Thermal Image Analysis for Detecting Facemask Leakage

Jonathan Dowdall*, Ioannis Pavlidis*, and James Levine#
*Department of Computer Science, University of Houston, 501 Philip G. Hoffman Hall,Houston, TX 77204-3010
#Division of Endocrinology Department of Internal Medicine Endocrine Research Unit
Mayo Clinic, Rochester MN 55905

ABSTRACT

Due to the modern advent of near ubiquitous accessibility to rapid international transportation the epidemiologic trends of highly communicable diseases can be devastating. With the recent emergence of diseases matching this pattern, such as Severe Acute Respiratory Syndrome (SARS), an area of overt concern has been the transmission of infection through respiratory droplets. Approved facemasks are typically effective physical barriers for preventing the spread of viruses through droplets, but breaches in a mask's integrity can lead to an elevated risk of exposure and subsequent infection. Quality control mechanisms in place during the manufacturing process insure that masks are defect free when leaving the factory, but there remains little to detect damage caused by transportation or during usage. A system that could monitor masks in real-time while they were in use would facilitate a more secure environment for treatment and screening. To fulfill this necessity, we have devised a touchless method to detect mask breaches in real-time by utilizing the emissive properties of the mask in the thermal infrared spectrum. Specifically, we use a specialized thermal imaging system to detect minute air leakage in masks based on the principles of heat transfer and thermodynamics. The advantage of this passive modality is that thermal imaging does not require contact with the subject and can provide instant visualization and analysis. These capabilities can prove invaluable for protecting personnel in scenarios with elevated levels of transmission risk such as hospital clinics, border check points, and airports.

Keywords: Thermography, epidemiology, facemask leakage, touchless monitoring

1. INTRODUCTION

With the emergence of Severe Acute Respiratory Syndrome (SARS) as an epidemic, one area of overt concern was respiratory droplet spread to incidental workers or bystanders. Potential transmission scenarios include health care settings [1], public transportation, and locations frequented by large numbers of people. When used properly, approved facemasks are effective physical barriers for preventing droplets from spreading viruses [2], however this is only true while the integrity of the mask is maintained and properly fastened [3].

We have devised a touchless method to detect facemask breaches in real-time. The method is based on the emissive properties of matter in the thermal infrared spectrum. All objects at finite temperature emit non-trivial amounts of electromagnetic radiation in the thermal infrared (3-14 μm). According to Planck's law the power of emission $M(\lambda, T)$ at a specific wavelength depends on the object's temperature as follows:

$$M(\lambda,T) = \frac{c_1}{\lambda^5}\left(\frac{1}{e^{(c_2/\lambda T)}-1}\right)\frac{W}{m^2-\mu m}, \tag{1}$$

where the first radiation constant , $c_1 = 3.7411\times10^8\, W-\mu m^4/m^2$, the second constant $c_2 = 1.4388\times10^4\ \mu m - K$, and λ is the wavelength expressed in μm. As the temperature increases, $M(\lambda,T)$ increases. The power of emission over several wavelengths can be obtained by integrating Equation (1):

$$M(\Delta\lambda,T)=\int_{\lambda_1}^{\lambda_2} M\left(\lambda,T\right)d\lambda\ , \qquad (2)$$

where $\Delta\lambda=\lambda_1-\lambda_2$. In our case, $\lambda_1=3\ \mu m$ and $\lambda_2=5\ \mu m$ since our sensing device operates in the Mid-Wave Infrared (MWIR) spectrum. Human breath is typically at a higher temperature than indoor air and background objects (e.g., walls) in climate controlled rooms. Therefore, it emits at higher power than its usual indoor surroundings according to Equation (2). This emission can be captured passively using a thermal infrared imaging system. It can be viewed easily by the untrained eye when the emission is viewed in front of a colder background. Complications arise from the fact that the material amount of human breath is rather small and diffuses quickly in the atmosphere. Thus, although breath is at a relatively high temperature, its emissive power is rather limited in volume and duration. High quality instrumentation, careful calibration, and appropriate algorithmic processing of the thermal imaging data can potentially overcome these problems and detect leakage of human breath from defective or worn-out masks.

1.1 Related work

There have been other attempts to detect or control the spread of airborne diseases through means of advanced technology, such as single point multi-spectral thermography for the detection of SARS [4], but we are the first group that we know of to utilize a thermal vision system to try and detect breaches in a face masks integrity. Perhaps the most relevant precursor to mask leakage detection is the body of work done on automatic breath detection. There are numerous documented approaches in the literature for automatically measuring the breath rate of a subject. These include contact modalities such as electrocardiograms (ECG)[5][6], and nasal temperature probes[7], as well as more relevant touchless modalities including radar [8] and thermography [9]. Our method does not need to directly measure the breath rate of a subject, but rather relies on the bi-product of the periodic breath cycle [10] to extract the necessary information for mask breach detection.

