Closed-Loop Control in Wearable Machine Interface Architectures

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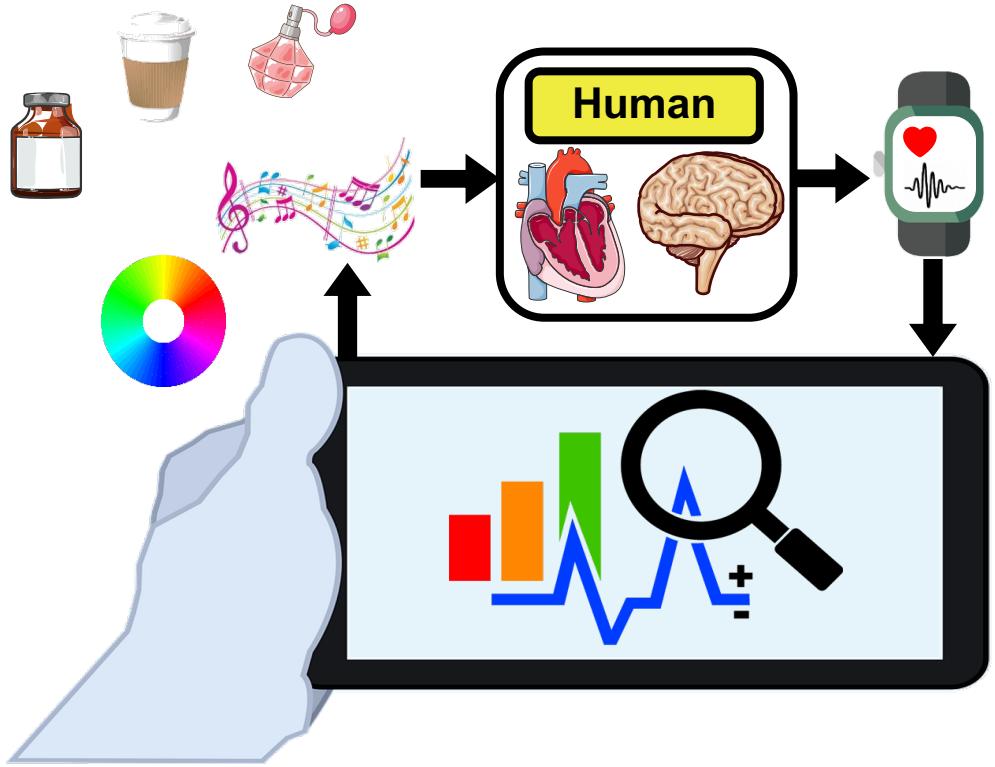
Computational Medicine Laboratory

2021 CPS PI Meeting

Introduction: Wearable Machine Interface (WMI) Architecture

Employing wearable devices to:

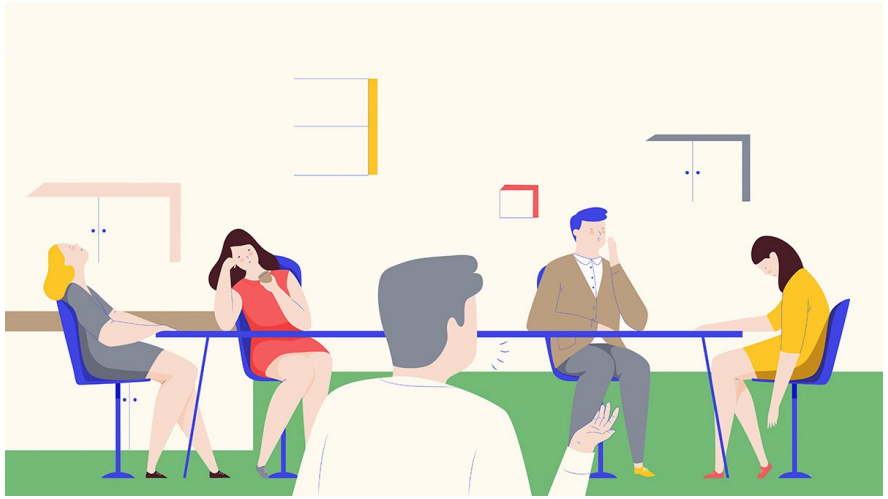
- Infer neural stimuli underlying pulsatile physiological signals - *(Deconvolution)*
- Estimate an unobserved state from underlying pulsatile stimuli - *(State Estimation)*
- Closing the loop to maintain the hidden state within a desired range - *(Control)*



