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of Science and Technology

Angle-of-Arrival-Based Gesture Recognition Using Ultrasonic Multi-Frequency Signals

Authors: Hui Chen, Tarig Ballal, Mohamed Saad, Tareq Y. Al-Naffouri

Speaker: Hui Chen
University: King Abdullah University of Science and Technology (KAUST)

Human Gestures

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A form of non-verbal communication:

- Conveying information
- Expressing emotions
- Language for disabled people

Human-machine Interactive Products

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Camera

(Microsoft Kinect)

Lasers & IMU

(HTC Vive)

Accelerometer

(Synertial Glove)

Ultrasound

(Ellipticlabs)

IR cameras and infrared LEDs

(Leap Motion)

A Demo of Writing "KAUST"

Write 'K', 'A', 'U', 'S', 'T'
continuously within a window.

A Demo of Writing "KAUST"

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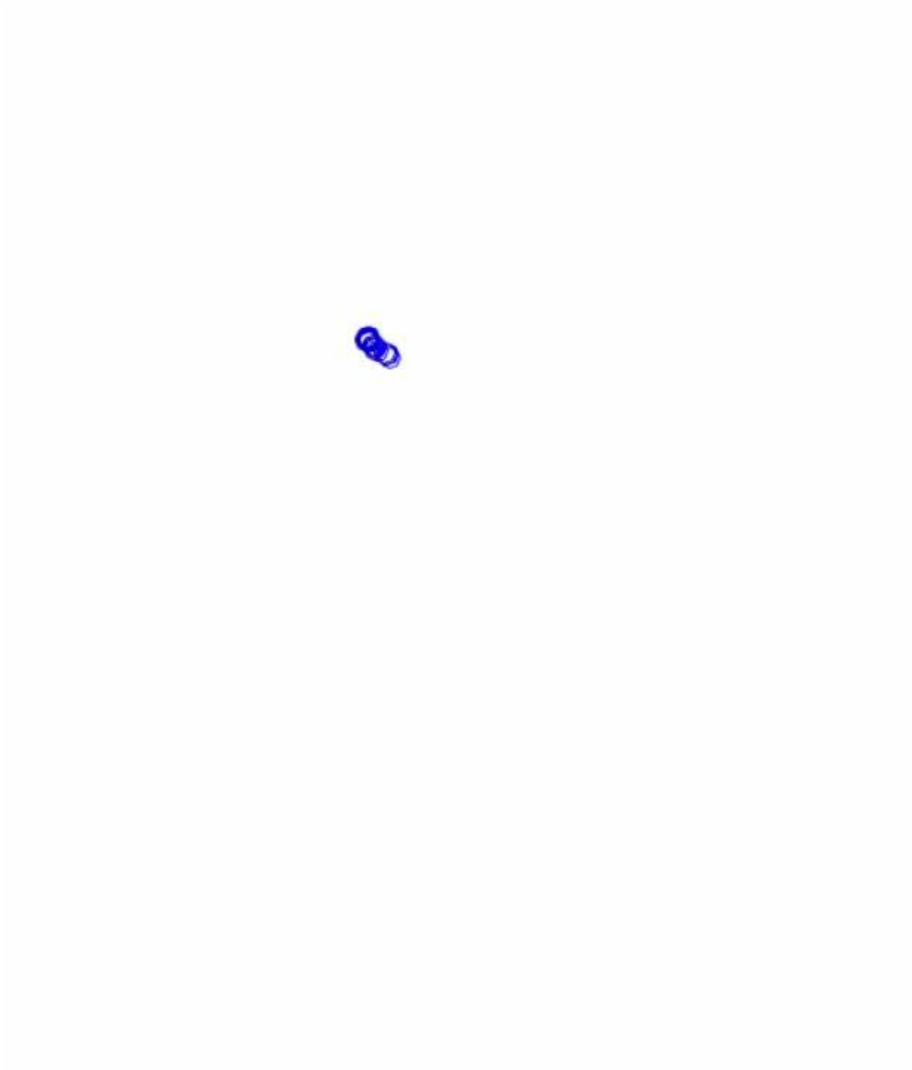

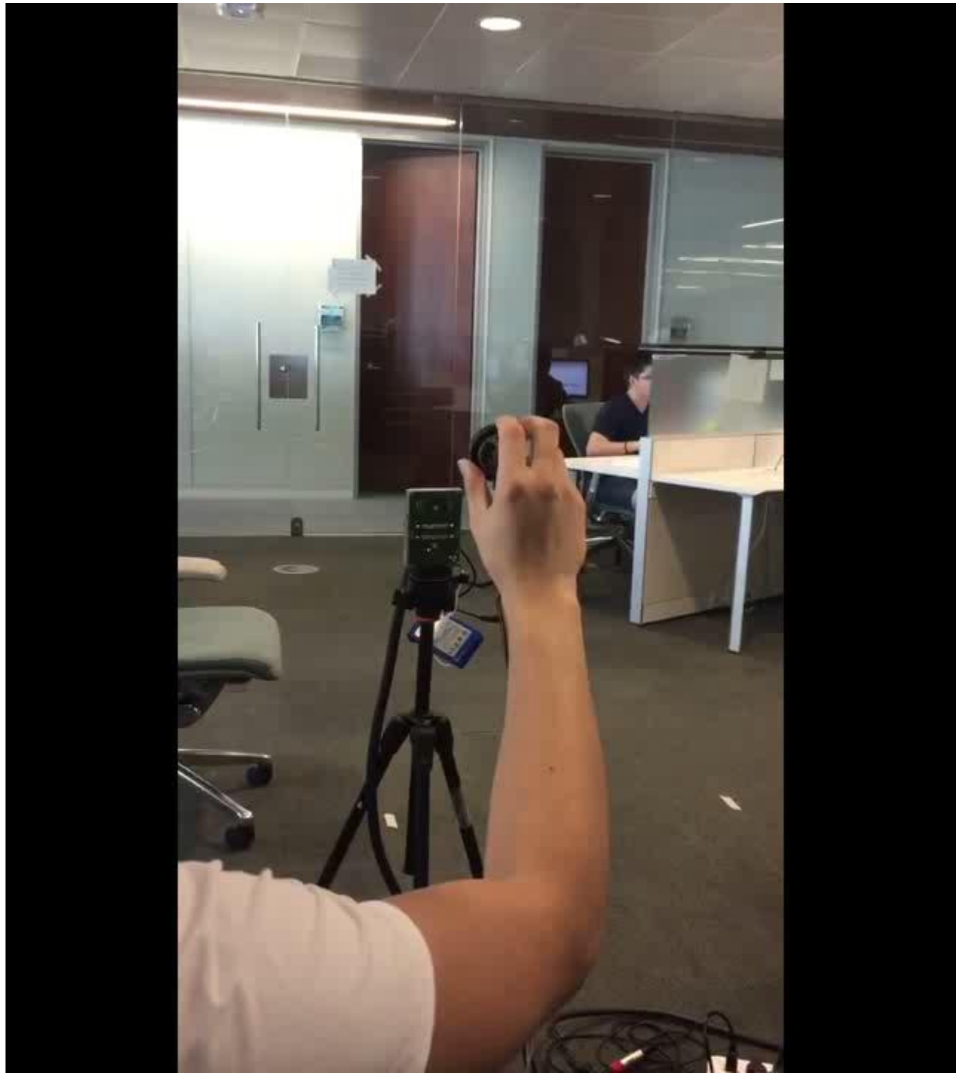

A Demo of Writing “KAUST”

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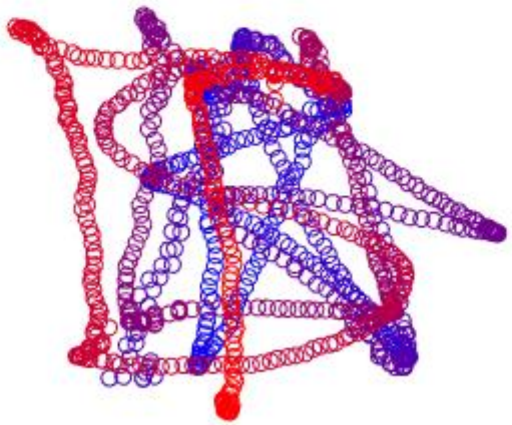
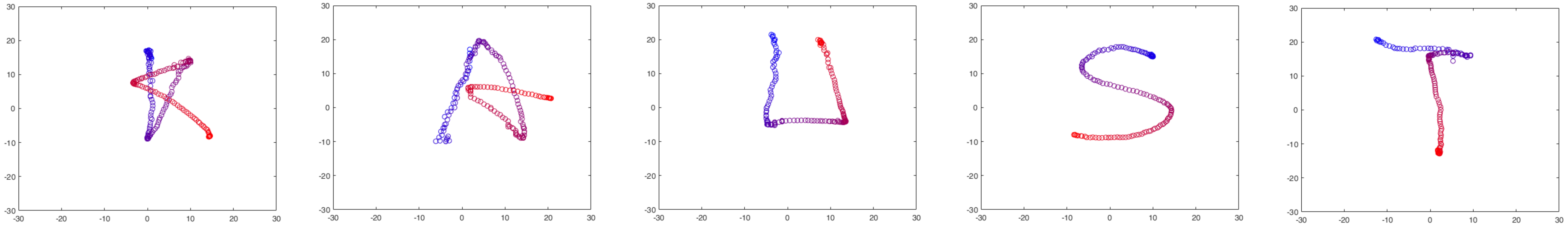


