.

2.6 Filaments used for 3D-printed parts

PLA (Polylactic Acid): PLA is currently the most widely used filament for 3D printers. It is a synthetic polymer made from renewable resources, most commonly from maize or sugar cane. It's created by fermenting starch or sugar, which is the base for the production of lactic acid. The lactic acid is used to create lactide, which can be synthesized into PLA. Since PLA is made from plant-based materials and is biodegradable, it’s environmentally friendly. It possesses good mechanical and physical properties and offers simple and reliable printability. The disadvantages of PLA include poor heat resistance, a low melting point, low impact resistance, and sensitivity to moisture. (Kuru & Kaya, 2023)

2.6.1 PET-G:

PET-G stands for Polyethylene Terephthalate Glycol, and it’s a non-toxic, recyclable thermoplastic polyester. It is a material that has better heat resistance and can withstand impact better than PLA. PET-G is a hydroscopic material that can absorb moisture from the air. Parts made of PET-G can turn brittle if not stored in a dry place. Compared to PLA, PET-G can be slightly more complicated to print (TWI, n.d.)

2.7 Arduino

The Arduino used in this project was Arduino Mega 2560. It is a microcontroller that can be used either by connecting it to a computer using a USB cable or by using batteries or an AC-to-DC adapter. An Arduino board can read a variety of input signals through sensors, like temperature, vibrations, and speed. It also has built-in support for pulse width modulation (Arduino, n.d.).

A microcontroller can be described as a computer on a small, single chip that is created to do specific tasks within a built-in system (Schneider & Smalley, 2024).

2.7.1 Arduino IDE

The Arduino IDE is the software used to program the Arduino boards. It's an open-source software based on the C++ programming language that can be used with both Microsoft Windows, Mac OS, and Linux (Chatterjee, 2023).

2.8 PWM (Pulse Width Modulation)

Pulse Width Modulation can be described as a system that lets one single data connection control analog signals from a digital output. It controls the signals by switching constantly between a LOW and a HIGH output at an even interval.
Duty cycle and frequency are the two main parameters of PWM. The period is measured in seconds and displays how long it takes for the signal to complete one cycle. Frequency, measured in Hertz, Hz, is the number of full periods the signal can complete within one second, and a full period is when the signal goes from LOW to HIGH and back to LOW again. This pattern is then repeated.

The period and the frequency are closely connected, and the frequency affects the length of the period; the slower the frequency becomes, the longer the period, and thus, a faster frequency creates shorter periods (Toulson & Wilmshurst, 2016).

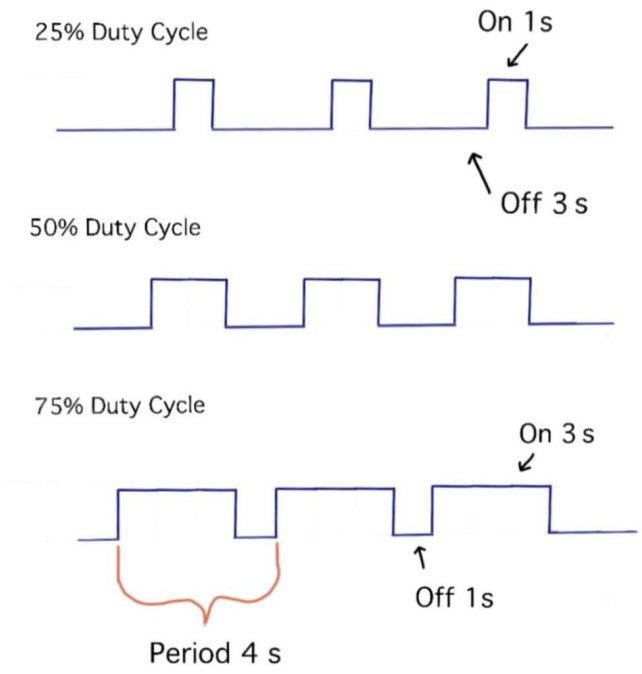

Figure 2.2: *Pulse Width Modulation demonstration. Adapted from Borkar (n.d.)*

The PWM can be used to simulate the voltage between 5V and 0V on the Arduino Mega Board. This can be done by changing the ratio of how much the signal spends being switched on and off. The Pulse Width is the part where the signal is the part of the time during which the signal is switched on, and to get different analog results, the PWM can be changed (Hirzel, 2022).

PWM has an important role in this project since it is used to regulate the speed and torque of the brushless DC motor. This is accomplished by controlling the voltage supplied to the motor; a long pulse width gives the motor a higher voltage, and thus, increases its speed and gives higher torque, while a low pulse width gives it a lower amount of voltage, which slows the speed down and decreases the torque. The Duty cycle represents the amount of time, in percent, the DC motor is supplied with power during each cycle; a long cycle means more power to the motor, while a shorter cycle means less. When the motor starts, the duty cycle is initially low, but as the speed increases, the duty cycle becomes larger, and as both the voltage and speed increase. When the desired speed has been reached, the built-in controller adjusts the duty cycle to maintain it. With the DC motors' hall sensors, the PWN can adjust

the speed based on real-time input from the sensors. A lower speed can be received in the same manner, by reducing the voltage to the motor, the duty cycle gets smaller, and for an abrupt stop, the duty cycle is set to zero. For brushless DC motors, the PWM technique is a good way to control speed that is both efficient and offers precise speed control (Borkar, n.d.).

