Improving Understanding of Biocide Availability in Facades through Immersive Analytics

Negar Nouri*  Snehanjali Kalamkar†  Forouzan Farzinnejad‡  Verena Biener§  Fabian Schick¶  Stefan Kalkhof||  Jens Grubert**
Coburg University of Applied Sciences and Arts, Germany

ABSTRACT

The durability of facades is heavily affected by multiple factors like microbial growth and weather conditions among others. Biocides are often used to resist these factors and protect the facades. However, the biocides get washed out due to rains and other factors like geometric structure of the facade, orientation of the building. It is therefore, important to understand how these factors affect the durability of facades, leading to a requirement of expert analysis. In this paper, we propose a technical pipeline and a set of interaction techniques to support data analysis within the immersive environment for our case study. Our technical pipeline mainly consists of three steps: 3D reconstruction, embedding sensor data and visualization and interaction techniques. We made a formative evaluation of our prototype to get insights from microbiology, biology and VR experts. The remarks from the experts and the results of the evaluation suggest that an immersive analytic system in our case study could be beneficial for both experts and non-expert users.

Keywords: Immersive Analytics, Biocide Availability, Visualization Techniques, Virtual Reality, 3D Reconstruction, Sensor Data

1 INTRODUCTION

Various factors affect the durability of facades, such as microorganisms, material, microclimate, and construction method. Microorganisms can cause greenish or blackish coatings on house facades, resulting in structural damage and high remediation costs. Therefore, biocides are often used to improve the weatherability of facades. However, these are gradually dissolved out by rain, which can reduce their effectiveness as well as endanger the environment. In addition, weathering factors such as humidity, temperature, solar intensity, material properties, wind, dew, etc., influence the extent of degradation or release as well as microbial infestation of facades and thus ultimately the long-term weather resistance. Finally, the geometric structure of the facade and contextual factors such as the orientation of the building can have an influence on the washout of biocides. The joint exploration and analysis of these manifold parameters are complicated.

Hence, within this paper, we propose to utilize Immersive Analytics to support the exploration of biocides in facades of a building. Specifically, we propose to merge data originating from sensors embedded at the building, additional datasets (e.g., building orientation, location) as well as 3D reconstructions of the building itself into a joint immersive analytics system.

To this end, we propose both a technical pipeline as well as a set of interaction techniques to support data analysis within the immersive environment.

2 RELATED WORK

Our work is based on prior contributions in immersive analytics, 3D reconstruction and sensor data visualization.

Immersive Analytics is a steadily growing field with substantial potential to aid the analytic process of domain experts but also numerous challenges [8]. For recent surveys we refer to the works by...
Fonnet et al. [11] and Kraus et al. [15]. Our work is specifically related to immersive and situated analytics systems focusing on analyzing data within physical contexts or 3D reconstructions of physical sites. For example, Benko et al. [3] presented VITA (Virtual Interaction Tool for Archaeology), a multimodal, collaborative mixed reality system for documenting and exploring excavation sites using a combination of 3D reconstructions and additional digital data. Skarbez et al. [20] gave consideration to a number of possibilities, including how 3D scans can be viewed at several scales and how this could change the analytical process for archaeologists.

While the majority of conventional urban design tools use 2D displays, immersive analytics based on head-mounted displays (HMDs) can be a potential alternative. To this end, Zhang et al. [24] presented a comprehensive immersive analytics system that incorporates analysis and visualization methods to assist decision-making in the urban site development. The efficiency and viability of their proposed system have been confirmed by quantitative user studies and qualitative expert feedback.

Sun et al. [22] combined geographical with time-series data from chemical sensors as well as meteorological data in an immersive virtual reality environment.

Natephea et al. [18] proposed to combine sensor data with building information modeling (BIM) data. The findings demonstrated that the developed system could display various indoor environmental data of the building using VR technology, giving users access to information that can be used to monitor the building’s indoor thermal comfort conditions in real-time. The HoloSensor project sought to improve the visualization and visual analytics data sourced from various sensors throughout various locations inside a building [13].

On the other hand, the use of data representations arranged in connection to pertinent things, places, and people in the real world for comprehension, sensemaking, and decision-making is known as situated analytics. Situated analytics enables users to easily analyze virtual data that is situated in the real environment while gaining access to the power of the data and analysis [23]. Related to that, Ens and Irani also put out the idea of “Spatial Analytic Interfaces”, which intends to use spatial interaction to facilitate situated analytical activities [9].