Captured hand motion with proposed system

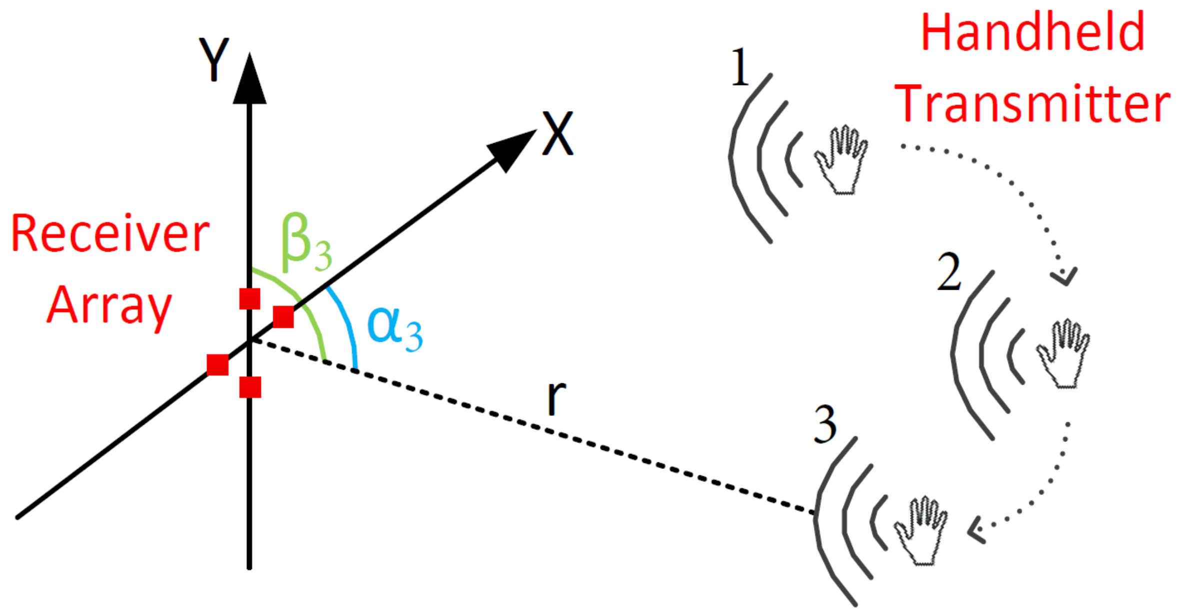
Start from blue to red

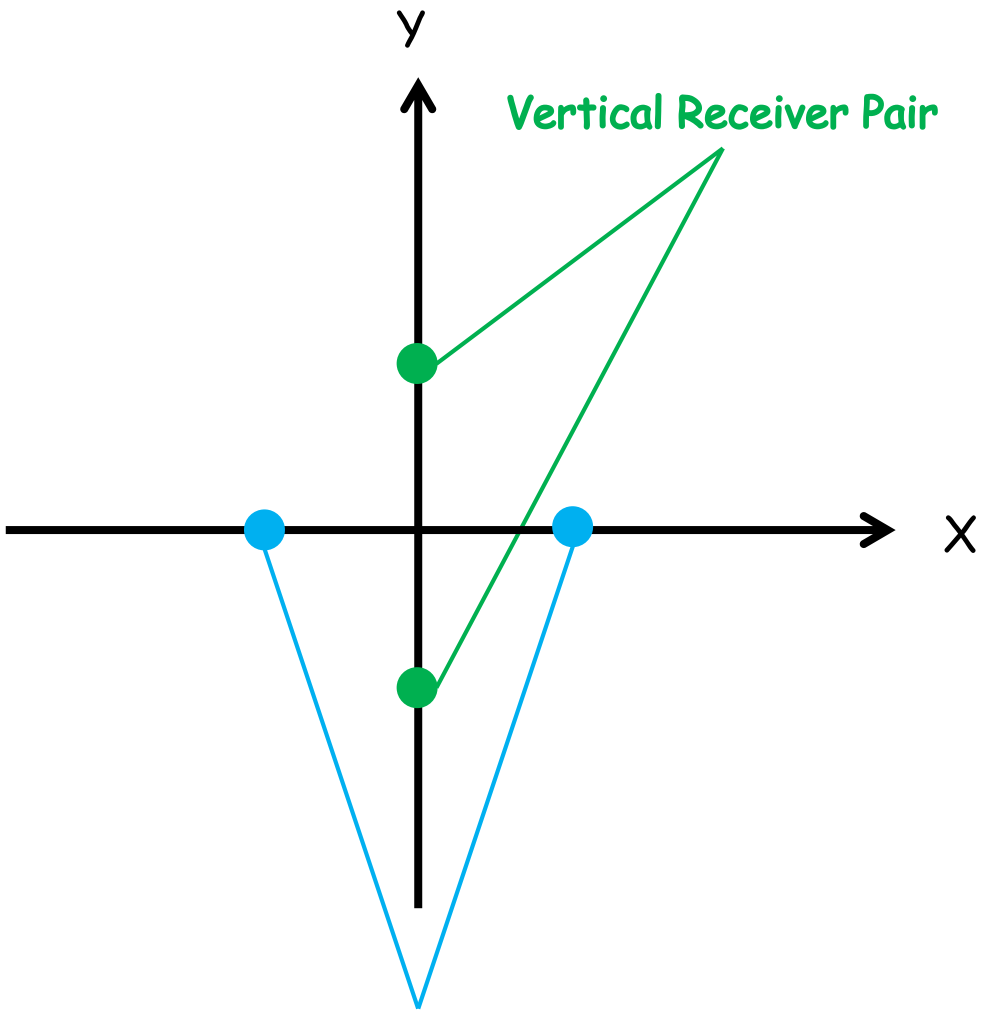


Extracted Segments

How it works?

Angle information → Classify





Proposed System

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1 AOA estimation:

Ultrasonic signals are transmitted from the transmitter. AoA algorithm is used to obtain the angle information for each sample.

2 Classification:

Estimated angle data are processed and sent to classifier to recognition this gesture.

Signal Design

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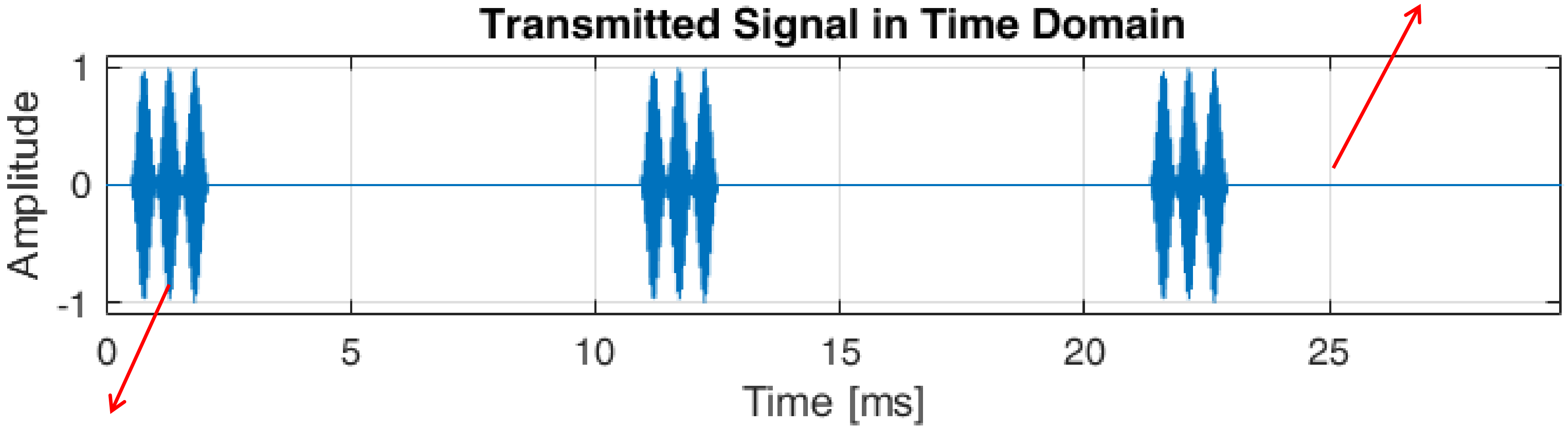
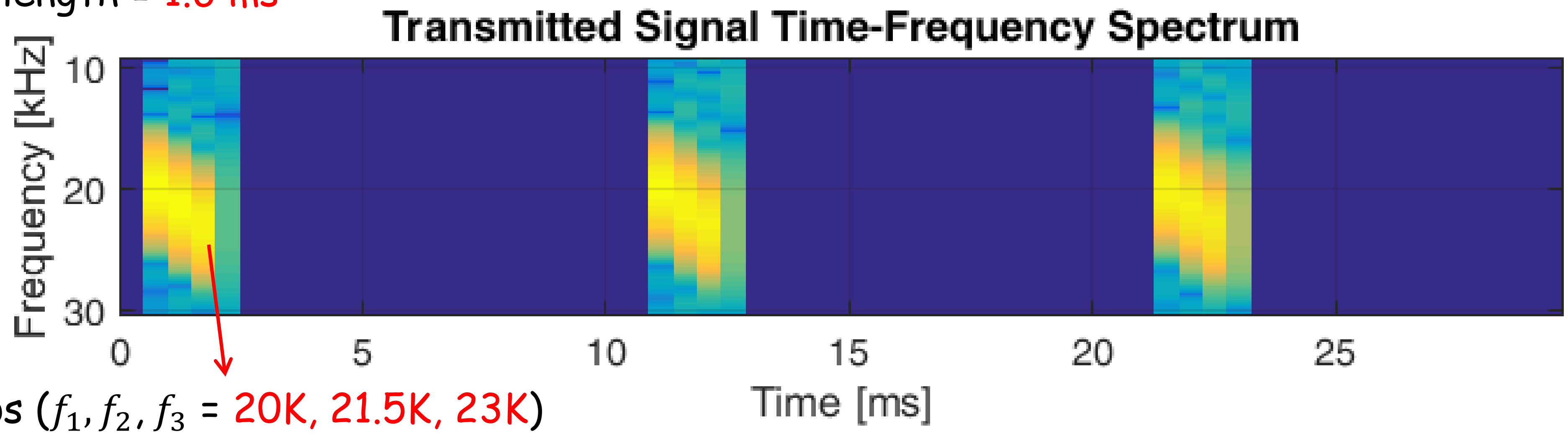
Measurements/Frame per second: 100 (Hz)



