Portable Magnetic Resonance Imaging Device

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I. Introduction

1. Problem and Solution Overview

As image and signal processing become more developed and prevalent in the medical industry, advanced scanning devices are needed for the diagnosis of many diseases and such equipment is essential to many healthcare centers. However, according to [1], a low-field MRI device can cost up to 150,000 USD, and a state-of-the-art MRI device that produces detailed images usually requires between 1 million to 3 million USD for purchase and installation. Moreover, a modern MRI usually takes up a tremendous amount of space and maintenance for it to function normally, and an appointment for an MRI scan can take lots of time. Such expense and space constraints mean that it would be hard for smaller clinics or medical-related organizations/groups to adopt and utilize MRI scanning technologies during emergencies or on-site operations.

In order to reduce the size and cost of traditional MRI devices, we propose a portable MRI device that incorporates a non-uniform, non-linear magnetic field and two sets of RF coils. The magnetic field with unique spatial encodings will be done by rotating two individual magnets and therefore informing the RF coils about the voxel locations through predefined Larmor frequencies. The two sets of RF coils are going to be surface coil arrays that act as transmitters and receivers, respectively. The data collected from these surface coil arrays will be then analyzed and processed by our control unit, which performs current amplification as well as analog-to-digital conversion so the raw image with digital signals can be sent to our image processing unit. The image processing unit will then use parallel imaging and deep learning techniques to reconstruct images[2], ultimately producing an intelligible image of the scanning volume.

2. Visual Aid

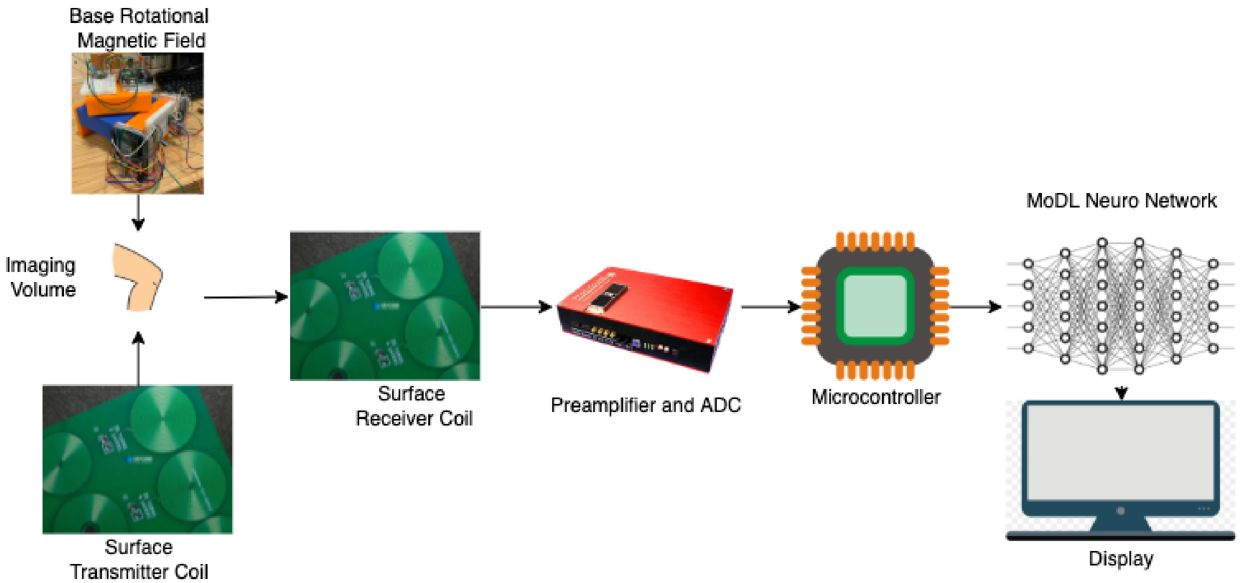

Figure 1. Visual Aid for the High-level Systems

3. High-Level Requirements List

- The final device should be able to generate an intelligible image scan of the target region and achieve an SSIM (Structural Similarity Index) of above 0.5.
- The portable device needs to be relatively constrained in terms of its size and weight. The total size of the scanning device should not exceed 30cm x 30cm x 30cm, and the total weight of the scanning device should not exceed 20kg.
- The power consumption of the entire system (scanning device + computing device) should be limited, and the device should not consume more than 1000W.
- The overall scan time for the device should be limited due to the urgent-care nature of our device, and we aim for a scan time of 5 minutes.

