Modeling, Detecting, and Tracking of Freezing of Gait in Parkinson Disease using Inertial Sensors

Prateek Gundannavar Vijay
Advisor: Arye Nehorai

Research Overview

Preston M. Green Department of Electrical & Systems Engineering
Washington University in St. Louis

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Collaborators

- Program in Physical Therapy and Department of Neurology
  - Dr. Gammon M. Earhart, PT, PhD
    Director of the Program in Physical Therapy
    Professor of Physical Therapy, Neurology, Neuroscience.
  - Dr. Pietro Mazzoni, MD, PhD
    Associate Professor Associate Professor of Clinical Neurology.
  - Dr. Ryan Duncan, PT, DPT
    Assistant Professor of Physical Therapy, Neurology.
- KTH Royal Institute of Technology
  - Dr. Isaac Skog, PhD
    Assistant Professor at Linköping University, Sweden
    Formerly, Researcher at KTH Royal Institute of Technology, Sweden.

Background: Parkinson Disease

- Parkinson Disease (PD) is a neurodegenerative disorder that affects that affects 1-1.5 million people in the United States alone.
- The main cause of PD is a loss of dopaminergic, subcortical neurons, which leads to motor impairments[1].
- Many individuals with PD experience difficulty walking, the emergence of which is considered as a red flag for onset of disability[2].
- Approximately 50% of people with PD experience freezing of gait[3] (FOG), a "brief, episodic absence or marked reduction of forward progression of the feet despite the intention to walk".
- FOG events, which are a known risk factors for falls, occur suddenly, generally last for a few seconds, and tend to increase in frequency and duration as the disease progresses.

[1] H. Braak, E. Ghebremedhin, U. Rüb, H. Bratzke, and K. Del Tredici, "Stages in the development of Parkinson's disease-related pathology," *Cell and Tissue Research*, vol. 318, no. 1, pp. 121-134, 2004.

[2] L.M. Shulman, A.L. Gruber-Baldini, K.E. Anderson, C.G. Vaughan, S.G. Reich, P.S. Fishman, and W.J. Weiner, (2008), "The evolution of disability in Parkinson disease," *Mov. Disord.*, 23: 790-796.

[3] N. Giladi and A. Nieuwboer, (2008), "Understanding and treating freezing of gait in parkinsonism, proposed working definition, and setting the stage," *Mov. Disord.*, 23: S423-S425

Background: Parkinson Disease (Cont.)

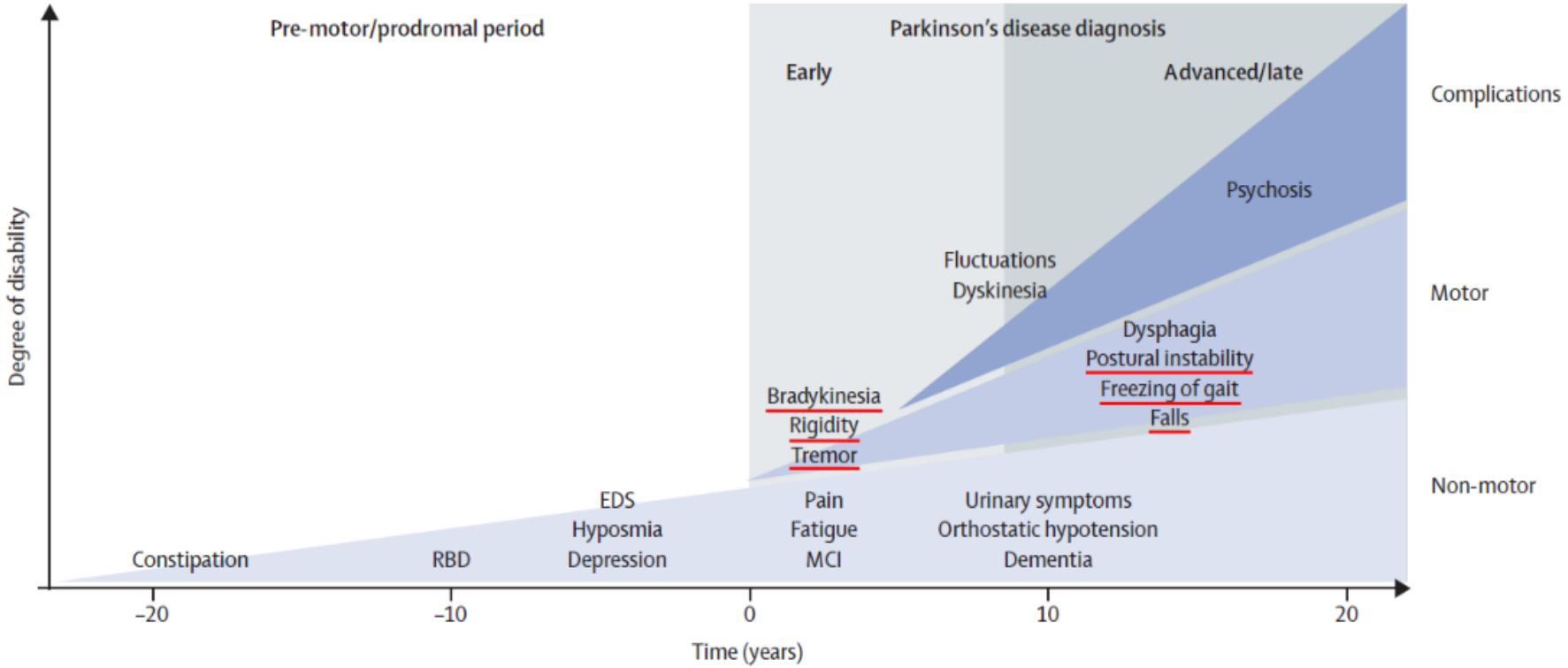


Figure 1: Progression of Parkinson disease clinical symptoms[4].

[4] *Image source*: L.V. Kalia and A.E. Lang,"Parkinson's disease," *The Lancet Neurology*, vol. 386, no. 9996, pp. 896-912, April 2015.

