Modeling Urban Complexity in Point Clouds and Sound

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Abstract: The urban landscape is becoming denser, spreading not only horizontally but also vertically above and underground. In the fields of landscape architecture and urban landscape planning, today's digital models especially employed as virtual reality applications have significant limitations when it comes to a holistic perception of the urban environment. The work described in this paper attempts to develop ways of creating a virtual reality application which allows users to navigate through a digital environment at a large scale while retaining a high overall level of feature details. Some new approaches to data acquisition, audio visual parity, navigation and scaling in the digital environment and at dynamic levels of detail have been developed to this effect.

Keywords: Urban landscape, spatial perception, VR, game engine, point cloud

1 Introduction

Due to the densification of cities, the urban landscape is increasingly multi-layered, spreading not only horizontally but also vertically (KOOLHAAS 1995, PARRIAUX et al. 2004). The stacking and interlocking of built elements above and below ground makes spatial understanding and planning of complex urban situations increasingly challenging. Three dimensional processes in the planning and design of urban landscapes are obstructed by invisible and poorly represented structures especially in the underground. Subsequently, a constructive coexistence between urban services and urban landscape fails to work due to a lack of congruence.

In addition to densification of urban areas, climate change has led to new challenges and approaches in urban landscape design. In the heat mitigation planning of the city of Zurich, for example, the planting of trees is proposed as a valid approach to combat the heat island effect[1]. However, in some situations this is hardly possible due to the build-up of infrastructure in the subsoil or to insufficient mapping of the underground. This situation results from a lack of awareness about underground space. This is in part due to the underground being poorly represented in two dimensional vectorial plans.

In the fields of resource-efficient, adaptive reuse, sustainable construction and historical preservation, the strategy of "continued construction" gains more importance (LEYSER-DROSTE et al. 2016). A detailed understanding of the existing built substance by professionals, stakeholders and laymen is key to performing precise operations in the existing context successfully.

The disciplines of landscape architecture and urban planning play key roles in addressing today's challenges but landscape architects and planners increasingly encounter challenges in

[1] Fachplanung Hitzeminderung (Stadt Zürich (Ed.), 2020).

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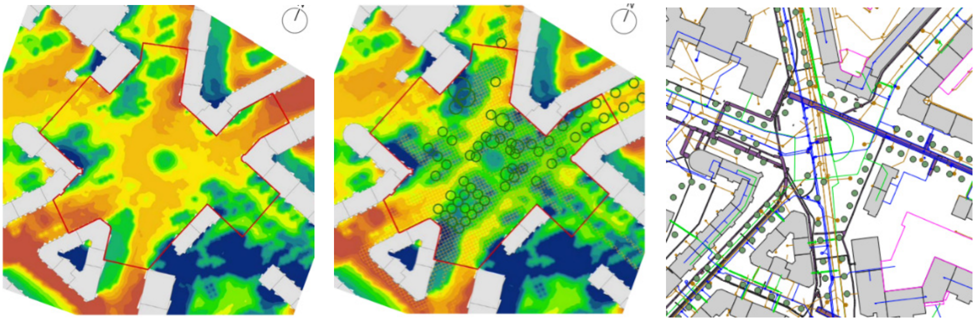
the underground and lack an adequate tool to be able to analyze and visualize the urban complexity above ground and below ground effectively.



(a) (b) (c)

Fig. 1: (a) Current Situation[1]; (b) Climate-optimized situation; (c) Pipe cadastre / Bullingerplatz, Zürich