Pulse length = 1.6 ms



3 hops (f_1, f_2, f_3 = 20K, 21.5K, 23K)

Signal Design

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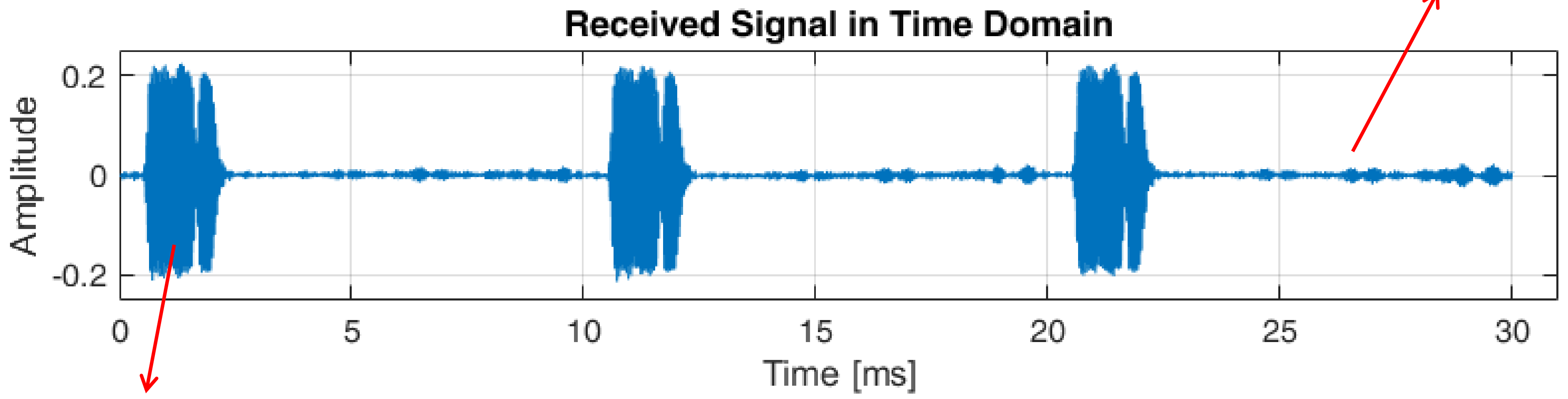
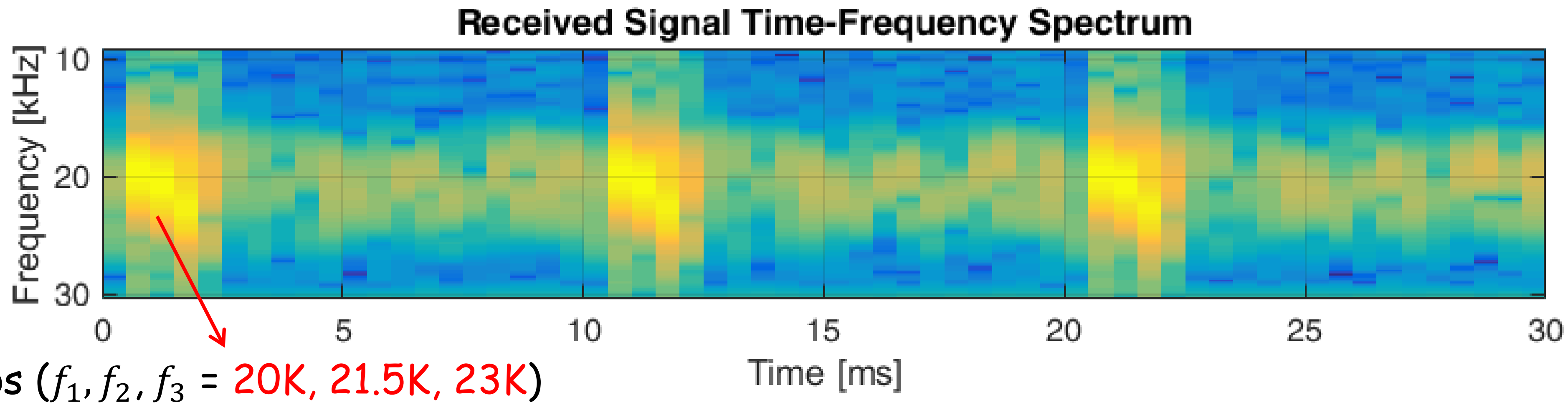
Measurements/Frame per second: 100 (Hz)

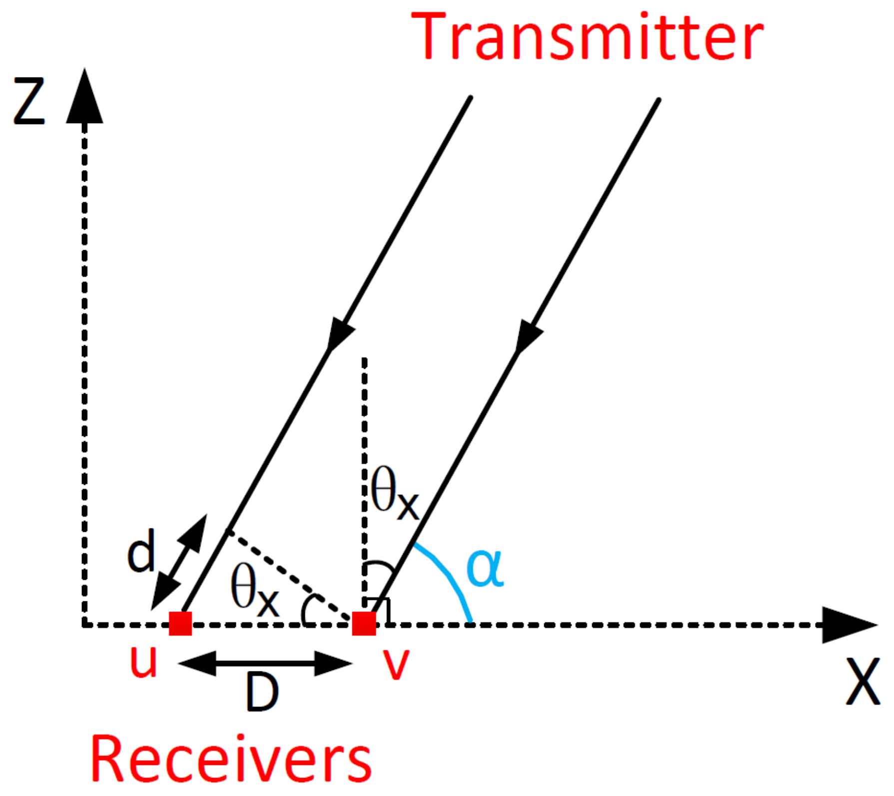


Pulse length = 1.6 ms



3 hops (f_1, f_2, f_3 = 20K, 21.5K, 23K)

Far-field Model of AOA



Far-field Model of
Horizontal Receivers

$$\boxed{sin\theta_x = \frac{d}{D} = \frac{\Delta\varphi}{2\pi f} \cdot \frac{c}{D}}$$

Given:

θ_x:	Horizontal angle
d:	difference of arrival
$\Delta\varphi$:	phase difference
F:	frequency of current signal
C:	Sound speed
D:	Sensor distance

How to get:

Horizontal angle θ_x and vertical angle θ_y

Proposed Angle of Arrival Estimation Algorithm

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1 Estimated phase difference $\hat{\psi}_{x,i}$ for carrier frequencies f_1, f_2, f_3 using cross power spectrum:

$$\boxed{\hat{\psi}_{x,i}} = \operatorname{ang}(Y_u(f_i) \cdot Y_v^*(f_i)) = \hat{\phi}_{x,i} - 2\pi N_{x,i}, \qquad (1)$$

$Y_u(f_i)$ is the DFT (Discrete Fourier Transform) of the received signals at sensor u;

$(\cdot)^*$ indicates the complex conjugate operation;

$\hat{\phi}_{x,i}$ is the real phase difference;

$N_{x,i}$ is an integer which makes estimated phase difference $\hat{\psi}_{x,i}$ within (-π, π];

