

A BASIC BUILDING BLOCK OF TRANSCRANIAL MAGNETIC STIMULATION SYSTEM

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Abstract - Repetitive transcranial magnetic stimulation (rTMS) is a non-invasive neuromodulation technique that induces electric current in cortical tissue through a time-varying magnetic field, but commercial systems remain costly and rarely disclose coil or drive circuit parameters suited to academic prototyping. This paper presents the first stage of a MATLAB Graphical User Interface (GUI) platform for rTMS coil design, covering three tracks. The first is a circular coil sized for combined AC and DC excitation, with turns, resistance, drive voltage, power and weight computed from a target field and paired with a proposed isolation transformer, rectifier and PWM switch drive circuit. The second is a review of cranial nerve anatomy to guide coil placement. The third is a square coil GUI extended from a single loop to a sixteen element (4 by 4) array with independently adjustable size, turns and current polarity, evaluated under both co-directional and opposing excitation. Results confirm the platform as a low-cost design and teaching tool and a basis for a future hardware-validated coil array.

Key Words: Repetitive transcranial magnetic stimulation (rTMS), circular coil, square coil, coil array, MATLAB GUI, AC/DC drive circuit, cranial nerves, coil design.

1. INTRODUCTION

TMS is defined as a form of non-invasive neuromodulation wherein a coil placed on the scalp produces a rapid magnetic field pulse that creates an electrical impulse in the neural tissue beneath, thus providing a way to modulate neuron activity without having to touch the brain in any manner whatsoever. When administered as repetitive pulses, the method, known as repetitive TMS (rTMS), can either increase or decrease cortical excitability based on the frequency of stimulation. It has been accepted as a therapeutic treatment for major depressive disorder, while other potential applications include the treatment of migraines, Parkinson's disease and stroke recovery. An rTMS device is made up of a high voltage power source, a capacitor for storing energy, a switch mechanism and the stimulating coil; hence, its field strength and waveform depend on both the coil design and the drive circuitry.

Because commercial systems are expensive and rarely publish detailed coil or circuit parameters, an accessible,

parametric coil-design workflow is a useful starting point for in-house research prototyping.

The circular coil was the earliest TMS geometry; it penetrates relatively deep into tissue but activates a broad, non-focal region, whereas the later figure-of-eight coil concentrates the induced field at the intersection of two opposing loops to give much better spatial focality. Across coil designs generally, greater penetration depth can only be achieved at the cost of a wider field spread, and multi-coil arrays have been proposed as a way of reaching several stimulation sites with a smaller overall footprint than a set of separate coils. MATLAB-based tools already exist for related analysis, including wire-based field solvers for coil and array design and comparative studies of square- versus circular-geometry coil pairs; the present work follows this same computational approach but treats coil geometry, per-element current polarity and the supporting AC/DC drive circuit as jointly adjustable parts of a single design workflow rather than as separate, fixed problems. Because stimulation safety and site-selectivity also depend on the anatomy beneath the scalp, the documented course of the cranial nerves is reviewed in this project as a companion study to guide coil placement.

This paper reports the first-stage results of an ongoing project building a MATLAB GUI platform for rTMS coil design, organised around three parallel threads. The first is a circular-coil GUI that sizes the number of turns, wire length, resistance, drive voltage, power and weight required for a target field, paired with a proposed AC-mains-to-coil drive chain built from an isolation transformer, bridge rectifier, filter capacitor, PWM-controlled MOSFET/IGBT switch and gate driver, so the coil can be operated from either rectified AC mains or a regulated DC bus. The second is a review of cranial nerve anatomy carried out to guide coil-placement decisions. The third is a square-coil GUI, developed from a single adjustable loop into a sixteen-element (4 × 4) planar array in which the size, turns and per-coil current, including its polarity, can be set independently, and which has been analysed under both co-directional and opposing current excitation. The remainder of the paper presents the circular-coil design and drive circuit, the cranial-nerve review, the square-coil and array results, a discussion of the combined findings, and conclusions with directions for the planned hardware prototype.

