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Team 513: Danfoss – Automated Shaft Flux Measurements

9/26/2023



# Abstract

The abstract is a concise statement of the significant contents of your project. The abstract should be one paragraph of between 150 and 500 words. The abstract is not indents.

*Keywords*: list 3 to 5 keywords that describe your project.

# Disclaimer

Your sponsor may require a disclaimer on the report. Especially if it is a government sponsored project or confidential project. If a disclaimer is not required delete this section.

# Acknowledgement

These remarks thank those that helped you complete your senior design project. Especially those who have sponsored the project, provided mentorship advice, and materials. 4

* Paragraph 1 thank sponsor!
* Paragraph 2 thank advisors.
* Paragraph 3 thank those that provided you materials and resources.
* Paragraph 4 thank anyone else who helped you.

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# Notation

|  |  |
| --- | --- |
| A17 | Steering Column Angle |
| A27 | Pan Angle |
| A40 | Back Angle |
| A42 | Hip Angle |
| AAA | American Automobile Association |
| AARP | American Association of Retired Persons |
| AFM | Automated Flux Measurement (Device) |
| AHP | Accelerator Heel Point |
| ANOVA | Analysis of Variance |
| AOTA | American Occupational Therapy Association |
| ASA | American Society on Aging |
| BA | Back Angle |
| BOF | Ball of Foot |
| BOFRP | Ball of Foot Reference Point |
| CAD | Computer Aided Design |
| CDC | Centers for Disease Control and Prevention |
| CU-ICAR | Clemson University - International Center for Automotive Research |
| DDI | Driver Death per Involvement Ratio |
| DIT | Driver Involvement per Vehicle Mile Traveled |
| Difference | Difference between the calculated and measured BOFRP to H-point |
| DRR | Death Rate Ratio |
| DRS | Driving Rehabilitation Specialist |
| EMM | Estimated Marginal Means |
| FARS | Fatality Analysis Reporting System |
| FMVSS | Federal Motor Vehicle Safety Standard |
| GES | General Estimates System |
| GHS | Greenville Health System |
| H13 | Steering Wheel Thigh Clearance |
| H17 | Wheel Center to Heel Pont |
| H30 | H-point to accelerator heel point |
| HPD | H-point Design Tool |
| HPM | H-point Machine |
| HPM-II | H-point Machine II |
| HT | H-point Travel |
| HX | H-point to Accelerator Heel Point |
| HZ | H-point to Accelerator Heel Point |
| IIHS | Insurance Institute for Highway Safety |
| L6 | BFRP to Steering Wheel Center |
|  |  |
|  |  |
|  |  |

# Chapter One: EML 4551C

## Project Scope

### Project Description

The objective of this project is to design a device that will be capable of fully measuring and recording the magnetic flux of the magnetized portion of the compressor shafts in an automated way that allows for accurate measurements, repeatability, and less overall firsthand work for the operator.

### Key Goals

The primary goal of this project is to design a device that can automatically collect data for the magnetic flux of the shaft. With the current legacy device, Danfoss reports that they have wasted time and resources with their need to manually run it as well as lacking the availability to invest their own time into these improvements. Therefore, this new device must limit the need to monitor the measurement and reduce the overall amount of operator input. The device itself must also be able to take measurements every 5mm in circumference and every 5mm axially or better. This device needs to be compatible with Danfoss’s VT series shafts. The accuracy, repeatability, and reliability of this device is very important to the customer, and it must be created with as much non-magnetic material as possible to avoid skewing the measurements.

### Markets

Our primary market for this device is Danfoss Turbocor, as they have approached and sponsored Team 513 to resolve the time and resource consuming issue of obtaining accurate and consistent magnetic flux measurements on their compressor shafts.

Secondary markets for this project would include other companies in the manufacturing industries such as Denso, or Saylor-Beall that also utilize magnetic shafts. Another applicable secondary market would be companies invested in magnet testing such as the National High Magnetic Field Laboratory or the Applied Superconductivity Center since this project could provide consistent measurements useful in research.

### Assumptions

To ensure project completion, it is assumed that one flux meter and one sensor will be used and that they both will be correctly calibrated and supplied for us by Danfoss. In addition, it is assumed that testing will need to be done within the Danfoss Turbocor facility. Furthermore, the software used to interact with our hardware will be open-sourced (free) or another licensed software used by Danfoss. It is assumed that the product will be used for testing 2 to 3 months out of the year. Lastly, the operator will need to be able to lift the shaft onto the device.Lastly, the operator will need to be able to lift the shaft onto the device.

### Stakeholders

The main stakeholder for this project will be Danfoss as they have invested time and money into this project. More stakeholders within Danfoss are our main contacts and advisors William Bilbow and Cole Gray. Dr. McConomy is also a stakeholder as he has contributed his effort and time into making sure our team possesses the skills necessary to collaborate and communicate with other stakeholders, our team, and project advisors. Lastly, the Danfoss employees will also be stakeholders as they will be the receivers and the ones using the device.

**Table 1: *Stakeholders***

|  | **Investor** | **Decision Maker** | **Advisors** | **Receivers** |
| --- | --- | --- | --- | --- |
| **Sponsor**  Danfoss | X | X | X | X |
| **Manager**  Dr. McConomy |  |  | X |  |
| **Operators**  Danfoss Employees |  |  |  | X |
| **Advisors**  William Bilbow and Cole Gray |  | X | X | X |

## Customer Needs

### Investigating Needs

Danfoss has sponsored a project through the FAMU-FSU College of Engineering to redesign and optimize their current flux measurement tool. Danfoss has appointed Cole Gray, mechanical design engineer, and William Bilbow, director of technology and project management, as points of contact for the team. During the first meeting held on September 20th, 2023, at 1:00pm EST, the team conducted a customer interview with these Danfoss engineers via a face-to-face meeting held at Danfoss Turbocor. These questions focused on the problems and improvements that Danfoss Turbocor seeks to refine their current method. The feedback received from these questions will help the team determine the most important aspects of the project and the areas that we need to focus on. Our questions mainly focused on how the magnetic flux of the shaft is measured, why it is important to measure, and why is the current measuring device no longer suitable. Then, from each customer statement, the team interpreted the needs and the underlying requirements. This interview was important and by defining our customer needs, it will help the team in many aspects including reducing the amount of scope creep in our project. It will minimize the waste of important resources and reduce the overdevelopment of unnecessary aspects of our project.