II. Design

1. Block Diagram

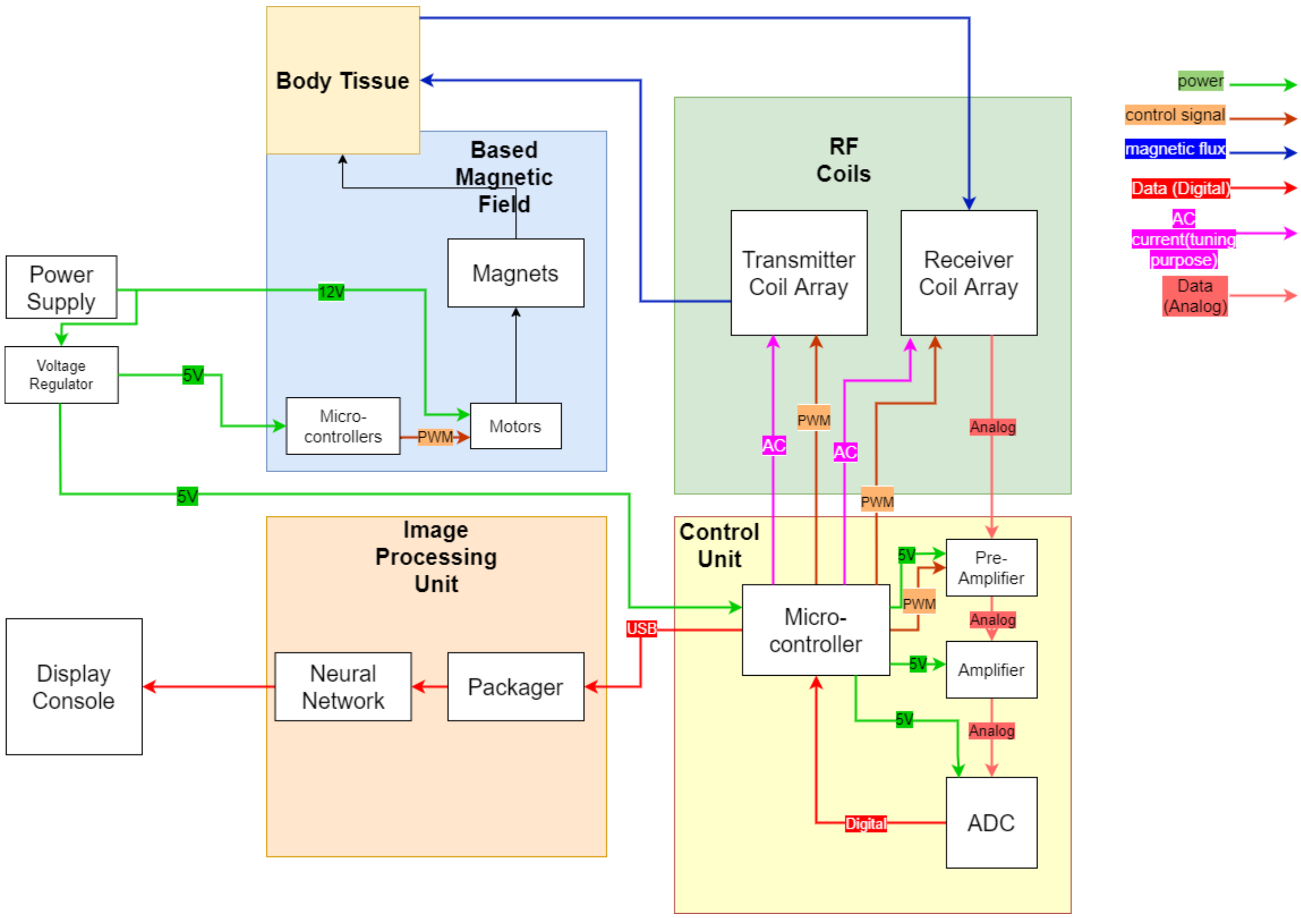

Figure 2. Block diagram of subsystems

2. Physical Design

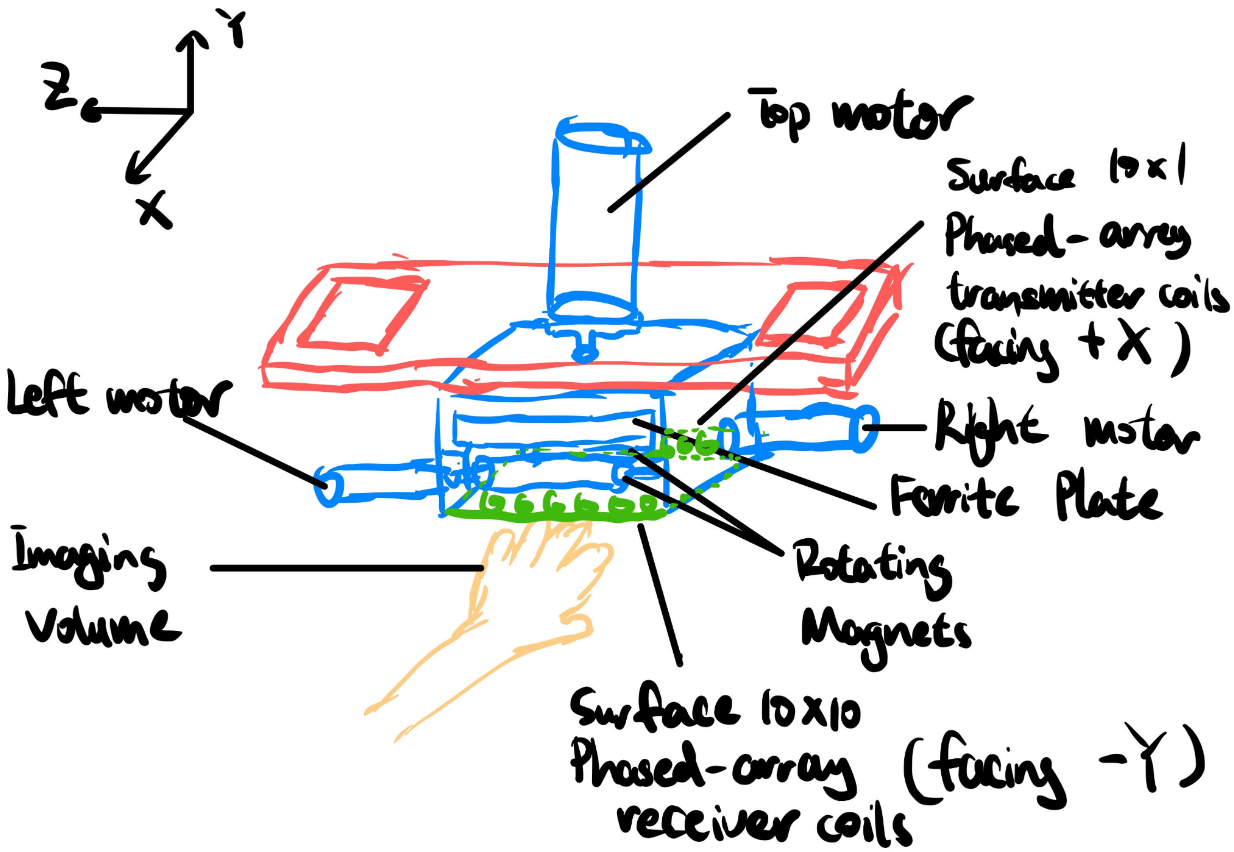

Figure 3. The physical design of hardware component

A rough physical design of our project is shown in the above figure. The figure mostly shows the two hardware components, namely, the base magnetic field and surface RF coils, which are denoted with the colors blue and green respectively. During operation, the patient will insert a target region underneath the device, where the surface receiver coils, as well as the surface transmitter coils, will be placed as close to the imaging region as possible to maximize the signals. The operator will hold the two openings in the red structure, and the rest of the components will be able to move smoothly under the command of the control unit.

3. Base Magnetic Field

a. Introduction

The primary purpose of this subsystem is to create a non-linear and non-uniform magnetic field in order to utilize that unique magnetic field strength to create a spatial encoding for all the surface coils in the RF Coil subsystem. Two **diametrically magnetized magnets** with a surface field of 7220 Gauss(K&J magnet: DCCDIA) are placed parallel to each other, with 180 degrees of difference in their magnetization direction to ensure the maximum magnetic flux in the imaging volume. Each magnet will be placed in a chamber that is attached to the shaft of a **gearmotor**(NeveRest Orbital 20 Gearmotor), which can be individually rotated by the control unit. Above the two chambers is a **ferrite plate**(Digi-key: 399-FPL100/100/12-BH1T-ND), which serves the purpose to block off unnecessary magnetic flux loss to further increase the magnetic field strength in the imaging volume. We provide another degree of freedom by adding an extra gear motor on the top of this base structure so that we can also rotate the entire magnetic field to ensure the uniqueness of field strength in our imaging volume. The rotation procedure consists of two loops; in the inner loop, the two magnets will be rotated by a fixed angle and in the outer loop, the top motor will rotate the entire base field by a fixed angle. The angle will be determined by the minimal amount of rotations we need to create a unique encoding for each surface coil.

