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PyTES: A Python toolbox for closed-loop transcranial electrical stimulation

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ABSTRACT

Closed-loop transcranial electrical stimulation (TES) is attracting increasing interest, but limited hardware and software solutions impede wide adoption. In particular, existing solutions are restricted to specific hardware, operating systems, and commercial software packages. We present a Python-based toolbox – PyTES – for closed-loop TES. PyTES is open-source, easy to integrate with existing Python packages for real-time brain decoding, and is able to interface with a wide range of low-cost hardware solutions. In this paper, we review existing solutions for closed-loop TES, introduce the design principles of PyTES, and demonstrate how to realize a closed-loop TES protocol with PyTES.

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Code metadata

Current Code version

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Software code languages, tools, and service used

Compilation requirements, operating environment & dependencies

If available link to developer documentation/manual

Support email for questions

0.1

<https://github.com/ElsevierSoftwareX/SOFTX-D-22-00212>

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Python, SCPI command

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<https://github.com/TateXu/pytes>

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1. Introduction

Transcranial electric stimulation (TES) is a low-cost, non-invasive, and convenient to use neuromodulatory technique while facing mixed results [1–3], and limited efficacy [4–6]. One potential reason that can hamper the overall performance of TES is the conventional fixed-parameter stimulation setup, which cannot cope with the heterogeneity [7,8] and the dynamics of the brain [9]. Therefore, the adaptive tuning of the stimulation parameters attracts increasing attention, in particular, with behavioral- or neural feedback in a closed-loop system [10,11].

By definition, a closed-loop system can self-regulate its output to the desired state based on the feedback signal. This type of

system possesses stable adaptiveness that is desirable for the TES study. Hence, this has yielded many promising new avenues of closed-loop TES research [10,12,13]. Most related studies, however, focus on the neurophysiological mechanism or algorithmic performance, while a general guideline for implementing a closed-loop TES system has not yet been demonstrated. Moreover, most available implementations are closed-source or inconvenient to use or limited to certain operating systems, e.g., Windows, or specific programming languages, e.g., Matlab. These restrictions introduce additional obstacles that hinder the related closed-loop TES studies. Therefore, this paper presents a novel Python-based solution to tackle the difficulties mentioned above based on an original and open-source Python toolbox – PyTES (Code is available at¹). To establish a closed-loop system, this toolbox can be seamlessly integrated with the hardware,

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¹ <https://github.com/TateXu/pytes>

Table 1

Summary of closed-loop system implementation with following abbreviations: RealTime eXperiment Interface — RTXI [18], Closed-Loop Manager — CLM, Not available/applicable — N/A.

Reference	Year	Stimulation type	Stimulator	DAC	Software/Language
[19]	2013	TES	DCSP	NI-DAQ PCI	RTXI (C++)
[20]	2013	TES	DCSP	NI-DAQ PCI-6221	RTXI (C++)
[21]	2016	TES	DCSP	NI-DAQ PCI	RTXI (C++)
[22]	2016	TES	DCSP	N/A	N/A
[23]	2018	TES	DCSP	Cerebus Neural Signal Processor	N/A
[24]	2018	TES	DCSP	Arduino Due board	Matlab
[25]	2019	TES	DCSP	NI-DAQ USB-6343	Matlab
[26]	2020	TES	DCSP	NI-DAQ USB-6343	C++
[27]	2021	TES	DCSP	NI-DAQ USB-6229	Matlab
[28]	2013	TES		StarStim	CoreGUI
[29]	2018	TES		StarStim	CoreGUI
[30]	2018	TES		StarStim	CoreGUI
[31]	2018	TES		StarStim	Matlab
[32]	2021	TES		StarStim	CLM
[33]	2014	TES	Self-designed	N/A	N/A
[34]	2018	TES	Self-designed	N/A	N/A
[35]	2017	TES	Soterix	Powerlab 26T (to trigger stimulator)	
[36]	2019	TES	ANT Neuro	Arduino Due board	Matlab
[37]	2019	TES	NeuroMod16	N/A	N/A

e.g., stimulator or digital-analog-converter, and other Python-based frameworks, e.g., PsychoPy [14], or OpenVibe [15]. More details about the required hardware for a closed-loop system can be found in Section 2.2. In addition, PyTES also supports other types of TES like high-density TES (multichannel simultaneous stimulation) [16] and envelope transcranial alternating current stimulation (tACS) (irregular/arbitrary signal stimulation) [17], etc.

The remainder of this paper is organized as follows: We first summarize the general guideline for constructing a closed-loop TES system and review existing hardware solutions in Section 2.1. Next, a novel Python-based implementation is introduced in Section 2.2 and more details about the PyTES toolbox are presented in Section 2.3.

