Augmented Reality for Massive Particle Distribution

Anna Bahnmüller*, Jan Wulkop*, Jonas Gilg*, Daniel Schanz†, Andreas Schröder†, Georgia Albuquerque*, Andreas Gerndt*§

* German Aerospace Center
Lilienthalplatz 7
38108 Braunschweig
anna.bahnmueller@dlr.de
jan.wulkop@dlr.de
jonas.gilg@dlr.de
georgia.albuquerque@dlr.de

† German Aerospace Center
Bunsenstraße 10
37073 Göttingen
daniel.schanz@dlr.de
andreas.schroeder@dlr.de

§ University of Bremen
Bibliothekstr 1
28359 Bremen
andreas.gerndt@dlr.de

Abstract: Understanding the behavior of aerosol particles remains a key concern especially during the current corona pandemic times. In this paper, we present a method for visualizing the distribution of aerosol particles in augmented reality (AR) using the Microsoft Hololens device. We use this technology to obtain better spatial perception of particles in the real world which are invisible to the naked eye. As a case study, we show the flow field of exhaled aerosols with and without wearing a mask. To do this, we first measure the particle flow under laboratory conditions. Then we trace a certain amount of exhaled particles. Using the particle system component of the Unity game engine, our AR application also takes each particle's 3D position into consideration. Furthermore, 3 different particle visualization approaches are evaluated to develop the ability to visualize the maximum number of particles on Microsoft HoloLens without compromising on visual quality. Finally, we were able to show virtual particles in the real world. Without mask they propagate forward and with mask they ascend. With an optimized implementation, we achieved a simultaneous display of nearly 80,000 moving particles at an average rate of 35 frames per second.

Keywords: Particle system, Visualization, Augmented Reality, Microsoft HoloLens 2

1 Introduction

The current COVID-19 pandemic, also known as the coronavirus pandemic is a challenging case throughout the world and affects everyone. In particular, there is a risk of infection to humans through the exhalation of a large amount of small particles called aerosols. These particles, which are invisible to humans in the real world, are present in space for an extended period of time. Due to their small size and the associated high air friction, aerosols sink very slowly to the ground. To a first approximation, they behave like large gas molecules. Geometrically, aerosol particles of a size of 5 µm can carry more than 10,000 viruses. In the literature various techniques have been used to investigate the protective effect of different types of masks with different particle sizes. In particular, when coughing, speaking, sneezing or breathing. In these measurements, large amounts of data are collected in time-consuming laboratory preparations, and the exhaled particles distribution is recorded and processed with cameras. The results can be displayed in a 2D format as video or image. However, a video is not fully capable of conveying the real world perception of 3D datasets, therefore, more immersive visualization approaches such as Augmented Reality (AR) or Mixed Reality (MR) are needed.

The goal of this paper is to use AR to visualize large amount of aerosol particles with real world 3D perception. AR is one of the latest trends in visualization technologies. By overlaying virtual content onto the real world, the ability to visualize invisible quantities and materials can be developed. AR systems that employ holographic lenses and render virtual objects can help to improve perception. Nowadays, standalone and wireless AR headsets, like the Microsoft Hololens, allow users to move freely around virtual objects. On the downside, however, it has limited computing power due to its compact form. Using different scenarios (with and without mask), we illustrate the measured dispersion of a variable number of virtual particles in AR. In order to represent them fluidly, different methods are investigated.

The main contributions of this paper are: a new technology for measuring the distribution of particles behaving like aerosols, with and without a mask; a visualization method of predefined particle quantities based on particle flow using the Hololens; a technical evaluation of different methods for real-time visualization.

First, we give an overview of the related work in section two. In section three, the particle measurement under laboratory conditions is briefly described. Based on these results, we explain the particle tracing in section four and present the visualization in AR in section five. In section six, we evaluate the performance of particles in our application in AR. Finally, conclusions are drawn and an outlook for further research opportunities is given.

2 Related Work

In this section, we summarize previous work that uses particle systems to visualize different particles in various use cases in AR. Further, literature on aerosol particle studies is presented which is relevant to our work.

