Humanoid Sensors and Actuators
Institute for Cognitive Systems
Technische Universität München
Prof. Gordon Cheng

Sound-source localization with head movement

1. Motivation

When there is sound, human's brain can automatically use the intensity, spectral to localize the sound source, which makes listening easier and more concentrated. To simulate human's auditory system, localization is the first step. On this basis, the robot can learn to track and implement more complicated tasks. Besides, this project is a good combination of sensors and actuators, which we have learned in this lecture with knowledge about ADC, Timer controller, PWM Signal generator, Servo Motor Control and UART.

2. Overview

The goal is to determine the sound source with two microphones and make the servo motor to rotate to the specific angle. The procedures are as follows:

1. Get sound information with two microphones, get their amplitudes with two ADC.
2. Find the relationship between the amplitudes and source angle.
3. Use this angle as duty cycle to generate a PWM signal.
4. Use PWM signal to control servo motor.

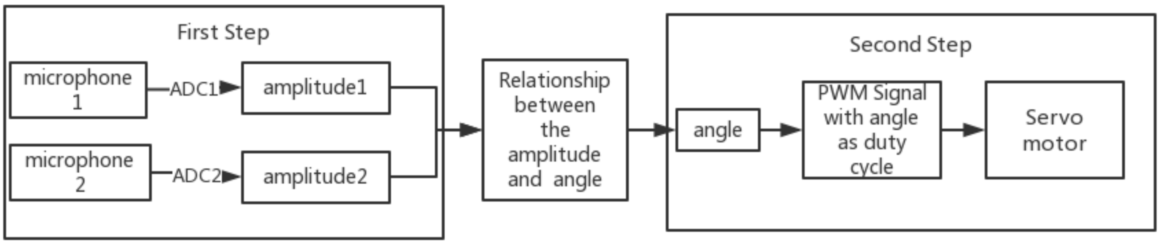

Figure1 Flowchart

In the first step, use ADC to transfer the sound signal to digital signal as the amplitude. Set ADC prescaler as two (the clock frequency of the ADC is half of the CPU frequency), in the free running mode and in 8-bit mode.

In the second step, given the calculated angle, use the angle value as duty cycle. With the comparison of an 8-bit Timer0 and output compare register OCR0, get PWM signal for servo motor control. The frequency of the control signal is 60Hz (16.67ms) and the width of positive pulse controls the rotation angle. The servo has the neutral position at 1.5ms pulse width and the lower and upper pulse width limits within 1ms and 2ms.

Thus, the main problem becomes how to find the relationship between the amplitudes and the source angle. Aim to find the relationship, three experiments will be proposed in this report. The largest challenge for angle determination is to point at the specific angle while as the mean time against the fluctuation of the amplitudes, namely robust as well as accurate.

3. Experiment 1 Intersection of two circles

3.1 Experiment1 theory

Assume two microphones as center of two circles, namely P_0 (x_0, y_0), P_1 (x_1, y_1) below. According to the relationship in the triangular, the sound position P_3 (x_3, y_3) can be calculated as:

$$x_3 = x_2 - \frac{h(y_1 - y_0)}{a + b} \quad y_3 = y_2 - \frac{h(x_1 - x_0)}{a + b}$$

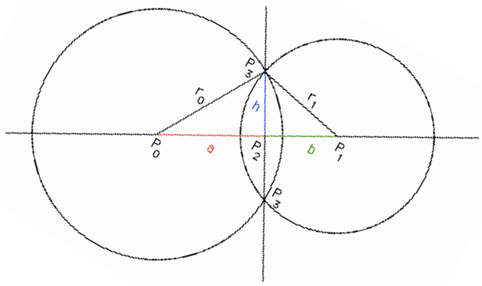

Figure2 Intersection points between two circles on a plane

From above, given two radiuses of these two circles, the sound position can be calculated. The problem now becomes: how to determine the radius (distance to the sound source) according to the amplitudes. If there is sound source, the amplitude obeys the inverse square law:

$$Amplitude = A + \frac{B}{distance^2}$$

The next step is to determine these two parameters A, B. The first experiment is implemented.

3.2 Experiment1 settings

1. Set the sound source as 1000Hz sine wave.

2. Set the distance of two microphones as 15.5cm.

3. Separately for each microphone, measure the amplitude when the distance between microphone and sound source increases every 5cm, from 10cm to 200 cm in total.