3 IMMERSIVE ANALYTICS SYSTEM

The hazard potential of a building facade depends on a large number of structural, microclimatic, and material parameters. For an evaluation of the influencing variables as well as clarification for technically remote users, fast and precise data evaluation as well as interactive data visualizations are of particular importance. Typically, microbiology researchers use 2D desktop applications or web dashboards to analyze and evaluate biocide data, such as biocide concentrations in the building facade. However, it is rather complex to investigate the correlation between multivariate data with attributes such as temperature, moisture, and biocide concentration in facades using these tools. Further, it can be challenging for experts to visualize this multivariate information using single or multiple physical displays and to represent them with respect to their spatial properties.

Hence, we aim to visualize data from various sensors embedded in the building facade in a virtual reality environment, which aims at supporting experts in comprehensively understanding the effects of multivariate data (such as temperature, moisture, and biocide concentration on the facade of the building) in the spatial context of the facade.

To this end, we propose an immersive analytics system, consisting of three parts: 3D reconstruction, embedding sensor data, and an accompanying set of 3D visualization and interaction techniques.

Figure 2: 3D Reconstruction: (a) Some sample images of the building facade, (b) 3D model of the building facade.

3.1 3D Reconstruction

Representing a 3D model of building facades in virtual reality allows experts to observe multivariate sensor data in the spatial context they originated from. For example, the 3D model can support domain experts to gain a better understanding of the architectural design and the position of doors and windows, which might affect measurements. Furthermore, they will also have the opportunity to observe variation and correlation of the measurements in different areas of the facade.

Photogrammetry is a mature 3D reconstruction approach that also can be utilized with ordinary smartphones, as it only requires a set of ordinary images. Recent developments in Structure from Motion (SfM) and Multi-View Stereo (MVS) have enabled the automation of some phases, such as camera motion determination and scene geometry reconstruction. Still, achieving satisfying 3D reconstructions, specifically in large-scale environments, can be challenging due to the large number of required images as well as the parameterization of SfM pipelines.

We employ an SfM pipeline for 3D reconstruction, which is aimed at non-professional users [7]. This pipeline also facilitates the creation of 3D models of the required buildings. Further, for a more comprehensive understanding of the measurements and correlations between variables such as temperature and moisture, the position of the embedded sensor can be integrated into the 3D model using game engine software such as Unreal Engine 1. Besides, in our case, we used a typical smartphone to capture images and several sample images can be seen in Fig. 2 along with a 3D model of the building.

A complimentary high-quality reference model can be generated by a LiDAR scanner.

3.2 Embedding Sensor Data

A number of factors affect the durability of facades, such as microorganisms, material, microclimate, and construction methods. In addition, weathering factors such as humidity, temperature, solar intensity, material properties, wind, and dew influence the extent of degradation or release, as well as the microbial infestation of facades has an impact on the long-term weather resistance [19]. Hence, various sensors need to be employed for collecting relevant data at or near a facade. The three main groups of relevant data include weather station data on-site, data from sensors embedded in the plaster as well as data collected from eluates. In our project, sensors have been embedded in different regions of a sample facade to jointly collect this data (see Fig. 3).

A variety of weather data is collected on-site, such as wind, rain, temperature, and radiant intensity. A plaster sensor measures conductivity, humidity, and temperature. Lastly, eluates collection includes volume, characterization, and toxicity analyses. It is also possible to investigate the characterization of the plant cover. We used the ThingsBoard IoT platform 2 to store this data.

1https://www.unrealengine.com
2https://www.thingsboard.io/
We propose to use three main strategies that support analytical reasoning of live data generated from the sensors embedded in the facades. These strategies include time series visualization, data interpolation, and multi-scale navigation.

### 3.3 Visualization and Interaction Techniques

#### 3.3.1 Time Series Visualization

Time series data consists of a set of attributes that change over time and can be categorized into a variety of groups: linear time, cycle time, time intervals, time point, sequential time, etc [10]. Sensor data can be measured in different intervals depending on the purpose. Temperature and moisture attributes, for instance, can be measured either monthly or seasonally, which can be referred to as cycle time. Time series data is specifically relevant for our use case as reasoning about biocides in facades needs to take into account changes over potentially many weeks, months or even years. In the case of biocide concentration, we can use a seasonally time series because it will change significantly throughout the different seasons and will assist the expert to analyze the data more effectively. Further, multiple variables can be considered for selecting appropriate time series, such as the correlation between moisture, temperature and biocide concentration, architecture, location, and orientation (e.g., north or south facing) of the building facade, as well as conditions of the area (e.g., if lakes or woods are nearby a facade).

In principle, various visualization methods can be used for showing different types of time series data (e.g. spiral diagram, calendar view, ThemeRiver view, and dynamic visualization [10]). In our use case, time series data of sensors is displayed on a spatial referent (the facade). Hence, besides taking the nature of attribute data and the correlation between multiple variables into account, we also need to consider the spatial reference frame for choosing appropriate time-series visualization techniques.

