Depth Aware Finger Tapping on Virtual Display

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Motivation

Traditional tapping-based interaction:

- Require physical devices
- Limit the freedom of user hands

Motivation

Tapping-in-the-air:

- Hands are free to interact with other objects
- Depth measurements provide different levels feedback

Limitation of Prior Arts

Customized depth-cameras

- Low accuracy:
  Centimeter-level accuracy (without different levels feedback)
- High latency:
  Low frame rate and high computational requirements

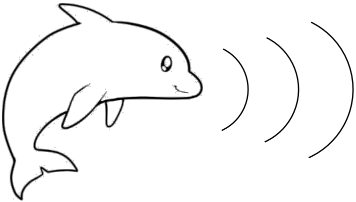
Problem Statement

Can we suppport tapping-in-the-air without depth-cameras?

and meet these design goals

- High accuracy (mm-level)
- Low latency (< 20 ms)
- Different levels feedback (finger bending angle)
- Low computational cost (works on mobile devices)

Basic Idea



Dolphin navigation:

Ultrasound + Vision

- Use ultrasound based sensing, along with one COTS mono-camera, to enable 3D tracking of user fingers with high frame rate.

Basic Idea

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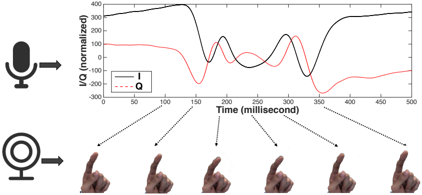


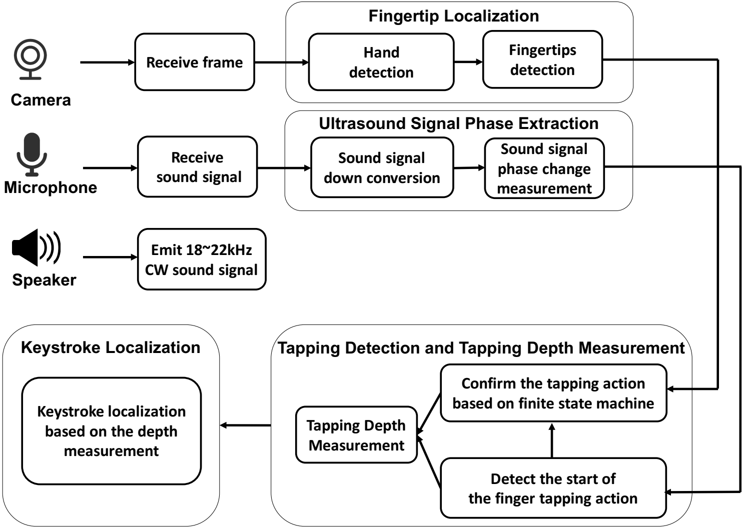
Ultrasound

High sampling rate (48 kHz)
Sensitivity to the depth direction
Only 1D information

