Design Optimization of 3D Printed Digital Stethoscope for Low-Cost Telemedicine

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***Abstract*— Modern day acoustic stethoscope is a necessary equipment to aid clinical practitioners in performing diagnosis on patients. For initial assessments and long-term medical evaluations, it is beneficial for patients to be able to monitor their health status between check-ups and for doctors to be able to diagnose patients remotely. In this work, the viability of MEMS-based digital stethoscope as an alternative solution for a low-cost diagnostic equipment is proposed. The impacts of various design parameters of a 3D-printed stethoscope's chest-piece on the sound quality has been investigated. Signal-to-noise ratio (SNR) analysis of various designs achieved up to approximately 5.24 dB, indicating clear and audible heart sounds. In addition, the development and implementation of a novel web-based application with digital stethoscope is also proposed in this work for potential real-time remote auscultation.**

***Keywords*— MEMS, Stethoscope, 3D Printing, Design Optimization, Web-Based Application**

I. INTRODUCTION

Traditional acoustic stethoscopes such as the 3M™ Littmann® Classic III Stethoscope Series continue to be essential tools in healthcare for its ease of use and accuracy for basic auscultation. More recently, 3D printed acoustic stethoscopes have been proposed as a viable alternative solution [1]–[4]. 3D printing technology offers the opportunities for personalization and customization, advanced functionality, and integration with modern healthcare technologies. As digital capabilities become increasingly prevalent, digital stethoscopes started gaining attraction for their improved sound quality in terms of amplification, clarity, accuracy and recordability [5].

Various MEMS-based stethoscope has been studied including the implementation of MEMS-based digital sensor [6], [7], MEMS-based acoustic sensor [8], MEMS-based electronic stethoscope with fluid-solid coupling encapsulation [9]. In 2022, Lee et al. demonstrated the workings of a soft wearable stethoscope for real-time auscultation and potential automatic disease diagnosis through machine learning [10]. Fan et al. investigated the accuracy and reliability of a Stemoscope, a wireless electronic stethoscope, in valvular heart disease (VHD) detection [11]. The novelty of such designs verifies the viability of digital stethoscopes and the improvements they bring, mostly in the context of AI integration.

Today, high quality electronic and digital stethoscopes are readily available such as the 3M™ Littmann® Electronic Stethoscope Model 3100 and 3M™ Littmann® CORE Stethoscope but at a very high cost. For patients and medical workers in poorer regions or countries, such equipment may not be easily accessible. Some works have looked into sound acquisition by using smartphone applications [3][4], which allows patients to carry out their health monitoring easily on their own and medical workers to perform rapid diagnosis if required. With digital stethoscopes becoming more available, the implementation of remote auscultation in medical platforms will be possible.

Nonetheless, real-time data processing with low latency AI also requires an efficient hardware design and this is especially so in the medical field, where collected data must be interpretable. As many studies have investigated the implementation of remote diagnosis, real-time processing or AI in the healthcare field [10]–[14], an optimized design of

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3D printed stethoscope should be identified for a seamless system.

As such, this work focuses on various 3D printed digital stethoscope designs with an integrated MEMS microphone and assesses the audio quality of each design. In particular, the impact of adjusting different parameters of a 3D printed stethoscope on audio quality is addressed here. The design parameters include the diameter of the stethoscope's chest-piece, curvature of the chest-piece shell, and location of the MEMS microphone within the chest-piece. As such, this work shall contribute to the iterative process of testing different chest-piece designs by obtaining and analysing heart auscultation data from among three of the authors. By changing one design parameter at a time, an optimum design is chosen at the end based on the signal-to-noise ratio (SNR). The process also eases any need of design customization for individual patients, which may be necessary for overall comfort and experience. Investigation on the stethoscope designs on real patients and other volunteers will be carried out in a future study.

Firstly, this paper highlights the main design parameters that will be investigated followed by a concise summary of the manufacturing, assembly, and quality measurement method. The data collected will then be analysed and compared with a control design. In the discussion section, the performance quality of each design is assessed and summarised to identify the best design, along with cost consideration. Finally, an implementation of a web-based application that can be integrated with the stethoscopes will be demonstrated.

II. METHODOLOGY

A. *Design Parameters of 3D-Printed Stethoscope*

Fig. 1 shows various designs of the chest-piece part of the stethoscope are drawn using computer-aided design (CAD) through SolidWorks. The unique design parameters are listed out and shown in TABLE I and Fig. 2. As a short reference, the different stethoscope designs are referred to as T1, T2, T3 and T4.