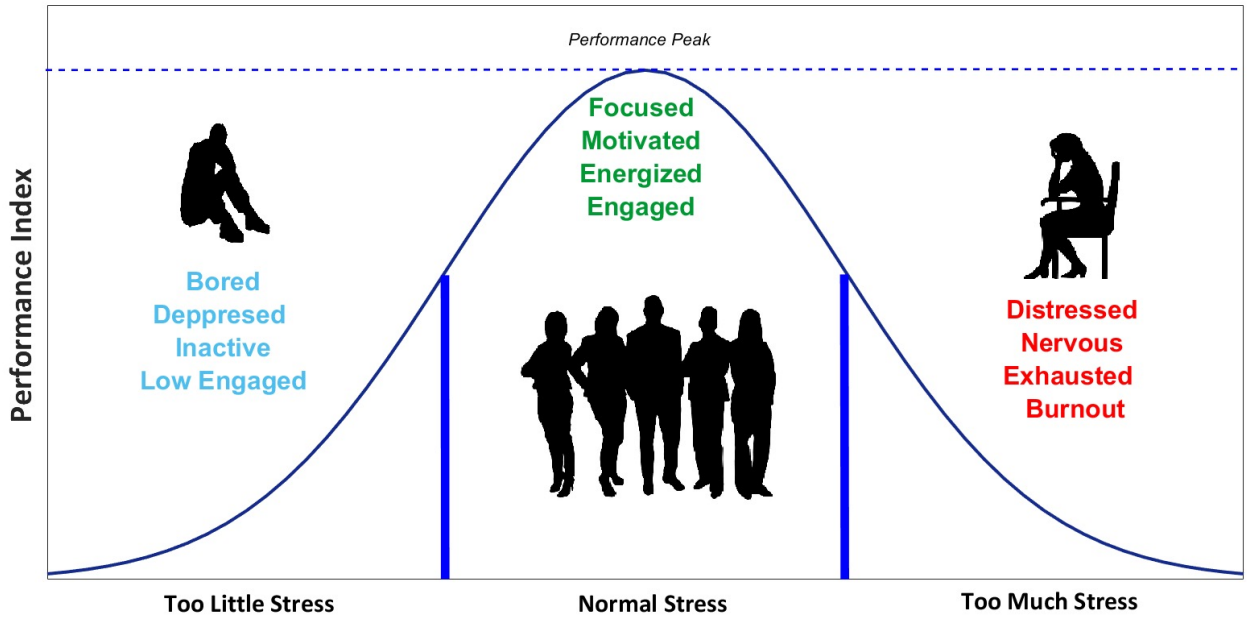
Problem I: Closed-loop stress management
Problem II: Closed-loop energy regulation

Motivation - Cognitive Stress Management

- Stress – “The Health Epidemic of the 21st Century”*
- Stress management could enhance the quality of life







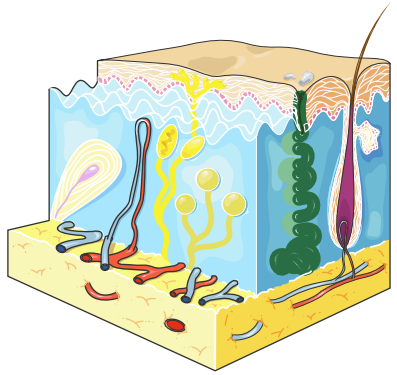
*https://thriveglobal.com/

Skin Conductance

- Sweat gland secretions primarily serve a thermoregulation purpose

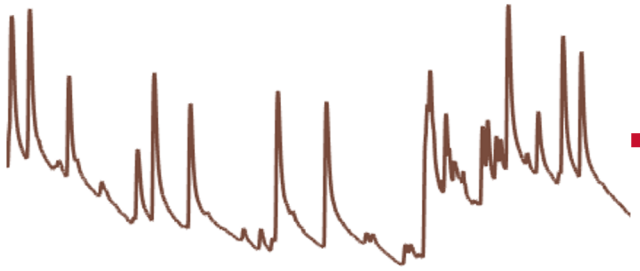




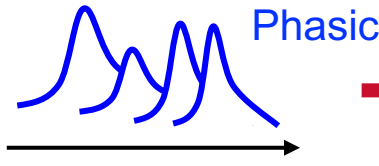


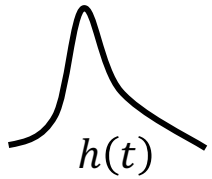
- Changes are also related to *psychological arousal*

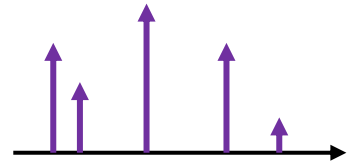
$$y_{SC}(t) = b(t) + \mathrm{h}(t) * n(t)$$