2. LITERATURE REVIEW

Repetitive transcranial magnetic stimulation has been examined extensively as a non-invasive treatment for major depressive disorder, with recent scoping work tracing its neurobiological mechanisms from cortical excitability changes through to clinical translation [1]. Preclinical systematic reviews report consistent antidepressant-like effects across animal studies, though stimulation frequency, intensity and coil type vary widely between them, limiting direct comparison [2]. In patients with depression secondary to traumatic brain injury, meta-analytic evidence points to measurable improvement in mood and cognitive performance following rTMS courses, while tolerability reviews in older adults describe the intervention as generally safe, with scalp discomfort and transient headache the most commonly reported effects rather than serious harm [3], [4]. This clinical literature establishes rTMS as a mechanistically plausible and largely safe intervention whose outcome nonetheless depends heavily on the exact field parameters delivered by the coil and its drive electronics, motivating closer attention to the hardware design questions this project addresses.

A second strand of literature concerns coil geometry itself. Comparative reviews of coil biophysics show that a simple circular winding produces a broad, ring-shaped field that penetrates comparatively deep but activates a wide cortical area, whereas the figure-of-eight winding concentrates the field at the junction of its two loops for improved focality at some cost to depth [5]. Formal optimisation studies confirm that this depth-focality trade-off is structural rather than design-specific: greater penetration depth necessarily broadens the region of tissue exposed to a stimulating field, whatever the winding shape [6]. Narrative reviews of coil orientation further show that the yaw and roll angle at which a coil is held against the scalp shifts both the magnitude and cortical location of the induced field because of the differing electrical conductivities of scalp, skull and grey matter [7]. Multi-coil array configurations have also been proposed as a way of reaching several target regions electronically, without physically repositioning a single coil, the same principle extended in this project's 4 × 4 square-coil array [8].

A third body of work addresses the computational tools used to design coils ahead of physical construction. Wire-based MATLAB packages that solve the Biot-Savart or Neumann integral for arbitrary winding geometries compute the self- and mutual inductance and induced field of TMS coils and arrays, and have been validated against measurements on physical reference coils [9]. Separate MATLAB studies comparing square- and circular-geometry Helmholtz coil pairs report that a square cross-section can give more uniform field coverage over a larger central region than an equivalent circular pair of the same separation [10], while lightweight, openly distributed Biot-

Savart solvers provide a further teaching-oriented basis for rapid field simulation [11], [12]. These tools confirm MATLAB as a practical, widely used environment for parametric coil design, but each is generally scoped to field computation for a fixed geometry alone; few published tools combine coil-field design with drive-circuit sizing and a run-time-adjustable multi-coil array within a single interface, which is the gap the present study addresses.

3. METHODOLOGY

The proposed methodology consists of three main stages: circular-coil design, a preliminary study of cranial nerves, and square-coil array analysis using a MATLAB GUI. The overall procedure was developed to connect theoretical coil design with MATLAB simulation and practical hardware implementation.

3.1 Circular-Coil Design

A circular coil was initially designed for magnetic-field generation and detection studies. The required magnetic field, coil radius, current, frequency, and conductor diameter were selected as the main design inputs. Based on these parameters, the number of turns, wire length, resistance, voltage, power, volume, and approximate coil weight were calculated. The circular-coil design was evaluated for both DC and AC excitation, and the corresponding electrical requirements were considered for hardware implementation.

The magnetic field at the centre of an N-turn circular coil was calculated using

$$B = (\mu_0 N I) / (2R) \quad (1)$$

where B is the magnetic field, μ_0 is the permeability of free space, N is the number of turns, I is the current, and R is the coil radius. A MATLAB GUI was developed to change the design parameters and obtain the corresponding coil characteristics (Fig -1).