**Table 2: *Customer Interview***

| **Question Asked** | **Customer Statement** | **Interpreted Need** |
| --- | --- | --- |
| What is the purpose for designing this specific flux measurement device and how will this device differ from what is already on the market? | The purpose of this device is to simplify user interaction and for it to take reliable and accurate measurements. The current device was built as a temporary placeholder and is no longer an efficient method. There is no current device that satisfies our needs. | The purpose of this system is to provide a consistent and non-labor-intensive flux measurement method. |
| What are physical restrictions the team should consider, and should this be designed with the purpose of being compatible with other devices? | Due to the strong magnetic fields induced by the shafts, you should try to limit the number of magnetic components near the shaft. | Manufacture the device with mostly nonmagnetic components in the areas near the shaft. |
| How is the magnetic flux measured now? What is bad about it? | A flux meter and sensor are manually held and placed on the shaft, and measured values are manually entered. It is too much work for the operator. | The current measuring device is very hands on and requires a lot of input from the operator. We are tasked with partly replacing the manual labor with automated work by the device. |
| Why is automation important to this task? | Current operators are spending 8 hours, on average, per test. | Limiting labor intensity is a main objective of this project. |
| What is the variation of sizes of shafts that will be measured by this device? | The shafts that will be measured with this device will be about 3 feet long and weigh around 60 pounds. | The shafts being measured are long and heavy. The device will have a moderate safety factor to account for the weight and be able to make contact over the whole length of the flux region. |
| What types of shafts should this device be able to measure? | The fixture needs to accommodate the VT Series shafts. Time permitting, the fixture should be compatible with the 2 pole TT series shafts. | Our main goal is to build a fixture for the VT Series Shafts. If this is completed, we will expand onto the 2 pole TT Series Shafts and beyond. |
| What is the minimum resolution that this device should measure? | Needs to have 5 mm axial and circumferential resolution. Highly preferred to select up to 1 mm resolution. | The intervals for the magnetic flux resolution are at most 5 mm axially and 5 mm circumferential. |
| What is the most desirable metric of the system? | The most important metrics are reliability, repeatability, and automation. These are more important than the speed of the device. | Our project will require the use of software to enable automation. The system must be carefully designed to ensure a high confidence level. |
| Where does the legacy device get stored at Danfoss? Does it get moved around for testing? | The current device gets stored on top of a cabinet inside the machine shop. And when it is used, the operator must move it around and set it on a table. It doesn’t have a designated spot but if the new device works well enough, we will find a permanent spot for it. | The new device is preferred be small enough to be easily moved around by 1 to 2 people for testing. |
| Where will we complete prototype testing? | Due to the NDA, all testing must be done at Danfoss. | The new device will only be able to be tested inside their facility under supervision of the team’s technical advisors. |

### Explanation of Results

For these interpreted needs, we determined the areas that will need the most improvements as we move forward in this project. These questions were designed to gather an overall understanding of the flaws that currently exist and what our team could do to eliminate them. Some features that we wish to include in the future design would be limited user interaction and an automated data collection system. Furthermore, we want to make the device reliable, repeatable, and consistent.

## Functional Decomposition

### Introduction

Functional decomposition is a process in which the project’s broader components are broken down into specified tasks and outcomes. This project was broken down into three broad categories which includes human interaction, body, and controls. These categories were then broken down into smaller units within the hierarchy chart shown in Figure 1. This process helps organize each of the functions before they are sorted into a cross reference chart where the importance of each can be ranked and sorted.

### Data Generation and Hierarchy

The AFM (Automated Flux Measurement) device was dissected into subsystems through the construction of the hierarchy chart shown below. Each section and subsection were designed based on the actions and outcomes expressed in the customer needs evaluation by questioning how those needs translate to performing the desired tasks. As stated before, the AFM was first divided into three sections, namely, human interaction, body, and controls. These initial sections were then comprised of a total of six subsections that categorize eleven actionable items that we need the AFM device to perform.

**Diagram 1: *Hierarchy Chart***

### Discussion of Hierarchy Chart

The primary goal of this project is to develop a device that can automate the measuring process to find the magnetic flux of compressor shafts. Keeping in mind that the customer wanted a device that can perform and send the measurements to a computer with minimum operator intervention, the three main functional categories that were determined for this device are human interaction, body, and controls.

Human interaction is of importance for this project because the team wants to determine which of the tasks the device will complete by itself and which tasks we should leave to be done by the operator. The human interaction function focuses on initial setup for the tests as well as setting the testing parameters. Within these focuses, there are four subsections which are the loading of the shaft onto the device, the unloading of the shaft from the device, the process of powering on the device and other devices connected to it like external computers, and the setup of initial conditions like resolution before starting the measuring process.

The body function focuses on the components that make up the device itself and is divided up into two subsections which are the frame and movement of the device. Within the frame subsection, the team wants our device to be able to securely hold the given shaft and allow it to be measured properly. We also do not want the shaft to be unlevel when loaded, so special attention must be made to ensure the frame of the device can withstand the loading forces. Within the movement subsection, the team wants the device to move at controlled speeds with a consistent interval in between when measurements are taken.

Lastly, for the controls function, the team wanted to consider the desire to intake data while providing consistent movement of the device to insure reliable magnetic flux readings. To incorporate everything, this function was divided up into a software and hardware subsection. For the actions within the hardware section, the team wants the device to successfully and repeatably maintain the variable spacing, distance, and speed, for a properly loaded shaft. For the actions within the software section, the team wants the device to be able to store the recorded measurements from the flux meter and digitally transfer them to an external computer for further processing and analysis.

### Connection to Systems

The three major functions of our device are human interaction, body, and controls. Although all these functions are important, the two with the highest importance are body and controls. The body function will determine whether the AFM device is able to structurally hold the shafts and will determine how the actual shaft’s flux is measured. Secondly, the control function is essentially the brains of the device and will determine the sequence for how the shaft is measured and determine how the data recorded is stored and transferred. Although the human interaction function is important, since it is how the operator interacts with the device, the team felt that how the device will test for the flux is more important. With that said, all these functions have a large impact on the project and the success of each of these will ultimately determine the success of our final device.

### Cross Reference Table

The cross reference table below, Table 3, shows a cross-functional relationship matrix, which visualizes how functions may relate to many of our systems, other than the primary system the function was in. The team attempted to have our subsystems incorporate as many functions as they could without requiring a new subsystem to reduce complexity, especially regarding out-of-sync errors that are common in automated systems with independent subsystems. The three main functions are labelled as the columns of the matrix and the eleven sub-sections are the rows. An ‘X’ shows if the sub-section is directly related to one of the three main functions.

**Table 3: *Cross Reference Table***

|  |  | **Human Interaction** | **Body** | **Controls** |
| --- | --- | --- | --- | --- |
| **Loading sample** |  | **X** | **X** |  |
| **Unloading sample** |  | **X** | **X** |  |
| **Activating electronic systems** |  | **X** | **X** | **X** |
| **Setting initial conditions** |  | **X** | **X** | **X** |
| **Secures sample** |  | **X** | **X** |  |
| **Levels sample** |  | **X** | **X** |  |
| **Moves at consistent intervals** |  |  | **X** | **X** |
| **Moves at a controlled speed** |  |  | **X** | **X** |
| **Provides reliable measurement feedback** |  |  | **X** | **X** |
| **Collects sensor data** |  |  | **X** | **X** |
| **Transfers sensor data** |  | **X** |  | **X** |

### Smart Integration

The cross reference table above, Table 3, shows how some of the various functions in the hierarchy chart are integrated and share relationships with the other sub-systems. The loading and unloading of the shafts from the device will require both human interaction and body functions. The reason is because the operator will need to manually load and unload, and the device will need to be able to support the shafts weight during the loading process. Securing the shaft onto the device and leveling the device will also fall under the same functions. The device will need attachments to secure the shaft level and the operator will be required to secure the shaft into place as well as making sure the shaft is install properly and level. Activating the electronic systems and setting the initial conditions will require all three functions. The operator will need to power on the device and set the resolution of the test as well as start the testing procedure. Then, the device itself will need a way to allow the user to power it on, set the desired resolution, and start the test. Lastly, the device’s software will need to allow for the resolution to be set for the test and perform a start-up procedure. The actions that require the device to move will require the body and controls functions. The device will need to have attachments, such as stepper motors, that allow for consistent interval measuring and controlled speed during testing. The device will also need programmed software that tells those attachments when to stop and start their function. Providing feedback and collecting data will also fall under the body and controls functions. The device needs hardware to measure the flux and it will need software to collect that data. Lastly, the transferring of data will go in the controls function for having software that sends the data elsewhere, and the human interaction function for having the operator collect the data on another external computer to analyze it.