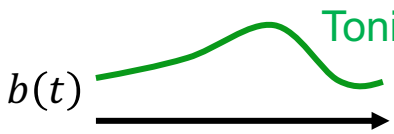
Skin Conductance Signal





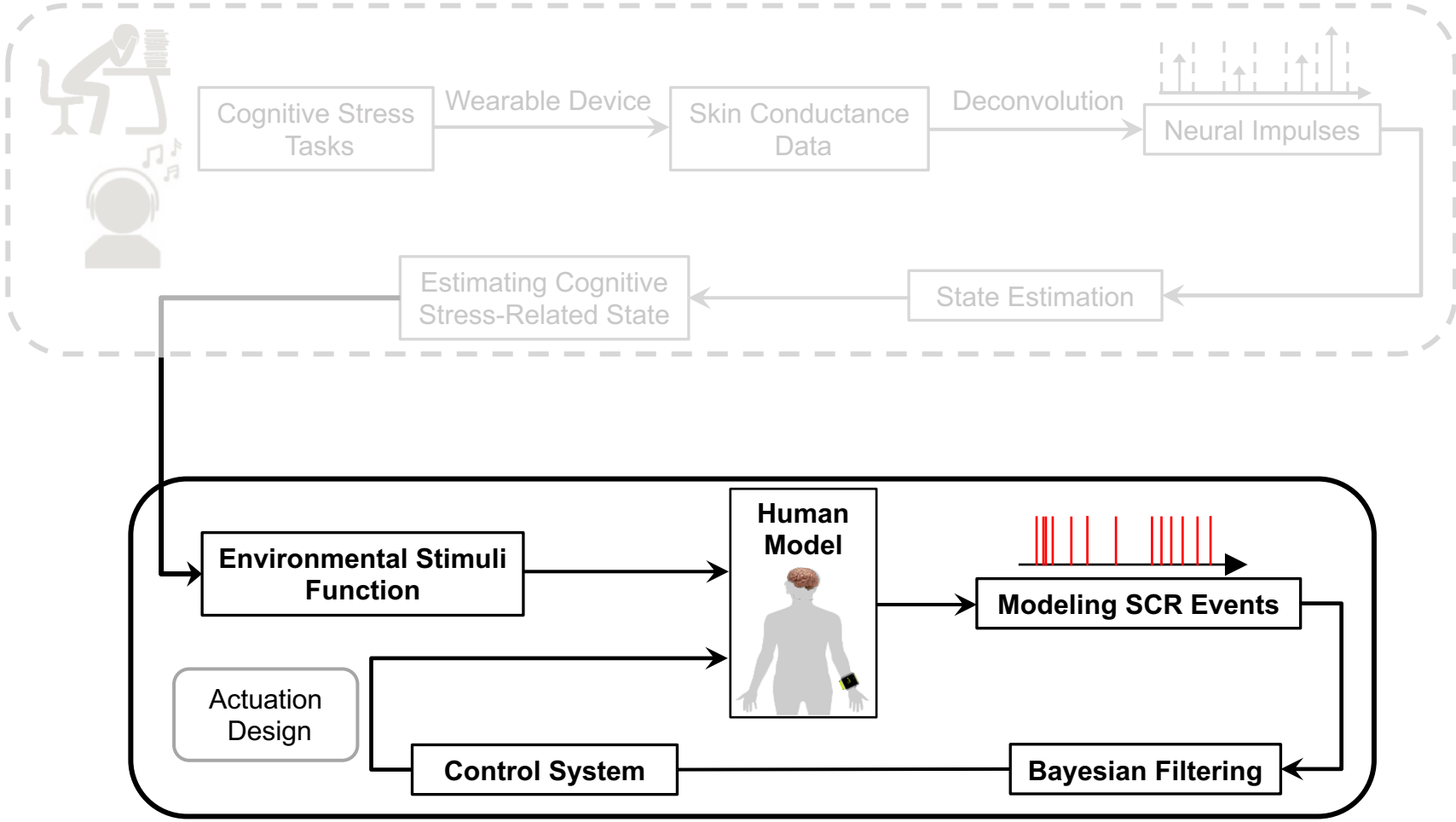


Neural Driver Impulses
$n(t)$



Skin conductance response (SCR) events

Closed-Loop Design



Birjandtalab, Javad, Diana Cogan, Maziyar Baran Pouyan, and Mehrdad Nourani. "A non-EEG biosignals dataset for assessment and visualization of neurological status." In 2016 IEEE International Workshop on Signal Processing Systems (SiPS), pp. 110-114. IEEE, 2016.