b. R&V Table

Requirement	Verification
1. Power Distribution Board distributes 12V +/- 5% to each of the outlets with a 12V DC input from the function generator. 2. 10A fuses on the Power Distribution Board are functional and will break the circuit if the current were to exceed 10A. 3. The circuit is broken if the input polarities have been reversed.	1A. Measure the output voltage from each outlet using an oscilloscope, ensuring that the output voltage stays within 5% of 12V. 2A. Plug 10A fuses into the Power Distribution Board. 2B. Power the gear motor with a 12V power supply. 2C. Stall the motor using a torque test stand and check if the fuses break the

4. Magnetic field strength within the effective imaging volume should range from 1mT to 200mT. 5. Motor can rotate by 30 degrees at each scanning iteration. 6. The time needed for each rotation iteration (for each imaging step) should not exceed 2 seconds. 7. Time for motor stalling does not exceed 2 minutes and 54 seconds. 8. The operating temperature does not exceed 80℃.	circuit. 3A. Plug the 12V DC power supply generated by the function generator into the Power Distribution Board with reversed polarities. 3B. Check to see if Schottky diodes are placed in the right direction to prevent the motors from rotating. 4A. Rotate magnets to zero position (magnetization direction is 90 degrees and 270 degrees, respectively) 4B. Place the Gauss meter at the point of interest in the imaging region. 4C. Place the probe of the Gauss meter in parallel to the X-axis, rotate the probe by 360 degrees on the XY plane, and find the maximum reading. 4D. Rotate each magnet by 30 degrees, repeat step 4B-4C 5A. Press the RESET button to return the motors to their zero position. 5B. Press the TEST button(debug) to perform one iteration on the motor. 5C. Measure the angle of rotation to ensure that motors rotate by the correct amount at each iteration. 6A. Do step 5A-5B, and measure the time needed for one rotation using a stopwatch. 7A. When a motor begins stalling, use a stopwatch to record the time that it has been stalling and cut the power source immediately when the stall time exceeds 2 minutes and 45 seconds. 8A. During the time of operation, use an IR thermometer to make sure that the temperature of the motor as well as the microchip is below 80℃

