SAMPLLAB Signal Acquisition Modeling Processing and Learning

WEIZMANN INSTITUTE OF SCIENCE

ICASSP 2023

Paper ID: 4132

Sparse Non-Contact Multiple People Localization and Vital Signs Monitoring Via FMCW Radar

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Motivation and Contributions

- The increase in cardiopulmonary morbidity, disease transmission and burden on medical staff has led to extensive investigation of non-contact monitoring approaches
- Remote technology such as radar does not require users to wear, carry, or interact with any additional electronic device
- We present multi-person non-contact vital signs monitoring (MP-NCVSM) via SIMO FMCW radar, in a noisy environment
- Our approach is based on joint-sparse recovery (JSR) which accurately localizes humans in a clutter-rich scenario involving equidistant people, where known techniques struggle
- Vital Signs-based Dictionary Recovery (VSDR) method is then used to estimate their vitals (Respiration Rate (RR) and Heart Rate (HR)) yielding superior results compared to current NCVSM approaches

Extended SIMO FMCW Model

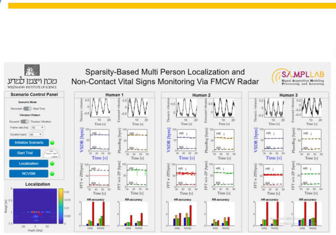
- We suggest the following signal model based on SIMO FMCW radar:

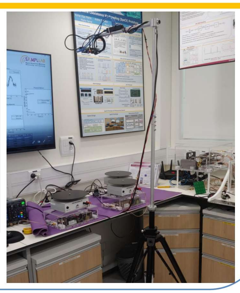
$$y[n,l,k]=\sum_{p=1}^{P}\sum_{m=1}^{M}x_{m,p}e^{j(2\pi f_m nT_f+\psi_{m,p}[l]+\phi_p[k])}+w[n,l,k]$$

- $f_m \triangleq \frac{2S}{c}d_m$
- $v_{m,p}[l]\triangleq\sum_{q=1}^{Q}a_{m,p,q}\cos(2\pi g_{m,p,q}lT_s)$
- $\psi_{m,p}[l]\triangleq\frac{4\pi}{\lambda_{\max}}(d_m+v_{m,p}[l])$
- $\phi_p[k]\triangleq\frac{2\pi}{\lambda}r_k\sin\theta_p$

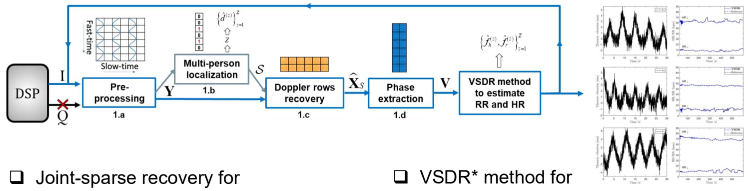
- $\{v_{m,p}[l]\}$ models the possible vibration of each object.
- The set $\{g_{m,p,q}\}$ includes the RR and HR of each human, denoted by $\{f_h^{(z)},f_r^{(z)}\}_{z=1}^{Z}$ for $Z \ll MP$ humans in the FOV
- Reshaping each L frames => $\boxed{\mathbf{Y}=\mathbf{C}\tilde{\mathbf{X}}+\mathbf{W}}$

Hardware Demonstration





Sparsity-Based Multi-Person Localization and NCVSM



- Joint-sparse recovery for multi-person localization

Ideal window corresponding to normal breathing frequencies — *L-size DFT matrix*

$$\bar{\mathbf{Y}}=\frac{1}{L}\left(\mathbf{F}_L^H\left(\mathbf{\Pi}\odot\mathbf{F}_L\mathbf{Y}^T\right)\right)^T \Rightarrow \mathcal{S}$$

$$\min_{\tilde{\mathbf{X}}\in\mathbb{C}^{PM\times L}}\left\|\bar{\mathbf{Y}}-\mathbf{C}\tilde{\mathbf{X}}\right\|_F^2+\lambda\left\|\tilde{\mathbf{X}}\right\|_{2,1}$$

- Doppler rows recovery

$$\mathbf{X}_S=\left(\mathbf{C}_S^H\mathbf{C}_S\right)^{-1}\mathbf{C}_S^H\mathbf{Y}$$

- Phase extraction

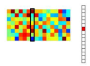
$$\mathbf{V}(l,z)\triangleq unwrap\left(\angle\left(\mathbf{X}_S(z,l)\right)\right)^T,\begin{cases}z=1,\dots,Z\\ l=1,\dots,L\end{cases},$$