2 Calculate real phase difference $\hat{\phi}_{x,i}$ for $\theta_x = \theta$ (eg: θ = -90°) for all the 3 frequencies:

$$\boxed{\frac{2\pi f_i D \sin(\theta)}{c}}$$

$$\sin(\hat{\theta}_x) = \frac{d}{D} = \frac{\boxed{\hat{\phi}_{x,i}}\, c}{2\pi f_i D}, \qquad (2)$$

Proposed Angle of Arrival Estimation Algorithm

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3 Obtain wrapped real phase difference $\tilde{\psi}_{x,i}$ from real phase difference $\hat{\phi}_{x,i}$;

$$\boxed{\tilde{\psi}_{x,i}(\theta)} = \text{wrap}(\tilde{\phi}_{x,i}(\theta)) = \text{wrap}\left(\boxed{\frac{2\pi f_i D \sin(\theta)}{c}}\right), \qquad (3)$$

4 Calculate the error between estimated phase difference and at all frequencies (i = 1,2,3);

$$\sum_{<i>} (|\hat{\psi}_{x,i} - \tilde{\psi}_{x,i}(\theta)|)$$

5 Repeat 2,3 for all the angles θ_x = -90 : 1 : 90 and find the θ gives min error as the estimated angle.

$$\boxed{\hat{\theta}_x} = \arg\min_{\theta} \sum_{<i>} (|\hat{\psi}_{x,i} - \tilde{\psi}_{x,i}(\theta)|), \qquad (4)$$

AOA Estimation Summary

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1 Estimated phase difference $\hat{\psi}_{x,i}$

$$\boxed{\hat{\psi}_{x,i}} = \mathrm{ang}(Y_u(f_i) \cdot Y_v^*(f_i)) = \hat{\phi}_{x,i} - 2\pi N_{x,i}$$

2 Calculate real phase difference $\hat{\phi}_{x,i}$ for θ = -90° : 1 : 90 at all the 3 frequencies:

3 Obtain wrapped real phase difference $\tilde{\psi}_{x,i}$

$$\boxed{\tilde{\psi}_{x,i}(\theta)} = \mathrm{wrap}(\tilde{\phi}_{x,i}(\theta)) = \mathrm{wrap}\left(\boxed{\frac{2\pi f_i D \sin(\theta)}{c}}\right)$$

4 Obtain absolute error (difference) summation of $\hat{\psi}_{x,i}$ and $\tilde{\psi}_{x,i}$;

5 Find the θ gives min error as the estimated angle.

$$\boxed{\hat{\theta}_x} = \arg\min_{\theta} \sum_{<i>} (|\hat{\psi}_{x,i} - \tilde{\psi}_{x,i}(\theta)|)$$

Classifiers

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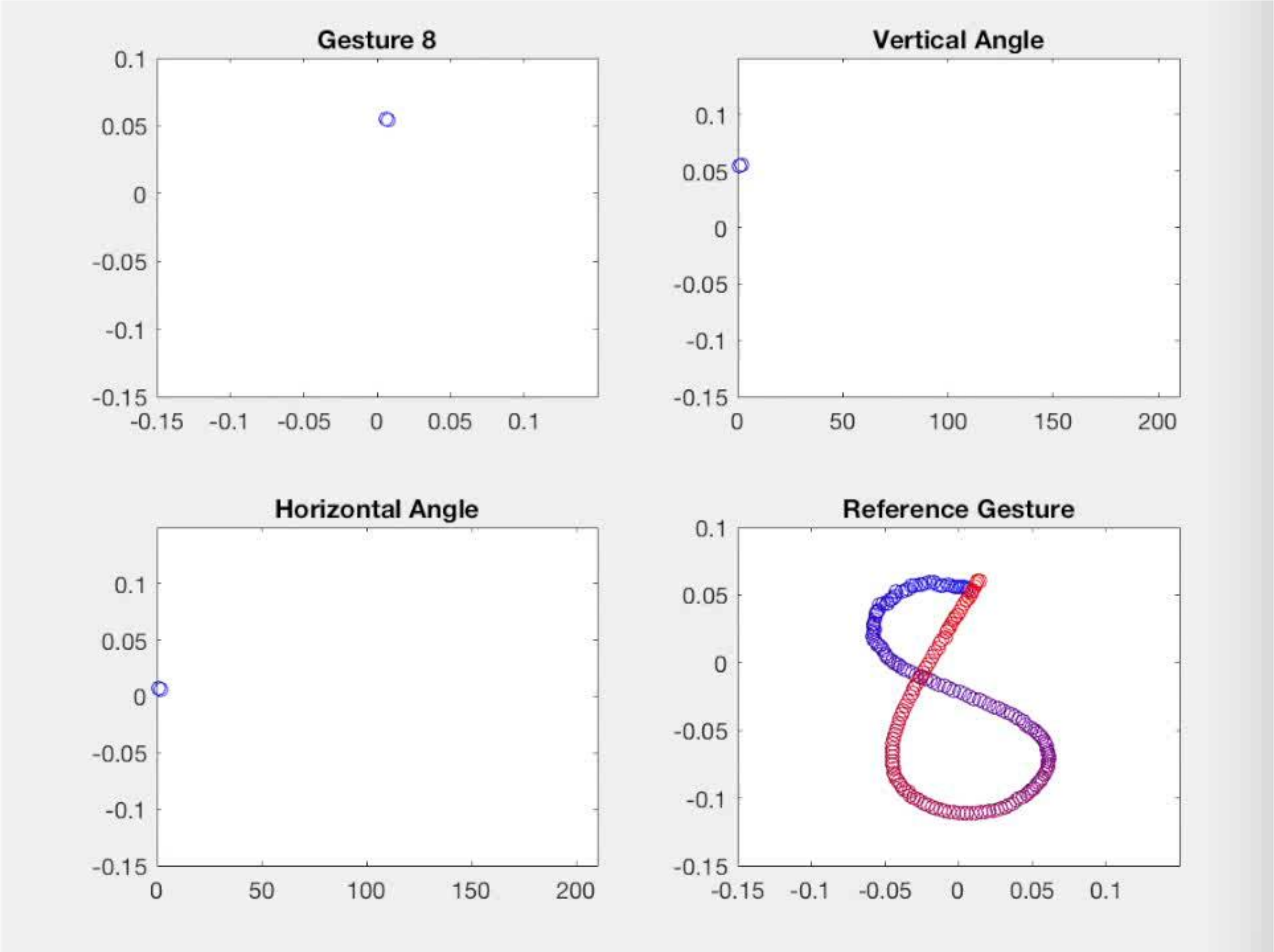
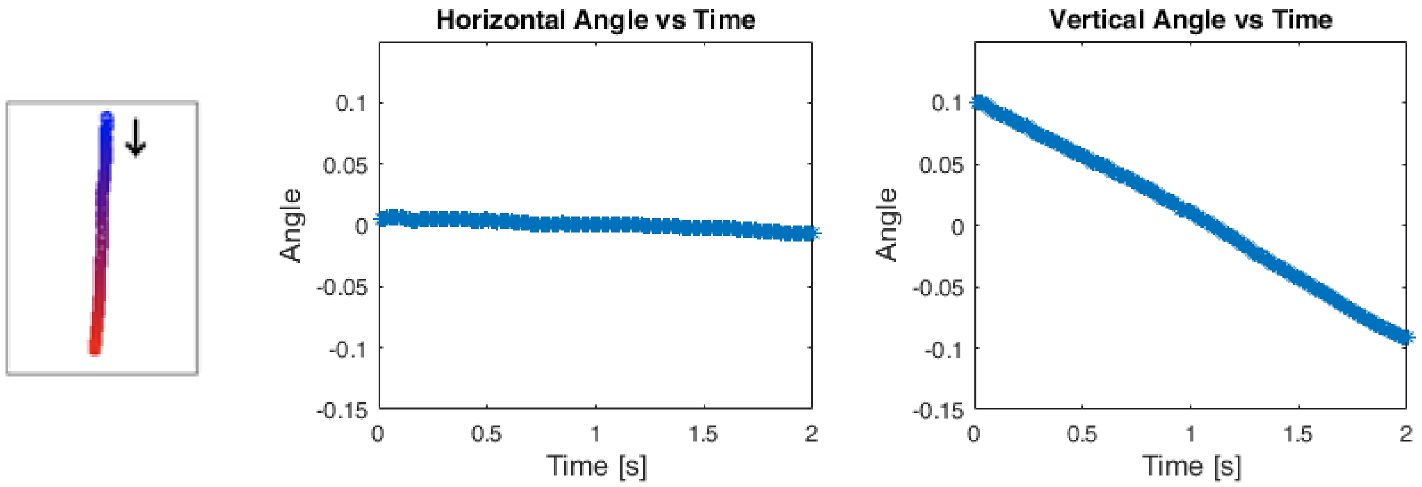
Proposed classifier	Benchmark Classifier
Redundant Dictionary Matching; (RD classifier) ▪ No training procedure;	Neural Network Model Trained by: (NN classifiers) ▪ Train the model with angle data ▪ Train the model with constructed image ▪ MNIST database