B. *Printing and Assembly of Stethoscope*

Each chest-piece design was printed on a 3D printer (Zortrax M200 Plus, 1.75 mm filament diameter, 0.4 mm nozzle diameter, with scaffolding) using acrylonitrile butadiene styrene (ABS) plastic blend with 90 % infill and 0.09 mm layer height. A PET diaphragm was attached to each of the chest-piece head with all-purpose adhesive glue. A silicon MEMS microphone sensor (SEN0487, DFROBOT) was secured within each of the stethoscopes, at the bottom part of the chest-piece for T1, T2, and T4, and at the top part of the chest-piece for T3. Fig. 3 shows an example of the final assembly of a ready-to-test stethoscope. M2 nuts and bolts and Paraffin film (parafilm) was used to ensure the chest-piece parts are tight-sealing.

C. *Quality Measurement*

For the purpose of verifying audio quality, the performance of 3D printed chest-pieces are compared against a control unit, which is an aluminium stethoscope embedded with the same MEMS microphone sensor as seen in Fig. 4.

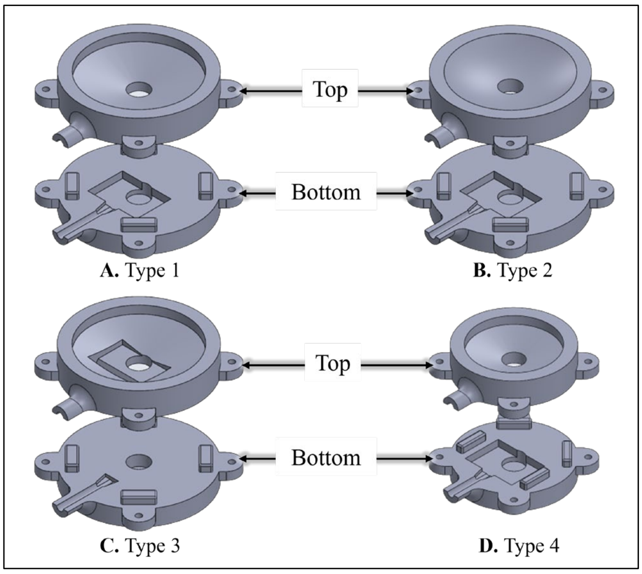

Fig. 1. CAD parts of four stethoscopes with different design parameters.

TABLE I. Design Specification and Estimated 3D Printing Cost of Stethoscopes

Model	*Type 1*	*Type 2*	*Type 3*	*Type 4*
Outer diameter/mm	44	44	44	36
Inner diameter/mm	36	36	36	28
Inner wall	Flat	Curved	Flat	Flat
MEMS placement	Bottom	Bottom	Top	Bottom
Material usage/g	23	24	23	17
Price of 3D print/USD	1.41	1.47	1.41	1.04

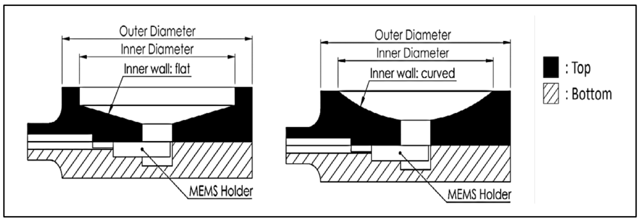

Fig. 2. Design Parameters of 3D printed stethoscope.

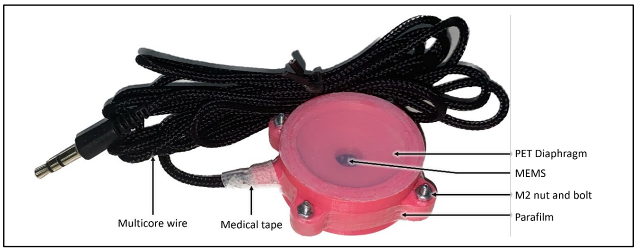

Fig. 3. A fully assembled stethoscope.

Fig. 4. Aluminium stethoscope with MEMS microphone embedded (left), fully assembled (center), and its back view (right).