- VSDR* method for estimating HR and RR given $\mathbf{V}=[\mathbf{v}_1,\dots,\mathbf{v}_Z]$:
  - Assuming that

$$\mathbf{v}_z=\mathbf{D}^{(R)}\mathbf{a}_z^{(R)}+\mathbf{D}^{(H)}\mathbf{a}_z^{(H)}+\mathbf{n}_z$$

    with known $\mathbf{D}^{(R)}$ and $\mathbf{D}^{(H)}$

  - $$\begin{cases}\hat{\mathbf{a}}_z^{(R)}=\mathbf{D}^{(R)T}\mathbf{v}_z\\ \hat{\mathbf{a}}_z^{(H)}=\mathbf{D}^{(H)T}\mathbf{v}_z\end{cases} \Rightarrow \boxed{\left\{\hat{f}_r^{(z)},\hat{f}_h^{(z)}\right\}_{z=1}^{Z}}$$



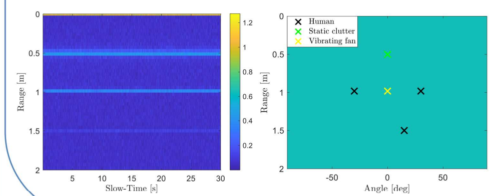
Localization Results for Cluttered Scenario

- A simulated environment with three persons (two equidistant), a vibrating fan, and static clutter.

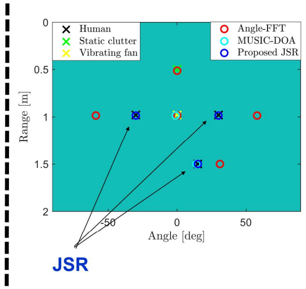
Object type	$x_{m,p}$	d_m [m]	θ_p [°]	$\{v_{m,p}[l]\}_{l=1}^{L}$
Static clutter	1	0.5	0	0
Human #1	0.3	0.98	−30	Based on [24]
Vibrating fan	0.3	0.98	0	$a_{\text{fan}}\cos(2\pi f_{\text{fan}}lT_s)$
Human #2	0.3	0.98	+30	Based on [24]
Human #3	0.2	1.5	+15	Based on [24]

Table 1: Setup of multiple objects scenario.

[24] S. Schellenberger et al., "A dataset of clinically recorded radar vital signs with synchronised reference sensor signals," *Scientific data,* vol. 7, no. 1, pp. 1–11, 2020.

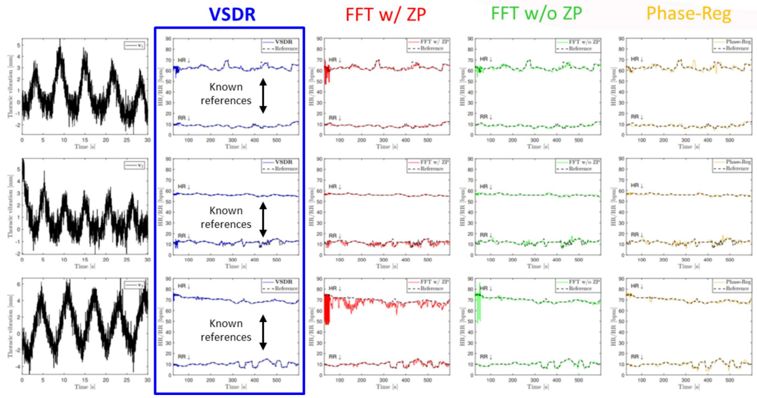


- Only the proposed JSR method indicates the correct locations of the humans!

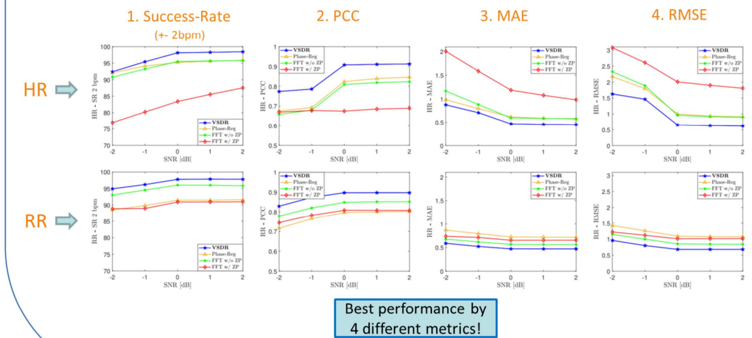


NCVSM Results

- Example of NCVSM of 3 people simultaneously based on correct automatic human localization
- Both the HR and RR estimates by the VSDR approach show great resemblance to those of the reference, compared to other techniques in which the noisy setup impairs their assessments



- VSDR outperforms the other compared methods in 4 different metrics, for any examined SNR
- In the more challenging task of HR monitoring, the gap between the VSDR and the other techniques is prominent



* Y. Eder, and Y.C. Eldar, "Sparsity-Based Multi-Person Non-Contact Vital Signs Monitoring Via FMCW Radar", to appear in IEEE Journal of Biomedical and Health Informatics, June 2023.