### Actions and Outcomes

The AFM device will be able to make accurate and consistent magnetic flux measurements on VT-series compressor shafts. Upon activating the AFM, the user will load the shaft onto the device, then set measurement parameters such as what interval of distance the measurements will be taken from and will choose file saving settings for the collected data. Once this initial set-up is complete, the operator will be free to go about their business while the device begins its data collection. A sensor will take flux measurements about the circumference of the magnetic region of the shaft at the intervals set by the user. While sensor readings are being taken, the readings will be translated by a fluxmeter and then sent to be recorded on a computer. The recorded data is to then be saved as specified during set-up. Once the appropriate measurements are taken and data is saved, the user will once again be needed to unload the sample from the device. To obtain accuracy and consistency, the frame of the device will secure the shaft firmly in place and structure of the sensory probe will keep the sensor in constant contact with the shaft.

### Function Resolution

In its most basic sense, the design can be divided into three categories: human interaction, body, and controls. The human interaction category covers all the scenarios in which a user should interact with the device and can be broken into two ideas, how a user physically sets up the device, and how the user sets measurement parameters. Physical set up will include loading and unloading of the sample being measured. The user also sets measurement parameters by activating the electronic systems and setting initial measurement conditions and save settings.

The body category explains how the static and dynamic parts of the device accomplish project needs and can be separated into frame and movement subcategories. The frame of the device is to both secure the sample and keep the sample at a constant level. The movement subcategory consists of the movement involved with changing where the positioning of the magnetic sensor is along the magnetic part of the sample at user specified intervals and, controlling the speed at parts of the design move.

Controls is a category that refers to design parameters that handle measurement data. This can be broken into two subcategories being: hardware and software. Hardware in this case refers to the physical parts of the device used in providing ideal conditions for the sensor to take magnetic flux readings. This includes constant and consistent sensor contact with and limited use of magnetic materials around the magnetic region of the sample. Software in this setting refers to how the device utilizes microcontrollers and computer programs to collect, transfer and ultimately store measurement data. In a simple sense the AFM device will take accurate and consistent magnetic flux measurements of VT-series compressor shafts with limited need for user interaction.

## Target Summary

### Target and Metrics

After establishing the functions for this device, each function was given relevant targets and metrics that satisfy their operation. The targets assigned represent a quantifiable value that a given function must fulfill within that constraint. The metric assigned represents a specific parameter that aligns with its target to finalize its respective function.

### Critical Targets and Metrics

**Table 4: *Critical Targets and Metrics***

| ***System*** | ***Function*** | ***Target*** | ***Metric*** | ***Description*** |
| --- | --- | --- | --- | --- |
| Body | Secures sample | 1 | Binary | Shaft remains stable while measurements are being taken. |
| Body | Consistent measurements around the perimeter of shaft | 5 mm | Resolution | Measurements are taken in 5 mm intervals about the circumference of the shaft. |
| Body | Measurements taken around the perimeter of the shaft | 360° | Angle | Measurements are taken over the entire 363 mm circumference of the shaft. |
| Body | Consistent measurements taken along axial direction of shaft | 5 mm | Resolution | Measurements are taken in 5 mm intervals axially about the shaft. |
| Body | Measurements taken along the entire distance of the shaft | 173.8 mm | Distance | Measurements are taken over the entire length of magnetic region of shaft. |
| Controls | Provide reliable measurement feedback | 1 | Binary | The sensor probe will keep consistent contact with shaft during measurement. |
| Controls | Collects and stores sensor data | 1 | Binary | Data processed through open-source code and stored in a file. |
| Controls | Transfers the sensor data | 1 | Binary | The measurement data is transferred to an external computer for review and analysis. |

### Derivation of Targets and Metrics

To establish the proper criteria for the AFM’s targets and metrics, the desired actions were differentiated. Each of the operations in all three of the major systems were broken down into more specific, distinct, functions so that the targets and metrics could be determined, and each component verified. The targets set are categorized by real values and the metrics as the category of measurement.

In Table 4, the four main types of metrics were used: resolution, angle, distance, and binary. Each metric held a corresponding target, which was derived from the customer’s needs while others were determined by Team 513 as important functions of this mechanism. These targets act as a guide to the user as a way of setting expectations of performance times, calculations performed, path taken, and data gathered.

From the major systems, the body system is broken down into five individual functions. The first function covers the task of properly securing the sample shaft to the mechanism. This metric is categorized as binary, and the target is set to one as this needs to be achieved by the mechanism. The one represents success whereas a zero would represent failure. The next two functions focus on the frequency of each sensor measurement taken, where the target range for this as specified by the customer’s need is every 5 mm and where the metric for this is resolution. The last two functions for the body account for the path taken by the sensor. More specifically, the sensor will travel 360° around the shaft and thus cover the entire 173.8mm circumference along the magnified portion of the shaft. These values are the targets, and their metrics are Degrees and Distance, respectively.

The controls system consists of three functions that work together to collect data. The first function will maintain proper sensor contact, the next will collect and store the data, and the last function will be to transfer the data. Each of these functions will be performed by the system itself and therefore were assigned as binary for their unit of metric. The targets were also assigned as one because this function should always be fulfilled.

### Method of Validation

Due to the drastic implications that even one hairline shift could yield, the functions for axial and circumferential motion must be optimized for minimum error. After engaging with our advisors at Danfoss, we were informed of the severity of “not missing a spot” on the shaft. This led us to devise a series of tests to ensure our targets are met. Our target for maintaining a resolution of 5 mm can be validated by having our sensor contain a marker to mark its contact points and manually using a string to measure the distance between points which is a practical way to measure arc length and can also be used for our axial displacements. Additionally, we will compare the total amount of measurements with the theoretical number of measurements, which can be determined by dividing the area of the test section by the ‘unique’ space occupied by the sensor, where unique is defined as the area the sensor covers without overlap during the process. Based on provided Excel data of previous tests, we expect there to be 1000 point measurements per test. Once these targets have been met, we will expand on them to include an option to reduce the resolution to 1 mm for both movements, which will be tested in a similar fashion. Arguably even more critical are the functions for collecting and storing the data. We will ensure this is done right through completing multiple tests and comparing them with manual placements to see if the mapping has sufficient similarity. Additionally, we will have a failsafe built into the code to report any severe discrepancies within error to record or detect a reasonable value.

Furthermore, we will validate the structural stability by controlled ‘bumps’ and ‘shakes’ that will simulate the work environment. Specifically, the AFM device will be used in a controlled, indoor facility, but we would still like our system to keep our shaft secure from moderate stresses that can be expected. Likewise, we will do similar tests to ensure the shaft is properly secured.

Lastly, we will need to validate that indeed our control system is providing reliable measurement feedback which can be evaluated in real-time with if-statements in our code. Target validation will be conducted at the Research and Development Prototype Shop at Danfoss Turbocor facilities.

### Discussion of Measurements

The methods of validating the targets set in this design require an array of tools and supplies. When validating the resolution targets a caliper will be used to check the intervals between measurement locations axially, while the circumferential distance will be verified using a combination of yarn and caliper. Calipers can be used to make measurements as fine as the hundredth of a millimeter making them an ideal tool for verifying that the resolution of measurements are within an acceptable margin of the stated 5mm target. A circular protractor will be used to validate the angles at which measurements are taken about the shaft. When validating that the sensor covers the entire circumference of the shaft, writing or drawling tools such as a non-permanent marker will be used to confirm that the entire circumference sees measurement by the sensor probe. All targets with binary metrics will not require any particular tools for verification since they are determined by simple inspection.

### Summary

Overall, the targets and metrics established above will be the determining factors for how successful our AFM device will be. Our team wanted to define real, specific targets with the intention of setting values and a basis to accomplish this project accurately. The data used is currently based on values that the team determined and will ensure desirable fulfillment of the project and customer needs. However, with that in mind, some of these may be subject to change as the final prototype is developed and tested. A complete target catalog is included in Appendix C and shows both the critical and non-critical targets and metrics that we are aiming for.

