SAMPLLAB Signal Acquisition Modeling Processing and Learning

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Remote Vital Sign Monitoring During Large Movements Using FMCW Radar

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Motivation and Contributions

- Real-world healthcare scenarios, e.g., patients shifting in bed, or monitoring uncooperative subjects, require robust non-contact vital sign monitoring (NCVSM) during movement
- Proposed solution for moving people using SISO FMCW radar : extends [1] by
  - (1) Sparsity-based localization scheme involving Kalman filtering for tracking people during large movements
  - (2) Signal separation framework leveraging cardiopulmonary patterns and movement dynamics
- The Extended Vital Signs-based Dictionary Recovery (E-VSDR) [1] method is then used to continuously estimate the heart rate (HR)
- Our signal separation approach yields superior NCVSM results compared to state-of-the-art separation methods

Extended Model for Non-Stationary People

- We suggest the following signal model based on SISO FMCW radar:

$$y_l[n,g] \triangleq \sum_{m=1}^{M} x_{l,m} \exp\left(j\left(2\pi f_m[l]nT_f + \frac{4\pi}{\lambda_{\max}}(d_m[l] + s_m[l]gT_g)\right)\right) + w_l[n,g],$$

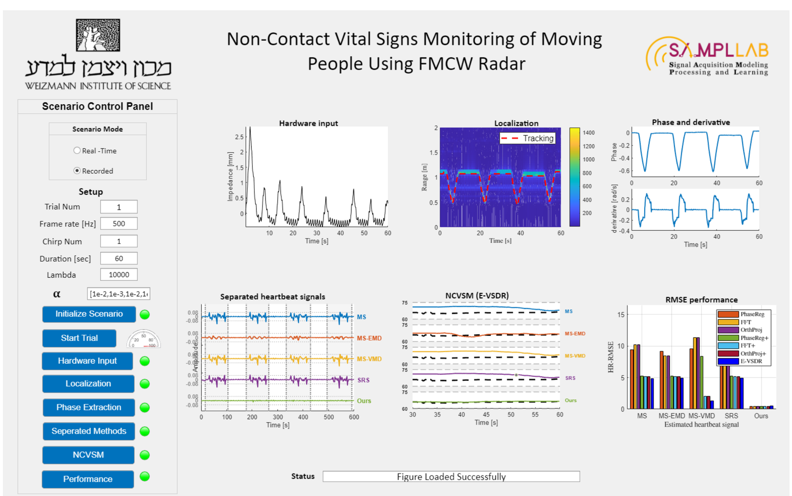
$$f_m[l] = \frac{2S}{c} d_m[l] \qquad d_m[l] \triangleq d_m^0 + d_m^w[l] + d_m^v[l]$$

$$s_m[l] \triangleq s_m^w[l] + s_m^v[l] \qquad d_m^v[l] \triangleq \sum_{q=1}^{Q} a_{m,q} \cos\left(2\pi f_{m,q}^v lT_s\right)$$

