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Automatic Extraction of Textures from Infrared Image Sequences and Database Integration for 3D Building Models

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Summary: This article presents an approach for extraction of façade textures from low resolution infrared (IR) image sequences and their integration into a database. Two strategies are presented for matching the images and the given 3D model: the first one is based on the determination of the camera parameters using three corresponding points, and the second strategy involves the estimation of planes in the image sequence via computation of homographies. Textures are extracted using an algorithm based on the principles of ray casting to generate partial textures for every visible surface in every single image of the sequence. Furthermore, textures generated from different images yet belonging to the same façade are combined. Different combination strategies are briefly described. The resulting textures are integrated into a GIS database in a format that is conformal to CityGML. Integration and visualisation techniques for those textures are discussed with the intension to extend the CityGML format for multi-textural purposes.

Zusammenfassung: *Automatische Extraktion von Texturen aus Infrarot Bildsequenzen und Datenbankintegration für 3D Gebäudemodelle.* Dieser Beitrag behandelt die Extraktion von Fassadentexturen aus niedrig aufgelösten Infrarot (IR) Bildsequenzen und deren Integration in einer GIS-Datenbank. Für das Matching von Bildern und dem gegebenen 3D-Modell werden zwei Verfahren vorgestellt: die Bestimmung der Kameraparameter mittels drei korrespondierenden Punkten in einem Bild und dem Modell, und die Schätzung von Ebenen in Bildsequenzen durch Homographie. Die Texturen werden unter Verwendung eines Ray Casting-Algorithmus extrahiert, um partielle Texturen für jede sichtbare Oberfläche jedes Einzelbildes der Sequenz zu erzeugen. Die Texturen, die aus verschiedenen Bildern der Sequenz erzeugt werden und zur selben Fassade gehören werden anschließend kombiniert. Verschiedene Strategien für die Kombination werden kurz vorgestellt. Die gewonnenen Texturen werden in eine GIS Datenbank integriert, die auf CityGML basiert. Es werden Integration und Visualisierung diskutiert, um CityGML für die Anforderungen von Mehrfachtexturierung zu erweitern.

1 Introduction

Today, the acquisition and exploitation of thermal imagery is gaining considerable attention. Infrared (IR) images are acquired from different platforms and used for different applications. For instance, satellite images are the common basis for vegetation monitoring (Quattrochi & Luvall 1999), the analysis of urban heat islands (Lo & Quattrochi 2003), or fire detection (Siegert et al. 2004). Airborne IR-systems are applied for detecting stationary vehicles (Stilla & Michaelsen 2002, Hinz & Stilla 2006) and moving objects (Kirchhof & Stilla 2006) or exploration of leakages in district heating systems (Koskeleinen 1992). On the other side, the irradiation of façades is typically recorded with ground cameras in order to get insight into a building's thermal behaviour (Klingert 2006).

Urban areas reveal complex thermal characteristics due to the mutual influences of man-made objects like buildings, roads etc. Aside from object materials, the whole 3D

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geometric outline of the recorded scene plays an importand role for the heating caused by the sun and radiation and irradiation between buildings. In many urban studies, 3D information has not been exploited for the interpretation of the acquired scenes.

NICHOL & WONG (2005) applied simple prismatic building models to investigate the influence of building geometry on urban heat effects. Spaceborne thermal images are used to texturize a digital terrain model. For every building roof an averaged temperature of the corresponding image area is determined. The temperature of building walls are guessed from the roof temperature and the temperature of the surrouding ground. Due to the coarse resolution of the satellite images, a detailed investigation of building surfaces is not possible.

This paper investigates strategies for a detailed texture mapping of building façades to support a thermal inspection. Typically, thermal inspections of building façades are carried out in single images from the observed objects. Larger building parts require several images to be analysed. An integral way of viewing buildings recorded from different images is difficult without combining those images. This problem is getting worse, when images from different cameras or views need to be combined and stored for further processing without any geometric reference.

The main challenge for the extraction and combination of textures refers to the estimation of the exteriour orientation of the camera for the projection of the 3D model into the image plane. In a second step, combined textures have to be integrated in a given database.

