AUGMENTING 3D CITY MODELS WITH VISUALIZATION OF REAL-TIME METEOROLOGICAL PHENOMENA

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Abstract: General interest in visualizations of digital 3D city models is growing rapidly, and several applications are already available that display such models very realistically. Many authors have emphasized the importance of the effects of realistic illumination for computer generated images, and this applies especially to the context of 3D city visualization. However, current 3D city visualization applications rarely implement techniques for achieving realistic illumination, in particular the effects caused by current weather-related phenomena. At most, some geospatial visualization systems render artificial skies—sometimes with a georeferenced determination of the sun position—to give the user the impression of a real sky. However, such artificial renderings are not sufficient for real simulation purposes.

In this paper we present techniques to augment visualizations of digital 3D city models with real-time display of georeferenced meteorological phenomena. For this purpose we retrieve weather information from different sources, i. e., real-time images from cameras and radar data from web-based weather services, and we use this information in the rendering process for realistic visualization of different weather-related issues, such as clouds, rain, fog, etc. Our approach is not limited to a specific setup, and we have evaluated the results in a user study presented in this paper.

1 INTRODUCTION

Availability of digital 3D city models is on the rise, and more and more applications for visualizing such models are forthcoming, ranging from Google Earth and Microsoft Virtual Earth to academic or industrial visualization systems (Beck, 2003; Dodge et al., 1998; Steinicke et al., 2006). Although the amount of data has increased dramatically, these visualization and simulation applications can provide very detailed views of a city. Often digital 3D city models are derived from cadastral maps available as two-dimensional CAD data sets which include each building's footprint as well as the number of floors and the height between floors. In addition, information about the infrastructure, street furniture and vegetation, and also aerial photographs or satellite pictures may be available. Usually facade images as well as some highly-detailed 3D models of architecturally prominent buildings, so-called *3D landmarks*, are integrated. All these features contribute to the realism of a visualized city model.

Currently, most of the systems for visualization of urban areas concentrate on displaying the earth's surface including the objects located on the surface, i. e., the terrain with buildings, roads, trees, etc.; for instance Google Earth displays highly-detailed and textured terrain models onto which city models are placed. Although many authors have emphasized the importance of the effects of realistic illumination for computer generated images, techniques for achieving realistic illumination are rarely applied in current 3D city visualization applications. Research is focussed on improving rendering of the ground surface instead, e. g., using different caching strategies for huge amounts of terrain data (Ropinski et al., 2007), whereas rendering with realistic lighting and the impact on the visualization of the city model is rarely considered. For instance, when planning a new building it is important from where and with what inten-

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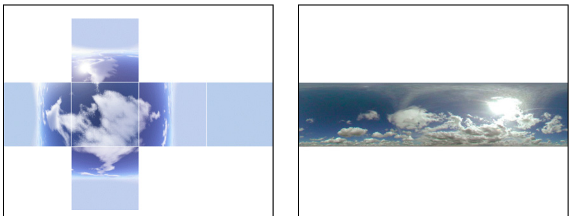
sity the sun hits the outer walls and the roof in order to optimize energy consumption. Another example is the problem to position a patio or a balcony in such a way that it has as much sun exposure as possible. Some approaches have been presented which consider the effects of light and shadow in city models, but they are focussed on light interaction between virtual buildings only, without considering global effects caused by the virtual sky (Döllner et al., 2006).

In this paper we present techniques to augment visualizations of city models with real-time meteorological phenomena. We include information from real-time video captured with web-based or specialized weather cameras, and retrieve current weather information from web-services, for example, data about precipitation, cloudiness or fog. Combining all this information we render a virtual sky having a visual appearance that comes close to that of the real sky, and hence the perception of the current weather for a virtual city model is improved.