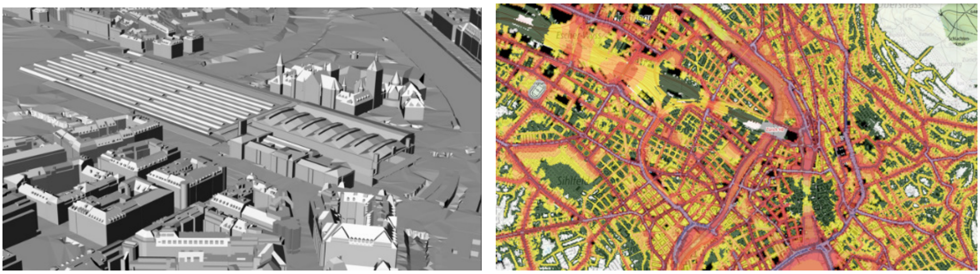
2 State of Research

2.1 Acoustic Models

Digital models can be helpful in examining given spatial situations (YAMU 2014) and make visual and acoustic elements more tangible together. New forms of digital models and their audiovisual experience can improve the understanding of complex situations and provide the basis for a better assessment of the situation and the precise interventions that ensue. As Nadine Schütz (2017) states in the introduction to her dissertation *Cultivating Sound*: "Landscape is a multimodal spatial experience that could more generally be defined as a meaningful and dynamic sensory relationship between humans and their environment." Sound therefore can help recreate this sort of relationship through simulation (LINDQUIST et al. 2016).

Acoustics research in architecture has mostly been visually driven. Osswald who leaded the first acoustic department of the ETH in 1928 invested in making "Schallphotographie" (sonic photography) and built sophisticated apparatuses to study acoustic phenomena in the calmness of a lab (S. VON FISCHER 2019). This sort of approach might have been somewhat effective to monitor indoor space, but it certainly was not applicable to the complex soundscape of a landscape where a more holistic approach was needed. Per Hedfors further states that the aim of "objectivity" in acoustic landscape perception is complex due to the interrelation between physical and psychological effects and the missing possibility to research sound without using visual representations or words (HEDFORS 2003). Our approach could be a contribution to a research through perception in a controlled lab environment. Or to paraphrase the historian of science Hans-Jörg Rheinberger "[with] a kind of attention that includes a keen sense of secondary tones" and "is not too rigidly focused on a predetermined goal, a floating attention, that is." (RHEINBERGER 2014).

Mapping with sound or using sound in geographical visualization to study the acoustic environment had been done long before 3D models were rendered in real time by computers. The concept of soundscape as first suggested by Schafer (1993) influenced an emerging field of sound studies, where maps of environmental sounds play a big role. In 1969, Michael Southworth already presented a soundmap in the Journal of the Acoustical Society of America (S. VON FISCHER 2019). At the beginning of the millennium, different soundmap projects arose, with the aim of raising awareness about sound ecology and engaging the public as well as providing data for researchers (WALDOCK 2011). Urban planners and policy makers (see: Swiss Federal Noise Protection Ordinance) took interest in the field of soundecology to discriminate sound in categories of environmental noise from road traffic, aircraft, railway and machinery. The purpose was to understand their impact on health. Therefore, this type of auralisation was focused on "unwanted" sound (THOMPSON 2017) and on the enhancement of urban areas, which needed a designed (manipulated) auralisation. Our approach can therefore be called geo-referenced-documentary in that it remains (unmanipulated).



(a) (b)

Fig. 2: (a) City Model Zurich, LOD2 + DTM (City of Zurich); (b) Road traffic noise (swisstopo)

2.2 Point Cloud Models

Measured geo-data environments which represent existing urban space with metric precision such as City Models are nowadays used for visual representation in urban planning, but are usually restricted to triangulated, rather abstract models. The models focus more on providing geo-information rather than refining the digital environment it's representation and perception. The digital City Model of Zurich, for example, is based on the real and projected building ground plans of the official cadastral survey supported by stereoscopic image evaluation. Due to its origin in two-dimensional space, it lacks most details about the urban landscape.

Although the available LOD 0-2 could be useful for some applications, for example climate analysis and cast shadows (BILJECKI et al. 2017) as well as wind simulations (GARCÍA-SÁNCHEZ et al. 2021), this paper argues that for more in-depth spatial analysis, the introduction of a high level of detail and data in three-dimensional space would increase the usefulness and understanding of such 3D models.

