Enabling Secure Voice Input on Augmented Reality Headsets using Internal Body Voice

Abstract—**Voice-based input is usually used as the primary input method for augmented reality (AR) headsets due to immersive AR experience and good recognition performance. However, recent researches have shown that an attacker can inject inaudible voice commands to the devices that lack voice verification. Even if we secure voice input with voice verification techniques, an attacker can easily steal the victim's voice using low-cast handy recorders and replay it to voice-based applications. To defend against voice-spoofing attacks, AR headsets should be able to determine whether the voice is from the person who is using the AR headsets. Existing voice-spoofing defense systems are designed for smartphone platforms. Due to the special locations of microphones and loudspeakers on AR headsets, existing solutions are hard to be implemented on AR headsets. To address this challenge, in this paper, we propose a voice-spoofing defense system for AR headsets by leveraging both the internal body propagation and the air propagation of human voices. Experimental results show that our system can successfully accept normal users with average accuracy of 97% and defend against two types of attacks with average accuracy of at least 98%.**

Index Terms—**AR headsets, voice spoofing attack, liveness detection.**

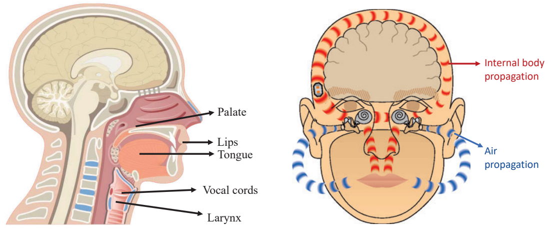
I. Introduction

Augmented reality (AR) applications that overlay a user's perception of the real world with digitally generated information are on the cusp of commercial viability. To provide better user experience, AR experiences are primarily delivered to AR users via wearable glass devices and head-mounted devices. For example, Microsoft, Google Vuzix, and other companies have been working on bringing AR to us in the eyeglass form. Moreover, different from traditional human-computer interactions, most existing interactivity technologies (e.g. typing, tapping, clicking, and swiping) have become irrelevant and obsolete in the AR world. Because of the real-world interaction of AR experience, the input methods for AR headsets should fit what a human can understand. Therefore, most AR headsets adopt voice, eye gaze, and gestures as input methods. Among these three input methods, voice-based input is usually used as the primary input method for three reasons: 1) Voice is the primary way to deliver information in daily life, so voice-based input can provide immersive AR experience; 2) Many low-cost AR devices do not have capabilities to track eye gaze and recognize gestures; 3) Most gesture and gaze interfaces have problems with responsiveness and accuracy.

However, voice-based input suffers from various voice spoofing attacks. Recent researches [7], [24], [28] have shown that an attacker can inject inaudible voice commands to the devices that lack voice verification. Moreover, unlike other human biometrics, the human voice is often exposed to the public in many different scenarios, e.g., people making a presentation in public. Even if we secure devices with voice verification techniques, an attacker can easily steal the victim's voice using low-cast handy recorders and attack voice-based applications with the help of state-of-the-art voice synthesis/conversion software. Several security issues are, therefore, caused by the leakage of people's voices and pose a severe threat to voice-based applications [13], [21], [27]. For instance, with a replay device, an adversary could impersonate the victim to spoof the Google Trusted Voice once they acquire enough victim's voice samples. Since voice is considered as unique biometrics of a person, these voice-spoofing attacks would result in severe consequences harmful to victim's safety, reputation, and property.

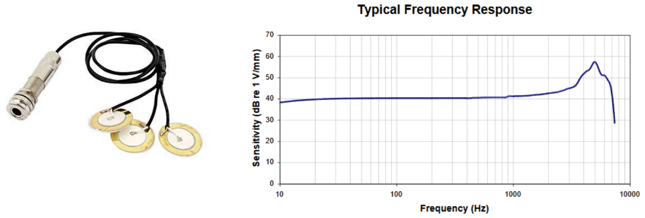
To defend against voice-spoofing attacks, the voice-based systems need to determine whether the voice is from the person who is using the AR headsets. To achieve this goal, traditional systems primarily use two solutions: 1) Check the channel noises introduced by recording and the replay devices (loudspeakers); 2) Analyze the reverberation of replaying far-field recordings. However, these solutions have high false acceptance rates of up to 17%, which makes them unsuitable to be used for commercial systems. Recently, many liveness detection systems are proposed to fight against voice-spoofing attacks by studying the differences between the human vocal system and loudspeakers using phoneme location [30], articulatory gestures [29], magnetic fields of loudspeakers [9], and throat voice [19]. However, all of them are designed for smartphones. Considering the special locations of microphones and loudspeakers on AR devices, current liveness detection solutions cannot be implemented on AR headsets. For example, the approach proposed in [29] can fight replay attack by reusing a pair of microphone and loudspeaker as a Doppler radar. However, this system requires that both the loudspeaker and the microphone should be in front of the user's mouth during the speech, which is hard to be ensured on AR headsets.