## Concept Generation

### Introduction

Concept generation is a crucial part of the design process and determines how the objectives of the project are physically addressed and how the solution is later identified. With an understanding of the targets and constraints of the project, our group held both group and individual brainstorming sessions to generated one hundred potential concepts for our automated flux measuring device. All one hundred ideas are shown in Appendix D of this report. However, the concept generation tools used, and the five medium and three high fidelity concepts are discussed in the sections below in more detail.

### Concept Generation Tools

It was difficult for our team to generate one hundred different concepts, so we utilized tools including brainstorming, biomimicry, crap shoot, forced analogy, and anti-problem to make it easier. For the brainstorming portion, team members created and shared all types of ideas that might potentially fulfill the devices desired needs no matter how unrealistic or feasible these ideas actually were. In this portion of concept generation, team members often used other team members previous ideas to build off of and rearranged specific elements of them to create new separate ideas. Biomimicry was used to generate ideas by looking at elements in nature that deal with similar issues to our device. By looking at different creatures, natural phenomena, and ecosystems, we were able to generate additional ideas that resembled these ideas and focused on completing the primary function of our project. The next concept generation tool that was used was crap shoot. This consisted of listing at most six items under three main categories for our project and then randomly selecting one item under each category. After three items were randomly selected, each from a different category, an idea was generated that combined all of the items selected. By using crap shoot as a generation tool, some concepts with actual merit were created and added to our list. Force analogy was the next generation tool used and this consisted of generating a random list of unrelated things and attributes to each of those things. After that we forced analogies and solutions using the attributes listed to generate new concepts for our project. The last concept generation tool that was used was the anti-problem and this encouraged the team to come up with ideas that solved the opposite solution to our project’s problems. For example, how can we make it more difficult to measure the magnetic flux of the VT series shaft? Then, we gathered the attributes of these anti-solutions to generate additional concepts that dealt with our problem. The SCAMPER checklist was also a handy concept generation tool used in the ideation process. There were many cases in the concepts list where one of the concepts is a concise alteration or addition to a prior design mentioned in the list. The SCAMPER checklist was a helpful tool in pushing through these mental blocks. Overall, these concept generation tools were very helpful in our concept generation phase of the project and allowed us to generate ideas that were outside of our normal range of thinking and ideas that we otherwise would not have come up with. To differentiate what concepts were created using which method, subheadings for each tool are listed in Appendix D and the concepts within those subheadings were created using that method.

### Medium Fidelity Concepts

From the detailed list in Appendix D, the team identified five medium fidelity concepts which met both the project objectives and key goals. The five medium fidelity concepts are listed and explained below.

### Concept #3: Vertical Lathe Center and Rail Movement Device

This design represented below shows a vertical lathe system. The shaft is secured with a chuck system and rests on a spinning platform in a notch on the base and a motor is used to spin the shaft at a controlled speed. The sensor is set up on a vertical motorized track where its movements are predetermined by the user input. Some key problems with this design would be keeping the shaft vertical since the weight will create wear on the spinning plate, chucks, and motors.

**A diagram of a mechanical system

Description automatically generated**

**Figure 1: *Vertical Lathe Center and Rail Movement Device (Concept #3)***

### Concept #5: Robotic Arm

The robotic arm medium fidelity concept was generated in reference to 3D printing using robots. In this design a robotic arm wielding the flux sensor probe reaches all around a shaft that is suspended in a simple frame. Due to the six degrees of freedom of movement the arm would have, it can reach any position along the magnetic region of the shaft. The main problem limiting this design is the complexity of the design and the difficulty presented in programming a device that can accurately and precisely place a delicate sensor when the arm has so many moving joints.

A drawing of a robotic arm

Description automatically generated

**Figure 2: *Robotic Arm (Concept #5)***

### Concept #12: Helical Cage

The third medium fidelity concept is a helical cage structure that is fixed around the shaft which is mounted vertically. For testing, the flux meter travels along the helical path and takes measurements for the magnetic portion of the shaft. Below is a sketch of the helical cage design.

Diagram of a mechanical device with a spiral spring

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**Figure 3: *Helical Cage (Concept #12)***

### Concept #13: Conveyor Belt of Rollers Device

The fourth medium fidelity concept we generated keeps our sensor stationary throughout the entire process. It keeps the shaft horizontal and uses a conveyor belt of rollers to move it. A motor will drive the rollers to turn the shaft precisely. This offers a huge advantage that the sensor will always have the exact same contact pressure on the shaft, ensuring consistent measurements. Possible issues could be friction from the roller/shaft contact, as well as friction that the sensor will experience.

**A blue and grey rolling pin

Description automatically generatedA blue tube with yellow arrow pointing to a white object

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**Figure 4: *Conveyor Belt of Rollers Device (Concept #13)***

### Concept #29: Typewriter Style Rail System Device

Our fifth pick in the medium fidelity category is a unique concept where, unlike nearly all others, the shaft remains stationarity during the entire process. Three primary issues associated with having to rotate the shaft include the torque needed to rotate the shaft, friction from the supports (wedge blocks) that can disrupt accuracy in measurements, and the initial set up process most likely being a two-man job. The system orbits about the center of the test section along a gear shell (seen in red) which is driven by a servo motor (seen in pink). The smaller servo motor is connected to a cam follower system that will fully automate the mechanism of sensor-interface contact. Another concern would be the wires and weight of the power supply (seen in orange). However, due to the context of our issue this can most likely be done if we have a long enough sensor cord and a strong enough ‘gear cage.’ This whole system must be attached to ground, therefore a pin-in-slot structural support attached to the orbiting plate (blue box).

**A diagram of a machine

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**Figure 5: *Typewriter Style Rail System Device (Concept #29)***

### High Fidelity Concepts

From the detailed list in Appendix D, the team also identified three high fidelity concepts which we thought were the best at meeting both the project objectives and key goals. The three high fidelity concepts are listed and explained below.

### Concept #2: Horizontal Lathe Center and Rail Movement Device

The first high fidelity concept is a lathe inspired device that secures the shaft using a chuck system and maintains its leveling using a live center. The device spins the shaft using a motor and the sensor is moved along a table plate slot and is moved linearly using a second motor. This design allows for precise measurements to be taken and repeated.

**A diagram of a mechanical device

Description automatically generated**

**Figure 6: *Horizontal Lathe Center and Rail Movement Device (Concept #2)***

### Concept #33: Horizontal Roller Bearings Device

The next high fidelity concept is a device that holds the shaft horizontally when measuring. It has a motor connected to one end of the shaft that spins it during testing. Then, the flux meter is mounted on a track that allows it to move along the length of the shaft and it takes flux measurements along the magnetic portion of the shaft. Additionally, two blocks are used to support the weight of the shaft and have roller bearings attached to them at the contact points with the shaft to allow for easier spinning of the shaft, less stress on the motor, and less friction.

