# A Real-Time Transcranial Current Stimulation Platform

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***Abstract*—Transcranial current stimulation (tCS) is a an experimental brain stimulation treatment that appears to show potential in both treating impairments and improving functional memory. Due to its recent advent and lack of FDA approval, most commercially available tCS platforms are relatively simple and lack real-time capabilities, making experimentation involving closed-loop control systems impossible. This work seeks to remedy this issue by creating a "real-time transcranial current stimulation platform" (RTtCS) that seeks to allow real-time signal generation and improve upon the capabilities of contemporary platforms. The device constructed is able to operate in four modes: as an arbitrary waveform generator, a reference current tracker, a pulse generator and a square wave generator. Each mode was thoroughly tested across both a resistor modelling the impedance of a human head and across the rectus femoris and vastus lateralis muscles of the leg with success observed in both contexts. Promising preliminary results were also gathered in the viability of a closed-loop control system using an EEG in conjunction with the stimulator.**

## I. Introduction

TRANSCRANIAL current stimulation or "tCS" is an experimental non-invasive brain stimulation treatment that uses electrical current to stimulate specific parts of the brain. From studies showing promise to "accelerate learning and boost task performance" to being "successfully applied to reduce symptoms of depression" [1], tCS appears to be an technique with a variety of potential applications. Two main methods of tCS have been used for experimentation thus far: transcranial direct current stimulation (tDCS), a method applying a constant current to the scalp, and transcranial alternating current stimulation (tACS), a method applying a consistent sinusoidal waveform to the scalp.

Though offering some flexibility in the experiments that are able to be performed, the methods lack versatility as they both involve pre-generated, constant waveforms. As such, the potential of tCS has been largely unexplored due to the current experimental paradigms. A particularly large unrealized potential of tCS is its role as an actuator in a neural feedback system, that is, using some method of neuroelectrical signal acquisition (for instance EEG recordings) to provide a reference signal to the stimulator in a typical feedback loop configuration. This feedback loop could then be used to realize a closed-loop neuroelectrical control system with potential to improve results found in current literature and grant a better understanding of the effects of tCS as a whole.

Unfortunately, as the treatment is not currently FDA approved, the market of available devices is limited and many, if not all, stimulators are not particularly robust. While some stimulators do offer time-varying signal generation, they only offer offline pre-programming that must take place before the session and cannot respond to external stimulus (such as a reference signal from an EEG). A natural result of this limitation then, is the inability to create this proposed feedback-based control loop.

This paper proposes a novel stimulator with real-time signal generation capabilities to rectify this issue. The proposed stimulator makes an improvement to commercially available stimulators in two regards: (1) the ability to generate arbitrary waveforms to be safely applied across the brain in real-time; and (2) the ability to receive some external reference in order to allow the capability of a closed-loop stimulation platform. The following sections describe the construction of the proposed stimulator and provide some preliminary results regarding its capabilities.

## II. System Architecture

### A. High-Level Description of the Stimulator

Using the "transcranial burst electrostimulation device" proposed by Wang et al [2] as a reference for software controlled tCS, the architecture of the stimulator was created. The architecture is described by the high-level block diagram seen in Figure 1.

