Tsinghua University

Acousticcardiogram
Monitoring Heartbeats using Acoustic Signals on Smart Devices

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Motivation

- Heart rhythm is a critical vital sign for health.



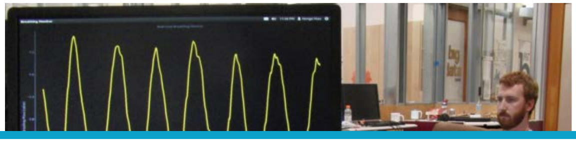
- Daily monitoring is especially important.

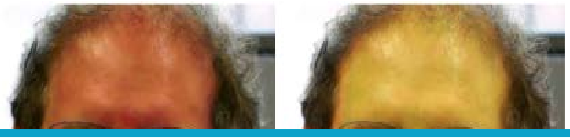


Existing Approaches.

Electrocardiograph

Wearables

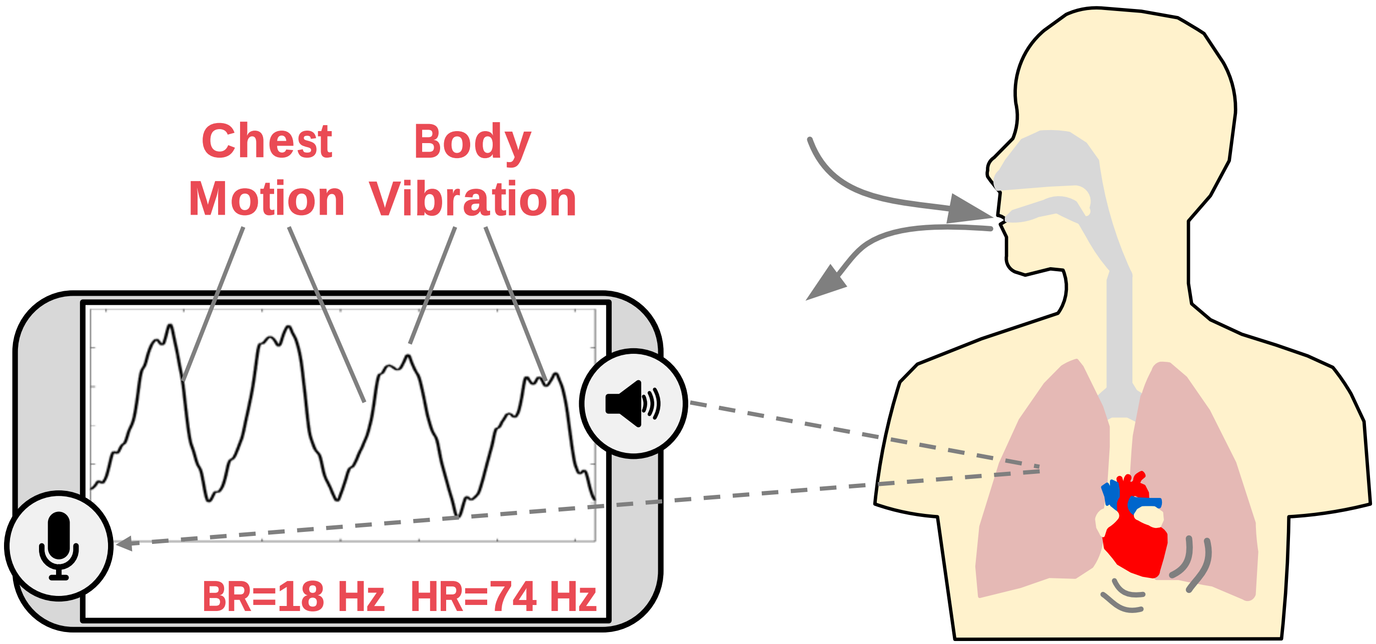




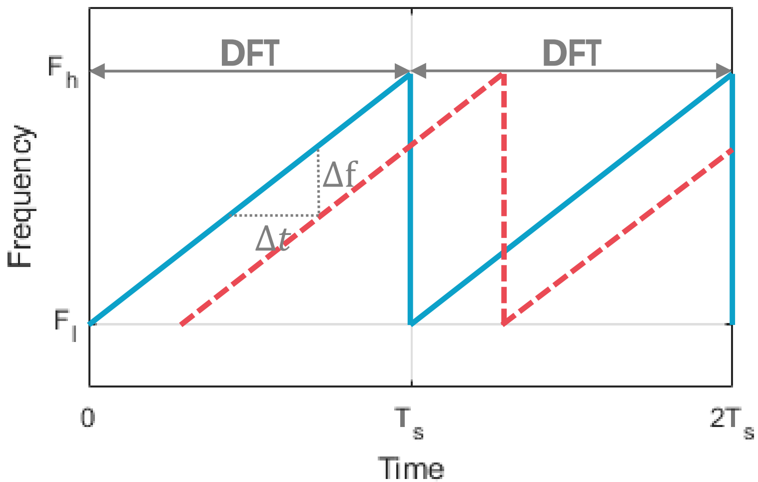
Major drawbacks: specific equipment, high sensitivity to environment, inconvenience.

