Modeling indoor Air quality and Aerosol Transport with Simulation Digital Twins

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1 Introduction

Concentration of different particles in the air in indoor environments determine the safety and comfort of people in many different applications. Existing operation modes of air quality monitoring and safety optimization do not take the concentrations of different respiratory aerosols or other pollutants into account. However, it could be used to significantly improve the safety of people susceptible to exposures to airborne diseases such as COVID-19, influenza and mitigate risk factors. It is of high importance in spaces such as hospitals and other healthcare facilities, classrooms in the context of public health and safety.

Several challenges make the implementation of sensor based systems that inform of risk factors pertaining to airborne viruses and other pollutants difficult. One of the challenges is the lack of sensor equipment for general use, existing devices are designed for specific application scenarios (e.g use for electronics manufacturing clean room facilty) and the high price of the devices render their use cost prohibitive in many general use cases. One of the alternatives is to use computational fluid dynamics (CFD) simulation as a proxy for physical sensors to inform the design and operation of indoor spaces and the air circulation. However, CFD simulations require significant compute power and difficult to set up without appropriate domain expertise for different environments. We aim to create smartphone based system that could be used to address the difficulties concerning the cost and compute and provide accurate results to the highest possible degree.

We aim to create simulation digital twins of physical systems that model indoor air quality monitoring risk associated with human respiratory droplets and aerosols which could be deployed in real life environments to inform, manage and mitigate risk factors associated with airborne pathogens and other pollutants. The plan is to also consider other pollutants relevant to health risks in addition to the respiratory aerosols. The digital twin model would be comprised of one or more machine learning-based models trained and validated using data from mobile and air quality sensor data and CFD simulation. In order to obtain reliable results, emphasis will be given on the incorporation of physics principles within the models to ensure that the predictions are consistent with laws of physics. Simulation based on CFD would also be used to potentially augment the models.

2 Data Collection

In order to develop the smartphone based system, we plan to collect data to develop machine learning models, potentially augment the collected data with data obtained from CFD simulation to improve and validate the models. For the data collection, we would like to propose the following stages-

1. **Controlled Laboratory Environment**: In this stage, we aim to validate and verify that all the devices for the data collection work as intended and collect a small volume of data. Analysis of the data from this stage will be used for proof of concept and potentially improve the plan for more extensive data collection.

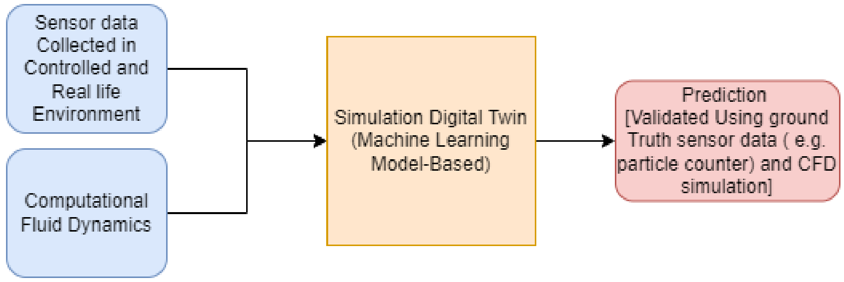

Figure 1: Simplified block diagram depicting the development of simulation digital twins

For this phase, the plan is to create a simplified version of a typical indoor space where monitoring respiratory emissions could be useful (e.g. modeled based on hospital room for diagnostic testing or classroom). The types of data to be collected include air quality parameters including the concentration of different size particles, levels of C02 and other pollutants, thermal imaging with human presence, and depth data for room contents (devices and sensors discussed in more detail in later section).

We plan to conduct experiment with simulated respiratory events using mannequins and cough simulation mechanisms. Several methods for simulating coughing, sneezing and breathing have been proposed in the current literature. For the initial phase, we plan to use simple mechanisms such pressurized canister as validated in [4] and utilize more complex setup such as proposed in [2, 3, 7] at later phase of the experiment. Complex simulators make use of adjustable spray nozzles or motors with metal bellows to control the intensity of simulated cough which the simplified mechanisms fail to produce and so would be included as part of the experiment. Moreover, although we plan to use single source of the respiratory events, we would also use multiple simulator tools. The use of human shaped mannequin with such mechanisms would also allow experiment with the use of face masks and other protective equipment. The captured data might also include video of droplet dispersion under UV light for the simulated cough (to be captured using RGB cameras under UV light). The placement of the smartphone and other sensors would be varied within the room for different instances of the data collection. In addition, the simulated cough source locations would also be varied. The data would be collected with the devices described in the next section. The collection protocol would include short periods of data collection with the simulation of cough or other events and continue the recording of data for at least fifteen minutes afterwards.

