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VeriMask: SENSOR PLATFORM FOR DECONTAMINATION OF N95 MASKS

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In response to the mask shortage during the first wave of the COVID-19 pandemic, we developed an open-source wireless sensor platform, *VeriMask*, to facilitate per-mask verification of the moist-heat decontamination process for N95 masks. The aim of VeriMask was to enable safe, easy, and accessible moist-heat decontamination in under-resourced facilities to protect frontline healthcare workers by lowering their risk of infection from reused N95 masks. In this article we will introduce the VeriMask platform, challenges we encountered in this emergency-response design, design criteria, and lessons learned from our interactions with clinical and near-clinical partners. We hope to raise attention as to how society can be better prepared against future pandemics and other forms of crises by leveraging the expertise of the mobile computing, trustworthy computing, and medical communities.

N95 MASK SHORTAGE AND DECONTAMINATION

N95 mask shortages have been a persistent and enduring problem in almost every significant pandemic, including the SARS outbreaks in 2003, H1N1 influenza in 2009, and the recent COVID-19 pandemic. An American survey from early 2020 [2] showed that during the first wave of the COVID-19 pandemic, more than 50% of 21,000 nurses surveyed were required to reuse their disposable N95 masks for at least 5 days on average. In contrast, the US CDC recommends an 8-hour usage limit on these disposable masks to ensure the safety of the wearer. Over time, the warm and humid environment caused by breathing can accelerate the spread of captured microorganisms to the inner layers of the mask, posing a risk of contaminant exposure for the wearer. This posed the urgent need to properly decontaminate these disposable masks before reusing them.

The CDC recognized a combination of moisture and heat as one of the most effective and accessible methods for decontaminating N95 masks. This method requires treating a batch of contaminated masks with a temperature of 70-85°C and relative humidity of 50-100% for at least 30 minutes. Such simple requirements opened up the potential for immediate implementation of this method to mitigate the mask shortage using non-specialized ovens and warming cabinets that are already present in hospitals, thereby avoiding the considerable costs and residual chemical hazards of other decontamination methods (e.g., hydrogen peroxide [3,4]).

THE MISSING PIECE

However, several problems were preventing wide, rapid, and reliable deployment of moist-heat decontamination, raising the need for our VeriMask platform [1]. First, such non-specialized ovens often have non-uniform heat distribution, humidity leakage, and unpredictable failures. Second, the lack of monitoring mechanisms for verifying adequate decontamination increases the chance of overlooking potential decontamination failures due to temperature and humidity fluctuations. Furthermore, manual checking of each mask is almost impossible as the number of masks to be decontaminated increases, especially given the time constraints of healthcare workers.

VERIMASK DESIGN

Overview

To address these problems, we developed the VeriMask platform for clinical use. We engaged with healthcare professionals, including nurses and sterile process managers who had actual experience in conducting moist-heat decontamination to receive iterative feedback for improving VeriMask's functionality and interface. Figure 1 shows a typical decontamination cycle using VeriMask in a clinical workflow. VeriMask facilitates the decontamination procedure by automating the verification of each mask's temperature and relative humidity conditions and maximizing the number of masks that can be decontaminated over time.

VeriMask consists of two major components: wireless sensor nodes and an Android app running on smartphones. The nodes, each one associated with a container that contains an N95 mask and a wetted paper towel that provides the required humidity (Figure 2), periodically send temperature and relative humidity readings to the Android App, which performs real-time monitoring, verification of the decontamination conditions, and optimization of the overall decontamination process. The scalable system is designed to support decontamination of up to hundreds of masks simultaneously. The low power- and high temperature-resistant VeriMask sensor nodes with a size of 3.5 x 3.8 cm (1.4 x 1.5 inches) can work continuously for more than 1000 decontamination cycles without a battery change and cost only $15.66 per 1000.