As Urech et al. (2020) describes, over the last decade laser scanning has become a prevalent technology to record space. It is capable of depicting spaces in a very precise, detailed and legible manner. This is confirmed in a practical approach which states that laser-scanned datasets provide spatial information across all planning and design scales. Spielhofer et al. (2017) has proven that data obtained from Laserscans (LiDAR – Light Detection and Ranging) is most suitable to represent landscapes. When visual models are combined with congruent environmental sound, virtual landscape scenes can enhance the level of perceived realism (LINDQUIST et al. 2016). And as J. Fischer et al. (2020) state, ambisonic sound can, when spatially embedded in a VR scene, increase the perception of space and therefore the sense of immersion. These digital environments could be categorized as metrically accurate measured models. They can be used as tools for spatial communication as well as analytical processes and provide a basis for future planning. Each representation can be optimized for a specific purpose and the digital environment and modes of navigation and interaction are strongly limited accordingly.

2.3 Game Engines

In the field of game design, interactive three-dimensional environments have been present for a while and have gone through a lot of development. Their environments and representation allow for a wider range of movement and applications than conventional 3D models. These meshed models are very detailed and the design of the environment meets the highest acoustic and visual standards. However, the immersion of the player comes in the foreground and these models are designed accordingly; the reference to reality in the background (even in reconstructions) is secondary. Measured models and the point cloud format are rarely used. Due to triangulation, geometrically abstract forms with potentially lower resolution are common. Analog to the visual model, the embedding of sound through sound design is also widely used. This means mostly single sonic sources are used in game design and the soundscape of a game world is produced by a series of single events which are then spatialized by a game engine. The aim of these strategies is often not to depict a specific “real-world” environment with high accuracy, but to establish a coherent second world with an immersive user experience in the latter. Still, the popularity of games and game development in recent decades has helped the development of game engines and made them accessible to a wider group of users. Unity (game engine) is one of them and has been used in the experiment presented.

2.4 Virtual Reality

Driven by the goal of greater immersion, virtual reality (VR) glasses were developed. Since then, VR applications have been used to increase the degree of immersion within the scientific field of landscape and urban planning (WISSEN HAYEK et al. 2016). The design with one distinct screen per eye enables stereoscopic vision (or stereopsis), but also increases the computing power required to display a virtual environment compared to conventional viewing. If point cloud models are used with this type of display, data management becomes a key issue. Beside the possibilities of VR, the use of game engines allows various forms of interaction. However, the spatial boundaries with regards to physical movement in a virtual environment require an appropriate translation (KEIL et al. 2021). Interaction with the representation of digital models should take place at different scales, particularly when addressing complex structures, (DEMBSKI et al. 2020). In an orthographic projection (an approximation can be achieved f.ex. by scaling the model or the viewer) in this regard it is far more effective than the perspective bird’s eye view, it supports the recognition of features and the estimation of distances when moving through space (TOFT et al. 2020). Finally, if audiovisual continuity is maintained during the experience, spatial relationships are perceived with greater acuteness and clarity (CANDAN SIMSEK 2017).

2.5 Audiovisual Models

In the field of landscape architecture and urban design, digital models employed in virtual reality applications still have significant limitations when it comes to defining a more a holistic perception. Especially measured and metrically accurate environments consisting of point cloud models and ambisonic geo-referenced recordings are difficult to produce (VIRTANEN et al. 2020). The size of the mentioned environments and the details contained are critical and still very limited. The described work attempts to develop ways of creating a Virtual Reality application which would allow users to navigate in a large scale environment while retaining a high overall level of detail. Therefore, approaches to navigation and dynamic levels of detail also need to be considered. Instead of a monofunctional application, focusing on certain aspects of the environment, this project aims at the perception of the whole environment through audiovisual aspects.