Problem Statement

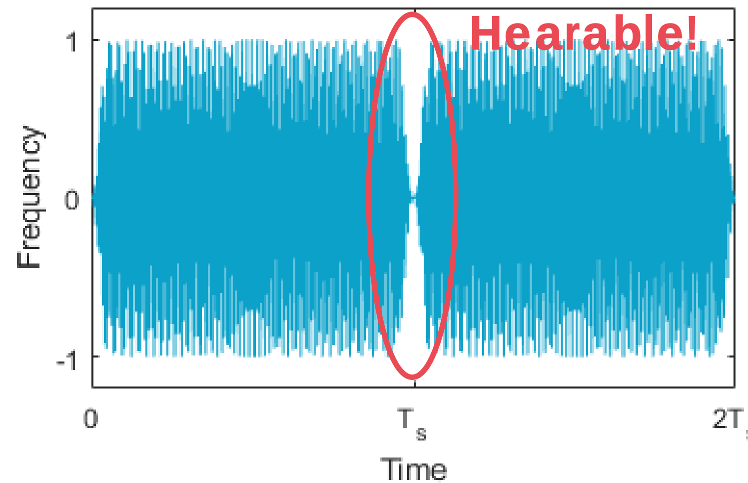
- Can we passively monitor vital signs on prevail smart phones?
  - Indirect measure body motion with customized sonar.



FMCW Sonar Design



Ideal FMCW spectrogram



Real FMCW spectrogram / Chirp Signal

$$s(t) = A\cos\left(2\pi\left(f_c t + \frac{B(t - NT_s)^2}{2T_s}\right)\right)$$

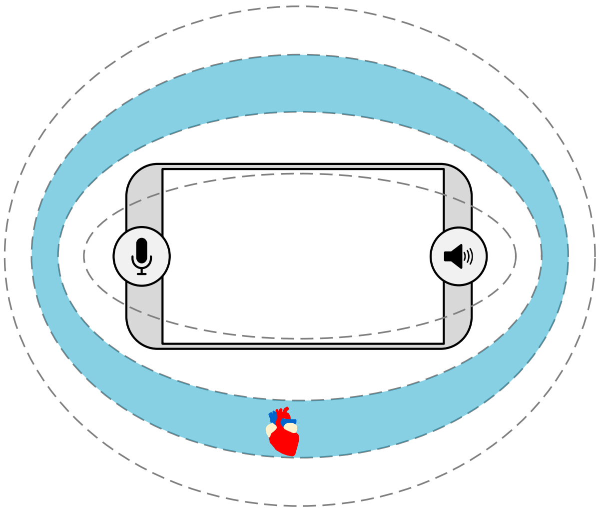
$$s(t) = w(t)\cos\left(2\pi\left(f_c t + \frac{B(t - NT_s)^2}{2T_s}\right)\right)$$

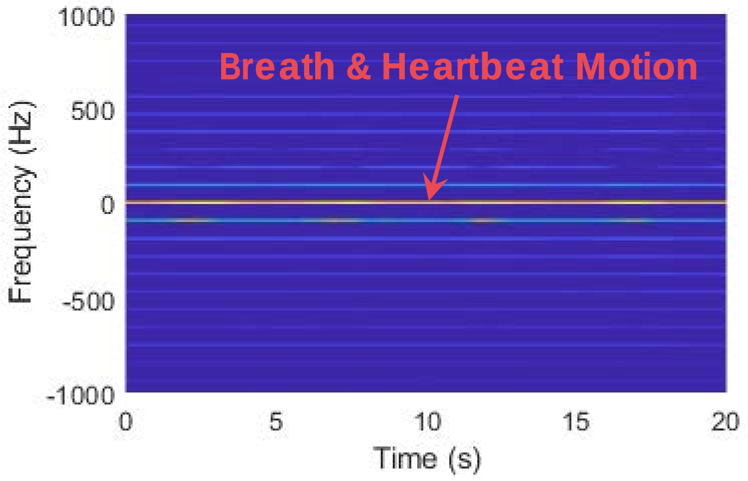
Limited Resolution: Challenge

- Sonar implemented on smart phone has poor ranging resolution.