Wireless Sensors

The VeriMask sensor nodes use unidirectional bluetooth low energy (BLE) advertising to broadcast sensor data to the smartphone app. Utilizing the BLE functionality supported by most smartphones enables fast deployment compared to other customized wireless protocols that require dedicated transceivers and display devices to be designed and manufactured. BLE advertising (as opposed to the more traditional "pairing") allows more masks to be monitored and decontaminated at the same time. It also reduces the power consumption of the sensor nodes and the effort required to add new nodes to the system.

VeriMask uses a dense one-for-one sensing topology by associating one sensor node to each individual mask in the containers to monitor reliably the temperature and humidity of each mask. The dense sensing topology allows VeriMask to deal with any model of heating device with various heat and humidity distributions and dynamics. The sealed containers with wetted paper towels are used to provide an environment with adequate humidity and to avoid cross-contamination between masks as well as mask shape deformation. We carefully characterized the BLE packet loss rate with an increasing number of sensor nodes and ensured less than 2.7% packet loss with up to 100 nodes (equivalent to 100 masks in a batch).

Android App

The Android app is highly flexible so that operators can easily configure different decontamination parameters such as the desired temperature and relative humidity ranges based on the actual use scenarios. When the app detects a violation of the desired decontamination conditions for a mask (e.g., relative humidity dropping out of the acceptable range due to an improperly sealed container), it immediately alerts the operators and changes the state of that mask to decontamination failure. At the end of each decontamination cycle, the app prompts the operator to select the masks for reuse or disposal, according to the decontamination success state of each mask displayed.

The VeriMask app also provides a decontamination optimization functionality that guides the operators to change the decontamination settings to maximize the number of successfully decontaminated masks over time. It is worth pointing out that we found *fewer masks and containers placed in the heating device sometimes led to more successfully decontaminated masks*. By analyzing the sensor readings, we found

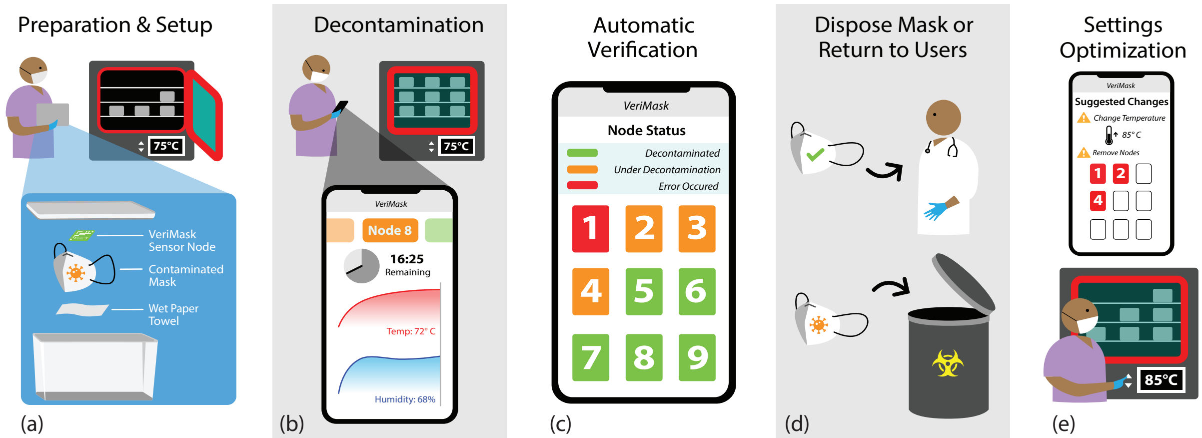

FIGURE 1. VeriMask is a wireless sensor platform that facilitates moist-heat decontamination of N95 masks. (a) The decontamination operator arranges each mask with a VeriMask sensor node and a wet paper towel, generating humidity in a sealed container, and sets up the commercial heating device and VeriMask app. (b) VeriMask monitors the per-mask conditions during decontamination. (c) VeriMask app automatically verifies if each mask has been successfully decontaminated. (d) The operator selects the decontaminated masks and returns them to the users. (e) The operator then optimizes the decontamination settings following VeriMask's suggestions for the next decontamination cycle.