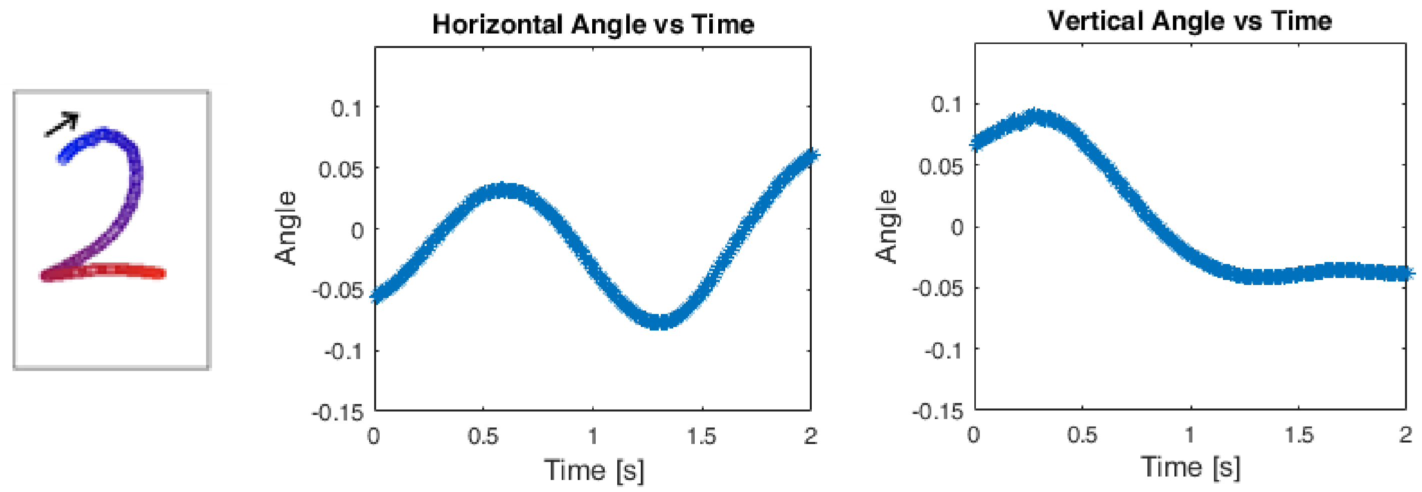
4 classifiers

A Demo of Angle vs. Time



Template Dictionary





Same applies for 3, 4, 5 ~ 9, 0

Horizontal angle vector

+

Vertical angle vector

+

Normalize

=

Template dictionary

Template Dictionary

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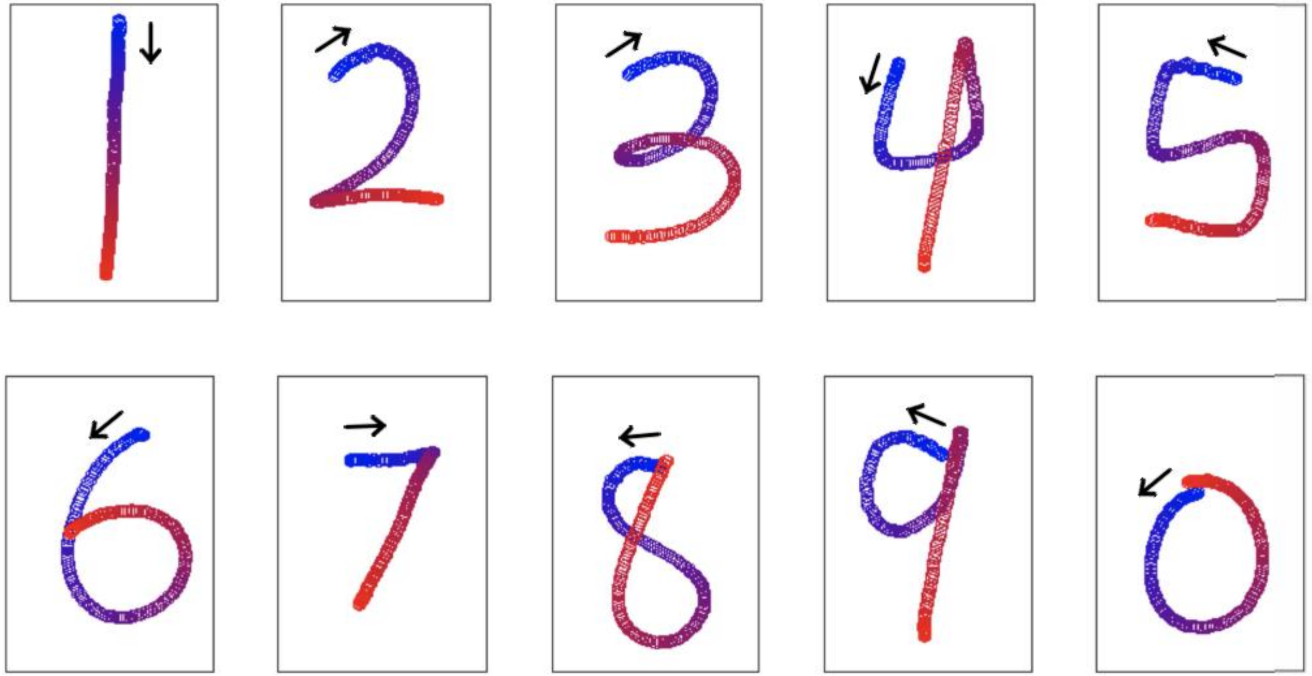
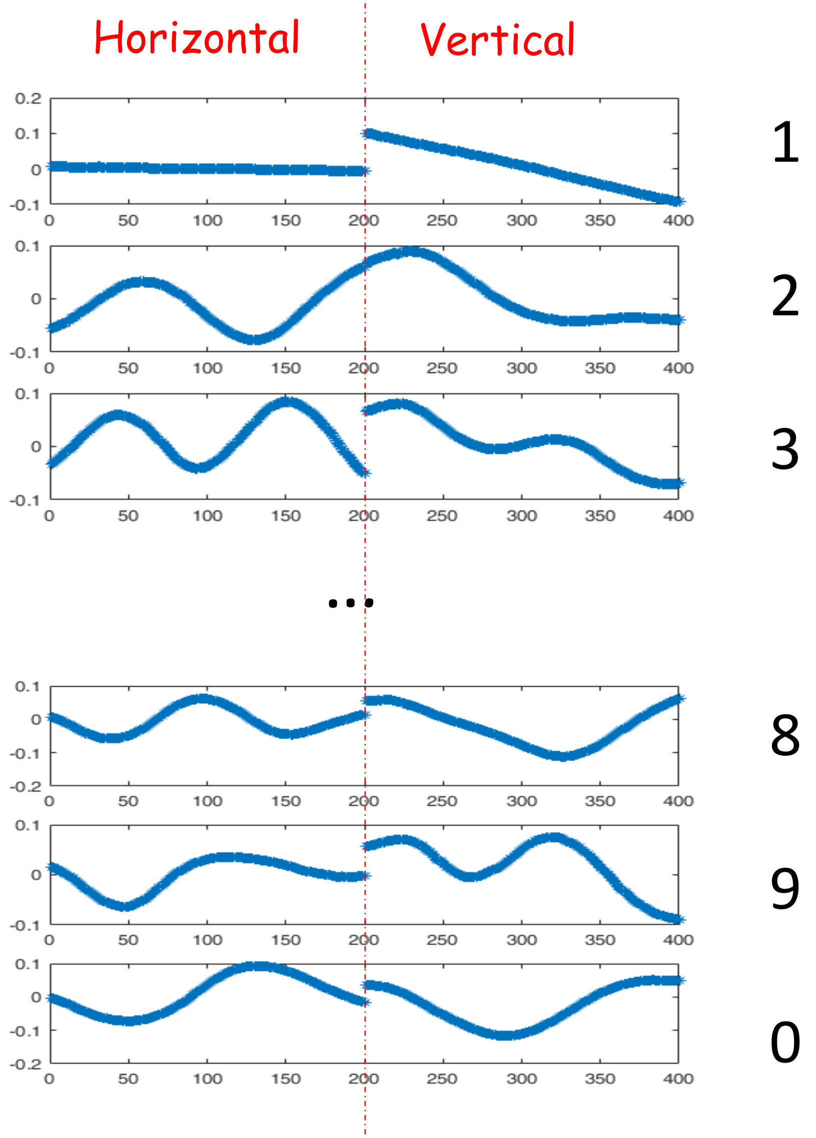
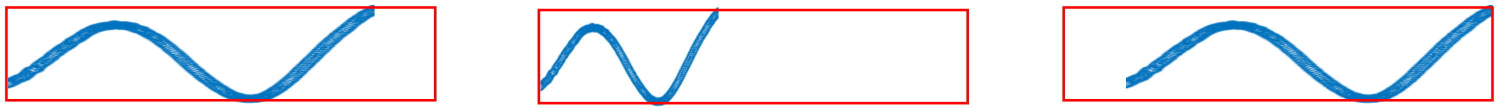


Fig. 4. Templates of the Gestures



Redundant Dictionary

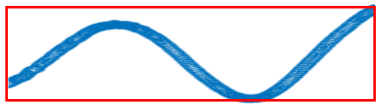
Users have different habits:



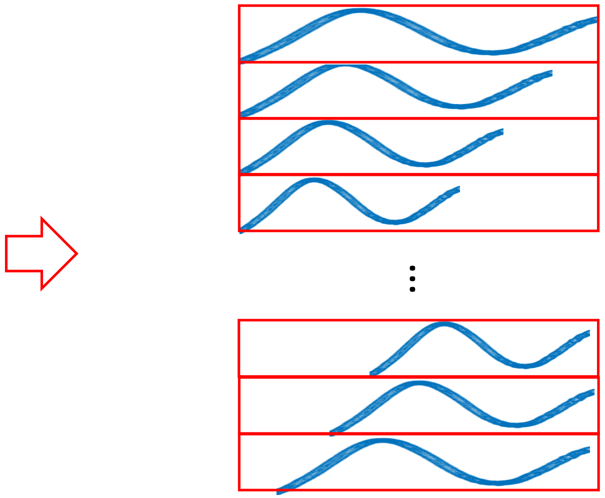
Slow | Faster | Slow delayed

Writing Speed → Shrink

Delay → Shift



Template dictionary



Redundant Dictionary

Redundant Dictionary—One Example

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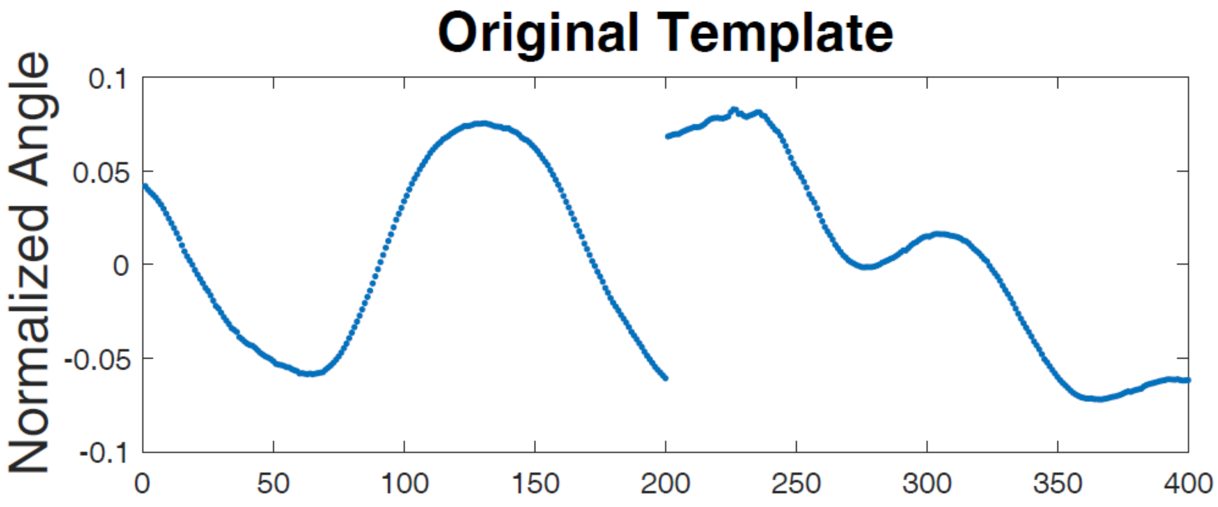

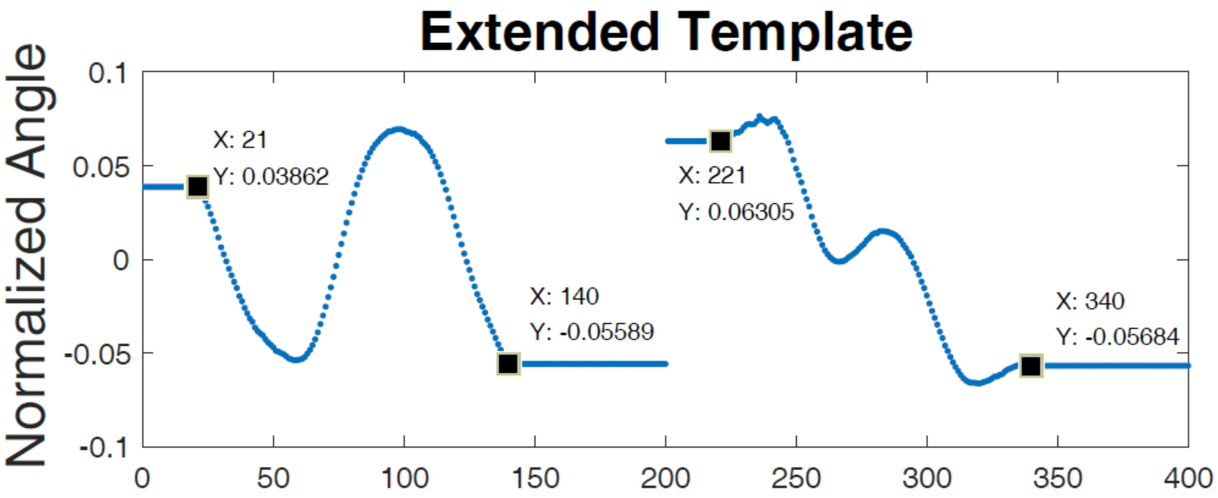

Shrink sample = 20; Shift sample = 20;

200 samples → 1 start point

180 samples → 2 start points

...

100 samples → 6 start points

Extend to 21 templates

Dictionary A_r: 400 by 210

RD Classifier—Classify

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$$r = A_r^T g. \tag{6}$$

r: vector of inner products;

A_r: redundant dictionary matrix;

g: normalized angle information using linear interpolation to fit the size of the dictionary.

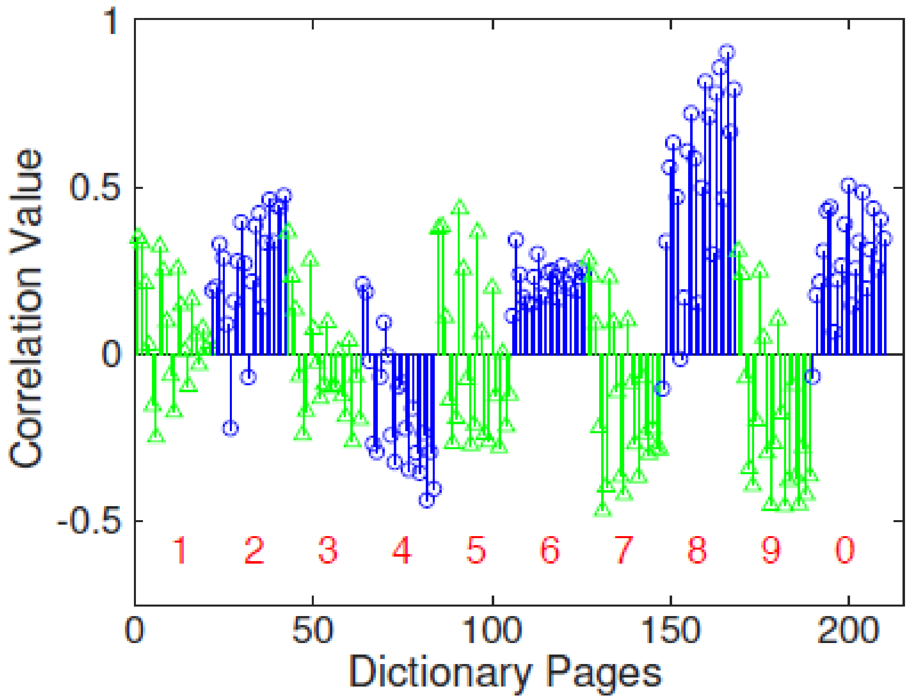

Fig. 9. An Example of Dictionary Matching for Gesture '8'