2.6 Approach

To take the perception of complex urban landscapes a step further, a combination of new and modified tools was integrated in the development and production process. To create a measured and metrically accurate digital environment and to be able to communicate it through a VR application the production workflow was entirely reconsidered. To create a multisensory immersive experience, the audio-visual approach was integrated from the beginning of the process and both sensory impressions were treated with equal importance. With the help of a customized game engine and a specifically developed dynamic level of detail system, accompanied by refined recording techniques, a large scale, high level detail point cloud environment with ambisonic sound was created, suitable for a VR application. Through intuitive navigation, the viewer is now able to continuously roam through the surroundings at different scales.

3 Recording and Modeling the Urban Landscape

This paper is based on the case study of Zurich's main railway station located in the city center. The methods that are explained were applied and tested through data acquisition on site; this led to the modeling and programming of a virtual environment with a VR based user interface.

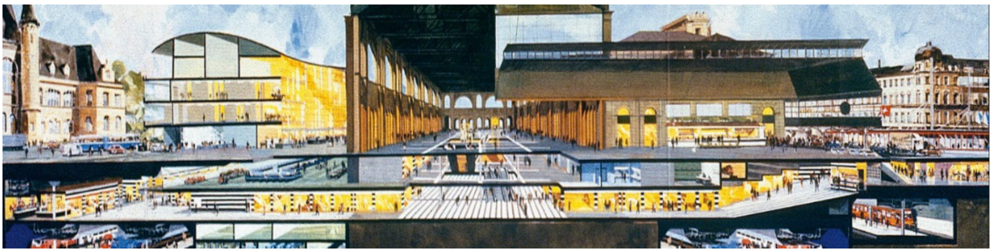


Fig. 3: Cross section through the main station with underground rail facilities (Meili Peter Architekten, 1995)

Zurich's main railway station is the prime example of an evolved structure that has grown into a complex spatial configuration in the urban context. The overlapping of different functions (traffic, production, consumption and recreation), historic protected and modern structures, and the step-by-step expansion have led to a complex, elusive spatial situation, as it is often found in today's urban landscapes. With these characteristics, and its large spatial extension, it proved to be a prime site for a case study of the described work.

3.1 Laser Scanning

With the aim of creating a metrically accurate digital model of the existing spaces, laser scanning was used as the visual acquisition technique. The latest generation of laser scanners allow for the measurement of up to 500'000 measurement points per second and one scan-position every 3-4 minutes. With this increase in speed, larger and more complex spatial structures can be recorded in less time. In the described case study over 600 overlapping scan positions were combined into a digital model. Still, the time factor on site remained a dominant parameter which determined point cloud density and overall completion of the visual model.

This terrestrial acquired (TLS) model was supplemented with airborne (ALS) and mobile (MLS) LiDAR data. Some of which had been acquired by the Swiss Federal Railway (SBB), others by the Federal Office of Topography (swisstopo). The applied spectrum of data acquisition methods and recording devices achieved a high level of detail and large-scale coverage of the survey, enabling observations at different scales with high quality of representation while the overall recording time was kept as short as possible.

The point cloud acquisition takes place one position after the other and therefore is a sequential process that combines different temporal states in the final model. Especially in areas with high movement, the mix of different moments in time can produce undesired results. Although newer laser scanners include features to help with this phenomena, the only theoretical solution to this issue is to scan with a multitude of scanners at the same time, which to this extent is in practice unrealistic.

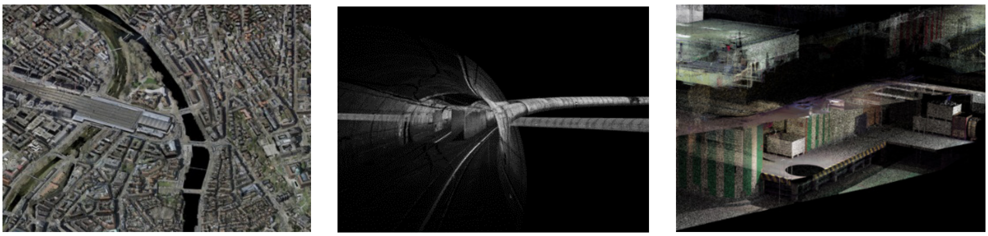


Fig. 4: ALS data (SWISSTOPO 2018), MLS data (SBB 2014-2021) and TLS data (SCANVISION 2018)