Considering the limitations of current solutions, we propose a voice-spoofing defense system for AR headsets by leveraging the internal body propagation of human voices. Our system determines whether the voice is from the person who is using the AR headsets by leveraging: 1) Both the internal body propagation and the air propagation of human voices; 2) An tiny and low-cost contact microphone to collected internal body voice. First, human voices propagate through both the air and the internal body (skull). If two voices are from the same person, they should share common features in the



(a) The human vocal system (b) Two propagation paths

Fig. 1. Human vocal system and two propagation paths of the voice



(a) Contact microphone (b) Frequency response of contact microphone [1]

Fig. 2. Contact microphone and its frequency response

frequency bands of human voices. Second, by attaching a contact microphone on the user's head, we are able to collect the voice propagating only through the internal body. The small contact microphone can be easily integrated into existing AR headsets. To achieve our goal, we solve two challenges in the design of our system. First, the signal-to-noise ratio (SNR) of the voice propagates through the internal body is still low, which makes it hard to extract voice features from the raw time-domain signals. To address this issue, we transform the signal from the time domain to the time-frequency domain and leverage spectrogram enhancement techniques to extract the voice from raw signals. The second challenge is to measure the correlation and similarity between the internal body voice and the air voice of the user. In order to robustly measure the correlation and similarity between the two voices, we match high-energy blocks that exist in both spectrograms of two voices.

We summarize our contributions as follows:

- We show it is feasible to capture the internal body propagation of human voices using a low-cost contact microphone. We also present an approach to extract voice features from noisy internal body voice.
- We propose a robust and low-cost solution for defending against voice-spoofing attacks on AR headsets with high accuracy. To our best knowledge, our system is the first to protect the voice input for AR headsets.
- We develop a prototype and conduct comprehensive evaluations. Experimental results show that our system can successfully defend against obstruction and replay attacks with an accuracy of at least 98%.

II. Preliminary

A. Human voice production and propagation

As shown in Fig. 1(a), the mechanism for producing the human voice can generally be subdivided into three parts: the lungs, the vocal cords, and the articulators (e.g. lips and tongue). The lung first produces adequate airflow and air pressure to vibrate vocal cords. The vocal cords vibrate and chop up the airflow from the lungs into audible pulses that form the laryngeal sound source. Then, the length and tension of the vocal cords are adjusted to produce 'fine-tune' pitch and tone. The articulators consisting of tongue, palate, cheek, lips further filter the sound generated from the larynx to strengthen it or weaken it. After the voices are produced by the human vocal system, they mainly propagate through two media, as shown in Fig. 1(b). First, the voice propagates via the air and reaches the microphone, which is common for the use case of current voice input. Besides propagating through the air, the voice can also propagate through the speaker's internal body, and that is why a person's voice sounds different to them when it is recorded and played back. Although the tone of the voice received through the internal body is lower than that of the voice received through the air due to the special propagation medium, two voices should have a strong correlation and a lot of information shared. For the attacker who wants to issue a fake voice command obstruct the victim's experience, the attacker's voice reaches the AR device only through the air. Therefore, the internal body voice of the victim should not have much-shared information with the air voice.

Strong attackers can also use high-quality loudspeakers and recorders to break voice-based authentication. The loudspeakers usually use an electromagnet to translate an electrical signal into an audible sound. The electromagnet is a metal coil that creates a magnetic field when there is an electric current flow through it. When electrical pulses pass through the coil of the electromagnet, the direction of the magnetic field is frequently changed. Also, there is a permanent magnet fixed firmly into the loudspeaker. With rapidly changing magnetic field, the coil is attracted to and repelled from the permanent magnet. As a result, the cone attached on the coil will vibrate back and forth, pumping sound waves into the surrounding air and the smartphone's speaker. Since the replay attacker can only record and replay the air voice of the victim, there is no internal body voice during the replay process. Moreover, since the internal body voice of a person is different from those of others even for the same word, a stronger replay attacker cannot impersonate the victim's internal body voice by wearing the AR headset and saying the same words.

B. Piezo contact microphone

As shown in Fig. 2(a), contact microphone is a form of microphone that senses audio vibrations through contact with solid objects. Unlike normal air microphones, contact microphones are almost completely insensitive to air vibrations but transduce only structure-borne sound. By attaching a contact microphone near the speaker's temple, we are able to collect the voice that propagates mainly through the body of the speaker. In addition, contact microphones have a wide frequency response, as shown in Fig. 2(b). Since the voiced speech of a typical adult will have a fundamental frequency for up to 255Hz [3], the contact microphones have enough capability to capture the internal body voice.

C. Attack model

In our attack models, a malicious user aims to either spoof the voice verification system on the AR headset or obstruct the normal use of voice-based input. The capability of the attacker is limited in the sense of:

Obstruction attack for voice commands. In obstruction attack, a malicious user who can show up closely around the normal user aims to issue a voice command with high volume. For example, the malicious user can issue a ”remove” voice command to clear the victim’s virtual objects. The malicious user can also issue a voice command to display redundant information in the field of vision of the normal user, which poses threats if the normal user needs clear sight (e.g. the normal user is driving). During the attack, we assume that the victim is not using the voice input, otherwise, the victim’s voice is expected to overshadows that of the attacker.