2.1 Particle System in AR

Over the last few years, previous studies have applied particle systems to visualize various moving particles in AR and pointed out their benefits. Heinrich et al. [HTM08] used a particle system on a belt mounted AR computer to provide the impression of different forms of phenomena such as raindrops, snow or hail. Hedley et al. [HL12] went a step further and used a tablet/smartphone to visualize raindrops interacting with a real water surface. Weir et al. [WSS+13] used a head-worn display to visualize virtual flames and smoke to create the illusory experience of burning hands. Asgary et al. [ABF19] used the Microsoft Hololens to visualize volcanic eruptions. Specifically, they reported it can be used for training, public education or entertainment. Our application also gives an impression of particle distribution in the real world. In contrast to previous work that used particle systems to generate special effects, we have developed a particle system that visualizes a predefined number of particles based on generated position data.

2.2 Aerosol Particle Studies

A lot of literature in aerosol research is available investigating tidal breathing in more detail. Depending on the measurement approach and individuals involved, various results with different counts of particles have been produced.

Fabian et al. [FBH+11] investigated human rhinovirus (HRV)-infected subjects and measured a particle concentration between 0.1 and 7,200 particles per liter (p/L) of exhaled air with an aerosol size between 0.3 and 0.5 µm. In a previous study they found 67 to 8,500 particles with a diameter of less than 1 µm. Other studies by Bake et al. [BLL+19] reported aerosol concentrations in the breath of healthy humans of 98 p/L of sizes between 0.5 and 20 µm, whereas Scheuch et al. [Sch20] reported a particle concentration of a few tens to several thousand p/L for particles smaller than 5 µm. Edwards et al. [EMB+04] used a Fleisch pneumotachograph with a connected T-adapter with a six-channel optical particle counter to measure the number and size of exhaled particles. He showed that particle concentrations in tidal breathing of participants ranged from 1,000 to 10,000 particles per liter of air with a particle size < 1 µm.

For the visualization of particle distribution, a variety of techniques are used. One of them is background oriented schlieren (BOS) imaging using a medical simulation mannequin [VPP+21]. Verma et al. [VDF20] used a fog machine, where the smoke emitted by a coughing manikin is shown with the help of a laser source. Other approaches are 3D-simulations [DD20] and images of 2D-simulations [JPGM20].

In contrast to previous studies to visualize particle distribution, we use AR to provide an intuitive way to depict how particles disperse in real-world environments with regard to particle counts. The present depth perception in AR is particularly significant in this context.

3 Particle Measurement

In a dedicated laboratory, we measured the particle flow exhaled when wearing a mask and without a mask, and then visualized the particle distribution in real time using an AR device. Our goal is to investigate different methods to fluently represent a large number of particles as well as to improve the spatial perception of particle distribution in reality using AR.

As part of a series of experiments under laboratory conditions, we have analyzed the influence of masks on the breathing flow and thus on the dispersion of aerosols in the environment. We performed a large-scale 3D Lagrangian Particle Tracking (LPT) experiment that allows instantaneous tracking of up to 3 million submillimeter helium-filled-soap-bubbles (HFSBs)

[BKW09] as passive tracers in a 12 m^3 generic test room. The measurement allows to resolve the flow field in the complete room around a cyclically breathing, heated thermal manikin with and without mouth-nose-masks (see Fig. 1). We combined six high-resolution CMOS streaming cameras, an array of powerful pulsed LEDs and the Shake-The-Box [SGS16] LPT algorithm.

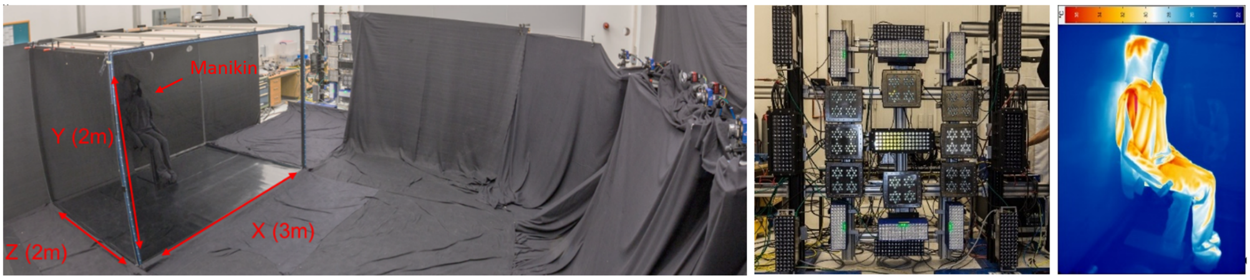

Figure 1: (Left) Experimental set-up with a seated manikin in a 12 m^3 glass room, and imaging system with six high-resolution CMOS cameras; (middle) LED-array for illumination of the full room; (right) thermographic image of the heated manikin.

