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# Automated metric characterization of urban structure using building decomposition from very high resolution imagery

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ABSTRACT

Classification approaches for urban areas are mostly of qualitative and semantic nature. They produce interpreted classes similar to those from land cover and land use classifications. As a complement to those classes, quantitative measures directly derived from the image could lead to a metric characterization of the urban area. While these metrics lack of qualitative interpretation they are able to provide objective measure of the urban structures.

Such quantitative measures are especially important in rapidly growing cities since, beside of the growth in area, they can provide structural information for specific areas and detect changes. Rustenburg, which serves as test area for the present study, is amongst the fastest growing cities in South Africa. It reveals a heterogeneous face of housing and building structures reflecting social and/or economic differences often linked to the spatial distribution of industrial and local mining sites. Up to date coverage with aerial photographs is provided by aerial surveys in regular intervals. Also recent satellite systems provide imagery with suitable resolution. Using such set of very high resolution images a fully automated algorithm has been developed which outputs metric classes by systematically combining important measures of building structure. The measurements are gained by decomposition of buildings directly from the imagery and by using methods from mathematical morphology. The decomposed building objects serve as basis for the computation of grid statistics. Finally a systematic combination of the single features leads to combined metrical classes.

For the dominant urban structures verification results indicate an overall accuracy of at least 80% on the single feature level and 70% for the combined classes.

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## Introduction

The 21st century is often referred to as the urban century, because more than half of the world population lives since 2008 in urban areas. The urban areas of the world are expected to absorb most of the population growth expected over the next decades (United Nations, 2012). There is obviously a need to monitor this urbanization process in many application domains (Patino and Duque, 2013). Remote sensing offers perfect solutions for regular monitoring, which is essential to catch up with the speed of growth and allow a controlled development of these areas (Maktav et al., 2005). In this context, the availability of quantitative measures play an important role, because it lowers the semantic abstraction and allows comparison of different data sets.

This study presents an automated method to provide a metrical characterization of urban built-up area derived from multispectral aerial imagery. The characterization is based on features derived from building statistics, which are combined to metrical classes. This is in difference to traditional urban classification methods, which by majority deal with qualitative descriptions of functional urban units as, for example, the distinction between residential, industrial or business zones. In contrast, the presented method yields on purely quantitative classes and does not include any qualitative interpretation. Of course it is open to the potential user to subsequently derive qualitative descriptors from these measures, but this is a step, which is left out intentionally in our methodology itself. While Herold et al. (2005) already underline the importance of spatial metrics and promote their use for urban characterization, studies investigating such metric characterization are still rare. Besides filling this gap in urban remote sensing research an additional motivation for such metrical description is to respond to the often non unique correlation between quantitative measures and

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qualitative classes. Different qualitative urban classes may appear with the same metrical values and in return different metrical values may be present within areas of the same qualitative class. While metrical measures can be directly and automatically derived from remotely sensed imagery the assignment of qualitative classes is for large parts dependent on human interpretation using non image based background knowledge. This metrical approach is meant to be complementary to qualitative analysis and purely restricts to mathematical descriptors. Nevertheless, it can be used in combination with qualitative classifications or to complement qualitative classes with metrical values.

Traditional urban classification aims to delineate areas of specific functional characteristics by allocating classes of varying informational depth. Several authors limit their investigation to more general classes, which in return often leads to higher accuracies and has lower demands on the data. An example for those is the study of Baraldi and Parmiggiani (1990), who differentiate between urban area, soil and vegetation. It focuses on the distinction of urban area from other land use classes. As a result the only urban characteristic of such mappings is the extend of built-up area. When applying such methods on time series the growth of cities can be monitored, while structural characteristics remain unknown. An extension of such mappings was presented by Dell'Acqua et al. (2003) who extract similar classes using SAR data but additionally include information from road networks. Other authors, often using technically complex classification systems, aim at further differentiation of the built-up area itself. An early approach towards such classifications by Barnsley and Barr (1996) distinguishes between different residential types, commercial and industrial area. Zhan et al. (2000) subdivide urban area in residential, commercial and green space. Some more recent approaches try to extract the objects, which make up an urban environment and do not aim on functional urban zones; for example Salehi et al. (2012) differentiate, amongst other objects, between parking lots, roads and buildings. Most of these classifications have in common that they derive semantic classes directly from the image data by classifying the grey values of the spectral bands. A different concept but with the same objective is presented by Zhang et al. (2013) who use LiDAR data instead of spectral imagery in order to extract objects like vehicles and power lines in urban areas. Further, some publications focus on the distinction of residential areas by social criteria. While the appearance of those urban areas on image data can vary strongly between geographic regions such approaches are mostly restricted to a single specific location. Recent studies are from Owen and Wong (2013) who integrate terrain information to differentiate informal from formal residential areas in the high relief energy area of Guatemala City and Kit et al. (2012) delineate slums in Hyderabad, India, based on their homogeneous appearance within specific texture features.