1.1 *Automatic Extraction of Textures*

Several techniques for estimating the exteriour orientation have been reported in the literature. A suitable solution depends on the number of images and the number of point correspondences between the IR images and the projected 3D model. The estimation of exterior orientation from a single image works with at least 3 correspondences (3-point algorithm) between image and model (HARALICK et al. 1994). Techniques for 4- and 5-point estimation are elicited by QUAN & LAN (1999) and TRIGGS (1999). For 6 and more correspondence points the Direct Linear Transformation (DLT) can be applied (TRIGGS 1999). Generally, the distribution of the points in object and image space has to be observed to ensure a certain accuracy of the estimated parameters or a solution at all.

Due to the small field of view and the limited spatial resolution of the IR images together with the low level of detail of the given building model, only few point correspondences between IR image and 3D model can be identified. Alternatively, one may first co-register all images of the sequence via tie points (as in stereo photogrammetry (LONGUET-HIGGINS 1981)) and then establish the correspondence of the whole image strip with the 3D model. The exterior orientation of the individual images can then be inferred from the transformation parameters. For façade structures approximately forming a 3D plane, algorithms for homography estimation can be applied to detect planes in image pairs. This enables the direct determination of the orientation of the camera in relation to these planes (HARTLEY & ZISSERMAN 2000)

1.2 *Database Integration of Textures*

3D city models are widely used in different applications like disaster management, city planning or transmitter placement for mobile communications. The enrichment of building models with additional data related to parts of the building geometry is subject of ongoing research. There exist many proprietary data formats for 3D city models which support textured geometric models and factual data as independent objects, but they do not support factual data assigned to a building model (KOLBE & GRÖGER 2003). This drawback was first addressed in CITYGML (KOLBE et al. 2005, DÖRSCHLAG 2006) which is an exchange format based on the Extensible Mark-Up Language XML (W3C 2001). The semantical, topological and geometrical models were developed to exchange all fundamental building-related informations. Nevertheless, this standard supports only the common data of a building like address, storey height, roof type, year of construction, etc. Here, we propose an extension scheme which allows the integration of multiple image data (e. g. multispectral, multi-aspect, multi-temporal) and additional data (e. g. texture resolution distribution, texture completeness, meteorological data, cartographic signatures).

2 City Model and Data Acquisition

A part of the untextured 3D model selected as test object from the database is shown in Fig. 1. For enriching the building database with thermal textures, IR images were recorded with 50 frames per second at a sampling grid of 320×240 pixels. Two cameras capture the midwave (3–5 µm) and longwave (8–12 µm) infrared band (see the left and middle camera in Fig. 2 and resulting images in Fig. 3). An additional video camera captures the visual information for verification purposes (see the right camera of Fig. 2). The camera position is recorded using a GPS. This is only used, however, for the initial position of the virtual camera since narrow streets and high buildings led to positional errors for lack of sufficient GPS signals. The building models are stored in a database according to the CityGML exchange format for 3D models. Meteorological data are gathered to estimate temperature values from the measured radiation. Additionally, a timestamp was stored for synchronization of meteorological data, camera position and the infrared image sequences.

3 Pose Estimation, Texture Extraction and Texture Combination

3.1 *Position Estimation and Matching between IR Images and 3D Models*

All camera parameters must be known in order to project the 3D model onto the image plane. The interior orientation of the camera is determined by a off-line calibration. The *approximate position of the camera* is recorded during the image acquisition. *Pan, tilt and roll angles of the camera* are estimated from ground control points given by the vertices of the 3D model. Two strategies are described in this section to automate the assignment of correspondence between the 3D model and IR images.