Human Brain Modelling and State Estimation

State-Space Model:

$$x_{k+1} = x_k + u_k + \eta_k$$

Hidden stress state

Control input

Environmental input

$$\eta_k = s_k + \nu_k \quad \text{s.t.} \quad \nu_k \sim N(0, \sigma_\epsilon^2)$$

Environmental stimuli

Observations:

- SCR interarrival times n_k

Nonlinear relationship

Bernoulli distribution

$$P(n_k \mid q_k) = q_k^{n_k}(1-q_k)^{1-n_k}, \qquad q_k = \frac{1}{1+e^{-(\beta+x_k)}}$$

Linking function

- SCR amplitudes r_k

Linear relationship

$$r_k = \rho_0 + \rho_1 x_k + \omega_k$$

State Estimation*:

Bayesian Filtering

$x_{k|k}, \sigma_{k|k}^2$

- Binary observations

$$N^K = \{n_1, n_2, \ldots, n_K\}$$

- Corresponding amplitudes

$$R^K = \{r_1, r_2, \ldots, r_K\}$$

Expectation

$x_{k|K}, \sigma_{k|K}^2$

Maximization

Internal Arousal Estimates

$$X^K = \{x_1, x_2, \ldots, x_K\}$$

* Wickramasuriya, Dilranjan S., and Rose T. Faghih. "A Marked Point Process Filtering Approach for Tracking Sympathetic Arousal From Skin Conductance." *IEEE Access* 8 (2020): 68499-68513.

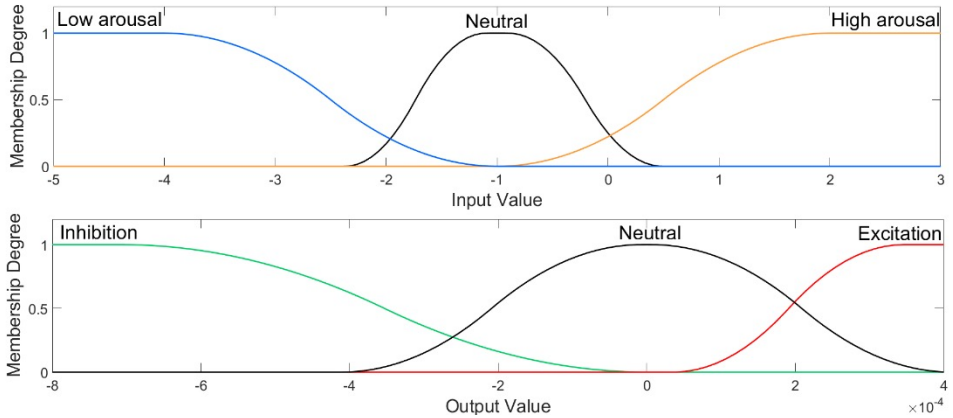
* Wickramasuriya, Dilranjan S., Md Amin, and Rose T. Faghih. "Skin conductance as a viable alternative for closing the deep brain stimulation loop in neuropsychiatric disorders." Frontiers in neuroscience 13 (2019): 780.

Control Systems

Knowledge-based Control Systems

Fuzzy Logic

Rule #	Stress State	Control
1	High arousal	Inhibitory
2	Low arousal	Excitatory
3	Neutral	Neutral



Model-based Control Systems

MPC and LQR

$$\min_{x_{t+1},\ldots,x_{t+T-1},u_{t+1},\ldots,u_{t+T-1}} J = \sum_{\tau=t}^{t+T-1} x_\tau' Q x_\tau + u_\tau' R u_\tau$$

Fixed Q and R

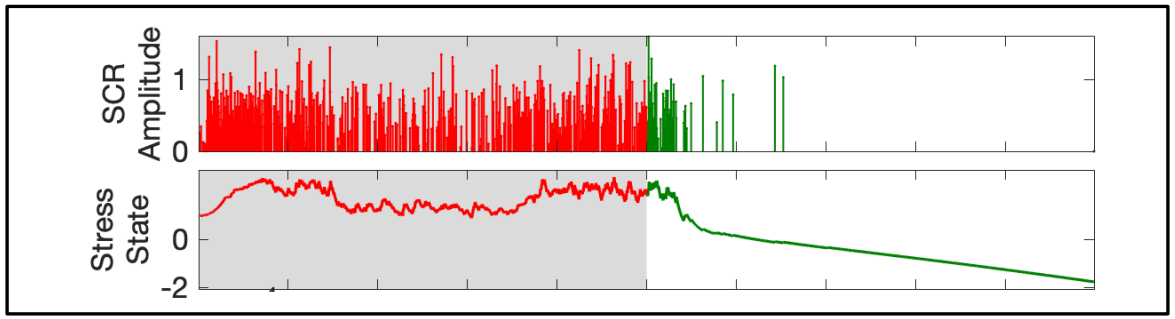
Fusion of Model-based and Knowledge-based Approaches

Fuzzy inference to tune Q and R weight matrices in **MPC** and **LQR** structures

