Identi-wheez — a Device for in-Home Diagnosis of Asthma

Guy Satat, Krithika Ramchander, and Ramesh Raskar

***Abstract*—Asthma is the most common chronic illness among children. The skills required to diagnose it make it an even greater concern. In this work, we present a child-friendly wearable device, which allows in-home diagnosis of asthma. The device acquires simultaneous measurements from multiple stethoscopes. The recordings are then sent to a specialist who uses assistive diagnosis algorithms that enable auscultation (listening to lung sounds with a stethoscope) at any location in the lungs volume by sound refocusing. The specialist is also presented with a sound "heat map" which shows the location of sound sources in the lungs. We present design considerations of our device, as well as the algorithms for assistive diagnosis and their analysis which demonstrate reduction of ambient and measurement noise by over 10dB.**

I. INTRODUCTION

Asthma affects millions of people around the world and is the most common chronic illness among children. It is difficult for parents to assess the severity of a child's asthma flare in-home, and they often face difficulties in deciding whether the child requires administration of medicines, a visit to the physician or emergency medical care. Diagnosis of asthma in children is challenging. Children under 6 years usually do not comply with a spirometer and the diagnosis has to be performed by auscultation. Auscultation is a challenging task, as it requires precise positioning of the stethoscope and assessment of the lung condition based on the contact location and associated audio features. This becomes more complicated in crying children and noisy hospital environments. Therefore, only highly trained physicians can diagnose asthma; to our knowledge, there is no device that enables parents to easily monitor the state of asthma episodes in-home. With the recent popularity of e-health and m-health, it is evident that parents and patients are interested in solutions that make self-management of conditions such as asthma possible.

Here we present Identi-wheez, a portable and low-cost device that aims to reduce the difficulties of asthma diagnosis and monitoring. Identi-wheez enables auscultation without the need of an expert during the measurement process, and is composed of a novel measurement hardware and diagnosis algorithm. A schematic of the device is presented in Fig. 1a. The device consists of a vest with an embedded synchronized array of digital stethoscopes. Together, the stethoscopes record lung sounds in multiple locations, which are then sent to a specialist for interpretation. Refocusing algorithms allow the specialist to choose any position in the lungs and listen to the sound generated at that point. A "heat map" shows potential sound sources and allows the physician to visualize their location in the lung volume. This map assists the specialist in the diagnosis process by pointing him to points of interest.

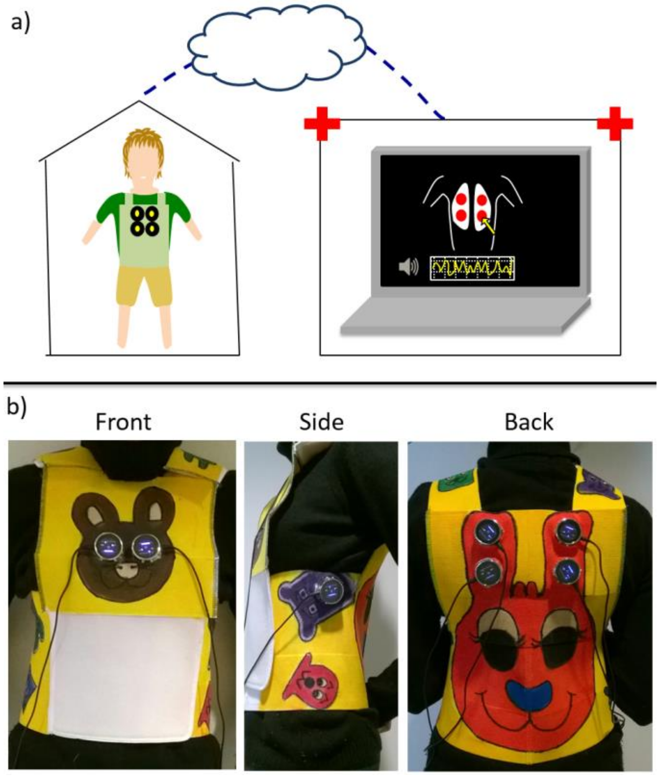

Figure 1. a) Schematic of Identi-wheez. A vest with embedded array of synchronized stethoscopes captures lung sounds from multiple positions simultaneously. Recordings are electronically sent to a specialist for interpretation. Assistive algorithms allow the specialist to select and listen to any point in the lung volume (by refocusing the array to that point). The algorithms also create a "heat map" of sound sources in the lungs. b) The measurement device, showing front, side and back view.

