URBAN STRUCTURAL DAMAGE ASSESSMENT WITH OBLIQUE UAV IMAGERY, OBJECT-BASED IMAGE ANALYSIS AND SEMANTIC REASONING

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KEY WORDS: damage assessment, oblique, UAV, OBIA, OOA, semantics

ABSTRACT: Structural damage assessment is a priority following disaster events but, especially in complex urban settings, remains a significant challenge. Many studies have explored the potential of virtually every type of remote sensing data, but in particular vertical images have been found to have substantial limitations, as damage information is largely restricted to roofs and proxies such as blow-out debris near buildings, which may signal extensive damage even in case of an intact roof. Oblique imagery has been identified as a more useful data source that provides multi-perspective information, overcoming the perspective constraints of vertical imagery. This paper addresses damage assessment based on multi-perspective, overlapping, oblique images obtained with unmanned aerial vehicles (UAV). 3D point-cloud assessment and object-based image analysis (OBIA, also referred to as object-oriented analysis, OOA) are used to extract damage indicators from both façades and roofs. The research focuses on creating a methodology that supports the ambiguous classification that characterizes especially the intermediate damage levels, aiming at producing more reliable per-building damage scores. The idea is to provide a tool that determines the comparatively clear damage cases (very heavy damage and complete destruction), and for the intermediate and lower cases creates a virtual model of the building with the option for an analysis to switch on additional damage layers to aid in the damage scoring. The results show that geometric parameters derived from the 3D point cloud can reveal damage indicators that are difficult to detect in the original imagery. They also demonstrate that the developed OBIA rulesets are capable of extracting all relevant damage features, and are able to cope with different types of façade and architectural scenes. This paper shows that the use of OBIA to extract damage information from the buildings, when coupled with 3D point cloud information, leads to a more comprehensive and less subjective building damage assessment that is interesting for the stakeholders in disaster response. The work is related to the currently ongoing FP7 project RECONASS (www.reconass.eu), and the upcoming INACHUS project.

1 INTRODUCTION

Disaster situations are characterized by a diverse need for information, ranging from immediate metrics on the event itself (e.g., type, location, extent), to more specific damage, needs and recovery information. The insights generated need to match the category the many governmental, non-governmental, inter- an multinational, as well as military disaster stakeholders fall into. In particular early and continuous intelligence of a disaster site is best gathered with remote sensing methods, which has led to a vibrant research and application scene whose roots can be traced back to the 1907 San Francisco earthquake, where the extensive damage was mapped by a kite-borne 20 kg camera from a height of several hundred meters. Since then virtually all air- and spaceborne sensor-platform combinations have been tested for their potential to help map disaster damage and other consequences. The most recent type to be established commercially is high spatial resolution satellite-based video coverage of disaster sites, offered by Skybox (2013). For recent reviews on the utility of remote sensing for damage mapping see for example Dell'Acqua and Gamba (2012) or Ehrlich et al. (2009). The value of such air- and spaceborne technologies in the more general crisis response domain was reviewed by Kerle et al. (2008) and Zhang and Kerle (2008), respectively.

1.1 The limitations of image-based damage mapping

Despite image-based structural damage mapping being one of the oldest remote sensing applications, it remains an insufficiently solved challenge. Expectedly, the continuous increase of the spatial resolution of spaceborne image data (with Worldview-3, launched in August 2014, providing 0.31 m panchromatic imagery), frequent stereo coverage, high spatial resolution radar instruments (e.g., TerraSar-X's 1 m resolution imagery resolving individual buildings for damage assessment; Uprety et al., 2013), coupled with versatile airborne laser scanners (LiDAR) providing data for detailed structural damage assessment (e.g., Oude Elberink et al., 2011; Khoshelham et al., 2013) has led to progress in damage mapping. For example, for the 2010 Haiti earthquake the amount of building damage mapped with 15 cm aerial images was approximately an order of magnitude greater than what had been mapped with Geoeye-1 satellite images (0.5 m resolution; Lemoine, 2010). However, all traditional (vertical) image sources, quite regardless of spatial resolution, meet a limit as to the amount of damage they can reveal. This is largely due to damage being a three-dimensional phenomenon, one that is equally expressed in roofs that satellites see, as in façades or a building interior. Imagery being largely limited to roof information also results in a high dependence on proxies, e.g., changes in shadows, or evidence of blow-out debris. Damage has also been described as more of a concept than a physical state (Kerle and Hoffman, 2013), in part because the physical damage indicators we can detect have a different meaning for different stakeholders, and do not neatly add up to a final, per-building damage score.