2.9 Brushless DC Motors

DC motors are commonly used for motor control applications, and two widely used versions are DC motors with brushes and brushless DC motors. Both variants rely on attraction and repulsion between coils and permanent magnets to function. The brushes are used to control the current direction to make the motor axis rotate, while the brushless DC motors use electrical control for this purpose. A brushless DC motor has permanent magnets fixed to the rotor, and the stator has windings, usually three connected in either “star” or “delta” configuration. It runs by using electrical commutation to rotate the stator’s magnetic field, and to do this, active control electronics are used (Millett, 2022).

The DC motors can rotate in each direction by connecting the white wire to ground or leaving it unconnected. The speed is controlled by sending PWM signals to the blue wire. The yellow cable sends out the hall signal to the Arduino for rpm monitoring. (Appendix A)

3. Method

3.1 Use of artificial intelligence

Artificial intelligence (AI), with an emphasis on large language models (LLMs), has been developed rapidly in recent years. Their misuse has also increased, particularly within academic contexts.

As noted by Masukume (2024), “The analysis reveals a surge in the use of “delve”, “realm” and “underscore”—words presently associated with AI chatbots—during 2023

and 2024, highlighting the growing influence of AI chatbots like ChatGPT, introduced in November 2022, on academic writing".

This clearly visualizes the problem as seen in figure 3.1, relying on LLMs and copying the output from the LLMs with very little input from the publisher.

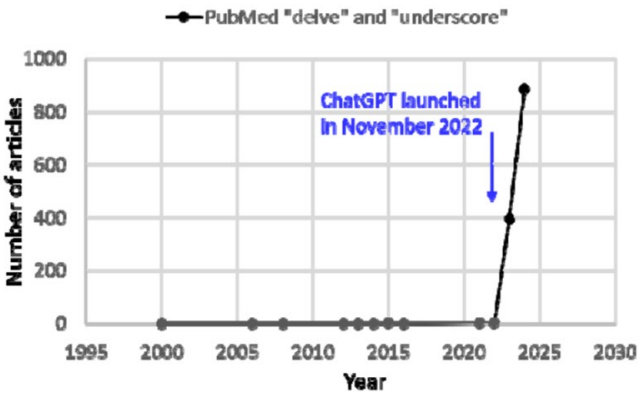

Figure 3.1: *Use of "delve" and "underscore" in academic papers compared to the launch of ChatGPT*

LLMs can't be used at face value and need skepticism when using them, as they can make up or lie about facts and statements as truth, while in reality, they are false. It can be a great use to get the ball rolling or help you if you are stuck on some part when writing. But it can't be relied on solely, and for this project, if there are some problems or a lack of understanding, ChatGPT has been used to explain and give examples to better understand the problem.

3.2 Software

The initial Arduino code was generated using ChatGPT. For example, an input such as "Write code for an Arduino Mega board for an NTC sensor". The generated code was then modified based on the project's requirements. Assignment of the ports for the Arduino's input and outputs was assigned based on what else was connected to the Arduino, see appendix A-C.

3.3 System Description

The motor test bench setup consists of a wooden board on which all components are fastened (figure 3.2). The motors are secured in 3D-printed motor holders that are attached to the board with screws. The motor shafts are connected to a common rod via 3D-printed adaptors. Sensors are connected to one motor to measure vibrations and temperature to the Arduino. Hall sensors are connected to both motors to measure the speed of the motors. The Arduino controls the speed of the motors by sending out PWM signals to them.

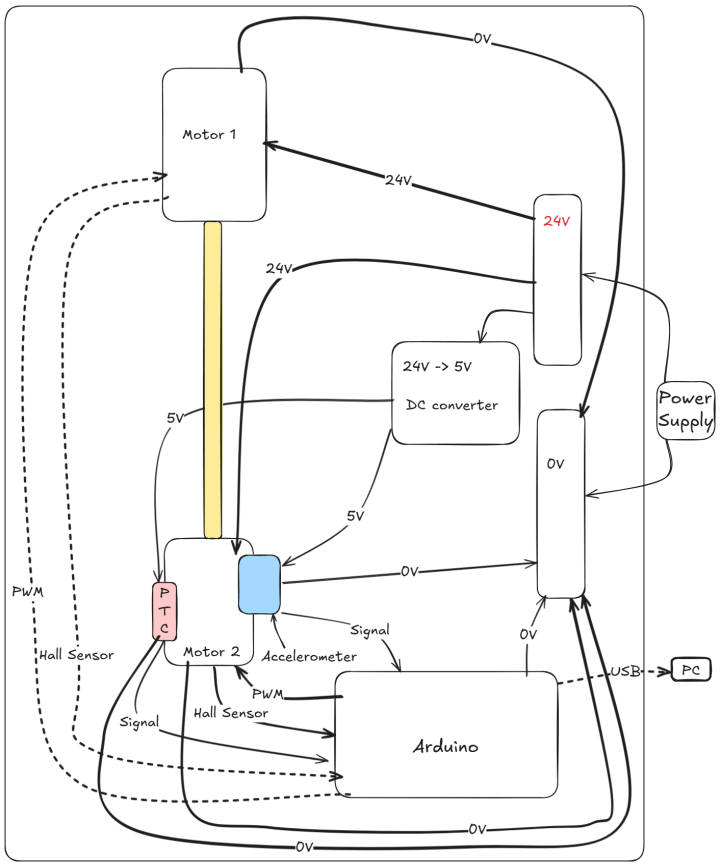

Figure 3.2: *Schematic of the test bench*

3.4 Initial information gathering

Information gathering started with discussions with the customer and by reviewing related projects. The customer provided a photo (figure 3.3) of a prototype of a test bench with DC motors mounted on an MDF board to give an idea of what the final product could look like. The customer specified that the test bench would have to feature two 24V DC motors and be controlled by Arduino and Raspberry Pi.

