FAÇADE STRUCTURE RECONSTRUCTION USING SPACEBORNE TOMOSAR POINT CLOUDS

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ABSTRACT

Very high resolution SAR tomography using multiple data stacks from different viewing angles enables us for the first time to generate 4D point clouds of the illuminated area from space with a point density comparable to LiDAR. They can be potentially used for façade reconstruction and monitoring in urban environment.
In this paper, we propose an approach for façade detection and reconstruction from such point clouds. Firstly, the façade region is extracted by thresholding the point density on the ground plane. The extracted façades points are then clustered into segments corresponding to individual façades by means of slope analysis. Surface (flat or curved) model parameters of the segmented building façades are further estimated. Finally, the elevation estimates of each raw TomoSAR point is refined by using its more accurate azimuth and range coordinates, and the corresponding reconstructed surface model of the façade. The proposed approach is illustrated and validated by examples using TomoSAR point clouds generated from a stack of 25 TerraSAR-X high spotlight images

Index Terms— SAR tomography (TomoSAR), TerraSAR-X, point clouds, façade reconstruction

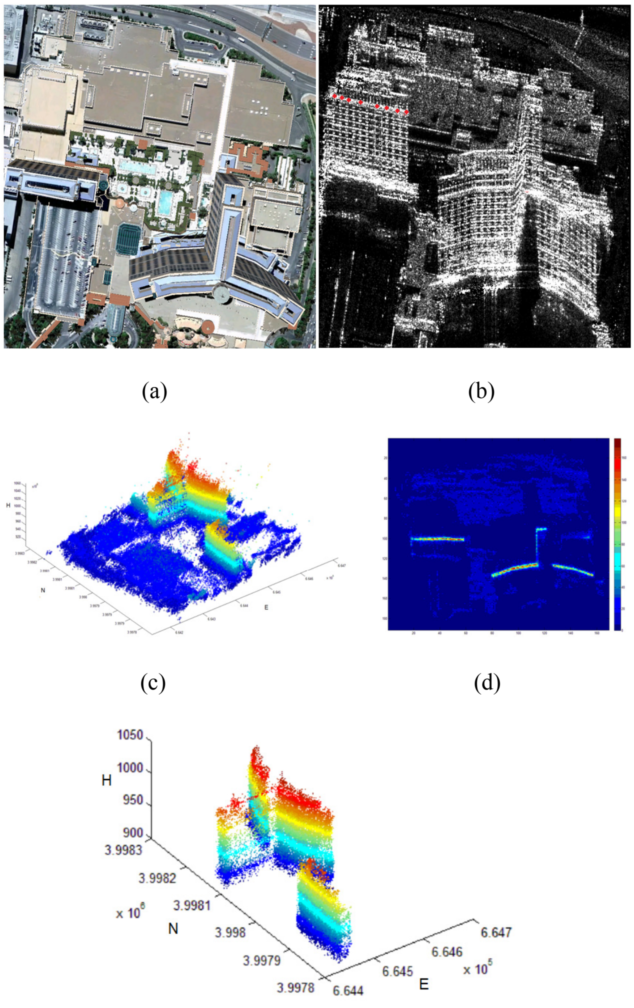
1. INTRODUCTION

Along with the launch of modern meter resolution SAR sensors, multi-pass InSAR techniques, including persistent scatterer interferometry (PSI) and tomographic SAR inversion (TomoSAR), are for the first time used to reconstruct the shape and motion of individual buildings and urban infrastructures [1][2][3]. Among them PSI exploits bright and long-term stable pixels, i.e. the persistent scatterers (PSs). TomoSAR extends the synthetic aperture principle into the elevation and temporal domain for 3-D and 4-D imaging [3][4]. It resolves the layover problem by separating multiple scatterers along elevation direction. Without any pre-selection of pixels as PSI does, TomoSAR offers tremendous improvement in detailed reconstruction and monitoring of urban areas, in particular man-made infrastructure [3]. E.g. experiments using TerraSAR-X high resolution spotlight data stacks show the scatterer density obtained from TomoSAR is in the order of 600,000~1,000,000/km^2 compared to a PS density in the order of 40,000~100,000 PS/km^2 [2][6]. The rich scatterer information retrieved by TomoSAR from multiple tracks enables us for the first time to generate 3D point clouds of the illuminated area with a point density comparable to LiDAR (see Fig. 1(c)). These point clouds can be potentially used for building façade reconstruction in urban environment from space with the following considerations:

- TomoSAR point clouds reconstructed from spaceborne data has a poor 3D positioning accuracy in the order of 1m, while (airborne) LiDAR provides accuracy typically in the order of 0.1 m [7]; The location error of TomoSAR points is highly anisotropic with an elevation error typically one or two orders of magnitude higher than in range and azimuth; Another peculiarity of TomoSAR and PSI point clouds is that due to multiple scattering ghost scatterers [8] can be generated that appear as outliers far away from a realistic 3D position;
- Due to the coherent imaging nature and side-looking geometry, TomoSAR point clouds emphasize different objects: 1) The side-looking SAR geometry enables TomoSAR point clouds to possess rich façade information. Results using pixel wise TomoSAR for high resolution reconstruction of a building complex with very high level of detail from space borne SAR data are presented in [6]; 2) incoherent objects, e.g. trees, cannot be reconstructed from multi-pass spaceborne SAR image stacks.
- Complementary to LiDAR and optic sensors, 1) SAR is so far the only sensor capable of providing the fourth dimension information from space, i.e. temporal deformation of the building complex; 2) Microwave scattering properties of the façade reflect geometrical and material features. Besides 3-D positioning, TomoSAR point clouds carry

much more information e.g., deformation measurement [3][4].

Yet in order to provide a high quality spatial-temporal 4D city model, object reconstruction from these TomoSAR point clouds is emergent. Motivated by these chances and needs this paper attempts to detect and reconstruct the building façades from TomoSAR point clouds.



(a) (b)

(c) (d)

(e)

Fig. 1. Test building - Bellagio hotel: (a) Optical image (© Google); (b) TerraSAR-X mean intensity map (the red dots are the analyzing points in Fig.5;); (c) TomoSAR point cloud in UTM coordinates [6]; (d) Point (scatterer) density in 3 x 3 m^2 grid; (e) Extracted building façade points.

2. APPROACH AND EXPERIMENTS

Typically, 3D object reconstruction techniques from point clouds are widely employed using LiDAR data, e.g. making use of the fact that man-made structures such as buildings usually have parametric shapes. After selecting local sets of coplanar points using 3D Hough transform or RANSAC algorithms, 3D objects are reconstructed by surface fitting in the segmented building regions [10]. Numerous methods are employed for building roof segmentation and reconstruction such as unsupervised clustering approaches [11], region growing algorithms [12] and graph based matching techniques [13]. These techniques, however, cannot be directly applied to TomoSAR point clouds due to different object contents illuminated by the side looking SAR. In this paper, we propose an approach for building façade detection and reconstruction from TomoSAR point clouds. The proposed approach is illustrated and validated by examples using TomoSAR point clouds generated from a stack of 25 TerraSAR-X high spotlight images reported in [6]. Our test building is the Bellagio hotel in Las Vegas. Fig. 1 (b) shows the TerraSAR-X mean intensity map of the area of interest while Fig. 1 (a) is the corresponding optical image. Fig. 1 (c) gives an overview of the input TomoSAR point clouds in UTM coordinates.

2.1. Façades (detection) extraction

As a first step towards the approach, the building façade regions are extracted out. This is done by thresholding the point density on the ground plane (vertical view). I.e. the point density is calculated by counting the number of points (scatterers) in a certain resolution grid first. By exploiting the fact that the point density is higher for vertical structures, the building façades are then extracted.