In-home diagnosis is made possible by the following advantages of Identi-wheez:

1. The device eliminates the need of precise positioning of the stethoscope by measuring multiple positions and sound refocusing algorithms.
2. It reduces measurement time by simultaneously measuring all positions.
3. It improves the signal-to-noise ratio (SNR) by comparing signals from different stethoscopes.
4. It is a child-friendly wearable device.

So far, numerous attempts have been made to come up with novel technologies for asthma diagnosis and monitoring. Examples include acoustic-based sensors to monitor lung

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capacity, tidal volumes and airflow during respiratory cycles[1]. Digital stethoscopes[2] which allow signal acquisition, processing and data transfer are a key component of many solutions. Hori *et al*.[3] suggested an information support system for tele-auscultation. The system employs stethoscopes to detect lung sounds and display them in conjunction with parameters such as contact condition, breath and position on a view of the patient's chest. However, it requires a remote specialist to be online during the measurement. Sen *et al*.[4] developed a multi-channel device that could detect wheezes and crackles by recording and storing data acquired from 14 stethoscopes. Although this device used multiple stethoscopes, it didn't suggest microphone array features like our device.

In parallel to improved acquisition modalities, significant work has been done on development of data-driven algorithms that enable skillful and efficient diagnosis. For example, identification of respiratory signals and distinction between healthy subjects and patients with pulmonary disorders[5].

Apart from internal conditions, efforts have also been made to develop systems that monitor environmental conditions, such as air quality, to trigger warnings and alerts. An example is a wearable device called DexterNet[6], which passes on information over a wireless network regarding a patient's activities, geographic location and air pollution, to provide an information service for asthma.

Though significant advances have been made in this field, there continues to be a lack of an ideal solution that would facilitate in-home asthma diagnosis. Table 1 presents a comparison of existing solutions and demonstrates where Identi-wheez finds its relevance.

II. DEVICE DESCRIPTION

The device is composed of 8 ThinkLabs One digital stethoscopes. The stethoscopes are sampled with a dedicated electronic board for synchronized measurements. The recordings are transmitted to a remote computer for processing. Fig. 1b shows a photograph of the device. We describe several key factors that have been taken into account during the design process.

A. *Stethoscopes Positions*

Identi-wheez consists of stethoscopes placed on the chest, the sides and the back to measure and record lung sounds from all lobes. These multiple measurement positions increase signals diversity and SNR.

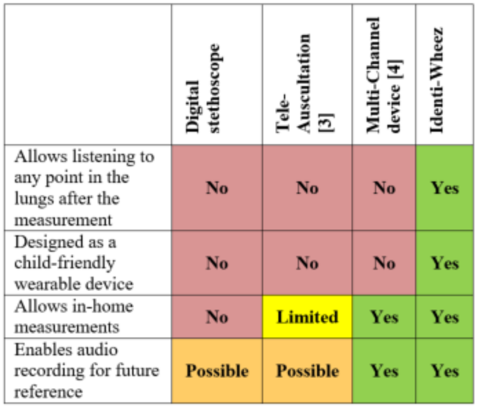
B. *Body Contact*

To ensure that the stethoscopes are in complete contact with the body, Identi-wheez is made of fabric to maximize flexibility. Slots are used to hold the stethoscopes firmly in position while also allowing for three-dimensional rotational freedom. Velcro on the shoulders and back helps the device fit users of different body structures.

C. *Sensitivity to External Pressure*

Stethoscopes can be sensitive to the external pressure applied by the user. We overcome this by eliminating the need for user interference/contact during the measurement process.

Table 1. Comparison of different assistive auscultation devices.



	Digital stethoscope	**Tele-Auscultation [3]**	**Multi-Channel device [4]**	**Identi-Wheez**
Allows listening to any point in the lungs after the measurement	**No**	**No**	**No**	**Yes**
Designed as a child-friendly wearable device	**No**	**No**	**No**	**Yes**
Allows in-home measurements	**No**	**Limited**	**Yes**	**Yes**
Enables audio recording for future reference	**Possible**	**Possible**	**Yes**	**Yes**

D. *Child-Friendly Design*

Fabric is, in general, more appealing than rigid devices. The stethoscopes are embedded within cartoon figures. This is meant to help children cooperate and facilitate adoption.