Replay attack for voice-based authentication. In this type of attack, we assume that an attacker can physically access the victim’s headset in the case of not being noticed. Moreover, the attacker can record or morph the victim’s voice and replay it to voice-based authentication system using loudspeakers. To achieve better attack performance, we assume that the attack can produce the corresponding internal body voice by shadowing the replayed voice of the victim.

D. Use case

In order to successfully defend AR users against two types of attacks, our system requires users to attach a contact microphone around the temple. Since the AR users need to wear the AR headset, this condition can be easily satisfied by integrating the contact microphone into the frame of the AR headset. We leverage the contact microphone to capture the internal body voice and use the existing normal microphone on current AR devices to collect the air voice. The distance between the normal microphone and the user’s mouth is about 10 centimeters. Since the distance is pretty short, the time delay between two audio signals is less than 13 samples when the sampling rate is 44,100 samples per second. While speaking, the user can be in any stationary posture, like sitting and standing.

E. Feasibility study and challenges

In order to defend against two attacks we consider, we need to fully leverage the relationship between voices through the air and the skull. Fig. 3 shows the spectrograms of two voices when the user says “Five”. We can observe two facts: 1) There exists a strong correlation between two voices on both the time and frequency domains. If a normal user interacts with the headset using voice, we should observe a voice through the internal body is produced at the same time. 2) The voice that propagates through the internal body only reserves partial low-frequency features (200 Hz to 2000 Hz). If we can see high-energy blocks in the spectrogram of internal body voice, we should see high-energy blocks at the same location in the spectrogram of the air voice. These observations illustrate that it is feasible to defend against two attacks by measuring the correlation and similarity of two voices.

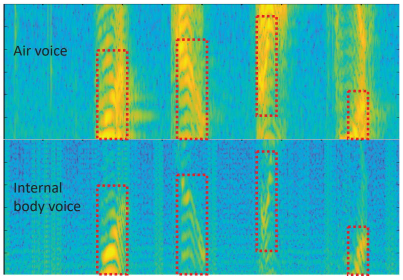


Fig. 3. The spectrograms of voices through air and internal body

To achieve our goal, we solve two challenges in the design of our system. First, even with amplifier, the signal-to-noise ratio (SNR) of the voice that propagates through the internal body is still low, which makes it hard to extract voice features from the raw time-domain signals. To address this issue, we transform the signal from the time domain to the time-frequency domain and leverage spectrogram enhancement techniques to extract the features of two voices from their raw signals.

The second challenge is to measure the correlation and the similarity between the internal body voice and the air voice. This is difficult because both voices have different capabilities for capturing users’ voices. More specifically, the internal body voice only contains partial low-frequency features, but it is nonsensitive to environmental noise. The mouth voice reserves much more features, but it is easy to be influenced by environmental noise. In order to robustly measure the correlation between two voices, we first convert the two voices to spectrograms on the time-frequency domain of three dimensions: time, frequency, and energy. The correlation and the similarity of two voices are measured by matching high-energy blocks that exist in both spectrograms.

III. System design

A. System overview

The key idea underlying our system is to fully leverage two propagation paths of the human voices. When the AR user says a voice command, the normal microphone will capture the user’s voice that propagates through the air, and the contact microphone on user’s head can record the voice that only propagates through the user’s body. By comparing the information in two voices, our system can determine whether the voice is from the normal user or from two types of attackers. For a new AR user, there are two stages to use the system. In the training stage, the new user is asked to say a few words using our system. These training instances are used to quickly build a classifier. After the training stage, the system is ready to be used. In the testing stage, our system will check whether the command is from the normal user who is using the AR headset using the trained classifier. If the voice

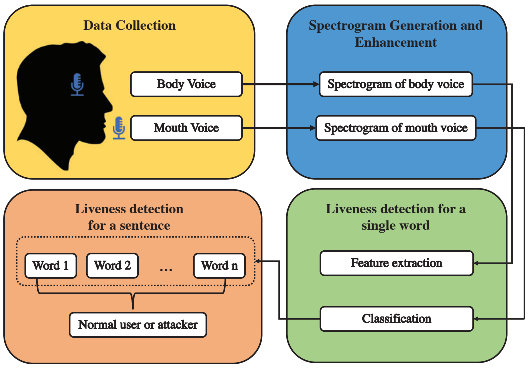

Data Collection
Body Voice
Mouth Voice
Spectrogram Generation and Enhancement
Spectrogram of body voice
Spectrogram of mouth voice
Liveness detection for a sentence
Word 1
Word 2
...
Word n
Normal user or attacker
Liveness detection for a single word
Feature extraction
Classification

Fig. 4. System pipeline

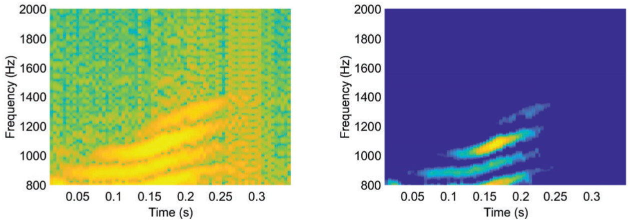
is from the normal user, the user can interact with AR headset normally. Otherwise, the voice command will not be parsed to the AR headset for futher verification.