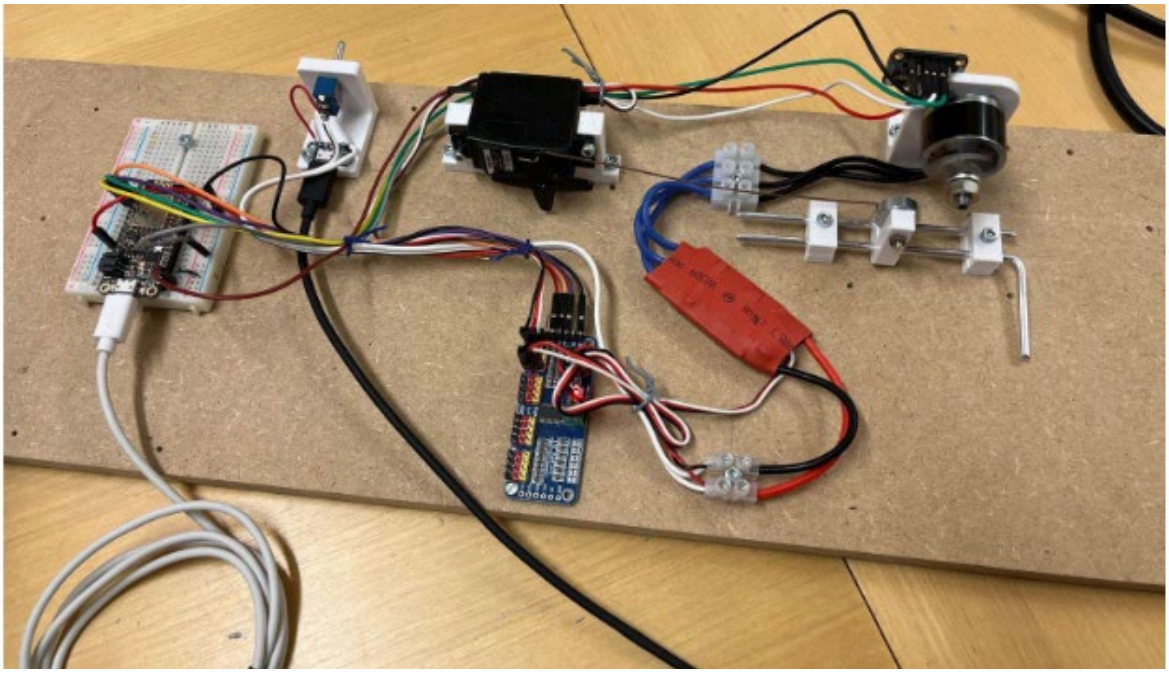

Figure 3.3: *Prototype Test Bench with DC motors built by Göran Stigler at Chalmers, (duplicate of figure 1.1).*

For the project, the customer specified that small motors would be used, small enough to be fitted on an MDF board and small enough to enable stacking of several test benches in a lab setting. To allow this, it was decided that the entire test bench would have to be at a size that makes handling and moving it easy enough to be done by one person.

A customer demand specification was created (appendix D), and once the frames were set for the prototype. To learn about how these could be used for the project, guidebooks, online tutorials, and an Arduino Test Kit were used for training.

The use of brushless DC motors or DC motors with brushes was discussed, and after a comparison of the two options, it was decided early on that brushless motors would be used since they have a longer lifespan than motors with brushes.

The choice of using an MDF board as the base for the testbench was decided after a recommendation from the customer and by looking at the prototype used as a template. It was also a material that was already available in the lab where the test bench would be constructed. The board was cut into 60x40 (cm) to make it a size that would be easy to handle.

Holders for the two motors that would allow the construction the customer requested were not available to order; therefore, it was decided that 3D printing would have to be used to create custom holders for the motors. Several types of filament were compared, and ABS plastic was the choice that filled all the requirements.

Since ABS filament was not available at the lab, a prototype of the holders was made with PLA plastic.

The motors used came with a gearbox attached that was removed in the PSL labs to be able to connect it to the axis. Once the gearbox was removed, only a small gear remained. It could not be removed without risking damaging the motor. To attach the axis between the gears of the two motors, an axis coupler had been ordered. On arrival, it was discovered that the axis-coupler's diameter of 6 mm didn't fit with the gear's diameter of 6,2 mm.

Figure 3.4: *After removing the gearbox, a gear remained.*

To solve that issue, a horizontal lathe was used to drill bigger holes in the axis, and it was also used to press fit the axis coupler onto one of the motors. The other axis coupler was attached manually in the PSL lab, and it was then discovered that there was a slight angle to the motor holders, which caused friction issues when running.