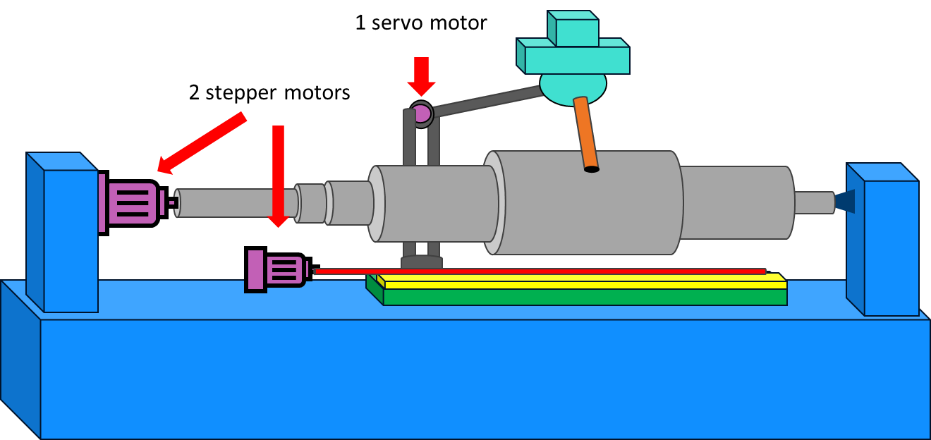
A diagram of a machine

Description automatically generated

**Figure 7: *Horizontal Roller Bearings Device (Concept #33)***

### Concept #59: Lean and Peck Device

The next concept is the lean and peck style probe arm that reaches down and presses sensor to shaft that rotates. The lean and peck high fidelity concept was formed using the biomimicry concept generation method. In this design the shaft is placed on a frame with a stepper motor on one side that the shaft connects to supply rotation to the shaft, and a tapered bearing on the other to allow the shaft to fit snugly and rotate freely guided only by the motor. The sensor probe will be suspended on a linkage system that allows for a bending motion similar to that of drinking bird toys. A servo motor would be used to induce rotation allowing for the sensor to be moved into and out of contact with the shaft. Axial movement in this design is accomplished by rolling the linkage system on a track. The rolling is induced by a worm gear that is attached to a second stepper motor built into the device’s frame.

****

**Figure 8: *Lean and Peck Device (Concept #59)***

## Concept Selection

After concept generation where 100 different concepts were created, our team has narrowed it down to five medium fidelity concepts and three high fidelity concepts. It is now of interest to determine which of these eight concepts is most suitable for our project.

The concept selection process for this project was completed in four steps to narrow down our list and removing bias from the process. The four steps that were used were doing a Binary Pairwise Comparison, creating a House of Quality (HoQ), then creating Pugh Charts, and lastly by doing an Analytical Hierarchy Process (AHP). The complete selection process and outcomes can be found in Appendix E.

### Binary Pairwise Comparison

In order to properly evaluate the different concepts generated in the section above, the customer requirements and engineering characteristics for our project were first decided. Next, a binary pairwise comparison matrix was created by listing the customer needs into the rows and columns. These needs were then evaluated against each other by level of importance with a ‘1’ being more important, and a ‘0’ being less important. The binary pairwise comparison outputs the important weight factor of each customer’s need which is then utilized in the House of Quality in the next section. From Table 5 below, it was determined that the accuracy and automation of our device were most essential to the design.

**Table 5: *Binary Pairwise Comparison Matrix***

****

### House of Quality (HoQ)

The second step in our concept selection process was creating the House of Quality which is shown below in Table 6. The House of Quality helps in concept selection by providing the team with a method for relating the customer requirements to quantifiable design variables. Using a log numbering scale of 0, 1, 3, and 9, engineering characteristics were ranked on how well that certain characteristic helped to meet the particular customer requirement. If they were not related, then the cell was left blank. After completion of the House of Quality, it was found that the three most important engineering characteristics were providing reliable measurement feedback, consistent measurements, and ensuring measurements were taken around the entire magnet region of the shaft. These engineering characteristics are very important for our project and need to be emphasized in the final design process.

**Table 6: *House of Quality Chart***



### Pugh Chart

Team 513 used three iterations of Pugh Charts to narrow down the pool of concepts being selected from eight to three. This tool is used to directly compare the different concepts to a datum concept and in the chart a plus (+) means that the concept is better than the datum, a minus (-) means that the concept is worse than the datum, and an ‘S’ means that the concept is ranked the same as the datum. Then at the bottom of the charts, the number of pluses and minuses were counted and used to eliminate and rank the ideas. The datum concept for each iteration was also assigned to a middle-ranked idea for each iteration that way the charts would not just have all pluses or all minuses.

Below is a list of the eight total concepts that were compared using the Pugh Charts.

* Concept #2: Horizontal Lathe Center and Rail Movement Device
* Concept #3: Vertical Lathe Center and Rail Movement Device
* Concept #5: Robotic Arm
* Concept #12: Helical Cage
* Concept #13: Conveyor Belt of Rollers Device
* Concept #29: Typewriter Style Rail System Device
* Concept #33: Horizontal Roller Bearings Device
* Concept #59: Lean and Peck Device

For the first iteration of the Pugh Chart, Concept #33 (Horizontal Roller Bearings Device) was selected as the datum because the team felt like it was a good average between all the other concepts. By comparing all of the high and medium fidelity concepts to Concept #33, the team was able to determine that three concepts could be eliminated as they were perceived to satisfy the selection criteria the least compared to the other concepts. The robotic arm, helical cage, and conveyor belt of rollers device were all eliminated during the first iteration.

**Table 7: *Pugh Chart First Iteration***



In this second iteration of the Pugh Chart, Concept #29 (Typewriter Style Rail System Device) was used as the datum and Concept #59 (Lean and Peck Device) ended up performing the worst and was eliminated. This left only four concepts remaining for the final iteration of the Pugh Chart.

**Table 8: *Pugh Chart Second Iteration***



For the third and final iteration of the Pugh Chart, Concept #3 (Vertical Lathe Center and Rail Movement Device) was used as the final datum due not only to the fact that it performed moderately in the second iteration Pugh Chart but also because it was the only remaining concept in which the shaft would be secured vertically. Concept #59 (Lean and Peck Device) was eliminated in the third iteration leaving only three concepts left. After completing the Pugh Charts, the remaining concepts are Concept #2 (Horizontal Lathe Center and Rail Movement Device), Concept #3 (Vertical Lathe Center and Rail Movement Device), and Concept #29 (Typewriter Style Rail System Device). Ultimately Concept #2 (Horizontal Lathe Center and Rail Movement Device) was determined to best satisfy the selection criteria in all three Pugh Charts.

**Table 9: *Final Iteration of the Pugh Chart***



### Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP) was used to ensure objective concept rankings by applying weighted values to our selection criterion (detailed in Appendix E). This is accomplished by treating each selection criteria in the Criteria Comparison Matrix as a datum with respect to the others and ranking all other needs in reference to the datum. See Tables 9 and 10 below for details. To determine the values, we went around in a group and voted on each using a number based ranking of 1,3,5,7, and 9 (where 1 signifies equal value and a 9 means it is a high priority compared to the datum as read in each column. A decimal value implies less weight in comparison to the datum). In table 9, the gray cells represent the datum need and all values to the right of the datum (blue cells) were manually determined by team 513.

**Table 9: *Analytical Hierarchy Process Chart***

The Analytical Hierarchy Process was used to find which engineering characteristics were most significant and it validated the concept selection within the Pugh Charts. It also ensured that the criteria weights were not biased to one design or another. Below is a figure of the normalized AHP chart as well. The rest of the charts and calculations can be found in Appendix E.

which was crucial to complete the Pugh charts (our process of narrowing down our concepts).

**Table 10: Normalized *Analytical Hierarchy Process Char**t***

### Final Selection

After analyzing the data gathered from the Binary Pairwise Comparison, House of Quality, Pugh Charts, and AHP, Team 513 was able to evaluate the benefits and drawbacks of each concept as well as rate the engineering characteristics by importance. This process led to the results shown in Table 11.

**Table 11: *Final Selection Values***

|  |  |
| --- | --- |
| **Concept** | **Alternative Value** |
| Horizontal Lathe | 0.389 |
| Vertical Lathe | 0.275 |
| Typewriter System | 0.336 |

These results show that the Horizontal Lathe had the highest Alternative Value, meaning, this design best fits the criteria used in the Pugh Charts. Notably, the Typewriter System presented with a value relatively close to that of the Horizontal Lathe. The team took this into consideration before deciding that the mechanics of the typewriter systems will ultimately lead to more complications and difficulty of use compared to the Horizontal Lathe.