1.2 Organization

In the rest of the paper we first describe the specialized device we have designed for this project (Section 2) and then we outline our algorithmic method along with the experimental results (Section 2.1). We conclude the paper with a discussion of the potential applicability of this technology (Section 5).

2. METHODOLOGY

We have developed a thermal imaging system, to remotely detect facemask breaches due to punctures. The system (see Fig. 1) consists of the following components:

Fig. 1. The custom thermal imaging system used in our experiments.

1. A Phoenix InSb 320x256 Mid-Wave IR (MWIR) Camera with Real Time Imaging Electronics (RTIE)[11]. The Phoenix Camera Head has a 320x256 Indium Antimonite (InSb) sensor on ISC9803 readout integrated circuit, which is sensitive in the 3-5 μm waveband. The RTIE provides 14-bit digital output at 12.2 MHz, with a maximum full window frame rate of 60Hz. The camera features temperature sensitivity of 0.01^0 C.
2. A Mid-Wave IR (MWIR) 50mm Lens, f/2.3, Si:Ge, bayonet mount; It features a motorized focusing mechanism with RS-232 interface.
3. A Santa Barbara Infrared model 2004, 4" Differential Blackbody (-15^0C to 35^0C delta T) with RS-232 interface[12]. It features temperature sensitivity of 0.01^0C, which matches the temperature sensitivity of the camera.
4. A Quickset Pan Tilt Head (model QPT-90/1301C) 150 lb capacity. Pan 435^0, 8^0/sec. Tilt $\pm 90^0$, 3^0/sec[13]. It features RS-232 interface.
5. A consumer level computer.
6. A custom mobile platform.

The thermal imaging system operates in two modes: calibration and recording (see Fig. 2 and Fig. 3 respectively). The system features an automatic two-point calibration procedure against the black body. This automated calibration routine is performed upon initialization and approximately every three hours thereafter. We have determined experimentally that the camera sensitivity degrades to unacceptable levels approximately three hours after calibration (see Fig. 4). By having the system auto-calibrate periodically it maintains sufficient temperature sensitivity (0.01^0C) for experimental accuracy at all times.

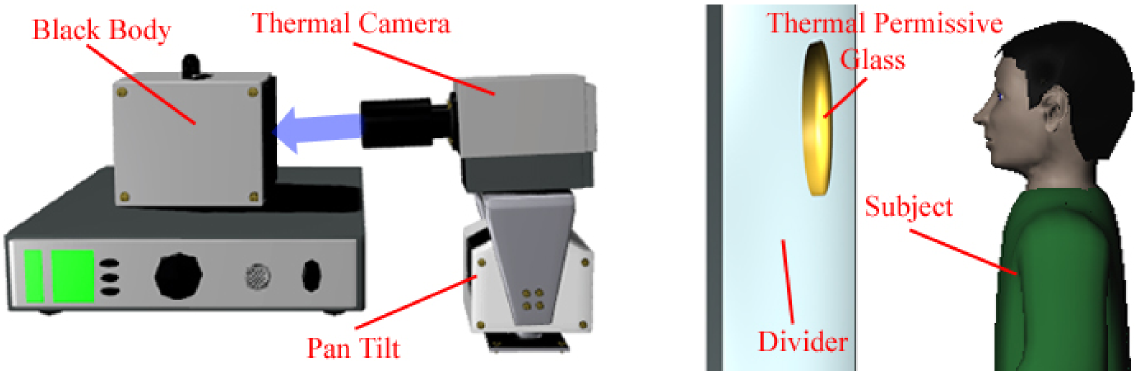

Fig. 2. The thermal imaging system in calibration mode. The camera's filed of view is being locked on the black body surface.