It was discovered during the test process that there was a need to be able to take apart the axis coupler and put it back on again. This made it impractical, since to attach the coupler with a lathe to get a good fit required both a lathe (which the project group didn't have access to at the PSL) and to attach it, it required the removal of both motors from the holders.

To solve this issue, new axis couplers were needed that were easier to attach with simpler tools and without removing the motors from the holders.
Two new, simpler couplers were created in CAD and printed out in PLA. They were constructed so that they could be pressed on or attached with the help of a rubber hammer.

Two new holders for the motors were developed from the ones that came with the motor, figure 3.5. The new motor holders made it possible to easily fit the holders onto both the motor and the MDF board.

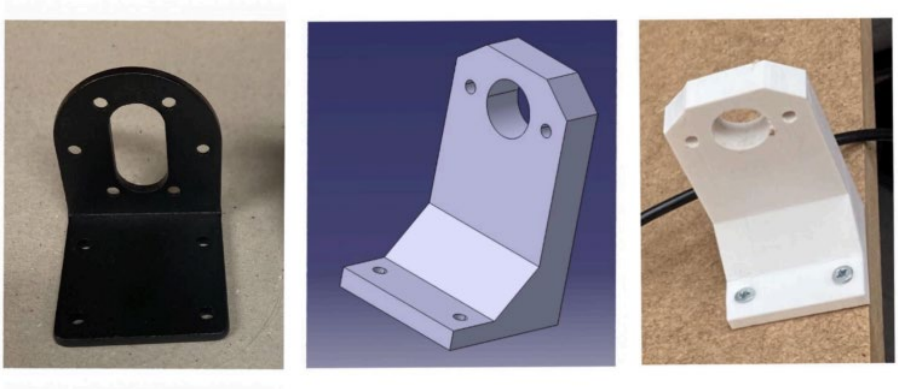

Figure 3.5: *Motor holder in metal that came along with the motors, CAD model of the second design, Motor holder of the second design printed in white PLA.*

After testing the new holders, it was discovered that it was complicated to screw them onto the board with the motors connected to them. This meant that the motors and the rod would need to be installed after the holders were attached to the board.

3.5 Rapid prototyping

“Rapid prototyping is a group of techniques used to quickly fabricate a physical part or assembly from a three-dimensional design. With rapid prototyping, engineers and designers can create a better final product, iterating several times between digital designs and physical prototypes with a quick and cost-effective workflow” (Formlabs, n.d.).

To develop the motor test bench, the rapid prototyping method was selected. This meant that the development of new parts for the test bench was made in CAD and 3D-printed to test out the design and functionality of the part. Through an iterative process, every new part will have improvements compared to the previous one. It is then printed and tested out with the motor test bench, and depending on performance, it’s either kept or used as a base for a new version of it that would be re-designed in CAD, printed out, and tested again.

The focus was on redeveloping parts and not calculating and simulating the parts, but instead on testing them by trial and error.

4. Results

4.1 Motor holders

The design of the motor holder was changed several times. After the removal of the gearboxes, the pre-bought holder didn’t fit the motors. A new design was therefore modeled in CAD and produced in PLA.

During testing, the second version of the axial holders obstructed the shaft rotation, as the shaft made contact with the adjacent motor holder. To resolve this, material was gradually removed from the holder until sufficient clearance was achieved. This, however, compromised stability, and the PLA holder became unsuitable for continued use. Consequently, the holders were redesigned to be thinner and reprinted in PET-G with 100% infill (Figure 4.1).

The final PET-G design allowed unrestricted shaft rotation and provided improved heat resistance and structural stability compared to the PLA prototypes.

Figure 4.1: *Sawed PLA version of motor holder and final version in PET-G.*

4.2 Motors

The DC motors came with a pre-attached gearbox that was not needed for this project. The gearboxes were therefore removed, and the gear that was left functioned as the motor shaft.

4.3 Coupler

The first couplers tested were metal axis couplers. After gearbox removal, the couplers did not fit on the motors anymore and had to be drilled to be able to fit on the axis. One coupler was press-fitted onto the motor shaft using a lathe, while the second was manually attached in the PSL laboratory (figure 4.2).

Figure 4.2: *First axial holder fitted onto the gear of the motor.*

Subsequent testing revealed alignment challenges, as the couplers were difficult to reattach at precise angles. Because repeated assembly and disassembly were required, this solution proved impractical.

A simpler design was developed, and new, simpler axis couplers were printed out in PLA. These allowed faster attachment but demonstrated insufficient durability. The gear of the motor gouged out the holder,s and the new PLA couplers broke, see figure 4.3.

Figure 4.3: *Critical failure of the test version of the coupler.*

A second set of couplers was designed with a spider configuration. This design provided improved grip on the gear and the axis and allowed a small angle difference between the gear and the axis couplers. They can be further secured onto the objects by screwing in a screw and a nut to tighten the grip.

4.4 Arduino

The Arduino served as the central controller for the test bench. It reads the data from the DC motors' hall sensors, the NTC sensor, and the accelerometer. It also sends out PWM signals to the motors. A potentiometer was connected to the Arduino to allow manual adjustment of the PWM signal during operation.