4. Since the sound will fluctuate, collect the maximum and minimum value from every 100 ADC value, the amplitude is the subtraction of maximum and minimum. However, the value "100" makes two ADC values not simultaneously, which will be discussed later.

3.3 Experiment1 results

With the two amplitudes from the experiment, using the regression model, parameters $A_1 = 138.32$, $B_1 = -55.95$ for microphone1 and $A_2 = 60.67$, $B_2 = -20.33$ for microphone2 are calculated.

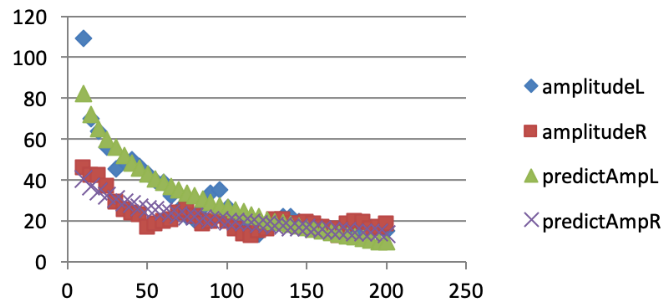

Figure3 Regression model between amplitude and distance

Put this relationship back, the angle with the amplitude of two microphones can be calculated. In the offline verification, it works well. For example, if the amplitude of microphone1(left) is 50 and the amplitude of microphone2 (right) is 45, the calculated angle is 159.15°.

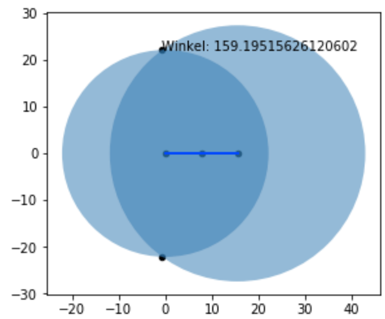

Figure4 Simulation to find sound angle with two amplitude

Then to find the possible sound angle, hundred rules are set up. For example:

if (amp1 == 5 && amp2 == 5) {//Rule1 angle = 126;}

else if (amp1 == 5 && amp2 == 6) {//Rule 2 angle = 92;} and so on.

When applying these rules to the real application, it does not work. Because these rules are extremely strict and theoretical. But in reality, the value of the amplitude will fluctuate a lot.

But additional information is obtained through this experiment. If the distance between two microphones is **30 cm**, there are 1006 possible rules to determine the angle, comparing 886 rules in the case of 15.5 cm. Which means, with the distance of two microphones as 30cm, two amplitudes are more distinguishable.

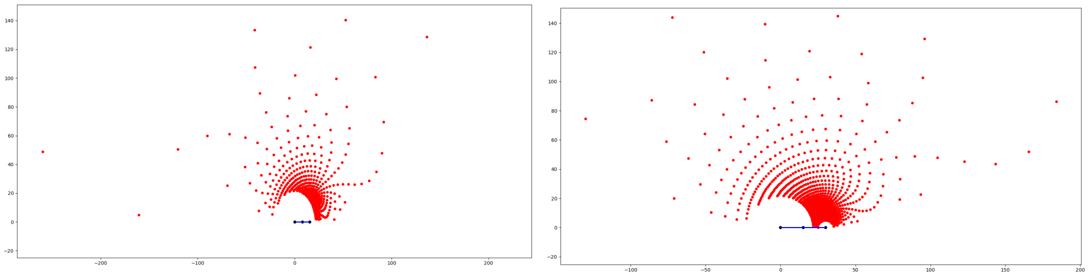

Figure5 Possible angles to be detected under 15.5cm(left) and 30cm(right)

4. Experiment2: Amplitude Ratio according to Interaural Level Difference (ILD)

4.1 Experiment2 theory

Since the first experiment failed, indicating separately analyse each amplitude is insufficient, what if combining two amplitudes together? According to the Duplex Theory, there is a relationship between the amplitude and sound angle, namely Interaural Level Difference:

$$\frac{A_L}{A_R} = 1.0 + K sin\theta^{1}$$

Given a specific angle, two amplitudes can be measured, the only unknown parameter is K. In order to obtain the constant K, the second experiment is set up.

4.2 Experiment2 settings

1. Set the sound source as 1000Hz sine wave.

2. Set the distance of two microphones as 30 cm (with the conclusion in experiment1), set the direction of microphones both face to the front.