The remainder of the paper is structured as follows. Section 2 examines work related to visualization of meteorological phenomena. In Section 3 we describe our hardware setup and the data acquisition from different sources about the past, current and upcoming weather. Furthermore, we explain how to interpret and combine this data. This information is used by the rendering techniques described in Section 4 to generate a realistic sky. Section 5 presents a user study in which we evaluate how close the visual appearance of generated virtual skies comes to their real counterparts. The paper concludes in Section 6.

2 RELATED WORK

Visualizing physical phenomena, e. g., atmospheric scattering, is one of the main research topics in computer graphics (Schafhitzel et al., 2007). Most of the early work is based on ray tracing, which is an appropriate method for creating photo-realistic representations of the atmosphere. However, due to the high computational costs, an interactive visualization was not possible at that time and therefore other approaches had to be applied. In most systems for visualizing 3D city models the sky is modeled with spherical or cubical shapes surrounding the virtual camera. Textures showing corresponding images of a sky are added to the shapes and give the impression of a sky. When using a *sky box*, the virtual sky is composed of six images forming the sides of a cube, i. e., left, right, top, bottom, front and back textures (see Figure 1(a)). With such a configuration the appearance of the virtual sky is limited to an infinite distant sky,



(a) Skybox textures (b) Skydome texture

Figure 1: Texture-based approaches for generating static virtual skies.

and moreover animations like moving clouds cannot be integrated easily. Alternatively one can use spherical domes to which distorted textures are applied (see Figure 1(b)). Multiple transparent *sky domes* can visualize different layers of clouds and stars.

In general, the textures applied to certain sky geometries already include meteorological information, such as color transitions, virtual clouds or a virtual sun. Since *static* images are used, the visual appearance is restricted in such a way that changes of the sky caused, for instance by winds etc., cannot be incorporated. In order to allow smooth changes in the visualization of the sky, *geodesic domes* composed of uniform patches can be used. A geodesic dome is an almost spherical structure based on a network of patches that lie approximately on the surface of a sphere. Each patch is defined by a certain number of vertices (at least three), whose color can be changed in real-time.

Many authors focus on certain properties such as sunlight or scattering (Riley et al., 2004). Clouds, for instance, can be modeled as volumetric objects, as flat images, so-called *3D impostor* projected on a sky dome, or using hybrid approaches (Harris and Lastra, 2001; Wang, 2004). Further rendering techniques for meteorological features have been proposed, such as using particle systems (Reeves, 1983) for rain rendering (Tatarchuk, 2006) or for visualizing falling and accumulating snow (Sims, 1990; Fearing, 2000). Most of these features can be realized using programmable shaders in order to allow simple and efficient rendering on the GPU (Roden and Parberry, 2005). Some of these aspects have been included in sky rendering libraries, such as SilverLining (Sundog Software, 2007) or SkyWorks (Harris, 2004). However, while these systems provide a good-looking impression of a virtual sky, they are more targeted on high rendering performance than on realism. In particular these applications do not take into account real-time weather information in order to present an updated sky.

The information required for rendering such a sky can be retrieved from different sources. Refined data about general weather conditions is available via several web-services. Satellite images comprise cloud coverage and rainfall, but lack resolution for the relatively small area covered by a city. Stationary cameras that capture the sky provide a more local data source. The obvious approach to augment the visualization of a 3D city model is to use the resulting video live streams as background information for the visualization. However, a direct mapping of these images is not sufficient since they are limited to specific positions, and usually these cameras cannot record the entire sky. The latter problem could be diminished by using *all-sky cameras* (FMI, 2007) which are used in astronomy and meteorology for studying aurorae, meteors and cloud coverage. They are based on fish-eye lenses or spherical mirrors and can observe the whole sky at once due to their very wide field of view (FoV). However, the resulting distortion and their limited availability makes all-sky cameras unsuitable for visualization purposes. Another problem with a stationary camera occurs when the user navigates the virtual camera in such a way that the visible virtual sky corresponds to a real sky which is out of range of the stationary camera, and thereupon no data is available for rendering the sky.