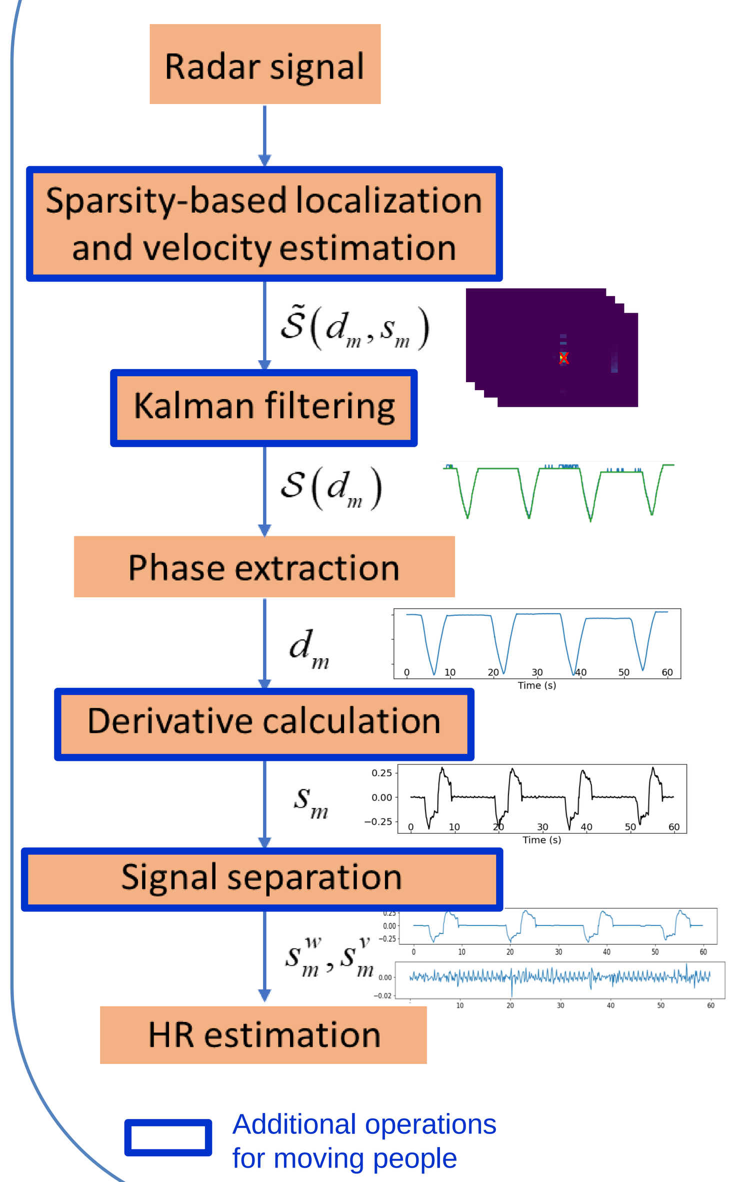
- $d_m^v[l]$ and $s_m^v[l]$ model the possible vibration of each object.
- $d_m^w[l]$ and $s_m^w[l]$ model the large movement of each object.
- The set $a_{m,q}$ determines the heartbeat pattern of each human
- Matrix form => $\mathbf{Y}_l = \mathbf{A}\mathbf{X}_l\mathbf{B} + \mathbf{W}_l, \quad l = 1,\dots,L,$

$$\mathbf{A}(n,u) \triangleq \exp(j2\pi f_u[l]nT_s) \in \mathbb{C}^{N\times U} \qquad \mathbf{B}(p,g) \triangleq \exp(j\tfrac{4\pi}{\lambda_{\max}} s_p[l]gT_g) \in \mathbb{C}^{P\times G}$$

Graphical User Interface



Localization and Signal Separation



- Sparse recovery for window localization

$$\min_{\mathbf{X}_l \in \mathbb{C}^{U\times P}} \left\|\mathbf{Y}_l - \mathbf{A}\mathbf{X}_l\mathbf{B}\right\|^2 + \left\|\mathbf{X}_l\right\|_1, \quad l = 1,\dots,L$$

$$\Rightarrow \{\mathcal{S}^{2D}\}_l \quad \Rightarrow \{\tilde{d}_m, \tilde{s}_m\}_l$$

- Kalman filtering

$$\{\tilde{d}_m, \tilde{s}_m\}_l \Rightarrow \text{Kalman filter} \Rightarrow \{\tilde{\tilde{d}}_m\}_l \Rightarrow \{\mathcal{S}^{1D}\}_l$$

- Phase extraction

$$\mathbf{X}_{S_l} = \frac{1}{N}\mathbf{A}_S^H\mathbf{Y} \quad \Rightarrow \quad \hat{d}_m(l) = \frac{4\pi}{\lambda} unwrap\left(\angle\left(\mathbf{X}_{S_l}\right)\right)$$

