Portable Magnetic Resonance Imaging Device

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Team 54

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I.Introduction

1. Problem

As image and signal processing becomes 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, state-of-the-art MRIs are relatively expensive and extremely large in size, which makes it difficult for smaller clinics to utilize or for professionals to quickly perform a scan on their patients on a more casual occasion.

2. Solution

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[1], ultimately producing an intelligible image of the scanning volume.

3. Visual Aid

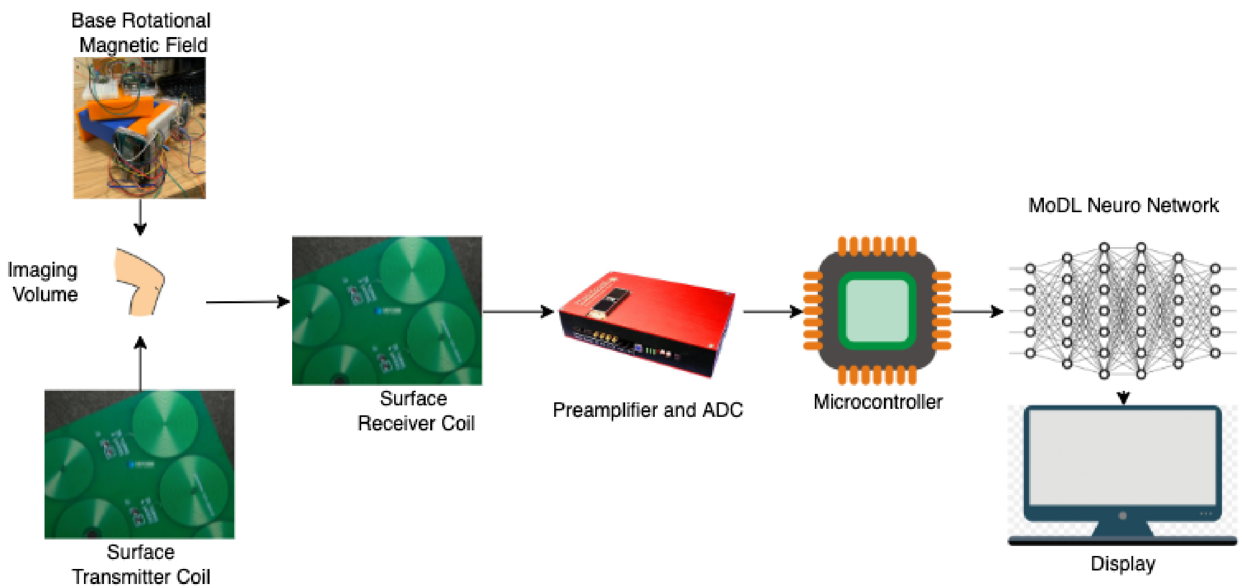

Figure 1. Visual Aid for the High-level Systems

4. High-Level Requirements List

- 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 final device should be able to generate an intelligible image scan of the target region (human knee), and achieve an SSIM (Structural Similarity Index) of above 0.5.