4. Surface RF Coils

a. Introduction

The radio frequency coil subsystem can be divided into two components, both a 10cm x 10cm surface coil array. The surface coil array will be placed perpendicularly to the base magnetic field to make sure that we excite and detect the nuclear spin change in the desired orientation. The transmitter coil array functions as a nuclear spin excitation trigger, which sends a signal to the target imaging volume and excites the nuclear spin of hydrogen atoms in that region. In order to excite specific atoms, the transmitter coils will have to operate at Larmor frequency, which is calculated from the base magnetic field strength as well as the gyromagnetic ratio of the target atoms. Transmitter coils will only excite the hydrogen atoms when the control unit sends an excitation signal, and it will be turned off for the rest of the time. The receiver coil array, on the other hand, detects the magnetic field change in the target region and records the strength as well as time spent for the nuclear spin to return to its original state (under the influence of the base magnetic field). To do so, the receiver coils need to be tuned to the corresponding Larmor frequencies as well through the control unit. Once the nuclear spins have been distorted, the control unit will send a detection signal, and the receiver coils will begin to collect data. Then, the output from these receiver coils will be sent to the control unit to be converted to digital signals and packaged for further processing before we can visualize the image. Both transmitter and receiver coil arrays will be made up of PCB coils because we can arbitrarily decide the number of turns and layers of these PCB coils and also minimize the area of the coils.

b. R&V Table

Requirement	Verification
1. Transmitter and receiver coils can be tuned by the microcontroller to the desired Larmor frequency. 2. Receiver is able to detect the magnetic	1A. Use a microcontroller to generate the AC current oscillating at the Larmor frequency. 1B. Connect to the coil array and use an oscilloscope to measure the AC current

field change. 3. Receiver is turned off while transmitting, for protection purposes.	through the coils, ensure that it’s corresponding with the Larmor frequency 2A. After the receiver coil is tuned and turned on, use an oscilloscope to measure the current through the coils. A significant increase of current amplitude indicates the magnetic field change of the target region. 2B. Observe that the current amplitude returns to the initial value, which indicates that the receiver is able to capture the nuclear’s returning to its original state. 3A. In the microcontroller IDE, assert the PWM pin of receiver coils to be off while transmitting. 3B. Run the program of coils, while transmitting, use an oscilloscope to probe the receiver and make sure there’s no current flow.

5. Amplifier and Control Unit

a. Introduction

The Control Unit is in charge of all the signals as well as part of the data processing; not only does it need to tell the other subsystems when to rotate, excite, and detect, but also it performs the analog-to-digital conversion and sends the resulting data to the image processing unit serially. The signaling operation requires a **microcontroller**(ATMEGA32U4) with sufficient computing power to realize the code that will be written with Arduino IDE. The **ADC**(TBD) is another crucial component in the control unit, which is needed for making the signal directly available for image processing; furthermore, due to the relatively weak field strength and certain requirements of ADC, we need to utilize a **preamplifier**(TBD) and an **amplifier** to increase the amplitude of the received signal to an appropriate level before digitizing and minimize the effect from the offset. To detect and distinguish between different body tissues, we need a **Phase Detector** and **Comparator** for comparing the magnitude and phase difference between the reference and input signal in the receiver coils. The ADC as well as the preamplifier, Phase Detector, and Comparator will be embedded in the PCB, which will then be connected to the microcontroller.

b. R&V Table

Requirement	Verification
1. The microcontroller can generate correct control signals based on the embedded program. 2. Preamplifier should be able to minimize the offset and Noise caused during the transmission. 3. Amplifier should be able to detect the phase difference between the reference signal and input signal and the amplitude difference.	1A. Motors are operated correctly based on the program. 1B. We can verify and monitor the signal output by using the oscilloscope for the output pins of the microcontroller, which should give us the output signal graph that aligns with the program command. 2A. Based on how much offset and Noise we will get, the output should be roughly smooth and clean. Detailed tolerance analysis will be calculated after we have the sample signal. Again, the signal can

4. ADC needs to have enough resolution (>= 12 bits) to be able to convert massive analog signals, and digital signals should be able to match the analog pattern. 5. ADC needs to have reasonable quantization error(<= +/- 0.5 bit) which can be calculated using Matlab after we have the sample signal.	be verified by using an oscilloscope to get the waveform and checking the offset and Noise by comparing it with the ideal signal. 3A. Comparator should be able to compare the amplitude of the input and reference signal and output logic high if the input is higher. This can also be verified by using an oscilloscope to plot the waveform and compare them with the input and a reference relationship. 3B. The phase detector should be able to detect the phase difference and generate output signals that can visualize the delay between reference and input signals by using an oscilloscope. 4/5. The digital signal output pattern should match the analog input signal pattern, and we can compare them by plotting the output digital signal using python and reading the input from the oscilloscope.