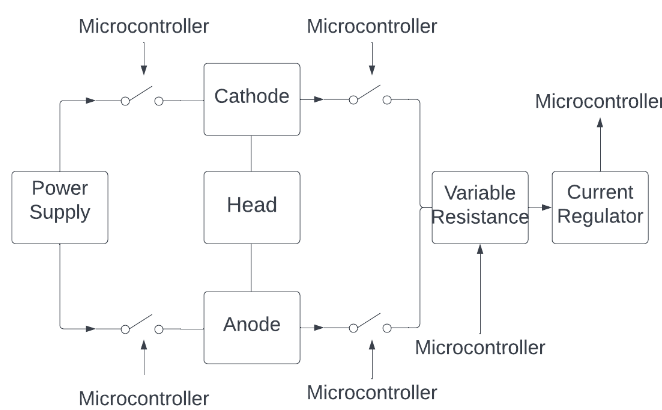


Fig. 1: High-Level Block Diagram of the Stimulator

The positive terminal of the power supply is connected to the anode and cathode in an H-bridge configuration of switches that are controlled by a microcontroller. This configuration allows for both anodal and cathodal stimulation, meaning that the current can flow either from cathode to anode or anode to cathode depending on the command sent from the microcontroller. This current passes through the user's head in typical tCS fashion and is sent into a variable resistance that is set by the microcontroller. This variable resistance can increase and decrease the current from roughly zero to two milliamps with two-hundred fifty-six intermediate resistance points, allowing for theoretically arbitrary signal generation. The signal then goes into a current regular which creates a hardware maximum current of two milliamps, ensuring the safety of both the user and the hardware itself. Finally, the signal is fed back into the microcontroller so a stable current can be maintained should there be changes in impedance across the head. The microcontroller can be controlled in real-time through a GUI, allowing for straight-forward signal generation.

### B. Hardware Description of the Stimulator

Figure 2 shows the full circuit diagram of the stimulator. A list of parts can be found in Appendix B.

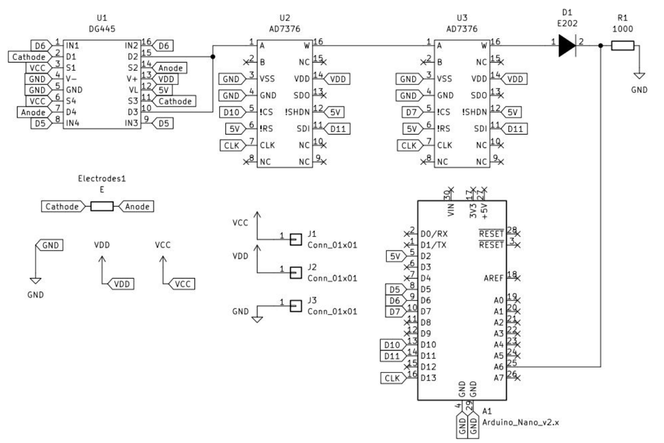


Fig. 2: Circuit Diagram of Stimulator

Though initially prototyped on a breadboard, a PCB was generated using the software KiCad and sent in for fabrication. Figure 3 shows the PCB layout that was created.

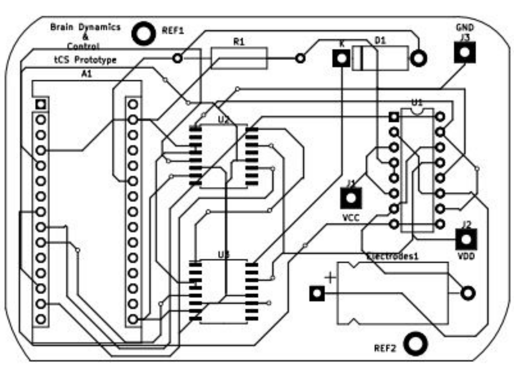


Fig. 3: PCB Layout of Stimulator

### C. Operation Modes of the Stimulator

The stimulation platform can be run in four distinct modes: (1) arbitrary waveform generator; (2) reference current tracker; (3) pulse generator, and (4) square wave generator.

*1) Arbitrary Waveform Generator:* When run as an arbitrary waveform generator, the stimulator will prompt the user to provide a text file containing a time-series describing a desired waveform as well as a desired sampling rate. The stimulator will then attempt to repeat this desired waveform until instructed otherwise. For the time being, the time-series must be constructed by hand and written into the driver file before it can be used.

*2) Reference Current Tracker:* When run as a reference current tracker, the stimulator will attempt to match the current provided as reference either though direct user input or through an external input to the microcontroller. This mode of operation best lends itself to feedback operation and is able to quickly respond to quickly changing reference values.

*3) Pulse Generator:* When run as a pulse generator, the stimulator will prompt the user to provide the number of pulses desired, the amplitude of the pulses, the DC offset of the pulses and the duty cycles (on/off time) of the pulses. The pulse will then be repeated until the user chooses to end the session.

