Coupled Oscillator Model parameter optimization with UKF on fMRI data

H. Khalegpoor
S.Karaoglu

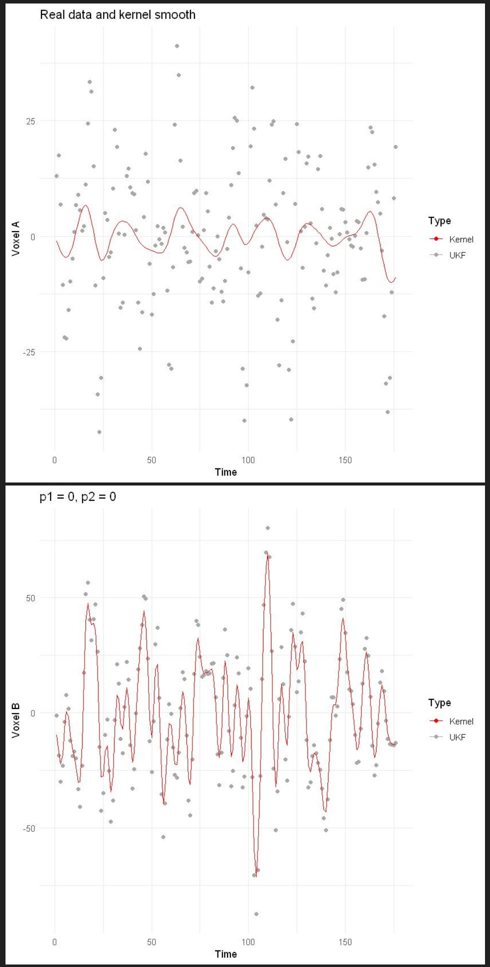
Goals of the Project

This project aims to leverage nonlinear system identification techniques, focusing on the **Unscented Kalman Filter (UKF)**, to enhance modeling and understanding of neural dynamics from **fMRI** data, addressing the direct challenges of noise and indirect measurement.

- ✓ UKF on different fMRI signals (different regions, different subjects)
- ✓ Coupled oscillator model modification - New model
- ✓ Parameter estimation methods comparison - Optimization methods
- Measuring coupling on more than 2 regions simultaneously - Possible

Datasets

- Voxel A & B data (accessible through Harvey)
- Harvard - Oxford atlas dataset
  - 2 subjects
  - 1 ASD and 1 Normal condition
  - voxel A: 18th voxel (Left Amygdala)
  - voxel B: 26th voxel (Left Accumbens)
  - https://scalablebrainatlas.incf.org/human/HOA06
  - https://www.kaggle.com/datasets/mhkoosheshi/asdfmri?resource=download&select=Harvard-Oxford+Atlas+%28Label+of+Brain+Regions%29.csv



Normal Subject 01 voxels #18 and #26

Coupled Oscillator Model

Coupled pendulum approximation. “**p**” are unknown parameters to estimate (other parameters could also be optimized or determined).

$$w_1 + a_1 \sin\theta_1 + p_1 \sin\theta_2,$$

$$w_2 + p_2 \sin\theta_1 + a_4 \sin\theta_2.$$

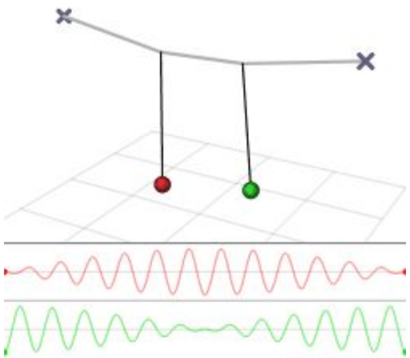
* *In the experiment, w_1 & $w_2 = 0$, a_1 & $a_4 = 1$.*

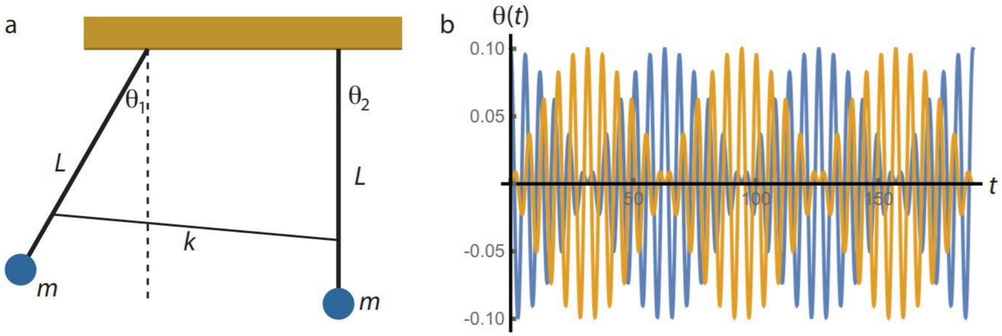
Coupled Oscillator Model

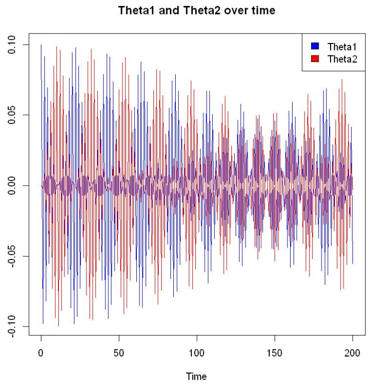
Two identical pendulums of length L and mass m, which are connected by a weak spring with spring constant k.