After 3D calibration, up to 3 million long-living and neutrally buoyant HFSBs with 370 µm mean diameter were introduced into the room using four nozzles in the back wall of the room, connected to a LaVision HFSB generator. After stopping the HFSB seeding, we waited 2 min to allow the disturbed flow to settle before starting image acquisition using a DaVis10.x software package. The large-scale illumination of the entire room was realized using a planar arrangement of pulsed LED arrays (see Fig. 1). The DLR implementation of the Shake-The-Box (STB) method [SGS16] has been applied for the evaluation of the gained time-series of particle images captured by the camera system at 26 Hz over time spans of 50 seconds for each test case. The resulting Lagrangian particle trajectories allow following between 1.5 and 3 million individual HFSBs in time and space inside the complete volume of the 12 m^3 room (see Fig. 2, top for a case of heavy breathing with and without mask). Subsequently, the data assimilation method FlowFit [GHSS16] has been applied to the STB data. In this step, the parameters of a grid of cubic B-splines are fit to the discrete particle information (velocity and acceleration), while using flow physics information via a regularization by the Navier-Stokes equations. The resulting system of B-splines for each time-step constitutes a continuous function in space, which can be arbitrarily sampled, providing time-resolved 3D velocity gradient and pressure fields. The complete Eulerian representation of the flow field enables additional insights into the turbulent mixture by vortical flow structures in the room which are mainly forced by the cyclic breathing and the thermal plume of the heated manikin (see Fig. 2, bottom).