3.2 Ambisonic Mapping

The acoustic acquisition makes use of the technical possibility of a virtual reality environment to create an intuitive and immersive perception. Technically an ambisonic recording method was used to record single points in the field to later geo-locate them in digital space – the 3D model. The ambisonic recording method makes it possible to record a three-dimensional perception of sound (spatial axis) and decoding it related to the listener's head orienttation (head related transfer function). The individual recordings were recorded over the entire area of the case study and inserted into the digital model according to their recording position and orientation. The result is a constant sound field which fades between the mentioned recordings. As described for the visual acquisition, the acoustic recordings are not synchronized in time. But due to the fact that time is needed to move through the model the loss of synchronicity is not perceptible.

3.3 Registration and Georeferencing

After the acquisition of over 600 single terrestrial scans, the scan positions were put in a spatial relation to each other to create one connected model. In a next step, the terrestrial scans were attached to the geo-referenced airborne and mobile scans. With all the point clouds in a geo-referenced position (using the Coordinate System Swiss CH1903+ / LV95), over 1.5 billion measurement points have been accumulated in the case study area within an approximate dimension of 400×400m. Based on the acquired data a virtual environment was created in the game engine Unity. To handle the amount and different sources of data, a three dimensional grid was created and overlaid on all point cloud data. Tiles with the same geographic location but with data from a different source were then combined to get a set of unique tiles.

3.4 Level of Detail

For the upcoming paragraph the difference between the overall level of detail, which stands in relation to the data acquisition and the density of the point cloud model, and the dynamic level of detail, where models are simplified dynamically during the viewing process to increase computer graphic capabilities, should be mentioned.

The large amount of data and the limited number of simultaneously rendered points possible (especially for VR Applications) led to the development of a dynamic loading and unloading system of point clouds within the game engine Unity. In contrast to the conventional dynamic LOD (Levels of Detail) as used in 3D computer graphics such as computer games, a new strategy was pursued. Unlike the usual approach, the various levels of detail were not replaced but complemented by each other. This becomes possible due to the structure of the point cloud model, consisting of "unconnected" measurement points in contrast to other forms of 3D models like the common mesh of triangles. With this approach the total data volume did not grow with the creation of LODs, as each point appears only once throughout all LODs. By avoiding multiple versions of the same geometry replacing each other in different LODs, the loading speed could be increased.

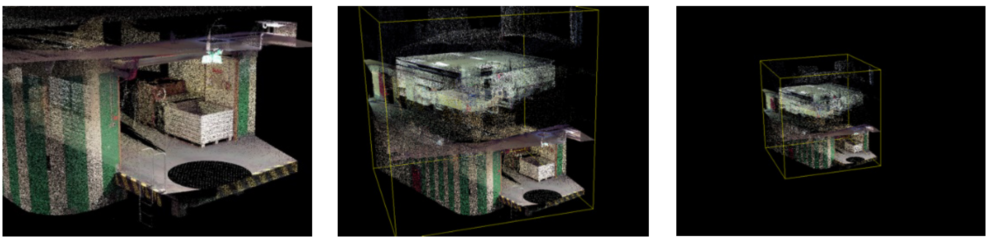


Fig. 5: LOD 2 (high resolution), LOD 1 (medium resolution), LOD 0 (low resolution)