$$L\ddot{\theta}1 = -g\,\sin\theta1 - k\,L\,(\sin\theta1 - \sin\theta2),$$

$$L\ddot{\theta}2 = -g\,\sin\theta2 + k\,L\,(\sin\theta1 - \sin\theta2)$$

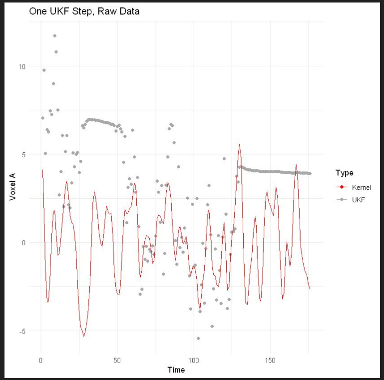


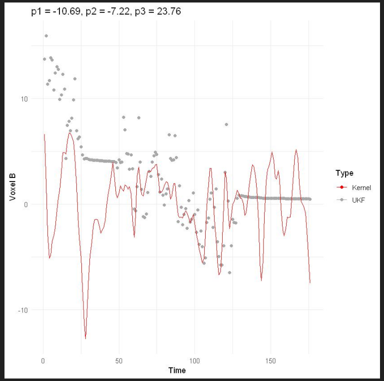




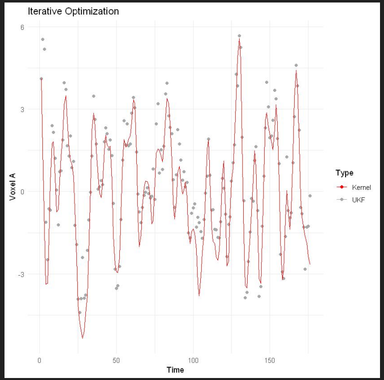
UKF & New Coupled Oscillator Model

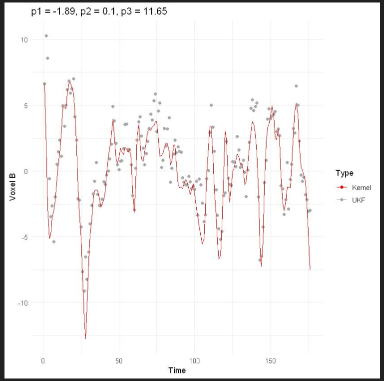
One Pass, g = -10.69, L = -7.22, k = 23.76, chi2 = 62.6



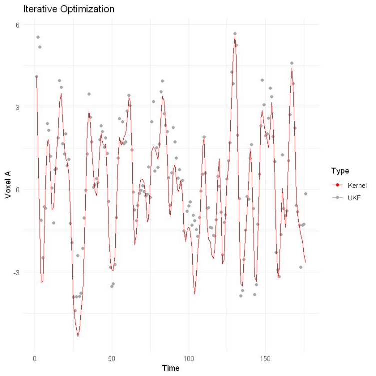


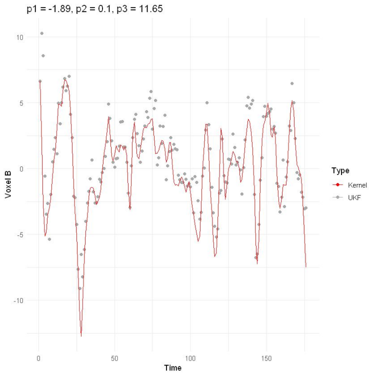
Iterative Opt., g = -1.89, L = 0.1, k = 11.64, chi2 = 4.33



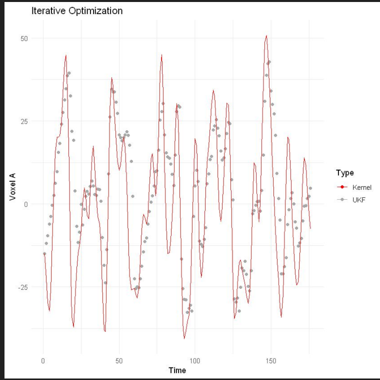


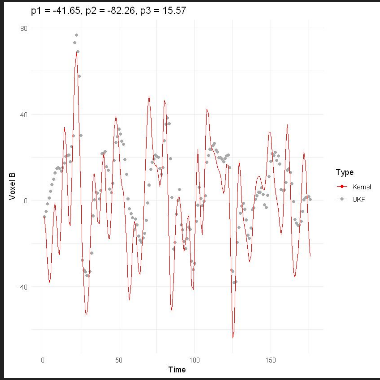
Iterative Opt. smoothed data, g = -1.89, L = 0.1, k = 11.64, chi2 = 4.33