*4) Square Wave Generator:* When run as a square wave generator, the stimulator will prompt the user to provide a low resistance value, a high resistance value and a desired frequency. The square wave will then be generated until the user decides to end the session.

A full documentation of these operation modes as well as the code used to create them can be found in the repository provided by Appendix C.

## III. Results & Analysis

### A. Physical Implementation

Figures 4 and 5 show the front profile and overhead view of the stimulator created.

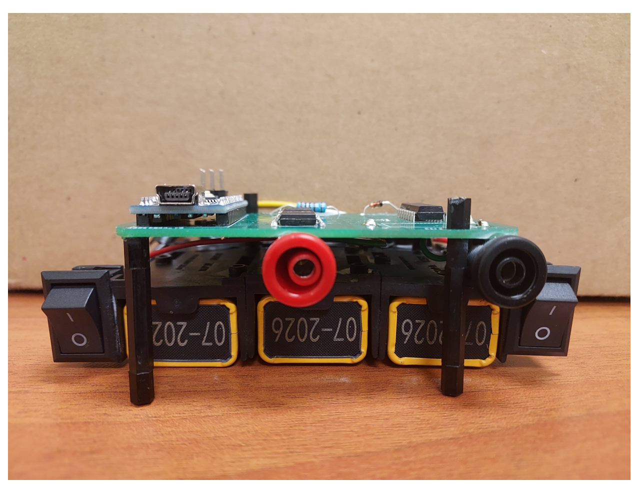

Fig. 4: Front Profile of Stimulator

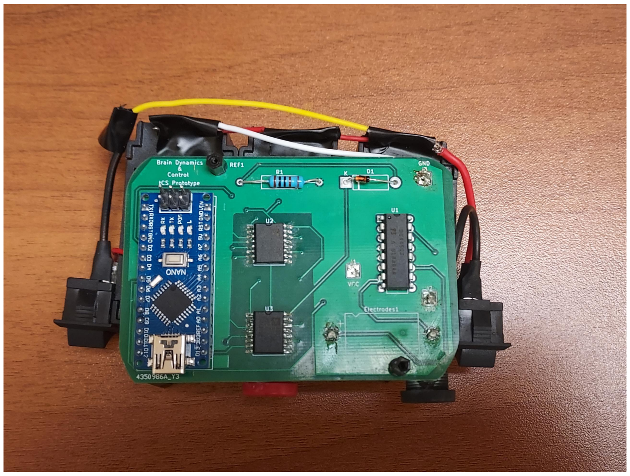

Fig. 5: Overhead View of Stimulator

The right-hand switch allows the digital potentiometers and switching IC to to receive power while the left-hand switch allows the voltage to be applied to the anode and cathode, serving as a physical kill switch to end a session. The right hand banana-plug jack is where the anode is to be plugged in and the left-hand banana-plug jack is where the cathode is to be plugged in. The correct order of powering the stimulator is important as applying a voltage across the ICs without powering them can cause undefined behavior. As such, the correct booting procedures involves: (1) turning the right-hand switch on; (2) plugging the Arduino Nano into your computer with its micro-USB port; and (3) turning the left-hand switch on when you are ready to begin the session. Powering off the stimulator follows the same steps in reverse order.

### B. Arbitrary Waveform Generator

The stimulator is able to successfully generate arbitrary waveforms based on a given time series. Figures 6 and 7 show two possible waveforms produced by the stimulator across a resistor modelling the impedance of the head. Figure 6 shows a triangular wave and Figure 7 shows a saw-tooth wave.