E. *Scalable Design*

The fabric makes it easy to add slots for increasing the number of stethoscopes or modifying the measurement locations. Using Velcro enables the device to fit users of different weights and ages.

F. *Stethoscope Selection*

The ThinkLabs One allows easy connection with an audio jack and a wide frequency response. Future work will consider a cost effective option for an in-home device.

III. LISTENING TO ANY POINT IN THE LUNGS VOLUME

The array of stethoscopes is analogous to a sensor array assembly commonly used in signal processing [7]. This facilitates multi-channel acquisition [8] from multiple stethoscopes in order to listen to any particular position and reject noise.

One of the primary features of Identi-wheez is that it allows a physician to choose any coordinate in the lungs' volume and listen to the associated sounds. First, we describe a simple forward model for our measurement process. Assuming a target at position T within the lung volume generating sound $x(t)$, and K stethoscopes at positions $\left\{S^i\right\}_{i=1..K}$, the corresponding measurements will be time-shifted and attenuated, such that:

$$m^i(t) = \frac{1}{d\left(T,S^i\right)^2}\, x\left(t-\tau\left(T,S^i\right)\right) \tag{1}$$

where $d(T,S^i) = \left\|T - S^i\right\|$ is the distance between the *i*-th stethoscope to the target, and $\tau\left(T,S^i\right) = d\left(T,S^i\right)/c$ is the time delay from the target to the stethoscope (here c is the speed of sound). Fig. 2 shows an example of this forward model.

This is the forward model we aim to invert. When the specialist selects a position L to listen to, we shift all signals by the corresponding time delay and correct for the attenuation. The reconstructed signal is achieved by averaging over all shifted measurements:

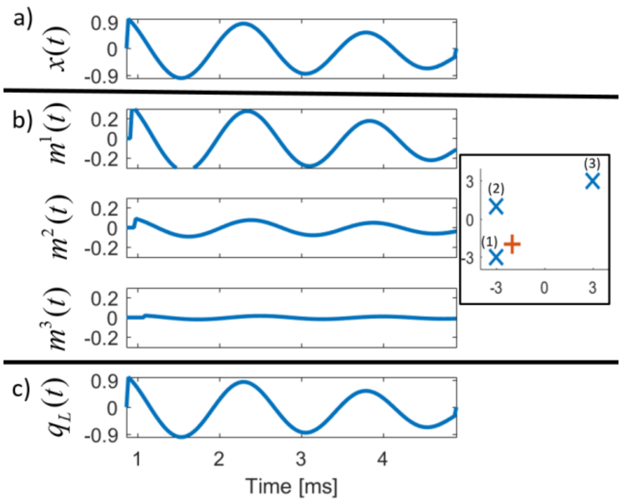


Figure 2. Refocusing audio using multiple stethoscopes. The exact source is reconstructed although it is not directly measured by any stethoscope. a) Original signal at position *T*. b) Measurements from three stethoscopes. Inset shows geometry, stethoscopes are blue X's, the target (position *T*) is a red '+' embedded 1cm below the stethoscopes measurement plane. Further stethoscopes show more time delay. c) The recovered signal for position *L=T*.

$$q_L(t) = \frac{1}{K}\sum_{i=1}^{K} d\left(L,S^i\right)^2 m^i\left(t+\tau\left(L,S^i\right)\right) \tag{2}$$

This inversion is demonstrated in Fig. 2c. If we choose $L=T$ and there are no other sources or noise, we get a perfect reconstruction of the source.

The refocusing algorithm inherently enables noise cancellation. To demonstrate this we consider two cases: additive measurement noise and ambient sounds.