$$\Delta = \frac{v}{2B} \approx \frac{346\ m/s}{2 \times 2000\ Hz} = 8.65\ cm$$

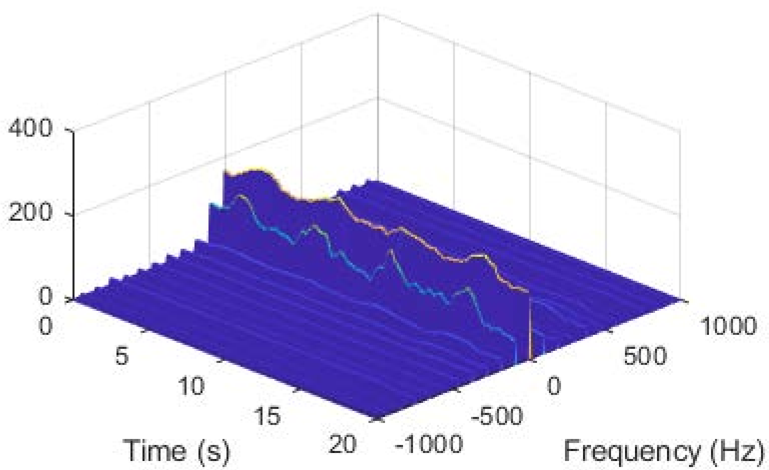
- In contrast, human heartbeat $\sim 1\ mm$.

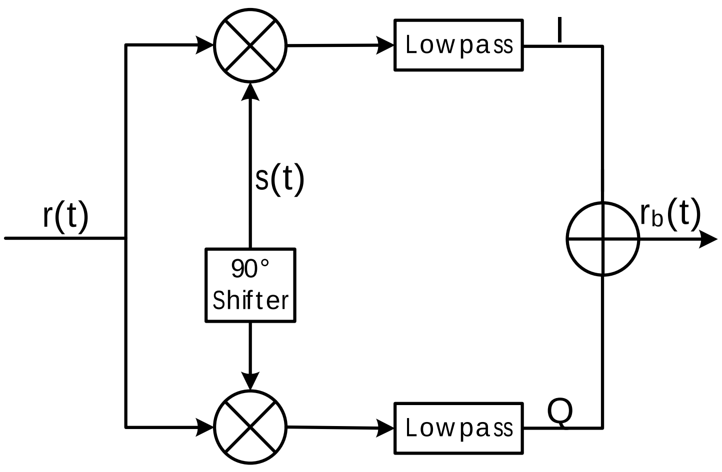




Baseband Conversion

- Measure signal variation within sonar resolution.
  - View FMCW sonar as a spatial filter.
  - Track signal phase of the target spatial signal.





Baseband Processing

- Passband signal reflected by human chest.

$$r(t) = \alpha \cos\left(2\pi\left(f_c(t-\tau(t)) + \frac{B(t-\tau(t)-N'T_s)^2}{2T_s}\right)\right), N' = \begin{cases} N-1, t \in P_1 \\ N, t \in P_2 \end{cases}$$

- Baseband signal.

$$r_b(t) = \begin{cases} \alpha e^{j2\pi\left(f_c\tau(t) + \frac{B(t-NT_s)(\tau(t)-T_s)}{T_s} - \frac{B(\tau(t)-T_s)^2}{2T_s}\right)}, t \in P_1 \\ \alpha e^{j2\pi\left(f_c\tau(t) + \frac{B(t-NT_s)\tau(t)}{T_s} - \frac{B\tau(t)^2}{2T_s}\right)}, t \in P_2 \end{cases}$$

$$P_1 = \left(NT_s - \frac{T_s}{2}, NT_s - \frac{T_s}{2} + \tau(t)\right];$$

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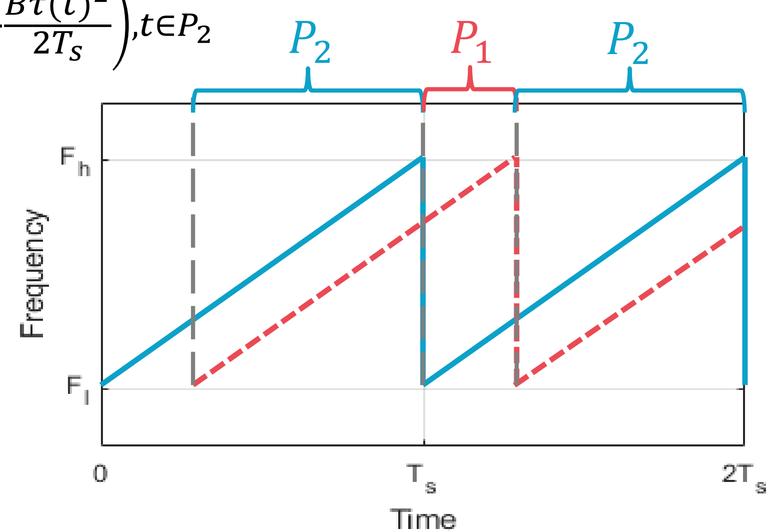


Frequency Ambiguity: Challenge

- Signal of Interest with frequency shift $f = \frac{\tau(t)B}{T_s}$.