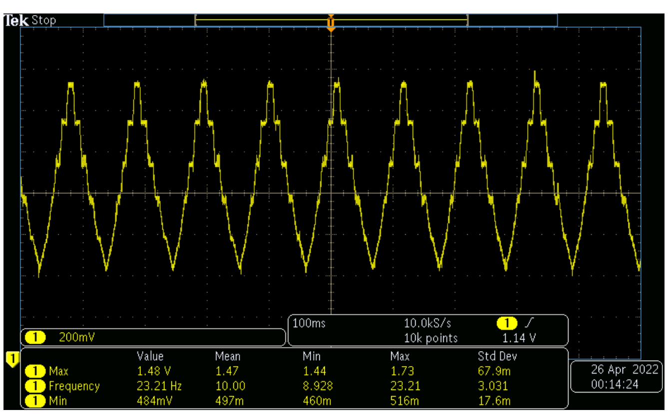


Fig. 6: Triangular Wave Generated by the Stimulator

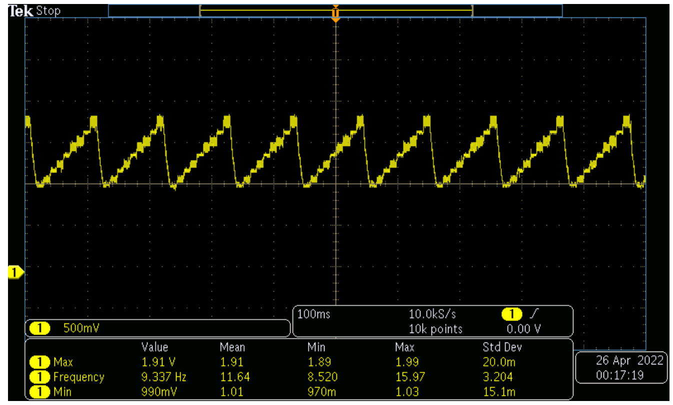


Fig. 7: Sawtooth Wave Generated by the Stimulator

A key performance note is that the current implementation of the arbitrary waveform generator allows a minimum sampling time of 10 milliseconds, that is, a time series with steps smaller than 10 milliseconds cannot be used. The current software implementation is not fast enough to keep up with sampling rates higher than this and are therefore disallowed from use at all. It is postulated that this is strictly a software limitation and a more efficient implementation of the function will likely allow shorter sampling rates.

### C. Reference Current Tracking

The stimulator's reference current tracking is able to match the reference to within 0.1 milliamps for reference currents greater than 1.5 milliamps and to within 0.05 milliamps for reference currents smaller than 1.5 milliamps. The tracker was originally designed to attempt to match the reference exactly, however a range was given in order to avoid thrashing between a current above the reference and below the reference continuously in the case that the exact reference cannot be reached due to the discrete nature of the potentiometers. Additionally, the software only allows the wiper of a single potentiometer to change by one every fifty milliseconds in order to reduce discomfort in the user. This limitation was enacted in order to mirror the purpose of a ramp-up and ramp-down period commonly found in many tCS procedures.

### D. Pulse Generator

The pulse generator mode of operation was designed to be able to take up to one-hundred pulse inputs from the user with a minimum time between pulses of one millisecond. This one millisecond time restriction was decided arbitrarily and faster performance can likely be found should that be desirable in the future. While this mode is quite versatile, its efficacy in tCS procedures is questionable and it is more intended to be a debugging tool when recording EEG measurements in order to determine which signals are from the stimulator and which are from brain activity. Figure 8 shows an example pulse train produced by the stimulator across a resistor modelling the impedance of a head.

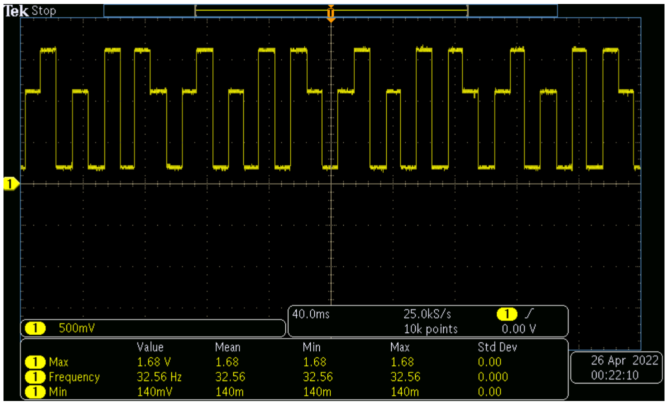


Fig. 8: Arbitrary Pulse Train Generated by Stimulator

### *E. Square Wave Generator*

The square wave generator mode of operation is able to produce consistent square waves between 1 Hertz and 650 Hertz from -2 to 2 milliamps or anywhere in between. The limitation on the high end is due more to the speed limitations of the Arduino Nano than the hardware limitations of any of the IC parts. It is not likely that frequencies higher than this are desirable and as such software improvements have not been investigated. Similarly to the pulse generator function, it is not clear if square waves are desirable in tCS procedures, though they are very useful in EEG measurement debugging. Figure 9 shows the square wave produced across a resistor modelling the impedance of a head at 650 Hertz.