Due to the small field of view, the low spatial resolution of the IR images and the low level of detail of the given building model, only few point correspondences between IR image and 3D model can be identified (Fig. 4a). A straightforward solution is thus the application of the 3-point algorithm proposed by HARALICK et al. (1994). For

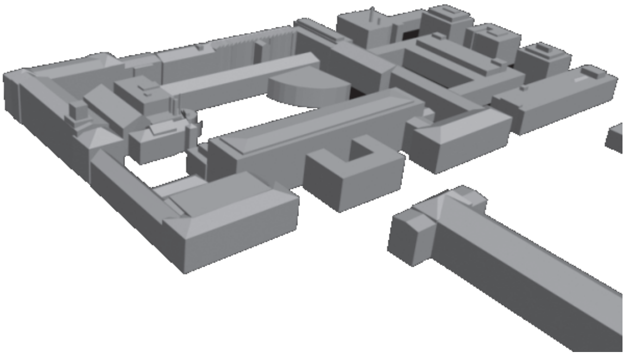

Fig. 1: 3D model of the test site.

Fig. 2: Camera system.

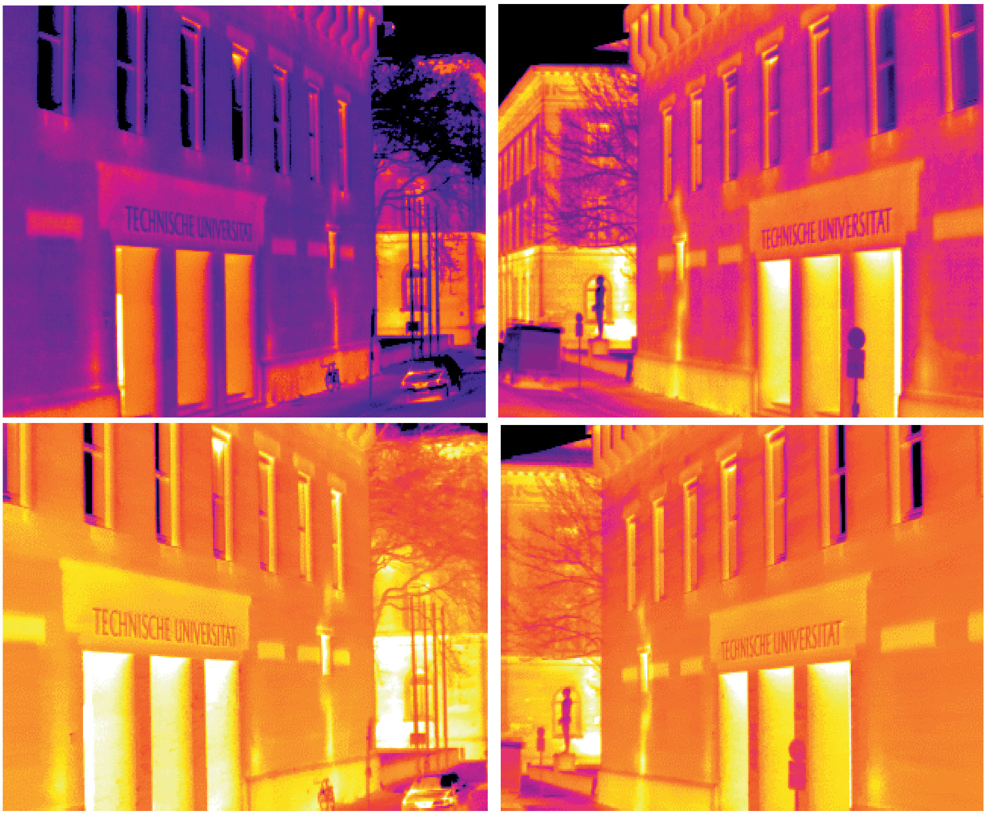

Fig. 3: from upper left to lower right: forward and backward view of midwave IR camera and longwave IR camera.

a given camera position, the image with the corresponding time-code is selected, first. Then, common interest operators are applied to extract salient points and edges. Long horizontal and vertical edges are supposed to be façade edges, thereby including some tolerance values to accommodate perspective effects. Intersections of horizontal and vertical edges finally yield the 2D coordinates of façade corners.