Our goal is to provide a rendered sky with a visual appearance that comes close to the real sky at the present time. Furthermore, it should be possible to visualize weather forecasts as well as weather history. The virtual skies should be augmented by real-time information from the acquired camera images as well as information obtained from other discrete sources such as weather radars.

3 DATA RETRIEVAL AND ANALYSIS

In this section we describe the different sources from where we retrieve the data, in particular current weather information, in order to generate a virtual city model and augment it with a realistically looking virtual real-time sky.

3.1 Digital 3D City Model

In cooperation with the urban development, city planning and transport planning office as well as the land surveying and land registry office of the city of Münster in Germany, we have developed a semi-automatic process to generate a digital 3D city model from the cadastral data provided for a city. The cadastral data include for each building its footprint as well as the number of floors and the height between floors, position and type of street furniture, information about vegetation, etc. Moreover, the data provides an elevation model with corresponding aerial photographs captured during overflights. For the digital 3D model a solid representing a building is generated by lifting the polygon describing the building's footprint by its total height which is calculated from its number of floors and the height between floors. Since a building's roof type as well as information about its facades are not included in the cadastral data we apply heuristics in order to generate a prototypical appearance of these features. In addition we apply shader-based *clipmapping*-techniques in order to display the enormous amount of areal images, which include overall 120 GB of uncompressed data (Ropinski et al., 2007). This technique enables us to visualize shadows of clouds on the ground as described in Section 4. Since automatically processing virtual buildings as described above lacks most of the details of their real counterparts particularly for architecturally prominent buildings like churches. For this reason we have modeled several of these *3D landmarks* with a very high level-of-detail manually (Steinicke et al., 2006). The entire model consists of more than 150,000 buildings, vegetation objects and street furniture as well as more than 50 landmark buildings. Besides the concepts described in this paper, the model can also be enhanced with a sky based on textured virtual skyboxes or virtual domes as described in Section 2. But as mentioned above this procedure is limited to static skies, whereas no current meteorological information can be incorporated. The image shown in Figure 2 illustrates the virtual city model of the city of Münster. The sky in this image is displayed using a virtual sky box with the textures from Figure 1(a).

Figure 2: Virtual city model combined with a virtual sky box showing computer generated static images.

Figure 3: Image of the MOBOTIX HiRes IP camera.

3.2 Steerable Weather-Camera

We have installed a MOBOTIX network camera (model M12M-Web-D43) on the roof of an eight-storied building at the coordinates 51° 57′ 58.5″ N, 7° 36′ 11.5″ E (see Figure 3) (Gliet, 2007). The camera provides a resolution of 1280×960 pixels with a wide angle lens (43 mm, F=2.0). It can be steered 360 degrees horizontally, whereas the vertical pitch is about 80 degrees. Live stream from the camera and further information is available via a web-based interface[1].

Figure 4 shows an image captured with the camera during the summer in July about noon. Although this camera provides good images for our approach, the concepts are not restricted to this specific model. Any camera or even static images may be used to interpret the sky and get information as described below. Alternatively we provide a GUI via which the user can specify the parameters in an arbitrary way.

A trivial approach to generate a virtual sky from the acquired camera images would be to extract only the sky and to integrate this video stream into the virtual city model. However, besides image quality problems due to restricted resolution as well as color falsification, the limited area which can be captured with the camera prevents this approach since it results in insufficient images.

Hence, we choose a different approach. We apply computer vision strategies in order to extract information from images that show parts of the sky. From a computer vision perspective the given task is to segment an outdoor image into three main components: the sky, the clouds and the ground. In fact the latter is not relevant itself, but is used for the detection of the horizon and the skyline. We detect the horizon (see Figure 4) and crop the image such that only the sky is left. Thereupon we classify the sky pixels as cloud or background. On this clustering result further parameters for the proposed weather rendering technique could be deducted. We assume the horizon as a vertical line and use an extension of the method of Ettinger et al. (2003) for the detection of the horizon line. The horizon is an important reference line. With known internal camera parameters and known global position of the weather camera, the captured pixels are embedded in a real world reference system. Ettinger et al. classify sky and ground pixel by minimizing the inner variances of the two RGB-distributions. We adopt their idea and formulate the optimization criterion