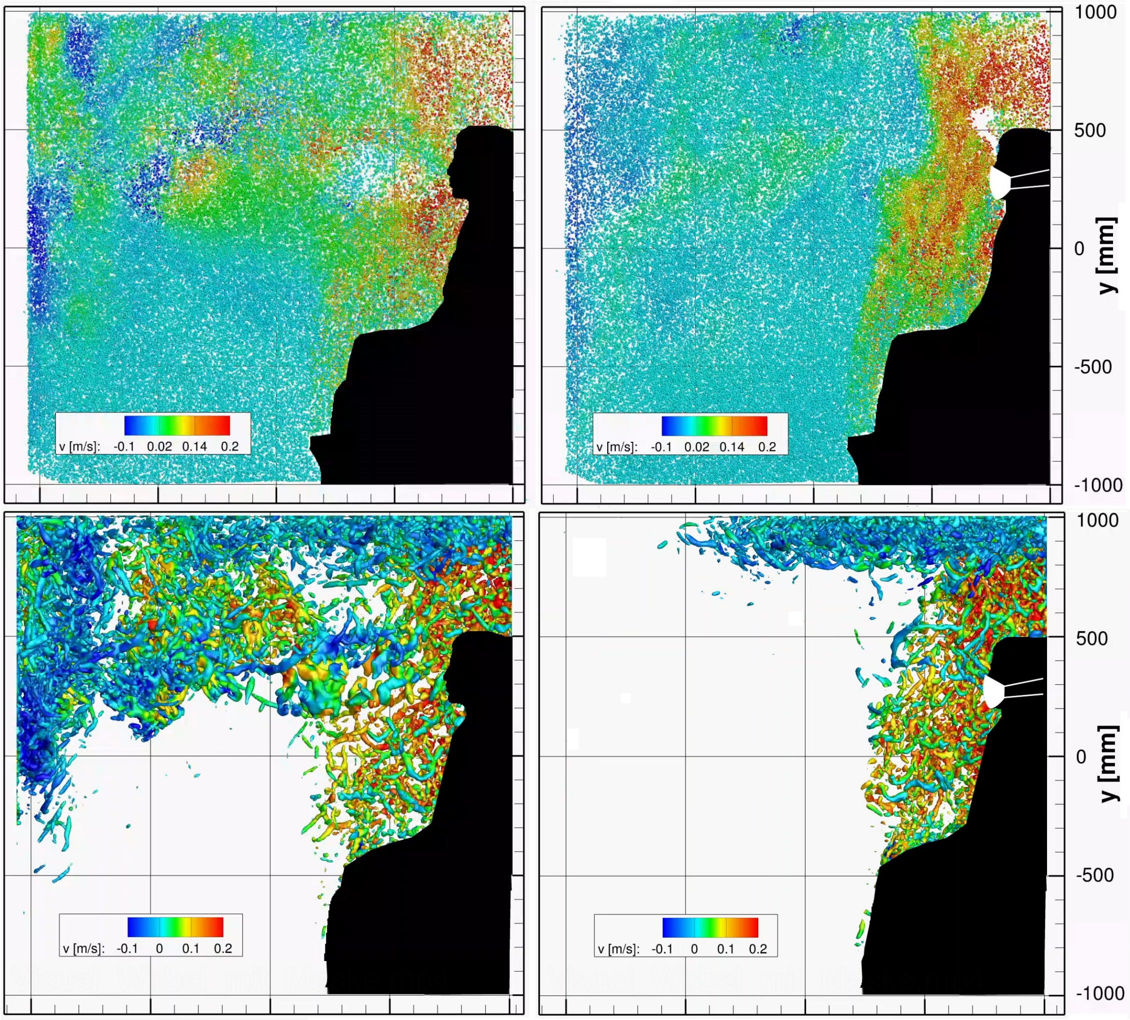

Figure 2: Tracking of millions of HFSBs in 3D using 'Shake-The-Box' in a 24 cm (out of 300 cm) thick slice in the y-z plane for a heavy breathing case without (left, top) and with (right, top) face mask; related vortical structures in the full 12 m^3 volume based on FlowFit data assimilation without (left,bottom) and with (right, bottom) face mask. Colour coded vertical velocity.

4 Particle Tracing

The measurements resulted in a total of about 160 GB of particle stream data for each of the two scenarios. The results gained from the STB particle tracking with subsequent FlowFit interpolation were used as input for the particle tracing in ParaView[1]. The FlowFit B-spline system was sampled on a grid of 202 x 136 x 140 cells with a resolution of 1.5 cm and converted to the VTK file format. This was done for faster and easier detection and separation of exhaled particles, as well as the ability to vary the number of particles independently. The temporal dimension contains 1130 timesteps and has a resolution of 0.04 s between steps. We used the ParaViews particle tracer to advect aerosols through

[1] https://www.paraview.org/

the dataset. Particles were injected in front of the dummy's mouth using a point source. Particle injection was performed at all time steps at which the dummy exhaled to ensure that the particles represented aerosol flow. The time steps were selected by analysis of the velocity field. Since only respiration information was used for AR, the amount of data to be processed initially could be reduced to 0.5 - 1 GB.

In the scenario without mask, exhalation was evident by a very high velocity change on the z-axis (horizontal axis in viewing direction). In the scenario with mask, it was observed that the air flowed out of the top and bottom of the mask. This was measured by small increases in the absolute y-axis velocity component. The amount of particles traced without a mask was chosen based on the results in [EMB+04]. Here, a particle concentration of 1 up to 10,000 particles per liter of air was measured during normal breathing. The upper limit of 10,000 particles was chosen, to obtain better visual results in AR. Since each breath contains about 500 ml of air, this results in approximately 5,000 traced particles per breath.

During the laboratory measurement in section 3, no particles were generated by exhalation in the first few seconds, resulting in a total particle tracing time of 42 seconds. The 42 seconds of data contained eight whole breathing cycles and thus 41,279 particles were traced through the dataset.

The particle counts for the second scenario were based on the findings of Gawn et al. [GCMC08] and Asadi et al. [ACB+20], who reported a sixfold reduction in particle outflow when wearing a mask. Therefore, around 830 particles were injected in each breathing cycle and 6,583 particles were injected in total over the entire 42 seconds. Our results are shown in Fig. 3, where the particle distributions after the 42 seconds are shown in ParaView. The colors of the particles indicate the time since injection, with red representing the newest particle and green representing the oldest.