The pipeline of data collection and processing is shown in Fig. 4. After collecting the user's voices at two channels, we first segment the voice for each word to remove the internal between neighboring words. For the voice signals of each pair of words, we transform the signals from the time domain to the time-frequency domain. Since both raw voice signals contain background noise, we further leverage spectrogram enhancement techniques to remove the noise and extract the information of the voices. Then, we measure the correlation between two enhanced spectrograms of each pair of words. If the correlation exceeds a threshold, the pair of signals is further checked for the second round. In the second round, we measure the similarity of two spectrograms. Here the similarity is defined as the proportions of shared information between two voices. If the proportions of shared information fit the trained classifier, the word is regarded to be from the normal user. To tolerate wrong classification results, the final detection result of a sentence (voice command) is determined by a voting procedure of all words in it. Only if the number of votes that represent the voices are from the normal user exceeds the voting threshold, the voice source is regarded as the normal user.

B. Word segmentation and spectrogram generation

Each audio signal includes two parts: the voice and background noise. The voice contain abundant features of the user's voice, while the noise part only records the acoustic noise in the background. In our system, we only focus on the user's voice in order to reduce the influence of the acoustic noise in the background. Since the voice recorded by the normal microphone has much more features of the user's air voice, we segment each audio sample into different words by performing HMM-based word segmentation techniques [18] on the audio sample recorded by the normal microphone.

Also, we need to find features to measure the relationship and differences between two voices collected from two microphones to distinguish whether the voice is from a normal user. In order to capture features on time-frequency domain,



(a) Raw internal body voice (b) Enhenced spectrogram

Fig. 5. Spectrogram enhancement

we perform STFT on each word and each audio sample with a window size of about 22 ms based on:

$$X(\tau,\omega)=\sum_{n=t_s}^{n=t_e} x[n]w[n-\tau]e^{-j\omega n} \tag{1}$$

where τ is the time axis, ω is the frequency axis, $x[n]$ is the an audio signal in the time range $(t_s, t_{})$, $w[n]$ is the window, and $X(\tau,\omega)$ is a complex function representing the phase and magnitude of the signal over time and frequency. Then, for each time frame, the spectrogram of the complex function $X(\tau,\omega)$ is computed based on:

$$E[f,t]=|X(\tau,\omega)|^2 \tag{2}$$

where $E[f,t]$ is the power of f^{th} frequency band and t^{th} time frame. f and t are positive integers with range $1\le f\le M$ and $1\le t\le N$.

C. Spectrogram enhancement

In real usage scenarios, the contact microphone cannot touch the skull directly, which leads to low SNR of recorded internal body voice even with an amplifier. Also, the air voice is also influenced by background noise. To extract features from both voices, we leverage spectrogram enhancement techniques to extract high-energy clusters that are only produced by the user's voice on the generated spectrograms. After obtaining the spectrogram of each word, we first apply frequency domain denoising method by subtracting the noise floor (non-voice part) from the spectrogram. Since the microphone of the AR headset is close to the user's mouth, most power should distribute on the voice part as shown in Fig. 5(a). Therefore, the noise floor is set to 80% of the power in the spectrogram of each word. If the resulting magnitude becomes negative after subtraction, we set it to zero. Second, since the internal body voice collected from contact microphone contains strong noise under 800 Hz, we only reserve the spectrograms from 800 Hz to 2000 Hz for the following analysis. As shown in Fig. 5, most of the noise are removed from the spectrogram, and only the information of the voice are reserved.

D. Feature extraction and classification

Since two voices are generated from the same vocal system at the same time, we should be able to observe strong correlations between them for a normal user. Ideally, the subtraction of two spectrograms should be zero. In our system, we measure the correlation between two spectrograms instead of directly calculating the differences between them

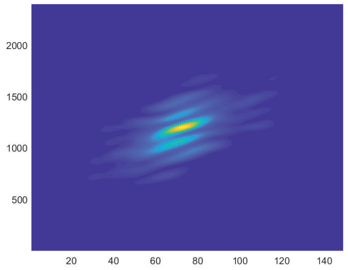
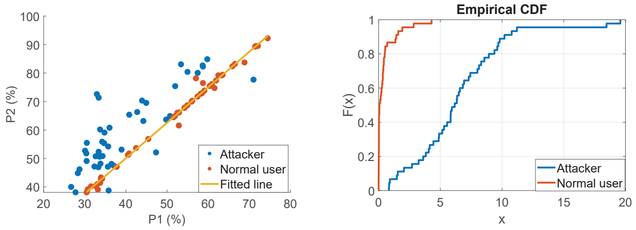