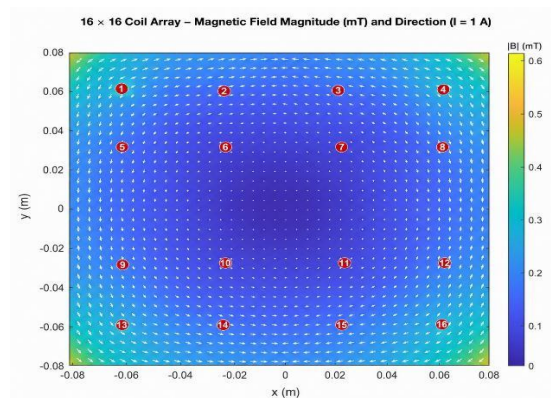


Fig -1: MATLAB GUI for circular-coil parameter design.

For the 0.05 T circular-coil design, a preliminary hardware arrangement consisting of an isolation transformer, rectifier, DC filter, DC bus, switching circuit, and magnetic coil was considered to provide the required controlled excitation current (Fig -2). The arrangement was evaluated for both DC and time-varying AC operation of the designed coil.

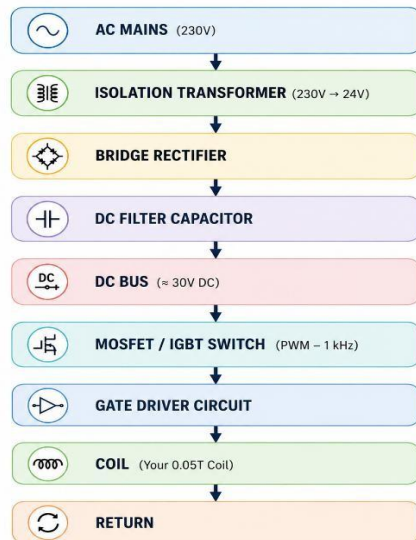


Fig -2: Hardware arrangement for 0.05 T circular-coil excitation.

3.2 Cranial Nerve Study

A basic study of the twelve pairs of cranial nerves was carried out to understand their anatomical locations and primary functions. This study was included as supporting information for understanding the relationship between magnetic-field generation and neural stimulation applications.

3.3 Single Square-Coil Design and 4×4 Configuration

Following the development of circular-coil geometry, the single square coil was created using MATLAB to analyze its magnetic field properties. The input parameters such as the dimensions of the coil, the amount of current, and the area of the simulation were specified, and the magnetic field pattern was computed and presented using the MATLAB interface. The single coil configuration formed the basis of the multi-coil configuration (Fig -3).

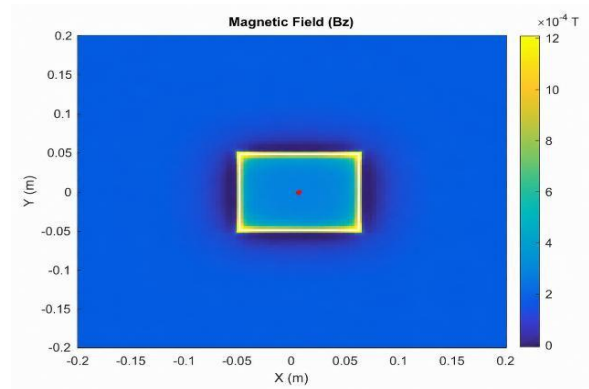


Fig -3: MATLAB GUI-based design and magnetic-field analysis of a single square coil.

For practical implementation of the proposed 16-coil system, a hardware connection was developed to provide independent excitation and control of each square coil (Fig -4). The system consists of an AC supply, isolation transformer, rectifier, DC-link capacitor, DC bus, 16-channel power driver, square-coil array, current sensors, STM32 microcontroller, and MATLAB GUI. The individual coils are driven independently, allowing the magnitude and direction of current to be controlled for generating different magnetic-field distributions.