2. **Controlled Indoor public setting**: At this stage, the data collection would be performed in more realistic environment - spaces where we plan to deploy the developed systems such as rooms used for diagnostic testing(X Ray, MRI), hospital waiting room, classroom. The data collection at this stage may be performed for shorter period of time when the spaces are not open to the public. Some examples of this include an MRI Room not being used for actual patients, empty classroom. Specific constraints may be imposed such as number of human present in the room, the kind of activities performed by the humans and how the space is organized. Data from this stage will be used for developing preliminary versions of the model and address any potential issues that may arise for more extensive data collection experiment.

3. **Indoor public setting (Uncontrolled or In-the-wild)**: At this final stage, the data will be collected from realistic everyday setting without imposing constraints. This final stage will be deployed once it is validated that any potential issues and challenges have been adequately addressed.

We plan to collect the following types of data-

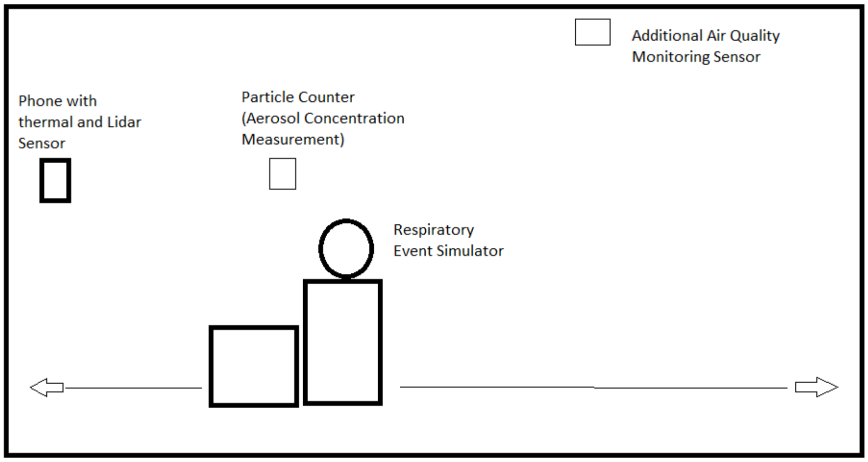

Figure 2: Simplifed figure depicting laboratory data collection experiment

- **Aerosol Concentration**: The concentration of particles of different sizes inside a room would be measured.
- **Non Speech Audio data**: In order to detect respiratory events such as coughing or sneezing audio data may be used. Models to ensure that speech data are not recorded would be integrated, however metadata such as intensity or volume of speech and location of the speech origin may be recorded since talking is also a contributing factor for respiratory aerosol droplet generation.
- **Thermal data**: Thermal data would be collected and would be used for getting temperature information inside the room and to detect the location and body temperature of the humans inside the room.
- **Image and depth data of indoor space**: Depth Cameras on Smartphone (Lidar) and RGB images will be used to get information regarding the structure and content of the indoor space (dimension, location of vents and doors, seating area arrangements) and used by the models and for CFD simulations.

2.1 Data Collection Devices

1. **Particle Counter**: The Fluke 985 device would be used for collecting information about aerosol concentration. This has previously been validated for use for collecting aerosol concentration information in public spaces [6] and lab environment [5].
2. **Air Quality Monitor**: Dylos DC 1100 Pro air quality monitor can be used to count small and large particles and would be used in conjunction with the Fluke 985 device. This device has been used for monitoring air in home environment [1].
3. **Smart Phone**: The iphone 13 pro includes a lidar sensor which would be used for collecting depth data and information regarding the room structure and distances. In addition to the lidar sensor, the RGB camera may also be utilized for empty rooms (no human present)- initially before setting up. The microphones in the smartphone would also be used to collect the audio data.
4. **Thermal Camera**: The FLIR ONE Pro device can be attached to smartphones and used for collecting thermal data.

(a) Fluke 985 Particle Counter

(b) Dylos DC 1100 Pro air quality monitor

Figure 3: Devices for measuring particles of different size and characteristics in the air, with varying levels of precision of support for different size particles (Fluke device to be used for capturing fine grained and Dylos devices for more coarse grained information)

Figure 4: FLIR ONE Pro thermal Camera

5. **Portable Hard Drive**: A 2TB portable hard disk drive may be used for data storage during the collection of data.