It is important to consider several factors when displaying time series data in conjunction with a physical referent. A given measurement can be designed with geometric primitives or more complex geometric shapes (e.g., cubes, cylinders, drops of water), depending on the attribute. In our case, cubes or circles can be used to display temperature data. A cube for example, can be used to show multiple values related to the data point on its different faces. We used diverging colormaps to visualize our attributes, temperature and moisture. Specifically, for temperature, all temperature values above 0° were interpolated with RGB values towards a yellow to red color space, indicating more heat. All temperature values below 0° were interpolated with RGB values towards a blue color space, indicating less heat.

Water droplets and circles are used to display moisture data, and they can also be displayed seasonally (see Fig. 4). Similar to temperature, all moisture values above 50% were interpolated with RGB values towards a blue shade, indicating higher humidity. All temperature values below 50% degrees were interpolated with RGB values towards a yellow shade, indicating a dry weather.

#### 3.3.2 Data Interpolation

Since current measurements of the sensor data are limited to specific positions at the facade of the building, but data on further locations or whole areas of the facade can be relevant for facilitating understanding, it is necessary to perform attribute interpolation. However, simple interpolation schemes like linear interpolation are not suitable for all measurements. For example, in the case of moisture data, the design of the building facade and the position of the doors and windows will influence moisture distribution.

Generally, spatial interpolation can be subdivided into point and areal interpolation. In areal interpolation, attribute information is transferred from source zones with known values to other regions. Point interpolation predicts values at unknown locations based on information from sample points, which are considered to vary over space continually. Point interpolation approaches include inverse distance weighting, ordinary kriging models, kriging with external drift, and spline [5]. However, spatial interpolation profoundly impacts a variety of aspects, including sample size, sample design, and the nature of the data. Furthermore, it is complicated to predict how all those factors impact the performance of the interpolation method [21].

In our current interpolation, for instance, in Fig. 5 (b), point-based interpolation (kriging) is employed to determine values in unknown areas such as green rectangle. Please note, that this assumes homogenous regions of the facade. However, this might not always lead to correct values. For example, as can be seen in Fig. 5 (a), in the given area of the facade, which includes embedded sensors and windows, it is challenging to apply interpolation to calculate data in an unknown point (e.g., green rectangle) due to the presence of the windows (that constitute areas without biocide concentration). Besides, other factors such as sample size, the type of embedded sensor, and building material can influence spatial interpolation efficiency. Hence, it can be challenging to select an appropriate spatial interpolation method for a given specific input data set due to variation within the data. In our case, one possible alternative to overcome the problem of the existence of the windows is to embed more sensor data close to the windows, which will help to apply a more accurate interpolation between all those sensor data.

Further, multiple factor analysis can be performed among different sensor data, as discussed in embedding sensor data. For example, moisture and temperature can influence biocide concentration among other factors. Particular parts of the facade of the building, such as windows and doors, can absorb more water during rainfall. Accordingly, the sample area will record different values for moisture, temperature, and biocide concentration. In Fig. 5, sample area (a) has more moisture and less temperature compared with sample area...
We have implemented an initial immersive analytical system, used as regions around specific sensors (see Fig. 6). In our use case, various methods (via the D-Pad of a controller) in the initial scale and teleporting (b) and hence, has less biocide concentration and more microbial growth. Consequently, moisture and temperature can be used to predict biocide concentrations and microbial growth in different areas of the facade. Please note, that our aim is not to propose novel algorithms for multifactor analysis, but to enable domain experts to investigate multiple factors in the spatial context they arise.

3.3.3 Multi-Scale Visualization

Scale change in virtual reality has been investigated for various applications that allow the user to view the diverse elements of the virtual environment and become more familiar with its intrinsic hierarchical patterns [1].

In the context of analyzing biocides on facades multiple scales are relevant. For example, the domain expert might want to get an overview about selected data distributions on the whole facade as well as regions around specific sensors (see Fig. 6). In our use case, as seen in Fig. 6, right, initially, the user and the environment are on the same scale (i.e. as a human would observe the facade if she is standing in front of the physical building). While manifold travel techniques have been proposed (for an overview we refer to [2, 6]), in our current implementation, we enable both steering-based travel (via the D-Pad of a controller) in the initial scale and teleporting (both in the initial and into/out of further scales). Various methods including orbit-then-zoom, curvilinear zoom, and zoom-then-rotate can be utilized [16] for transitioning between scales. In our current implementation we use a discrete scale change (i.e. teleporting to a new location while rescaling the underlying 3D model).