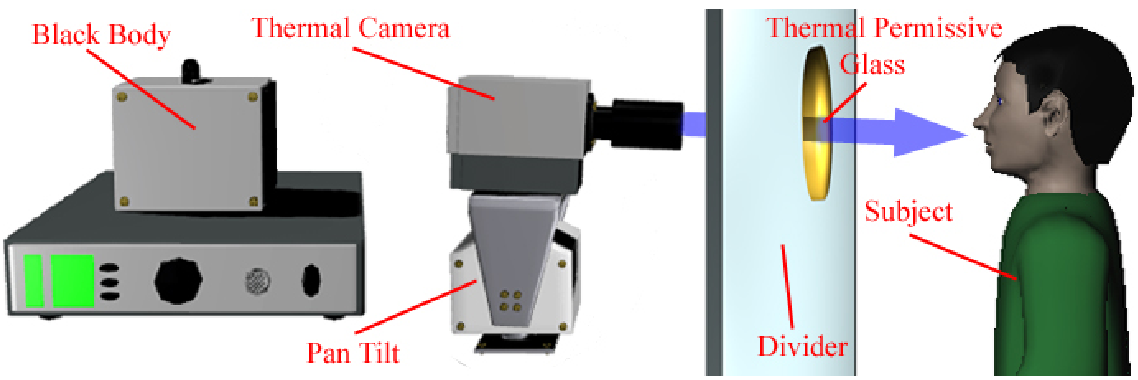

Fig. 3. The thermal imaging system in capturing mode. The camera's field of view is being locked on the subject's face.

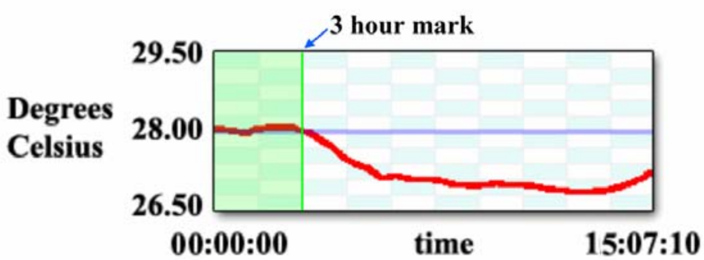

Fig. 4. Graph of the average drift in temperature accuracy during 15 hours of operation for our thermal imaging system. After the first three hours the imaging system introduces a non-trivial error in computing the absolute temperature of the medium. This may have detrimental effects in subtle measurements such as those of human breath.

The rigorous calibration process combined with the high quality of the hardware provides for extremely accurate thermal data. This data is collected when the system is in recording mode and locks on the face of the subject. A tracking algorithm interacts with the pan-tilt device to guarantee that the subject's face is centered in the image despite motion.

2.1 ALGORITHMIC PROCESSING

From the raw thermal imagery, facial features are identified and the facial contour is defined. An algorithmic process separates the breath from the background by subtracting the exhalation image from a reference image of the subject taken during inhalation. This differencing operation enhances the contrast between breath and the rest of the background (see Fig. 5(b)). Thermal currents emanating from the facial contour are then recognized and from these images any physical breach of the mask is easily identified (Fig. 5(e)). A novel algorithm that compresses non-linearly selected portions of the color map range aids the visualization by highlighting the air-leakage (Fig. 5(f)).

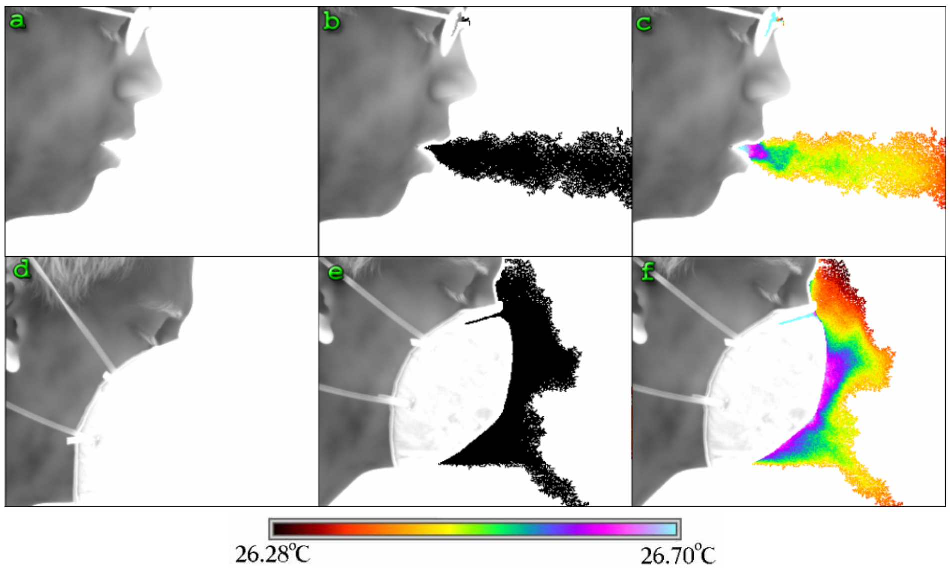

Fig. 5. Algorithmic steps demonstrated on a masked and unmasked subject. (a) Reference input image of subject inhaling. (b) Image of subject exhaling with the non-skin region subtracted from image 'a'. (c) Automatic breath colorization using our non-linear color-mapping scheme.(d) Reference input image of subject inhaling with a punctured mask. (e) Image of subject exhaling with the non-skin region subtracted from image 'd'. (f) Automatic breath colorization using our non-linear color-mapping scheme. The protruding air current is indicative of a tiny puncture in the facemask.