Fig. 6. Correlation matrix for two voices from the same user



(a) Feature distribution (b) Distance distribution

Fig. 7. Feature analysis

for two reasons. First, both voices have different capabilities for capturing users' voices. More specifically, the internal body voice only contains partial low-frequency features, but it is nonsensitive to environmental noise. The mouth voice reserves much more features, but it is easy to be influenced by environmental noise. Second, even if two microphones are synchronized, there may still exist small synchronization bias in the collected voices. Similar to one-dimension cross-correlation measurement, given two spectrograms S_1 and S_2, we measure the correlation between S_1 and lagged copies of S_2 as a function of the horizontal lag i and the vertical lag j. For this copy, assume that S_1 and the lagged copies of S_2 have an overlapped area of size $M \times N$, the correlation coefficient of the specific shift is:

$$Corr[i,j] = \sum_{k=1,\, l=1}^{k=M,\, l=N} O_1[k,l] \times O_2[k,l] \tag{3}$$

where O_1 is the overlapped part of S_1, and O_2 is the overlapped part of S_2. Hence, the positive integer i is from 1 to $2M-1$, the positive integer j is from 1 to $2N-1$. The best matching of two spectrograms is found if corresponding correlation coefficient is maximal. In our system, two voices are highly correlated, so the highest correlation coefficient must appear around the center of correlation matrix $Corr$, as shown in Fig. 6. Based on this observation, a word is detected to be from a live user if

$$\frac{|j-M|}{2M} < \lambda \quad and \quad \frac{|i-N|}{2N} < \lambda \tag{4}$$

where λ is the decision threshold.

A pair of spectrograms that satisfy Equation 4 cannot ensure that two voices are from the normal user. Although we know two spectrograms are highly correlated from Equation 4, it is not clear how much information or features are shared between two spectrograms. Therefore, we further measure the similarity between two voices by finding the proportion of shared information. Based on our observations, the amount of shared information should make up a large proportion of either of two voices. In other words, if an entry is non-zero in the spectrogram of internal body voice, it is very likely to be non-zero in that of the mouth voice, and vice versa. To quantitatively describe how similar two spectrograms are, we first use the measured lags to calibrate our synchronization to get the best match. For each word, the proportion of the shared information that is in S_1 is defined as:

$$P_1 = \frac{Sizeof(\{(i,j)|S_1[i,j] > 0 \;\&\; S_2[i,j] > 0\})}{Sizeof(\{(i,j)|S_1[i,j] > 0\})} \tag{5}$$

Similarly, the proportion of the shared information that is in S_2 is defined as:

$$P_2 = \frac{Sizeof(\{(i,j)|S_1[i,j] > 0 \;\&\; S_2[i,j] > 0\})}{Sizeof(\{(i,j)|S_2[i,j] > 0\})} \tag{6}$$

The similarity between two voices is defined as the smaller one of P_1 and P_2.

Fig. 7(a) shows the values of the proportion of the shared information for both normal user and attacker. Ideally, the proportion of the shared information should be high for normal users. However, since different users have different speaking habits (e.g. different speeds of speech and different accents), the proportions of shared information may not always be a high value. Also, unpredictable noise during data collection may also influence the final results. Therefore, it is hard to determine the legitimacy of the speaker using a fixed threshold on each dimension. By studying the data distribution on 2-dimension feature hyperplane, we find that data of normal users lies on a straight line, while that of attackers is far away from the line. Fig. 7(b) shows the distribution of distances from the data point to the straight line that is fitted using the normal user's training data. We can see that over 95% of the normal user's data points have the distance less than 2, while over 85% of the attacker's data points have the distance larger than 2. This fact enables us to detect the legitimacy of the speaker by calculating the distance from the data point to the line that fits the training data. After collecting several training data from the user, we first fit a straight line using least squares, as the yellow line in Fig. 7(a). A word is considered to be from the normal user if

$$\frac{|aP_1 + bP_2 + c|}{\sqrt{a^2+b^2}} < \gamma \tag{7}$$

where P_1 and P_2 are the features calculated using Equations 5 and 6, a, b, and c are coefficients of a straight line $ax+by+c=0$. γ is the decision threshold and is set to the 95% largest distance of normal user's training data. A word is considered to be from a normal user if and only if both of Equations 4 and 7 are satisfied.

E. decision combination

AR users usually speak a sentence or passphrase that consists of multiple words to AR headsets. For example, the

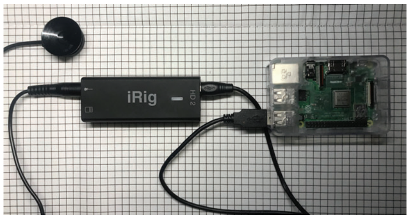


Fig. 8. Testbed for collecting internal body voice

general voice authentication systems ask the user to speak a 6-digit passphrase. In order to give an accurate detection result for each sentence, we need to combine the results of multiple words after getting the correlation and similarity measurement of each of them. In a voting procedure, three questions need to be answered: 1)Who should be eliminated from voting; 2)What is the weight of each player; 3) What is the Minimum number of votes needed to pass a vote. To answer the first question, the voter whose data cannot satisfy either of Equations 4 and 7 is eliminated from voting. Second, since both P_1 and P_2 reflect the propagations of shared information between two voices, the word with high values of P_1 and P_2 should have a higher weight for voting. Therefore, for each word in the voting procedure, we let the smaller value of its P_1 and P_2 be its weight. Third, to accurately reject the attacker and accept the normal user, for a sentence or a voice command with n words, the minimal number of votes is set to $0.2 \times n$. If there is no result whose number of votes exceeds $0.2 \times n$, the user is regarded as the attacker.

