Optimizing MRI Pulse Sequence using Reinforcement Learning

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What is (Nuclear) Magnetic Resonance Imaging?

Magnetic

Protons can interact with external magnetic field $\vec{B}$.

$$\frac{d\vec{\mu}}{dt} = \gamma\vec{\mu} \times \vec{B} \qquad \text{(Equ. of Motion)}$$

$$\omega = \gamma B \qquad \text{(Larmor Precession Formula)}$$

Resonance

Larmor frequency ω of $\vec{B}$ meets the frequency ω_0 of RF magnetic field $\vec{B}_1$.

$$\omega = \omega_0 \qquad \text{(On-Resonance Condition)}$$

Imaging

Associate the position of protons with their precessional rates.

$$B_z(z,t) = B + zG(t) \qquad \text{(Frequency Encoding)}$$

Pulse Sequence in MRI

Pulse sequence refers to a sequential arrangement of time-dependent **magnetic field** and **events** designed to manipulate the interaction between protons and magnetic fields.

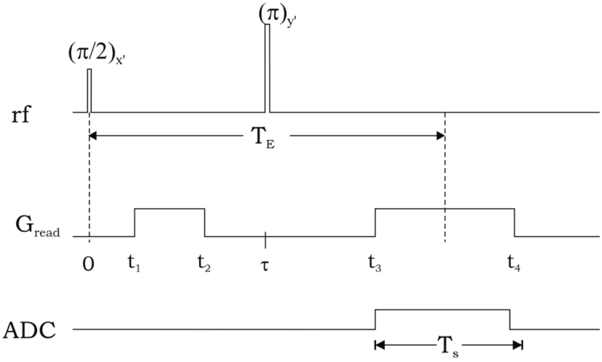

Figure: Sequence diagram for a spin echo with a π-pulse between two gradient lobes [1].

Pulse Sequence in MRI

Pulse sequence refers to a sequential arrangement of time-dependent magnetic field and events designed to manipulate the **interaction** between protons and magnetic fields.

Bloch Equation is used to describe the **interaction** between protons with its surrounding magnetic field over time.

$$\frac{d\vec{M}}{dt} = \gamma \vec{M} \times \vec{B}_{ext} + \frac{1}{T_1}(M_0 - M_z)\,\hat{z} - \frac{1}{T_2}\vec{M}_\perp \qquad \text{(Bloch Equ.)}$$

where:

- $\vec{M} = (M_x, M_y, M_z)$: position of a proton in a reference frame.
- $\overrightarrow{\boldsymbol{B}}_{ext}$: external magnetic field defined by the pulse sequence.
- $T_1,\ T_2$: intrinsic relaxation time.

Pulse Sequence in MRI

Pulse sequence refers to a sequential arrangement of time-dependent magnetic field and events designed to manipulate the interaction between protons and magnetic fields.

An **optimum pulse sequence** is designed to achieve specific imaging goals including:

- Enhance the image contrast.
- Minimum the scan time.
- Maximum the signal strength
- ...

Reinforcement Learning

Reinforcement learning (RL) is a subfield of machine learning focuses on training an **agent** to make sequences of **actions** interacting with an **environment** to maximize a cumulative **reward**.

Deep Reinforcement Learning

Deep reinforcement learning (DRL) combines reinforcement learning with deep neural networks. Characterized by deep neural networks, the agent can explore and learn complex data representations including images and sequential data.

RL in MRI

RL framework has been applied in MRI pulse sequence design.

- Gradient-Echo pulse sequence generator by RL [3].
- Virtual MRI scanners controller by DRL [2].

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Objectives

The primary objective of this project is to develop a DRL framework for optimizing gradient echo sequence subject to constraints on gradient slew rate for a 1-D object.

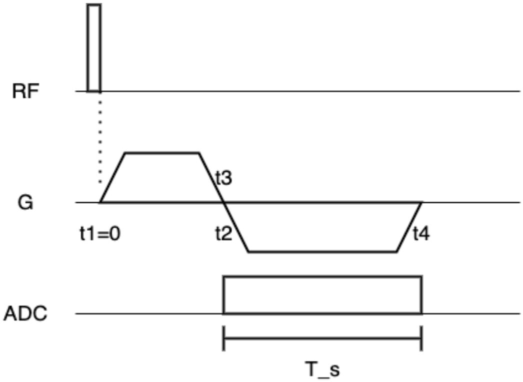

Figure: A 1D imaging protocol for a gradient echo sequence structure with two trapezoid-shaped gradient lobes.

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MRI Simulator

A MRI simulator is developed to simulate the interaction based on the Bloch Equation and matrix multiplication, which accepts a pulse sequence (action) as an input and outputs the corresponding signal strength with a pre-defined object and hardware parameters.