3. DATA

The seven subjects used in the experiment came from varying ethnic backgrounds and represented common levels of physical fitness. The represented fitness range is important because physical fitness is correlated with respiratory function, thus providing varying test cases for the experiment. Each subject wore 2 masks during the course of the experiment. The first mask was undamaged, the second mask was punctured with a 20 gauge needle. Each subject was imaged from both the profile and front views for both masks during the experiment.

4. RESULTS

When a subject is imaged from the side against a relatively cold background (e.g., wall), our method capitalizes on the higher emissivity of the leaked air stream from the mask (see Equations (1.1) – (1.2)) and the pinpoint puncture's condensed stream (see Fig. 6).

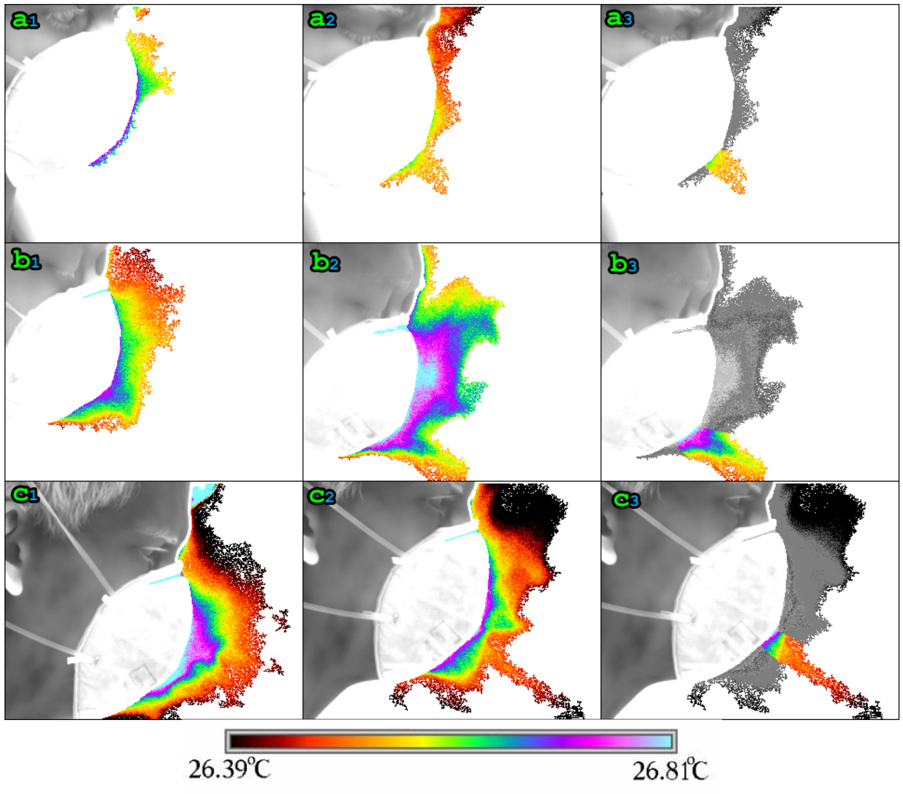

Fig. 6. Profile mask puncture detection on three subjects. (a1-b1-c1) Side view thermal images (60 frames/second, Indigo Phoenix Mid-Wave IR, 320x256 FPA) were recorded while three healthy subjects breathed through a facemask (N95; 1860, 3M, St Paul, MN). The method outlined in Figure 5 was applied to these images to automatically annotate the exhaled air. (a2-b2-c2) After collecting baseline thermal images for 20 sec, the mask was punctured using a 20 gauge (Terumo) needle. Thermal images were then captured for an additional 20 seconds. The protruding air stream from the needle-hole is apparent in all three cases. (a3-b3-c3) The visualization algorithm is adjusted to further highlight the leaking breath stream.

When a subject is imaged frontally, however, the background for the leaked air is the masked face of the subject, which is typically at about the same temperature as breath. Therefore, the discriminating advantage is lost in this view. However, the high pressure of the exhaled air that builds around the small punctured hole of the mask is responsible for producing a radial temperature elevation pattern. This characteristic pattern on the mask is indicative of air leakage during frontal imaging (see Fig. 7).