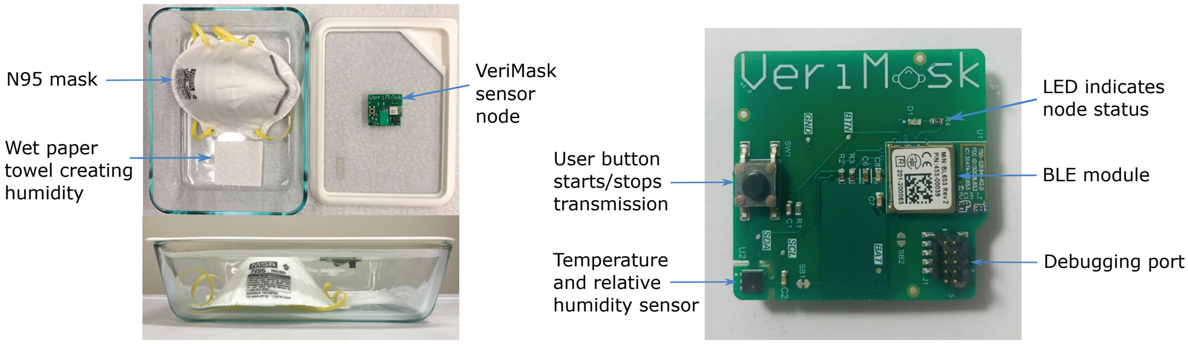

FIGURE 2. The VeriMask sensor node and configurations for decontamination.

this is because too many containers can block the flow of hot air and cause poorer heat distribution, thus preventing some masks from reaching the desired temperature range. This demonstrates that by introducing VeriMask into the decontamination process, more fine-grain information and control can be obtained at a lower cost than having specialized heating devices.

EXPERIENCE & LESSONS

VeriMask is the first realization of open-source design for verification of mask decontamination that is fully integrated with clinical workflows, navigating a host of design challenges caused by the setting, the pandemic, and the need for expediency. We encountered numerous challenges developing VeriMask during the pandemic. These ranged from developing complex safety and effectiveness specifications to dealing with practical constraints, such as supply chain disruptions and rapidly evolving healthcare regulations. By collaborating with medical and decontamination professionals, we extracted key design considerations and formulated them into the following reusable design criteria. These criteria are, in many ways, applicable to general emergency response hardware design.

Criterion 1: Fast Design & Deployment

Since crises such as pandemics often pose life-threatening risks, timely design and deployment are crucial. Designing simple and highly debuggable open hardware devices significantly accelerates implementation, deployment, and maintenance processes, and helps build a trustworthy relationship between designers and healthcare facilities [5]. In addition, utilizing common off-the-shelf (CoTS) components built and tested by trustworthy manufacturers and available in bulk facilitates implementation and enhances hardware reliability by avoiding long-time testing, calibration, and availability problems due to custom hardware. Unlike devices with novel sensing functionality or materials, it is imperative that emergency response open source designs use reliable and generic devices to ensure real-world use.

Criterion 2: Generality-oriented Robust Design

The desired generality is two-fold. First, the function-specific design should be made applicable to a large scope of deployment scenarios, e.g., using various types of heating devices. The actual use case in hospitals is often unpredictable because of the variance in their existing equipment and the healthcare regulations that prevent designers from directly accessing the deployment environment during pandemics. Second, the design's building blocks should have general and common enough functionality plus interface. Employing popular communication schemes, such as Bluetooth, reduces the cost by eliminating DIY communication modules and enables easier debugging, replacement, and use. Ensuring such common interfaces also enables the designers to easily replace the components in case of a local supply-chain shortage.