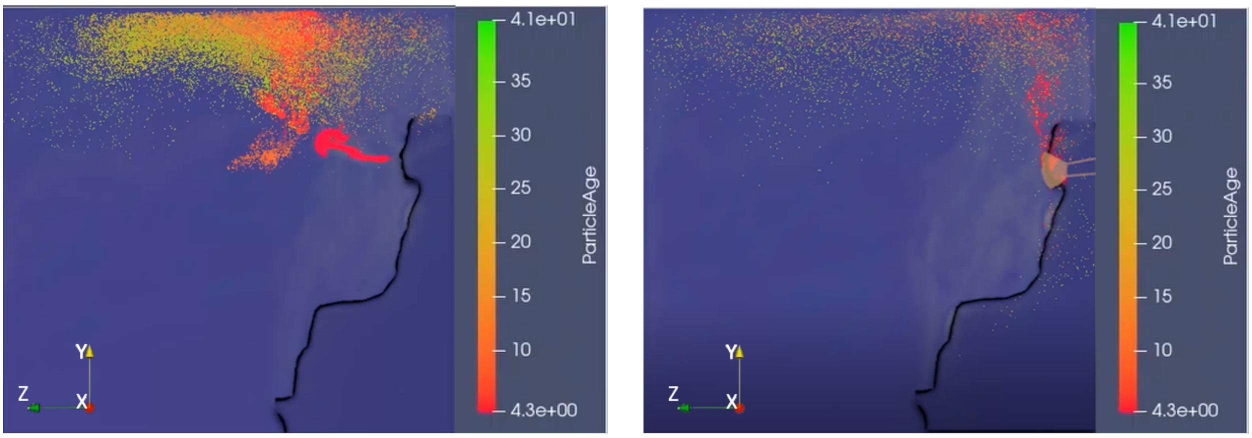

Figure 3: Left: Particle distribution without a mask. Around 41,000 particles are exhaled forward for a total of 42 seconds, 8x breathing. Color coded particle age in seconds. Right: Particle distribution with a surgical mask. For 42 seconds, a total of about 7,000 particles are distributed around the mask and ascend. Color coded particle age in seconds.

5 Particle Visualization in AR

The aim of this work is the efficient representation of aerosol particles in AR. Here, the user should be able to view the particle distribution in space as freely as possible and unbound by cables. Consequently, the AR device has to be mobile, autonomous, but also powerful in order to be able to represent even large amounts of particles fluently. Based on these criteria, we chose the second generation Microsoft HoloLens. The HoloLens is a stand-alone AR headset, able to perform all necessary rendering on the device itself without a stationary computer. Using the two screens built into the glasses and a combined field of view of 43° x 29°, virtual, three-dimensional content is projected into the real environment. The HoloLens uses a combination of a Qualcomm Snapdragon 850 Compute Platform and a coprocessor called Holographic Processing Unit [Qua21]. The CPU within the compute platform is a 64-Bit ARM based processor with 8 processing cores and a total of 4 GB memory of which 2 GB can be used by an application [Mic20]. The Unity3D graphics engine[2] serves as the basis for our Hololens application.

In order to visualize the particles on the AR-device, our application must be able to parse the particle position at each time from the given dataset. To prevent the application from regularly accessing the file system at runtime to read the dataset, we developed an asset importer that preprocesses the VTK data exported from ParaView before compiling the application. Positions and time steps are stored in lists that are loaded into main memory at device initialization to allow fast data access. In order to visualize as many particles as possible at the same time, we introduced several approaches for performant particle visualization. These approaches are explained in more detail in section 6.

When starting a HoloLens application, the origin of the used coordinate system is reinitialized. This means that the virtual objects are always dependent on the Hololens' initial position and thus appear at a different location in space each time the application is launched. To constantly view the particles at the mouth or mask, the application must recognize the right arrangement in space. We use the Vuforia library and two different image targets (Vuforia markers[3]) with a size of about 3 cm x 3 cm to always be able to set the appropriate position. One is placed on a person's mouth, while the other is placed on a surgical mask. At a short distance of about 10 - 15 cm between the marker and the AR headset, the markers are detected by the HoloLens 2's integrated camera. The positions of the particles in the data set can then be transformed in relation to the detected mouth or mask, resulting in the particles being displayed in three-dimensional space at the correct location. The results of the particle distribution in AR are shown in Fig. 4. During normal breathing, around 40 thousand particles are displayed without a mask in Fig. 4 (left), and around 6,5 thousand particles are presented with a mask in Fig. 4 (right). This corresponds to the amount of particles generated in section 4. As depicted in Fig. 4 (middle), a data set of roughly 80 thousand particles with a size of 1 mm was taken to better observe the particle dispersion

[2] https://unity.com/

[3] https://library.vuforia.com/

using a surgical mask. These visualizations show the difference in particle dispersion in particular. Particles are expelled forward without a mask, but they disperse upward with one.

Figure 4: Virtual particle distribution in real environment seen through a Hololens 2 providing depth perception. Left: In 42 sec, around 40,000 particles are exhaled forwarded without a mask. Middle: Using approx. 80,000 particles in total to better visualize spreading with a surgical mask. Right: Based on tracing results, around 6,500 particles with a surgical mask disperse upwards.

6 Evaluation of the Particle Performance in AR

We wanted to visualize the particle distributions in AR using only the HoloLens. However, due to the compact form factor of the HoloLens, the available computing power is limited. Especially in virtual reality but also in AR, it is advisable to achive a framerate of at least 30 frames per second (FPS) in order to minimize discomfort wearing the glasses.