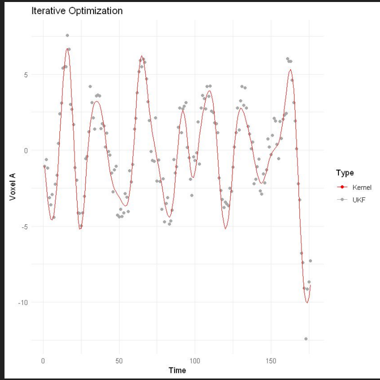


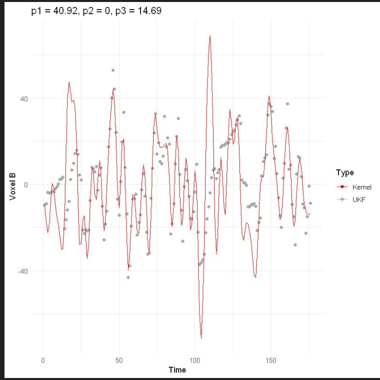
Iterative Opt. smoothed subj1 (ADS Subject 01), g = -41.65, L = -82.26, k = 15.57, chi2 = 592.5



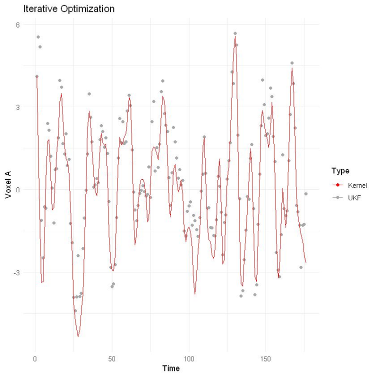


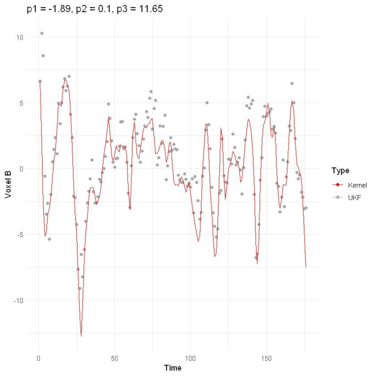
Iterative Opt. smoothed subj2 (Normal Subject 01), g = 40.92, L = -0.01, k = 14.69, chi2 = 315.4



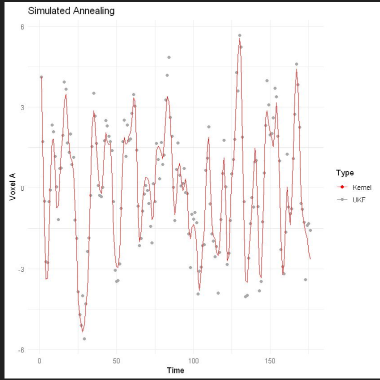


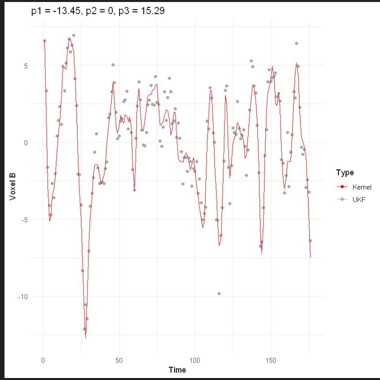
Iterative Opt. smoothed data, g = -1.89, L = 0.1, k = 11.64, chi2 = 4.33



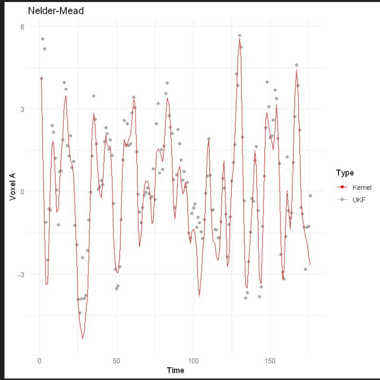


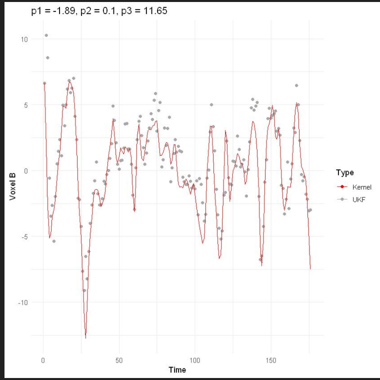
Simulated Annealing smoothed data + UKF, g = -15.4, L = 1.35, k = 15.53, chi2 = 1.4





Nelder-Mead smoothed data + UKF, g = -1.89, L = 0.1, k = 11.64, chi2 = 4.33





Conclusion

- New Coupled Oscillator model is efficient on fMRI data analysis
- As the number of parameters increase, the runtime and the search space increases.

Future Work

- More datasets and correlated voxels can be examined
- New model can be modified to have more parameters
- Parallelization for larger search spaces
- UKF function modifications

References

- https://phys.libretexts.org/Bookshelves/University_Physics/Mechanics_and_Relativity_(Idema)/08%3A_Oscillations/8.04%3A_Coupled_Oscillators
- https://scalablebrainatlas.incf.org/human/HOA06
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- https://groups.seas.harvard.edu/courses/cs281/papers/unscented.pdf