One specific aspect that needs to be taken into account when employing multi scale navigation within a 3D reconstructed environment is the scale of the original input images and the generated textures of the reconstructed 3D model. To enable meaningful multi scale navigation we capture the facade at multiple scales. An initial set of images is taken from the point of view of an observer standing in front of the building. A second set of images is taken at a closer range, but only for potentially relevant regions, such as around sensors. For rendering, all images can be utilized to generate a single 3D model with high and low resolution areas. Still, this model is bound by the maximum texture size that the 3D reconstruction system supports. As an alternative, multiple 3D models can be reconstructed and switched during runtime (e.g., using level of detail methods [17]).

4 IMPLEMENTATION

We have implemented an initial immersive analytical system, used to visualize the data from sensors embedded in the physical environment. This involved the following steps: 3D reconstruction of the required physical environments, receive sensor data and analyzed data for required attributes, and 3D visualization of respective data points relative to the environment in VR (see Fig. 1).
were employees or researchers at a university. All experts had normal, or corrected to normal eyesight and they saw everything clearly in the virtual environment. The two microbiology experts had no previous experience with VR. All experts were informed about the procedure and the content of the study, signed a consent form and filled out a demographic questionnaire. Next, the microbiology experts received a short introduction using the HMD (an HTC Vive Pro Eye) and how to work with the associated controller (see Fig. 8).

Next, while the experts were wearing a VR HMD and testing the application, they were interviewed. They were asked about how they felt about the application, what they liked or disliked, how practical it was, what kind of function they would like the system to have, which problems occurred, and what they would improve. Biology experts were also asked if they could imagine using VR for data analysis in the future. At the end, we gained valuable information from the experts through the interview.

In the beginning, we asked the biology experts how they felt while observing the system. Both (P02 and P03) liked working in virtual reality. They preferred the teleportation-based navigation method over the steering-based one. In addition, regarding 3D models, a more detailed model was suggested. They also liked how we presented temperature and moisture over time. Nevertheless, P02 pointed out that for the moisture element, a different color scheme can be used (e.g., moisture measurement: zero percentage can be red). A switching button was also recommended to attach to the sensor data, which enables the expert to select sensor data for daily, monthly or seasonal observation based on their goal. Both experts also suggested using a heat map instead of displaying temperature attributes in different time series. In addition, P03 stated that a heat map would help them gain information quickly; for example, red indicates regions with high temperatures. However, in that case, displaying information in heat map layers can be achieved by using data interpolation, which can vary over time by different layers. With respect to visualizing biocide concentration, P02 stated that a layer could be mapped to the wall so that it can be thick in the region with more biocide concentration and thin with less biocide. For visualizing sensor data, they were informed to name suitable places for the sensors to embed in the facade. They pointed out it depends on the type of sensor; for instance, the moisture sensor should be placed in the area close to windows, walls, and the plumbing, which creates a moist surrounding on the facade in case of the rainy season.

In the end, the biology experts pointed out that they could imagine using VR for analyzing data in the future if some conditions are met, such as having lighter HMDs with higher resolution. Besides, they said this system could benefit non-expert users, such as building owners and related companies interested in investigating biocide’s impact on building facades.

The VR expert also proposes the use of zoom or scroll feature to display temperature and moisture information based on our target. Scrolling or swiping is recommended to see all the elements over time. Also, the expert indicated that it would be beneficial to have information move through time. For example, initially, the temperature data points of the first four months could be displayed, on scrolling the data points from the next four months could be shown and so on. In order to apply the multi-scale navigation technique, the expert suggested that a square around the sample area could be used so that the observer could point through it. For displaying the sample area, it is recommended that the rest of the building is still visible but might be blurred. For zooming, an animation was suggested that moves the user closer. The expert speculated that analyzing data in a VR environment could be more effective than analyzing data in a computer since a VR environment could help to observe which data belongs to what part of the building and see the differences at one glance. However, using a computer could still be preferable for calculating statistical measurements (e.g., mean, median, etc.). Furthermore, the VR expert suggested a feature allowing the user to easily add their own buildings and sensor information.

After the immersive experience all three experts filled out a short questionnaire. This included three individual questions with a seven-item likert scale with 1 meaning “not at all” and 7 meaning “very much”. The questions “I would find the application to be useful” and “I would find the application easy to use” were rated with two 6 and one 7 (m = 6.3). The question “I would have fun interacting with the application” even got two 7 (m = 6.67). This indicates that all experts have a very positive attitude towards such a system. The simulator sickness questionnaire [14] resulted in a mean of 18.7 (sd = 9.9) which is rather high, but could be explained by the microbiology experts having no prior VR experience [4] and the very early state of the prototype.