Background: Freezing of Gait

- FOG patterns[5] include:
  - (i) Alternating trembling in the lower extremities (includes the hip, knee, and ankle joints, and the bones of the thigh, leg, and foot).
  - (ii) No movement of the limbs and trunk
- FOG events are a reflection of the patterns described in both (i) and (ii), and are characterized by small foot speeds and short stirde lengths[6].
- FOG events often follow a festinating gait that consists of progressive shortening and quickening of steps[7].

[5] J. G. Nutt *et. al*, "Freezing of Gait: Moving forward on a mysterious clinical phenomenon," *The Lancet Neurology*, vol. 10, no. 8, pp. 734-744, 2011.

[6] A. Nieuwboer *et. al*, "Abnormalities of the spatio-temporal characteristics of gait at the onset of freezing in Parkinson's disease," *Movement Disorders*, vol. 16, no. 6, pp. 1066-1075, 2001.

[7] N. Giladi *et* al., "Gait festination in Parkinson's disease," *Parkinsonism & Related Disorders*, vol. 7, no. 2, pp. 135-138, 2001.

Our Goal and Approach

Our goal

- Design an objective evaluation system to automatically detect and track FOG in real-time, and translate the developed methodology to an individual patient application.

Approach

- Use inertial sensors (accelerometers and gyroscopes) attached to the heel region of the foot and capture the sensor data measured in body-framework in wireless mode.
- Develop physically-based signal models for the sensor data, design statistical signal processing methods to detect FOG based on its patterns, and compute the probability of FOG (pFOG).
- Validate the system using data from experimental gait assessment in a group of people with Parkinson disease.

Human Gait Cycle

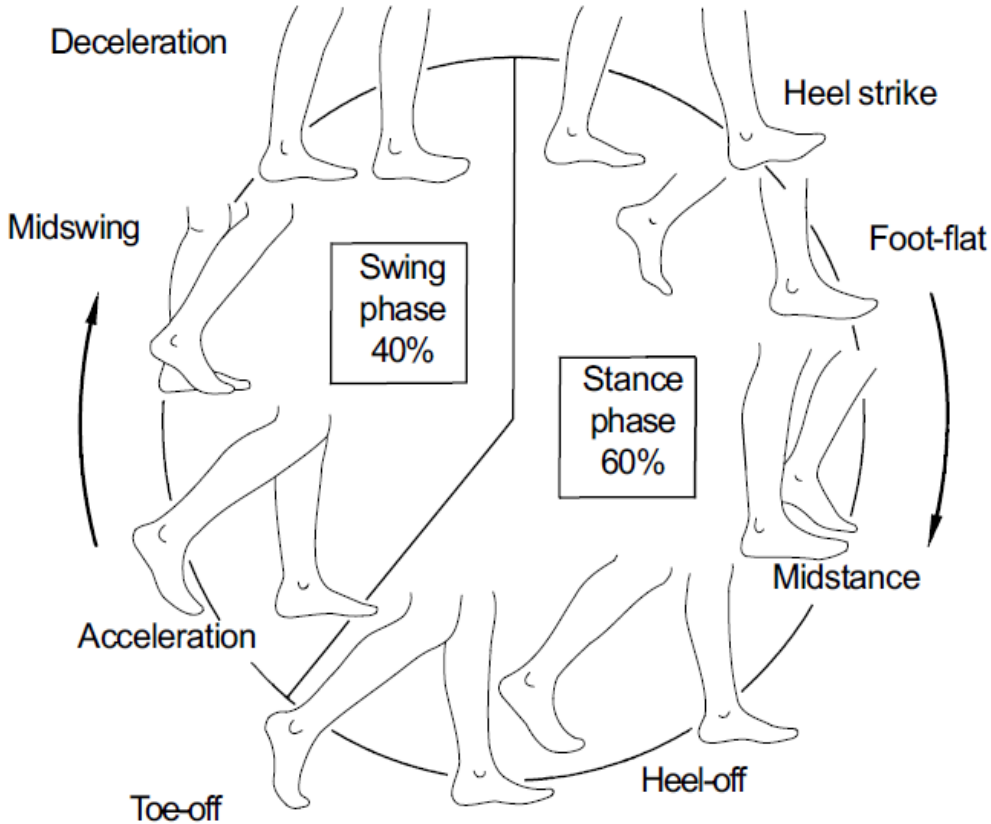


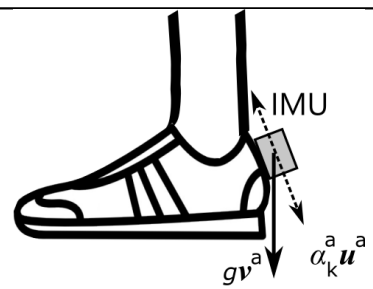
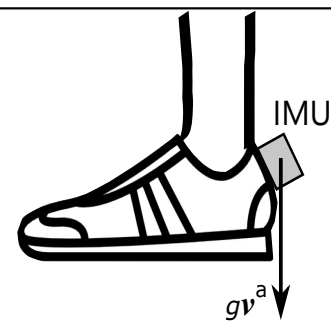
Figure 2: The traditional nomenclature for describing eight main events, emphasising the cyclic nature of human gait[8].

[8] Image source: C. L. Vaughan, B. L. Davis, and C. O. Jeremy, "Dynamics of human gait." (1999).

System Design: Overview

- We used inertial sensors attached to the heel region of the foot of the participant.
- We developed physically-based signal models for the sensor data associated with the FOG patterns.

Table 1: Summary of tremor event intervals (TREI) and zero-velocity event intervals (ZVEI).