2. Methods

2.1. General guideline and current hardware implementations

One significant problem for a closed-loop TES system is the automatic update of the stimulation signal, which is usually manually done in a conventional setup. This means that the stimulation parameters newly computed from the input and feedback signal should automatically update the analog stimulation signal. Therefore, to implement the hardware system, we need at least one software (program) to compute the parameters and one stimulator which can take the digital parameters or signals as input and output the analog stimulation signal. Furthermore, for some stimulators that do not support the input of digital signals or parameters, it is necessary to use a digital-analog converter (DAC) to convert the digital output of the software to the analog input of the stimulator. We hence reviewed the current hardware implementations of the closed-loop TES system and summarized them in Table 1 according to the general guideline stated before.

From Table 1, we can first notice the two dominant preferences about stimulators: the DC-Stimulator Plus (DCSP, Neuroconn, Germany) (9/19) [19–27] and Starstim (Neuroelectrics, USA) (5/19) [28–32], which has an integrated DAC. Another five studies either self-design the stimulators [33,34] or use other stimulators, e.g., Soterix [35], ANT Neuro [36], NeuroMod16 [37]. As for DAC, most DCSP based studies (6/9) use the national instrument data acquisition (NI-DAQ) cards [19–21,25–27]. In addition, C++ [19–21,26] and Matlab [24,25,27] are the popular language of software or program to compute the updated stimulation parameters.

Other neurostimulation toolboxes include MagPy [38] and the Python translation [39] of the MAGIC toolbox [40] for controlling the TMS signal. MagCPP offers a C++ solution for TMS [41], while the BEST toolbox is another novel option for closed-loop TMS with EEG and fMRI signals [42]. For closed-loop Vagus Nerve Stimulation (VNS), the CONTROL-CORE platform is a powerful tool and programmable with Python, Matlab, and C++ [43]. A Python-based solution for closed-loop VNS also includes a customized ASICs stimulator and waveform generator [44]. Activa (Medtronic, Inc.) and CereStim (Blackrock, Inc.) are common proprietary solutions for intracortical brain stimulation, while the NeuroStack stimulator is a recent alternative for a wearable platform for closed-loop stimulation [45].

2.2. An novel open-sourced Python-based implementation

The listed implementations provide diverse ways to control the stimulation parameters, while their usages are restricted in several aspects. First, the DAC-embedded stimulator, i.e., StarStim, requires an additional pro license for activating the remote control function [46] and only supports commercially licensed Matlab. Second, most DCSP-based solutions adopt the NI DAQ card as DAC, which requires tricky software installations, e.g., LabView and compulsory driver. Further, different DAQ cards demand diverse drivers and sometimes are only available on specific operating systems.

Considering these limitations, we decide to design a hardware implementation that should ideally be open-source with minimum installation requirements and compatible across multiple operating systems. Thus, we introduce a Python-based toolbox — PyTES, because Python supports low-level data communication for configuring the hardware and high-level analysis of the feedback signals with the advanced algorithms and displaying the experimental paradigms. Subsequently, to minimize the demand for installing drivers and dedicated software and reduce the cost, we adopt an arbitrary waveform generator (AWG) as DAC. AWG can stably output analog signals even with arbitrary shapes and can be easily configured by computer commands, e.g., standard commands for programmable instruments (SCPI). Finally, we adopt DCSP as the stimulator because StarStim only supports the Matlab language, which is beyond our open-source scope. One exemplary setup of the Python-based hardware implementation is shown in Fig. 1, in which we choose the PyTES (software), an SCPI command based AWG (Rigol DG1062Z, DAC), and the DCSP (stimulator).

