PulPy: A Python Toolkit for MRI RF and Gradient Pulse Design

Jonathan B. Martin[1], **Heng Sun**[2], **Madison Albert**[3], **Kevin M. Johnson**[4], **and William A. Grissom**[3¶]

1 Vanderbilt University Institute of Imaging Science, Vanderbilt University Medical Center, Nashville, United States of America **2** Department of Biomedical Engineering, Yale University, New Haven, United States of America **3** Department of Biomedical Engineering, Case Western Reserve University, Cleveland, United States of America **4** Department of Medical Physics and Radiology, University of Wisconsin School of Medicine and Public Health, Madison, United States of America ¶ Corresponding author

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Summary

We present PulPy (Pulses in Python), an extensive set of open-source, Python-based tools for magnetic resonance imaging (MRI) radiofrequency (RF) and gradient pulse design. PulPy is a Python package containing implementations of a wide range of commonly used RF and gradient pulse design tools. Our implemented functions for RF pulse design include advanced Shinnar-LeRoux (SLR), multiband, adiabatic, optimal control, B_1^+-selective and small-tip parallel transmission (pTx) designers. Gradient waveform design functionality is included, providing the ability to design and optimize readout or excitation k-space trajectories (John Pauly et al., 1989). Other useful tools such as vendor-specific waveform input/output, Bloch equation simulators, abstracted linear operators, and pulse reshaping functions are included. This toolbox builds on the RF tools introduced previously in the SigPy.RF Python software package (Martin et al., 2020). The current toolbox continues to leverage SigPy's existing capabilities for GPU computation, iterative optimization, and powerful abstractions for linear operators and applications (Ong & Lustig, 2019). The table below shows an outline of the implemented functions.

Table 1: List of modules within PulPy and their basic functionality. Exemplary references are included.

Module	Description
.rf.adiabatic.py	Adiabatic/frequency-swept RF pulses e.g., Garwood (2001)
.rf.b1sel.py	B1-selective pulses e.g., Martin et al. (2022)
.rf.multiband.py	Pulses for simultaneous multi-slice e.g., Norris et al. (2011)
.rf.optcont.py	Large tip angle optimal control design e.g., Connolly et al. (1986)
.rf.ptx.py	parallel transmit pulse designers e.g., Grissom et al. (2006)
.rf.shim.py	parallel transmit RF shimming e.g., Mao et al. (2006)
.rf.slr.py	Conventional SLR and variations e.g., J. Pauly et al. (1991)
.rf.util.py	RF pulse design utilities
.grad.waveform.py	Gradient and trajectory designers e.g., Kim et al. (2003)
.grad.optim.py	Gradient and trajectory optimization e.g., Lustig et al. (2008)
io.py	Vendor-specific scanner input/output
linop.py	Linear operators for pulse design e.g., Grissom et al. (2006)
sim.py	1-D/N-D/N-coil Bloch simulation e.g., Mansfield & Morris (1982)
verse.py	RF pulse/gradient reshaping tools

Preliminary development of this toolbox was presented in Martin et al. (2020). The pulse design tools were initially implemented as a sub-package in the SigPy Python package for signal processing and image reconstruction (Ong & Lustig, 2019). PulPy migrates those tools into a pulse design specific package, with SigPy as an external dependency. PulPy has been streamlined and expanded to include a larger collection of RF and gradient pulse design methods from the literature, as well as additional utility tools for I/O, pulse reshaping, and experimental B_1^+-selective pulse design algorithms. The toolbox has proved useful for prototyping novel pulse design algorithms, enabling the publication of Martin et al. (2022) by the authors and several works from other groups Wu et al. (2023). Figure 1 shows an example of RF and gradient waveforms produced by PulPy.

Statement of need

The field of magnetic resonance imaging is currently experiencing rapid growth in available open source imaging tools. Tools have been made freely available for MRI hardware development (Amrein et al., 2022; Anand, 2018), system simulation (Stöcker et al., 2010; Villena et al., 2014), pulse sequence programming (Layton et al., 2017), image reconstruction (Ong & Lustig, 2019; Uecker et al., 2015), and post-processing and analysis (Avants et al., 2014; Duval et al., 2018; Soher et al., 2023). The great increase in open-source tools has helped enable fully open-source imaging systems (Arndt et al., 2017; Artiges et al., 2024). However, one critical aspect of the imaging pipeline which has seen limited open-source tool development is RF and gradient pulse design. While RF pulse and gradient designers increasingly share code online in independent repositories, there are few sets of common pulse design tools maintained in a rigorous and consistent manner with easy-to-read code and tutorials. This is despite the reality that in many cases, carefully designed or application-specific RF and gradient pulses are crucial to the success of MRI or NMR techniques. An open source pulse design code library would facilitate the development and dissemination of novel techniques and the comparison of approaches, similar to how BART (Uecker et al., 2015) and SigPy (Ong & Lustig, 2019) have made advanced parallel imaging and reconstruction methods widely accessible. To meet this need, we have developed a library of MRI pulse design tools. We call this new package PulPy, short for Pulses in Python.