The data types and devices to be used are summarized in the following table -

Data Type	**Sensor Device (s)**
Particle Counts	Fluke 985 Particle Counter, Dylos DC 1100 Pro air quality monitor
Thermal Image	Flir One Pro
Depth Image	Lidar (iPhone)
Audio	Microphone (Smartphone)

2.2 Smartphone App for Data Collection

A smartphone application is planned to be developed to facilitate the data collection process and to be used as platform for initial proof of concept and potential deployment of the developed platform. This application would be used to capture all thermal, image and audio data. Initially, the app would be developed on iPhone platform since the devices contain Lidar sensor. The app will interface with the cloud and/or local server to store the collected data from different sensors. The proposed app will have two modes of operation:

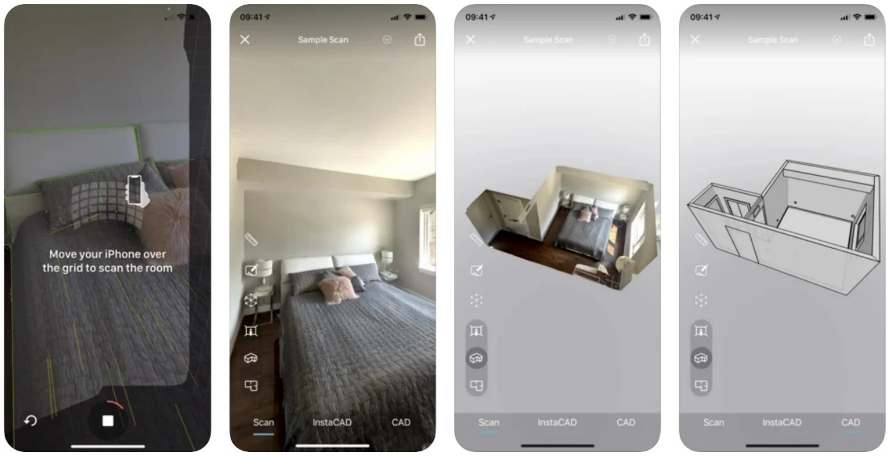

Figure 5: Example of room scanning using Lidar sensor (Image source: Canvas app iPhone app store listing)

Room Scanning Mode: The target is to capture the layout of the indoor space which includes the following

- Vertical and horizontal 2D layout or a combined 3D layout of the room structure (room content such as furniture may be omitted in the initial stage and added at later phase). Layout includes the location of air inlets and outlets in the room including doors and windows
- Dimension of the room - initially as manual input- to be inferred using lidar at later stage

The *Lidar* and RGB camera modules of the smartphone would be utilized to capture the aforementioned data types. The use of existing apps [1] [2] that utilize the lidar sensor for constructing 3D models and their potential integration with the app would be investigated. This mode needs to be operated initially and occasionally for calibration purpose.

Thermal Imaging and Audio Capture mode: The app during its operation would operate in this mode which entails continuous monitoring of thermal images and ambient audio.

Thermal images would be used for the detection of humans and capture the temperature variations within the room. This would require the use of the following

- Model to detect the presence of humans in thermal images and their location relative to the camera (Lidar data may be used in addition to the thermal image for obtaining distances)
- Potential inclusion of tracking different objects and humans in time at later phase

The Flir camera module would be used for capturing the thermal data.

Audio will be used for the detection and recording of human respiratory events such as cough and sneeze. Previously validated machine learning-based models would be used to achieve this. In addition continuous meta data such as the the volume of the speech data (no recording of the actual sound), their location relative to the camera would be collected.

The app would include options to customize frequency of the recording of each of the modality of data. The app would include option to view and remove the collected data.

The following table summarizes the sensors and data streams to be processed, the required processing steps and related information:

[1] https://apps.apple.com/us/app/canvas-lidar-3d-measurements/id1169235377
[2] https://apps.apple.com/us/app/polycam-lidar-3d-scanner/id1532482376