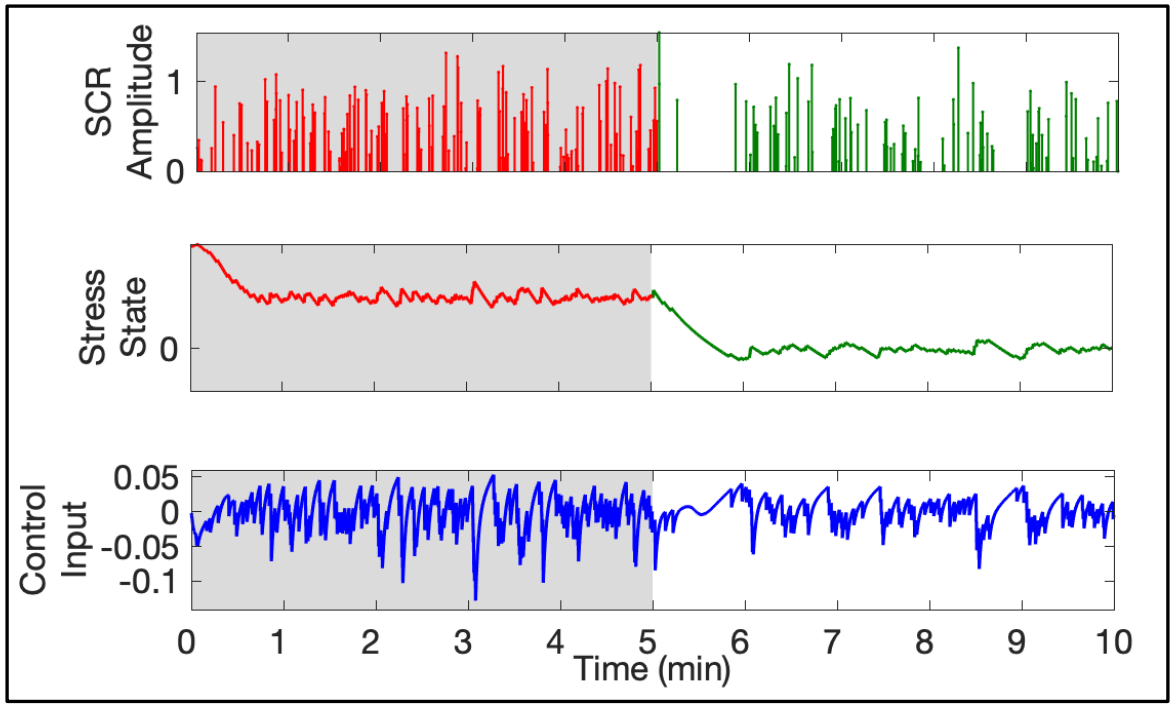
→ **Supervised Control Systems**

Results

Open-Loop



Closed-Loop
Supervised Control System



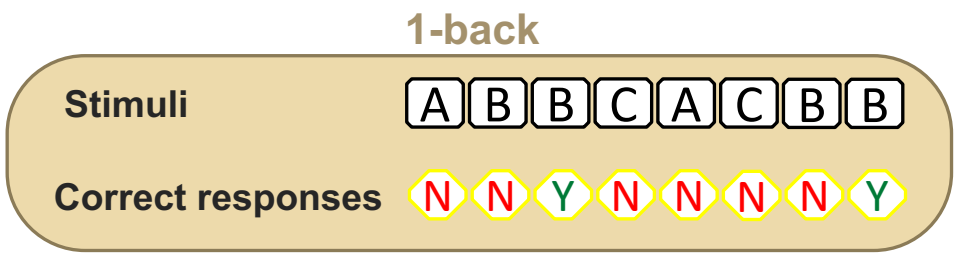


Experiments

- Wearable devices to collect physiological signals



- Performing multiple experiments (e.g., working memory n-back tasks and watching fear of height videos)