- Derivative calculation $\hat{s}_m(l) = \hat{d}_m'(l)$
- Signal separation

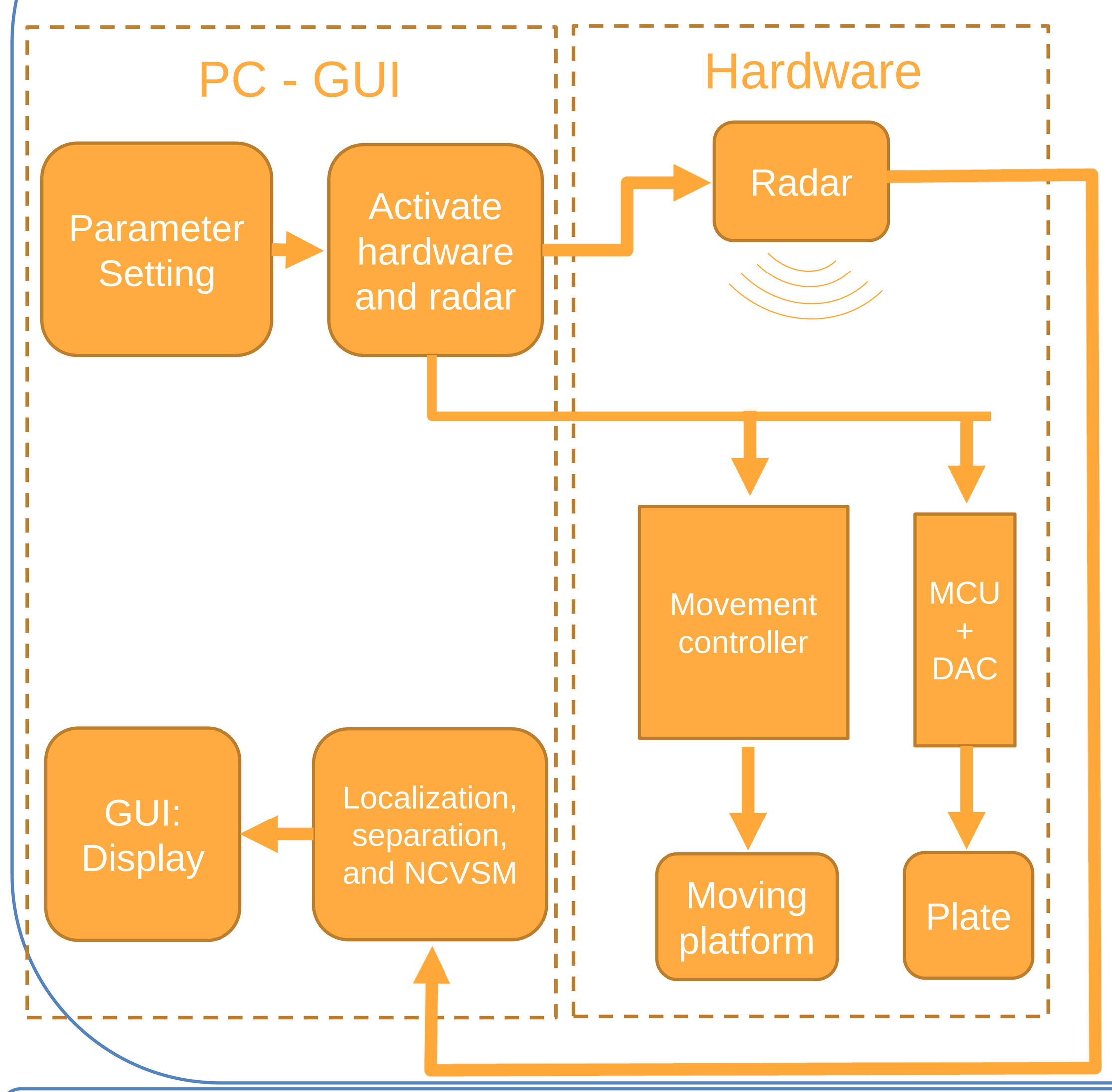
$$\min_{\hat{\mathbf{s}}_m^w, \hat{\mathbf{s}}_m^v}\{\alpha_0\left\|\mathbf{W}_F\hat{\mathbf{s}}_m^v\right\|_2^2 + \alpha_1\left\|\mathbf{D}\hat{\mathbf{s}}_m^v\right\|_2^2 + \alpha_2\left\|\mathbf{D}\hat{\mathbf{s}}_m^w\right\|_1 + \alpha_3\left\|\mathbf{M}\hat{\mathbf{s}}_m^v\right\|_2\}$$

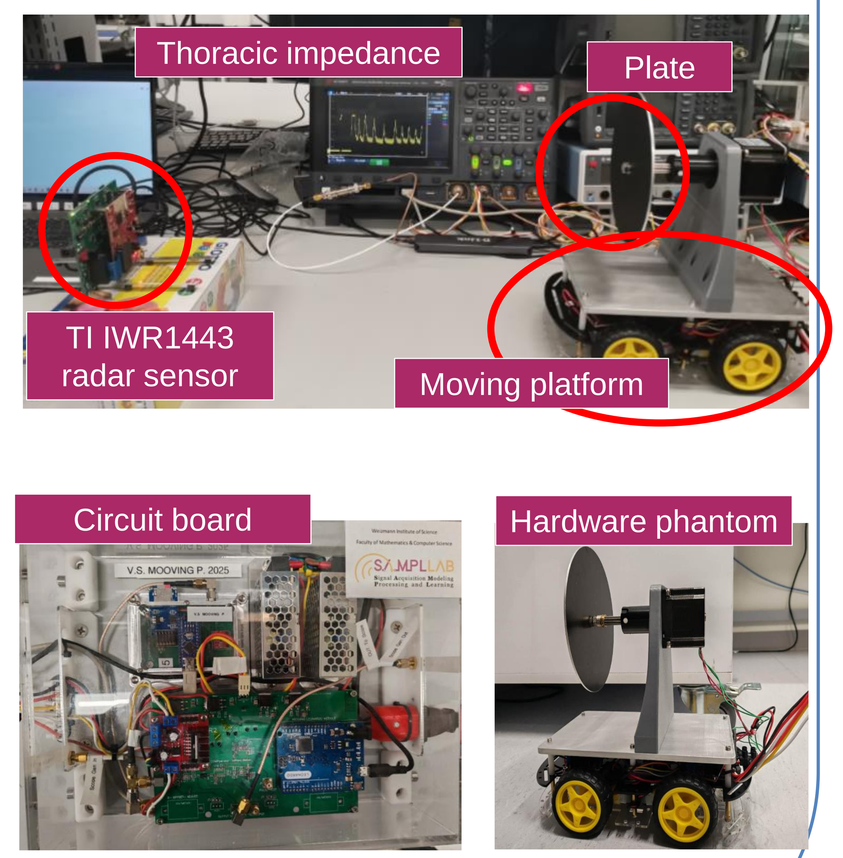
$$s.t. \qquad \hat{\mathbf{s}}_m^w + \hat{\mathbf{s}}_m^v = \hat{\mathbf{s}}_m,$$