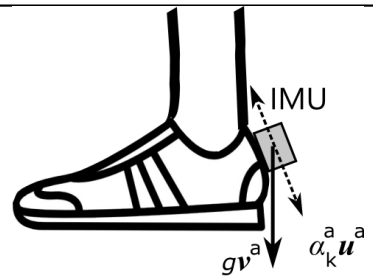
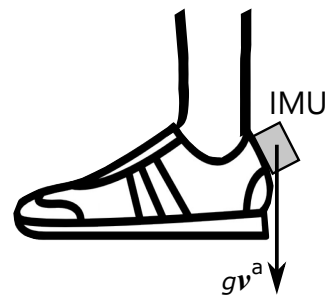
Sensor	Definition of Physical Models	
	TREI (tremor event intervals)	**ZVEI** (zero-velocity event intervals)
Accelerometer	$g\boldsymbol{v}^{\mathrm{a}} + \alpha_k^{\mathrm{a}}\boldsymbol{u}^{\mathrm{a}}$ Unknowns: $\boldsymbol{v}^{\mathrm{a}}$,$\boldsymbol{u}^{\mathrm{a}}$, and α_k^{a}	$g\boldsymbol{v}^{\mathrm{a}}$ Unknowns: $\boldsymbol{v}^{\mathrm{a}}$
Gyroscope	Cannot be modeled.	$\mathbf{0}$ Unknowns: None
		

- Further, ZVEI is a special case of TREI because when $\alpha_k^{\mathrm{a}} = 0$ where k is sample index in the TREI signal model, we get ZVEI signal model.

System Design: Overview (Cont.)

- The physical models are associated with the following gait patterns:

Table 2: Associated gait patterns

Gait type	**TREI** (tremor event intervals)	**ZVEI** (zero-velocity event intervals)
Freezing of gait	Alternating trembling in the lower extremities	No movement of the limbs
Festinating gait	Heel lift-off phase	On toes and forepart of the feet with short, quickening steps
Normal gait	Heel lift-off and heel strike phase	Flat foot phase with normal stride lengths
		

- Not all trembling and zero-velocity event intervals detected are associated with FOG.
- Therefore, to filter out the gait events not associated with FOG, we considered the fact that FOG is associated with small speed of feet.

System Design: Overview (Cont.)

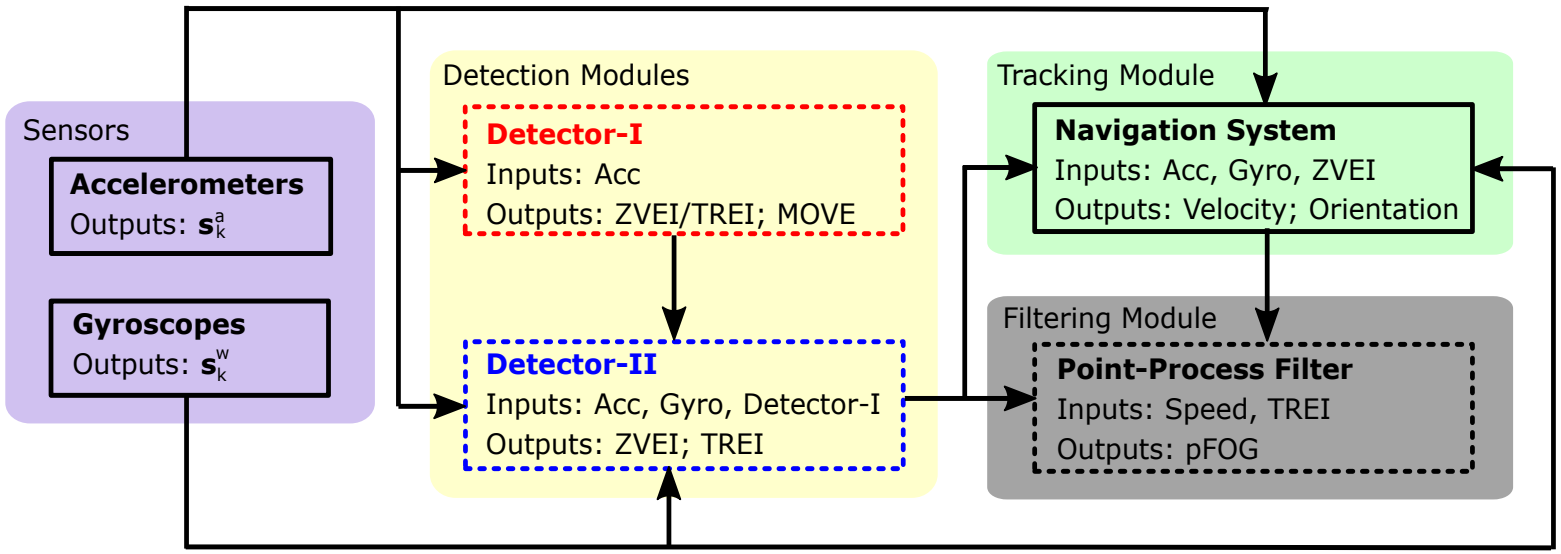
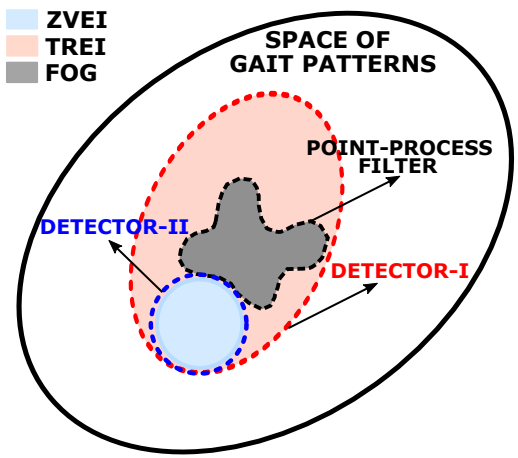


Figure 3: A block diagram of the system used to calculate the pFOG.



System Design: Overview (Cont.)