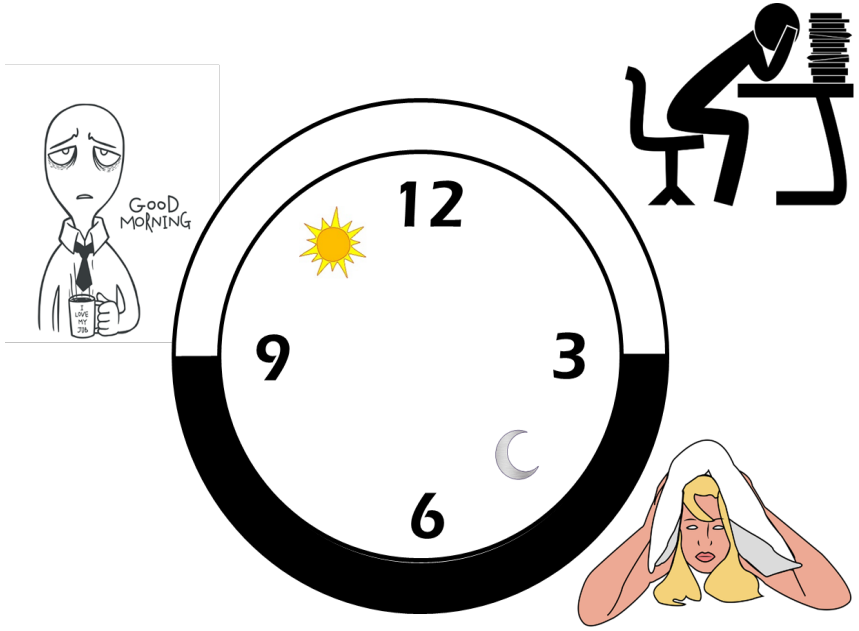
- Investigating the influence of noninvasive actuation (e.g., coffee and music) in regulating arousal state