II. Design

1. Block Diagram

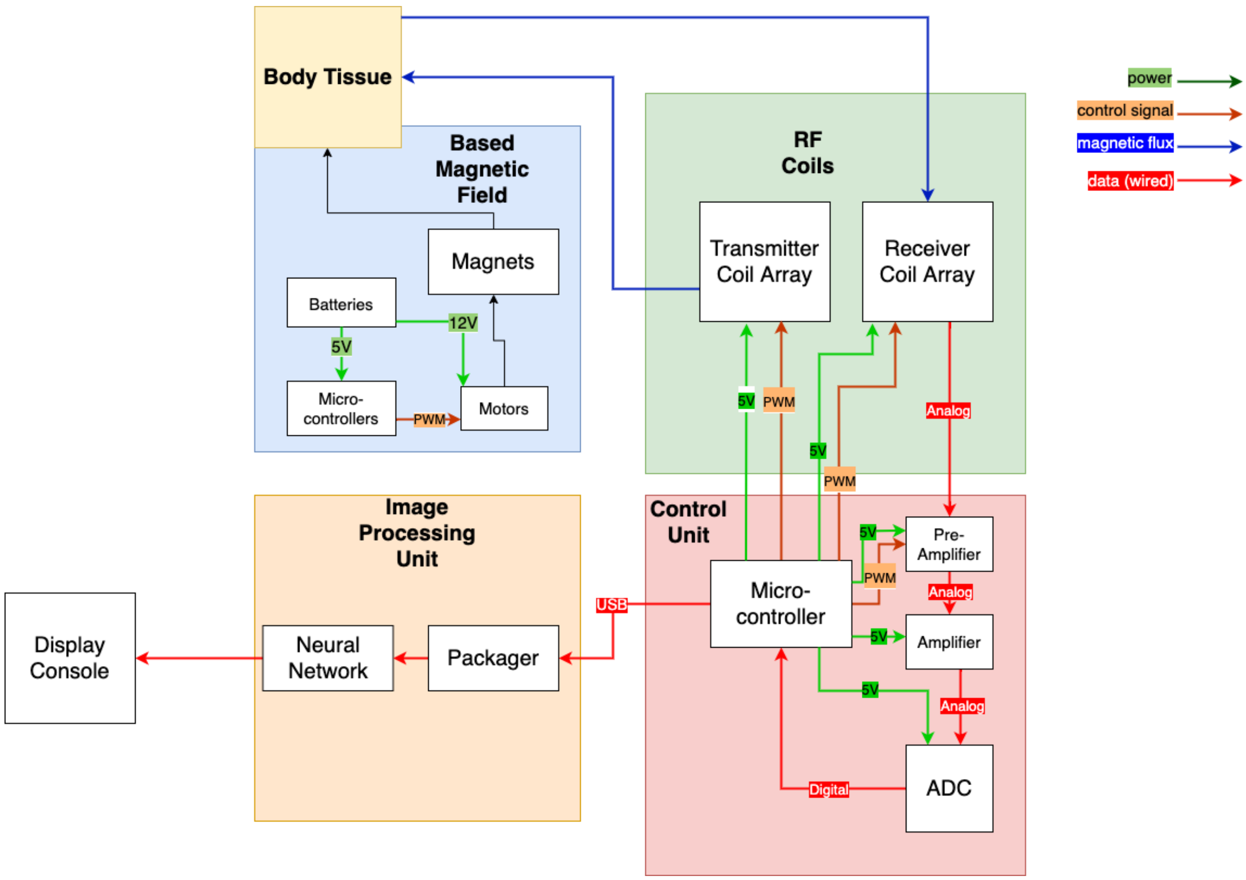

Figure 2. Block diagram of subsystems

2. Subsystem Overview

a. Base Magnetic Field

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 surface field of 7220 Gauss(K&J magnet: DCCDIA) are placed parallel to each other, with a 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 gearmotor 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, where 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. Surface RF Coils

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.

c. Amplifier and Control Unit

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 **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.

d. Image Processing Unit

The image processing unit will receive the digital signals serially through 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.

3. Subsystem Requirements

a. Base Magnetic Field

- Motors can be rotated to arbitrary angles when the control unit sends the rotation signal and kept in a stationary pose for the following nuclear excitation and data collection steps.
- Motors need to be able to negate the pull force between magnets as well as between each magnet and the ferrite plate.
- The magnetic field strength at any location within the imaging volume should not be lower than 1mT.

b. Surface RF Coils

- RF transmitter coils have the proper number of turns such that they can operate at the desired Larmor frequency (assuming the excitation of hydrogen atoms).
- RF receiver coils are tuned to the corresponding Larmor frequencies of the transmitter counterparts.

c. Control Unit

- The control unit is able to signal the base magnetic field to rotate
- The control unit is able to signal the transmitters to excite body tissues.
- The control unit is able to receive data from the receiver coils in analog form.
- The preamplifier is able to minimize the noise and the offset to generate a relatively clean output.
- The amplifier is able to amplify the difference between reference and input signal.
- The ADC can successfully perform analog-to-digital conversion within 20 seconds for each rotational iteration, and have enough resolution to pass the entire signal.

d. Image Processing Unit

- The image processing unit is able to receive input data serially from the control unit through USB.
- The packager can correctly construct an image in k-space for each iteration.
- The final image should achieve a structural similarity above 0.5.