6. Image Processing Unit

a. Introduction

The image processing unit will receive the digital signals serially through a USB connection from the control unit, and it performs both packaging as well as image reconstruction to produce a final image scan of the target region. Each package will consist of the individual coil input as well as the time for the nuclear spin to return to its original state. With this information, the packager sends an image in the k-space, and Inverse Fourier Transform will be performed to produce an image in the image space. Then, the set of image-space outputs will be fed into the neural network, and by using parallel imaging techniques, the image is reconstructed and presented by the display unit as the final output. The operations above will be done by a computer with proper computational power to minimize the time needed for the whole process.

b. R&V Table

Requirement	Verification
1. Packager correctly receives digital signals from the microcontroller in serial fashion. 2. MoDL Neuro Network is trained for the body part that is being scanned with a training accuracy of above 0.9 3. MoDL Neuro Network can achieve a testing accuracy of above 0.5	1A. Program the controller to send arbitrary variables as output signals. 1B. Check the packager to make sure the constructed image in k-space corresponds to the arbitrary variables. 2A. Clone the MoDL repository from GitHub, and download hand MRI data from the USC hand MRI project. 2B. Run trn.py file with hand MRI data. 2C. Check to make sure that the training accuracy is above 0.9. 3A. Generate a set of images of hand scan using our device in the k-space. 3B. Run test.py file with the generated images to get an output of the reconstructed image. 3C. Check to make sure that the testing accuracy is above 0.5.

7. Tolerance Analysis

a. Magnetic Pull Force:

Motors' performance could be affected significantly by the pull force generated from the magnets, and the motors are required to perform some relatively precise rotational movements(such as stopping after rotation for some certain degrees). The Motor must have enough stall torque to be able to negate the torque generated by the combination of the two magnetic pull forces and stabilize the magnets. The estimated pull force between the magnet and the ferrite place is 25N, whereas the estimated pull force between the two magnets is 50N. Knowing the magnets have a diameter of 20mm, The torque generated by the two pull forces combined can be approximately calculated as

$$\tau_{total} = F_{magtomag} \times r + F_{magtoplate} \times r$$

$$\tau_{total} = 25N \times 0.01m + 50N \times 0.01m$$

$$\tau_{total} = 0.75N \cdot m$$

Therefore, we have chosen a gear motor with a stall torque of 1.236 N•m to ensure motor functionality.

b. Magnetic Field Strength:

The quality of our image will greatly depend on the magnetic field that we operate in. Therefore, it is important to maximize the magnetic field strength, and in the below figure, we simulated the magnetic flux in our imaging volume. The physical magnetic field should be somewhat aligned with the field portrayed in our simulation to ensure the functionality of the entire device.