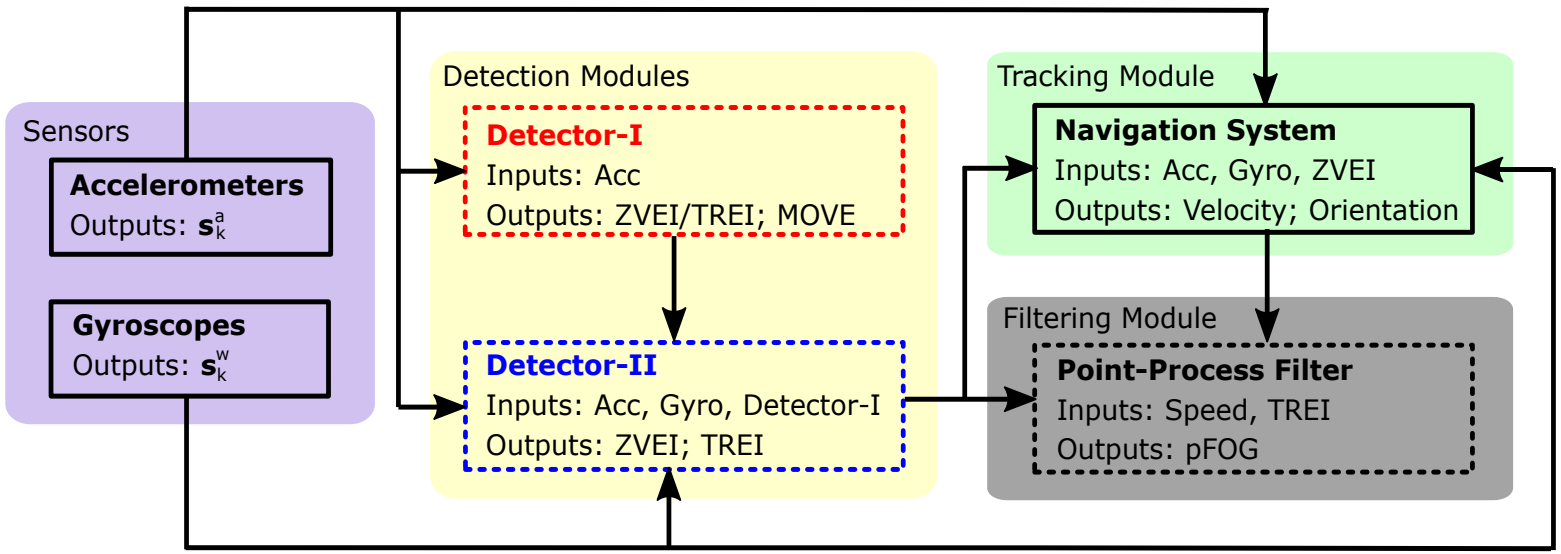
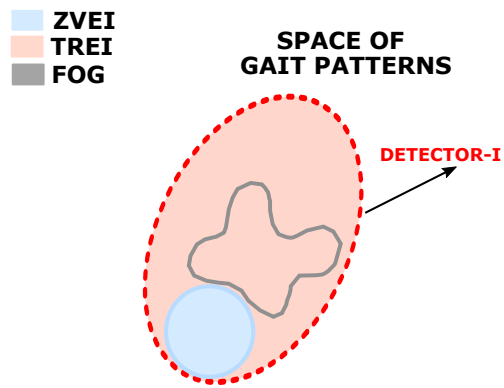


Figure 3: A block diagram of the system used to calculate the pFOG.

- **Detector-I**: Filter gait patterns that are not modeled as ZVEI or TREI.



System Design: Overview (Cont.)

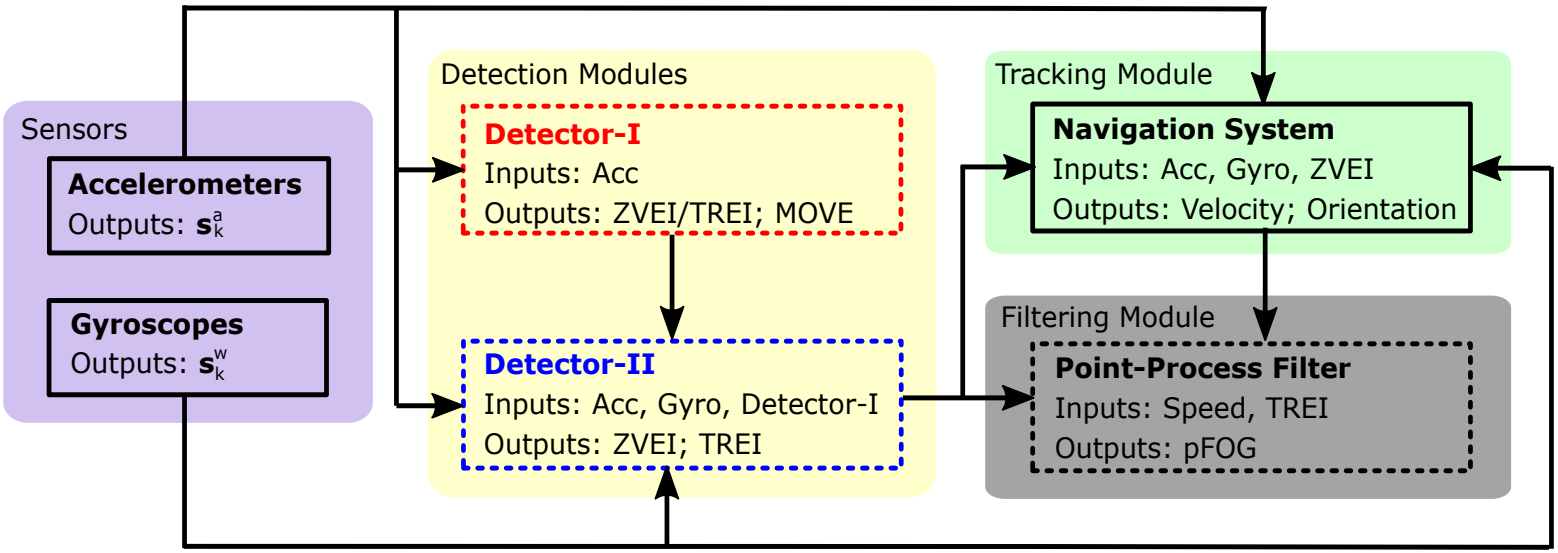
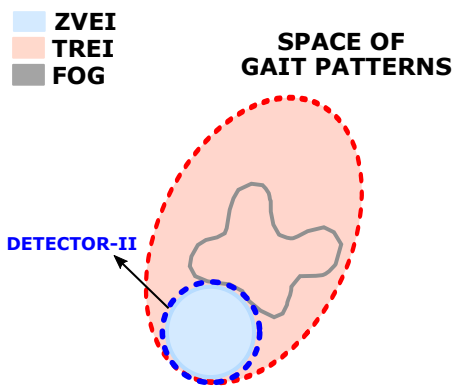


Figure 3: A block diagram of the system used to calculate the pFOG.