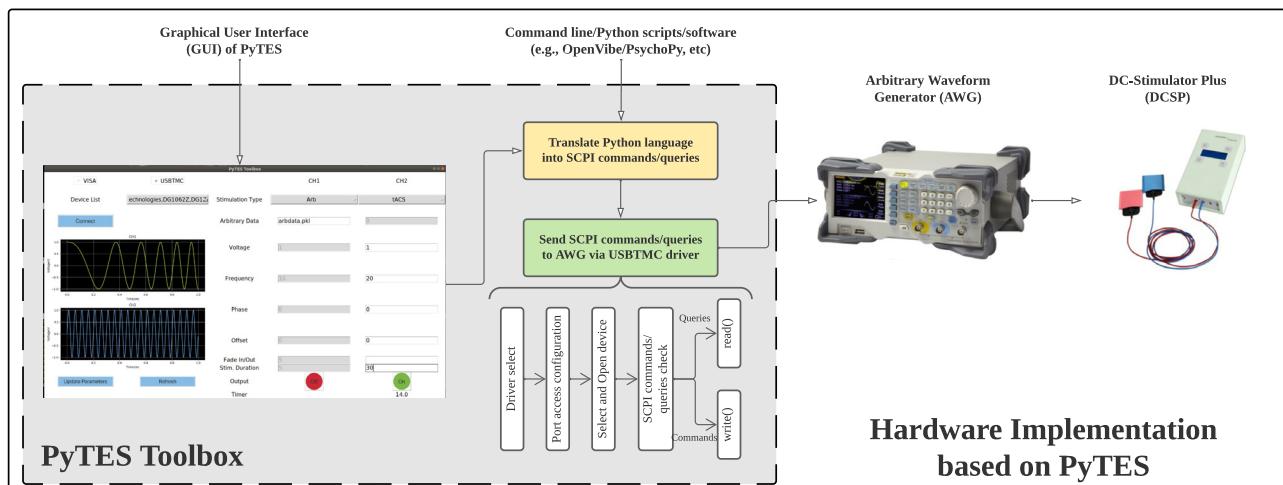


Fig. 1. Example of PyTES toolbox based hardware implementation for closed-loop TES and architecture of PyTES toolbox design. From left to right are: Graphical User Interface (GUI) and architecture of PyTES Toolbox (Software), Arbitrary Waveform Generator (Rigol DG1062Z, DAC) and DCSP (Stimulator).

To adapt our implementation to a closed-loop system, PyTES can be seamlessly integrated with other open-source Python-based frameworks to control the stimulation parameters, e.g., PsychoPy for presenting experimental paradigms [14] or OpenVibe for processing real-time feedback signal [15]. More details for the integration can be found on the [GitHub page](#). Our implementation also supports a “plug-and-play” feature for the Linux system, i.e., installation-free for drivers and Python packages. In addition to the ease of installation, the presented implementation possesses several more notable features that benefited from PyTES, which are introduced in Section 2.3.

2.3. PyTES – Python based toolbox

One fundamental feature to facilitate deploying a closed-loop TES system is the remote control of the stimulation signal. Moreover, some other special TES techniques require further features. For instance, the high-density tACS requires multichannel simultaneous stimulation and the unconventional TES like the amplitude-modulated tACS (AM-tACS) [16], and envelope-tACS [17] demands an arbitrary shape of the stimulation signal. Furthermore, current implementations are limited to a specific operating system, mainly Windows, and the compatibility with other systems like Linux is less investigated.

To address these requirements, we design our PyTES toolbox with a two-level architecture, as shown in Fig. 1. The lower level communicates and configures the hardware with SCPI commands, i.e., a common hardware language. Also, this layer deals with compatibility issues across multiple operating systems by using diverse drivers. On the Linux system, we leverage the built-in driver for Universal Serial Bus Test Measurement and Control (USBTMC) [47] to realize the “plug-and-play” feature. We also adopt the Virtual Instrument Software Architecture (VISA) protocol, which can interface multiple operating systems and devices. However, this VISA protocol requires additional installations, which are elaborated on the [GitHub page](#). Reaping the benefit of the lower level, the higher layer only needs to translate the Python commands into SCPI commands and can be easily called by other Python programs or frameworks without worrying about the encapsulated driver. For example, the intensity of the stimulation signal can be easily adjusted via:

```
from pytes.signal_generator import SignalGenerator
control = SignalGenerator()
control.amp(value=1, chn=1, stim_mode='tACS')
```

For the closed-loop application, this Python command can be inserted into any experimental or online Python frameworks, e.g., PsychoPy or OpenVibe, to automate the real-time update of the stimulation signal. We also designed a graphical user interface (GUI) dedicated to the TES applications to further facilitate the usage. This GUI also covers several other functions, e.g., multichannel simultaneous stimulation, arbitrary stimulation, fade in/out, etc. Importantly, these features can be seamlessly integrated into the closed-loop TES system.

3. Conclusion

To address the technical challenges of the closed-loop TES studies, we first review the current solutions and then introduce a novel implementation based on PyTES. PyTES is an original Python toolbox with effortless installation and usage. The convenience, low cost, and the open-source features of PyTES clear the major obstacles to deploy the closed-loop TES system and even enable the possibility of at-home administration. However, one fundamental while the undiscussed topic is the safety concern. Even though we validate it for the presented setup, as shown in Fig. 1, it is still highly suggested to re-evaluate the safety and robustness of their setups as it is unrealistic for us to test all possibilities. Hence, the authors will not take liability for any risk or problem induced by using PyTES in their own setups. As a Python toolbox, the PyTES-based implementations enjoy the abundance and advance of algorithm-related resources. We believe these advantages will further facilitate and promote closed-loop TES studies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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