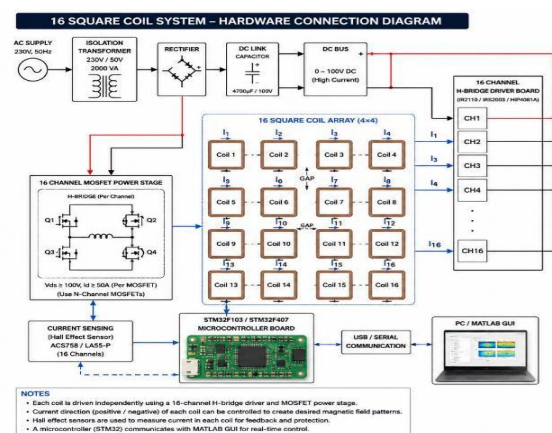


Fig -4: Proposed hardware connection diagram of the 16-coil square-coil system.

The model was then extended to a 4×4 square-coil arrangement consisting of sixteen individual coils. The GUI allows the current and dimensions of each coil to be varied independently. The total magnetic field was obtained by combining the contributions from all coils. Different current polarities were considered to study their influence on the resulting field distribution.

3.4 4×4 Square Array Simulation

The simulation was subsequently extended from a single square coil to a 4×4 array consisting of 16 square coils.

The magnetic field of a square coil was calculated by considering the contributions from its four conducting sides using the Biot-Savart law. For the 4×4 array, each coil was assigned an independent current, and the total magnetic field was obtained using the principle of superposition,

$$B_{total}(x, y) = \sum_{i=1}^{16} B_i(x, y) \quad (2)$$

The MATLAB GUI allows variation of coil size, inter-coil gap, and individual coil currents. Both equal-current and unequal-current conditions were investigated to study their effects on the magnetic-field distribution.

3.5 Magnetic-Field Distribution

A two-dimensional spatial grid was defined around the coil arrangement to calculate the magnetic field at different observation points. The magnitude of the resultant magnetic field was determined from its vector components as

$$|B| = \sqrt{B_x^2 + B_y^2 + B_z^2} \quad (3)$$

The resulting magnetic-field distribution was represented using a color map. The maximum field value, its corresponding location, and the field contribution of individual coils were also obtained from the MATLAB simulation.

4. RESULTS AND ANALYSIS

4.1 Circular-Coil Design Results

The circular-coil parameters were first calculated to obtain a practical coil configuration for magnetic-field generation. The design was developed using MATLAB, where the coil radius, current, frequency, conductor diameter, and number of turns were considered as the main design variables. For a circular coil, the magnetic field at the center was evaluated using Eq. (1), where B is the magnetic flux density, μ_0 is the permeability of free space, N is the number of turns, I is the coil current, and R is the coil radius.

For the selected design, a radius of 0.04 m, current of 50 A, and target magnetic field of 0.05 T were considered. The calculated number of turns was approximately 63.69, which can be rounded to a practical winding value during hardware implementation. The corresponding wire length, conductor area, resistance, voltage, power, volume, and weight were also estimated (Table -1).

Table -1: Circular-Coil Design Parameters

Parameter	Symbol	Value	Unit
Magnetic constant	μ_0	1.256×10^{-6}	H/m
Target magnetic field	B	0.05	T
Coil radius	R	0.04	m
Current	I	50	A
Frequency	f	1000	Hz
Wire diameter	d	0.003	m
Copper density	ρ	8960	kg/m ³
Resistivity	ρ_e	1.68×10^{-8}	Ω -m
Number of turns	N	63.69	turns
Wire length	L	16.01	m
Wire area	A	7.07×10^{-6}	m ²
Resistance	R_c	0.038	Ω
Voltage	V	1.90	V
Power	P	95.12	W
Coil volume	V_c	1.13×10^{-4}	m ³
Coil weight	W	1.01	kg

4.2 4×4 Square-Coil Configuration

After evaluating the circular coil, a square-coil configuration was developed in MATLAB. Initially, a single square coil was considered to establish the basic field distribution. The design was subsequently extended to a 4×4 array containing 16 square coils.