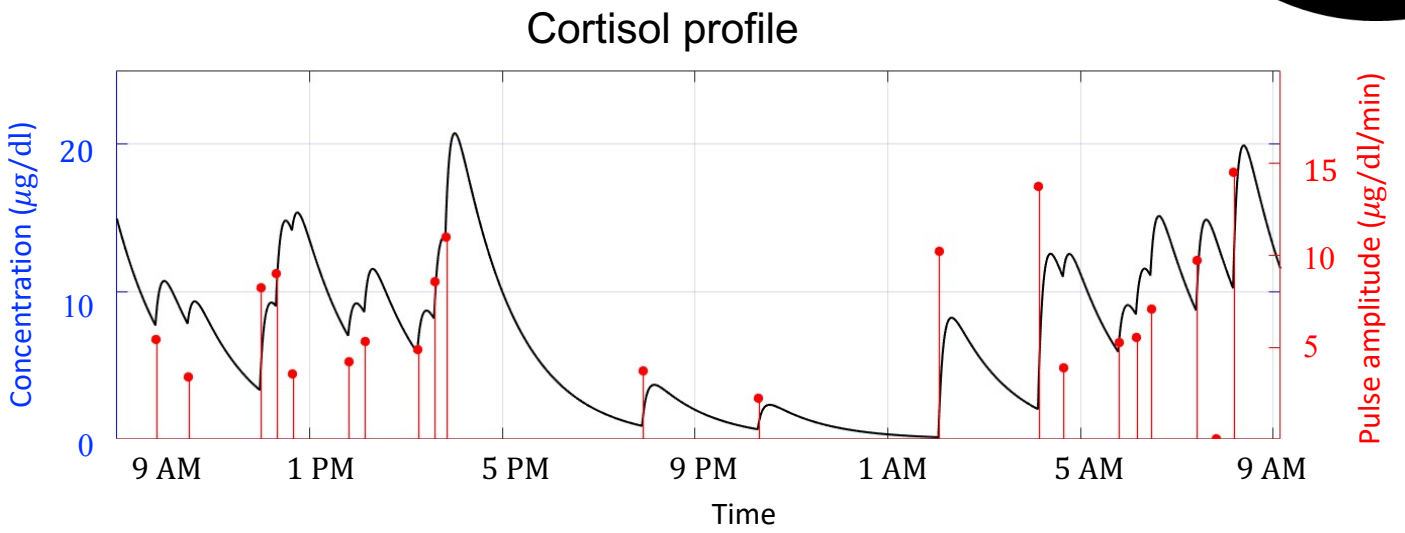




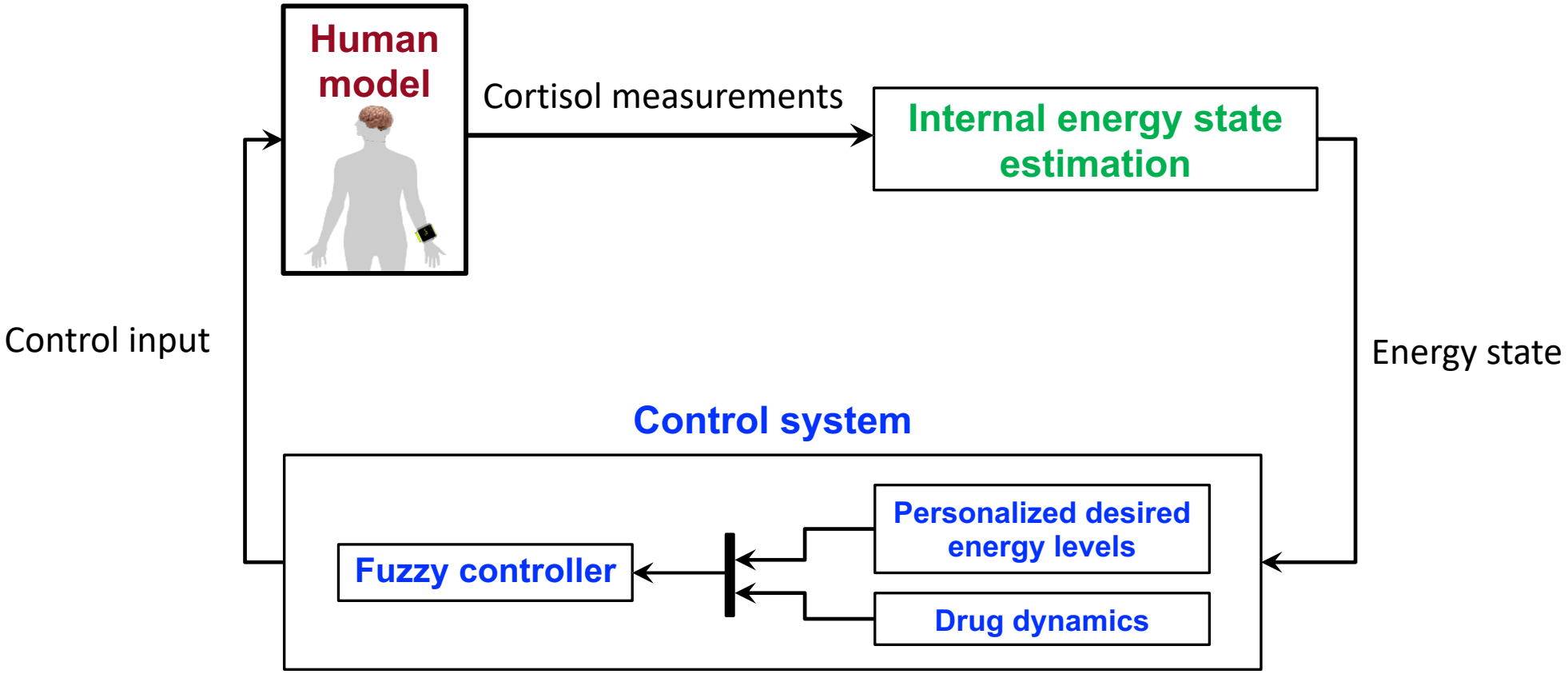
Motivation - Internal Energy Regulation in Hypercortisolism

- Stress hormone cortisol is released in pulsatile manner
- Cortisol secretion is tied to energy production
- Abnormal cortisol levels cause irregular daily energy patterns
- Hypercortisolism disorder (i.e., excessive level of cortisol) causes
  - Disturbed Energy Regulation
  - Feeling fatigue during day-time
  - Sleep disorder