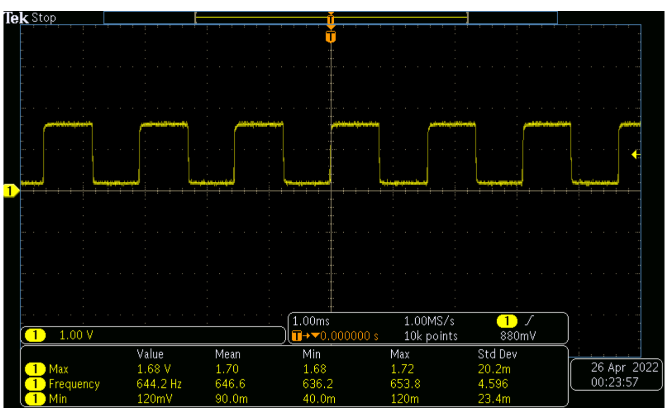


Fig. 9: 650 Hz Square Wave Generated by Stimulator

### *F. Preliminary Results Across Skin*

As the device is currently being reviewed by the institutional review board, a significant amount of data was not able to be gathered with the anode and cathode across a head. However, data was generated with the anode and cathode across the rectus femoris and vastus lateralis muscles of the leg. These experiments resulted in two interesting results: an observed decrease in skin impedance over time and a low-passing effect created by the skin's parasitic capacitance. It was observed that the current across the leg would slowly increase over time with no changes to the wiper values of the potentiometers. It is postulated that the skin's impedance decreases as current is continuously applied, implying that the closed loop system created for the stimulator is indeed a necessary factor if a constant current is desired. Figure 10 shows the low-passing effect of the skin for a 200 Hz square wave. While this effect is quite obvious in this case, it is unclear whether or not this is an issue in the context of further experimentation.

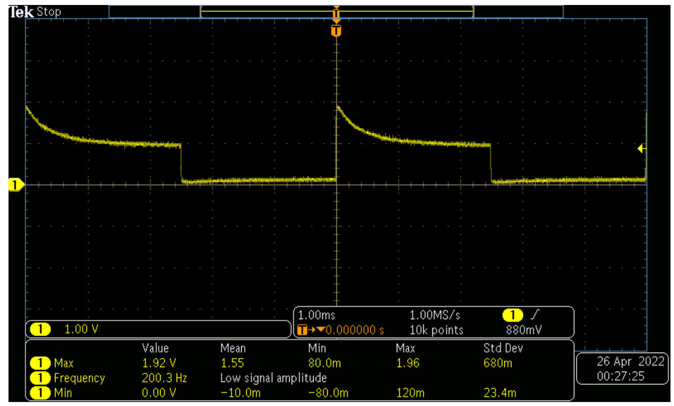


Fig. 10: Lowpassing Effect Across Skin for 200 Hz Square Wave

### *G. Preliminary Results with EEG*

The data that was able to gathered across a human head was done so with an electroencephalography (EEG) setup. In order to work towards the desired closed loop feedback system involving EEG, the controller must be able to delineate between the electrical signals created by the brain and those created by the stimulator. The initial results gathered (seen in Figure 11) show that the rise and fall times of arbitrary pulses applied across the head are short enough such that any brain activity in response is likely going to be able to be effectively measured without residual noise from the stimulator.

