VOXEL-BASED QUALITY EVALUATION OF PHOTOGRAMMETRIC BUILDING ACQUISITIONS

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ABSTRACT:

Automatic quality evaluation of photogrammetric building acquisitions is important to realize deficiencies of acquisition approaches, to compare different acquisitions approaches and to check the keeping of contractual specifications. For the decision-makers a procedure will be suggested taking a few, good interpretable quality measures into account. Therefore, useful quality measures have to be identified by the formulation of criteria. These quantities can be derived from the comparison of a test data set and a reference data set capturing the same scene. The acquired topology is usually uncertain as for instance two adjacent buildings may be acquired as one building or two buildings. Thus a screening of the registered area is suggested to compute the quantities. The approach is independent of the used acquisition method. For the application of large data sets the corresponding data structures will be explained. In experimental tests the buildings registered by two commercial acquisition systems will be compared by the quality measures determined in 2D and 3D.

1 INTRODUCTION

Motivation. The quality evaluation of extracted descriptions of real buildings is important for several reasons: It gives important information about the deficiencies of an acquisition approach and allows the comparison of different acquisition approaches. Concerning image analysis methods for the extraction of topographic objects, the reliability and completeness together with their automatic evaluation remains a major problem (Baltsavias, 2002).

Furthermore, quality values enable the contractor to check his measurements and the customer to check the quality of the delivered data with respect to specifications of contracts (Schuster and Weidner, 2003). These specifications are usually geometric aspects such as positional accuracy and completeness. To provide a feasible decision procedure for the decision-makers a few, good interpretable quality measures have to be chosen. Together with the knowledge about the input data useful meta information, e. g. the purpose of the acquisition, should incorporate into a simple decision process.

Methodology. The redundancy of one single test data set is not high enough to evaluate the quality of an acquisition. Therefore we assume the existence of second, high quality acquisition serving as reference data set. The computation of quality measures is based on the comparison of these data sets capturing the same scene. If the reference data is error-free, absolute quality assessments can be stated. If the reference data is accurate, the quality measures for the test data set are an approximation for the absolute qualities. If both data sets have the same accuracy, the inner accuracy (precision) can be derived leading to quality measures from repeated measurements.

Concerning photogrammetric building models we refer to instances of building models in the following. Usually the acquisitions consist of vector data in specific output formats; the buildings are modelled by boundary representations (b-rep) or constructive solid geometry trees (CSG) for instance. The topology of this photogrammetric models may vary due to the procedures during the data acquisition or different interpretations of the operators. Therefore the topologies of two acquisitions may be different and ambiguous while the metric — position and aggregation outline – should be the same. Quality measures like the root mean square (RMS) cause problems applied to complex buildings structures (Schuster and Weidner, 2003) since a point matching problem has to be solved.

To suppress the implication of different topologies we suggest the screening of the registered areas into volume elements (cells or voxel). In doing so we do not distinguish between different parts of buildings. The approach allows the evaluation in 2D (position) or in 3D (position and height) by using the same quantitative quality measures and methods.

Related Work. Based on the principle ideas of (McKeown et al., 2000) (an extension of (McGlone and Shufelt, 1994)) and (Ragia, 2001) a general concept is given in (Schuster and Weidner, 2003). Approaches which use the root mean squares for point coordinates as quality measures can be found in (Jamet et al., 1995), (Sester et al., 1996) and (Brenner, 2000).

Contribution. In (Schuster and Weidner, 2003) a general framework for the evaluation of 3D building models has been presented, which allows the treatment of the full 3D geometry, the 2D positional geometry or the height, depending on the requirements of the user. In this contribution the approach is consolidated, extended and examined by

- the formulation of criteria for the identification of reasonable, good interpretable quality measures,
- the formulation of guidelines for the decision process of contractor and customer,
- the comparison of acquisitions by two different acquisition systems, notably the InJect system (Inpho GmbH, 2005) and the CyberCity-Modeler (CyberCity AG, 2005), and
- the technical application of large data sets.

2 MODELLING

2.1 Data Representation: Vector vs. Raster

For the comparison of the test and reference data sets intersection and union sets have to be determined in respect of the registered volume or area. In principle these calculations can be done vectorial. However in the case of volume determinations these calculations and the corresponding data structures are rather complex and therefore extensive in terms of implementation and debugging. Particularly the treatment of special cases — e. g. resulting from grinding intersections — is numerically problematic. The suggested voxel-based approach (spatial enumeration) circumvents these problems (cf. tab. 1). The precision of the quality measures basically depends on the spatial resolution defined by the sizes of the volume cells.