1.2 The potential of oblique imagery

Oblique airborne images have the potential to image all exterior parts of a structure, and have thus been seen as a potential step forward in comprehensive structural damage mapping. Manned Pictometry © imagery coverage was flown following the 2010 Haiti earthquake, providing approximately 10 cm resolution vertical views, in addition to oblique (45º) images in the four cardinal directions, with resolution decreasing to about 16 cm, and with all 5 cameras acquiring overlapping frames. From these acquisitions disparity (depth) images, and subsequently 3D point clouds were extracted, and used to create digital surface models (DSM), above-ground features (nDSM) and orthoimages. From this collective set of data a wide range of spectral and geometrical derivatives was extracted and used in a machine learning based classification approach to map different damage elements (Gerke and Kerle, 2011). While individual classes related to damage could be well detected (approx. 70% accuracy), the data were not considered to be ideal. The manned system is expensive, inflexible and still yields relatively low spatial resolution. An alternative that has been rapidly gaining in availability and sophistication is unmanned aerial vehicles (UAVs, drones). They offer the potential for a more controlled and flexible survey than Pictometry-type systems, at far lower cost, even if only relatively simple instruments (consumer cameras) are typically carried by such platforms. However, photogrammetric processing has advanced to a point where also from uncalibrated images, and without availability of high-quality IMU or GPS data, detailed and accurate geometric information can be derived. The study presented here focuses on 3 parts: (i) 3D point clouds generation of damages structures based on multi-perspective UAV imagery, and identification of severely damaged or completely destroyed buildings from the extracted geometric information, (ii) use of object-based image analysis (OBIA) methods to extract damage indicators from the photos, also making use of the geometric information, and (iii) development of a strategy to include semantic reasoning in the damage assessment of different parts of a building, to work towards a meaningful per-building damage score. In the following we describe the data and methods used.

2 DATA AND METHODS

2.1 Data acquisition

The imagery used in this study was collected both with an Aibot X6 V.1 UAV (Fig. 1), and with a camera attached to a 7 m pole. The latter was necessary because the highly variable legal framework for civilian UAV deployment does not permit such devices to be used in a number of countries, and the pole allows oblique UAV data to be well simulated. On the UAV we used a Canon 600 D with a 70 mm fixed zoom length, resulting at a GSD of approximately 7 mm at a 70m flying height. On the pole we used a Canon PowerShot S100. Deployed at some 15 m from a target building the image GSD was approximately 1 cm. Images were acquired in Gronau (Germany), Enschede (The Netherlands) and at several locations near the city of Bologna (Italy), where a magnitude 5.8 earthquake in 2012 caused extensive structural damage.

Figure 1: Aibot X6 use in Gronau (Germany), leading to the data shown in Figures 3A/D.

2.2 Point cloud processing

We aimed at generating a detailed 3D point cloud that would allow detection of damage features typically associated with severely damaged or completely destroyed buildings, D4 and D5 in the commonly used European Macroseismic Scale of 1998 (EMS-98; Grünthal, 1998). Specifically, we aimed at identifying geometric evidence of complete collapse, collapsed roofs, rubble piles adjacent to structures, and inclined façades. A structure-from-motion approach was used to calculate the camera parameters (both intrinsic and orientation; for details on the algorithm see Musialski et al., 2013). The reconstructed scene was densified through dense image matching (Furukawa and Ponce, 2010). For adjacent points in the dense point clouds a local tangent plane was calculated. The z-component of the normal of this plane (scaled to range from 0 [vertical] to 1 [horizontal]) was the main parameter of interest in the subsequent analysis. While the analysis of LiDAR has advanced greatly, methods to extract and characterize useful features from 3D point clouds are still being developed (see for example Weinmann et al., 2013), explaining why we identified the damage features listed above visually in the point clouds and z-component.

