Analysis of urban areas combining high-resolution optical and SAR imagery

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Abstract. Modern space borne SAR sensors provide geometric resolution of one meter. Airborne systems acquire imagery with even higher resolution. In data of this kind many features of urban objects become visible, which were beyond the scope of radar remote sensing only a few years ago. However, layover and occlusion issues inevitably arise in undulated terrain and urban areas because of the side-looking SAR sensor principle. In order to support interpretation, SAR data can be analyzed using additional complementary information provided by optical data. The focus of this paper is on building extraction in urban scenes by means of combined SAR data and optical aerial imagery.

Keywords Recognition, SAR, High resolution, Fusion, Reconstruction, Urban, Simulation, TerraSAR-X

Introduction

This paper presents the current state of a research project that investigates the analysis of urban areas by combining building hints on feature level from high resolution optical and SAR imagery. Three main topics are investigated that will contribute to an iterative building detection and reconstruction approach: feature extraction based on real as well as on simulated data, building detection based on such features, and building reconstruction. This paper provides an overview of all three parts of the project.

The first part consists of finding features that can be used as building hints. Buildings appear differently in corresponding optical images and SAR images due to the different viewing geometries of the sensors and hence building hints look very different. Buildings in SAR images are usually characterized by bright lines due to multiple signal reflections between building walls and adjacent ground surfaces (corner

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lines). However, corner lines do not occur if the wall is directed in range direction or if it is occluded by, e.g., trees. Additionally, bright lines may be caused by other effects. Thus, an in-depth investigation of corner lines based on real and on simulated data has to be carried out in order to come up with statistics concerning the accuracy of the corner line detection process. Details are provided in the first section of this paper. Optical imagery can be exploited in order to extract additional features for supporting building detection hypothesis. A robust building detection approach for high resolution optical images based on an initial segmentation is used in this project [1].

In the second part, the features from both SAR and optical data have to be integrated into a joint classification framework for building detection. An overview of the approach currently used is given in the second section.

The third part follows the idea that overlaying a SAR image and an optical image will lead to displacements. This effect can be used for the extraction of height information [2] and building reconstruction under the assumption of locally flat terrain. Heights of elevated structures can either be estimated from one single SAR image or from the displacement between corresponding features of one SAR image and one optical image [3]. In order to correctly overlay both images, the exterior orientation of the sensors has to be known. Moreover, a Digital Terrain Model (DTM) is necessary in order to reduce effects due to the violation of the flat terrain assumption.

1. Feature selection and simulation

In this section, the typical appearance of buildings in SAR imagery is explained. Thereafter, the SAR specific effects are demonstrated using real high-resolution TerraSAR-X data as well as simulated data.

In Fig. 1 schematic views of a flat roofed building and a gable roofed building are shown. Both times the buildings are illuminated by the SAR sensor from the left and orthogonally to the principal building axis. The major signal returns are displayed below the building sketches in slant range and in ground range geometry with their approximate intensity. White indicates high intensity (strong signal return) whereas black indicates very low intensity (almost no signal return). θ depicts the viewing angle of the sensor and the thin straight black lines running diagonally from the lower left to the upper right of the sketch approximate the wave fronts of the incoming signal.

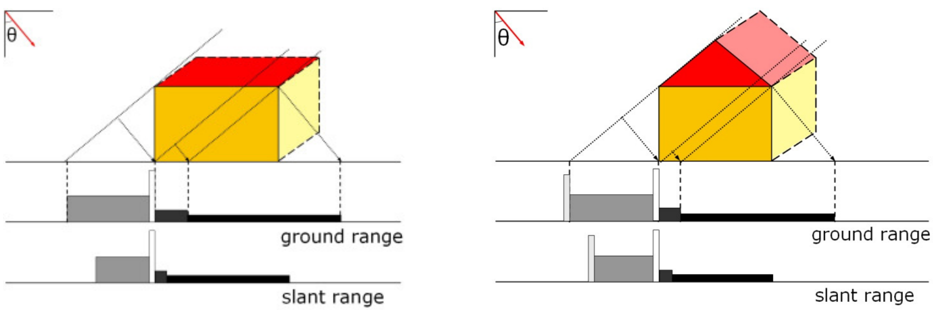

Figure 1. (left) schematic view of the appearance of a flat roofed building in a SAR image, (right) schematic view of the appearance of a gable roofed building in a SAR image (after [4]).