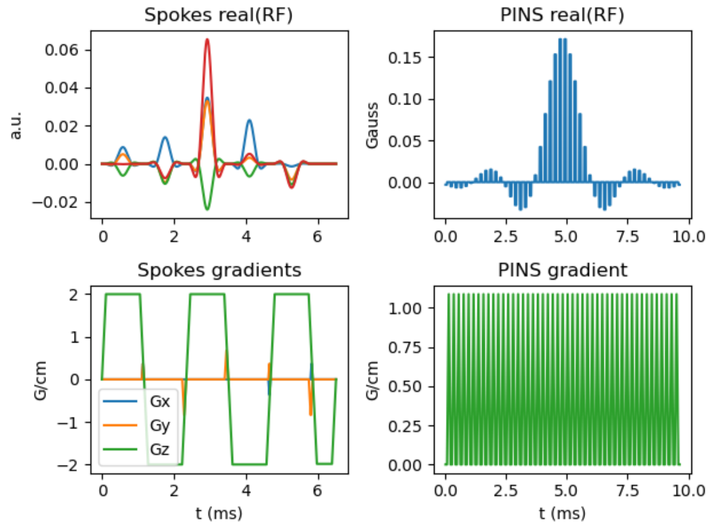

Figure 1: Example RF and gradient waveforms that PulPy can produce. Top left: 4-channel spokes RF pulse. Bottom left: associated 3-axis spokes gradient waveforms. Top right: PINS excitation RF pulse. Bottom right: associated slice-axis gradient

Target Audience

The PulPy toolbox has been developed for use by MRI researchers who are interested in pulse sequence design, MRI physics, signal processing, and optimization. We believe that it will serve as an essential building block for more general image acquisition tools which require specialized RF pulses. The previous iteration of this toolbox, SigPy.RF, has already been incorporated into open-source sequence development software such as Pulseq (Layton et al., 2017) and PyPulseq (Sravan Ravi et al., 2019) to provide RF pulses critical to the performance of various pulse sequences. We feel that PulPy, with its' more specific focus on pulse design, will be able to even more easily integrated into other MRI acquisition software toolboxes, and we encourage other MRI software developers to incorporate PulPy as a component of MRI acquisition software. Finally, end-to-end optimization of MRI pulse sequences and reconstructions is being increasingly explored (Radhakrishna & Ciuciu, 2023; Wang et al., 2022); with the RF pulse and gradient waveform design functions provided, the PulPy package could facilitate this research.

Reproducibility and standardization are critical needs in MRI , and any method of reducing methodological variability is desirable. We believe that having centralized references for RF and gradient pulses will help promote consistency between studies by providing common code sources for the most widely used RF and gradient pulses. PulPy's predecessor toolbox, SigPy.RF, also served as a hands-on teaching aid for researchers and students. An example is the educational ISMRM tutorial associated with SigPy.RF (Martin et al., 2020). This is a role that the PulPy toolbox will continue to fill. We have developed several tutorials, which are accessible to a wide audience with minimal prior MRI knowledge.

Availability and Use

The latest version of PulPy includes the latest stable release of the pulse design tools and is available from the main repository. It can be installed through pip- see the documentation for more details. Jupyter notebook based pulse design tutorials for PulPy are also available, which demonstrate the toolbox being used for several classes of pulse design.

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We would like to particularly acknowledge that this toolbox is indebted to the MRI scientists who created the RF and gradient pulse design innovations showcased in this software. These are cited as much as possible in this paper and in the PulPy source code. We are particularly thankful for John Pauly's invaluable MATLAB SLR pulse design toolbox (J. Pauly et al., 1991), which helped inform the core of PulPy's SLR pulse design module. The EPI gradient waveform designer was based on Jeff Fessler's MIRT implementation (Fessler, n.d.). Many other useful case-specific RF pulse design toolboxes not directly incorporated into this toolbox have been created, and we encourage PulPy users to investigate these toolboxes:

- Multiband-RF (MATLAB-based) for advanced multiband RF pulse design, incorporating (Abo Seada et al., 2019)
- Spectral-Spatial-RF-Pulse-Design (MATLAB-based) for designing spectral-spatial RF pulses for MRS and MR imaging, incorporating (Larson et al., 2008)
- FastPtx (Python-based) for designing pTx RF and gradient pulses, from (Bosch & Scheffler, 2023)