5. Discussion

5.1 Building the final version of the test bench

The motors were powered by a 24 V, 120 W power supply. To enable multiple connections, the positive and negative wires were stripped and connected to a coupling bridge. Standard color coding was maintained (red = positive, black = negative) to minimize the risk of short circuits. Additional visual markings were applied to the connections to further reduce the possibility of incorrect handling.

Components requiring 5 V were supplied via a DC–DC converter, stepping down from the 24 V input. To be sure that all the cables are connected correctly a multimeter is used to both test that each corresponding cable is connected correctly

and then turn on the circuit and measure the voltage between positive and negative for both 24 V and 5 V.

The mounting brackets for the motors need to be fastened as precisely as possible for the lowest possible angle difference when connecting the motors to the rod. The motors have 5 cables that correspond to: red = 24 V (positive), black = 0 V (negative), white = decides what way to turn based if connected to ground for turning counterclockwise and disconnected for clockwise, yellow = hall signal, blue = wpm signal for controlling speed (Appendix F).

The NTC sensor is connected with a 5 V connection from the DC–DC converter and 0 V ground to the power supply. The signal cable from the NTC sensor is connected to the Arduino for it to read the signal and calculate the temperature (Appendix C). The sensor needs to be close to the motor for it to accurately read the temperature of the motor in operation. This can be done by simply taping the legs of the sensor with electrical tape to the motor and not covering the sensor itself. A permanent mount was identified as a preferred solution for long-term stability.

The accelerometer was mounted in a similar manner and reinforced with screws to maintain alignment. The 5 V power and 0 V ground connectors were connected to the DC converter, while the signals for the x/y/z axis signals were connected to the Arduino; see Appendix B for a code example. The Arduino sends out PWM signals to the motors for control of the speed with the blue cable from the motors. The hall sensor (yellow) is also connected to the Arduino for the read of the hall sensors in the motors. With calculations, the rpm can be calculated from the hall sensors to read out the actual rpm from each motor and compare it to what the Arduino PWM signal sent out.

An issue was encountered when the Arduino was simultaneously powered by the DC–DC converter and connected via USB to a computer for monitoring. This configuration appeared to backfeed current into the USB connection, resulting in error messages from the operating system. This highlighted the importance of implementing a more robust power management strategy in future iterations.

The first version of the motor holders was severely prone to vibration due to the 90° angle between the vertical and horizontal sections, see appendix E. It was reduced by adding a ramp at the angle point for added support against vibrations.

It was observed that a test bench needs as little time as possible to adjust parts. The original holders included a bridge over the shaft hole, which made it impossible to remove couplers without detaching the motors. To resolve this, the holders were redesigned into a U-shape (figure 5.1), allowing couplers to be detached without full disassembly.

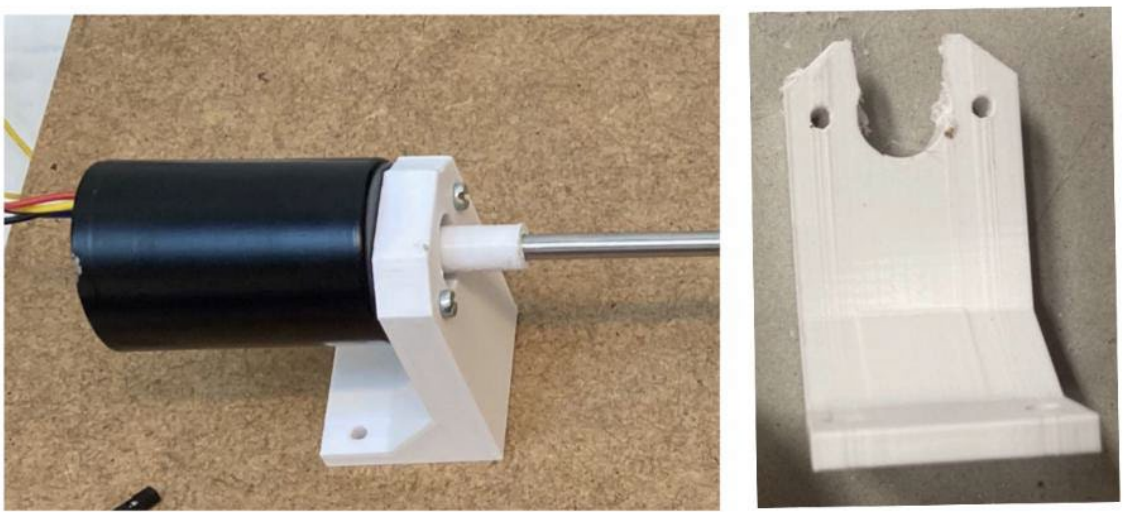

Figure 5.1: *Holder before and after the hole over the bridge was created.*

Additional interference was caused by the screw-and-nut fastener (figure 5.2) on the couplers, which collided with the motor mounting screws. This was solved by countersinking the motor mounting screws, ensuring clearance for coupler rotation. The screws to fasten the motor holder to the board were first designed to be under the motor, which made it impossible to secure the holder while the motor was attached to it. Redesigning the holder with the holes moved outward allowed fastening while the motors remained mounted.