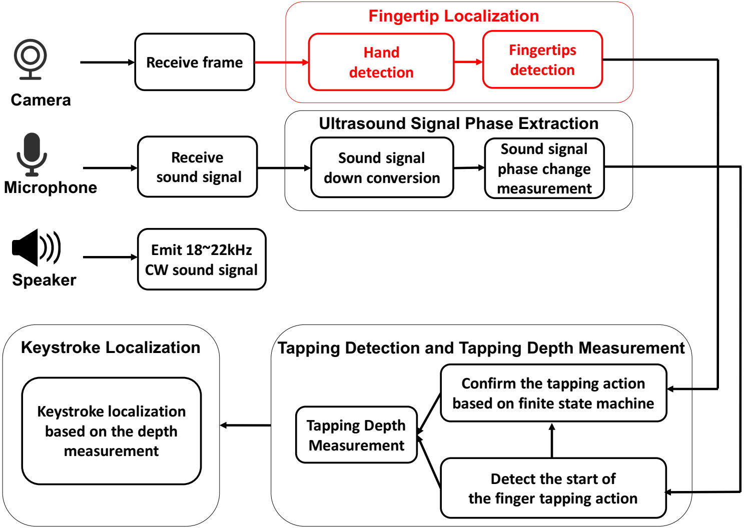
Mono-camera

Low frame per second (30 fps)
Accurate 2D information

System Architecture



Fingertip Localization



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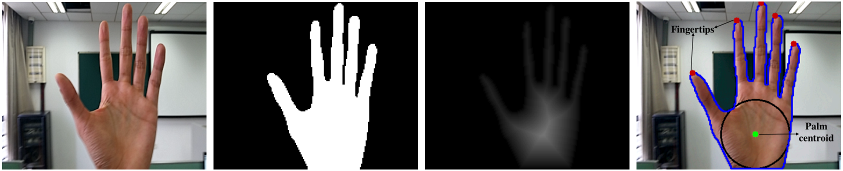
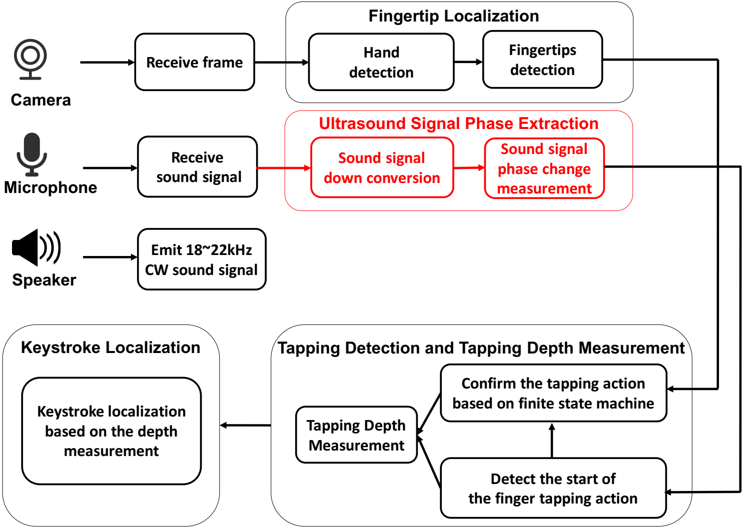


(a) Input frame (b) Binary image (c) Distance transform (d) Fingertips image

Light-weight computer vision algorithm to locate the fingertips in 2D

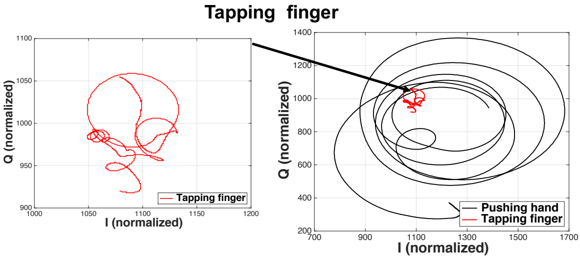
- Adaptive Skin Segmentation:
  Otsu's method calculates the optimal threshold
- Hand detection
  Find the centroid of the palm (Distance Transform)
- Fingertip Detection for tapping gesture
  Extreme-points-based scheme

Ultrasound Signal Phase Extraction



Ultrasound Signal Phase Extraction

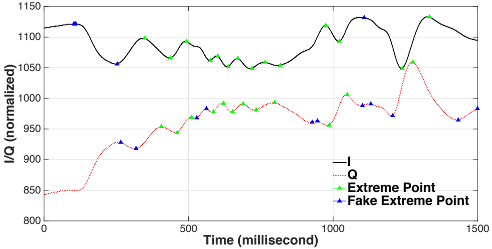
- Phase-based distance measurement
  - Measure phase changes caused by the movement
  - 16 single frequencies ($17 \sim 22$ kHz) linear regression



Challenge:

- Phase changes caused by the finger movements is much smaller.
- Multipath interference in finger movements is much more significant.