Fig. 1(d) shows the color coded point density image of the input TomoSAR point clouds shown in Fig.1 (c). The grid resolution is 3×3 m^2. The grid cells having point density less than a specified threshold are removed. A mask is then generated after morphological operation which in turn is used for building (façade) points extraction in each grid cell. Fig. 1(e) shows the extracted points belonging to the façades of two different buildings.

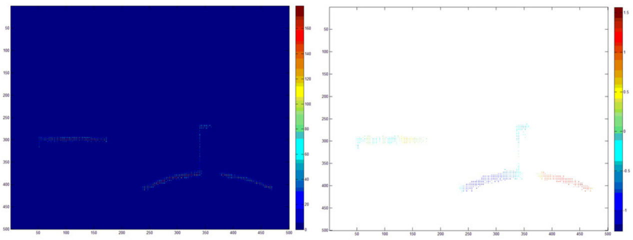
2.2. Segmentation

To reconstruct individual façades, the extracted points belonging to different façades need to be segmented. Most approaches make use of unsupervised clustering techniques for segmentation. They typically search for plane features and then perform neighborhood analysis after clustering planar regions to detect different features for reconstruction. Only considering the planar segments can be restrictive as in that case curve surfaces are also modeled using smaller plane segments which can be better modeled using second or higher order polynomials. Therefore instead of searching for planar regions, we follow an intuitive slope analysis procedure to segment different façades of the buildings.

2.2.1. Slope estimation

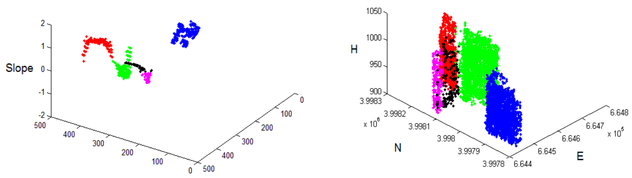
Slope estimation is carried out by first up-sampling the point density image (see Fig. 1(d) and Fig. 2(a)) by a factor of 3. It is required to obtain a more fine reconstruction of the façades footprints. Let's define a 3×3 kernel window around each grid point (seed). The slope is estimated by taking all the grid points inside the window using weighted least squares method. The weight of each point is equivalent to the point density. If there exists no point inside the kernel window other than the considered up-sampled point, that point is no longer considered to be part of any façade footprint and is therefore removed.

The estimated slope along façade footprints are shown in Fig. 2(b). The slope change between different façades is quite evident that motivate us to further use them for clustering purpose.



(a) (b)

Fig. 2. (a) Up-sampled version of Fig. 1(d); (b) Slope estimates on each grid point (seed) of (a).



(a) (b)

Fig. 3. Segmentation results (a) Clustered grid points (seeds) and their slope variation (b) Corresponding clustered TomoSAR points.

2.2.2. Clustering

In this section, the extracted façades points are clustered into segments corresponding to individual façades. As mentioned above, we use the slope estimates of different façades to cluster the points. To cater the issue of grid points that have similar slopes but are spatially far, we also incorporate spatial and offset (intercepts) parameters as features in the feature vector for clustering. The well-known K-means clustering algorithm is used here for segmentation. In our example, the extracted points are clustered into five segments. Fig. 3(a) (b) shows the color-coded clustering of grid points (seeds) in feature space and their corresponding TomoSAR points in UTM coordinates, respectively.

2.3. Reconstruction

The façade consists of planes, intersection lines (ridges), edges (façade boundary) and the corresponding vertices. These features will be reconstructed in this section. Mostly, reconstruction approaches follow the strategy of fitting planes in the segmented points and use some distance metric to identify adjacent segments. Instead of fitting planes in the segmented points, we adopt a different strategy: the surfaces are first classified to flat or curve surfaces by performing slope analysis inside each segmented cluster, i.e. flat surfaces possess constant slope while curve surfaces show gradually varying slope; the façade footprint is then estimated using the weighted least squares method.