Heart auscultation data was obtained by holding a stethoscope firmly on a researcher's chest where the pulmonary valve is [15]. Three researchers provided the data in this work where each recording taken was 30 seconds long. For each recording, as shown in Fig. 5, five cardiac cycles (S11) were extracted. The amplitude of five S1 and S2 peaks were recorded and averaged to obtain $S1_{ave}$ and $S2_{ave}$. Then, the RMS amplitude of systoles, S12, and diastole, S21, for each of the 5 cycles were recorded and averaged. The signal-to-noise ratio (SNR) was analyzed for each stethoscope design and compared with the control unit, where SNR is [6]:

$$SNR = \frac{Signal\ Power}{Noise\ Power} = 10 \log \frac{Signal\ Power}{Noise\ Power}\ dB \qquad (1)$$

As the RMS of amplitudes recorded in Audacity are in dB, SNR can then be calculated using the logarithm quotient rule:

$$\text{SNR} = \text{Signal} - \text{Noise} \qquad (2)$$

where Signal = $S1_{ave}, S2_{ave}$, and Noise = $S12_{ave}, S21_{ave}$.

III. RESULTS AND DISCUSSION

A. *SNR Result*

SNR analysis in TABLE II indicates stethoscope T4 having the highest audio quality followed by T2, T1, T3 and finally the control unit.

Among the four 3D printed stethoscopes, the placement of MEMS microphone on the top part of the chest-piece yields the lowest SNR due to the lack of amplification provided by the top half of the shell and being placed near the PET diaphragm. The usage of a curved inner wall instead of a flat surface as used in design T2 indicates better sound projection towards the MEMS microphone, as compared to T1.

The metallic control unit shows the lowest SNR at about 1.06 dB compared to all 3D printed stethoscopes. It is suspected that echoes are more prominent when audio signal are obtained from MEMS microphone installed in the control unit. The lack of any sealant usage could be another factor of the low SNR. On the contrary, stethoscope T4 with a smaller overall diameter compared to T1 proved to be the best design in terms of both the printing cost and performance. Since it is smaller in size, there would be less discomfort during usage, on top of the ease of handling. From these findings, a combination of design T2 and T4 could give the best SNR for auscultation purposes.

The 5.24 dB SNR of T4 is close to the 6.9 dB SNR of a standard 3200-type of 3M Littmann stethoscope [9] although lower than the 13.58 dB SNR of a piezoelectric MEMS acoustic sensor in [8]. This indicates that the quality of 3D-printed designs must be further improved in order to approach the SNR of a standard 3M Littmann 3200 electronic stethoscope at 23.3 dB [2] to be considered as high-quality.

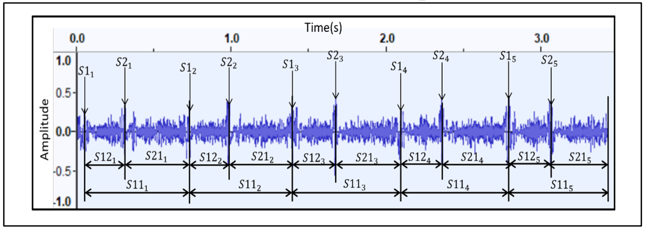

Fig. 5. Audio signal collected for SNR analysis in Audacity software.

TABLE II. Calculated SNR for each Stethoscope Type

Model	**Subject**	**Signal to Noise Ratio, dB**		**Mean**		**Standard deviation**	
		$S1_{ave} - S12_{ave}$	$S2_{ave} - S21_{ave}$	$S1_{ave} - S12_{ave}$	$S2_{ave} - S21_{ave}$	$S1_{ave} - S12_{ave}$	$S2_{ave} - S21_{ave}$
Control	**Researcher 1**	3.2906	2.5777	1.9882	1.0585	1.0155	1.1609
	Researcher 2	1.8612	-0.2401				
	Researcher 3	0.8130	0.8379				
Type 1	**Researcher 1**	2.8480	4.0944	4.4480	4.7234	1.8516	1.1667
	Researcher 2	3.4528	3.7168				
	Researcher 3	7.0431	6.3590				
Type 2	**Researcher 1**	6.0501	2.8738	5.2539	4.2871	0.5887	0.9998
	Researcher 2	5.0665	5.0299				
	Researcher 3	4.6452	4.9577				
Type 3	**Researcher 1**	2.6820	2.5169	3.3177	2.6638	0.4496	0.3408
	Researcher 2	3.6452	3.1347				
	Researcher 3	3.6259	2.3397				
Type 4	**Researcher 1**	5.8090	6.3613	5.2393	4.6754	0.7738	1.3285
	Researcher 2	5.7636	3.1144				
	Researcher 3	4.1453	4.5503				

B. *Implementation of Web-Based Application*

Fig. 6 illustrates the user interface (UI) of the real-time listening web-based application. The application allows medical workers to perform remote real-time listening from the electronic stethoscope input from the patient's side across browser. The interface is similar to today's communication applications. Section (1) and (2) shows the participants present in a call and a chat section respectively. Section (3) contains the visualizer showing the audio signal with Fast Fourier Transform (FFT) and amplitude while audio controls and a 'leave call' button is in Section (4).