NN Classifier—Image Constructing

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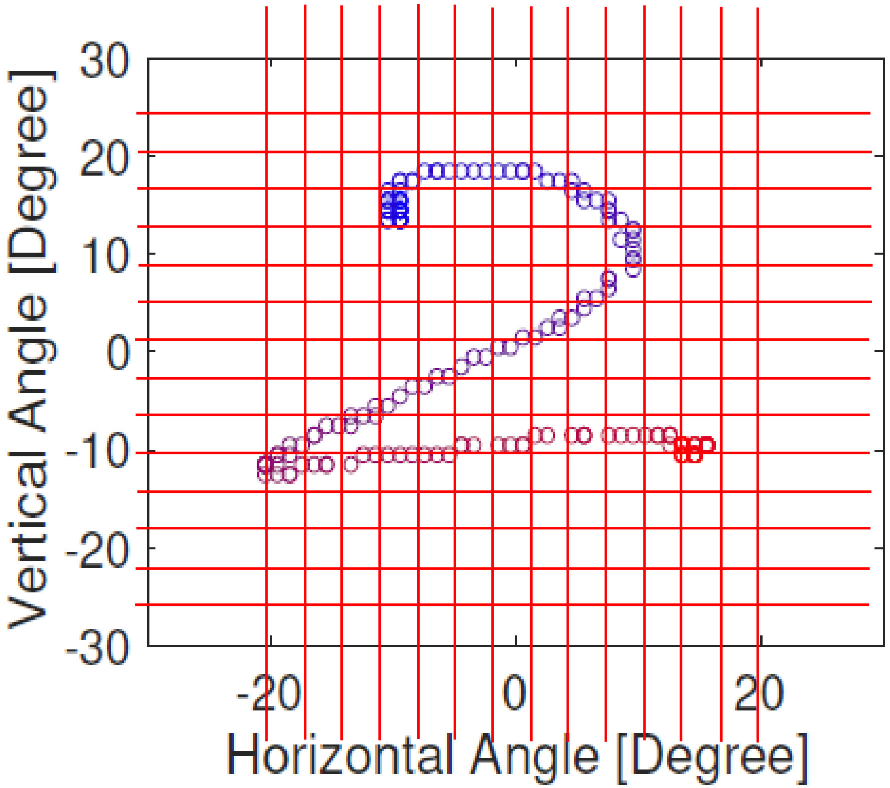
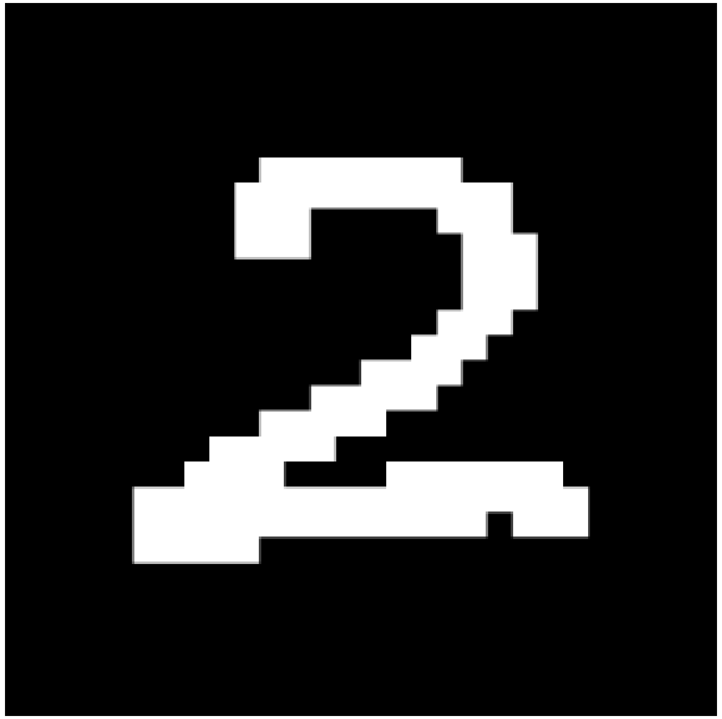
Grid into a 28 by 28 matrix



(a) Gesture '2'



(b) Binarized Image

NN Classifier—training data sets

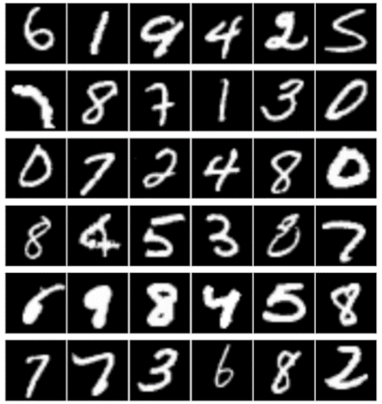
Model: Stacked auto-encoder model from Matlab Neural Network Toolbox.

Training data sets:

1 Train the model with angle data; (1x400 vector)

2 Binarized MNIST database; (28x28 image)

3 Train the model with constructed images; (28x28 image)



MNIST database

System Setup

Handhold ultrasound transmitter

$\downarrow \vec{Z} \rightarrow$

Perform gesture

Receiver array

Computer

Classify the gesture

Receiver Array

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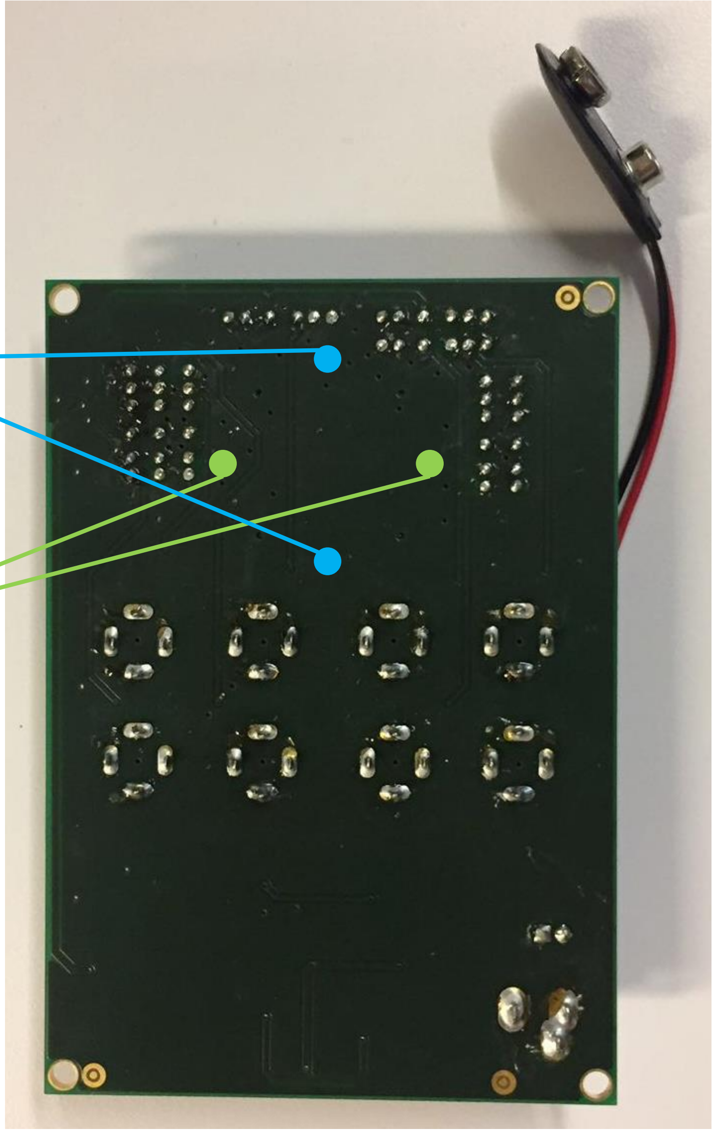
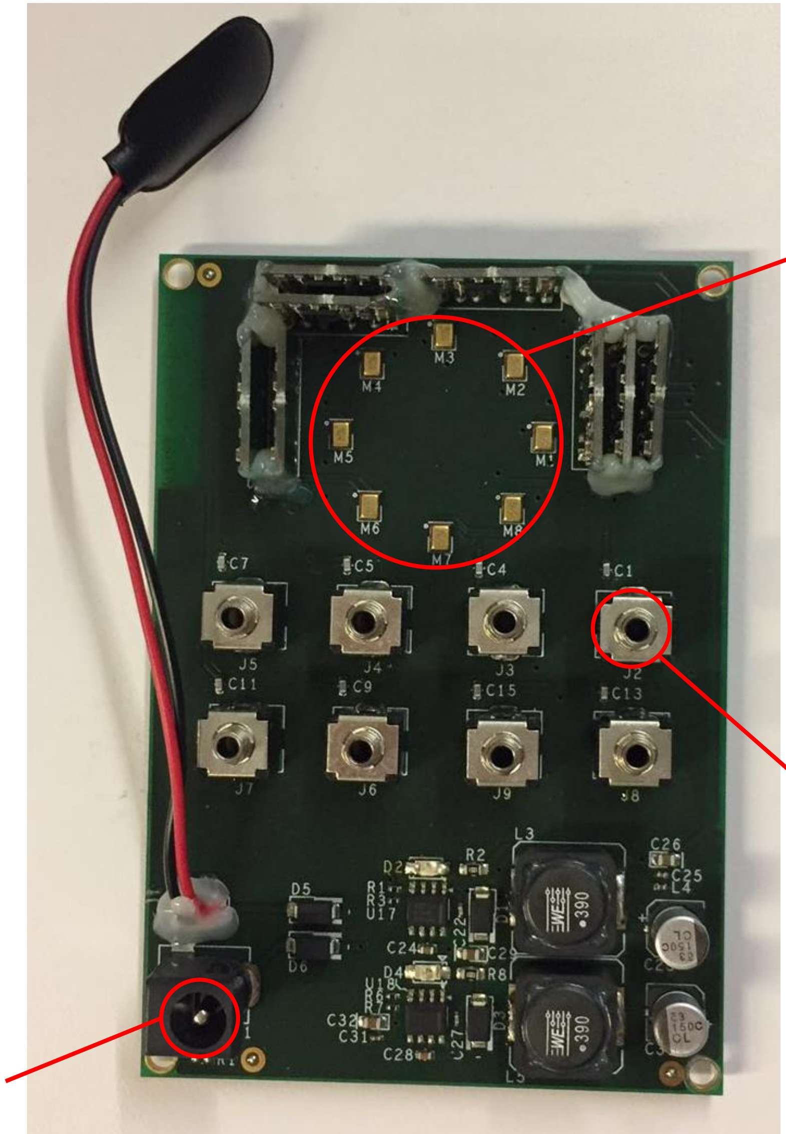
Vertical pair

Horizontal pair





Circular Receiver Array

Connector

Power

Angle Accuracy Test Result

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- Receiver is placed 1 m from the ground;
- Data is collected from 6 points with Vertical angle = 0 (transmitter is the same height with the receiver)