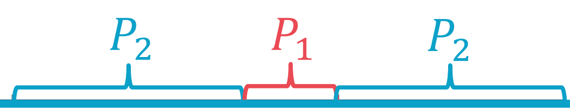
$$b(t) = 2\alpha \frac{T_s - \tau(t)}{T_s} e^{j2\pi\left(f_c\tau(t) - \frac{B\tau(t)^2}{2T_s}\right)}$$

Target term by P_2

$$+2\alpha \frac{\sin\left(2\pi B\tau(t)\right)}{2\pi B} \frac{\tau(t)}{T_s} e^{j2\pi\left(f_c\tau(t) - \frac{B\left(\tau(t)^2 - T_s^2\right)}{2T_s}\right)}$$

Interference term by P_1

- Why it matters in sonar?

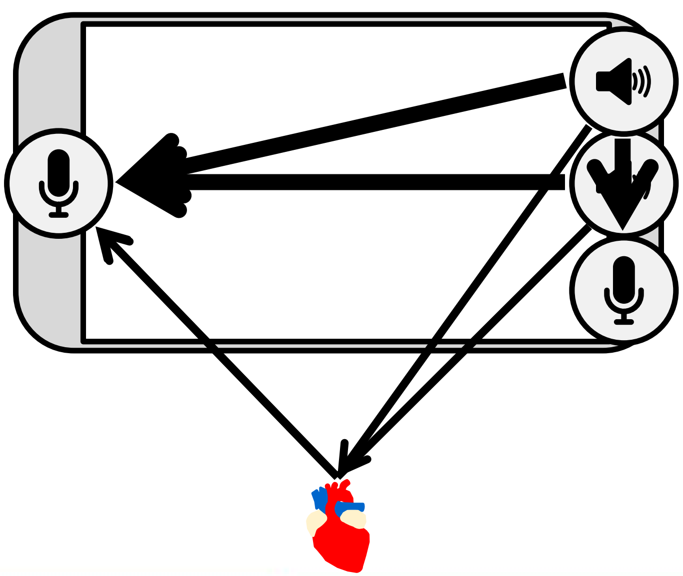


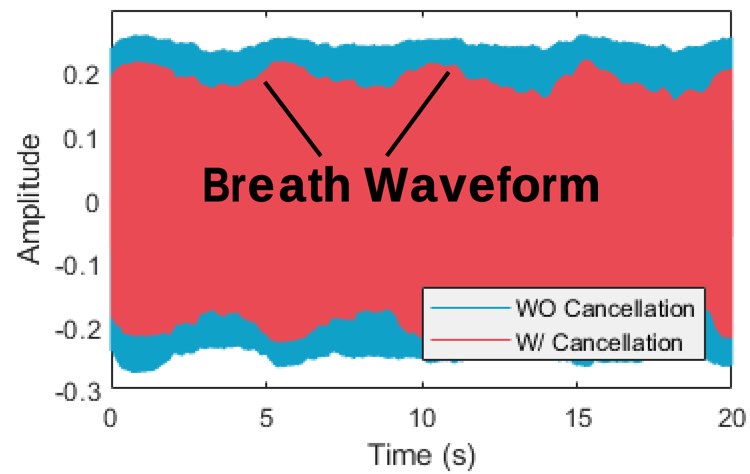
Solution: align reflection with transmitted signal, i.e., $\tau \approx 0$

Power Leakage Cancellation

- Direct power leakage from speaker to microphone.
  - Need to be cancelled for signal alignment.
- Use the secondary microphone as reference.
  - Calculate correlation c and delay δ_t between two mics.