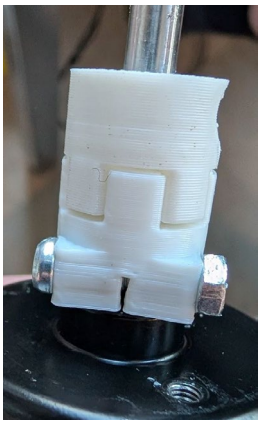

Figure 5.2: *Spider coupler printed with PLA*

Trials of universal couplers demonstrated further limitations. The first prototype suffered structural failure due to insufficient wall thickness around the screw holes (figure 5.3). A second prototype failed due to restricted angular flexibility caused by filament shrinkage during printing. In contrast, spider couplers provided superior performance, offering tolerance for misalignment and greater reliability.

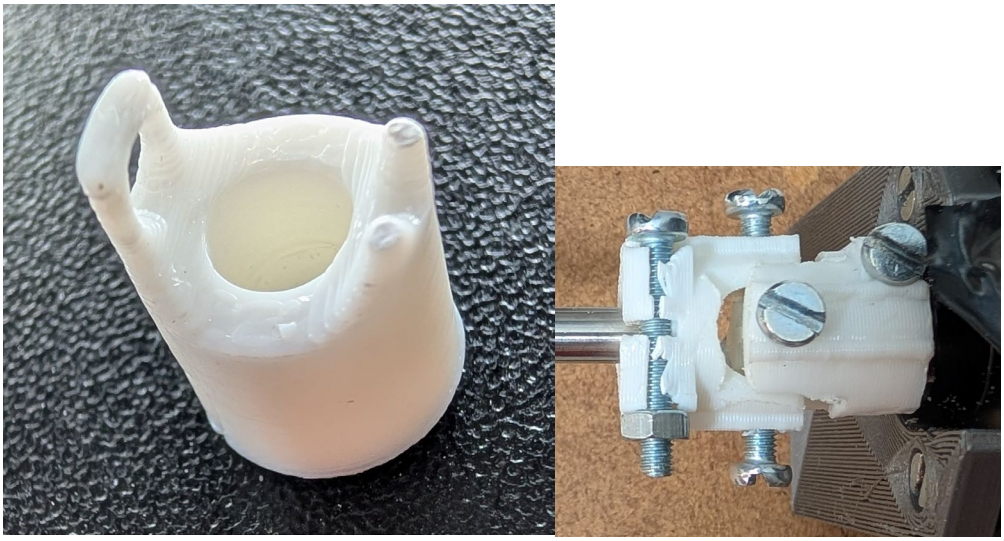

Figure 5.3: *Critical failure of universal coupler V1, Cracking of universal joint coupler V2*

5.2 Choosing material for the 3D-printed parts.

A comparison between the most common filaments for FDM 3D printing was conducted before printing. Since the DC motors wouldn't generate much power, but would become hot over time, the most important need was that the material needed to be able to withstand around 80 degrees, and for this purpose, ABS or Nylon would be the best choice for the final prototype.

Due to the unavailability of enclosed 3D printers, it was not possible to utilize Nylon or ABS in the prototype development.

For prototype evaluation, PLA was selected due to its availability in the laboratory. The material was considered sufficient for initial testing and could later be replaced once the final design was determined.

Table 1: Comparison table of abilities of common filament materials.

Filament	Heat Deflection	Impact Resistance	Tensile Strength	Needs Enclosure
PLA	Low	Very Low	Good	No
ABS	Very Good	Moderate	Moderate	Yes
PET-G	Moderate	Moderate	Good	No
Nylon	Very Good	Moderate	Moderate	Yes

Adapted from Prusa Research by Josef Prusa (n.d.).

5.3 Sustainability

The base of the test bench was manufactured from medium-density fibreboard (MDF). This material is composed of sawmill by-products such as sawdust and wood chips, making it more environmentally sustainable than virgin wood. However, MDF requires the use of adhesives, which are often non-biodegradable and may contain toxic compounds. Recycling of MDF is possible but less straightforward compared to pure wood (Nguyen, n.d.).

PLA is environmentally friendly since it is made of corn starch that is biodegradable. PET-G is less environmentally friendly than PLA as it is made from products derived from crude oil. It’s not biodegradable and can be harmful to the environment if not properly handled at the end of its life cycle. Both PET-G and PLA can be recycled (de Naoum & Piccoli, 2022).

ABS was the most suitable material for the finished product as it is a tough and sturdy material. However, it is not as sustainable as either PLA or PETG. ABS is not biodegradable as it's made from oil-based raw material. It contains chemicals that are toxic to both humans, animals, and the environment when it breaks down, and it also emits toxic fumes when printed. It is also difficult to recycle for several reasons; the components of ABS are chemically bonded to each other and are complicated to separate. At the end of its lifecycle, ABS has often been contaminated during usage, and it has poor thermal stability. As a consequence of this, recycled ABS has lower quality than virgin ABS (Nyländen, 2024).

An alternative material for the final version of the motor holders would be steel. Steel provides superior durability, higher temperature tolerance, and easier recyclability compared to ABS.

Using brushless motors instead of brushed motors is a more sustainable choice since they have a longer lifespan and need less maintenance, and there are no brushes that need to be replaced (Millett, 2022).