IV. EVALUATION

A. Hardware

Our system consists of two components: a testbed for collecting internal body voice and a smartphone for collecting air voice. We implemented our testbed using a Raspberry Pi 3, an iRig HD 2 soundcard, and an AXL contact microphone. Besides, we used a Nexus 5 to collect user's air voice and transmit it to the Raspberry testbed through WiFi. Both the smartphone and the Raspberry testbed were synchronized to the same server. Our experiments involved 8 volunteers (5 males and 3 females), and all of them were asked to repeat saying sentences of different lengths to our system. In order to make sure the contact microphone can capture the internal body voice during the data collection, we attached the contact microphone on a hat and asked each volunteer to wear it. Each volunteer wore the hat in their own way and was in a comfortable posture they prefered. For data analysis and processing, the data was then transmitted to a desktop computer with Intel(R) Core(TM) Devils Canyon Quad-Core i7-8700K @ 4.00 GHz CPU and 16 GB of RAM.

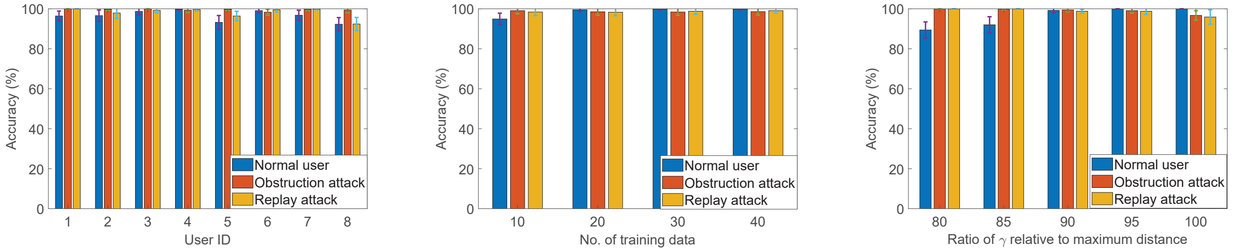
B. Overall performance

We first evaluated our system performance for normal users and against two types of attacks. In this experiment, we used the voices of 40 words collected from the normal user as the training data. The correlation threshold λ was set to 0.1, and the distance threshold γ was set to the 95% largest distance of normal user's training data. We asked each user to say a 5-word sentence 50 times. Moreover, we repeated this procedure for 10 times to study the variance of true acceptance rates of different volunteers, and the experimental results are shown in Fig. 9(a). We can observe that our system can correctly accept the normal user with mean accuracy of 97% for all users. Even in the worst case, our system can still achieve a high accuracy of 92.3% for normal users. By studying normal users' data that is wrongly rejected, there are two main reasons that degrade the performance. First, there are two volunteers who speak softly, which makes their voice is easier to be covered by background noise. Second, volunteers' activities may cause sight movement of the hat, which introduces high-energy noise to the internal body voice and reduces similarity between two voices.

We further evaluated how accurately our system can reject two types of attacks. To collect the data for the obstruction attack, we let a volunteer speak loudly while the normal user (another volunteer) was wearing the hat. To collect the data for the replay attack, we used a Nexus 6 smartphone record the victim voice at a distance of 0.5 meters. Then, we used the loudspeaker of a smartphone to replay the victim's voice to our system. At the same time, the replay attacker said the same sentence to our system while wearing the hat. Moreover, we made sure the genders of the victim and the replay attacker are the same. We leveraged the fitted straight line for the victim to determine the legitimacy of the attacker's data, and the results are shown in Fig. 9(a). We can see that our system can provide high accuracy against both types of attacks. More specifically, our system can provide a mean accuracy of 99.2% and 98% for defending the obstruction attack and replay attack, respectively. The accuracy of successful defenses is not 100% for two reasons. First, some internal body voices in the training dataset contained noise, which increased the distance threshold. Second, the slight movement of the user's head may also introduce random high-energy influence to the spectrogram. In rare cases, the filtered spectrogram of noise was similar to that of some words (e.g. "eight"). As a whole, our system can provide high-security protection for users against obstruction attack and replay attack while still ensuring good user experience for normal users.

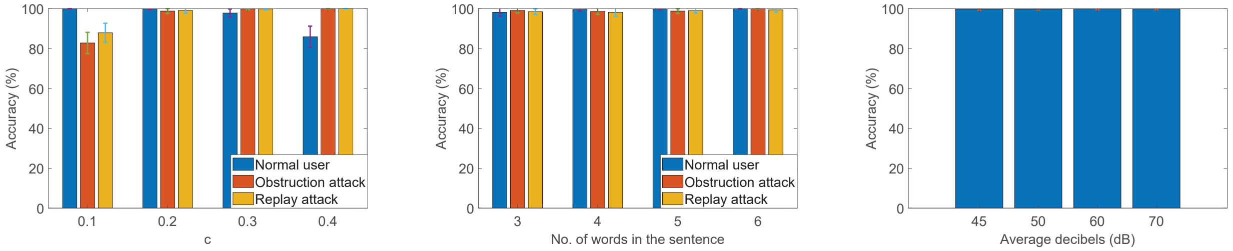
C. Influence of training dataset size

In practice, we want the number of training data to be as small as possible to reduce the training cost for new users. Therefore, we evaluated how many training data is needed by our system in order to provide both high-security protection and good user experience. Fig. 9(b) shows the system performance with different sizes of the training dataset. We can see that the average accuracy for the normal user is improved a lot by using more data for training since we have more knowledge about the distribution of the normal user's data. By contrast, the average accuracy of successful defense against either of two attacks is almost the same by using different numbers of training data. The reason behind this is that the data distribution of the attacker's data is significantly