Assumption: (1) Gradient ($\mathbf{D}$) of $\hat{\mathbf{s}}_m^w$ is sparse; (2) $\hat{\mathbf{s}}_m^v$ is band-limited ($\mathbf{W_F}\hat{\mathbf{s}}_m^v$), smooth ($\mathbf{D}\hat{\mathbf{s}}_m^v$), and unbiased ($\mathbf{M}\hat{\mathbf{s}}_m^v$)

$$\mathbf{D} = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ 0 & 0 & \dots \end{bmatrix} \qquad \mathbf{M} = \begin{bmatrix} 1 & \dots & 1 & 0 & \dots & \dots & 0 \\ 0 & 0 & 0 & 1 & \dots & 1 & 0 \\ \dots & \dots & \dots & 0 & \dots & \dots & 1 \end{bmatrix}$$

Hardware

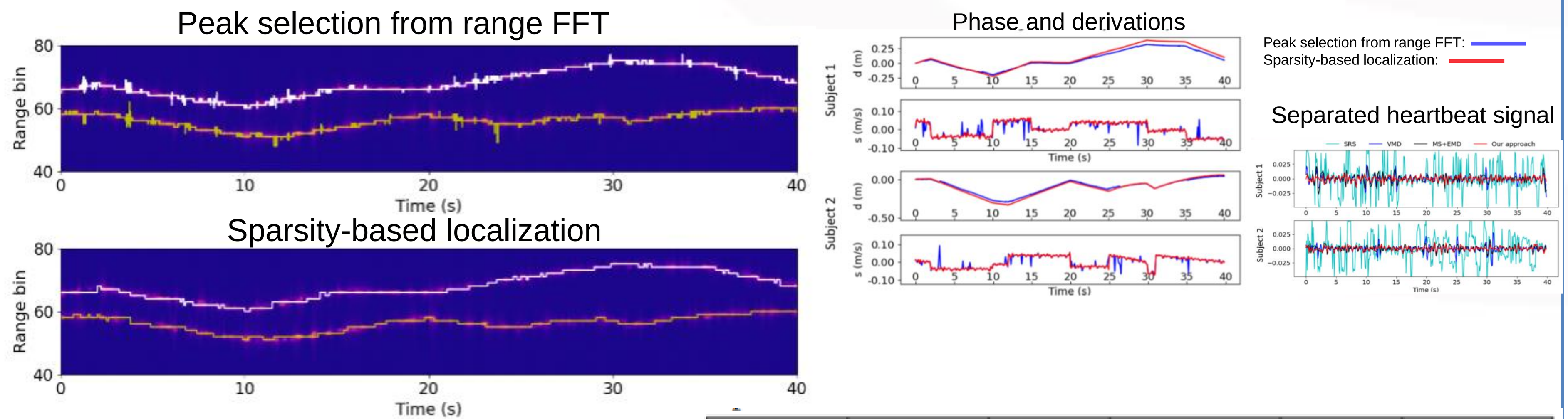




[1] Eder, Y., Zagoury, E., Savariego, S., Namer, M., Cohen, O., & Eldar, Y. C. (2025). Robust Phantom-Assisted Framework for Multi-Person Localization and Vital Signs Monitoring Using MIMO FMCW Radar. arXiv preprint