In case of the flat roofed building (Fig. 1 (left)), the resulting SAR image can be subdivided into four different parts. Beginning with the part which is located the closest towards the sensor (the most left part shown in light grey) the imaged backscatter signal consists of contributions from the roof, the façade, and the ground. This area is the so-called layover region. The following white line is the corner line being characteristic for buildings in high-resolution SAR imagery. It occurs due to multiple signal reflections on building walls and the ground. However, it is sometimes hard to detect or even invisible in real SAR data if the building façade is occluded by, e.g., trees. The area displayed in dark grey depicts the signal return from the right side of the building roof. Such part is mapped behind the layover area and the corner line since its distance to the sensor is longer than such of ground, façade, and the left part of the roof. Following thereafter, the radar shadow is shown in black. All objects located in the shadow area behind the building will not be mapped to the SAR image.

The appearance of a gable roofed building in a SAR image looks very similar. However, in addition to the corner line, a second bright line occurs which is oriented parallel to the former. It is due to single bounce signal return from the left side of the gable roof. Incoming signal and roof plane enclose an angle of approximately 90°. As a consequence, all points on the roof plane in range direction fall into the same range cell in the SAR image. Therefore, the entire roof plane is mapped to a line of variable width depending on the inclination of the roof [4].

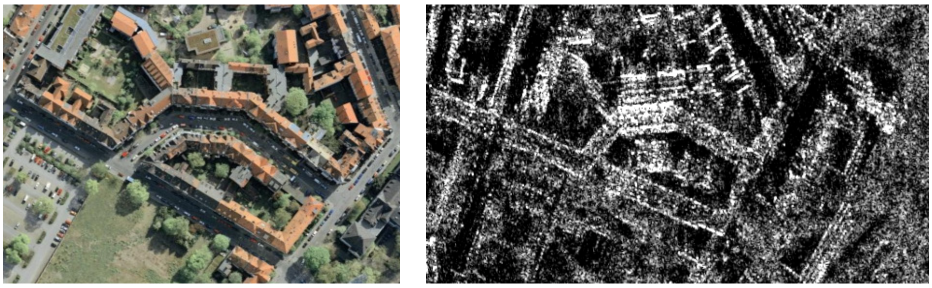

Figure 2. (left) Aerial view of the test site "Schneiderberg" (© Google Earth), (right) Cut-out of a TerraSAR-X image of the "Schneiderberg" test site (range direction bottom-up, slant range geometry, HH polarization, azimuth from right to left, pixel size 0.87 m (azimuth) x 0.46 m (range), viewing angle 33.7°).

In order to investigate corner lines and their detection accuracy in more detail, a test site located closely to the university campus of the Leibniz University of Hannover in Hannover, Germany, was selected. The left picture in Fig. 2 shows an aerial view of the test site "Schneiderberg" while the right picture shows a corresponding TerraSAR-X image acquired in high-resolution spotlight mode with a viewing angle of 33.7°. It contains several multi-story buildings with flat roofs and with gable roofs. In front of the buildings, with respect to the sensors perspective, no elevated vegetation occludes the building facades. One investigated street has buildings only on one side and, hence, the SAR sensor's view to the buildings is nearly unobstructed. Typical effects of SAR acquisitions like layover can be very well investigated under such conditions. A second street has buildings on both sides offering the possibility to investigate the interference of backscattered signals from multiple adjacent objects. A height model derived from LIDAR data was generated and used as input to a simulator based on ray tracing techniques [5]. It has been designed to deliver results with high geometric accuracy. A simulated SAR image using the same parameters as for the real TerraSAR-X image is displayed in Fig. 3. Simulated SAR images have the advantage that various combinations of acquisition parameters can be investigated systematically. In addition, images can be simulated for individual buildings without any interference by e.g. vegetation. Such simulations are compared to real TerraSAR-X images. The goal of this investigation is to come up with a statistical description of the position and rotation of corner lines in order to use them as building features in a statistical classification framework. Corner lines have already been studied in terms of their radiometric properties [6, 7] but not yet in terms of their geometrical accuracy.