5.3.1 Social and Economic Sustainability

Affordability and Accessibility: The goal of inexpensive, scalable benches inherently supports broader accessibility in research labs, educational institutions, and small-scale industries. Low-cost, open-source designs promote knowledge sharing and reduce duplication of resource-intensive development.

6. Conclusion and Future Development

6.1 Conclusion

The project successfully produced a prototype of a scalable test bench with the possibilities of the Arduino to control more sensors and motors. Ease of assembly was achieved by all parts being able to connect and disconnect independently from each other to assemble and disassemble the different parts of the test bench.

However, the prototype did not achieve the level of functionality required for replication and long-term use without further modifications. The design still requires replacement of certain components, such as the motors and axis couplers, with more durable and heat-resistant alternatives. Additionally, permanent sensor mounts capable of withstanding higher operating temperatures remain to be implemented.

In conclusion, the current state of the test bench offers a solid ground for future development, and with further adjustments and improvements, it can fully reach the end goal of the project to produce a test bench for the detection of motor anomalies that can be used over a longer time frame.

6.2 Future Development

Future improvements to the test bench include the replacement of the DC motors for a model that has a regular pin instead of a gear. This change would simplify coupling, reduce wear, and improve alignment.

The current motor holders are limited to a side-by-side arrangement, which restricts the number of motors that can be installed within a single bench. As the long-term goals are to have tens to hundreds of motors running at the same time the need in exploring the possibilities of having motors be able to stack on top of each other is a valuable approach to consider. There were some initial sketches for this approach as seen in figure 6.1 with aluminium extrusion at each side of the motor, with the possibility of stacking several motors on top of each other and mounting a sensor or more motors at the other sides of the aluminium extrusion. With stackable motors in the vertical direction, there will be a need to allow a height difference between the opposing motors. Universal couplers would be particularly suitable as a coupler to use for the height difference, as they allow for differences in angle and height.

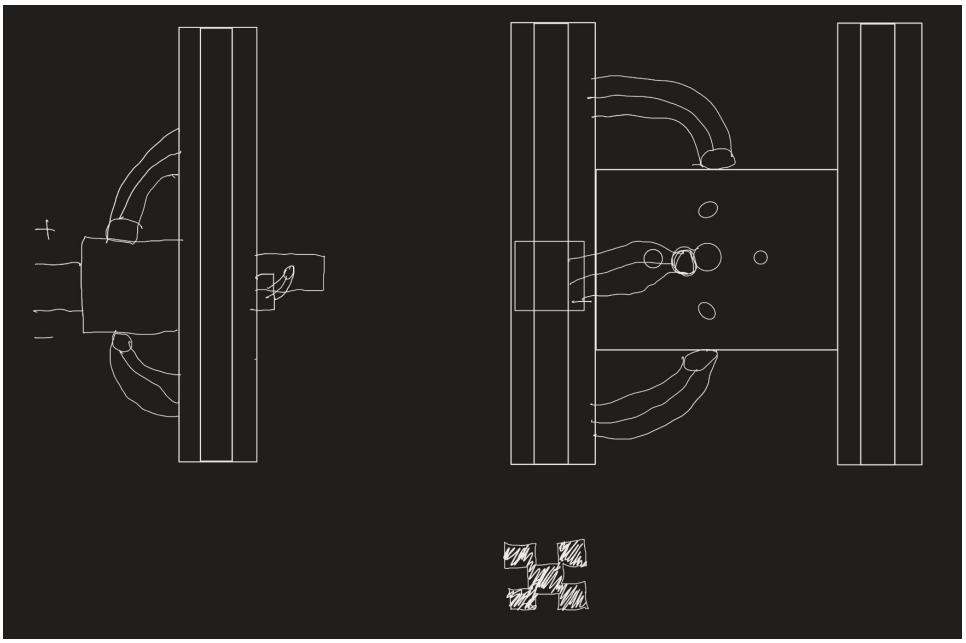

Figure 6.1: *Sketch of stackable motors and sensors on aluminium extrusions*

In addition, future versions should expand the range of sensors. Beyond the temperature and accelerometer sensors already tested, integration of current sensors and tachometers would enhance monitoring accuracy and provide valuable comparative data. To support these additions, sensor holders should be manufactured from heat-resistant materials such as ABS and designed for easy sensor replacement.

Finally, the integration of a Raspberry Pi for control and data acquisition, as outlined in the project proposal but not implemented within the current timeframe, should be prioritized. Such integration would significantly expand data logging capabilities and enable remote monitoring of the test bench.

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8. Appendix

Appendix A: Chatgpt generated code for Arduino PWM potentiometer control and hall sensor

```
// Define the pins
const int potPin = A0;  // Potentiometer connected to analog pin A0
const int ledPin = 9;   // LED connected to digital pin 9 (PWM pin)
const int hallPin = 2;
void setup() {
  // Set the LED pin as an output
  pinMode(ledPin, OUTPUT);
  Serial.begin(9600);
}

void loop() {
  // Read the potentiometer value (0 to 1023)
  int potValue = analogRead(potPin);

  // Map the potentiometer value to a PWM range (0 to 255)
  int pwmValue = map(potValue, 0, 1023, 0, 255);

  // Write the PWM value to the LED pin
  analogWrite(ledPin, pwmValue);

  // Small delay for smoother transitions
    int hallState = digitalRead(hallPin);  // Read the Hall sensor (HIGH
or LOW)

  // Print the Hall sensor state to Serial Monitor
  Serial.print("Hall Sensor State: ");
  if (hallState == HIGH) {
    Serial.println("HIGH");
  } else {
    Serial.println("LOW");
```

```
  }
  delay(5);
}
```