Criterion 3: Priority-centered Design

Given the complex design space, the most important criterion is to enforce a priority-centered principle. We summarize 3 categories of design goals ordered according to their priorities, namely safety, effectiveness, and usability. (1) **Safety:** Safety requirements are those that can directly endanger the users if not met. For example, being able to accurately and reliably determine whether each mask has been successfully decontaminated is a safety requirement for VeriMask. To ensure safety, the designers should fully understand the standards and requirements, choose the sensor monitoring scheme based on the worst-case scenarios, and carefully evaluate the information loss and consequences in sensor data transmissions. (2) **Effectiveness:** We define effectiveness as a combination of the degree of achievement for criterion 1 and 2, as well as other performance factors, such as the designed system's cost, battery life, size, etc. (3) **Usability:** Usability includes factors such as reducing the physical and mental workloads of the clinical end users. Designers should always design with the clinical operating protocol in mind for improving the actual usability. For example, we improve VeriMask's usability by automating the verification process and suggesting better decontamination settings to the operators.

Experience & Feedback

Our team started developing VeriMask in response to the serious N95 mask shortages in the US in mid-2020 and had the first working prototype in early 2021. Subsequently, we deployed and tested VeriMask in a clinical setting and collected opinions on VeriMask's usability. Some opinions provide very helpful insights into the possible future improvement. For example, it is suggested that VeriMask supports different operational modes (e.g., automatic and advanced modes) in the Android app according to different levels of user expertise. The automatic mode for ordinary operators can provide fully automated verification. On the other hand, the advanced modes for more experienced users, such as doctors and nurses, can allow more personalized interactions, such as setting fine-grain decontamination parameters. Other suggestions include providing detailed user guides for the operators to facilitate the adoption of VeriMask in different clinical settings, further reducing the sensor node dimension to improve the overall portability, etc.

Need-response Mismatch in Emergency Response Design

While VeriMask can be easily repurposed for other types of verification applications due to its high flexibility, the N95 mask shortage started ramping down when VeriMask was ready for clinical use. Our experience reveals the need-response mismatch commonly found in emergency response designs. We now briefly summarize the lessons learned to help future researchers and designers better address this mismatch problem and avoid common pitfalls.

First, emergency designs should be prepared long in advance. We identify three major reasons for such a common need-response mismatch: (1) The challenge of understanding the medical specification and standards; (2) The challenge of getting access to clinics for design and testing due to stricter health regulations in pandemic times; (3) The challenge of disrupted supply and fabrication chains, which seriously increases the hardware turn-around time. Second, designers should plan for the worst case and design for modularity. The problem of disrupted supply chain can not only delay fabrication, but also render the electronic components completely out of stock for months in pandemics. The designers should thus avoid assuming adequate supplies for emergency design, and even consider candidate components from the design phase or leave spaces on PCBs for alternative components. Finally, designers should engage early with medical professionals and end users so that both mobile computing researchers and clinics are prepared and have a framework to build around. Our team has been in direct contact with the N95DECON consortium [6] which is a volunteer collective of scientists, engineers, clinicians, etc., and dedicated to studying different methods of decontamination. Our communications enabled more efficient and down-to-earth specification derivation.

SUMMARY

In this article, we revisited the problem of N95 mask shortage during the COVID-19 pandemic, the challenges of deploying moist-heat mask decontamination, and the VeriMask platform that we developed for facilitating the decontamination in under-resourced healthcare facilities. We also summarized the key design considerations as reusable design criteria and our experience as well as lessons learned developing and deploying VeriMask during the pandemic.

Moving forward, we believe that low-cost portable mobile computing systems can play a more important role in facilitating various types of clinical verification applications, especially during the emergency of pandemics because of these systems' great potential of wide and rapid deployment. The main challenge for mobile computing researchers is to build a framework that enables proactive communications with researchers and end users from the medical side before crises happen. We also think it is worthwhile paying more attention to the existing gaps in crisis response mechanisms of the society and the possible future emergency situations reflected by our history. Ultimately, researchers will be able to better protect our society by developing preemptive crisis technologies. ■

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