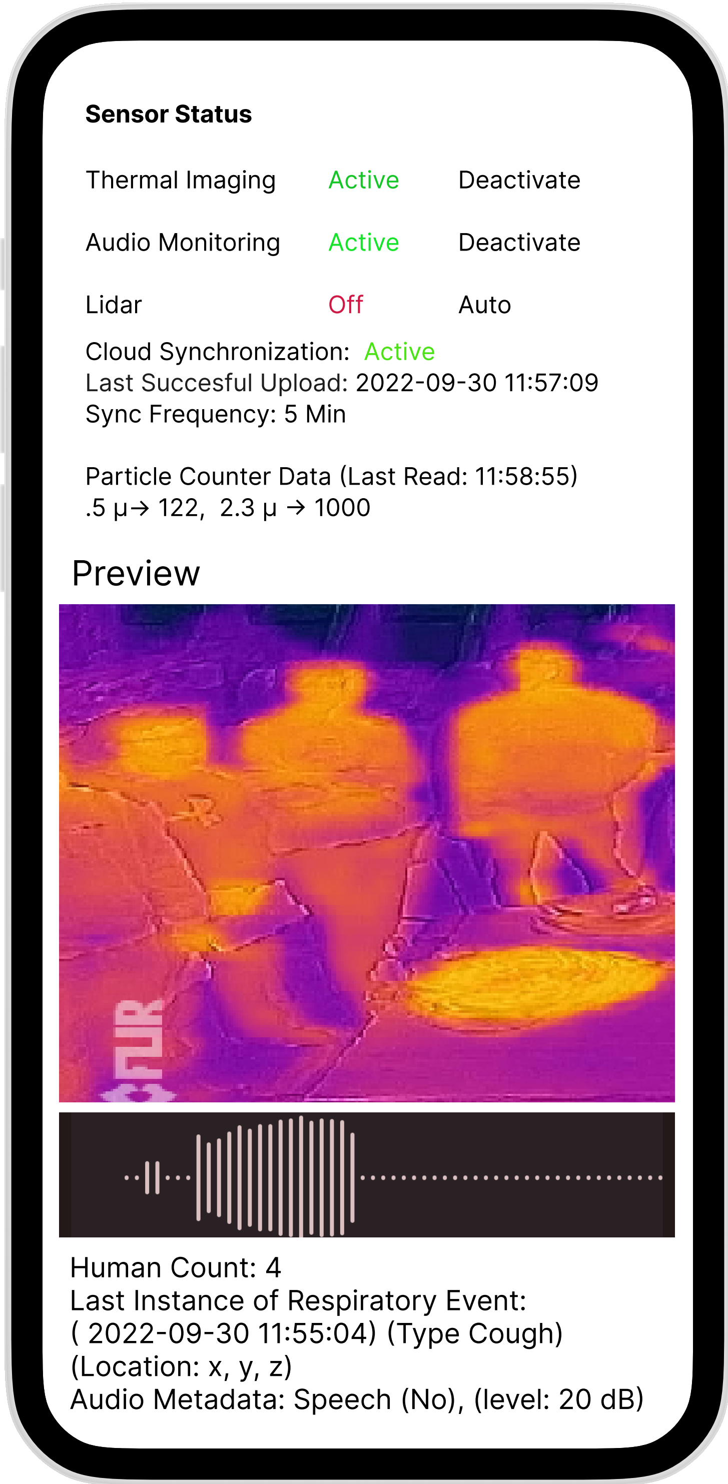

Figure 6: Sample Image of the application user interface during data collection operation mode

Sensor Type	***Interfacing***	**Data Stream type**	**Required Processing for data Collection**
Lidar (embedded in iPhone Pro Models)	data accessed through apple ARKit sceneDepth API, potential use of export from other scanning app without the API	depth map (similar to single channel image)	Extraction of distance information, processing to adjust units and scale
RGB (phone RGB camera module)	data accessed using UIImagePickerController API from phone camera	3 channel image and video	TBD
Thermal (FLIR Thermal Camera attached to smartphone)	Application and API from FLIR	single channel image, time series (depth video)	Post processing including image refinement, using ML models to find information such as people count, temperature within various zones inside room
Audio (internal phone microphone)	AVAudio Recorder API, Core ML Models	Audio data, extracted metadata (timeseries - csv format)	Extraction of metadata such as volume,presence of speech, detection and localization of respiratory events

3 Plan for Addressing Potential Privacy Issues

Since the data collection would involve human presence in the environments where the data will be collected, steps to ensure that any personally identifying information is not collected at any stage of the data collection process. The following measures would be used achieve this goals-

1. Personally identifying information will not be collected at any stage of the data collection process. RGB cameras may only be used in empty rooms initially and be turned off when people are present. Thermal camera image is expected to preserve privacy and permission from the participants may be acquired. Depth sensor would be utilized only for measuring distances.

2. Any speech audio would not be stored as part of the data collection process. Previously validated machine learning models would be used to distinguish the speech data from non speech data and all speech data would be discarded.

References

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