In a first approach, we considered each particle as a separate object updating its position at a given frequency. Each particle reads its next position from dataset based on the current global application time and its particle index. Using this approach, about 80 thousand particles were created as separate objects within Unity Engine. We created individual particles as a two-dimensional circle that is always oriented towards the user's eyes. In that way, we were able to avoid rendering a three-dimensional model per particle and replaced it with an easier-to-render two-dimensional texture of a circle.

To evaluate the performance of the application, we measured the average, maximum and first percentile minimum framerate as well as the CPU time spend in each function call. The first percentile framerate is the lowest framerate of the 99% fastest rendered frames. This metric is more stable than the minimum framerate, since individual outlier frames strongly affect the minimum framerate. Especially at the beginning of an application, the calculation of a single frame once can take significantly more time.

We tested the application with three different data sets: The first is a dataset with 41,279 particles acquired without a mask, and the second is a data set with a mask. The second dataset comes in two quality levels: one with 6,883 particles and the other with 79,245 particles.

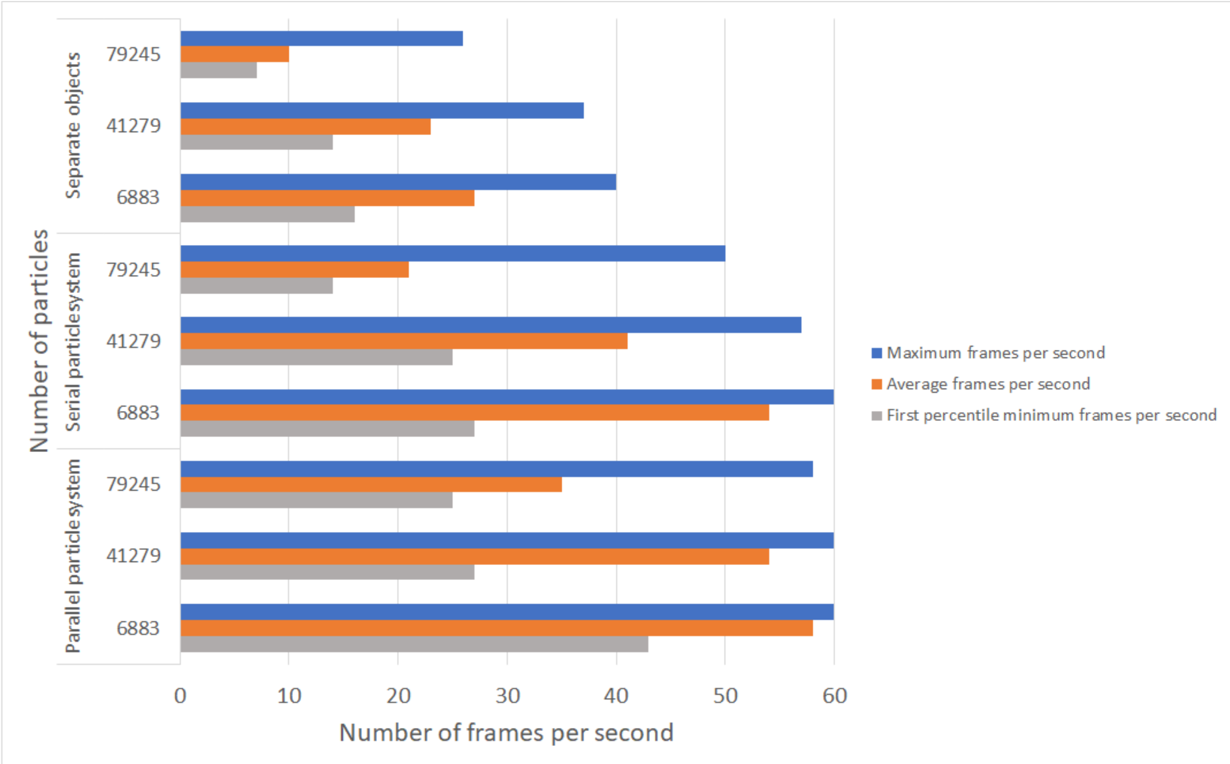

Figure 5: Application performance measured in frames per second

The application's performance is determined by the maximum number of visible particles at the same time. With our first approach, none of our datasets could be visualized with a sufficient frame rate (see Fig. 5, average frames per second for separate objects). Each particle position was updated an average of 73.4 ms per frame in the application with the largest data set. Although the operations required to update each particle position are simple, the administrative overhead slows down the application. Since we represent each particle as a separate object within the engine, this overhead increases linearly with the total number of particles.