As three points are known in 3D coordinates and should correspond to three points given in 2D coordinates, an estimation of the exterior camera orientation is possible. Every visible polygon is projected onto the image plane transforming its vertices from 3D camera coordinates to pixel coordinates and clipped using Sutherland-Hodgeman polygon clipping. The depth values and texture coordinates for all image pixels covered by the polygon are inferred from the plane equations of the polygon. Every pixel of the final projected scene image is assigned to the smallest depth value from all projected polygon images (z-buffer; Catmull 1974). To this end, an image with polygon ID, depth value and texture coordinates stored for every pixel is available for the projected scene. The intensity values of the IR image are now assigned to the corresponding texture and surface stored in pixels of the projected scene. Missing camera positions of frames are interpolated from frames with known position.

This strategy is feasible if at least three vertices of the model are visible in the image of the virtual camera and the corresponding corners can be found in the IR image. It might happen that, due to the given characteristics of the IR camera and the situation of image acquisition, the IR image shows only one or two façade corners so that there remain only two edges of the model for finding corresponding edges in the IR image. Two edges are not sufficient to estimate a unique camera orientation, as there are different combinations of camera position and viewing angle that can achieve the overlay of the two lines in the IR image and the model projection.

An alternative strategy, that circumvents the problem of missing vertices in the IR images, is the following:

Instead of calculating the position for individual key frames, the complete image sequence is incorporated into the image orientation procedure, i. e., the relative orientation between all consecutive image pairs is calculated first, before the whole strip is matched to the 3D model. This process can be simplified, since, for homogeneous façade structures that approximately form a plane, homography estimation is suitable to detect planes in image pairs and to infer the orientation of the camera in relation to these planes (Hartley & Zisserman 2000). Since many buildings have an approximately planar façade, the assumtion that significant façade structures lie also in a plane is often valid.

Hence, we establish the correspondences between two subsequent images through Harris interest points and employing a homography matrix H. The estimation of H involves a RANSAC procedure (Fischler & Bolles 1981) to cope with outliers and local extrema in the objective function. For the first image pair, the initial (GPS) camera position is used to estimate a façade plane that is close to the corresponding 3D model surface. For all subsequent image pairs (with frame distance d), a set of homographies is calculated to enable the estimation of the camera trajectory relative to the façade plane. Finally, the trajectory is smoothed by averaging the planes of the homographies. This strategy works well for homogeneous images with only one façade covering most of the image.

3.2 *Texture Extraction from IR Images*

Depending on attitude and trajectory of the camera, some building parts might be invisible due to self occlusion or occlusion from other objects. Thus, a search algorithm determines the visible surface points corresponding to the pixels of the image of the virtual camera:

First, a plane equation is calculated for every surface to receive the depth value and texture coordindates. This plane is then used for ray casting (Foley 1995), where every pixel is projected into the scene and assigned to an intersection point of that particular plane, which has the smallest depth value along the ray from the camera through the pixel. For the intersection point of this plane, the texture coordindates are interpolated from the texture coordinates of the vertices of the plane. The texture coordinates count from $(u, v) = (0,0)$ at the left lower vertex of the surface and are going up to $(u, v) = (1,1)$ at the upper right vertex. The ID of the intersected surface and the texture coordinates of the intersection point are returned to the pixel of the infrared image.

After this 3D to 2D transformation of the model surfaces into the image plane of the IR image, a 2D transformation is carried out to transform the IR image pixels to texture coordinates of the model surfaces. At the end, the intensity values of the IR image have been transformed to texture coordinates of points on the model surfaces.

Another 2D transformation is necessary to transfer the texture points to pixel coordinates for the surface textures. At first, the individual pixel coordinates of the texture are transferred into texture coordinates of the surface. Then, their interpolated values are calculated through a bilinear interpolation. If a pixel has only three surrounding points in u and v direction, the pixel value is interpolated using barycentric coordinates. If the pixel is outside the triangle defined by the three surrounding points, it is outside the visible part of the façade. Pixels with only two or less surrounding texture points also are outside the visible part of the façade and left in black (Fig. 4b).