- **Detector-I**: Filter gait patterns that are not modeled as ZVEI or TREI.
- **Detector-II**: Distinguish ZVEI from TREI.



System Design: Overview (Cont.)

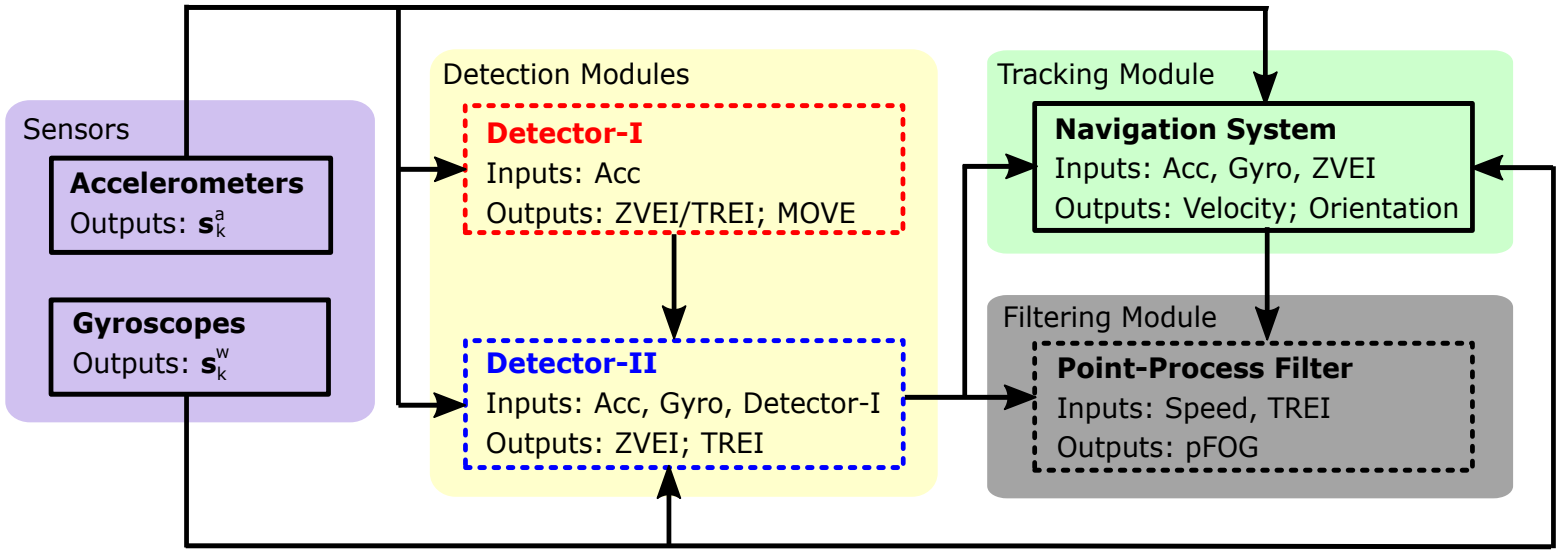
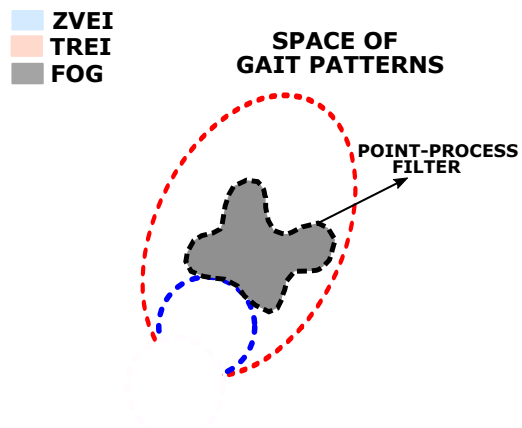
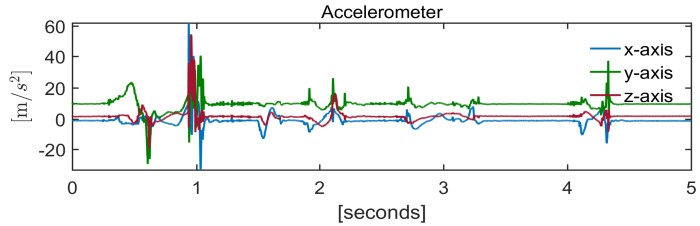


Figure 3: A block diagram of the system used to calculate the pFOG.

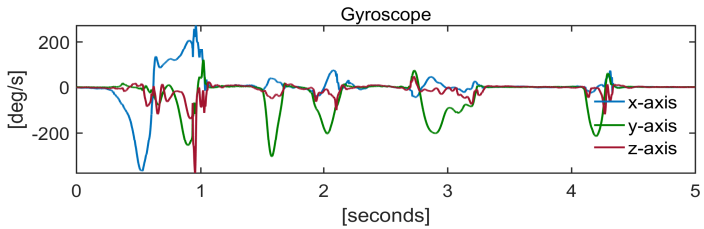
- **Detector-I**: Filter gait patterns that are not modeled as ZVEI or TREI.
- **Detector-II**: Distinguish ZVEI from TREI.
- **Point-process filter**: Identify FOG region accurately via the probability of FOG (pFOG).