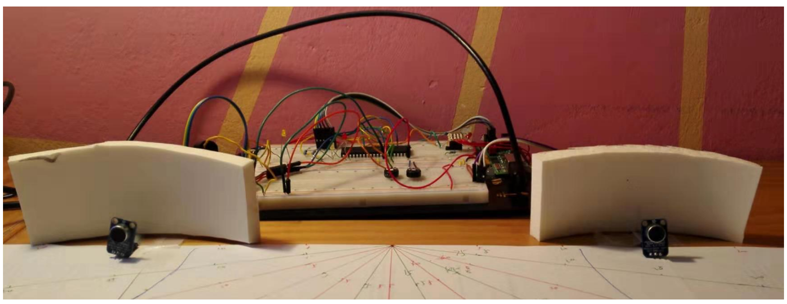

Figure6 Photo of experiment settings

[1] Note the angle mentioned in this experiment refers to the angles between the sound source and the central point, namely 0°… 90° in the right and 0°… 90° in the left.

3. Calibration of two microphones. Adjust their gain as the same value. After calibration, keep following things unchangeable: the location of 2 microphones, the location of 2 isolators, where the sound source coming from, namely the circle of this sound.

4. Set seven angles in each direction, 0°, 15°, 30°, 45°, 60°, 75° and 90°. In each angle, measure two amplitude with the distance of sound source to the central point as 5cm, 10cm, 15cm, 20cm, 25cm, 30cm.

5. Use sponge to reduce the interaction between two microphones. Note that the direction of sponge should correspond to the direction of microphones.

6. Get amplitude by subtracting maximum and minimum value from every 100 ADC value.

7. Separately save the amplitudes in each angle as one adcLog file.

4.3 Experiment2 results

To show the result, one angle, 30° in the left direction, is shown here as the example. The two amplitude and calculated K value corresponding to the ratio of two amplitudes are as below:

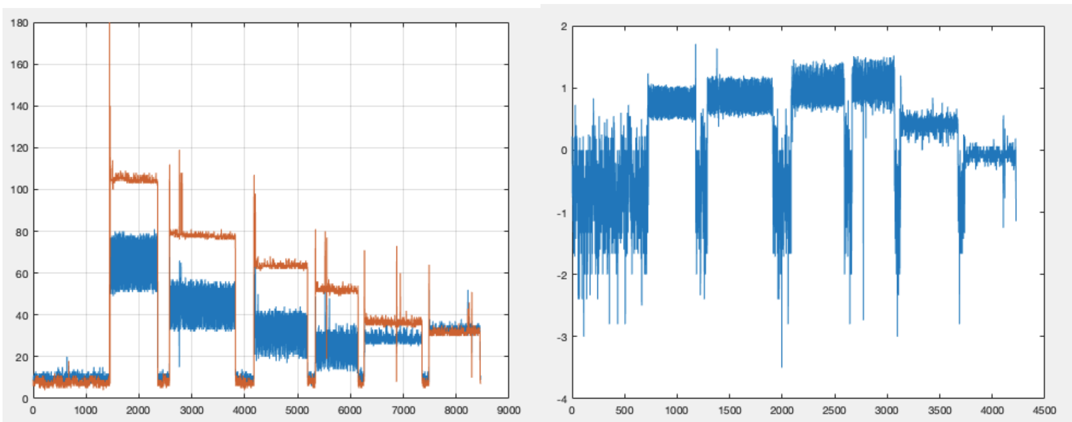

Figure7 Amplitudes(left) and corresponding K(right) under 30° in the left direction

There are 6 blocks in these diagrams, which corresponds to different distance of the sound source to the central point 5cm, 10cm, 15cm, 20cm, 25cm, 30cm. K should be a constant independent from angle and distance. However, here it fluctuates a lot.

4.4 Experiment2 further settings

Change the experiment settings and implement the second experiment further.

1. Change the direction of two microphones, like human ears, face to left and right separately.

2. Change the sound form, from 1000Hz Sine wave to **1000Hz square wave**.

3. Change the distance of the sound source to the central point in small distance 4cm, 7cm, 11cm.

4. Whenever the setting is changed, always recalibrate two microphones.

4.5 Experiment2 results2

Take one angle, 45° in the right direction, as an example, two amplitude and calculated *K* value are as follows.