Therefore, we have combined the particles into a single particle system. These are used when many small images or meshes are densely spaced and needed to be rendered for a visual effect, such as simulating smoke or fire. In our second approach, we used the performance-optimized particle system integrated into the Unity Engine. In this, the entire lifecycle of each particle, from instantiation to animation to disposal, is controlled. The benefit is that each particle does not require a separate object with associated overhead to be loaded into the scene. Instead, the Unity Engine manages it internally. Our application logic must control the particle system so that the particles appear in the right place at the right time. A self-written file importer is used to read in the dataset. Important parameters, such as the total number of particles and the time steps, are automatically determined and stored in the particle system. Using stored particle indices with corresponding time steps, the particle number and position could be efficiently determined and visualized at runtime. In addition, we used the "Unity Particle System job" to be able to change the particle positions at runtime. With the new approach, we were able to double our average frame rate for the larger dataset (see Fig. 5, serial particle system). However, even with this approach, particle positions are updated individually and serially.

Since the particle positions are known at the beginning of each time step, we assumed that setting all particle positions in parallel rather than serially would significantly reduce the computation time per frame. Such operations can be shared among the processor cores of the HoloLens. To parallelize the position setting, we used an extension of the Unity engine called Burst, which supports the Unity C# Job System. Burst compiles program code for Unity applications into bytecode optimized for parallel execution. Finally, in Fig. 5, the last three columns show the maximum, the average, and the minimum first-percentile frame rates of the third approach when visualizing the three particle data sets. It can be clearly seen, that by updating the particle positions in parallel, the required computation time per frame can be reduced, increasing the number of FPS. With this approach, we achieve the hardware constrained upper limit of the HoloLens screen of 60 FPS when visualizing the small and medium dataset.

7 Conclusion and Future Work

In this paper, we have presented a HoloLens framework to visualize a large set of particle distributions based on their position. In terms of our use case, our goal was to get a better idea and sense of how particles propagate in an enclosed space with and without a mask, as well as how to render them fluently in real world. With a use case inspired by the current Corona pandemic, we first measured the flow-fit data under laboratory conditions, using small helium-air-filled bubbles to represent aerosols. The result of the experiment was further processed to trace the outflowing particles from the mouth. The final data was used to visualize particle distribution in AR based on where different markers were placed on a real mask worn by humans, as well as where they were placed on the mouth. As a result, it can be seen that without a mask the particles are distributed to the front, while with mask the particles disperse upward. Further, we evaluated different methods to display as many particles as possible simultaneously on the HoloLens' limited computational capacity. We demonstrated that particle performance can be improved when all computational cores are used in parallel to update the particle system at an average of 35 frames per second.

For future work, our results are reproducible. And due to the easy handling of the hololens, the particle distribution can be displayed at any time and any place. Our framework is easily extensible. The number of emitted particles can be variably adjusted and additional particle information can be superimposed. Processing data from simulation instead of measurements can also be an interesting point in the study of particle dispersion.

This can lead to future research topics by studying the interaction and behavior of virtual particles colliding with real walls.

Independent of aerosol distribution, our framework can also be used for other use cases with corresponding dataset with comma separated values to represent particle distributions. Ultimately, advances in AR technology can provide new ways to interact with invisible quantities.

Acknowledgment

We acknowledge Johannes Bosbach, Reinhard Geisler, Andreas Kohl, Janos Agocs, Carsten Fuchs, Tobias Herrmann and Tobias Kleindienst for their contribution to the large scale experiment. We thank Azeem Syed Muhammad for his feedback during the writing of this paper.

References

[ABF19] Ali Asgary, Costanza Bonadonna, and Corine Frischknecht. Simulation and visualization of volcanic phenomena using microsoft hololens: Case of vulcano island (italy). *IEEE Transactions on Engineering Management*, 67(3):545–553, 2019.

[ACB+20] Sima Asadi, Christopher D Cappa, Santiago Barreda, Anthony S Wexler, Nicole M Bouvier, and William D Ristenpart. Efficacy of masks and face coverings in controlling outward aerosol particle emission from expiratory activities. *Scientific reports*, 10(1):1–13, 2020.