Each coil was assigned an individual current input, allowing the magnetic contribution of each coil to be controlled independently. The MATLAB GUI provides inputs for coil size, spacing, and individual coil currents. This arrangement enables the effect of different current combinations on the resultant magnetic-field distribution to be studied.

The selected square-coil dimensions were 0.08 m side length with a 0.12 m center-to-center spacing. The coils were arranged symmetrically around the central observation region.

4.3 Magnetic-Field Distribution With Positive Currents

The first operating condition was evaluated by applying the same positive current to all 16 coils. In the MATLAB GUI, each coil was assigned a current of +10 A. The resulting magnetic-field distribution demonstrates the combined contribution of all the coils.

The field distribution is obtained by superposition of the

magnetic-field contributions from the individual coils. Since the current directions are identical, the magnetic fields generated by the coils follow the same defined orientation and combine according to their spatial positions. The resulting field map provides a visual representation of the magnetic-field distribution over the complete 4×4 coil arrangement.

The MATLAB result also provides individual coil-field values and the calculated field at the central observation point. For the configuration shown in Fig -5, the GUI reports an overall center-field magnitude of approximately 0.0781 mT.

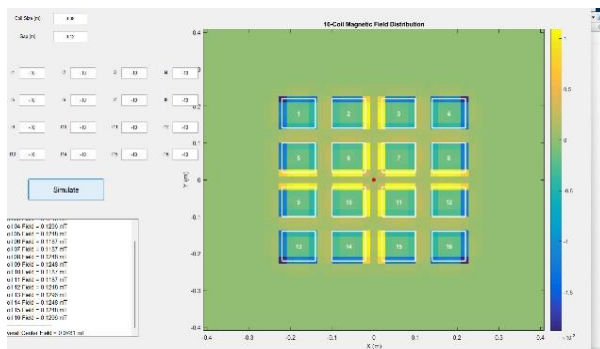


Fig-5: Simulated magnetic-field distribution of the 4×4 square-coil array for +10 A current in all coils.

4.4 Magnetic-Field Distribution With Negative Currents

In order to study the effect of current reversal, the current in each of the coils was reversed from +10 A to -10 A. This scenario is an example of reverse direction of excitation at constant current magnitude.

As can be observed from the simulation (Fig -6), reversing the current direction reverses the magnetic field vector direction. Therefore, the signed distribution changes its polarity compared with the positive-current case. However, when the magnitude of the magnetic field is considered, the spatial field pattern remains comparable because the magnitude of current and coil geometry are unchanged.

This result confirms that the MATLAB model can represent both aiding and reversed magnetic-field excitation by changing only the sign of the individual coil-current inputs.

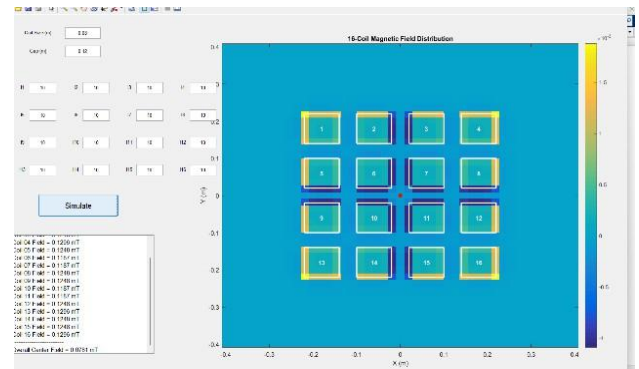


Fig -6: Simulated magnetic-field distribution of the 4×4 square-coil array for -10 A current in all coils.

4.5 Square-Coil Hardware Parameters

Based on the MATLAB design, the main hardware parameters of the 16-coil system were defined. The suggested system has 16 individual square coils in a 4×4 arrangement. The dimensions of each coil are 0.08 m per side while the spacing between coils is 0.12 m.