$$J = \frac{1}{\frac{1}{4} \cdot \min\{\mathrm{S}(\Sigma_G), \mathrm{S}(\Sigma_S)\} + \frac{3}{4} \cdot \max\{\mathrm{S}(\Sigma_G), \mathrm{S}(\Sigma_S)\}}$$

with the score function $\mathrm{S}(\Sigma) := |\Sigma| + \mathrm{trace}(\Sigma)^2$. Here Σ_S and Σ_G are the class-dependent (sky and ground) 3×3 covariance matrices of the red, green and blue channels. After detecting the horizon line (see Figure 4(a)), the skyline is extracted by a contour tracking method (based on a dynamic programming algorithm) and an objective function similar to the energy term J. We crop the sky part of the image for further processing (see Figure 4(b)).

The next step is to classify the sky pixels as clouds C_{cloud} or sky background C_{sky}. For this we utilize the observation that under normal conditions the background is colored whereas the clouds are rarely colored. The HSI-color model is adequately suited for such a classifying task, since the S-value represents the saturation of a pixel p. We use two thresholds t_{low} and t_{high} for classification and the following rule:

$$p \quad \mapsto \quad \begin{cases} C_{\mathrm{cloud}}, & \text{if } \mathrm{S}(p) < t_{\mathrm{low}} \\ C_{\mathrm{sky}}, & \text{if } \mathrm{S}(p) > t_{\mathrm{high}} \\ C_{\mathrm{both}}, & \text{otherwise} \end{cases} \tag{1}$$

The nonspecific class C_{both} is introduced due to the fact that clouds sometimes do not hold a sharp boundary. At the boundary this kind of clouds are transparent and the sky background is visible. Figure 4(c) shows the extracted sky background with original color value (H), full saturation (S) and full intensity (I) and the specific clouds in white. The intensity value (I) of the clouds are visible in Figure 4(d). Here the sky is represented in black. To compute the percentage of sky cover, we calculate the observed frequency of cloud pixels in relation to the complete sky region. The colorization of background can be estimated by averaging the sky background color depending on the vertical FoV. Furthermore, if individual clouds can be segmented, i. e., they have a visible boundary, we copy such clouds into the corresponding textures which are applied during the rendering

[1] `http://ifgicam2.uni-muenster.de`

(a) (b) (c) (d)

Figure 4: The images show the computer vision approach to retrieve information about the current weather: (a) original image with detected horizon, (b) cropped sky region, (c) pure color of sky pixel with saturation and (d) intensity of cloud pixel with saturation $\leq t_{\text{high}}$.

process for certain cloud structures (see Section 4). The entire process can be performed interactively.

3.3 Weather Radar and Web-based Weather Services

Recognizing certain weather-related features from a photograph of the sky is limited. For example, solely by using computer vision algorithms it is often difficult to distinguish clouds from background such as in Figure 6. Rain or snow can be distinguished only when precipitation is extremely high. Currently, we are working on a more flexible classification method for cloud and background pixels, which can operate in more general conditions (dusk, dawn, back light, halos and so on).

However, due to these limitations we extract further weather-related information from weather radar and web-based weather services. Our cooperation partner, the working group "climatology" of the Institute for Landscape Ecology, provides these services to retrieve data (Institute for Landscape Ecology, Münster, 2007) as well as to control and steer sensors, e. g., the weather camera. These services provide information about minimum and maximum temperature, direction and strength of wind, time of sunrise and sunset and percentage of possible sunshine, precipitation probability and amount of precipitation, atmospheric humidity, etc. This sensor data is encapsulated by standardized web services, where three services specified by the Open Geospatial Consortium (OGC) are used (Open Geospatial Consortium, 2007):

1. *sensor observation services (SOS)* which retrieve meteorological data (e. g. wind direction, wind speed, temperature),
2. *web coverage services (WCS)* that retrieve georeferenced weather radar data, and
3. *sensor planning service (SPS)* which enable to steer the camera.