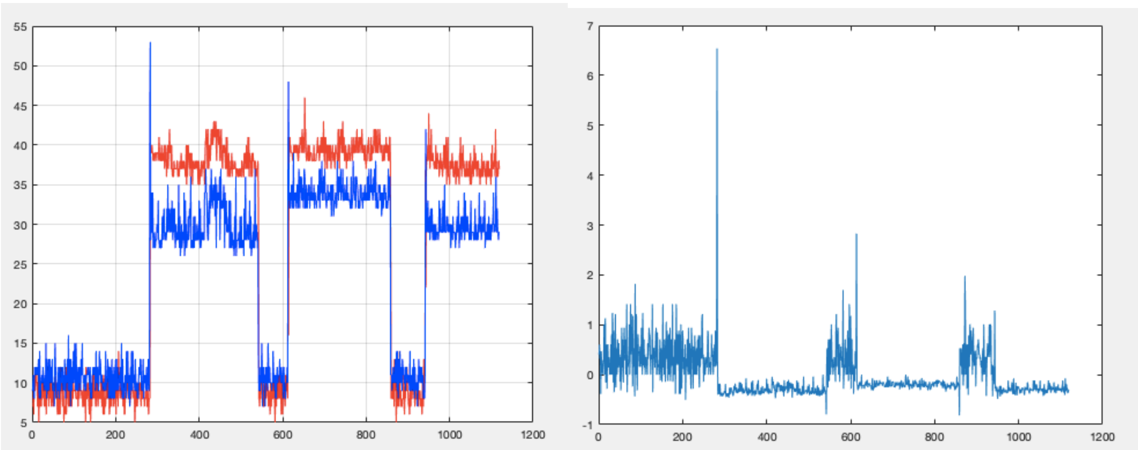

Figure8 Amplitudes(left) and corresponding K(right) under 45° in the right direction

There are 3 blocks in these diagrams, which correspond to three distances of the sound source to the central point. Compared with the diagram under sine wave, the amplitude fluctuates more, but their ratio and corresponding K is more stable. In this experiment, for each angle, the calculated mean value of K under different distances is shown as below.

Table1 mean value of K of each angle under different distances

Angle Distance	15(L)	30(L)	45(L)	60(L)	75(L)	15(R)	30(R)	45(R)	60(R)	75(R)
4cm	-0.41	-0.76	0.01	-0.55	-0.45	-0.15	-0.51	-0.58	-0.24	-0.33
7cm	0.15	-0.24	-0.05	-0.62	-0.70	-0.17	-0.29	-0.39	-0.19	-0.51
11cm	0.31	-	-0.17	-0.51	-0.40	-	-0.25	-	-	-0.38
average	0.15	-0.5	-0.05	-0.45	-0.45	-0.16	-0.29	-0.49	-0.22	-0.38

From this table, the average of K changes a lot, which does not obey that K should be a constant. When implementing this mean value as K to the equation above and predict the sound angle, it cannot predict angles well. What's more, because the collection of data is under very near distances (less than 10cm) to the central point. It does not work in the large distance.

From this experiment, several useful cues come out for the following experiments:

1. Square wave is better to analyse the ratio of two amplitudes compared with sine wave.

2. Collect the data from more far distance.

3. When the distance change, the performance will change a lot. Thus, specifying a specific distance to analyse possibly have better performance.

4. In this experiment, $\frac{A_L}{A_R}$ is a value around one, $sin\theta$ is a value less than one, within small scaling, it requires very high accuracy of the value K, which is nearly impossible in reality, therefore, when analysing the data, amplify the small values as much as possible.

5. Experiment3: combine ratio and difference of amplitude together

5.1 Experiment3 theory

The first experiment is to analyse two amplitudes separately, can be also regarded as the difference of two amplitudes; the second experiment is to analyse ratio of two amplitudes; Since both experiments can't success, what if combining them together? Therefore, here comes the third experiment.

5.2 Experiment3 settings

Through the failure above, some hints are summarized for the setting and measurement.

1. Generate a 2600Hz signal with a buzzer since ILD performs better in high frequency.

2. Set the distance of two microphones as 30 cm, set the direction of microphones in the 45° to the central point, namely half face to the front and half to the side.