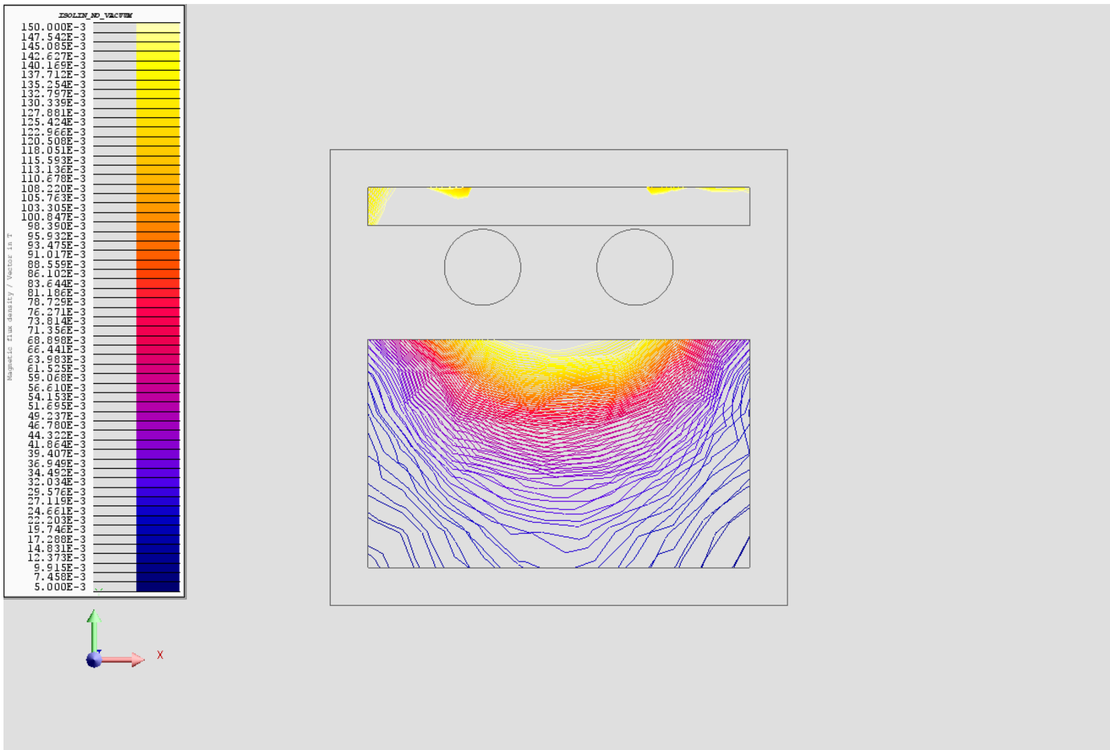

Figure 4. Magnetic Flux on XY-Plane at Zero Position

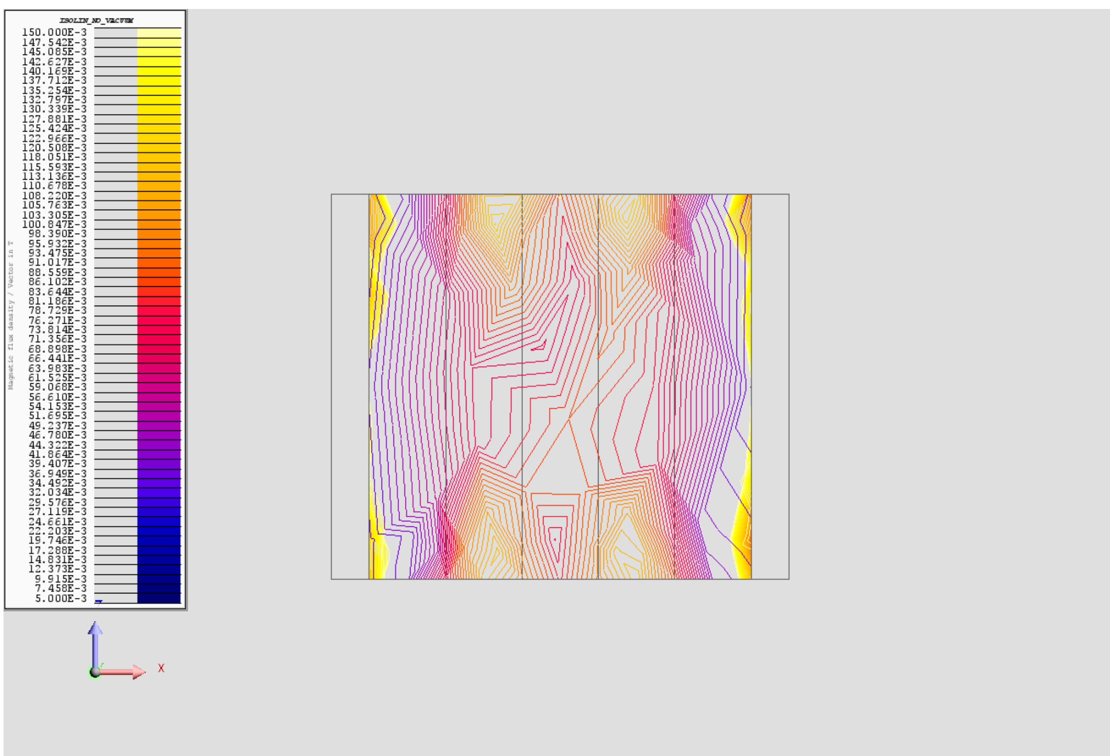

Figure 5. Magnetic Flux on XZ-Plane at Zero Position

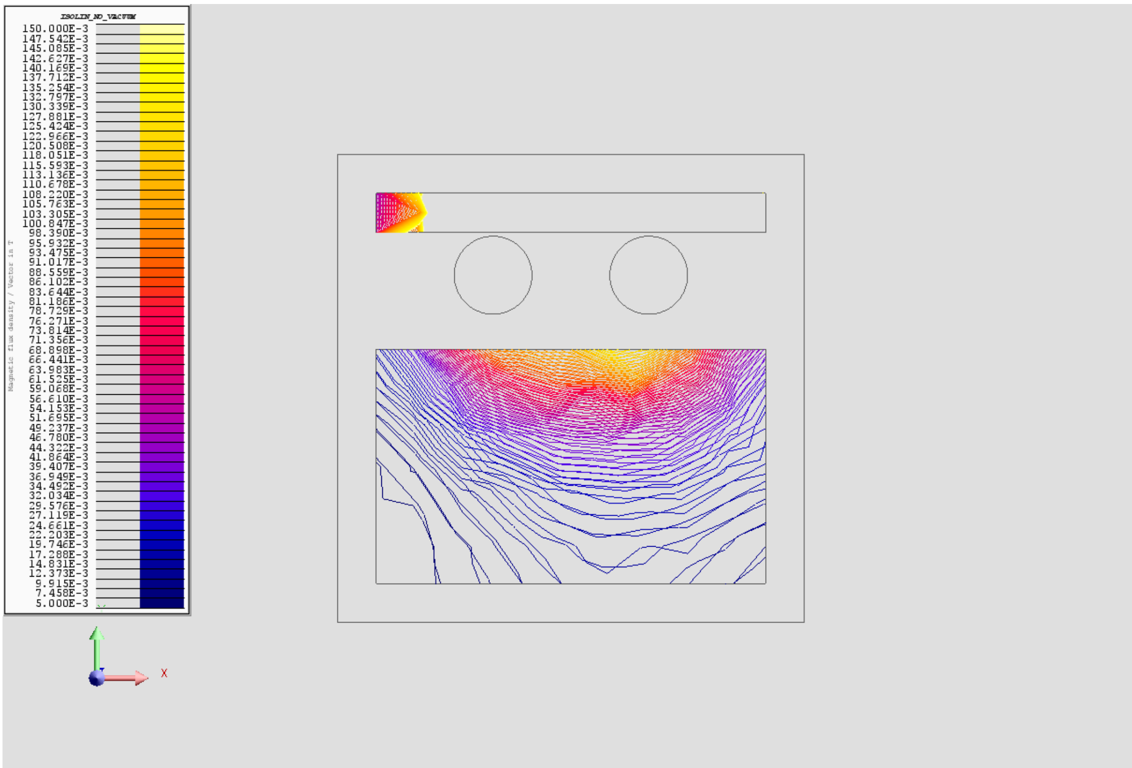

Figure 6. Magnetic Flux on XY-Plane at 30 Degree Rotation

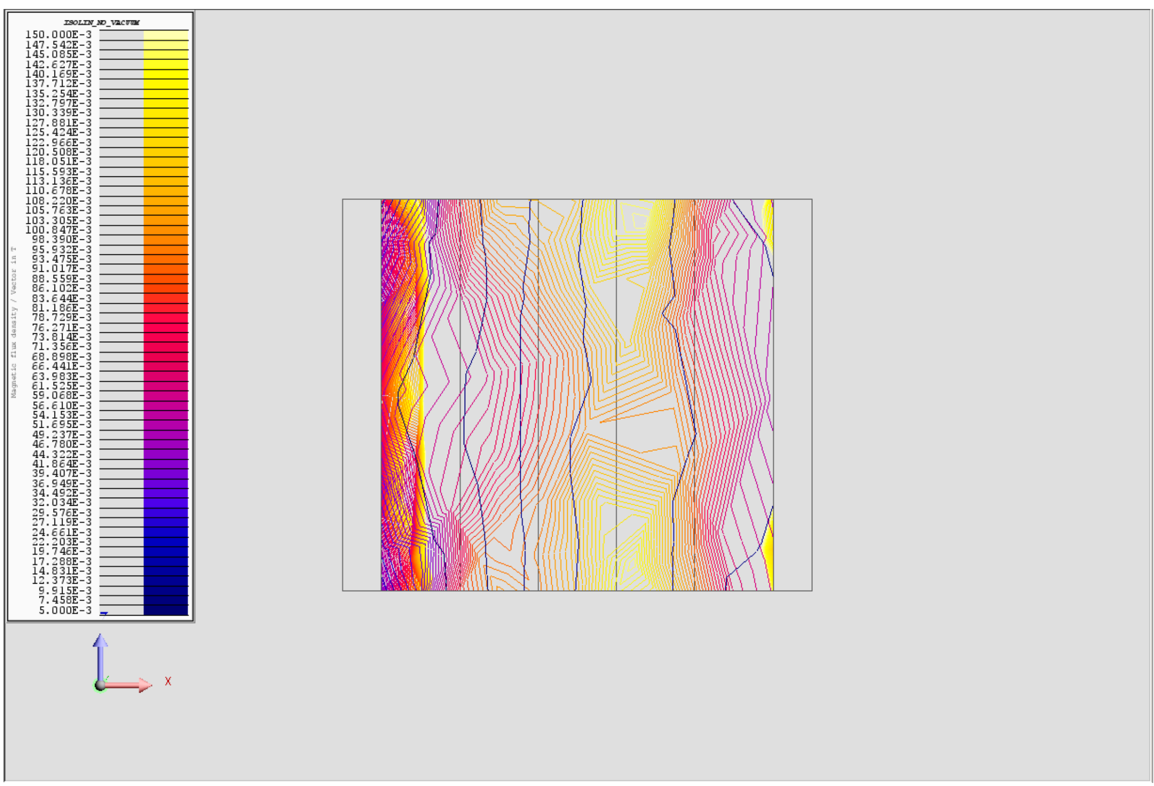

Figure 7. Magnetic Flux on XZ-Plane at 30 Degree Rotation

c. Larmor Frequency

In our portable MRI device, one of the most important subsystems is transmitter and receiver coils as they need to be tuned to specific frequencies in order to excite the body tissue and receive the corresponding signal. Our device will aim to excite hydrogen atoms because of its abundance in the human body, and the coils need to work at Larmor frequencies, which can be estimated by the following equation:

$$f = \gamma \cdot B_0$$

Where f is the Larmor frequency(MHz), γ refers to the gyromagnetic ratio for specific atoms, and B_0 is the base magnetic field strength(T). This working frequency is crucial to our coil subsystem because we will need to determine the material, area, and thickness of the PCB surface coils. If the coils we pick fail to function at the frequencies mentioned above, the SNR for this subsystem will be tremendously reduced and thus resulting in significantly compromised image qualities. In our case, the base magnetic field ranges from 1mT to 200mT, and the gyromagnetic ratio for Hydrogen atoms is 42.58; therefore, the range of the working frequencies for our coils should be between 42.58kHz to 8.516MHz.