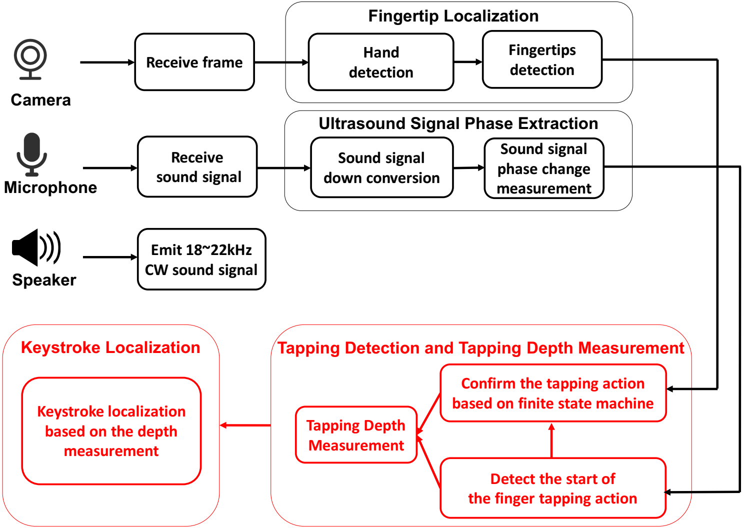
Ultrasound Signal Phase Extraction



Peak and Valley Estimation

- Find the peak and valley
  - Avoid the error-prone step of static vector estimation
- Exclude the fake extreme points:
  - "FingerInterval": the magnitude gap of the finger
  - "SpeedInterval": the speed of the finger
- Future: use modulated signal to locate the absolute distance and exclude other distance dynamic multipath

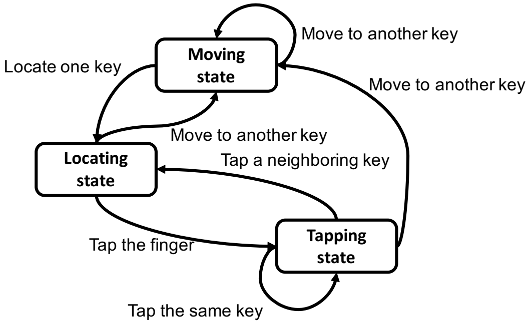
Tapping Detection and Tapping Depth Measurement



Finger Motion State

- "Moving state"–Moves their finger to the key
  - Audio: Difficult to build the model
  - Video: Easy to track the fingers
- "Locating state"–Keeps their finger on the target key position briefly
  - Video: Difficult to perceive
  - Audio: Easy to detect the short pause
- "Tapping state"–"Tapping down state" & "Tapping up state"
  - Video: Difficult to measure
  - Audio: Easy to measure the depth information

Finger Motion Pattern



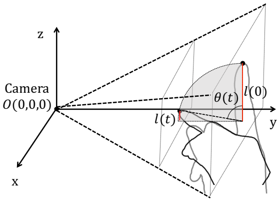
- Tapping a non-neighboring key
  - "Moving state" –> "Locating state" –> "Tapping state"
- Tapping a neighboring key
  - "Locating state" –> "Tapping state"
- Tapping the same key
  - "Tapping state"

Finger Tapping Detection

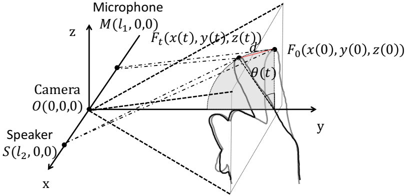
1. Audio to detect that the "tapping state"
   - Utilize the high sampling rate (48 kHz) –> Low latency
   - Utilize the sensitivity to the depth direction –> High accuracy
   - Use only 1D information –> High false positive rates
2. Video to look back to the previous frames
   - Measure the duration of "Moving state" and "Locating state"
   - Check the state machine to remove false alarms–> High robustness
   - Measure the depth of finger tapping
3. Keystroke localization
   - Calculate the location of the fingertip during the "Locating state"
   - Determine the fingertip with the largest bending angle
   - 1-NN determine the pressed virtual key

Measure the depth of finger tapping

- Measure the bending angle of the finger
  - Deep finger tapping: camera-based model



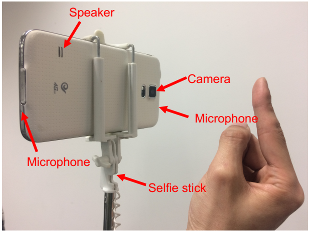
  - Gentle finger tapping: ultrasound-based model



Implementation

Implemented on Android with NDK

- Video: OpenCV C++
- Audio: C++



Video parameters used

24 frame per second
355×288 resolution

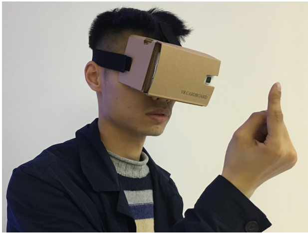
Audio parameters used

48 kHz sampling rate
512 samples per segment (10.7 ms)
16 single frequencies ($17 \sim 22$ kHz)