3.3 *Combination and Storage of Extracted Textures from IR Sequences*

For assembling an entire texture of a façade, its partial textures extracted from the individual images need to be combined, i. e., the intensity values of the combined final texture have to be interpolated from the values of the parital textures. To this end, two methods can be applied (see Fig. 5):

The first method transforms the texture coordinates of every projected IR image into a partial texture image, which in turn is used to interpolate the pixel values of the entire texture (cf. Fig. 5a). This allows to search for corresponding points and edges in the partial textures to correct for displacements. The displacements are caused by inaccuracies in the camera parameter estimation. However, besides residual displacements and inaccurate initial camera position more problems remain: The low resolution of the IR images leads to blurred edges and eventually to jittering edges between adjacent images. In addition, the small field of view and the small distance to the building allows only few edges to be seen, so that this positional inaccuracy is hard to correct.

The second method extracts the texture coordinates directly from the image sequence and combines them into one set of texture coordinates for the purpose of interpolating the pixel values of the entire texture (cf. Fig. 5b). Although it is not possible to correct displacements with this method, a higher interpolation accuracy can be achiev-

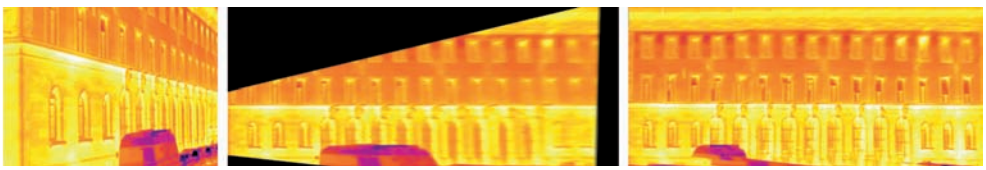

Fig. 4: Steps for generating a single texture: a) IR image, b) extracted single partial texture, c) combined final texture. The color table represents the intensity values of one IR band.

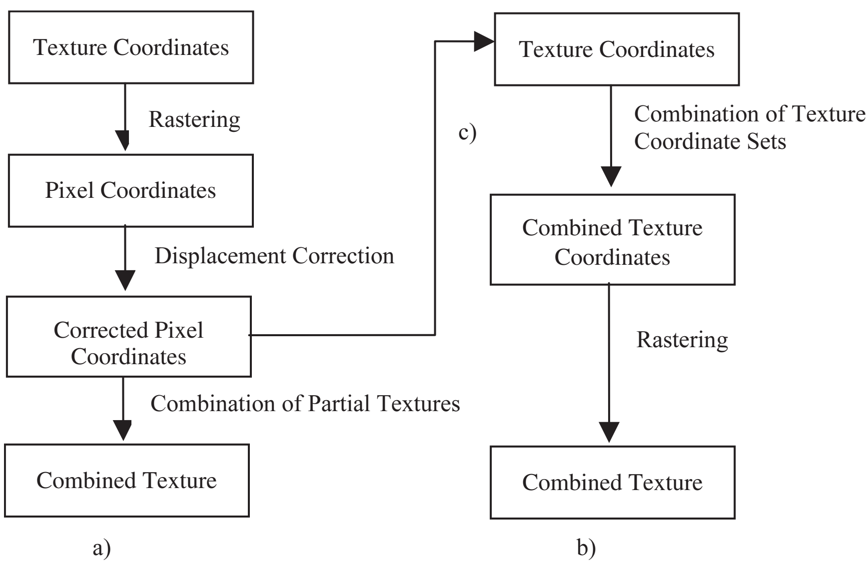

Fig. 5: Texture processing strategies: a) Combination of partial textures, b) Combination of texture coordinate sets, c) Combined strategy using the corrected partial textures to correct the texture coordinate sets.

ed because the original positions of the intensity values estimated during the texture extraction are used for the interpolation and no intermediate step using partial texture images is necessary.

Both methods are combined in the approach in this paper. At first, the partial texture images are used to find displacements between the partial textures like in the first method (cf. Fig. 5a). These displacements are transformed from pixel coordinates to texture coordinates and used to correct the relative positions of the texture points of the partial textures (cf. Fig. 5c). Then, the pixel values of the entire texture are interpolated from the complete set of texture points (cf. Fig. 5b, second method) using bilinear interpolation and barycentric interpolation as described in section 3.2. A combined texture is shown in Fig. 4c.