2.3.1. Model identification (flat or curve surface)

The surfaces to be modeled are firstly classified to flat and curve surfaces by analyzing slope derivatives. The curve surfaces have gradually changing slopes across their footprint compared to flat surfaces that have ideally constant slopes i.e., zero derivatives. We exploit this idea and compute the (weighted) slope derivatives of each façade footprint. Since the original slope derivatives are usually very noisy, we implement a polynomial fitting to the computed slope derivatives and the decision is then made based on the RMS fitting error. E.g. based on this idea, the extracted five façades in Fig. 3(b) are identified as two curve and three flat façades.

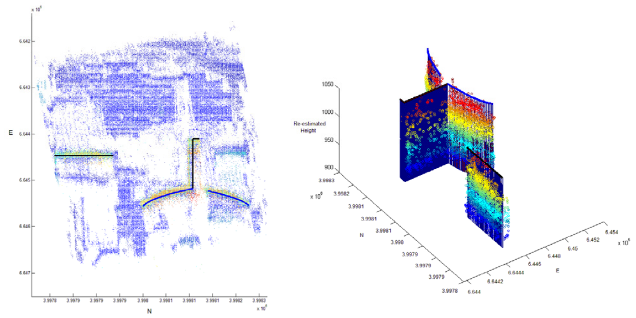
2.3.2. Parameter estimation

Finally, model parameters for each segmented façade are estimated: parameters of precise 2D façade footprint are estimated by using the weighted least squares method; Neighborhood (connectivity) analysis is then carried out to find the vertex points (i.e., façade intersection lines); These vertex points and the model (estimated) parameters are used to finally reconstruct 3D model of the buildings façades. Fig. 4(b) shows the reconstructed building façades models in our experiment.

2.4. Elevation estimates refinement

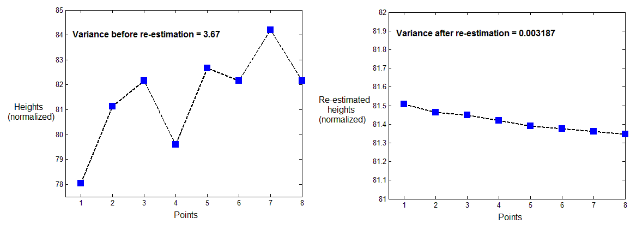
Once the façade footprint is estimated, the elevation estimates of the TomoSAR points can be refined by using their more accurate azimuth and range coordinates and the identified and modeled surfaces. I.e. we project the corresponding iso-azimuth-range lines of each point to the identified and modeled surface it belongs to and finally obtain a refined elevation by taking the elevation coordinate of the intersection point.

To validate this improvement, we carefully select points from the intensity image (see Fig. 1(b)) belonging to the façade portion at the same height. Fig. 5 compares the height estimates of the analyzing points before and after refinement. It is obvious that their height estimates are improved significantly. E.g. their height variance before and after refinement are 3.67 and 0.003 m^2, respectively.



(a) (b)

Fig. 4. (a) Estimated 2D façade footprint in UTM coordinates (b) point clouds with refined elevation overplotted on the reconstructed façade model.



(a) (b)

Fig. 5. Height estimates in meters of the analyzing points (shown in the Fig. 1(b)): (a) Before refinement (b) After refinement.

3. CONCLUDING REMARKS

TomoSAR point clouds are very attractive for dynamic city model generation. We propose an approach for façade reconstruction using TomoSAR point clouds. The proposed approach is validated by using TomoSAR point clouds from a stack of TerraSAR-X high resolution spotlight data reported in Fig. 1(b) (c). Compared to the raw TomoSAR point clouds, significantly improved elevation positioning accuracy is achieved. In the future, the approach will be extended to TomoSAR point clouds fused by using multiple stacks from different viewing angles to obtain the full structures of individual buildings from space.

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