2.3 Object-based image analysis

Traditional image-based damage assessment methods have made use of a wide range of feature or change-detection methods and classification schemes, typically using spectral or textural signatures corresponding to specific damage types (primarily rubble/debris). Ground-based damage assessment, however, proceeds differently, as explained in field manuals for post-earthquake building safety evaluation, such as the ATC-20 (ATC, 2005). Here all relevant damage indicators are considered in terms of their characteristics and severity, but also in terms of their location, spatial arrangement, proximity to load-carrying parts of the structure, and in consideration of the building type and material. In the remote sensing field object-based image analysis (OBIA) has been able to mimic the cognitive approach of manual or visual analysis, allowing effective processing based on feature or process knowledge. Here we used OBIA on images of roofs and façades to identify holes, cracks, dislocated roof tiles, and cracks intersecting with load-carrying structural element. In addition, a range of building parts and non-damage related features were identified: façades, intact roofs, windows and columns (the latter insofar as they are externally visible).

OBIA commonly comprises image segmentation and classification. In this case a 2-step segmentation approach was used, with a first multi-resolution segmentation with a small scale parameter leading to (over-segmented) small objects, which were merged with a spectral difference segmentation. This ensured that largely spectrally homogenous segments, such as façades, were predominantly merged into single large objects, while small, well delineated or heterogeneous features (cracks, holes, etc.) remained as small, isolated segments. Using typical size, shape and topological characteristics we carried out a classification for the above mentioned damage- and non-damage object classes.

The aim was not to use the OBIA-extracted damage features in an automatic damage mapping, but rather to provide value-added information to a damage analysis. Therefore, we also explored how the extracted damage features could be presented and visualized as extra layers on top of a building wire mesh model, where layers can be interactively activated by an analyst.

For an accuracy assessment we manually digitized a number of features and assessed the agreement with the automatically extracted results in terms of False Positive, False Negative, and True Positive.

More details on the point cloud processing, as well as on the steps and parameter values used in the OBIA processing, can be found in Fernandez Galarreta et al. (2014). In an earlier, more extensive study, it was also tested to what extent a number of damage analysis experts agreed on EMS-98 damage scores for a range of selected roof and façades images showing different damage, and how certain they were about their judgment. Further it was tested how damage scores for individual façades can be meaningfully merged to generate a single, per-building damage score (see Fernandez Galarreta, 2014).

3 RESULTS

3.1 3D point cloud-based damage assessment

An example of the 3D point clouds generated from one of the Aibot X6 surveys is shown in Figure 2. The 3D model is very dense, has high relative accuracy, and contains full color information for each data point. Such detailed models were calculated for both the UAV- and the pole-based surveys (Figures 3 A and B/C, respectively). Despite the detail, the actual color and 3D information is not well suited to detect damage such as a partly collapsed roof (A), rubble piles (B) or façade inclination. Those, however, become very evident in the z-component information (D-F). The gently sloping roof is well highlighted by the colors that change with the angle (D). The angle variation, together with

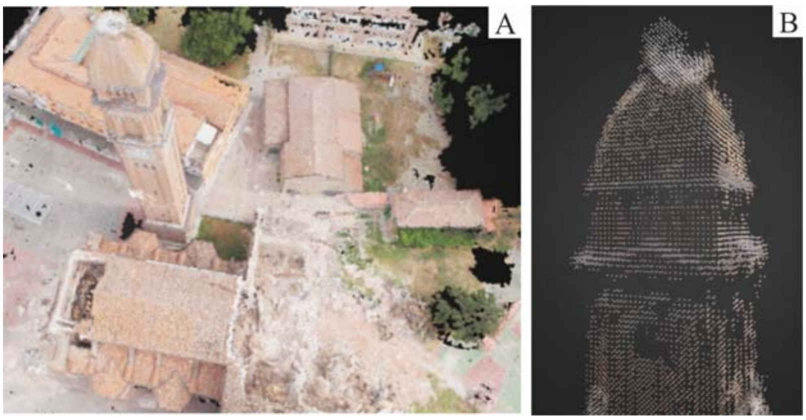

Figure 2: 3D point cloud of a damaged church in Mirabello (Italy)

the reddish color in (B), reveals rubble (any significant piles would also get revealed by their raised elevation). In (C) a perfectly vertical façade is shown in blue, while even a slightly inclined or non-planar façade would show a z-angle (= color) deviation, as illustrated by the green plane.