The Horizontal Lathe concept particularly fits the engineering criteria set in the selection process and offers users the benefit of a convenient and well-known operating system. Like a standard shop lathe, the shaft would be fixed between a chuck and a live center that together secure and level the shaft. The chuck is motorized in order to spin the shaft at the correct circumferential resolution and the sensor moves linearly using a motor as the tool post would on a lathe. This design prevents wires from getting tangled while maintaining the precise features of a lathe.

**A diagram of a mechanical device

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**Figure 9: *Initial Design Concept***

## 1.8 Spring Project Plan

# Chapter Two: EML 4552C

## 2.1 Spring Plan

### Project Plan.

### Build Plan.

# Appendices

# Appendix A: Code of Conduct

This document will serve as the group contract for Team 513 during the entire two-course Senior Design class lasting from the Fall of 2023 through the Spring of 2024.

**Mission Statement**

Our mission is to work collaboratively as a team to improve upon an existing method of measuring the magnetic flux of the VT Series shaft to ensure reliable measurements. The team intends to use the engineering design principles, knowledge, and experience learned throughout our undergraduate courses while also behaving in a productive, friendly, and professional manner.

**Outside Obligations**

This Senior Design team is expected to meet at least twice a week following both Tuesday and Thursday lectures. These will be general team meetings and will last for the duration of the remaining lecture time, unless otherwise stated unanimously by the team. If additional meetings are needed, they can be scheduled accordingly based on the availability of team members as determined in the “when to meet” meeting. For outside obligations, during additional meetings, the Microsoft Teams calendar is used to communicate availability and other commitments. Furthermore, the entire team is expected to attend meetings with the team’s sponsor and faculty advisor on a biweekly basis (every two weeks). All team members should be present at the general meetings except for situations which are effectively communicated by the relevant party at least 24 hours prior to the meeting time, with the exception of emergencies. Additional obligations for each team member beyond the scope of the project are listed as follows:

* **Sean Hemstreet** – Occasionally attends meetings for Tau Beta Pi, the Engineering Honor Society on Wednesdays. Also has other obligations for another class.
* **Liora Louis -** Works a total of 30 hours a week at the Applied Superconductivity Center as well as attends university courses.
* **Joshua Huls -** Works a total of 10 hours a week at the High Performance Material Institute, attends university courses, holds officer and committee chair positions in ΦMA Sinfonia, plays in Seminole sound pepband.
* **Andrew Atallah** - No outside obligations related to the university other than classes.

**Team Roles**

The following team roles have been agreed upon for the course of the project. Team roles have been reevaluated for the beginning of the spring semester and may change if deemed necessary.

|  |  |
| --- | --- |
| **Team Member** | **Team Role** |
| Sean Hemstreet | Design Engineer |
| Liora Louis | Materials Engineer, Test Engineer |
| Joshua Huls | Systems Engineer |
| Andrew Atallah | Hardware/Software Engineer |

**\*Note:** Additional duties and roles may be assigned, or changed with unanimous agreement of the team. Other duties will be discussed in mandatory meetings.

**Communication**

The primary and official form of communication will occur through Microsoft Teams where group discussions, documentation, and file sharing will occur. Official communication with Dr. McConomy, sponsors, faculty advisor, or other mentors should primarily be done through email with all the team members CC’d onto the email. Team members should have Microsoft Teams and email notifications enabled on their phone or computer and should aim to respond within 8 hours on weekdays and 24 hours on weekends. If no response is received in 24 hours for team members and 72 hours for non-team members, a follow-up email should be sent by the original sender.

Responding to messages and emails should be done in a professional manner with a polite and understanding tone that maintains formal diction and proper etiquette. Our team values open communication, honesty, and respect. Meeting notes will be taken in every meeting and If a team member misses a meeting for whatever reason, it is their responsibility to look at the recorded notes from the meeting and stay up to date with all project details.

**Dress Code**

General team meetings are considered informal events and there is no specified dress code. For sponsor meetings, advising meetings, either in person or online, the team is expected to dress in business casual attire unless otherwise discussed 48 hours before. For men, business casual refers to dress pants, dress shoes, and button-down shirts. For women, business casual refers to dresses, dress pants, blouses, and dress shoes. For virtual design reviews and other presentations, the team is expected to dress in coordinated business formal unless otherwise discussed 48 hours before. Business formal for both men and women will be a black suit, a white button-down, and dress shoes.

**Attendance Policy**

The attendance policy for the team is as follows. Attendance of normal class lectures fall under personal responsibility. Team members are responsible for attending general meetings on Tuesdays and Thursdays during the excess allotted lecture time. If a member must miss either an in-class or outside group meeting, they should notify the rest of the team in the Microsoft Teams chat prior to class time. If the team feels as though a team member has been negligent towards their group work or participation, the other team members can agree to give that member a strike. The team must notify that member when he or she has been given a strike. After two strikes against a single individual, a team intervention and meeting will be held to discuss how to fix the issue. If an individual is given a third strike, external support will be sought out from Dr. McConomy and the teaching assistants on possible solutions. The use of vacation days for a team assignment must be agreed upon unanimously by all team members. All team members are expected to hold 1 vacation day a semester in reserve for group assignment use.

**Contacting Dr. McConomy**

Contact with Dr. McConomy and the teaching assistants should be made by email and all team members must be carbon copied onto the email. Contact should only be made when necessary and in applicable situations. Applicable situations include but are not limited to:

* Sponsor is currently unavailable or has given no response for an extended period inhibiting the progress of the group.
* Problems among group members that were not able to be solved interpersonally after discussion.

**Amendments**

This document can be amended at any point during the project’s duration but requires a unanimous vote of agreement. The amendment must be clearly stated and understood by all team members. The updated code of conduct document has been resigned by all team members at the beginning of the Spring 2024 semester on January 11, 2024.

**Statement of Understanding**

By signing this document, you agree to the entire document and will uphold all that is said above.

**Signature: Date:**

A close-up of a document

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# Appendix B: Functional Decomposition

# Appendix C: Target Catalog

| ***System*** | ***Function*** | ***Target*** | ***Metric*** | ***Description*** |
| --- | --- | --- | --- | --- |
| Human Interaction | Loading sample | 5 Minutes | Time | Loading the sample onto the device manually. |
| Human Interaction | Unloading sample | 5 Minutes | Time | Unloading the samples off of the device manually. |
| Human Interaction | Activating electronic systems | 1 | Binary | All electronic systems will need access to power. |
| Human Interaction | Setting initial conditions | 1 | Binary | Operator sets measurement parameters. |
| Body | Secures sample | 1 | Binary | Shaft remains stable while measurements are being taken. |
| Body | Levels sample | 0° Displacement | Angle | Sample is level in a way that the displacement angle is 0° |
| Body | Consistent measurements around the perimeter of shaft | 5 mm | Resolution | Measurements are taken in 5 mm intervals about the circumference of the shaft. |
| Body | Measurements taken around the perimeter of the shaft | 360° | Angle | Measurements are taken over the entire 363mm circumference of the shaft. |
| Body | Consistent measurements taken along axial direction of shaft | 5 mm | Resolution | Measurements are taken in 5mm intervals axially about the shaft. |
| Body | Measurements taken along the entire distance of the shaft | 173.8 mm | Distance | Measurements are taken over the entire length of magnetic region of shaft. |
| Body | The device moves at a controlled speed | 20 mm/s | Velocity | Speed of moving parts is regulated at the given speed. |
| Controls | Provide reliable measurement feedback | 1 | Binary | The sensor probe will keep consistent contact with shaft during measurement. |
| Controls | Collects and stores sensor data | 1 | Binary | Data processed through open-source code and stores in a file. |
| Controls | Transfers the sensor data | 1 | Binary | The measurement data is transferred to an external computer for review and analysis. |
| Additional | Emergency stop | 1 | Binary | A failsafe to stop the device in the event of an emergency is to be implemented. |
| Additional | Signage for ease of use | 1 | Binary | The device will include some form of descriptive aid to assist with direct human interaction. |
| Additional | Display information | 1 | Binary | Measurement progress will be displayed in some fashion. |
| Additional | Maintain sensor/interface contact similarity | 1% | Pressure/Dis-placement | Our system must be able to provide a reliable way of repeated contact with the contact interface |