3. Calibrate two microphones. Adjust their gain as the same value.

4. Set seven angles between the sound source and the central point in each direction, 0°, 15°, 30°, 45°, 60°, 75° and 90°. In each angle, measure two amplitude with the specific distance range 30-35cm.

5. Use sponge to reduce the interaction between two microphones.

6. To get amplitude by subtracting maximum and minimum value from amount of ADC values. Instead of randomly chosen number 100, a specific value should be chosen to guarantee sampling frequency suitable for signal frequency. The signal time period is $3.846 \cdot 10^{-4}$ s, the sampling time is $10^{-6}/2*13=6.5 \cdot 10^{-6}$s (ADC's prescale is 2 and takes 13 cycles once), with $3.846 \cdot 10^{-4} / 6.5 \cdot 10^{-6} = 59$, which means one period consists of 59 samples. Therefore, set the

value as 59. If two exactly simultaneous amplitudes are not reachable, it is possible to sample them with the same time point of each period, which can minimize this difference.

7. Save the amplitudes under 13 angles as one adcLog file and analyse them parallel.

5.3 Experiment3 results

Two amplitudes, difference of amplitudes, ratio1 and ratio2 under 13 angles are shown in the diagrams above. There are 13 blocks in each diagram above, the sequence from left to right is 90°(left), 75°(left), …, 15°(left), 0°, 15°(right), 30°(right), … 90°(right). Ratio1 is amplitude 1 divide amplitude 2; Ratio 2 is inverse. Two ratios are set for the purpose to amplify the small scaling value, the ratio larger than one is better for analyse.

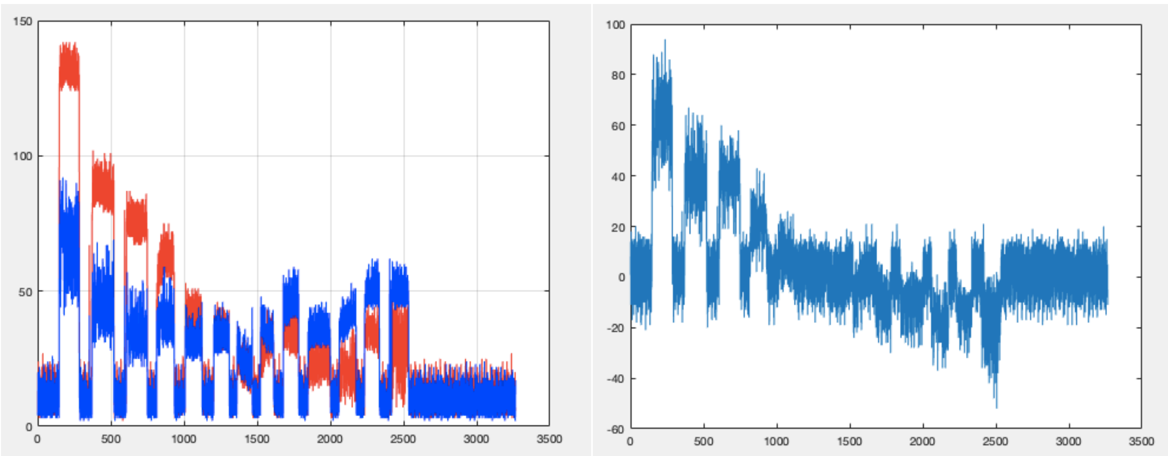

Figure9 Two amplitudes(left) and difference of the amplitude(right) under each angle