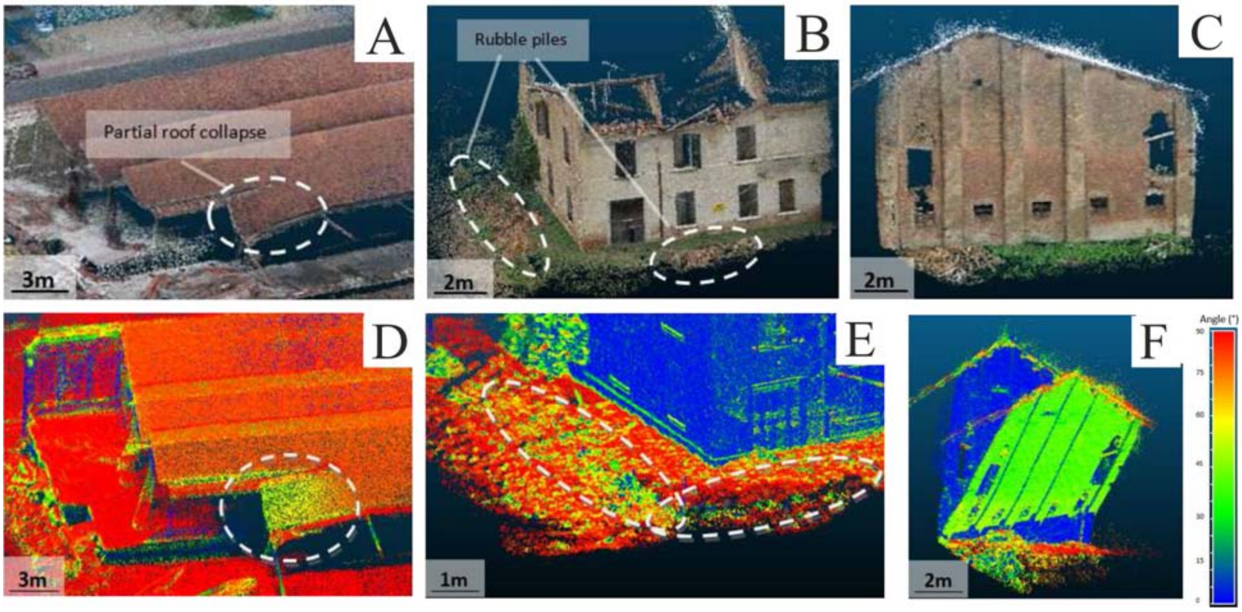

Figure 3: 3D point clouds of (A) a factory being demolished in Gronau (Germany, Aibot X6), and (B-C) buildings damaged by the 2012 earthquake near Bologna (Italy; pole-survey). Z-component of the normal of a local tangent plane calculated for adjacent points revealing geometric irregularities that correspond to different types of damage (D-F). See text for further details.

3.2 OBIA results

The OBIA analysis resulted in the classification of a number of relevant damage features, as summarized in Figure 4. In (A) detected dislocated roof tiles are shown (pole-survey). In figure (B), which shows a concrete façade, a wide range of successfully identified damage features are illustrated. A small amount of misclassification occurred in the crack category, where small sections were missed (hatched circle), and parts of the writing on the wall were falsely detected as cracks. In Figure 4 (C) cracks detected in a brick façade are shown.

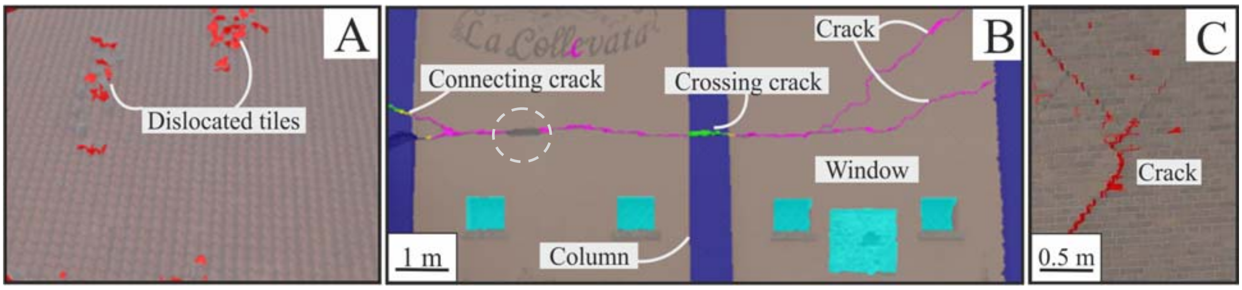

Figure 4: Damage features identified with object-based image analysis (OBIA) in images of a roof with dislocated tiles (A), various damage types on a concrete façade (B), and an image of a brick façade showing extensive cracks.