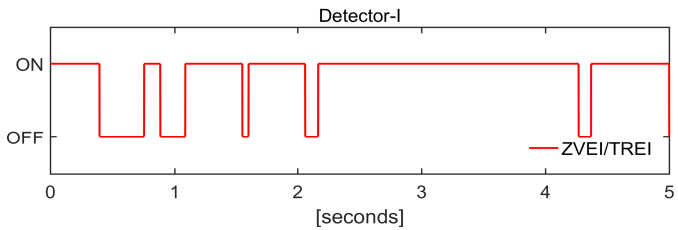
System Design: Detector-I



(a) Three axis accelerometer signal

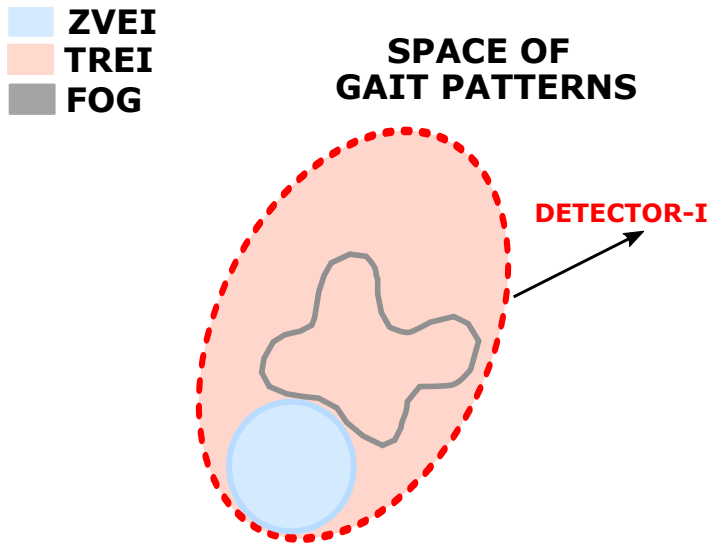


(b) Three axis gyroscope signal



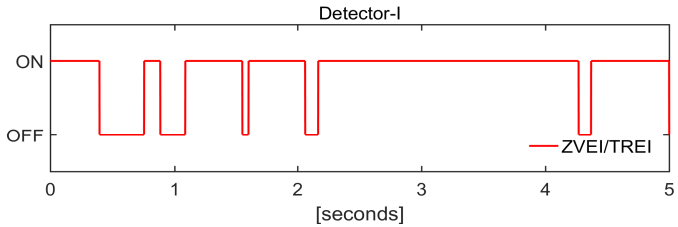
(c) Output of Detector-I (ZVEI/TREI)

Detect ZVEI or TREI region.

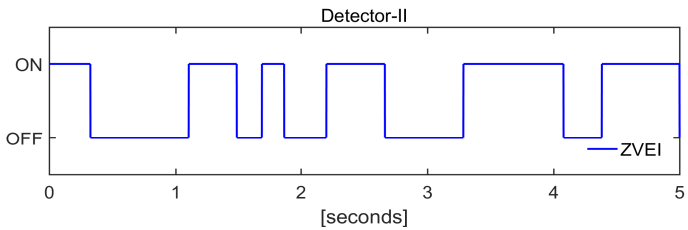


- Detector-I filters all those gait patterns that are not modeled as ZVEI/TREI.

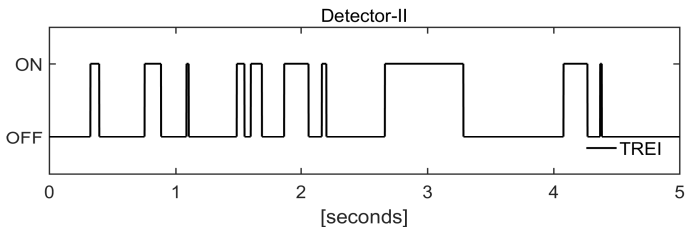
System Design: Detector-II



(a) Output of Detector-I (ZVEI/TREI)

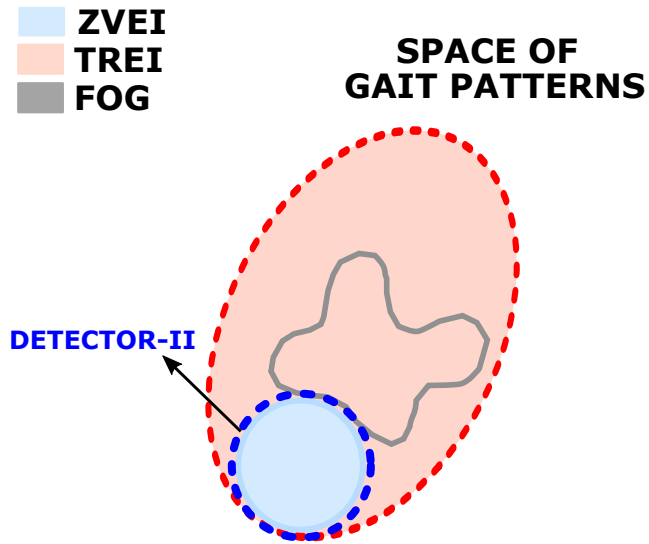


(b) Output of Detector-II (ZVEI)



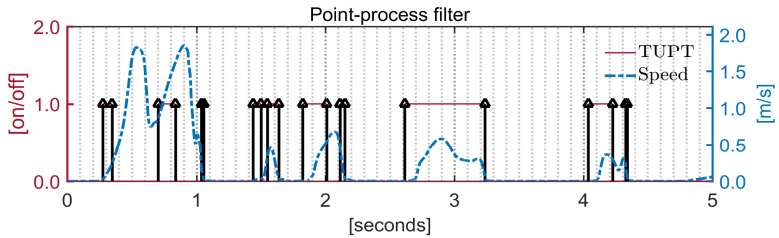
(c) Output of Detector-II (TREI)

Distinguish ZVEU from TREI region.

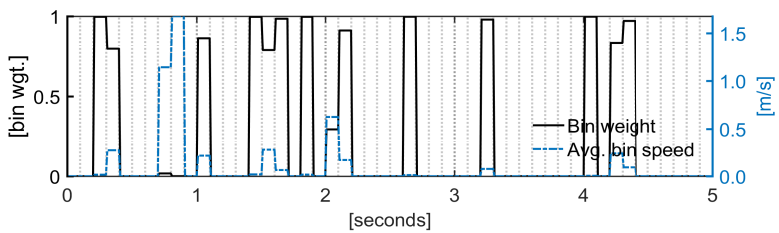


- The union of ZVEI and TREI regions gives us the region detected by Detector-I.