Data that is obtained from the weather services respectively the weather radar is compared to the interpretation of the camera images. When both differ, for example, the camera interpretation yields 80% cloud cover, whereas the weather service prognoses 70%, we average the results and tune the parameters such that the visualization of the virtual sky contains 75% clouds.

4 RENDERING TECHNIQUES FOR METEOROLOGICAL PHENOMENA

In this section we explain different rendering techniques that we use for the described meteorological phenomena.

4.1 Atmospheric Rendering

In our approach atmospheric rendering is based on a layered model composed of three geodesic domes. Each geodesic dome is composed of uniformly separated patches each having nearly the same size. This ensures that the sky shading is smooth across the entire dome surface. As depicted in Figure 5 we position the virtual sun represented by a virtual sphere on the surface of the outer dome with respect to the georeferenced position of the city model as well as the local time. The size as well as the color is determined by values derived from the weather web-service. In addition a distance light is set with respect to the sun's position and directed to the center of the 3D city model.

The visualization of the atmosphere is simulated by multiple intervals with linear color transitions, defining the color from the horizon to the zenith. The color values are defined with respect to the color values determined by the colors from pure color of the sky images as depicted in Figure 4. Since the camera's orientation as well as the FoV that records the image or video stream of the sky is known, corresponding colors are assigned to the vertices of the geodesic dome (see Figure 5). The vertices which cannot be assigned to pixels in the camera images are

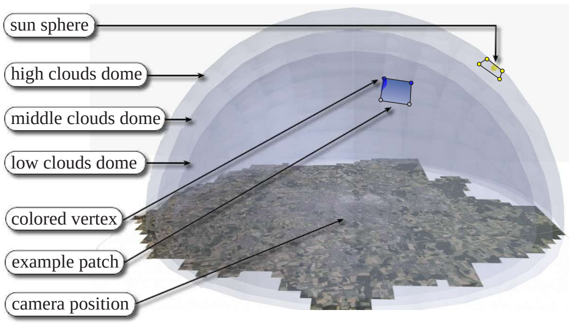


Figure 5: Arrangement of virtual skydomes supporting three different layers of clouds.

colored with respect to their distances to already colored vertices while the geodesic dome's symmetry is exploited, i. e., vertices which have the same height are colored in the same way. In addition when vertices are close to the virtual sun even the color of the virtual sun is merged into the color of the vertex (see Figure 5). Alternatively, the colors at the horizon and in the zenith can be defined by the user via a graphical user interface (GUI). Since the color assignment is performed in programmable vertex shaders rendering can be performed in real-time.

4.2 Rendering of Clouds

As described above the three geodesic domes are composed of almost uniform patches. Consequently, there is no singular point in which the patches converge, and thus distortion of textures applied to the surfaces is prevented. Each geodesic dome is associated to one family of clouds, i. e., high, middle and low clouds, which are represented as textures on the corresponding surface. According to (Howard, 1802) we classify clouds by the altitude of the cloud base. High clouds form above 5,000 meters in the cold region of the troposphere; they are denoted as *cirrus* or by the prefix *cirro-*. The clouds tend to be wispy and are often transparent, e. g., cirrus, cirrostratus, cirrocumulus, etc. Middle clouds develop between 2,000 and 5,000 meters and are denoted by the prefix *alto-*, for example, altostratus and altocumulus. Low clouds are found up to 2,000 meters and include the stratus (dense and grey). When stratus clouds contact the ground, they are called fog (see Section 4.3). Low clouds in this family include, for example, stratus, nimbostratus and stratocumulus.