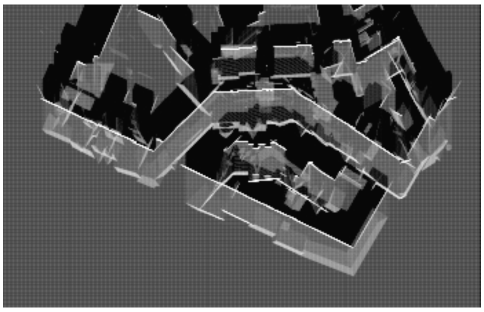

Figure 3. Simulated SAR image with the same parameters as for the TerraSAR-X image in Fig. 2 (right) (range direction bottom-up, azimuth direction from right to left).

2. Building detection

A variety of approaches for detection and reconstruction of buildings in high resolution SAR data already exists. In [8] façades in SAR images acquired from multiple aspects are used as building hints. A parametric building model is set up and optimized based on the extracted façades within a Bayesian framework. Another possibility is the use of two SAR images acquired with two slightly different viewing angles for building detection and reconstruction in a radargrammetric context [9]. Building recognition and reconstruction can be further improved based on interferometric SAR (InSAR) acquisitions from two orthogonal flight directions [10].

Nevertheless, automatic urban scene analysis based on SAR data alone is hard to conduct. SAR data interpretation can be supported with additional information from GIS databases or high-resolution optical imagery. Optical images offer the advantage of being widely available. In [11] high-resolution airborne InSAR data is combined with an optical aerial image in order to reconstruct bridges over water in 3D. Tupin and Roux [12] propose an approach to automatically extract footprints of large flat roofed buildings based on line features by means of a SAR amplitude image and an optical aerial image. Moreover, homogeneous regions in an aerial photo, represented in a region adjacency graph, are used in [13] to regularize elevation data derived from radargrammetric processing of a SAR image pair by means of Markov Random Fields.

The approach we propose is displayed schematically in Fig. 4 and described in detail in [14]. The first step in the SAR case consists of corner line detection using the line detector introduced in [15]. Buildings in the optical image are detected with a robust approach from literature [1] which is based on an initial segmentation of the optical image. A feature vector containing features like hue, shape, size, and shadow is generated. SAR corner lines and optical segments are then fused on segment level and building hypotheses are set up. Based on the previously generated feature vectors, the building hypotheses are evaluated. All segments are initially weighted with a weight of one and multiplied with a value between zero and one if a feature does not completely support a building hypothesis. Context is introduced, too, using neighboring buildings as supporting hints for other buildings located closely.

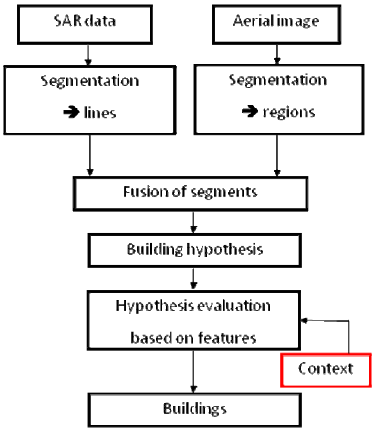

Figure 4. Sketch of the building recognition process.