A. *Overcoming Measurement Noise*

In case of measurement noise, a white noise $w^i(t)$ is added to each signal (Eq. 1). Performing the refocusing algorithm results in (plugging Eq.1 into Eq. 2):

$$q_L(t) = \frac{1}{K}\sum_{i=1}^{K}\left[\frac{d\left(L,S^i\right)^2}{d\left(T,S^i\right)^2} x\left(t+\tau\left(L,S^i\right)-\tau\left(T,S^i\right)\right)+w^i(t)\right] \tag{3}$$

If the listening position is chosen such that $L=T$ we get:

$$q_L(t) = x(t) + \frac{1}{K}\sum_{i=1}^{K} w^i(t) \tag{4}$$

As more stethoscopes are added, the second term vanishes and the SNR improves. This is demonstrated in Fig. 3a.

B. *Overcoming Ambient Noise*

In case of ambient noise, we consider a localized source in position *W* such that the measurements are given by:

$$\begin{aligned} m^i(t) = {} & \frac{1}{d\left(T,S^i\right)^2} x\left(t-\tau\left(T,S^i\right)\right) + \\ & + \frac{1}{d\left(W,S^i\right)^2} w\left(t-\tau\left(W,S^i\right)\right) \end{aligned} \tag{5}$$

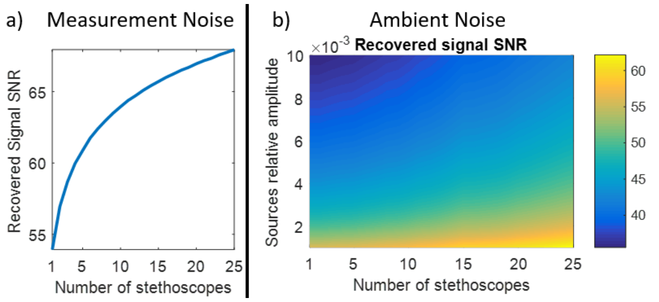


Figure 3. Overcoming noise. a) Rejecting measurement noise, the y-axis shows the improvement in the recovered signal's SNR as stethoscopes are added. The stethoscopes are placed on a uniform grid in the measurement plane. b) Overcoming ambient sounds. The x-axis shows improvement as more stethoscopes are added. The y-axis shows reduction in SNR as the amplitude of the ambient sound increases. Color represents the recovered signal's SNR.

Here, $w(t)$ is independent of the measuring stethoscopes. Applying the refocusing algorithm (and choosing *L=T*) results in:

$$q_L(t) = x(t) + \frac{1}{K}\sum_{i=1}^{K} w\left(t+\tau\left(L,S^i\right)-\tau\left(W,S^i\right)\right) \tag{6}$$

In this case, there is also performance gain. However, it depends on the ambient source. For example, there is no gain in SNR if the noise is harmonic such that $w(t) = w\left(t+\tau\left(L,S^i\right)-\tau\left(W,S^i\right)\right)$. Fig. 3b presents an analysis of SNR gains as a function of number of stethoscopes and the relative amplitude between the real target and ambient noise.

IV. Creating Lungs Sound Maps

Another key feature of our device is that it facilitates visualization of audio sources within the lungs in the form of a sound "heat map". Fig. 4 shows such a map where sound sources are presented as a function of depth.

In order to create the source map, we utilize the time-of-flight concept again. Specifically our goal is to find the most plausible source given the time delay between two stethoscopes recordings. This is achieved by calculating the autocorrelation between all stethoscope pairs:

$$AC^{ij}(\delta) = \int_t m^i(t)m^j(t-\delta)dt \tag{7}$$

Assuming one point source in the target volume, the autocorrelation will have a single peak at a time delay $\delta_{\max}$ corresponding to the difference between the times of arrival at the two stethoscopes. To formally demonstrate this, we assume a target at unknown position *T*; the autocorrelation between a pair of stethoscopes is:

$$AC^{ij}(\delta) = a\int_t x\left(t-\tau\left(T,S^i\right)\right)x\left(t-\tau\left(T,S^j\right)-\delta\right)dt \tag{8}$$

where *a* accounts for the attenuation pre-factors. The peak is achieved when the signals overlap:

$$\delta_{\max}^{ij} = \tau\left(T,S^i\right)-\tau\left(T,S^j\right) \tag{9}$$

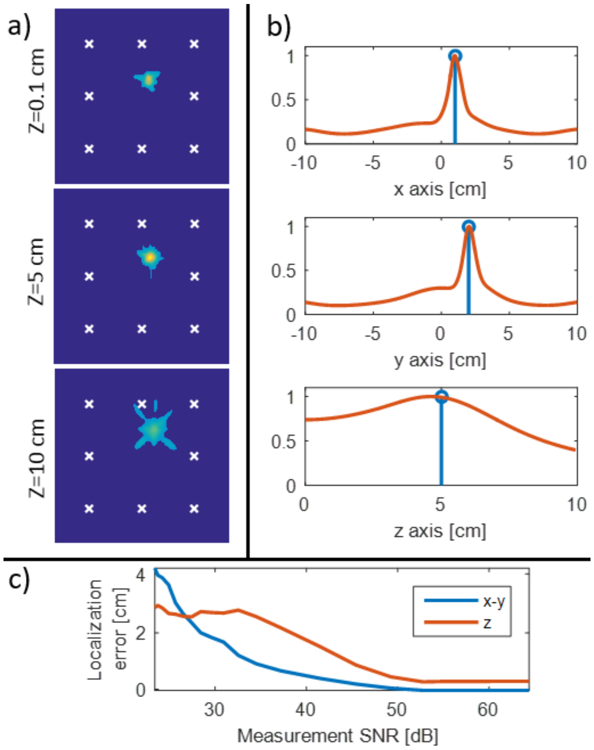


Figure 4. Simulation results for sound source "heat map". a) A map for different depths; white Xs show stethoscope positions on the z=0 plane, the target is located at the z=5cm plane. The map is thresholded (top 70%). b) Cross sections showing the focal spot characteristics. c) Localization error vs. measurement noise showing the error in x-y plane and z-axis.

In general, $\|r - S^i\| = \tau(T, S^i)c$ defines a sphere centered on the *i*-th stethoscope on which the target can be found. And so, $\delta_{\max}^{ij}$ defines the intersection of two such spheres (i.e. a circle). Using all stethoscope pairs allows to create more intersections and localize the source. In order to account for noise, time discretization and model mismatch, we define a Gaussian on the intersection such that:

$$G^{ij}(r) = \exp\left\{ -\frac{\left(\|r - S^i\| - \|r - S^j\| - \delta_{\max}^{ij} c\right)^2}{2\sigma^2} \right\} \qquad (10)$$

where σ is the Gaussian width which can empirically account for noise. We repeat the process for all stethoscope pairs and summing up all maps creates the final map, such that the intersection corresponds to the target location:

$$H(r) = \sum_{i=1}^{K} \sum_{j=i+1}^{K} G^{ij}(r) \qquad (11)$$

We then apply a threshold on $H(r)$ to remove the non-intersecting areas from the map. An example of such a map for different depths is presented in Fig. 4a. More sources are accounted by analyzing multiple peaks in the autocorrelation.

To evaluate the localization accuracy, we plot cross sections across the peak of the spot (Fig. 4b). The spot is localized within an accuracy of 0.3mm in the x-y plane and 3.5mm in the z-axis. The spot full width half max (FWHM) is 6.7mm in the x-y plane and 36mm in the z-axis.

Fig 4c. shows the localization error when measurement noise is added to the stethoscopes. We note that for SNR above 50dB we achieve constant performance (as described above); for stronger noise the localization error rises quickly in the z-axis and saturates. The localization error in the x-y plane continues to increase slowly as more noise is added. In this experiment, we chose constant $\sigma = 0.1$. Increasing the Gaussian width as more noise is added can help in reducing the localization error but increases the spot FWHM.

V. DISCUSSION

For simplicity, all the above analysis is given in continuous time. The sampling frequency should be taken into account for the measurement discretization (we assumed measurement above Nyquist rate). Simulation results are given for cases of stethoscopes placed on a plane, which significantly reduces the measurement diversity and the localization accuracy. Future work will take into account measurements from the sides and front.

We also plan to incorporate more data analysis on the measurements, which will further assist physicians in characterizing the signals. For example we can create a "heat map" of possible specific signals, such as crackles, wheezing, etc. This can assist in diagnosis of various lung diseases.

VI. CONCLUSIONS

We presented Identi-wheez, a child-friendly wearable device consisting of an array of stethoscopes. Algorithms which allow auscultation at any point in the lung volume post-measurement were presented and analyzed. The device facilitates in-home diagnosis of asthma, and can serve as a tool for diagnosis of other lung diseases.

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