The main difference of the described studies compared to the new quantitative characterization approach is that the later does not provide semantic classes derived by direct classification of the original imagery. Instead more universal and therefore also more objective statistics are derived based on prior prepared image components. The semantic approach is less transferable to cities in different geographical regions. Dependent on cultural and natural geographic factors cities might contain different structures or similar structures might look different. In such cases a pure metrical approach offers a clear added value.

As test case and for basic method development we chose the city of Rustenburg, which is amongst the fastest growing cities in South Africa. For Rustenburg high quality aerial imagery is available and future collection will be continued at regular intervals by the administrative bodies. This ensures the possibility of practical utilization of the described method in this area and the restriction of this method to common multispectral imagery facilitates its general applicability. In comparison to data types like LiDAR or SAR such data is easily available for several places and regions.

## Materials and methods

### *Study area and data*

The study area covers the city and surroundings of Rustenburg in South Africa (see Fig. 1). Its overall size comprises 459 $km^2$ of which about one quarter is covered by built-up structures. The city is located on flat terrain adjoining the Magaliesberg mountain range. Several mining sites can be found in the surroundings, which reinforce the heterogeneous built-up structure including various types of residential areas as well as industrial sites. Rustenburg is among the fastest growing cities of South Africa, which means a challenging situation for urban planning authorities. In this context a regular mapping of settlement characteristics could support the local administration in their efforts to upgrade all informal settlements.

As image data a set of 16 colour infra red (CIR) aerial photographs were available, which cover the complete urban area of Rustenburg. The images were captured during an aerial survey flight in 2010 by an external company on behalf of the South African National Space Agency (SANSA). Such survey flights are regularly carried out for large parts of South Africa and within time intervals of a few years. The imagery has been delivered to SANSA in a pre-processed and orthorectified state and the image tiles come with a ground resolution of 50 cm. Such spatial resolution is required since the smallest dwellings have a minimum side length of about 2 m. The images come with three spectral bands (near infrared, visible red and visible green) and have a radiometric resolution of 8 bits. A mosaic of the tiles is shown on the right side of Fig. 1.

### *Methodology*

The overall methodology for deriving metrical classes from aerial input images is subdivided into three major processing modules as shown in Fig. 2. All modules are implemented in Matlab® programming language and are combined to a full automated processing chain with aerial imagery as single input. The first module conducts a decomposition of buildings into single layers, of which each includes buildings of a specific size interval. The second module computes statistical features from these building objects. It consists of four sub-modules with each computing one specific feature: maximal building size, heterogeneity of building size, proportion of vegetation and building area as well as built-up density. The third module combines all single features into a set of metrical classes. Feature computation and classification is carried out on a grid cell basis as detailed in subsubSections "Computing grid statistics" and "Classification".

### *Morphological decomposition*

The morphological decomposition produces a set of images each containing building objects within a specific size interval. The flowchart in Fig. 3 summarizes the processing and Fig. 4 illustrates intermediate steps of the decomposition workflow as images.

The aerial CIR image is the only data input. The module requires few input parameters for image preparation: the size of the smoothing kernel, the minimum brightness threshold and the step size of iterative building size increment. For our study we used a step size of 2.5 m and constant kernel size and threshold.

From the three bands input image a luminance image is computed by selecting the pixel specific maxima from the red and the green band (Fig. 4b). The NIR band is not considered due to its sensitivity for vegetation. Based on our observation that buildings generally appear as bright objects on such luminance image

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