The approach was tested using InSAR data from a single aspect and an aerial image from a test site located in the city of Dorsten, Germany. In Fig. 5 (left) a magnitude image of the InSAR image pair is shown and in Fig. 5 (centre) the corresponding optical aerial image. The corner lines of the buildings can be seen in the InSAR magnitude image as vertically oriented bright lines (orthogonal to the illumination direction of the sensor). The right image in Fig. 5 shows the results of the proposed building detection approach combining InSAR corner lines and optical features. Most of the buildings could be detected whereas some gable roofed buildings remain undetected because their inhomogeneous roof goes to pieces during the segmentation step of the optical image. However, results could be highly improved compared to building detection from a single optical image. A possible application scenario of this rather simple approach would be damage assessment after a natural hazard. Features from an old optical image of the urban scene, taken before the hazard hit the region, could be combined with corner lines from newly acquired SAR data. A human interpreter would only have to check those buildings for damages in the SAR data that remain undetected thus accelerating rapid hazard response.

Figure 5. (left) InSAR magnitude image acquired with the Intermap AES-1 sensor (range direction from right to left), (centre) corresponding optical aerial image, (right) building detection results using both optical and InSAR features.

3. Height estimation

After buildings have been detected based on a combination of corner lines extracted from SAR data and on various features from the corresponding optical image, heights of buildings can be estimated exploiting the different viewing geometries of SAR and optical data.

A variety of publications have already investigated the possibility of object height retrieval from SAR data. In [16] the scattering properties of a building are modeled with regard to the dielectric properties of the building materials in order to estimate the height of the building via a deterministic approach. Brunner et al. [17] correlate simulated SAR images using a height model with varying height of an object to the corresponding real SAR image. The height of the height model that delivers the simulations with the highest correlation to the real SAR image is assumed to be the height of the real object.

Figure 6. (top) SAR image of a railroad bridge near Zellingen, SAR-sensor Memphis, Ka-Band, resolution 75 cm, range direction top-down (© FGAN-FHR), (bottom) Corresponding optical aerial image (© Google Earth)

We propose to model the height of objects making use of the different sensor geometries of SAR and optical sensors (refer to [3] for details) under the assumption of locally flat terrain. For instance, shadow is always an indicator for an elevated object. It can be seen in both optical and SAR data. Figure 6 shows a high-resolution aerial SAR image and the corresponding optical aerial image. Bridge body and shadow were extracted in the SAR image and projected to ground range geometry using the SRTM 3 height model. Subsequently, the distance D between the bridge body and its shadow was measured and put into Eq. (1). Knowing the viewing angle α the height h of the bridge can be derived.

$$h = D\frac{\tan(\alpha)}{\tan^2(\alpha)+1} = D\frac{\sin(2\alpha)}{2} \qquad (1)$$

Table 1 shows a comparison of estimated height values and real height values measured in the field. All calculated height values are systematically estimated too low. This effect is due to, first, the violation of the assumption of locally flat terrain and, second, the ortho-rectification step of bridge body and shadow using the SRTM 3 height model. This height model does not include high-frequency terrain height variations leading to a projection error. As a consequence, the distances *D* are systematically measured too short and thus all estimated heights are too low. Hence, the derived height values can only be seen as rough estimates.

Table 1. Estimated heights of the Zellingen bridge applying Eq. (1) (projection to ground geometry using the SRTM 3 height model)

Estimated heights [m]	Real heights [m]
18.17	23.66
18.21	19.28
14.52	16.73
12.38	16.11
12.73	15.83

4. Summary and Outlook

In this paper an overview of the current state of a research project dealing with building recognition and reconstruction combining features from high-resolution optical and SAR data was provided. All three parts of the project, feature selection, building recognition, and building height estimation, were briefly described.

Further research will comprise improvements of all three parts of the projects. First, the geometrical accuracy assessment of the corner lines needs a more detailed model as input. Currently, the test site "Schneiderberg" is modeled using close range photogrammetry. The result will be a real three-dimensional model containing all details in the order of the sensor's wavelength (3.1 cm). Second, building detection will be incorporated into a statistical framework. Third, height detection will be further investigated and integrated into an iterative building detection and reconstruction approach.

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