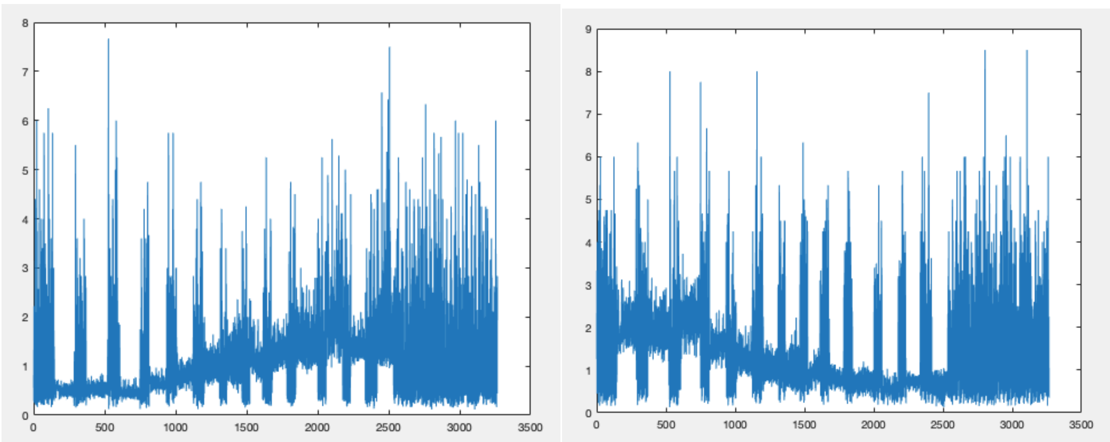

Figure10 Ratio1 (left) and Ratio2 (right) under each angle

From the inspiration of two experiments above, to find the specific rule for a certain angle, compare the difference, ratio and amplitude together to determine angle.

For example, from the amplitude we can know if there is the sound. The rule can be set as, if amplitude1 and amplitude 2 both larger than 25, there is sound, get ready to move.

For the easily determined angle, such as 90° (left), set the rule: if amplitude 1 larger than 120, point to this angle. However, after repeating experiments for several times, the value fluctuates even if they have the same settings. Therefore, it is reasonable to use the relative value (ratio or difference) instead of the absolute value (single amplitude). For example, use following rule to specify 90° (left): if(amp2>50 && ratio2>2).

For more complicated angle, the amplitudes, difference and ratios can be combined together. For instance, how to distinguish 15° (left) and 15° (right)? Their amplitudes are similar, and the ratios are also similar, in this case, firstly set one rule, then repeat the experiments several times to verify this rule until it can predict the angle correctly in the next experiment. What's more, because the rules for determining angles are parallel, so the rules of each angle will also affect others. In this case, sufficient experiments should be implemented to increase the accuracy. At last, the rules for 15° (left) and 15° (right) are as follows.

if (amp2<40 && ratio2<1.2 && ratio<1.2 && amp1>30), point at 15° (right).

if (diff2>6 && diff2<15 && ratio2<1.2 && ratio<1.2), point at 15° (left).

In addition, when using the angle value to control the servo motor, the motor will act wrongly due to some extreme value. To avoid this case, some threshold should be set up, such as, only if a certain angle is predicted for three times, the servo motor will point to this direction. Through these experiment, the prediction of angles increases accuracy, which is shown in the demo.

6. Experiment4 humanoid simulation

In the case of human's auditory system, when the head moves, two ears also move. To simulate this case, the next experiment is to put the microphones and servo motor on one board. Therefore, when the servo motor moves, two microphones also move correspondingly, so the testing environment is not exactly same as the training environments. From testing results (shown in the demo), in the easily determined angle, such like 0° (right) or 30° (left), the angel can still be predicted, and the whole board will move to the specific angle which controlled by the servo motor. However, for these complicated angles, such as 15° (right), it can't move accurately. The reason is that the sponges also move with the microphone, which means the absorbing method changed, which leads to two unknown relationship of the amplitudes. For coarse estimation, the angle prediction can still work, but for precise estimation, it loses audio information. Thus, to apply this model in a humanoid way, the anatomy of human ears should be considered additionally.

7. Conclusion

7.1 For experiment settings

1. For the sound source choice:

- When using the amplitudes to analyze the angle, high frequency wave has better performance.
- Square wave can get more stable ratio of two amplitudes compared with the sine wave, which is suitable for angle prediction.

2. For the location of two microphones and sound source:

- Set 30 cm as the distance of two microphones is good for distinguishing two amplitudes.
- Set the sound source 30-35cm far away to the central point.

3. Fit the sampling frequency and the signal frequency when sampling the amplitude.

7.2 For data analysis

1. Evaluate amplitude of different angles parallel instead of separately, it is easier to find the underlying relationship and distinguish angles.

2. To against value fluctuation in the reality, the value can be handled in following way:

- Don't use mean value, but the extreme value. In the second experiment, I used mean value of get K, but in the reality, since it will fluctuate, the extreme case must be considered.
- Don't use a certain value to set the angle, but with the range of value.
- Try not to use absolute value(amplitude), but use the relevant value (difference, or ratio)
- Amplify small scaling values.

7.3 For humanoid simulation

Consider the anatomy of human ears when applying in a humanoid way.