Closed-Loop Design

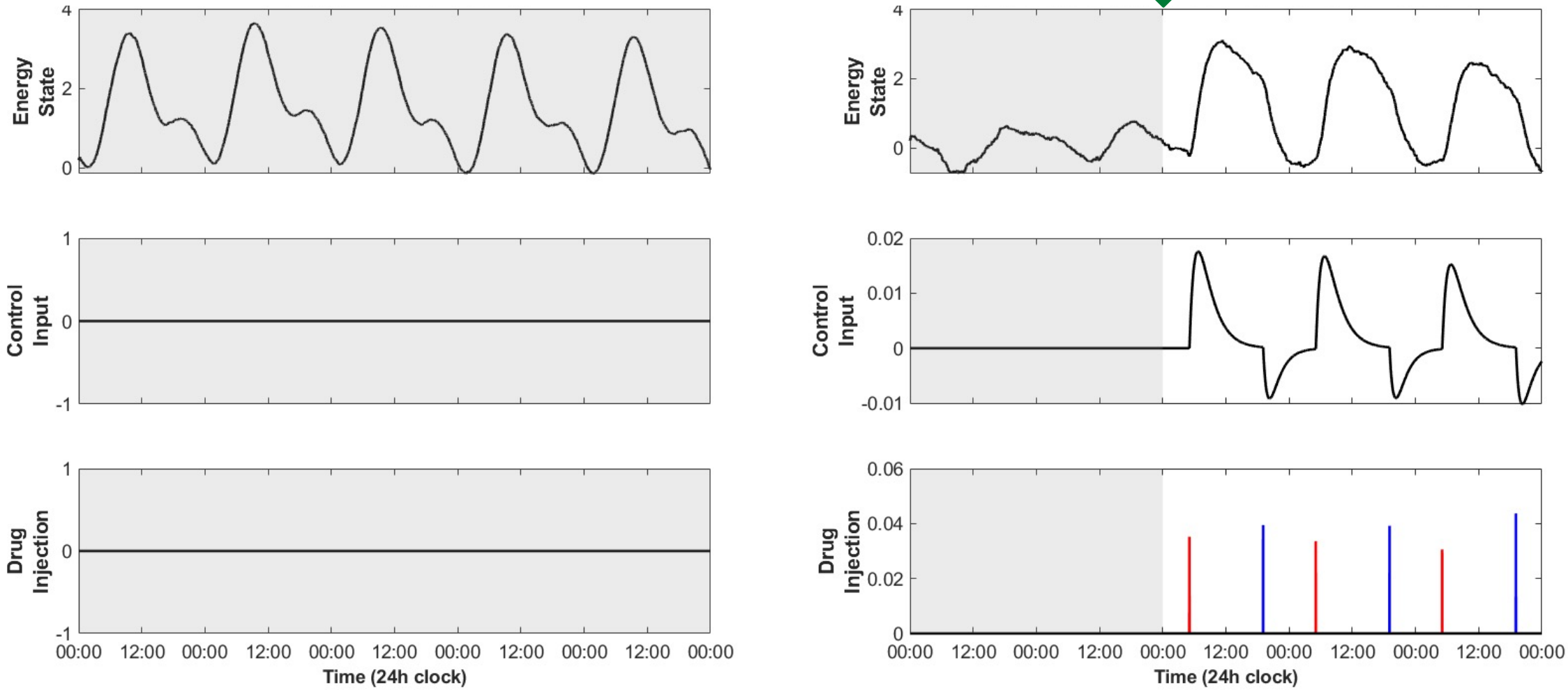


Results

Healthy subject

Cushing's patient

Starting day 3, closing the loop



Conclusion

In this research, using wearable machine-interface (WMI) architectures, we . . . . .

- ✓ simulated environmental functions to model responses in a simulation system.
- ✓ designed human model (i.e., brain response to both environmental stimulus).
- ✓ estimated internal hidden state (i.e., cognitive stress/energy) incorporating binary and continuous observations.
- ✓ designed closed-loop supervised control approaches to regulate the internal hidden state.
- ✓ designed experiments to investigate noninvasive actuation dynamics for cognitive stress regulation in a real-world setting

Future Directions

- ❑ Performing experiments and investigate the effects of multiple noninvasive actuation in regulating cognitive stress state
- ❑ Implementing advanced robust and adaptive control approaches for closing the loop

Thank You

Publications

[1] **Hamid Fekri Azgomi,** Dilranjan S. Wickramasuriya, and Rose T. Faghih. "State-space modeling and fuzzy feedback control of cognitive stress." In 2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), pp. 6327-6330. IEEE, 2019.

[2] **Hamid Fekri Azgomi** and Rose T. Faghih. “Wearable Brain Machine Interface Architecture for Regulation of Energy in Hypercortisolism”, in 53rd Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, 2019.

[3] Pednekar, Divesh Deepak, Md Rafiul Amin, **Hamid Fekri Azgomi**, Kirstin Aschbacher, Leslie J. Crofford, and Rose T. Faghih. "Characterization of Cortisol Dysregulation in Fibromyalgia and Chronic Fatigue Syndromes: A State-Space Approach." IEEE Transactions on Biomedical Engineering 67, no. 11 (2020): 3163-3172.

[4] Yadav, Taruna, Md Moin Uddin Atique, **Hamid Fekri Azgomi**, Joseph T. Francis, and Rose T. Faghih. "Emotional valence tracking and classification via state-space analysis of facial electromyography." In 2019 53rd Asilomar Conference on Signals, Systems, and Computers, pp. 2116-2120. IEEE, 2019.

[5] Ahmadi, Mohammad Badri, Alexander Craik, **Hamid Fekri Azgomi**, Joseph T. Francis, Jose L. Contreras-Vidal, and Rose T. Faghih. "Real-time seizure state tracking using two channels: A mixed-filter approach." In 2019 53rd Asilomar Conference on Signals, Systems, and Computers, pp. 2033-2039. IEEE, 2019.

[6] Pednekar, Divesh Deepak, Md Rafiul Amin, **Hamid Fekri Azgomi**, Kirstin Aschbacher, Leslie J. Crofford, and Rose T. Faghih. "A system theoretic investigation of cortisol dysregulation in fibromyalgia patients with chronic fatigue." In 2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), pp. 6896-6901. IEEE, 2019.

[7] Parshi, Srinidhi, Rafiul Amin, **Hamid Fekri Azgomi,** and Rose T. Faghih. "Mental workload classification via hierarchical latent dictionary learning: A functional near infrared spectroscopy study." In 2019 IEEE EMBS International Conference on Biomedical & Health Informatics (BHI), pp. 1-4. IEEE, 2019.

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