The extracted damage information was provided to 6 experienced damage analysts (for example superimposed on a wire-mesh as shown in Figure 5), to understand the value of such auxiliary information. Contrary to expectation, analysts saw little value in the highlighted structural damage features as shown in Figure 4, as those largely correspond to the features an experienced analyst can readily detect based on the spectral image information. However, the additionally extracted information based on the geometric derivatives (Figures 3 D-E), which cannot easily be detected in image data, were considered to be very useful.

The analysts were also asked to assign EMS-98 scales to a number of test images, and to rank their classification confidence. Reflecting well the fact that damage assessment is an interpretation of the consequence a given physical features has on the structural integrity of a structure, damage scores varied substantially, with the same façade damage image receiving scores ranging from D1 (negligible damage) to D3 (heavy damage). When scores for images corresponding to different façades/roof of a building were aggregated, final scores also ranged from D1–D3, indicating well the subjectivity that underlies structural damage mapping. Also the self-assessed confidence ranged widely, for both the individual images and for the total building damage score. Confidence was particularly variable for roof images, perhaps reflecting the fact that field damage assessors have relatively limited experience in roof damage appraisal. For more details on the expert-based damage assessment part of this study see Fernandez Galarreta et al. (2014).

Figure 5: Wire-mesh model of the building shown in Figure 3C, with the colored point cloud, as well as detected damage (windows/holes) overlaid. The point cloud, but also individual damage type layers can be selectively activated for enhanced interpretation by an analyst.

4 Discussion And Outlook

In this study we tested the value of multi-perspective UAV images for structural damage assessment, focusing on 3D point clouds and geometric derivatives, and the effectiveness of OBIA to extract structural damage features.

We showed that from high spatial resolution stereo images detailed and accurate 3D point clouds can be derived. Those, in particular when coupled with the z-component of the normal of a local tangent plane of adjacent points, very effectively reveal damage, including structural characteristics that are not readily identified in the original image data, such as façade or roof deformation. Based on a 2-step segmentation approach OBIA was also successful in extracting a wide range of damage features. Those can be visualized in a 3D building model to combine both the geometric and the visual damage indicators, and used by an analyst for enhanced damage assessment.

Despite those achievements the study also highlighted a number of problems that need further research. We showed that extreme damage states (in particular D5) can be readily identified in the 3D point clouds, a process that we think can be automated. However, intermediate damage states continue to be harder to detect, the main reason being that also experts carrying out visual analysts differ in their opinions. This prevents clear rules to be defined, and agreed-upon validation labels are absent. Furthermore, even if individual images of building sections are correctly classified and labeled, aggregating those labels to a final per-building score remains a substantial challenge, since also clear rules on the significance of individual damage features on the overall building integrity are absent. In our work we presented only an illustrative 2D wire-mesh model to the analysts for illustration purposes. More work is needed to create complete, interactive 3D building model (based on the processed stereo imagery), that allows a comprehensive appraisal of the entire structure from any perspective, and with all available information (mesh, point clouds, color, geometry, highlighted damage features). Also better tools to extract features directly in a 3D point cloud are needed.

We will continue our work in the context of two FP7 projects. The 3.5 year project RECONASS (Reconstruction and Recovery Planning: Rapid and Continuously Updated Construction Damage, and Related Needs Assessment; www.reconass.eu), which started in December 2013, focuses on post-disaster/-incident structural health monitoring of selected high-value facilities, such as ministries or hospitals, using wireless sensor networks on the inside, and UAV-based images for external damage assessment. Some of the needs for further research we identified above will be targeted in RECONASS. A further FP7 project with more than 20 partners will begin in late 2014 and run for 4 years, entitled INACHUS (Technological and Methodological Solutions for Integrated Wide Area Situation Awareness and Survivor Localisation to Support Search and Rescue Teams). In this project multiple technologies covering a rage of scales, from satellites to robots that can enter a structure, will be integrated to provide search and rescue forces with continuously refined information on where to search for victims and potential survivors. Our work will again focus on the use of UAVs, this time at a city-block level, aiming at automatically optimized image coverage (including real-time assessment of the 3D model completeness and coverage), as well as detection of damage-related gaps directly in the point cloud, thus working out the common ambiguity of gaps that can be natural, caused by occlusion, lack of texture, or structural damage.

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