# Appendix D: Concept Generation

**100 Concepts**

**Brainstorming:**

Note: Medium Fidelity Concepts are underlined, and **High Fidelity Concepts are bolded.**

1. A device that uses a worm screw being turned for axial movement.
2. **Using a lathe center and rail movement to secure and move sample, this is like a mini lathe (horizontal specimen).**
3. Using a lathe center and rail movement to secure and move sample, this is like a mini lathe (vertical specimen).
4. Lazy Susan motorized plate for securing and moving specimen.
5. Robotic arm to move sensor with six degrees of freedom.
6. Measurements taken with 73 flux sensory probes with only axial movement.
7. 3D printer double rail system for two axis movement including 1 sensor and needing 180 degree rotation and axial movement.
8. Device that has a mouse trap spring for holding sensor probe in contact with shaft.
9. Push spring design for keeping the sensor probe in contact with the shaft like a pen spring.
10. Cam follower spring mechanism for keeping sensor probe in contact with the shaft.
11. Rotating an outer shell around the shaft, possibly winding the shell.
12. Helical cage around the shaft that has the flux meter attached to it.
13. The shaft sits horizontally on a conveyor belt of rollers that are turned using motors, the sensor is stationary, and the shaft moves rotationally and horizontally.
14. Using a piezoelectric actuator to control contact with the sensor/shaft interface.
15. Vertical device with the use of a gear box to ensure adequate torque to rotate the shaft.
16. A device that has code that tells the sensor to go to every coordinate(s) the user has inputted to find the flux at each point.
17. 3D printer double rail system that supports the shaft and has a mirrored system underneath. Both take complementary hemispheres of data. The shaft is stationary.
18. Measurements taken with 35 flux sensory probes along the length of the magnetic portion of the shaft with only circumferential movement.
19. A device which has a vertical shaft where shaft is stationary, and the sensor is moved on rails up and down and axially.
20. 2 sensors attached to a plate placed above the shaft and takes measurements as the shaft spins. Plate then moves along the shaft to the next location.
21. Rail sleeving shaft with pop lock placements (horizontal).
22. Rail sleeving shaft with pop lock placements (vertical).
23. Sensor probe attached to a piece of magnetic material on wheels so it is kept in contact with shaft and can roll around its circumference.
24. Laser guidance system for moving arm wielding sensor probe to follow along haft, lines of light projected upon shaft and detected by a light sensor (horizontal).
25. Laser guidance system for moving arm wielding sensor probe to follow along haft, lines of light projected upon shaft and detected by a light sensor (vertical).
26. Rail system under the shaft and an arm like probe that reaches around shafts magnetic region.
27. Pop-lock rail system set up in 5mm intervals for axial movement.
28. Roller on rail system around shaft attached to sensor probe.
29. Typewriter style rail system where many measurements are taken in axial direction before a rotation then many more axial measurements are taken, and pop lock system used to keep consistent spacing.
30. Frame plate that shaft sits on and moves axially like a 3D printing bed.
31. Drop down probing arm wielding sensory probe.
32. While the shaft is off the ground and supported at each end. A device is then clamped onto the shaft and is able to move a flux meter around the magnetic portion of the shaft.
33. **A device that holds the shaft horizontally and spins it via a motor. The shaft will sit on roller bearings attached onto the device near the contact points of the shaft to enable easier spinning of the shaft and to reduce friction.**
34. A device that enables the user to load the shaft into it horizontally, then after the user initiates the starting sequence, it rotates the shaft to be vertically and then the flux measurements are taken.
35. A movable device that can hold the shaft and measure it, but also has wheels so it can easily be moved from room to room.
36. A device that holds the shaft horizontally and spins it via a motor. The shaft will sit on V-Blocks fit to the size of the shaft and there will be Kevlar attached at the contact points of the shaft to reduce friction and enable easier spinning of the shaft.
37. A device that has a fitted drawer that slides out to install the shaft and then is pushed fully into the machine during testing. This device will fully enclose the shaft during testing to reduce the environment around the shaft impacting the magnetic flux readings.
38. A device that has a built-in davit crane to allow the user to easily move the 90 pound shaft on and off of the testing surface.
39. A device that starts off close to the ground to allow for easy horizontal loading of the shaft and then is manually lifted up to a preferred measuring height by a built-in hydraulic trolley jack.
40. A device that allows the user to load the shaft into a fitted spot vertically, and then rotates the shaft horizontally for testing.
41. A device that keeps the shaft suspended in the air vertically by a cable and then the flux sensor probe goes around the shaft and measures the magnetic flux.
42. A device with a built-in computer that can be operated offline and without an external computer. The device will have a screen and show the data in real time.
43. Convert belt roller system with an axially spinning shaft. The parameters are set manually, and the sensor moves translationally.
44. A device with a built-in computer without a screen that is able to perform testing without an external computer and the data can then be transferred over to an external computer using USB after testing.
45. A device that spins the shaft using a belt that is connected to a motor and utilizes mechanical advantage.
46. 3D printer frame that controls a moving flux sensor and has robotic arms that spin the shaft.
47. A static frame that contains multiple sensor probes and moves the shaft translationally and requires manual parameter setting by the user.
48. A 3D printer frame with a stationary shaft that contains multiple sensor probes and requires the manual parameters to be set by the user.
49. A static frame that holds the shaft and allows is to move translationally and has the flux sensor move around the shaft’s circumference. The parameters for the tests are already preset by the device.
50. A device that holds the shaft vertically and allows for translational movement of the shaft up and down while also have a flux sensor capable of moving around the shaft’s circumference with multiple preset parameters.
51. A device with a static frame that is able to robotically load the shaft without the help of the user and for testing it moves the flux sensor around the stationary shaft.
52. A remote control device with tracks that goes along the length of the magnetic portion of the shaft and measures the flux. After measuring the entire length, it gets off the shaft and the shaft rotates 5 mm, then the process is repeated until the device is able to measure all the way around the circumference of the shaft.

**Biomimicry:**

1. Python sleeve flexes to fit around shaft and houses sensor probe.
2. Spider drone walks around shaft with measurement probe.
3. Monkey tail-like flexible sleeve slid along shaft that houses sensor probe.
4. Drone hovers about suspended shaft and places sensor probe at specified spots.
5. A sensory probe attachment that grasps the shaft similar to how a chameleon grabs onto tree branches.
6. A frame that grasps and moves the shaft similar to how a chameleon grabs onto tree branches.
7. Submerged shaft paired with swimming drone that wields sensor probe.
8. **Lean and peck style probe arm that reaches down and presses sensor to shaft that rotates.**
9. While shaft is suspended, a caterpillar like drone crawls along shaft circumference and moves axially along shaft while pressing sensor probe to shaft.
10. A weblike array of flux sensors covering the shaft all over.
11. A device that has the flux sensor probe trace around the magnetic region of the shaft in a honeycomb pattern.
12. A remote control device that has a flux sensor probe attached to it and it is able to hop around and stick to specified locations of the shaft to complete the measurements similar to how a frog moves and holds onto things.