(a) Overall performance (b) Influence of the size of training data (c) Influence of distance threshold γ

Fig. 9. Feature analysis



(a) Influence of voting threshold c (b) Influence of sentence length (c) Influence of background noise

Fig. 10. Feature analysis

away from that of the normal user. Therefore, our system can accurately reject two types of attacks even if the training data is limited. Overall, our system can provide both high-security protection and good user experience after collecting the voices of 20 words from the normal user, which is low-cost and easy to be used for new users.

D. Influence of the ratio of γ relative to the maximum distance

In our default experimental setting, the distance threshold γ is set to the 95% highest distance in the training data. In real scenarios, there is a trade-off on determining the value of γ. A small distance threshold can provide extremely high true rejection rate against two types of attackers, but it also makes it hard for normal users to use our system. A high distance threshold can ensure good user experience, but more attackers are wrongly accepted. In this subsection, we study what is the proper value of γ for different users. Fig. 9(c) shows the system performance with different values of γ. It is clear that the average accuracy for normal users rises with the increase of γ, while the average accuracy of successful rejection drops. When γ is the 95% highest distance in the training dataset, the true acceptance rate and the true rejection rate are nearly equal. Therefore, we let the γ be equal to the 95% highest distance in the training dataset to balance the need for security protection and user experience.

E. Influence of voting threshold

The performance of our system relies on a successful voting procedure. Hence, a proper voting threshold is important. Similar to the distance threshold, there is also a trade-off on determining the value of the voting threshold. If the voting threshold is too small, all normal users can be accepted, but some attacker may also be wrongly regarded as the normal user. If we assign a high value to the voting threshold, all attackers can be successfully rejected, but the user experience of normal users is ruined. In this subsection, we study what is the proper value of the voting threshold. Here we use $c*n$ to represent the voting threshold where c is a constant and n is the number of words in a sentence (voice command). We evaluated the performance for 5-word sentences using the default parameters and adjusted the value of c, and the results are shown in Fig. 10(a). We can see that the average accuracy for normal users drops rapidly when c is larger than 0.2. Moreover, our system can provide good security protection after c reaches 0.2. Therefore, we let the c be equal to 0.2 in our default system setting.

F. Influence of sentence length

We also evaluated the system performance for sentences of different lengths. Here the sentence length means the number of words in the sentence. When the length of the sentence is short, the wrong classification of a few words may dominate the voting procedure and give the incorrect detection result. For longer sentences, the voting procedure can tolerate a few wrong predictions by involving more players. In this subsection, we study what is the minimum sentence length to ensure good security protection and user experience, and the results are shown in Fig. 10(b). We can see that the system performance is improved with more number of words in a sentence. When the sentence length is 6, our system can provide average accuracy of about 100% for both accepting normal users and rejecting attackers. Moreover, with more numbers of words in a sentence (voice command), the variance of both true acceptance rate and true rejection rate are reduced, as shown in the error bar in Fig. 10(b). This fact implies that the robustness of our system is improved by saying a voice command with more words. Considering most voice commands supported by current AR applications have lengths of at least 3 words (e.g. open the navigation), our system can

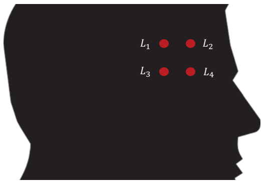


Fig. 11. Four positions around the temple

provide good enough security protection and user experience for them.

G. *Influence of background noise*

Since our system records the air voice using a normal microphone, the background acoustic noise (e.g. conversation or music) may cover the features in the air voice and degrade the performance for normal users. To evaluate the robustness of our system against background noise in terms of accepting normal users, we asked one volunteer to speak a 5-word sentence to our system. During the data collection, we used two loudspeakers to simulate different noise levels from 45 dB (average home noise) to 70 dB (inside a car at 60 mph). We did not consider greater noise in our evaluation for two reasons: 1) Most voice-based AR applications are not designed for noise environment (e.g. video call); 2) The performance of voice recognition and authentication systems can also be degraded by strong noise. Fig. 10(c) shows the evaluation results. We can observe that our system can achieve a high accuracy of at least 99.5% for all noise levels. We found that the reason why our system can still provide good performance in a noisy environment is that the AR users will subconsciously raise their volumes in a noisy environment, which makes the features of their voices are more significant than those of background noises. Therefore, by applying spectrogram enhancement techniques, the background can be largely removed.