4. Tolerance Analysis

- Pull Force between Magnets and between Magnet and Ferrite Plate:
  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 stop 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 force 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 gearmotor with a stall torque of 1.236 N•m to ensure motor functionality.
- 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.

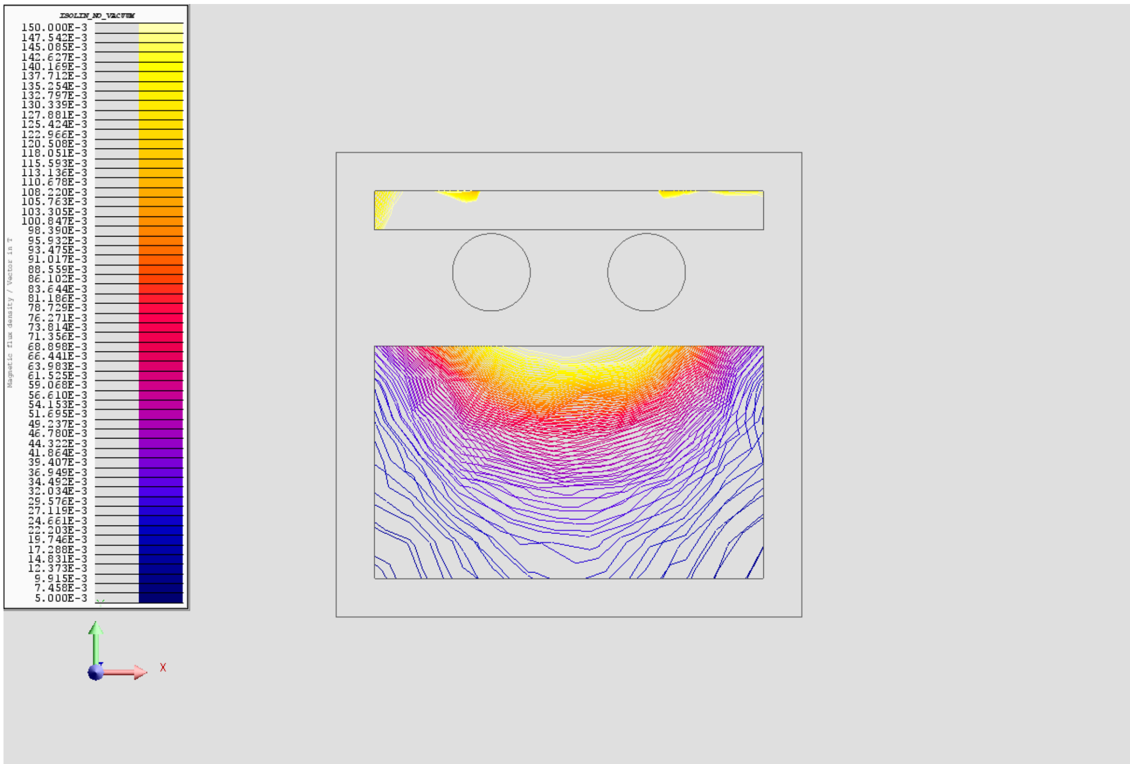

Figure 3. Simulation of Magnetic Field at Zero Position

- Larmor Frequency

  In order for the transmitter and receiver coils to function correctly, they need to operate at the roughly estimated Larmor frequencies. The Larmor frequency for hydrogen atoms (which is most commonly used for MRI devices) is calculated 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 (42.58 for H), and B_0 is the base magnetic field strength(T).

- 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.

III. Ethics

As our project is being progressively carried out, we should always prioritize ethics and safety. The [2] 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 the public properties and even individual personnels. The magnets are stored individually in appropriate locations and embedded in the mechanical structure with extra caution. Once the magnets are enclosed in its individual chambers and kept stationary by the motor shaft, the physical structure should prevent further potential damage. 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 [3], “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 [4]. 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 personnels. Misconduct of the device such as intentionally keeping the strong magnetic fields within close 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.

IV. References

[1] 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.

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

[3] 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].

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