d. Receiver Amplifier Input Offset and Noise Margin:

Due to the relatively weak magnetic field and non-ideal transmission environment, the input of the receiver is expected to be extremely noisy and have some offset compared to the reference signal, and all of those factors might have a huge impact on the result. During the experiment, we are going to measure the offset and the noise for the receiver and then we can choose our amplifier specifications to minimize the effect from them. The following equation can be used to illustrate the minimization of the offset with Vos1 and Vos2 being the offset for the input and output of stage1 and 2 and G being the amplifier gain.

$$V_1 = V_{in} + V_{os1}$$

$$V_2 = V_{os2} - G \cdot V_{os1}$$

$$V_{out} = V_1 + \frac{V_2}{G} = V_{in} + \frac{V_{os2}}{G}$$

III. Cost and Schedule

1. Cost Analysis

a. Labor

- Average salary received by course assistants, which best fit our condition, in UIUC ECE department: 11$/hour after tax [3]
- Our estimation of weekly working hours: 10 hours
- Total labor cost: 13200$

b. Part

Part Name	Qty	Unit Price ($)	Total Price ($)
NeveRest Orbit 20 Gearmotor	3	35	105
Power Distribution Board	1	44	44
NdFB Diametrically magnetized magnets	4	10.36	41.44
Ferrite Plate	1	61.88	61.88
ATMEGA32U4	30	5.27	158.1
ADC (AD9203)	100	6.07	607
Preamp (AD9864)	100	12.08	1208
PCB boards	3	60	180

c. Grand Total

The grand total for this project is estimated to be 13200 + 105 + 44 + 41.44 + 61.88 + 158.1 + 607 + 1208 + 180 = 15605.42 USD.