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References

Abo Seada, S., Price, A. N., Schneider, T., Hajnal, J. V., & Malik, S. J. (2019). Multiband RF pulse design for realistic gradient performance. *Magnetic Resonance in Medicine*, *81*(1), 362–376. https://doi.org/10.1002/mrm.27411

Amrein, P., Jia, F., Zaitsev, M., & Littin, S. (2022). CoilGen: Open-source MR coil layout generator. *Magnetic Resonance in Medicine*, *88*(3), 1465–1479. https://doi.org/10.1002/MRM.29294

Anand, S. M. (2018). *OCRA : a low-cost, open-source FPGA-based MRI console capable of real-time control*. https://dspace.mit.edu/handle/1721.1/121619

Arndt, F., Aussenhofer, S., Behrens, E., Blücher, C., Blümler, P., Brand, J., Ettinger, K. M., Fillmer, A., Grissom, W., Gruber, B., Guerin, B., Haas, S., Han, H., Hansen, M., Hasselwander, C. J., Hodge, R., Hoffmann, W., Ittermann, B., Jakubowski, M., … Zaitsev, M. (2017). Open source imaging initiative (OSI²)-update and roadmap. *Proc. Intl. Soc. Magn. Reson. Med*. https://doi.org/10.1002/mrm.26235

Artiges, A., Martin, J., Saimbhi, A. S., Stockmann, J., Sun, H., Wiggins, R., Zi, R., Geethanath, S., & Block, K. (2024). Adjustment and basic imaging sequences for the open-source MRI4ALL console using the PyPulseq and MaRCoS libraries. *Proc. Intl. Soc. Magn. Reson. Med.*

Avants, B. B., Tustison, N., & Johnson, H. (2014). *Advanced Normalization Tools (ANTS)*.

Bosch, D., & Scheffler, K. (2023). FastPtx: a versatile toolbox for rapid, joint design of pTx RF and gradient pulses using Pytorch's autodifferentiation. *Magnetic Resonance Materials in Physics, Biology and Medicine*, *37*(1), 127–138. https://doi.org/10.1007/s10334-023-01134-7

Connolly, S., Nishimura, D., & Macovski, A. (1986). Selective complex pulse design by optimal control theory. *Proc. Soc. Magn. Reson. Med.*, 1456–1457.

Duval, T., Leppert, I. R., Cabana, J.-F., Boudreau, M., Gagnon, I., Berestovoy, G., Cohen-Adad, J., & Stikov, N. (2018). Quantitative MRI made easy with qMRLab. *Proc. Intl. Soc. Mag. Reson. Med.*, 2288. https://doi.org/10.13140/RG.2.2.25014.34881

Fessler, J. A. (n.d.). *Michigan Image Reconstruction Toolbox*. http://web.eecs.umich.edu/~fessler/irt/irt

Garwood, M. (2001). The Return of the Frequency Sweep: Designing Adiabatic Pulses for Contemporary NMR. *Journal of Magnetic Resonance*, *153*(2), 155–177. https://doi.org/10.1006/JMRE.2001.2340

Grissom, W., Yip, C. Y., Zhang, Z., Stenger, V. A., Fessler, J. A., & Noll, D. C. (2006). Spatial domain method for the design of RF pulses in multicoil parallel excitation. *Magnetic Resonance in Medicine*, *56*(3), 620–629. https://doi.org/10.1002/MRM.20978

Kim, D. H., Adalsteinsson, E., & Spielman, D. M. (2003). Simple analytic variable density spiral design. *Magnetic Resonance in Medicine*, *50*(1), 214–219. https://doi.org/10.1002/MRM.10493

Larson, P. E., Kerr, A. B., Chen, A. P., Lustig, M., Zierhut, M. L., Hu, S., Cunningham, C. H., Pauly, J. M., Kurhanewicz, J., & Vigneron, D. B. (2008). Multiband excitation pulses for hyperpolarized 13C dynamic chemical shift imaging. *Journal of Magnetic Resonance*, *194*(1), 121–127. https://doi.org/10.1016/j.jmr.2008.06.010

Layton, K. J., Kroboth, S., Jia, F., Littin, S., Yu, H., Leupold, J., Nielsen, J. F., Stöcker, T., & Zaitsev, M. (2017). Pulseq: A rapid and hardware-independent pulse sequence prototyping framework. *Magnetic Resonance in Medicine*, *77*(4), 1544–1552. https:

//doi.org/10.1002/MRM.26235

Lustig, M., Kim, S. J., & Pauly, J. M. (2008). A Fast Method for Designing Time-Optimal Gradient Waveforms for Arbitrary k-Space Trajectories. *IEEE Transactions on Medical Imaging*, *27*(6), 866. https://doi.org/10.1109/TMI.2008.922699

Mansfield, P., & Morris, P. (1982). *NMR imaging in biomedicine*. Elsevier Academic Press. https://doi.org/10.1007/BF02797382