The proposed system uses independent H-bridge driver channels so that the current direction and magnitude of each coil can be controlled. A microcontroller-based interface can be used to communicate between the MATLAB GUI and the power-driving stage. The system and per-coil parameters are listed in Table -2 and Table -3.

Table -2: System Parameters of the 16-Coil Configuration

Parameter	Symbol	Value	Unit
Number of coils	N	16	–
Coil arrangement	–	4×4 array	–
Coil type	–	Single-turn square	–
Operating mode	–	DC / Pulsed	–
DC-bus voltage	V _{dc}	0–100	V
Driver topology	–	H-Bridge	–
Microcontroller	–	STM32F103 / STM32F407	–
Communication	–	USB / Serial	–
Current sensor	–	ACS758 / Hall Effect	–
Operating frequency	f	1–10	kHz

Table -3: Per-Coil Specifications

Parameter	Symbol	Value	Unit
Coil shape	–	Square	–
Side length	a	0.08	m
Center-to-center gap	g	0.12	m
Number of turns	n	1	turn

Wire diameter	d	1.0	mm
Conductor	–	Enamelled copper	–
Resistance (approx.)	R	0.027	Ω
Inductance (approx.)	L	1.28	mH
Maximum current	I _{max}	20	A

5. FUTURE SCOPE

The results reported here are simulation-stage outcomes, and the natural next step is to fabricate and bench-test a physical prototype of both the circular and square-array coils against the values predicted by the respective GUIs, so that winding resistance, drive voltage and field strength can be validated experimentally rather than only computationally. On the circuit side, the proposed AC/DC drive chain is currently a design-level block diagram; building and characterising an actual switching converter, including its thermal behaviour under sustained PWM operation and its electromagnetic compatibility with nearby sensing equipment, would be required before any human-facing use. The square-coil array can also be extended in several directions: increasing the element count beyond 4×4 , introducing independent timing control so that coils can be pulsed in sequence rather than only driven with a fixed current pattern, and applying an optimisation routine that automatically selects the per-coil current magnitudes and polarities needed to focus the composite field on a specified target region rather than requiring these values to be set manually. The cranial-nerve anatomical review is similarly intended to be developed further into a practical coil-placement protocol, ideally cross-checked against imaging-based or landmark-based targeting methods so that simulated field maps can be related to a specific, repeatable scalp position. Longer term, the platform is intended to support a fully integrated hardware-in-the-loop system in which the MATLAB GUI not only designs the coil but also drives and monitors the physical stimulator in real time, moving the project from a parametric design tool toward a low-cost, laboratory-grade rTMS research instrument.

6. CONCLUSIONS

This work has presented the first stage of a MATLAB GUI-based platform for the parametric design of rTMS stimulation coils, spanning circular-coil sizing for combined AC/DC excitation, an anatomical review of cranial nerves to guide coil placement, and a square-coil GUI extended from a single loop to a reconfigurable sixteen-element (4×4) array. The circular-coil tool was shown to translate a target field, radius, drive current and frequency directly into the winding turns, wire length, resistance, drive voltage, power dissipation and mass needed to realise that field, while the accompanying

isolation-transformer, rectifier and PWM-switching drive chain provides a practical route to operating the same coil from either AC mains or a regulated DC bus. The square-coil GUI, in both its single-loop and 4×4 array forms, produced consistent and physically plausible centre-field values under independently adjustable per-coil size, turns and current polarity, and the co-directional and opposing-current cases demonstrated that the composite field distribution of the array can be reshaped substantially without altering the coil geometry itself. Taken together, these three threads confirm that a single, low-cost, run-time-configurable simulation environment can support the early-stage electromagnetic and electrical design of rTMS coils that would otherwise require either expensive commercial hardware or a separate finite-element modelling package.

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