V. DISCUSSION

A. *Influence of the position of contact microphone*

In practice, the user may attach the contact microphone anywhere around the temple based on the framework design of the AR headset. Even for the same headset, we cannot ensure the user can attach it at the same position every time. In order to evaluate the robustness of our system against different wearing positions of the contact microphone, we collect the data from 4 different positions around the temple, as shown in Fig. 11. The distance between neighboring positions is about 2 cm. We collect training data from L_1 to predict the testing data from the other locations. Experimental results show that our system can still achieve the same performance (over 97%) for both normal users and attackers, which implies our system is robust enough to wearing position change.

B. *Long-term stability*

Considering the way of speaking may change for long-term usage, the fitted line that is based on historical training data may not accurately classify new data. To evaluate the robustness of our approaches during long-term usage, we further collect testing data from 2 volunteers after 5 weeks since collecting their training data. Experimental results show that our system can still successfully accept a normal user with an accuracy of 99.1%, which is in line with our expectation. Our system detects the legitimacy of the speaker by measuring the correlation and shared information between two voices. Therefore, as long as two voices are from the same live speaker, there always exists a high correlation between two voices no matter what speaking habit the user has. Moreover, the proportions of shared information should also be stable during long period since the internal body propagation of each user will not change too much.

VI. RELATED WORK

Voice-based AR applications. There are several benefits of involving voice in the interaction methods. First, voice-based interaction can improve the immersion of AR experience. Second, it is widely accepted that the audio is processed faster than the visual stimulus. For example, Barde et al. [5] showed that audio cues can reduce reaction time up to 50% for shooting games. Therefore, the voice is becoming one of the major input methods of current AR headset and applications. Current AR applications and headsets use voice for either controlling or authentication. Most AR headsets support speech recognition and voice-based control. For instance, HoloLens [2] uses the voice as the intention mechanism to issue a command. Besides, voice can also be used for authentication. These voice-based authentication applications offer opportunities to attackers who are able to launch a voice-spoofing attack by imitating a victims voice, tone, and speaking style. This attack could harm the victims reputation, safety, and property. The attacker could scam victims friends and family through fake phone calls and leave fake voice messages, etc.

Automatic voice recognition and speaker verification. Automatic speech recognition systems aim to modulate a speech signal to a series of words so that users can interact with their devices using the voice interface. In the course of the last few years, there has been a remarkable advancement in the domain of speech recognition [8], [17]. For example, Williams et al. [8] presented a neural network that learns to transcribe speech utterances to characters. The proposed approaches can achieve a low word error rate of 8%. Voice can also be used as the biometrics for authentication using speaker verification techniques. Typically, an automatic speaker verification (ASV) system is designed to accept or reject a speech sample submitted by a user for claiming certain identity [23]. Recently, the development of ASV systems has made major progress as they are widely adopted by mobile devices (e.g. smartphones) and online commerces [12], [15]. Most ASV systems are text-independent, which means the user needs to repeat a fixed passphrase. The reason text-independent ASV systems are widely selected for authentication application is that they are able to accept arbitrary utterances, i.e., different speaking habits and languages from speakers [6]. The current practice of building an ASV system involves two processes:

offline training and runtime verification. During the offline training phase, the ASV system uses several speech samples provided by the genuine speaker to extract certain spectral, prosodic [4], [22], or other high-level features [10], [16] and uses them to create a speaker model. Then, in the runtime verification phase, the ASV system uses the trained speaker model to verify the incoming voice.

Attacks on voice recognition and speaker verification systems. Both voice recognition and speaker verification system suffer from attacks. Recent researches [7], [11], [24], [28] have shown that spoken words can be mangled such that they are unrecognizable to humans, which poses a serious threat to voice recognition systems. For instance, [28] showed that it is feasible to send inaudible attack commands. Also, various are proposed to break the biometric identification of the victim [14], [25]. For example, [25] shows that an attacker can overcome text-dependent ASV systems by concatenating speech samples from multiple short voice segments of the target speaker. Due to the simplicity of voice spoofing attacks, a few research papers have been published in developing relay attack countermeasures [9], [19], [20], [26], [30]. However, all these countermeasure systems are particularly designed for smartphone, which makes them hard to be implemented on AR headsets. For example, the liveness detection system proposed in [29] can detect the replay attacker by reusing smartphone as a sound radar. However, this work cannot be implemented on AR headsets since AR headsets do not have a speaker that is towards the user's mouth.

VII. Conclusion

Voice-based interaction is usually used as the primary interaction method for AR headsets due to its good user experience and performance. AR users rely on accurate and secure voice input to communicate with AR headsets. However, recent researches have shown that an attacker can easily perform various attacks with the help of state-of-the-art voice synthesis/conversion software. To secure the voice input on AR headsets, we propose a robust and low-cost solution for defending against voice-spoofing attacks on AR headsets with high accuracy. Our system leverages a contact microphone to record the internal body propagation of the voice. A user legitimacy is determined by measuring the correlation and similarity between the internal body voice and air voice. To our best knowledge, our system is the first to protect the voice input for AR headsets. Experimental results show that our system can accept normal users with average accuracy of 97% and defend against obstruction attack and replay attack with average accuracy of 99.2% and 98%, respectively.

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