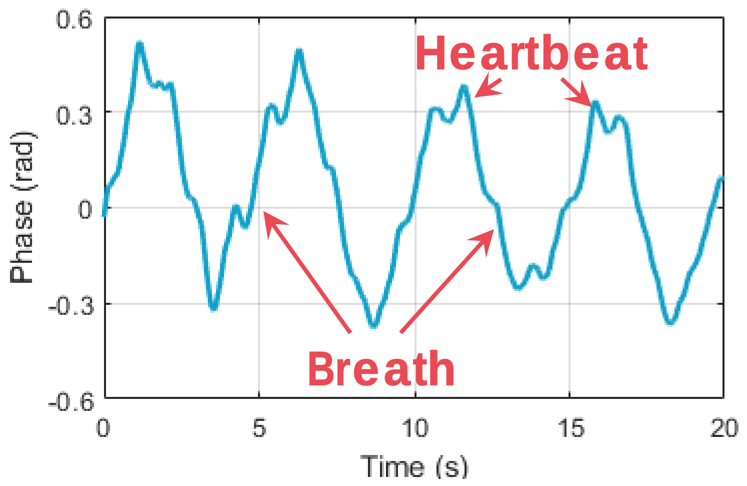
$$r(t)^{cancel} = r_1(t) - c r_2(t + \delta_t)$$

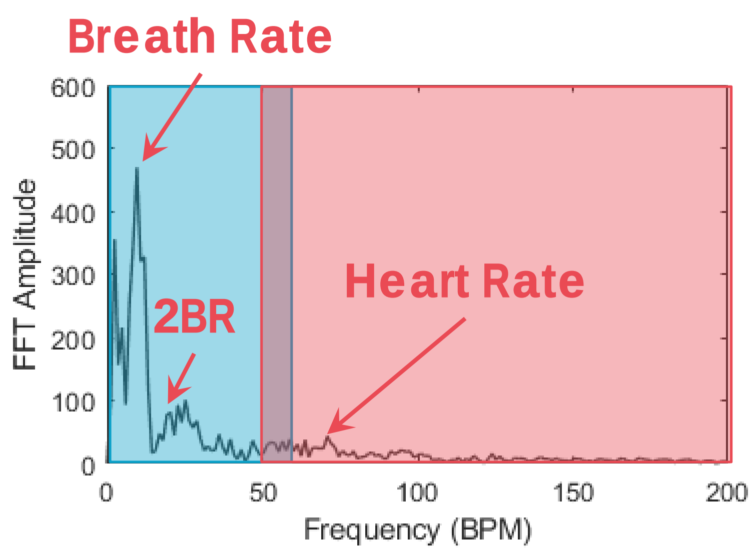




Vital Sign Measurement

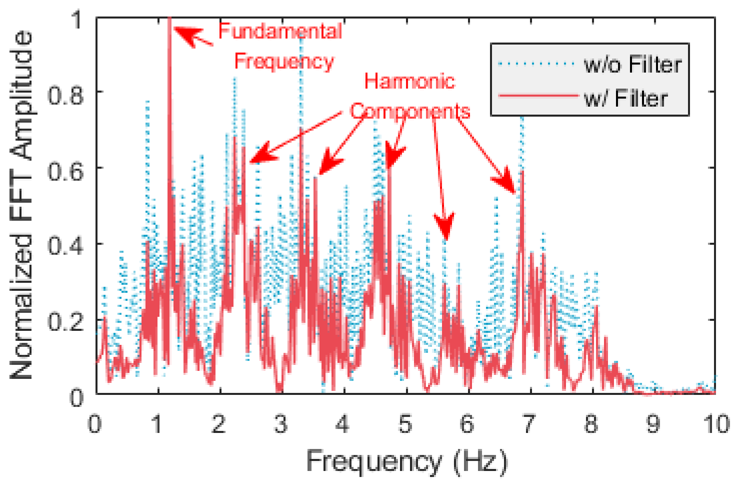
- Vital signs can be identified in signal phase.
- Vital signs can be estimated in frequency domain.
  - Breath Rate $\in (0, 60)$ BPM.
  - Heart Rate $> (2BR, 50)$ BPM.