Before the texture image is stored, the intensity values are quantified for a predefined bit depth (e. g. 8 bit or 24 bit). The absolute temperatures of surfaces are finally calculated by transforming the intensity values to temperature values using meteorological measurements as calibration data. This correction can be realised either on the partial textures or on the interpolated pixel values of the combined texture image.

Some simplifications can be made for a single-pass image sequence in case of a forward-looking oblique view and a moving camera with constant angle between the viewing direction and the façade: If the frame rate is high compared to the velocity of the movement, the differences of two adjacent images of the sequence are very small. For this reason, corresponding points in both surface textures can be determined within a small search area. Then, after matching two partial textures, the intensity values for the combined texture are calculated. It has to be observed that, for an image sequence acquired in the aforementioned way, the partial surface textures have different resolutions. The resolution decreases in the viewing direction of the camera caused by the perspective view (cf. Fig. 6a). During forward recording, each subsequent partial texture has a higher spatial resolution for the overlapping area than its preceding texture, but does not show the complete part of the preceding texture (cf. Fig. 6b).

In an initial step, the first partial surface texture is copied to the entire texture. The second partial surface texture is then copied to the entire texture and overwrites the pixels copied from the first texture that are copresent in the second one. For the first texture, only those pixels not belonging to the second texture remain in the entire texture. This procedure is continued for all partial surface textures of the image sequence. At the end, every part of the entire texture gains the highest resolution of this part in all images from the input image sequence (cf. Fig. 6c).

4 Integration of Thermal Data into CityGML

CityGML is based on the Extensible Mark-Up Language and can be visualised by the Aristoteles 3D Viewer and the commercial program LandXplorer. It supports the extension of project-specific schemes with help of namespaces. In this work the namespaces *xs* and *xAL* are respectively adopted for urban data and address data. An extended namespace *ir* is defined for infrared data. The 3D model of the Technische

Fig. 6: a) Resolution image of a single partial texture (compare Fig. 4a, 4b; bright : high resolution, dark: low resolution), b) Resolution image of a combination of several partial textures, c) Resolution image of the combined texture.

Universität München conforms to the CityGML structure and contains building geometries at the Level of Detail 2 according to the definition in Sig3D.

CityGML describes the building surfaces in terms of boundary representation BRep (Mantyla 1988). BReps are also referred to as ring polygons or linear rings. The material properties are described according to the same standards as VRML, X3D and COLLADA. Among others, CityGML supports the description of radiometrical values that are important for the derivation of the Bidirectional Reflectance Distribution Function (BRDF) of isotrope materials.

The scheme ir is stored in an instance file, with its semantical structure being defined in the *infrared.xsd* file. It contains (i) the meteorological data, (ii) all generated textures from the different wave lengthes that can be optionally visualised, (iii) the resolution textures that can be used to monitor the texture quality and (iv) time stamp. The *EXIF* format stores meta data of camera-specific information in the header of the *TIFF* file, like field of view, wave length, camera type etc.

For each texture, its corresponding meteorological data at the recording time can be used to derive the absolute temperatures from the stored texture intensity. This allows, for example, the inverstigation of the influence of weather conditions on the thermal behavior of building façades. A completeness factor for each façade texture is included in the *ir* scheme for the purpose of showing the coverage percentage of the surface by its infrared texture. With the exception of this completeness factor no information about the position of the missing parts is stored. Furhtermore the texture resolution is stored for every pixel in a resolution image (cf. Fig. 6c). CityGML supports the data transfer between the Oracle 9i database and the visualisation software.

The open source program Aristoteles 3D Viewer developed by Dörschlag & Drerup (2007) and written in Java 3D is adopted for the visualisation of thermal information. This software allows retrieval, manipulation and storage of CityGML files in a 3D environment. Aristoteles supports standard schemes. New plug-in tools can be created to visualise surfaces with multi-textures, temporal changes in texture sequences, geometrical structures, and their semantic attributes.