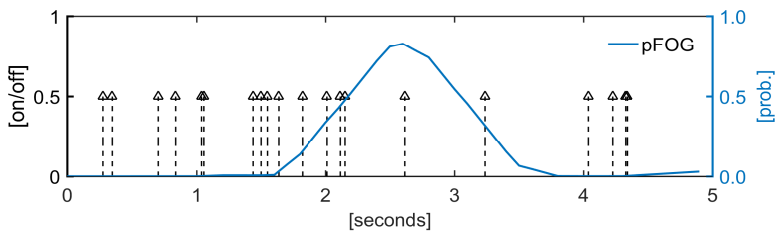
System Design: Point-Process Filter



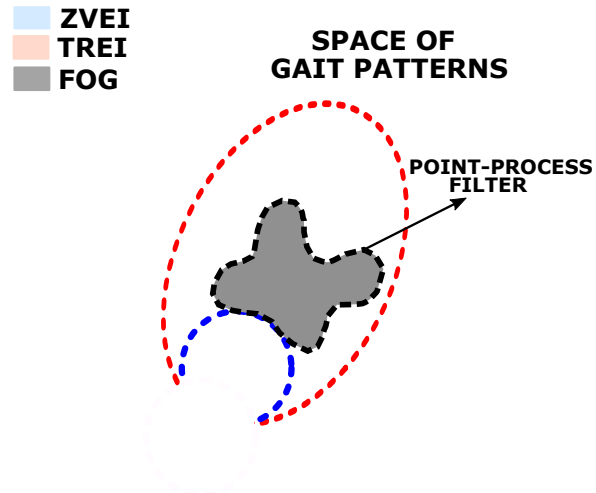
(a) Spikes with an overlay of foot speed



(b) Bin weights with $\Delta = 0.1$ seconds



(c) pFOG



Observation:

- The region consisting of high density of spikes with small foot speeds corresponds to an increase in the pFOG curve with some delay.

Experimental Evaluation: Comparison Examples

PID TT027–BLOCK (Left panel: FI method; Right panel: pFOG method)

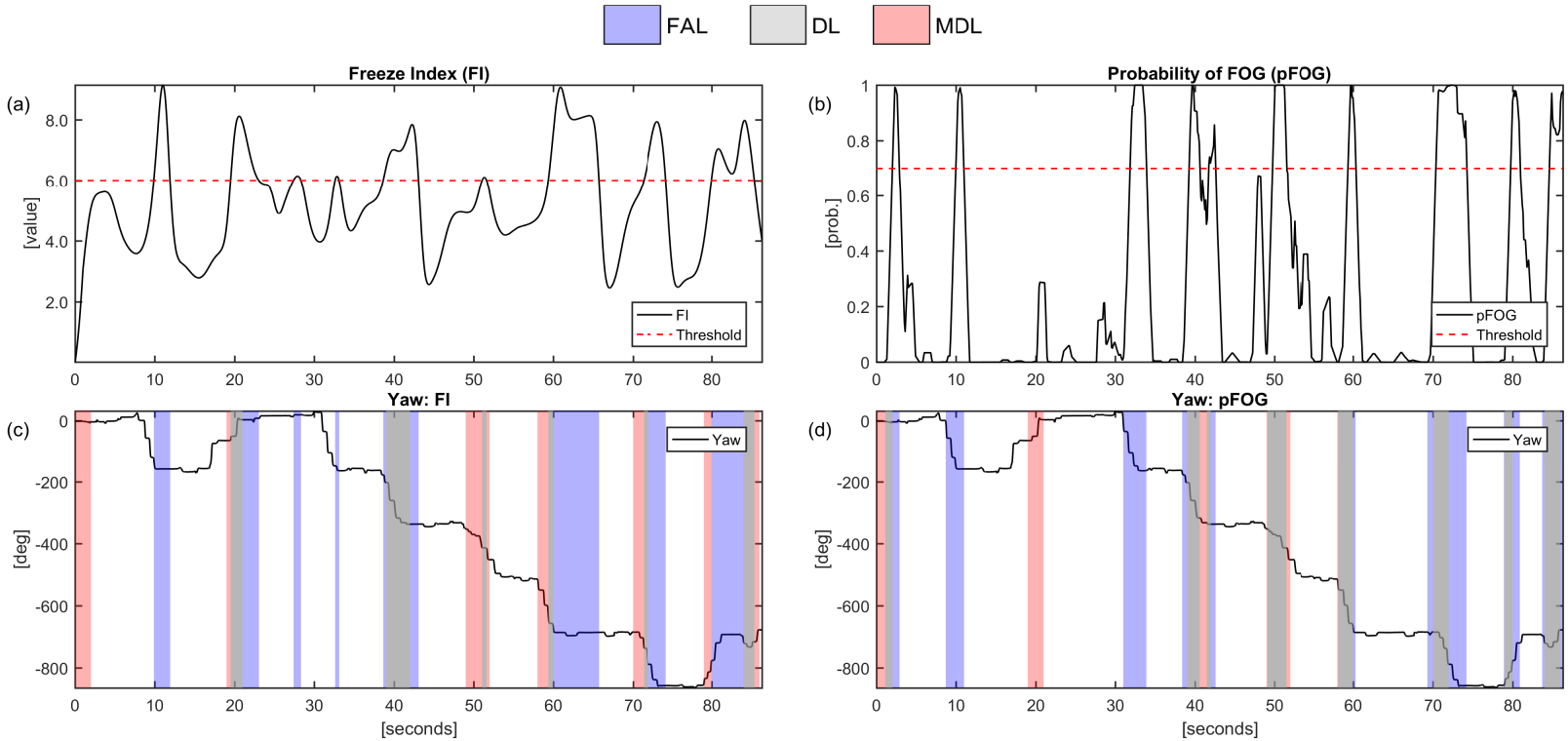


Figure 4: (a) Freeze-Index plot with FI-threshold set to 6.0. (b) pFOG plot with $\sigma_{\mathrm{s}} = 0.29$. (c) and (d) Yaw angle plot with an overlay of DL, MDL, and FAL. FOG region marked using video data[9].

[9] *Video commentary*: Froze when stood up from chair to walk to block. Froze when turning to go back to cone after second trial. Froze during turn in the fourth, fifth, and sixth trial. Questionable left foot freeze in turn for seventh and eighth trail. Froze after trials over, walking away.