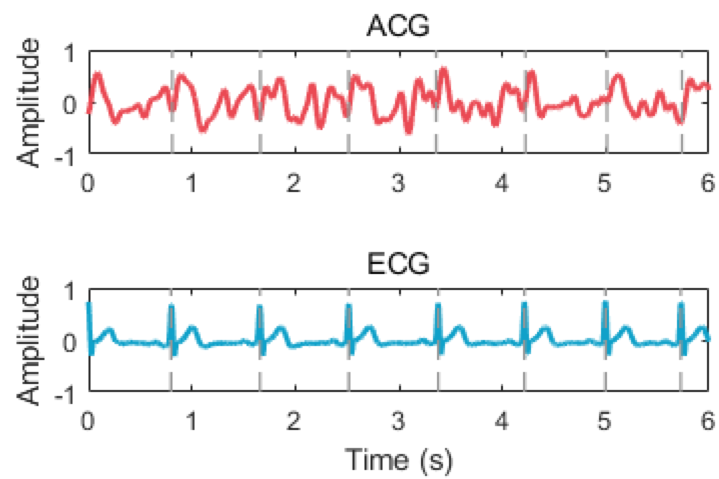




Heartbeat Measurement

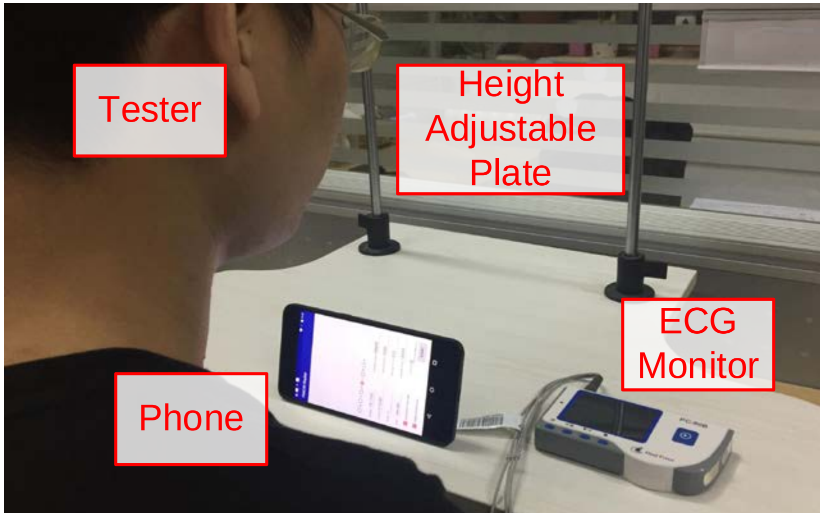
- Two-step estimation (MobiCom '17)
  - Calculate second derivative to amplify high frequency heartbeat signal.
  - Jointly optimize waveform and intervals with EM algorithm.
- Combat with high frequency noises.
  - Adaptive comb filter with order $= \frac{SamplingRate}{HeartRate}$.





Experiment Setup

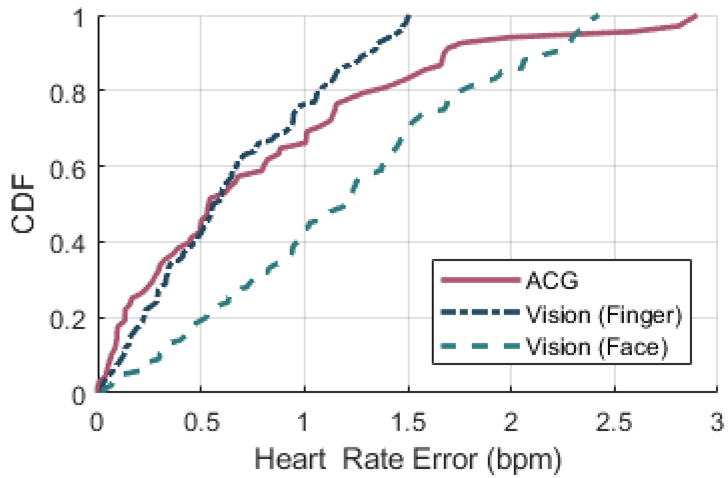
Parameters	Value
f_c	18 kHz
B	2 kHz
T_s	10.7 ms
F_s	48 kHz



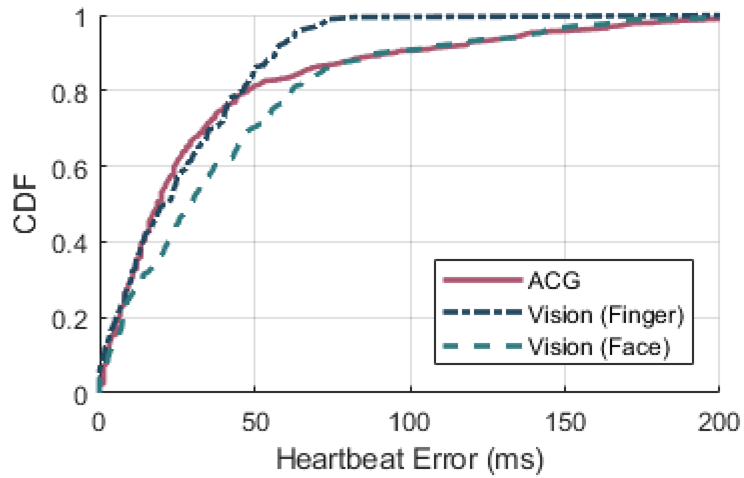
- Equipment
  - Google Nexus 6p
- Ground truth
  - Heal Force PC-80B
  - Sampling Rate 150 Hz
  - Resolution 6.7 ms
- Tester
  - 10 with single coat
- Comparison
  - CV-based approaches
  - Finger (contact)
  - Face (non-contact)

Overall Performance

- ACG achieves a median error of 0.6 bpm.
- ACG achieves a median error of 18.7 ms.