Mao, W., Smith, M. B., & Collins, C. M. (2006). Exploring the limits of RF shimming for high-field MRI of the human head. *Magnetic Resonance in Medicine : Official Journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine*, *56*, 918. https://doi.org/10.1002/MRM.21013

Martin, J., Abitha Srinivas, S., Vaughn, C. E., Sun, H., Griswold, M. A., Grissom, W. A., & Jonathan Martin, C. B. (2022). Selective excitation localized by the Bloch–Siegert shift and a B1+ gradient. *Magnetic Resonance in Medicine*. https://doi.org/10.1002/MRM.29271

Martin, J., Ong, F., Ma, J., Tamir, J., Lustig, M., & Grissom, W. (2020). SigPy.RF: Comprehensive Open-Source RF Pulse Design Tools for Reproducible Research. *Proc. Intl. Soc. Mag. Reson. Med.*, 1045.

Norris, D. G., Koopmans, P. J., Boyacioğlu, R., & Barth, M. (2011). Power independent of number of slices (PINS) radiofrequency pulses for low-power simultaneous multislice excitation. *Magnetic Resonance in Medicine*, *66*(5), 1234–1240. https://doi.org/10.1002/MRM.23152

Ong, F., & Lustig, M. (2019). SigPy: A Python Package for High Performance Iterative Recon- struction. *Proc. Intl. Soc. Mag. Reson. Med.*, 4819.

Pauly, J., Le Roux, P., Nishimura, D., & Macovski, A. (1991). Parameter relations for the Shinnar-Le Roux selective excitation pulse design algorithm (NMR imaging). *IEEE Transactions on Medical Imaging*, *10*(1), 53–65. https://doi.org/10.1109/42.75611

Pauly, John, Nishimura, D., & Macovski, A. (1989). A k-space analysis of small-tip-angle excitation. *Journal of Magnetic Resonance*, *81*, 43–56. https://doi.org/10.1016/0022-2364(89)90265-5

Radhakrishna, C. G., & Ciuciu, P. (2023). Jointly Learning Non-Cartesian k-Space Trajectories and Reconstruction Networks for 2D and 3D MR Imaging through Projection. *Bioengineering*, *10*(2). https://doi.org/10.3390/BIOENGINEERING10020158

Shin, D., Kim, Y., Oh, C., An, H., Park, J., Kim, J., & Lee, J. (2021). Deep reinforcement learning-designed radiofrequency waveform in MRI. *Nature Machine Intelligence 2021 3:11*, *3*, 985–994. https://doi.org/10.1038/s42256-021-00411-1

Soher, B. J., Semanchuk, P., Todd, D., Ji, X., Deelchand, D., Joers, J., Oz, G., & Young, K. (2023). Vespa: Integrated applications for RF pulse design, spectral simulation and MRS data analysis. *Magnetic Resonance in Medicine*, *90*, 823–838. https://doi.org/10.1002/MRM.29686

Sravan Ravi, K., Geethanath, S., & Thomas Vaughan Jr, J. (2019). PyPulseq: A Python Package for MRI Pulse Sequence Design. *Journal of Open Source Software*, *4*(42), 1725. https://doi.org/10.21105/JOSS.01725

Stöcker, T., Vahedipour, K., Pflugfelder, D., & Shah, N. J. (2010). High-performance computing MRI simulations. *Magnetic Resonance in Medicine*, *64*(1), 186–193. https://doi.org/10.1002/MRM.22406

Uecker, M., Ong, F., Tamir, J. I., Bahri, D., Virtue, P., Cheng, J. Y., Zhang, T., & Lustig, M. (2015). Berkeley Advanced Reconstruction Toolbox. *Proc. Intl. Soc. Mag. Reson. Med.*, 2486.

Villena, J. F., Polimeridis, A. G., Serrales, J. E. C., Wald, L. L., Adalsteinsson, E., White, J., & Daniel, L. (2014). MARIE a MATLAB-based open source software for the fast electromagnetic analysis of MRI systems. *Proc. Intl. Soc. Mag. Reson. Med.*, 0709.

Wang, G., Luo, T., Nielsen, J. F., Noll, D. C., & Fessler, J. A. (2022). B-Spline Parameterized Joint Optimization of Reconstruction and K-Space Trajectories (BJORK) for Accelerated 2D MRI. *IEEE Transactions on Medical Imaging*, *41*(9), 2318. https://doi.org/10.1109/TMI.2022.3161875

Wu, Z., Remedios, S. W., Dewey, B. E., Carass, A., & Prince, J. L. (2023). *AniRes2D: Anisotropic residual-enhanced diffusion for 2D MR super-resolution*. https://doi.org/10.1117/12.3008456