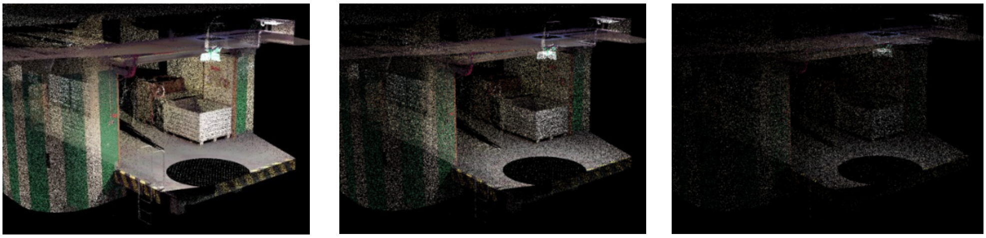
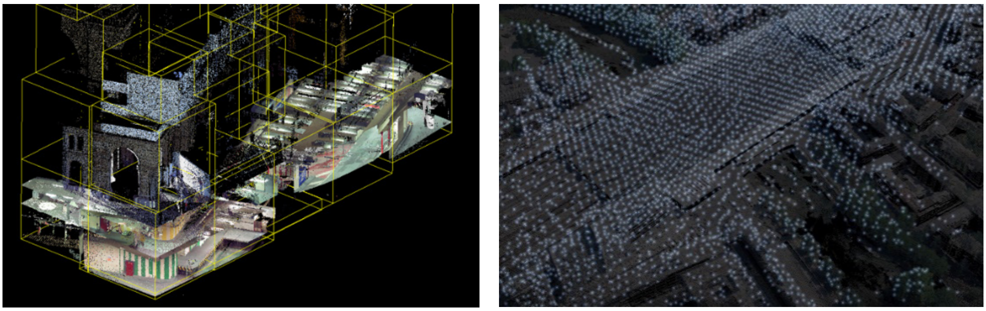


Fig. 6: LOD 2 (close distance), LOD 1 (medium distance), LOD 0 (greater distance)

A critical point was the large number of tiles loading and unloading simultaneously when moving (fast) through the model. To match the available performance with the desired maximum density of points, a grid with rather small tile-sizes was chosen: 10×10m. A single grid tile was filtered into different LODs, to visualize the maximum density, all LODs needed to be active simultaneously. This resulted in the presence of several ten thousand files, loading and unloading several thousand per frame when moving. To avoid larger performance issues, the system was reduced to three LODs: the low-res LOD being visible all the time and supplemented with the other two according to a set distance to the viewer.

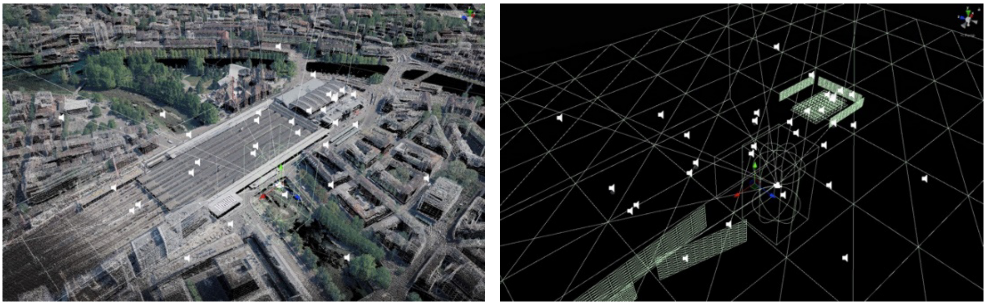


(a) (b)

Fig. 7: (a) Model subdivided into tiles of 10m x 10m; (b) Tiles anchor points for triggering the dynamic LOD

3.5 Auralization

To auralize the virtual environment, a geo-referenced-documentary approach was chosen. In order to support the immersion and preserve the sound continuity in great distance a wind sound and under earth a low rumbling noise was placed in the scene. Further, the recording time for all geo-referenced ambisonic sounds was chosen according to the perceived time of day in the model. Best matching recordings for the interior spaces of the train station were the ones recorded at around 21:00 – 22:00, with some human activity still on the street but not too many voices in the foreground. As for outside spaces, especially around the river, recordings from around 12:00 – 14:00 were better matching. All recordings were rendered and embedded in the digital model as loops. In the decoding process, attenuation, physical air absorption models were applied to filter sound for distance and the standard head related transfer models were used to let the user move freely in the 3D sound space. In addition to these processes, extra sound geometries (invisible planes) were added to occlude sound sources to the listener.