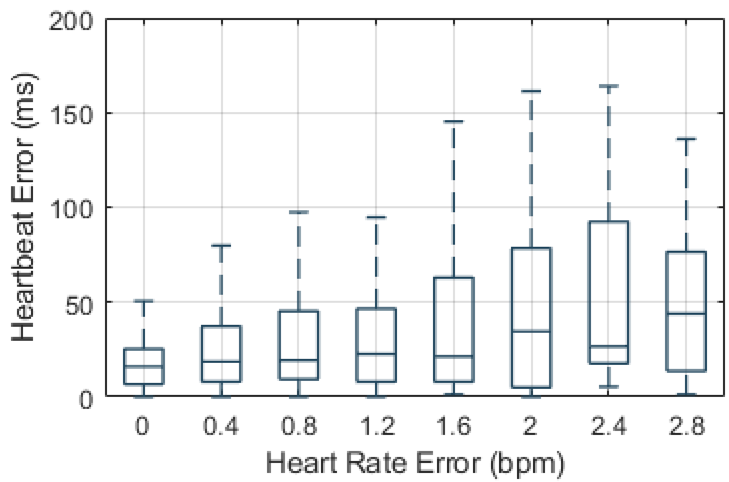
Heart Rate Accuracy



Heartbeat Interval Accuracy

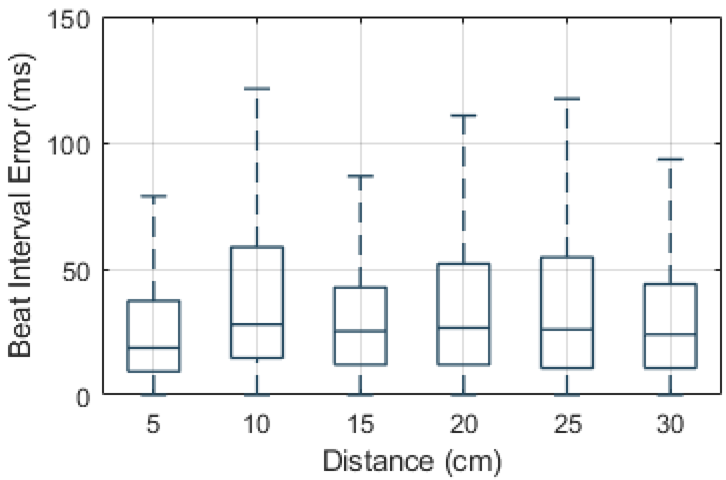
Error Correlation

- Heartbeat error increases with heart rate error.

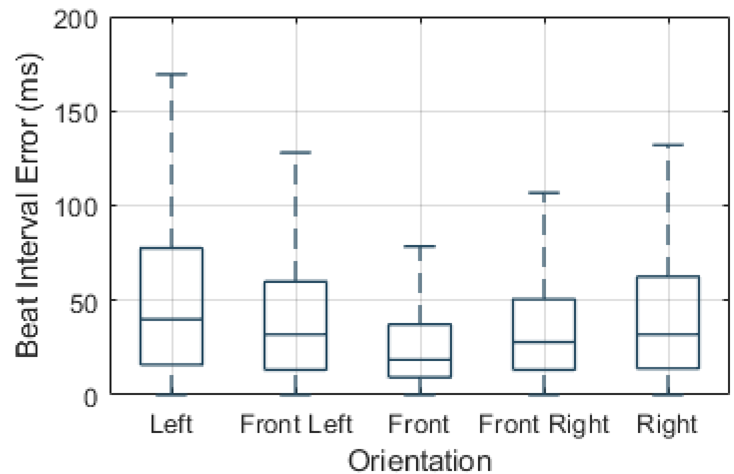


- We then only evaluate the impact of factors on accuracy of heartbeat interval.