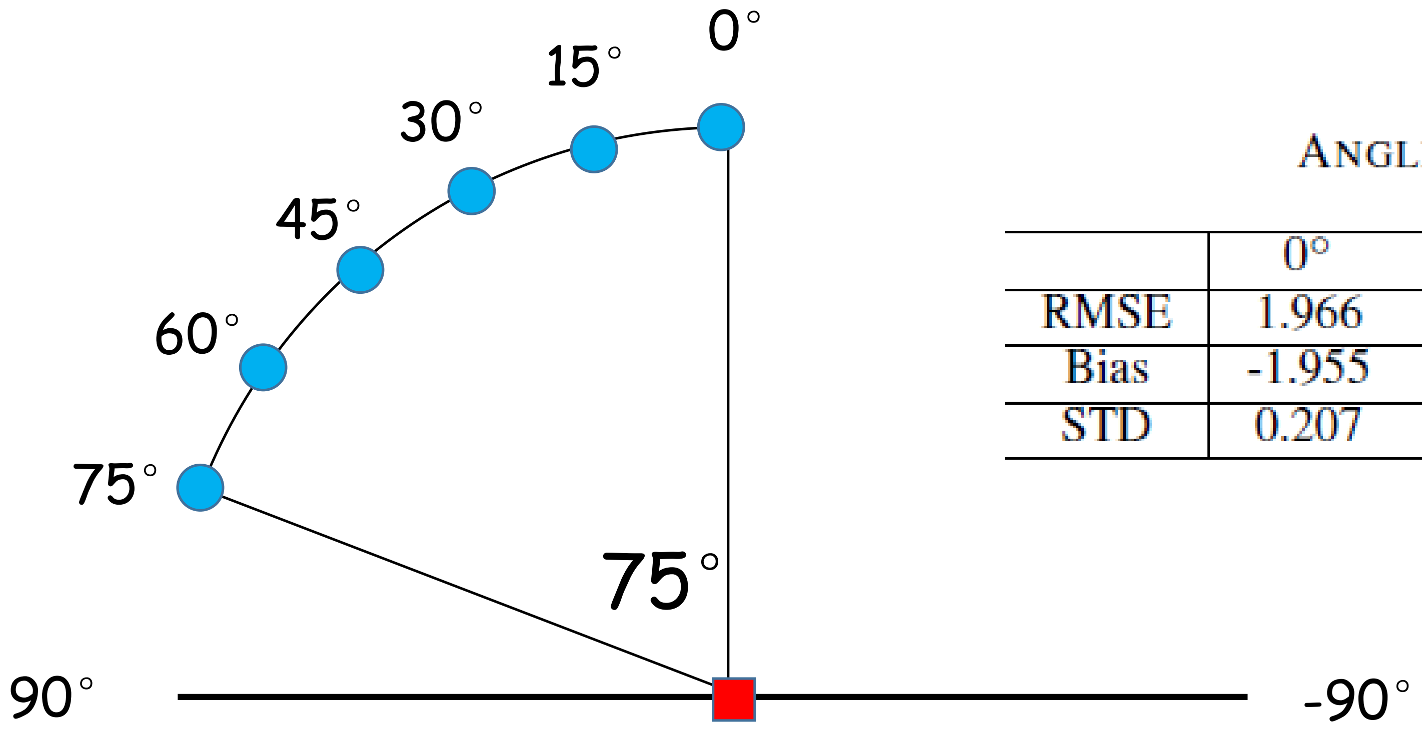

TABLE I
ANGLE OF ARRIVAL ACCURACY TEST

	0°	15°	30°	45°	60°	75°
RMSE	1.966	1.925	1.691	2.520	0.604	1.102
Bias	-1.955	-1.895	-1.620	-2.470	-0.145	0.155
STD	0.207	0.339	0.487	0.500	0.588	1.094

Classifier Performance

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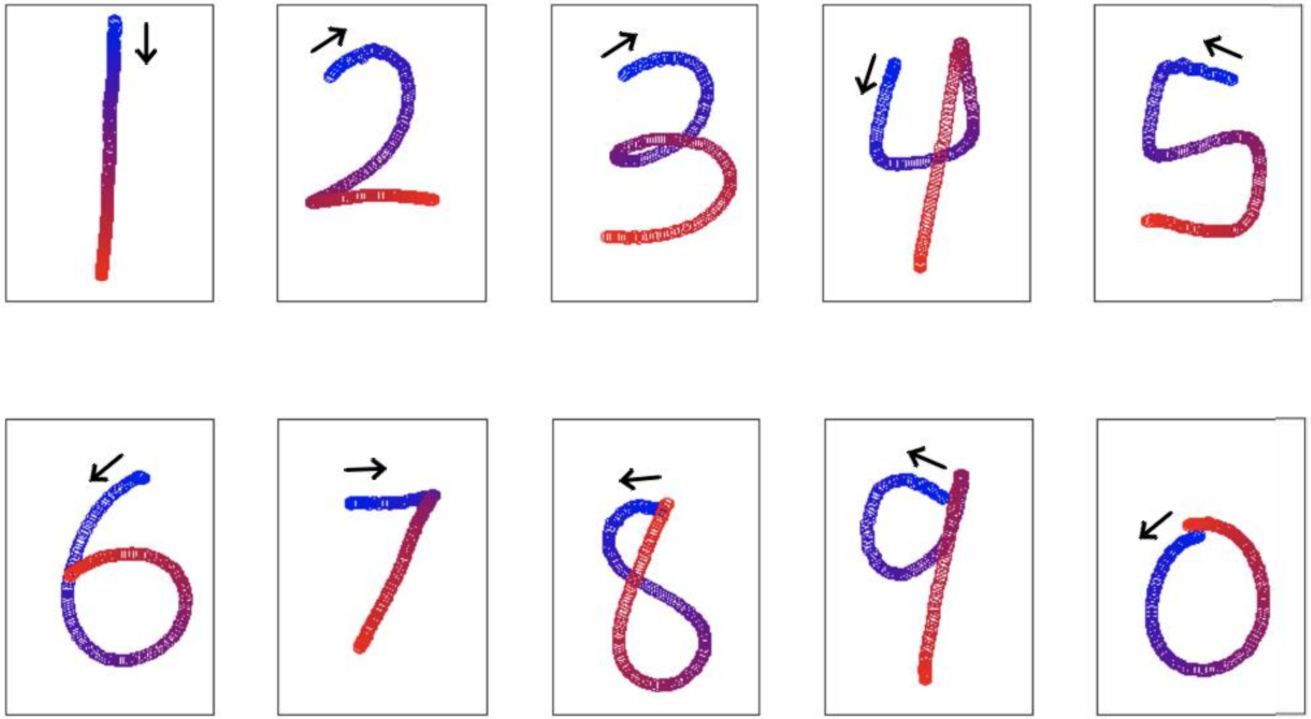

Gesture Templates

Data collection:

10 volunteers

10 gestures

Repeated for 10 times

1000 gesture data set

Classifier Performance

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Classifier	Accuracy
Redundant Dictionary Matching	95.5%
Neural Network Model	
▪ Train the model with angle data	94.4%
▪ MNIST database	66.5%
▪ Train the model with constructed image	91.1%

Result of Dictionary-based Classifier

TABLE II
CONFUSION MATRIX OF DICTIONARY-BASED CLASSIFIER

Actual Gesture	Classified Gestures (95.5% of 1000 gestures)									
	‘1’	‘2’	‘3’	‘4’	‘5’	‘6’	‘7’	‘8’	‘9’	‘0’
‘1’	96						3	1		
‘2’	4	91					5			
‘3’	5	1	91				3			
‘4’				81		5			9	5
‘5’	3				95			1	1	
‘6’						97				3
‘7’	9						91			
‘8’							1	99		
‘9’					1		1		97	1
‘0’						1				99

Summary

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1 A prototype of gesture recognition system;

2 AOA algorithm to obtain 2D angle information from the gesture;

3 Training-free Redundant dictionary classifier;

4 95.5% accuracy.

Current & Future Work

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1 Letter Recognition (√)

2 Hidden Markov Model Classifier (√)

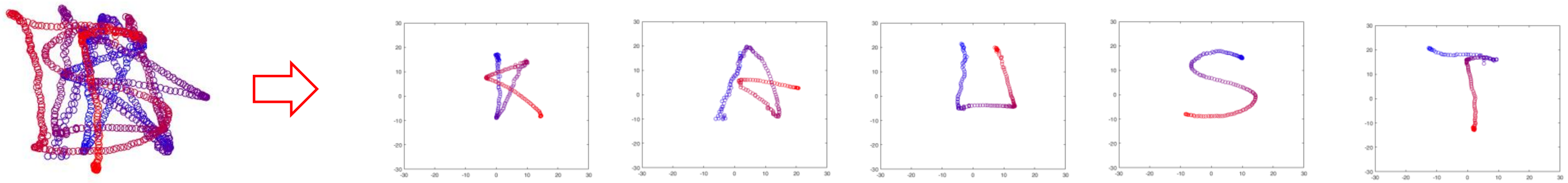
3 Decision Tree (√)

4 Word Recognition

Recent Letter Classification Results

1 With decision tree
- Redundant Dictionary: 96.09%
- Neural network: 95.45%
- Hidden Markov Model: 96.22%

2 Without decision tree
- Redundant Dictionary: 89.39%
- Neural network: 94.29%
- Hidden Markov Model: 95.45%



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Thanks for your time

Speaker: Hui Chen
Email: hui.chen@kaust.edu.sa
Date: 2017-08-25