2. Schedule

	Yaokun Shi	Zexuan Cheng	Yujiang Han
02/22/2022	CAD for the support structure, decide magnet layout and purchase magnets	Research PCB coil and decide the area, thickness, and material of our PCB surface coils	Research motor and distributor, purchase motor and distributor
03/01/2022	3D print CAD and assemble base magnetic field v2	PCB drawing and verification of surface coils	PCB drawing and verification for microcontroller
03/08/2022	Test magnetic field and record spatial encoding	Microcontroller IDE, generate control signals for coils	Microcontroller IDE, generate control signals for coils
03/15/2022	Integrate all the PCB boards with existing structure	Test the tuning process of coils,	Amplifier test and signal analysis.
03/22/2022	Write code for DTFT and test its functionality using arbitrary date from microcontroller	Test the communication between transmitter and receiver	Design second version Amplifiers based on data and result.
03/29/2022	Train MoDL with hand MRI scans	Test the integration of base magnetic field and the coil arrays	Test the second version of Amplifier performance.
04/05/2022	Make-up for any of the missing objectives in the previous weeks		
04/12/2022	Test the overall systems and debug with simple test phantoms or compound solution of water and added metals.		
04/19/2022			
04/26/2022	Test device on more complex materials(if and if only our device works on simple test), clean up		
05/03/2022	Prepare for demo		

IV. Discussion of Ethics and Safety

As our project is being progressively carried out, we should always prioritize ethics and safety. The [4] highlights the safety, health, and welfare of the public, which requires us to comply with the public rules and development practices, to protect the privacy of others, and to actively check for factors that might endanger the public or the environment. This piece of code applies to our projects which involves powerful magnets that could cause damage to public properties and even individual personnel. The magnets are stored individually in appropriate locations and embedded in the mechanical structure with extra caution. Once the magnets are enclosed in their individual chambers and kept stationary by the motor shaft, the physical structure should prevent further damage. Since the magnets that we are handling can create a surface magnetic field as strong as 200mT, it is also crucial to recognize the potential damage that such a powerful magnetic field can cause to the human body. In order to prevent this, the researchers who are working on the testing of the magnetic field as well as other operations that involve close exposure to the magnets should limit the time they spend within proximity to the magnets to below 2 minutes each time they perform such operations. Otherwise, as our project is heavily involved with electronic parts, there could be inevitable problems such as fire, electric, and chemical hazards. We will closely follow the research lab safety rules, for instance [5], “We will never work alone in the lab, will not bring food into the lab, will report any broken equipment, will clear off the working space so it is free of hazards, and will not use two hands on a circuit when powered.”

Additionally, our project explores MRI on a handheld scale, which is relatively novel and challenging. As a result, we should be rather delighted to take advice and criticism from other professionals, and make realistic assumptions based on researched data, obeying [6]. During construction and upon completion of our MRI device, we should keep in mind that it’s specifically designed for medical usage and should only be operated by authorized personnel. Misconduct of the device such as intentionally keeping the strong magnetic fields within proximity to other people’s electronic devices should be strictly prohibited. It is also crucial to acknowledge that the quality of the final output of our image will be greatly compromised due to the novel techniques that we are adopting as well as other constraints; therefore, the results should not be interpreted the same way as other MRI images and should only serve an educational purpose.

V. Citations

[1] “Why are mris so expensive at hospitals?,” *Heartland Imaging*, 19-Mar-2021. [Online]. Available: https://heartlandimagingcenters.com/2021/03/19/why-are-mris-so-expensive-at-hospitals/#:~:text=Expensive%20to%20Buy%20and%20Install,deliver%20the%20most%20detailed%20results. [Accessed: 24-Feb-2022].

[2] F. Knoll et al., "Deep-Learning Methods for Parallel Magnetic Resonance Imaging Reconstruction: A Survey of the Current Approaches, Trends, and Issues," in IEEE Signal Processing Magazine, vol. 37, no. 1, pp. 128-140, Jan. 2020, doi: 10.1109/MSP.2019.2950640.

[3] “University of Illinois at Urbana-Champaign Course ...,” *glassdoor*. [Online]. Available:https://www.glassdoor.com/Hourly-Pay/University-of-Illinois-at-Urbana-Champaign-Course-Assistant-Hourly-Pay-E142738_D_KO43,59.htm#:~:text=The%20typical%20University%20of%20Illinois,from%20%2411%20%2D%20%2417%20per%20hour. [Accessed: 25-Feb-2022].

[4] “IEEE code of Ethics, I.1” *IEEE*, 2022. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed: 11-Feb-2022].

[5] E. I. T. S. Services, “Lab,” *Lab :: ECE 445 - Senior Design Laboratory*, 2022. [Online]. Available: https://courses.engr.illinois.edu/ece445/lab/index.asp. [Accessed: 11-Feb-2022].

[6]“IEEE code of Ethics, I.5” *IEEE*, 2022. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed: 11-Feb-2022].