6 DISCUSSION, CONCLUSION, AND FUTURE WORK
We presented an initial immersive analytics prototype for supporting domain experts in understanding biocides in and microbial infestation of facades. To this end, we propose to combine 3D reconstruction of physical buildings with sensors embedded in the facades and to make these data jointly available in an interactive VR system. We furthermore proposed three important visualization and interaction aspects of this immersive analytics system (time series visualization, data interpolation, and multi-scale navigation) and conducted an initial formative evaluation with domain experts.

Our system initially focuses on visualizing only a few selected sensors. One challenge is how to not only visualize individual data sources but how to develop meaningful multivariate visualizations that add meaning within the context of the spatial referent (the facade). Further, data can come at different levels of granularity, which again could be spatial or temporal in nature.

With respect to the 3D reconstruction a number of factors need to
be taken into account (such as the level of expertise of the people on site and the need for capturing images at multiple scales). In addition, it is difficult to reconstruct some reflective, transparent, and non-rigid objects due to the inherent problems of image-based 3D reconstruction with textureless surfaces.

This project can be improved in several ways in the future. Developing visualizations for physical locations of the sensor in the 3D world, such as DNA structures of microbes found at the sample site, biocide concentration as 3D bar charts with respect to time, and temperature and moisture measurements with respect to time. Finally, biology experts pointed out the amount of biocides being still present within the facade material can be predicted based on material parameters, starting concentration and weathering data which can need to be considered in future.

ACKNOWLEDGEMENTS

This project received a grant from Bavarian State Ministry for Science and Art, program to promote applied research and development at universities of applied sciences. We would like to thank the Bavarian State Ministry for Science and Art and Coburg University of Applied Sciences and Arts for their support.

REFERENCES

[1] P. Abtahi, M. Gonzalez-Franco, E. Ofek, and A. Steed. I’m a giant: Walking in large virtual environments at high speed gains. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, pp. 1–13, 2019.

[2] M. Al Zayer, P. MacNeillage, and E. Folmer. Virtual locomotion: a survey. IEEE transactions on visualization and computer graphics, 26(6):2315–2334, 2018.

[3] H. Benko, E. W. Ishak, and S. Feiner. Collaborative mixed reality visualization of an archaeological excavation. In Third IEEE and ACM International Symposium on Mixed and Augmented Reality, pp. 132–140. IEEE, 2004.

[4] E. Chang, H. T. Kim, and B. Yoo. Virtual reality sickness: a review of causes and measurements. International Journal of Human–Computer Interaction, 36(17):1658–1682, 2020.

[5] A. Comber and W. Zeng. Spatial interpolation using areal features: A review of methods and opportunities using new forms of data with coded illustrations. Geography Compass, 13(10):e12465, 2019.

[6] M. Di Luca, H. Seifi, S. Egan, and M. Gonzalez-Franco. Locomotion vault: the extra mile in analyzing vr locomotion techniques. In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems, pp. 1–10, 2021.

[7] O. Dietz and J. Grubert. Towards open-source web-based 3d reconstruction for non-professionals.

[8] B. Ens, B. Bach, M. Cordeil, U. Engelke, M. Serrano, W. Willett, A. Prouzeau, C. Anthes, W. Büschel, C. Dunne, et al. Grand challenges in immersive analytics. In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems, pp. 1–17, 2021.

[9] B. Ens and P. Irani. Spatial analytic interfaces: Spatial user interfaces for in situ visual analytics. IEEE computer graphics and applications, 37(2):66–79, 2016.

[10] Y. Fang, H. Xu, and J. Jiang. A survey of time series data visualization research. In IOP Conference Series: Materials Science and Engineering, vol. 782, p. 022013. IOP Publishing, 2020.

[11] A. Fonnet and Y. Prie. Survey of immersive analytics. IEEE transactions on visualization and computer graphics, 27(3):2101–2122, 2019.

[12] C. Grévodz, S. Gasparini, L. Calvet, P. Gurdjos, F. Castan, B. Maujean, G. D. Lillo, and Y. Lanthony. Alicevision Meshroom: An open-source 3D reconstruction pipeline. In Proceedings of the 12th ACM Multimedia Systems Conference - MMSys ’21. ACM Press, 2021. doi: 10.1145/3458305.3478443

[13] J. Jang and T. Bednarz. Holosensor for smart home, health, entertainment. In ACM SIGGRAPH 2018 Appy Hour, pp. 1–2, 2018.

[14] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. The international journal of aviation psychology, 3(3):203–220, 1993.