(a) (b)

Fig. 8: (a) Geolocated ambisonic sources in the model; (b) Invisible audio-geometries and sound sources

3.6 Scale

In order to grasp the entire spatial structure, the application started with the avatar at a scale of 1:100, thus with a corresponding experience of an overview. In contrast to the common method of using a view from above (bird's eye view) and changing position in the Z-axis to create an overview, in this case the digital avatar was scaled. On the one hand, this changed the perception: The scaling of the digital body led to a change of the acoustic and visual projection of the environment. With the enlargement of the virtual interpupillary distance, an approximation towards the orthographic projection took place, which contributed to orientation and legibility as described by Toft et al. (2020). On the other hand, the scaling improved the use of the limited space the user had for its movement in the model. With the physical movement scaled by the same factor, it enabled, while adhering to the spatial restrictions (4×4 meters) given by the VR system, to move over 400×400 meters, which roughly corresponds to the dimensions of the shown site.

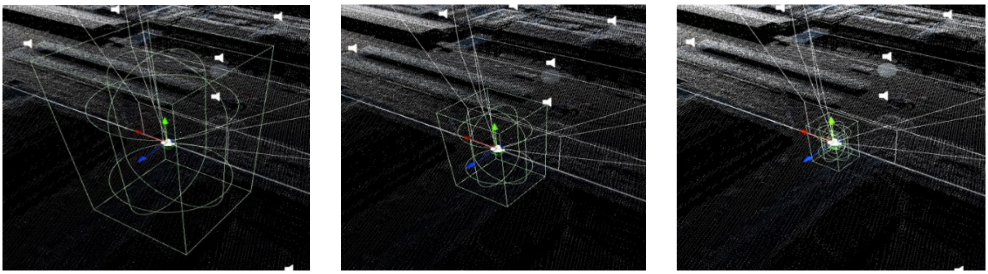


Fig. 9: The viewer, represented as a digital avatar, is scaled continuously between 1:1 and 1:100 scales

3.7 User Interface

Since physical movement and movement in digital space were coupled within one scale, the well-known problems of motion sickness in VR did not occur regardless of the high speed of movement in the model. Due to the fixed eye level at the start of the application on 30 meters above ground, the distance from the highest to the lowest point could be covered with a head movement – and therefore the area could be viewed from the air as well as from underground (30m -> -30m = 0.6m on a scale of 1:100). At this point an artifact should be mentioned that occurred in sound due to the scaling of the player. The game engine's built-in doppler effect (pitch shift due to movement towards and from a source) became extreme and had to be switched off in the scale 1:100.

By targeting visual anchors, it was possible for the visitor to leave the scale of 1:100 and experience certain places on a scale of 1:1. The transition to these places did not take place in a stepwise manner (teleportation), but in a linear continuous translation and scaling of the avatar. By maintaining audiovisual continuity, it was ensured that the viewer was constantly aware of its position in space and could establish a spatial relation between the starting point and the destination. The process of simultaneous scaling and displacement while the viewer's physical position remained unchanged was found to be critical in regards to motion sickness. Slowing down the overall movement and narrowing the field of view had both positive effects on motion sickness.

Fig. 10: To switch between the different scales, the viewer targets visual anchors by focusing on them with their eyes

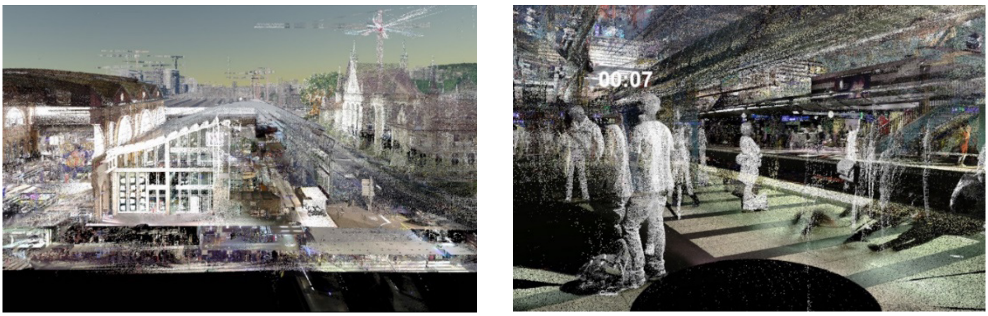


Fig. 11: VR environment in 1:100 scale with an active near clipping and VR environment in 1:1 scale

4 Conclusion and Discussion

The described experiment shows the possibilities and difficulties for medium to large-scale and overall high level of detail VR environments of measured data on both the acoustic and visual layer.