In order to be able to render clouds at different altitudes realistically we render each family of clouds on the corresponding geodesic's surface (see Figure 5). Since the approach is focussed on pedestrian navigation where clouds are reasonable far away from the user's perspective this approach yields to sufficient results (Wang, 2004). For each cloud family we have generated texture atlases that are composed of different cloud-based textures representing different cloud types. The textures are encoded in the RGBA format, i. e., each texel contains an RGB color entry as well as a transparency value α. Each type of cloud can automatically be switched on or off and the amount of each cloud can be controlled as described in Section 3.2. Alternatively clouds can be controlled via the GUI by means of controlling the color channels. For instance, black is associated to no clouds of the corresponding type, while white is associated to all clouds represented in the texture. The transparency of clouds is mapped directly from the α value in the texture. Furthermore, the color of the clouds can be changed by means of associating a grayscale value to each α value. Since we use shaders for each cloud family, clouds from the same as well as from different families can be combined arbitrarily in real-time.

Wind information that we retrieve from the weather web-service is used to move the clouds in the corresponding direction by means of rotating each geodesic dome. The rotation axes are determined by the cross product of the wind direction and the normal at the geo-referenced point to the ground model. Due to the different radii of the three geodesic domes we ensure that motion parallax caused by clouds is analog to the real world, i. e., lower clouds appear to move faster than middle clouds, the latter appear to move move faster than high clouds. The rotation speed and axis of each dome is determined by the wind speed. Furthermore, we use the cloud textures to apply corresponding shadows on the ground with respect to the sun position.

4.3 Rendering of Rain and Snow

In our system techniques to render rain and snow are similar to the rendering of clouds. Different textures represent different kinds of snow or rain, which are classified in corresponding categories again. For example, according to the amount of precipitation, rain can range from very light rain, i. e., the precipitation rate is < 0.25 mm/hour, to moderate rain—when the precipitation rate is between 1.0 and 4.0 mm/hour, and to extreme rain, where the precipitation rate is > 50.0 mm/hour. For each type of rain respectively snow textures are combined in texture atlases again. These textures are blended to the inner dome as well as to the near clipping plane. By means of modifying the texel position vertically the user gets the notion of falling rain respectively snow. However, currently rain and snow have no impact on the visualization of the ground, e. g., accumulation of fallen snow. Due to limitations in the computer vision process, we extract information about rain or snow via the weather radar only.

4.4 Rendering of Fog

The weather web-service gives information about the visibility range determined by the level of fog. Fog rendering is implemented in a fragment shader applied to each fragment, where transparent grayscale values are blended with respect to its depth value, i. e., objects which are far away from the camera are blended with less transparency than objects close to the camera.

5 SUBJECTIVE EVALUATION

In this section we present an evaluation in which users had to evaluate how close the visualization of virtual skies come to their real counterparts.

5.1 Tasks

We have prepared photographs which show a city from different locations with different weather conditions (see left images in Figure 6). After extracting the corresponding information to define parameters for the rendering process for the virtual sky as described in Section 3, we have rendered an image of the virtual 3D city from the same georeferenced position enhanced with a virtual sky based on our approaches. We have rendered four more images from the same position, but have applied a quasi-randomly (QR) generated sky, i. e., we restricted the visualization of that sky such that almost the same weather is shown, for instance, if the photograph does not show any clouds, we omitted clouds in the random process.

After comparing each rendered image side-by-side with the original photo 6 (5 male, 1 female) participant students had to state how close the visualization of the virtual skies mirror the real ones in terms of weather-related phenomena. The evaluation had to be performed on a ten point Likert-scale, where 1 corresponds to ”no similarity at all” and 10 corresponds to ”equality”, i. e., the images show the same weather. Thereby similarity of the virtual and real weather in terms of a subjective evaluation is possible, whereas a comparison based on HDR images would result in objective evaluation.

5.2 Results

The results of the user evaluation are illustrated in Table 1. The table shows the average score of how users reported the similarity of the sky visualized using our concepts in contrast to using the QR generated images with the corresponding photographs.