Evaluation Setup

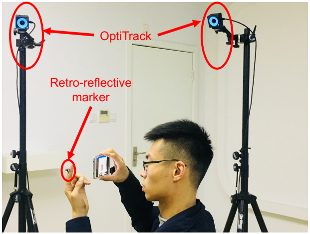
Three different use cases:

- Fix by selfie stick
- Hold in hand
- Set on the head by cardboard VR

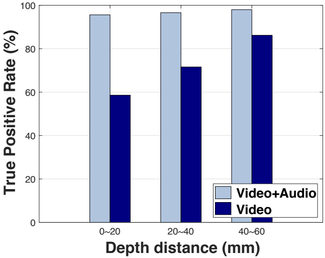


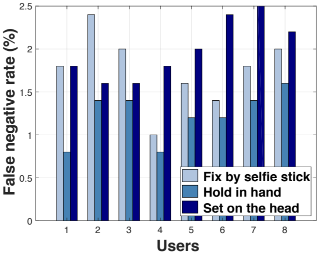
Depth ground truth:

- OptiTrack
  (4 depth cameras + 120 fps)



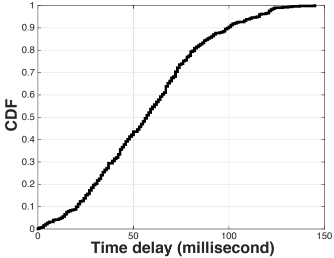
Result – Accuracy





- Average movement distance error of 4.32mm (SD $= 2.21\text{mm}$)
- Average 98.4% accuracy with FPR of 1.6% and FNR of 1.4%
- Improve the gentle finger tappings accuracy from 58.2% to 97.6%

Result – Latency



(a) Audio thread

	Down conversion	PVE	Tapping detection	Total
Time	$6.455ms$	$0.315ms$	$0.036ms$	$6.806ms$

(b) Video thread

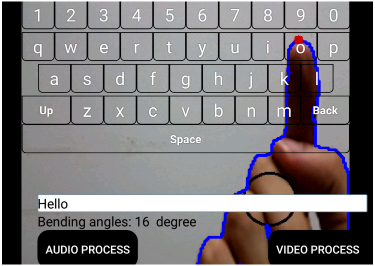
	Hand detection	Fingertip detection	Frame playback	Total
Time	$22.931ms$	$2.540ms$	$14.593ms$	$40.064ms$

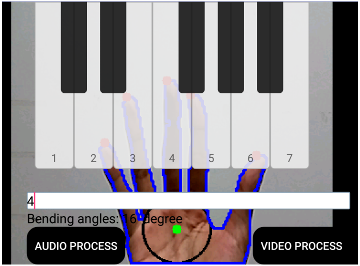
(c) Control thread

	Keystroke localization	Virtual key rendering	Total
Time	$0.562ms$	$10.322ms$	$10.884ms$

- Average response latency of 18.08ms on commercial mobile phones
- Average response latency is 57.7ms smaller than the video-based schemes

Result – Case study





- 12.18 (SD=0.85) WPM for single-finger inputs
- 13.1 (SD=1.2) WPM for multi-finger inputs
- Average 95.0% TPR for 4-level feedbacks

Result – Power consumption

	CPU	LCD	Audio	Total
Idle	$30 \pm 0.2mW$	/	/	$30 \pm 0.2mW$
Backlight	$30 \pm 0.2mW$	$894mW \pm 2.3$	/	$924 \pm 2.0mW$
Video-only	$140 \pm 4.9mW$	$895 \pm 2.2mW$	/	$1035 \pm 4.0mW$
Our scheme	$252 \pm 12.6mW$	$900 \pm 5.7mW$	$384 \pm 2.7mW$	$1536 \pm 11.0mW$

- Significant power consumption overhead of 48.4%
- More than 77% additional power consumption comes from speaker
- Future: reduce the power consumption of the audio system

Conclusion

Combining ultrasound sensing information and vision information to achieve tapping-in-the-air

Our system achieves design goals

- High accuracy
  4.32 mm distance error, 98.4% accuray
- Low latency
  18.08 ms, 4x faster than video-based scheme
- Different levels feedback
  based on different bending angles of finger tappings
- Low computational cost
  works on commercial mobile devices

Q&A

Thank you!

Question?