User Issue Study



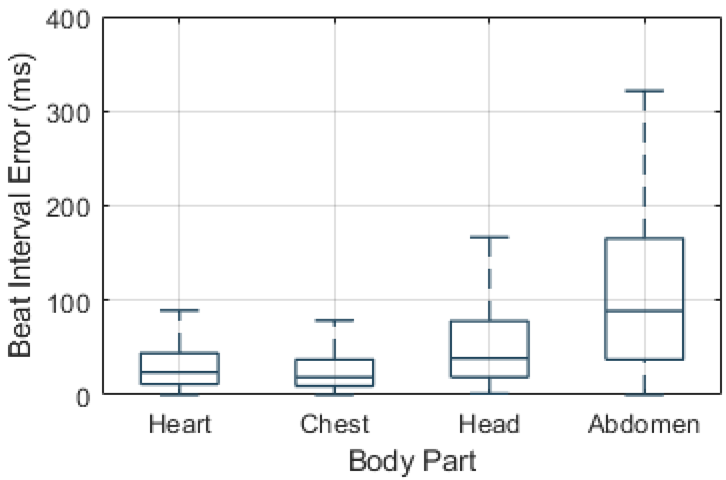
Impact of Distance



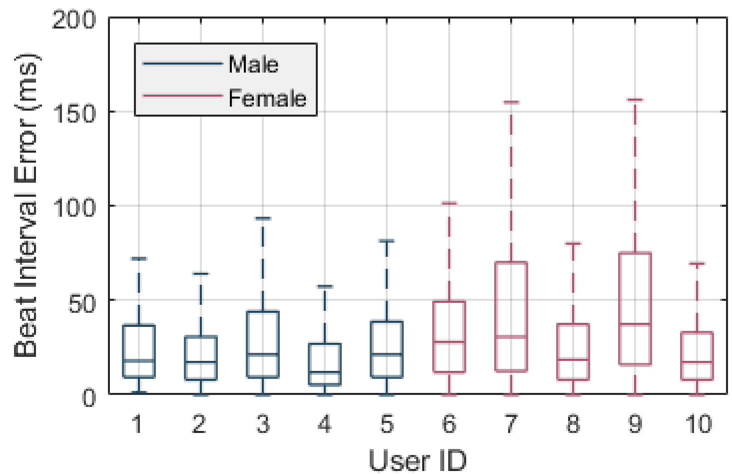
Impact of Orientation

- The accuracy slightly decreases with the increase of distance between phone and user.
- The accuracy decreases as the angle between orientations of phone and user increases.

User Issue Study



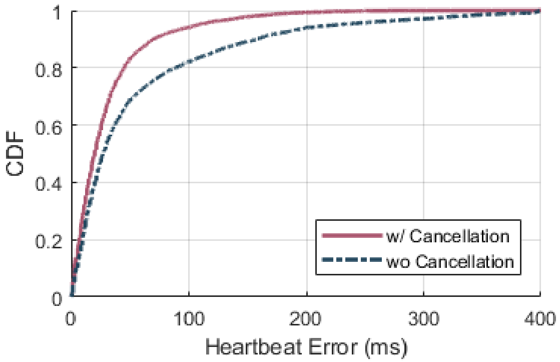
Impact of Body Part



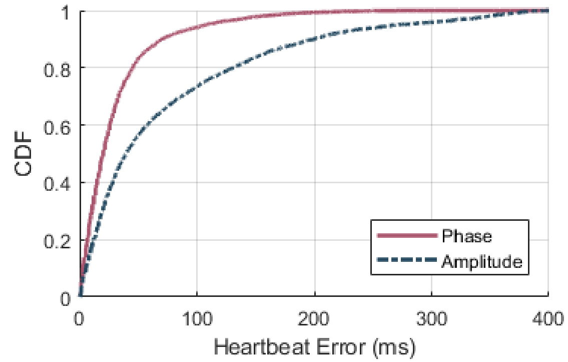
Impact of User Diversity

- ACG achieves high accuracy for heart and chest.
- ACG achieves higher accuracy for males than females

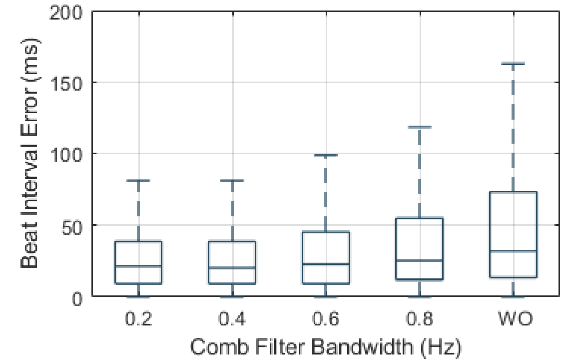
Key Process Study



Leakage cancellation



Use of signal phase



Adaptive comb filter

- Key processes contribute to accuracy of ACG.
  - Leakage cancellation: 27.9 ms → 18.7 ms
  - Use of signal phase: 40.7 ms → 18.7 ms
  - Adaptive comb filter: 32 ms → 18.7 ms

Conclusion

- ACG is a vital signs monitoring system.
  - Acoustic-based and contactless.
  - Working on COTS smart phone.
  - Comparable accuracy with CV-based approaches.
- ACG employs key techniques to enable vital signs monitoring on smart phone.
  - Power leakage cancellation.
  - Baseband signal processing.
  - Adaptive comb filter.

Thanks!
Q&A

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