5 Discussion

We have introduced a solution to automatically extract textures from low resolution IR image sequences for a given 3D building model and to integrate these textures into a database. The estimation of the exterior orientation of the virtual camera for the projection from GPS data is insufficient. The two possible ways for correcting the orientation are limited to certain environmental parameters. The 3-point camera correction fails in case of a low number of corresponding points in the 3D model view and the IR image. The homography-based orientation estimation works pretty well for large plane surfaces but has revealed some weaknesses for heterogeneous façades.

To get a texture for visualisation, a raster image has to be generated which may cause errors in the position of the measured values and the intensity value itself. The research for the influence of the type of combination of the textures, which can be conducted before and after rasterization and before or after the quantification of the values for the texture image, remains a substantial task in future work.

6 Outlook

Midwave thermal infrared and longwave thermal infrared normally reveal similar but not exactly the same thermal structures. Structures reflecting the sunlight are better visible in midwave infrared. However, this spectrum is strongly affected by weather changes. For example, the measured radiance changes immediately as soon as the sun is covered by clouds. This fact has inspired us to investigate the change of thermal behaviour over time with combined infrared datasets. The recorded scenes of our test site

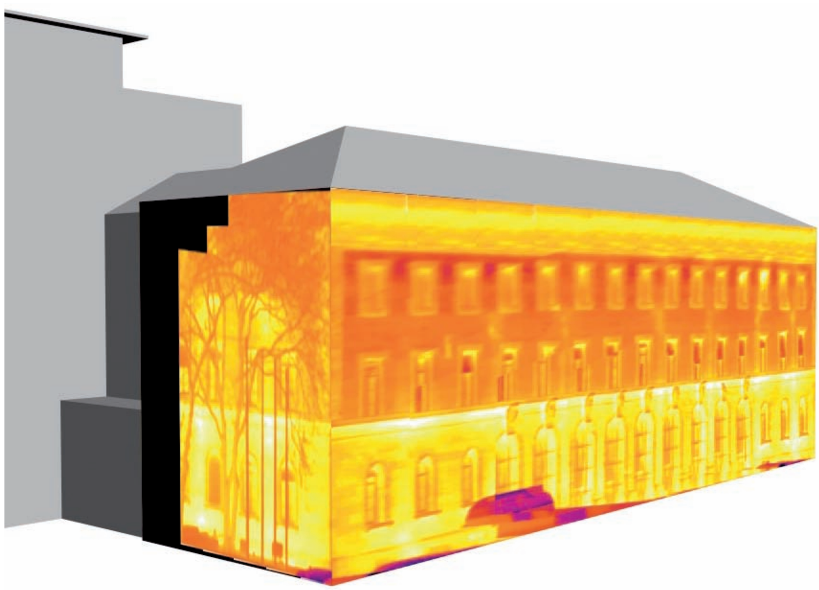

Fig. 7: Final texture on 3D building model.

in different wavelengths at different times and under different viewing angles allow us to compare the different behaviours of geometric structures and surface attributes (e. g. heating pipes, surface temperature) in midwave and longwave infrared. Whenever a thermal structure is detected in one texture, it can be inspected in other textures of the same façade from different times and wavelengths, even if it may be invisible in other structures. This allows verifying the detected structure and understanding its thermal behaviour.

In the current work, edges and vertices of the 3D model were used to find correspondences to image structures. The existing 3D model corresponds to the LOD2. That is, only building edges and roof structures are represented, but structures on the façade are not included. This causes problems in finding correspondences between the model and the image because only a small part of the objects is visible in the image due to the small field of view and short distance to the observed objects. One possible solution is to combine 3D model parts with surface structures detected from available textures of both visible and infrared domains so that additional edges and points for the matching can be generated. In particular, we will investigate the feasibility of using small structures extracted from textures of visible domain to refine the position estimation and matching process.

The existing techniques of 3D computer graphics that have been mainly focused on geometries and textures from visible domains need to be extended to include special symbolization and animations to display thermal information. We also attempt to highlight the time dependent thermal behaviour of small structures in different textures of the same façade. Instead of striving for the visualization of classified façade temperature based on the general knowledge about the typical material radiation by different weather condition, we concentrate on highlighting the distinctive characters of thermal structures such as heat bridges, heat insulation, and windows in relation to their surrounding.

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