Appendix B: Chatgpt generated code for Arduino accelerometer

```
#include <Wire.h>
#include <Adafruit Sensor.h>
#include <Adafruit_ADXL345_U.h>
// Create an ADXL345 accelerometer object
Adafruit_ADXL345_Unified accel = Adafruit_ADXL345_Unified(12345);
void setup() {
  // Start the serial communication
  Serial.begin(115200);
  // Initialize the sensor
  if (!accel.begin()) {
    Serial.println("Ooops, no ADXL345 detected ... Check your wiring!");
    while (1);  // Stay here forever if no sensor is found
  }
  // Set the range to ±16g (you can also use ±2g or ±4g depending on your
needs)
  accel.setRange(ADXL345_RANGE_16_G);
  Serial.println("ADXL345 Initialized.");
}
void loop() {
  // Create a sensor event object to hold the accelerometer data
  sensors_event_t event;
  accel.getEvent(&event);
  // Print the acceleration values for each axis (X, Y, Z)
  Serial.print("X: ");
  Serial.print(event.acceleration.x);
  Serial.print(" m/s², ");
  Serial.print("Y: ");
  Serial.print(event.acceleration.y);
  Serial.print(" m/s², ");
  Serial.print("Z: ");
```

```
  Serial.print(event.acceleration.z);
  Serial.println(" m/s²");
  // Add a small delay before the next read
  delay(200);  // Adjust the delay for smoother or faster readings
}
```

Appendix C: Chatgpt generated code for Arduino NTC sensor

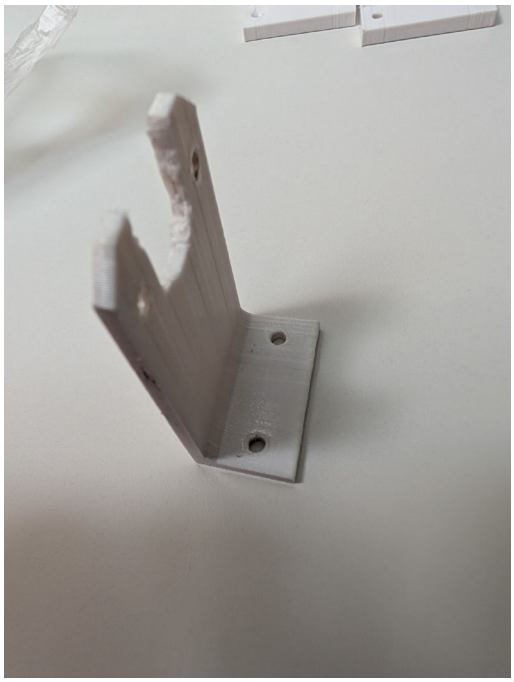
```
/*
HOW TO CONNECT NTC SENSOR:
(VCC 5V)
   |
   |
 [NTC Thermistor]
   |
   |--------> A0 (Analog pin on Arduino)
   |
 [Fixed Resistor]
   |
  GND
*/
const int ntcPin = A5;
const float seriesResistor = 10000; // Your fixed resistor in ohms
const float nominalResistance = 10000; // Resistance at 25°C
const float nominalTemperature = 25; // In Celsius
const float bCoefficient = 3650; // Look this up for your specific
thermistor
void setup() {
  Serial.begin(9600);
}
void loop() {
  int analogValue = analogRead(ntcPin);
  // Convert the analog reading to resistance
```

```
  float voltage = analogValue * 5.0 / 1023.0;
  float resistance = seriesResistor * (5.0 / voltage - 1.0);
  // Calculate temperature using the Beta formula
  float steinhart;
  steinhart = resistance / nominalResistance;     // (R/Ro)
  steinhart = log(steinhart);                     // ln(R/Ro)
  steinhart /= bCoefficient;                      // 1/B * ln(R/Ro)
  steinhart += 1.0 / (nominalTemperature + 273.15); // + (1/To)
  steinhart = 1.0 / steinhart;                    // Invert
  steinhart -= 273.15;                            // Convert to °C
  Serial.print("Temperature: ");
  Serial.print(steinhart);
  Serial.println(" °C");
  delay(1000);
}
```

Appendix D: Customer demand specification

	Description	Demand	Wish	Priority 1=high 2=medium 3=low
1	Test Bench should be able to be stackable/connectable	D		2
2	Data collection is shareable through the cloud		W	3
3	Control the Test Bench through Raspberry Pi		W	3
4	Replaceable motors with plug-in/out wires	D		2
5	Sensors can register vibrations	D		1
6	3D-printed platform		W	2
7	Screwed connections	D		2
8	Sensors can register additional parameters		W	3
9	Easy to replicate	D		1
10	DC Power supply	D		1
11	Motor fixture should be able to resist =<80C	D		1
12	Ability to run Test Bench remotely		W	3
13	Remote data collection		W	3

Appendix E: First version of the holder for motors with the bridge removed



Appendix F: Google Lens photo translate of instructions manual to motors from Chinese to English