Experimental Evaluation: Comparison Examples (Cont.)

PID TT027–BACK (Left panel: FI method; Right panel: pFOG method)

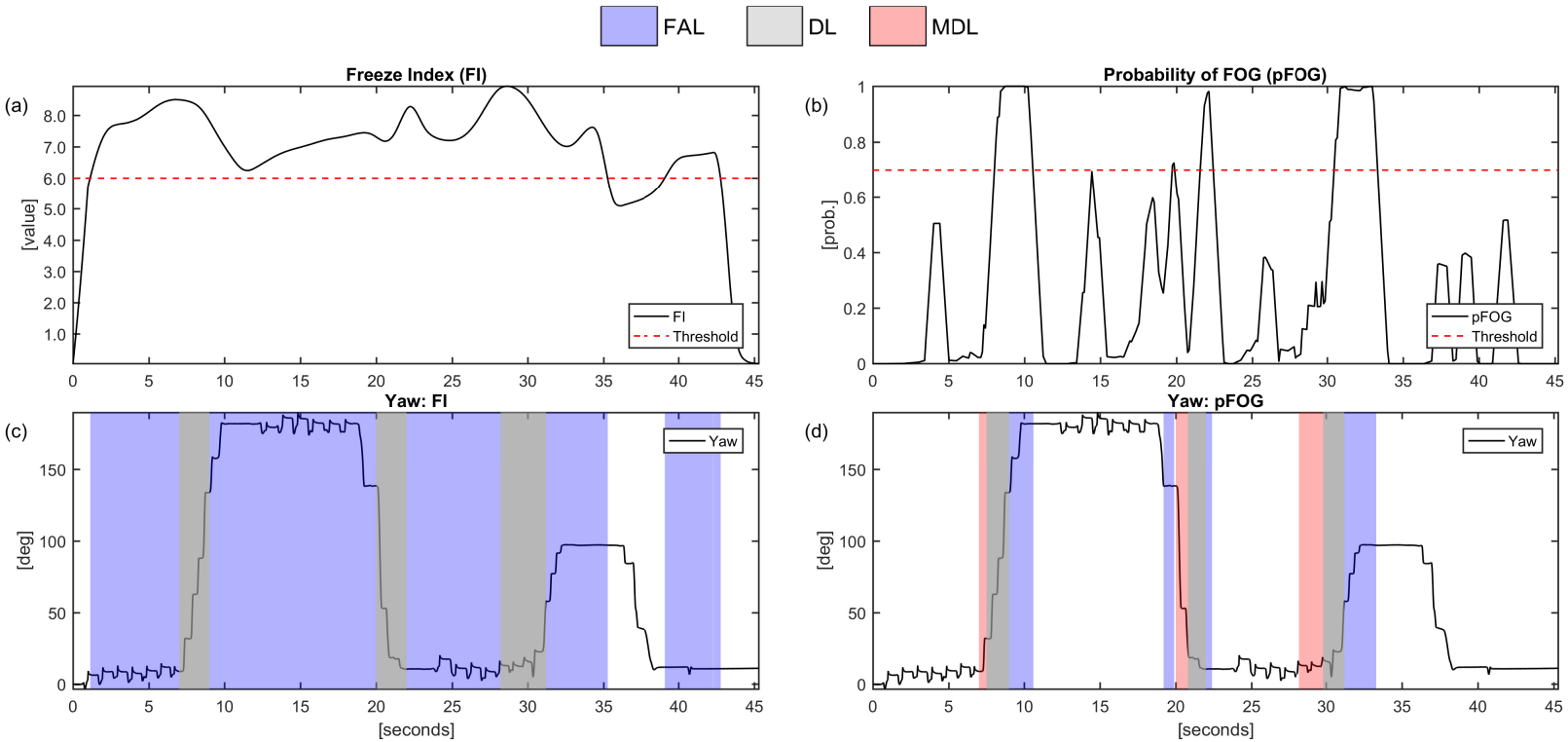


Figure 5: (a) Freeze-Index plot with FI-threshold set to 6.0. (b) pFOG plot with $\sigma_s = 0.29$. (c) and (d) Yaw angle plot with an overlay of DL, MDL, and FAL. FOG region marked using video data[10].

[10] *Video commentary*: Froze turning after first backward trial. Froze turning after second backward trial. Froze at the end of third backward trial into a turn.

Innovation

- We proposed a system[11] to address the problem of detection of the onset and duration of FOG using inertial sensors in real-time.
- To detect/predict the occurrence of an FOG event, we computed the probability of FOG (pFOG) using a Bayesian recursive filter that combines the output of the physically-based signal models used to describe the sensor data based on FOG patterns and the speed of the foot.
- The modularity of the proposed system will allow researchers to isolate, test, and make improvements to each of its modules, potentially resulting in the development of new patient applications that can improve patient outcomes.
- The proposed work is a unique multidisciplinary collaboration and will integrate methods from statistical signal processing, optimization, and machine learning with clinical expertise and movement science to address critical knowledge gaps.

[11] G. V. Prateek, I. Skog, M. E. McNeely, R. P. Duncan, G. M. Earhart and A. Nehorai, "Modeling, detecting, and tracking freezing of gait in Parkinson disease using inertial sensors," in revision for *IEEE Trans. on Biomedical Engineering*.

Significance

- A personalized healthcare gait analysis system using inertial sensors that will adapt to individual gait patterns and automatically detect FOG patterns explicitly in real time.
- The adaptive nature of the system will enable its use in a home setting, thus lowering cost of treatment, and providing access to larger amounts of sensor data which will enable better treatments.
- Clinicians can objectively evaluate disease progression, including evolution of FOG patterns and frequency, both in clinical and home setting.
- The ability to detect an actual or impending FOG event has the potential to enable the development of novel intervention strategies for tackling and alleviating this disabling symptom.
- The proposed system establishes logical connections between the underlying mechanisms of FOG and physical properties measured by the sensors, which are potentially useful in developing rehabilitative interventions to reduce the incidence of FOG.

Thank you!