**Forced Analogy:**

1. Magic carpet, the shaft is rolled about its full circumference on a carpet like mat with has flux sensory probes to measure the magnetic flux as the shaft is rolled.
2. The globe, the shaft is mounted diagonally onto a fixture and then spun around while a flux meter goes around the magnetic region of the shaft. Similar to how a rotating world globe is fixed.
3. Roller coaster, a custom track around the outside of the shaft and goes over the entire pathway of every needed measurement is built and the flux sensor rides on the track and measures the magnetic flux at each location.
4. Fishing reel style winding to pull sensor probe across and around magnetic shaft.
5. Drop sensor probe down on fishing line and use some kind of distance sensor to keep distance sensor is lowered constant between measurements, in this case shaft rotation is needed and reel moves axially.
6. A wheeled system rolls above shaft wielding sensor probe taking all axially measurements at once before rotation, such as if a wheelchair was being rolled over the shaft and someone held the probe up to the shaft.
7. Crank Rocker Mechanism for quick sampling.
8. A crane like device that has four legs and lifts the shaft up horizontally using two cables and is able to measure the shaft while it is suspended in the air. Similar to a boat gantry crane.
9. The windmill, a device that has 3 flux sensor probes attached to it and spins those probes around so that one contacts the shaft at a time. The spinning of the probe will allow for faster measurements since the device can continue moving and one sensor will contact the shaft every 5 mm.

**Anti-Problem:**

1. How can we prevent stability of the shaft? Set the shaft at an angle, don’t bolt in the shaft. Have the shaft elevated and at an angle.
2. How can we reduce the reliability of the system? Keep the motor-driven systems out of sync and ignore the lifespan of parts and lack of maintenance.
3. How can we ensure our data is inconsistent? Have inconsistent contact and resolution between the flux sensor and shaft and have it take random data points.
4. Submerge shaft in deionized water and control a mini submarine to take measurements.
5. Secure the shaft in a lot of playdough to ensure adequate stability.
6. Pulley system to secure the shaft.
7. Having a device that automates the circumferential measurement of the shaft by spinning the shaft around a fixed sensor but requires the user to move the shaft back and forth to allow the flux sensor probe to measure the entire length of the magnetic region of the shaft.

**Crapshoot:**

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Die 1- Body** | **Die 2- Human Interaction** | **Die 3- Controls** |
| 1. | 3D printer frame | User loaded | Moving senor |
| 2. | Conveyer belt rollers | Robotically loaded | Stationary sensor |
| 3. | Static frame | Multiple preset parameters | Multiple sensors |
| 4. | Permanent structure | Manual parameters | Cable transferred data |
| 5. | Vertical structure | Manual calibration | Digitally transferred data |
| 6. | Robotic arm | Sensor manually moved | Robotically controlled sensor |

1. (5,3,6) A vertical structure what properly balances the compressor shaft has measurements taken using a robotically controlled sensor where the parameters being set by the user are chosen from several preset parameters.
2. (1,1,3) A 3D printer style frame containing multiple sensor probes and requires the shaft to be loaded by the user.
3. (1,5,2) A 3D printer style frame that has a stationary sensor and the shaft moves along the axis, but the device must be recalibrated.
4. (2,1,2) Conveyer belt roller system that is controlled by a motor robotically loads a sample where the device’s sensor is stationary. The rolling pins move the pin rotationally and horizontally.
5. (4,6,4) A permanent structure where the sensor is manually moved, and the data is transferred via cable.
6. (1,3,4) A 3D printer style frame containing several preset parameters and the gathered data is transferred via cable.
7. (1,4,2) A 3D printer style frame with a stationary sensor where there are several preset parameters.
8. (6,5,6) A robotic arm that holds the shaft with a complementary robotic sensor probe, and the device needs to be calibrated for each use.
9. (3,1,2) A static frame that has a stationary sensor that is loaded by the user.
10. (1,5,4) A 3D printer style frame that transfers data via cable and requires calibration for each use.
11. (2,5,3) Conveyer belt roller system with multiple sensors and uses calibration each time.
12. (4,1,1) A permanent structure with a moving sensor where the user loads the shaft.
13. (1,2,5) A 3D printer style frame where the shaft is robotically loaded, and the data is transferred via a cable.
14. (1,2,4) A 3D printer style frame where the shaft is robotically loaded, and the data is transferred digitally.
15. (3,2,3) A static frame with multiple sensor probes where the shaft is loaded robotically.
16. (4,2,1) A permanent structure with a moving sensor where the shaft is loaded robotically.
17. (1,1,1) A 3D printer style frame with a moving sensor where the shaft is loaded by the user.
18. (6,1,6) A robotic arm with a robotically controlled sensor probe where the shaft is loaded by the user.
19. (4,3,2) A permanent structure with multiple preset parameters where the sensor is stationary.
20. (3,3,6) A static frame with multiple preset parameters where the sensor is robotically controlled.

# Appendix E: Concept Selection

**Binary Pairwise Comparison**



**House of Quality (HoQ)**

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**First Iteration Pugh Chart**

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**Second Iteration Pugh Chart**

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**Final Iteration Pugh Chart**

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**Analytical Hierarchy Process Criteria Comparison**

**Normalized Criteria Comparison Matrix for AHP**

**Consistency Check**

****

****

**AHP Design Alternatives for Loading and Unloading the Shaft**

****

**AHP Design Alternatives for Setting Initial Conditions**

****

**AHP Design Alternatives for Securing Sample**

****

**AHP Design Alternatives for Consistent Measurements**

****

**AHP Design Alternatives for Measuring Entire Magnetic Region**

****

**AHP Design Alternatives for Providing Reliable Measurement Feedback**

****

**AHP Design Alternatives for Collecting and Storing Sensor Data**

****

**AHP Design Alternatives for Transferring Sensor Data**

****

**AHP Design Alternatives for Leveling Sample**

****

**AHP Design Alternatives for Moving the Device at Controlled Speeds**

****

**Final Rating Matrix**



**Alternative Values**

****

# Appendix A: APA Headings (delete)

# Heading 1 is Centered, Boldface, Uppercase and Lowercase Heading

## Heading 2 is Flush Left, Boldface, Uppercase and Lowercase Heading

### Heading 3 is indented, boldface lowercase paragraph heading ending with a period.

#### Heading 4 is indented, boldface, italicized, lowercase paragraph heading ending with a period.

##### Heading 5 is indented, italicized, lowercase paragraph heading ending with a period.

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# Appendix B Figures and Tables (delete)

The text above the cation always introduces the reference material such as a figure or table. You should never show reference material then present the discussion. You can split the discussion around the reference material, but you should always introduce the reference material in your text first then show the information. If you look at the Figure 1 below the caption has a period after the figure number and is left justified whereas the figure itself is centered.



Figure 1. Flush left, normal font settings, sentence case, and ends with a period.

In addition, table captions are placed above the table and have a return after the table number. The second line of the caption provided the description. Note, there is a difference between a return and enter. A return is accomplished with the shortcut key shift + enter. Last, unlike the caption for a figure, a table caption does not end with a period, nor is there a period after the table number.

Table 1  
*The Word Table and the Table Number are Normal Font and Flush Left. The Caption is Flush Left, Italicized, Uppercase and Lowercase*

|  |  |
| --- | --- |
| Level of heading | Format |
| 1 | **Centered, Boldface, Uppercase and Lowercase Heading** |
| 2 | Flush Left, Boldface, Uppercase and Lowercase |
| 3 | Indented, boldface lowercase paragraph heading ending with a period |
| 4 | Indented, boldface, italicized, lowercase paragraph heading ending with a period. |
| 5 | Indented, italicized, lowercase paragraph heading ending with a period. |

# References

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