1) *Working Principle*

The web-based application utilises a webRTC module to perform real-time communication between browsers, thus achieving real-time listening of stethoschope input. As browsers are situated behind the firewall, Net Address Translation (NAT) devices and other security measures, transmission of data in real-time directly between two browsers is not possible. However, webRTC uses STUN and TURN servers to locate an optimal path of public IP to allow real time data transfer between the browsers, thus bypassing the firewall.

Fig. 7 shows the working principle behind the web-based application. Firstly, browser A and browser B gathers a list of Interactive Connectivity Establisment (ICE) candidates from the STUN and TURN server. The ICE candidates and session description protocol (SPD) are then exchanged between the browsers through a signaling server. Once the optimal connection is found, both browsers 'agrees' to a best connection path before a peer-to-peer connection between the browers is established, allowing data transmission.

2) *Data Privacy and Security*

To ensure data privacy and security, data transmitted from one server to the another are encrypted and secured. During the signalling process, data sent to the signaling server is encrypted by hosting the site using HTTPS to prevent man-in-middle attack. During the peer-to-peer data transfer however, data are encrypted by the webRTC using Datagram Transport Layer Security (DTLS) and Secure Realtime Transport Protocol (SRTP). DTLS is a secure communication protocol designed to provide privacy and data integrity by proctecting the data against eavesdroppping and tampering while SRTP adds another layer of security that encrypts and authenticates the data transmitted.

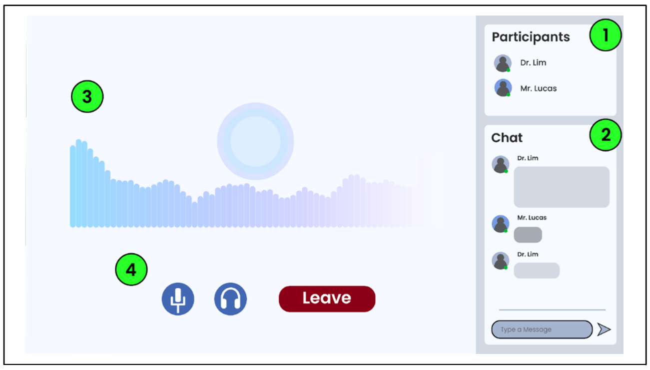

Fig. 6. UI of the web-based application, with 4 distinguished sections.

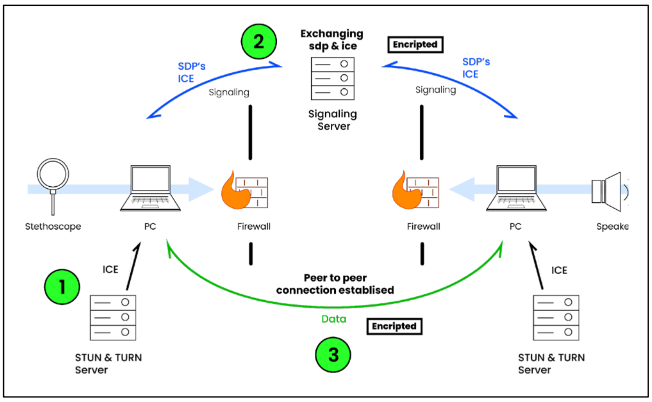

Fig. 7. Working principle behind the web-based application.

IV. CONCLUSION

This work demonstrated the effects of various design parameters of a 3D printed digital stethoscope on audio quality by changing the MEMS microphone location, curvature of the chest-piece's inner wall, diameter of chest-piece, and material type.

A web-based application was further implemented which can have significant impact on healthcare accessibility, medical technology, research, and education. The integration of 3D printed digital stethoscope into available healthcare systems is a viable solution for medical services in rural areas where access to medical professionals is difficult. Nevertheless, for this system to be completely implemented further study will be required to ensure its sustainability and reliability such as long-term durability assessment and possible increase in functionality as well as resolving any ethical concerns, medicolegal issues, algorithm validation and learning curve regarding AI and machine learning.

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