[BKW09] Johannes Bosbach, Matthias Kühn, and Claus Wagner. Large scale particle image velocimetry with helium filled soap bubbles. *Experiments in fluids*, 46(3):539–547, 2009.

[BLL+19] Björn Bake, Per Larsson, Göran Ljungkvist, Evert Ljungström, and Anna-Carin Olin. Exhaled particles and small airways. *Respiratory research*, 20(1):1–14, 2019.

[DD20] Talib Dbouk and Dimitris Drikakis. On respiratory droplets and face masks. *Physics of Fluids*, 32(6):063303, 2020.

[EMB+04] David A Edwards, Jonathan C Man, Peter Brand, Jeffrey P Katstra, K Sommerer, Howard A Stone, Edward Nardell, and Gerhard Scheuch. Inhaling to mitigate exhaled bioaerosols. *Proceedings of the National Academy of Sciences*, 101(50):17383–17388, 2004.

[FBH+11] Patricia Fabian, Joseph Brain, E Andres Houseman, James Gern, and Donald K Milton. Origin of exhaled breath particles from healthy and human rhinovirus-infected subjects. *Journal of aerosol medicine and pulmonary drug delivery*, 24(3):137–147, 2011.

[GCMC08] Jonathan Gawn, Mike Clayton, Catherine Makison, and Brian Crook. Evaluating the protection afforded by surgical masks against influenza bioaerosols: gross protection of surgical masks compared to filtering facepiece respirators. *Buxton: Health and Safety Executive*, 33, 2008.

[GHSS16] Sebastian Gesemann, Florian Huhn, Daniel Schanz, and Andreas Schröder. From noisy particle tracks to velocity, acceleration and pressure fields using b-splines and penalties. In *18th international symposium on applications of laser and imaging techniques to fluid mechanics, Lisbon, Portugal*, pages 4–7, 2016.

[HL12] Nick Hedley and Chris Lonergan. Controlling virtual clouds and making it rain particle systems in real spaces using situated augmented simulation and portable virtual environments. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 39:B2, 2012.

[HTM08] Marko Heinrich, Bruce H Thomas, and Stefan Mueller. Arweather—an augmented reality weather ystem. In *2008 7th IEEE/ACM International Symposium on Mixed and Augmented Reality*, pages 187–188. IEEE, 2008.

[JPGM20] Mahesh Jayaweera, Hasini Perera, Buddhika Gunawardana, and Jagath Manatunge. Transmission of covid-19 virus by droplets and aerosols: A critical review on the unresolved dichotomy. *Environmental research*, page 109819, 2020.

[Mic20] Microsoft. About hololens 2, 10 2020. `https://docs.microsoft.com/en-us/hololens/hololens2-hardware`. Accessed: 2021-05-21.

[Qua21] Quallcomm. Snapdragon 850 mobile compute platform, 2021. `https://www.qualcomm.com/products/snapdragon-850-mobile-compute-platform`. Accessed: 2021-05-21.

[Sch20] Gerhard Scheuch. Breathing is enough: for the spread of influenza virus and sars-cov-2 by breathing only. *Journal of aerosol medicine and pulmonary drug delivery*, 33(4):230–234, 2020.

[SGS16] Daniel Schanz, Sebastian Gesemann, and Andreas Schröder. Shake-the-box: Lagrangian particle tracking at high particle image densities. *Experiments in fluids*, 57(5):1–27, 2016.

[VDF20] Siddhartha Verma, Manhar Dhanak, and John Frankenfield. Visualizing the effectiveness of face masks in obstructing respiratory jets. *Physics of Fluids*, 32(6):061708, 2020.

[VPP+21] Ignazio Maria Viola, Brian Peterson, Gabriele Pisetta, Geethanjali Pavar, Hibbah Akhtar, Filippo Menoloascina, Enzo Mangano, Katherine E. Dunn, Roman Gabl, Alex Nila, Emanuela Molinari, Cathal Cummins, Gerard Thompson, Tsz-Yan Milly Lo, Fiona C. Denison, Paul Digard, Omair Malik, Mark J. G. Dunn, Catherine M. McDougall, and Felicity V. Mehendale. Face coverings, aerosol dispersion and mitigation of virus transmission risk. *IEEE Open Journal of Engineering in Medicine and Biology*, 2:26–35, 2021.

[WSS+13] Peter Weir, Christian Sandor, Matt Swoboda, Thanh Nguyen, Ulrich Eck, Gerhard Reitmayr, and Arindam Day. *Burnar: Involuntary heat sensations in augmented reality.* IEEE, 2013.