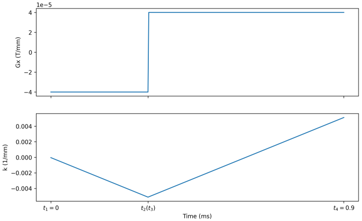

Figure: Pulse sequence and k-space trajectory

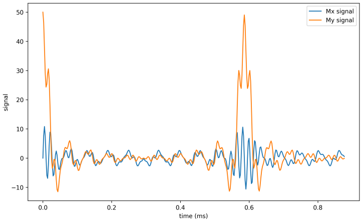

Figure: Generated signal with frequency encoding

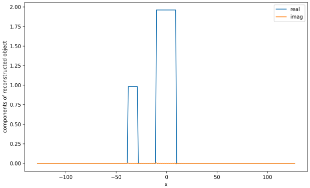

Figure: Real and image part of the decomposed signal

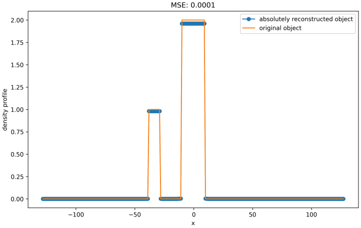

Figure: Density profile after Absolutely reconstruction

Deep Deterministic Policy Gradient

Aim

Train an agent which can generate actions (pulse sequences) within a **continuous action space**.

Reward Function

$$r_t = -\left(MSE(s_t, \rho) - MSE(s_{t-1}, \rho)\right) \tag{Reward}$$

- r_t: reward function at step t.
- s_t: state at step t.
- ρ: target density profile.

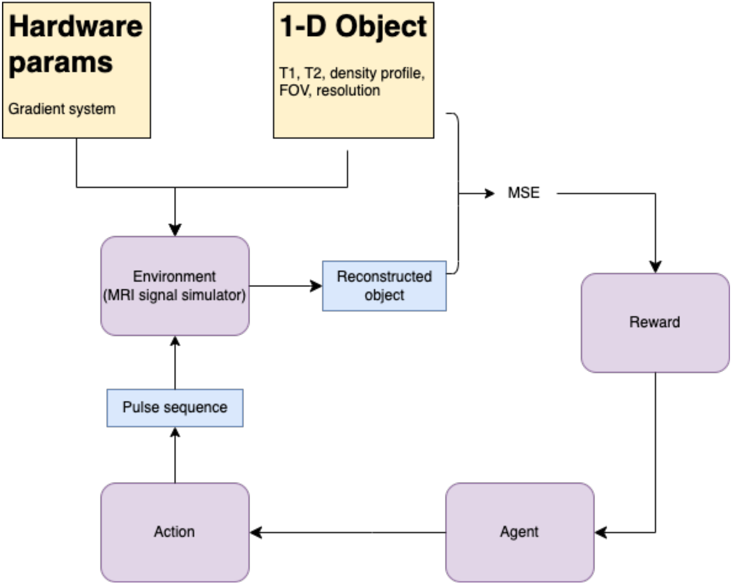

Figure: Schematic of the DDPG framework with MRI simulator.

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Assumptions

- All pulse sequences start after a $\frac{\pi}{2}$ radio frequency pulse.
- Intervals on the time space are equally spaced.
- Only two isosceles trapezoids shaped gradient lobes exist.
- Maximum values of two gradients are opposite.
- Timestamps $t_1 = 0,\ t_2 = t_3$ and pulse sequences end at t_4. The ADC period T_s is between t_3 and t_4.

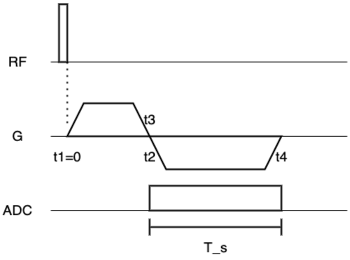


Figure: A typical gradient echo pulse sequence.

Examples

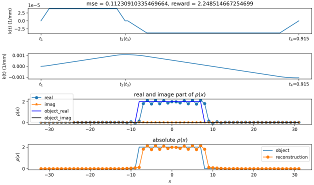


Figure: rectangle-shaped: a sample result

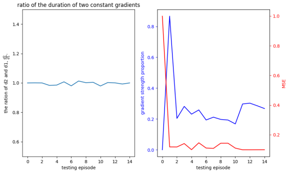
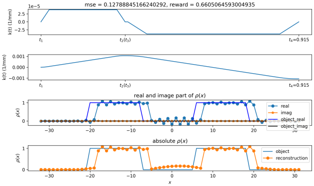


Figure: rectangle-shaped: testing results



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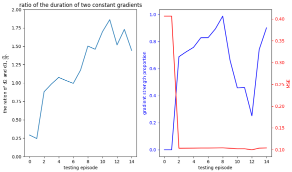

Figure: rectangles-shaped: testing results

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Conclusion

- Existence of a feasible solution.
- Stability of the DDPG model with a MR signal simulator.

Future Work

- Avoid fixing a constant time interval.
- Define a more sophisticated reward function.
- Extent to 2D imaging.

References I

[1] R. W. Brown, Y.-C. N. Cheng, E. M. Haacke, M. R. Thompson, and R. Venkatesan, eds., *Magnetic Resonance Imaging: Physical Principles and Sequence Design*, John Wiley & Sons Ltd, Chichester, UK, Apr. 2014.

[2] S. Walker-Samuel, *Control of a simulated MRI scanner with deep reinforcement learning*, May 2023.

[3] B. Zhu, J. Liu, N. Koonjoo, B. R. Rosen, and M. S. Rosen, *AUTOmated pulse SEQuence generation (AUTOSEQ) using Bayesian reinforcement learning in an MRI physics simulation environment*, (2018).

Thank you!