Table 1: Evaluation of rendered images with respect to photographs.

Image:	Score (ϕ):
Fig. 6 (a) (right)	7.2
QR image of Fig. 6 (a) (left)	4.6
Fig. 6 (b) (right)	8.2
QR image of Fig. 6 (a) (left)	4.8
Fig. 6 (c) (right)	8.1
QR image of Fig. 6 (a) (left)	5.2
Fig. 6 (d) (right)	8.4
QR image of Fig. 6 (a) (left)	4.45

The results show that users perceive the visualization of a virtual sky generated with our approach close to the real sky, for example, depicted in a photograph. Overall, users rated our concepts with 7.9 on average, while a QR image of the same weather has been rated with 4.76 on average.

6 CONCLUSIONS

We have presented techniques to enhance visualizations of digital 3D city models with real-time display of georeferenced meteorological phenomena, such as the visualization of atmosphere, clouds, sun, rain, snow and fog. In contrast to other sky rendering libraries we have integrated real-time information retrieved from different sources, i. e., images from cameras and data from web-based weather services, into the rendering process in order to achieve a realistic visualization. The evaluation has proven that skies rendered with our approach come close to the real skies shown in photographs. Our approach is not limited to a specific setup, i. e., the weather camera, but is applicable with any web-based camera as long as parts of the sky are visible.

In the future we will develop an interface such that that multiple images from the current sky can be combined to further enhance the visualization of the sky. Moreover, we will extend the computer vision process in order to retrieve more information from each image.

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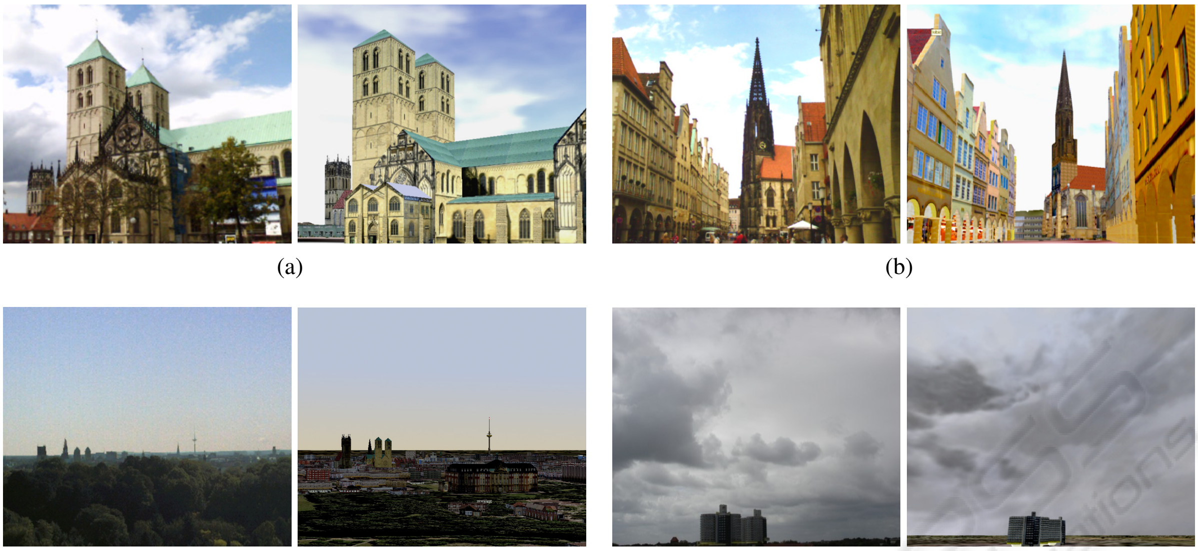

(a) (b) (c) (d)

Figure 6: Visual comparison between the real respectively virtual sky in photographs respectively rendered images from (a), (b) pedestrian perspective and from (c), (d) bird's-eye view.

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