Localization and NCVSM Results

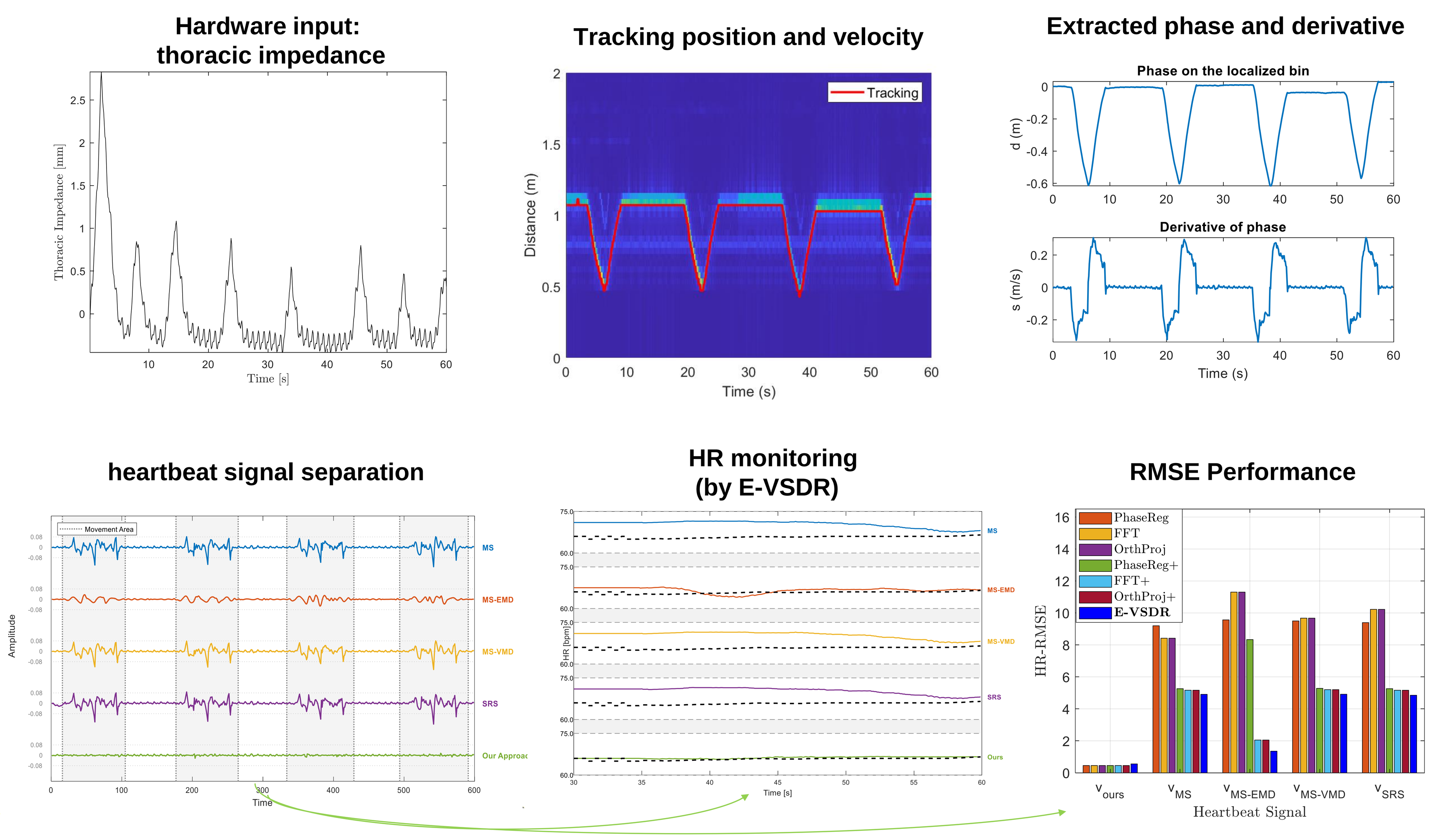
- Numerical simulations
  - Two subjects separated in range. The starting distance is 2.5 [m] and 2.8 [m], respectively
  - The subjects move at a piece-wise constant speed for a duration of 40 seconds
  - The true HRs for the two subjects are 71.8 and 64.4 BPM, respectively.



Subject	SRS	VMD	MS+EMD	Ours	True HR
1	43.3	**70.9**	70.7	**70.9**	71.8
2	77.3	100.8	72.2	**64.2**	64.4

- Hardware experiment

A dedicated platform where a mmWave FMCW radar is positioned on a table, while a movable platform holds a vibrating metal plate designed to mimic the motion of a human chest during large movements



Our separation technique yields accurate heart rate monitoring even during large movements!