It explains a workflow from data acquisition on site, to the modeling of a virtual environment and the programming of a VR based user interface and user experience. The developed application was tested at a public event and showed that with this method, a complex space like Zurich's main station can be conveyed within a short time frame of approximately 5 minutes including a short introduction to the operation. Although the point cloud model as well as the ambisonic recordings are not so common to the public, they are greatly accepted and communicate a realistic impression due to their high level of detail. The applied method of data acquisition, processing and rendering showed the possibilities for an analyzing and communication tool as well as its capabilities as a basis for planning processes in landscape architecture and urban design.

With the choice of the case study, the experiment successfully bridged the scale-gap between architectural size and urban landscape size environments. An application as described can bring more planning certainty and prior knowledge for projects in complex urban situations dealing with the underground or the existing built context. Whether it's for the use of heat mitigation in urban landscape planning or generally for a more sensitive approach in the future development of the existing urban fabric, the gained knowledge in modeling complex spaces can find a manifold application.

4.1 Limitations

The data acquisition in both the ambisonic recording method and the laser scanning survey create a distortion in time within the model, meaning different moments in time are combined. This could be avoided, as suggested, by using many different and synchronized recording devices simultaneously. At this moment, there is no feasible possibility for such a strategy but, if possible, this would be desired. Also, in the realm of data acquisition the difficulties of sound recording in the ground as well as in the sky are hurdles yet to be mastered. For airborne recordings noiseless blimps or balloons could be a viable solution, whereas geophonical microphones or acoustic sensors as developed by the sounding soil project (soundingsoil.ch) could be applied for below-ground recordings. Analoge the visual survey is limited to the light-based recording method of the laser scanner and cannot penetrate the ground (or other solid materials). In some cases, ground penetrating radar (GPR) could present an extension of the recording methods.

4.2 Sound Model

In regards to the immersion, the research around Lindquist et al. (2016) which shows that congruence between image and sound is crucial can be mentioned. They researched not only the positive effect of auralisation, but also the deterioration of the overall immersion of a non-matching soundscape. The aforementioned problems of choosing the recording time and the need to add sound to unreachable places (distance/under earth) shows that a higher immersion requires a certain degree of sound design. Further, the effect of flying to the entry point of the 1:1 model has been an unforeseen pleasant extra, which has been described by participants as a positive effect for immersion as well. Although the model has a potential for comparative hearing research, the before mentioned problems of synchronicity and the need of supporting immersion limits a generalization at this stage of the process. Nevertheless, this could be worth further investigation.

4.3 Point Cloud Model

As a result of the developed thoughts and techniques for a dynamic LOD in point cloud models, the necessary code to implement the method within Unity's own LOD-System has been written and will be accessible to the public soon. The dynamic LOD code as well as the other described processes may be useful beyond professional boundaries of urban landscape planning in fields dealing with large-scale, high level of detail point cloud models such as architecture, engineering or game design.

4.4 Scalability

The resulting experience can be useful for an amateur audience as tested in the experiment. But it should also be applicable for professionals to communicate site-specific attributes at the start of planning processes. The application could work for participative processes, public discussions, planning processes and political strategies. By design the created VR application can be extended with further functions such as simulations or the embedding of design proposals. Its use can range from environmental changes, city and landscape planning to architectural interventions. If the range of scales is enlarged beyond 1:1-1:100 such an application should also prove useful in regional planning scenarios.

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