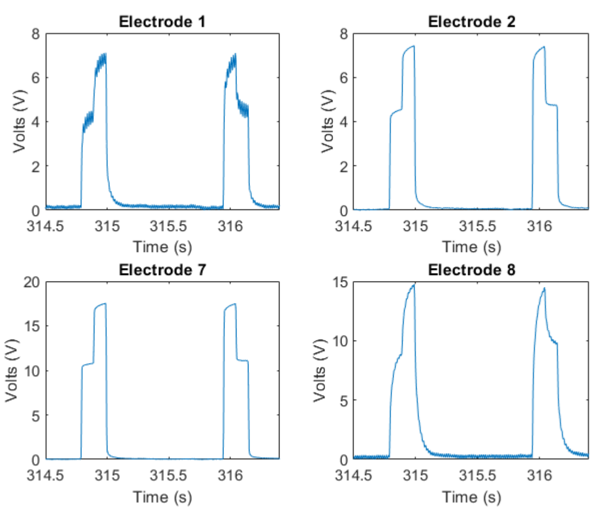


Fig. 11: Arbitrary Pulse Signals Gathered by EEG

## IV. Conclusion and Future Work

Despite some limitations, the stimulator is successfully able to serve as a real-time platform for transcranial current stimulation as well as offline arbitrary function generation. Though the stimulator is now able to be used as an actuator for a neural control system, the system itself now must be designed. The clear next step towards the goal of a closed-loop system is further experimentation with the stimulator run in conjunction with an EEG in order to determine the nature of the controller and the ability to gather clean EEG data while the stimulator is providing current. Overall, the preliminary results generated appear quite promising.

## Appendix A
## Safety Analysis

Of the numerous published studies using tDCS, there have been no significant adverse events recorded when stimulation is applied according to standard safety guidelines. The device itself follows a standard tDCS design in series with a digital potentiometer to down-regulate and modulate the typically used 2 mA maximum current. The FDA has deemed previous tDCS trials as NSR [3]. Meta-analyses have not found a statistically significant increase in reports of any adverse event due to using a tES device relative sham conditions (wearing an inactive device [4]).

## Appendix B
## List of Materials

Table I provides a list of materials used by the stimulators, a description of each part and their manufacturer.

TABLE I: List of Materials Used

| Part Name | Quantity | Description | Manufacturer |
|---|---|---|---|
| AD7376 | 2 | 100 kΩ Digital Potentiometer | Analog Devices |
| Arduino Nano | 1 | Microcontroller | Arduino |
| DG445 | 1 | Quad Normally Open Switch | Maxim |
| E202 | 1 | 2 mA Current Limiting Diode | Semitec |
| 1 kΩ Resistor | 1 | 5% Resistor | BOJACK |
| 9 Volt Battery | 3 | Power Supply | Duracell |

## Appendix C
## Code Repository

The code used by the Arduino Nano in this project can be found at https://github.com/JacobWheelock/TDCS-Software.

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## References

[1] H. Thair, A. L. Holloway, R. Newport, and A. D. Smith, "Transcranial direct current stimulation (tdcs): A beginner's guide for design and implementation," *Frontiers in Neuroscience*, vol. 11, 2017. [Online]. Available: https://www.frontiersin.org/article/10.3389/fnins.2017.00641

[2] S.-M. S. Wang, Y.-J. Huang, J.-J. J. Chen, C.-W. Wu, C.-A. Chen, C.-W. Lin, V.-T. Nguyen, and C.-W. Peng, "Designing and pilot testing a novel high-definition transcranial burst electrostimulation device for neurorehabilitation," *Journal of Neural Engineering*, vol. 18, no. 5, p. 056030, 2021.

[3] F. Fregni, M. A. Nitsche, C. K. Loo, A. R. Brunoni, P. Marangolo, J. Leite, S. Carvalho, N. Bolognini, W. Caumo, N. J. Paik, and et al., "Regulatory considerations for the clinical and research use of transcranial direct current stimulation (tdcs): Review and recommendations from an expert panel," *Clinical Research and Regulatory Affairs*, vol. 32, no. 1, p. 22–35, 2014.

[4] A. R. Brunoni, J. Amadera, B. Berbel, M. S. Volz, B. G. Rizzerio, and F. Fregni, "A systematic review on reporting and assessment of adverse effects associated with transcranial direct current stimulation," *International Journal of Neuropsychopharmacology*, vol. 14, no. 8, p. 1133–1145, 2011.