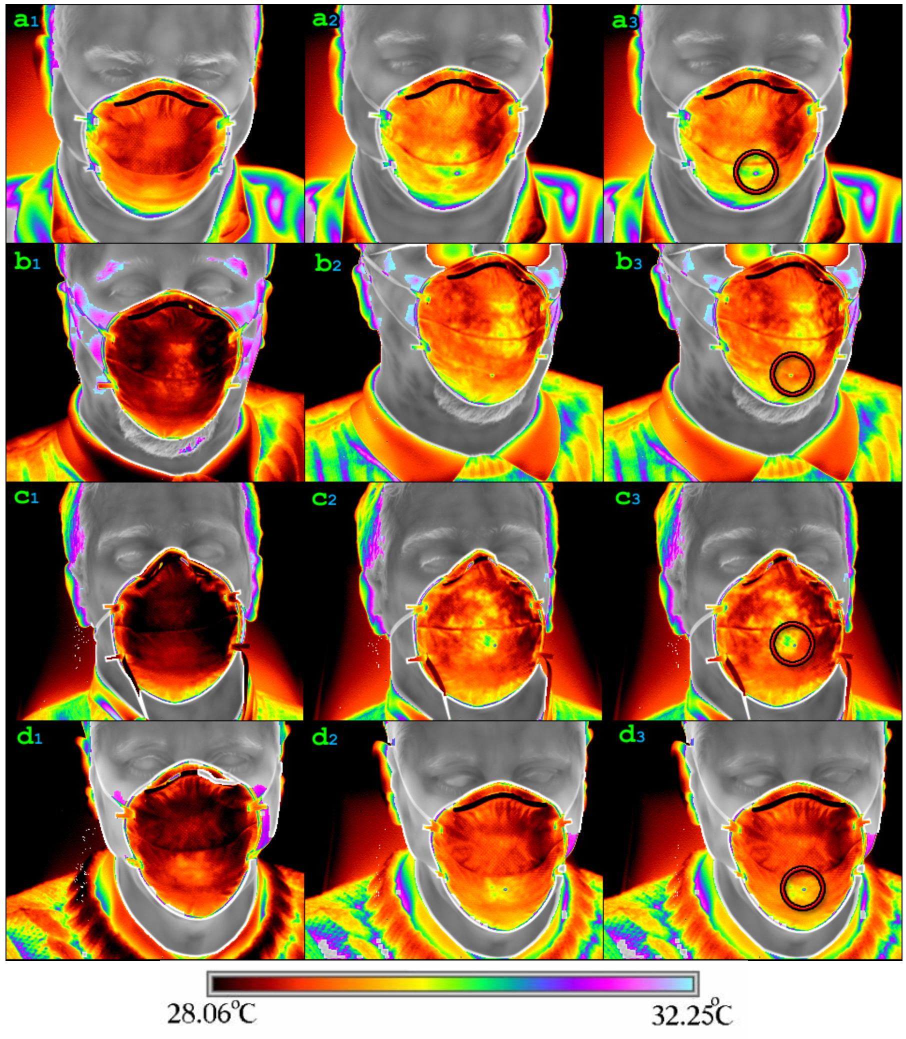

Fig. 7. Four masked subjects imaged frontally using the same procedure as in Fig. 6. Images a_1-d_1 depict the subjects breathing through an intact facemask. Images a_2-d_2 depict the subjects breathing through a punctured mask. Images a_3-d_3 are the same as images a_2-d_2 with the characteristic radial pattern around the needle-hole annotated.

By looking for the characteristic radial temperature elevation puncture pattern in the masks when the subjects were viewed from the front, we where able to identify all of the punctured masks. Likewise we where able to identify all of the punctured masks when the subjects where imaged in the profile view by looking for the protruding air stream from the needle-hole.

5. CONCLUSIONS

We have developed a system and a method for detecting minute air leakage in face masks. The approach is based on principles of heat transfer and thermodynamics and has been implemented using a specialized thermal imaging system. We have experimented successfully with seven different subjects wearing intact and punctured masks at frontal and side views. The advantage of this approach is that thermal imaging does not require contact with the subject and can provide instant visualization and analysis. Therefore, cameras could be placed remotely in hospital clinics, at border controls, or in airports. Where the protection of public servants from incidental infection with a host of respiratory agents has become highlighted as an area of major concern, thermal imaging might be broadly applied to adjunct respiratory isolation.

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*jbdowdal@Central.UH.EDU *ipavlidi@central.uh.edu #levine.james@mayo.edu