	Raster	Vector
resolution, precision	cell size	precise
data structure	simple	complex
speed of operations	high	low
intersection	simple (addition of cell values)	complex algorithms
topological relations	not stored	stored
graphical output	quality depends on cell size	depends on output device

Table 1: differences of raster and vector representation.

2.2 Choice of Quality Measures

There exist a number of quality measures taken from the literature; for a complete list refer to (Ragia, 2001). These have been derived for different tasks and can partially be converted in each other. Therefore, there is a strong redundancy resp. correlation. For a specific task it has to be checked, which quality measures are suitable with respect to relevance and evidence. A limitation to four or five measures seems to be wise with regard to the redundancy and the interpretation.

Selection Criteria. Selection criteria for the quality measures are

1. The values of the quality measures should be *reliable computed* with a *moderate technical effort.*

   The quality measures should be computable in any case. The treatment of special cases which can occur with empty sets for instance, should be avoided.

2. Because of the quality measures an *evaluation in 2D and 3D* should be possible without any change of methodology.

3. The quality measures should have a *limited range*.

   Measures with a range between 0 and 1 can be interpreted immediately as percentages. They allow the comparison of the results for different data sets.

4. The quality measures should *easily be interpreted.*

   Concerning the keeping of a specification, it should be possible to give a statement, e. g. '10 % of the area built on has not been acquired'.

5. The values of the quality measures should be *independent from the volume to be rastered.*

   The volume to be rastered is defined by a bounding box for each data set. Since this cuboid is often aligned with the coordinate axes, the volume depends on the coordinate system. A complement to the data set or a rotation of the data set can change the volume.

6. The quality measures should be locally and global identical and their values locally and global computable.

   This allows the comparison of a local measure value for a single house or an apartment building with the corresponding value for the entire data set, which can be seen as an average value. The interpretation of the results can be cared out hierarchical because of the same quality measure: First of all only the global 2D and 3D measures will be taken into consideration. If their values are insufficient, diagnostics can succeed with the visualization of local measure values.

7. The quality measures should be conceptual invariant regarding conjoint translations and rotations of the test and reference data set.

Quality Measures. The quality measures used in the following are based on the test data set $\mathcal{T}$ and the reference data set $\mathcal{R}$. Considering the quality measures listed in the literature there are just a few quality measures left satisfying the criteria specified above. Among these are

- the *quality rate*

  $$\rho_q = \frac{|\mathcal{T} \cap \mathcal{R}|}{|\mathcal{T} \cup \mathcal{R}|} \qquad \rho_q \in [0,1] \tag{1}$$

  The value of the quality rate is independent of the assignment of the test and reference data set (symmetry). Its optimum is one.

- the *type II classification error*

  $$\beta = \frac{|\mathcal{R} \setminus \mathcal{T}|}{|\mathcal{R}|}, \qquad \beta \in [0,1] \tag{2}$$

  reveals the rate of the buildings or building parts not detected. Its optimum is zero.

- the *branch factor*

  $$\rho_b = \frac{|\mathcal{T} \setminus R|}{|\mathcal{T} \cap \mathcal{R}|} \tag{3}$$

  shows the rate of objects falsely detected. Its optimum is zero.

- the *miss factor*

  $$\rho_m = \frac{|\mathcal{R} \setminus \mathcal{T}|}{|\mathcal{T} \cap \mathcal{R}|} \tag{4}$$

  reveals the rate of objects not acquired. Its optimum is zero.

These four measures are frequently itemized in the literature, but can be reduced to a minimal number of two independent measures, e.g. the branch factor and the type II classification error. See (Weidner, 1997) for an overview of the interrelations.

The measures (3) and (4) do not fulfil the criterion 3, but are good interpretable. The aforementioned quantities can be computed in 2D and 3D for the whole scene. In addition they can also be computed for single apartment buildings. The quality rate (1) can also be computed with weights. The weights for this *weighted quality rate* can result from a distance transformation. Thus larger deviations become more apparent within the calculations.

Meta Information. An evaluation of the results only because of the aforementioned quality measures is not sufficient. Especially the aim of the acquisition is not taken into consideration. Further meta information for the test and reference data sets is:

- the *geographical name* of the acquired region
- the *image scale* of the aerial images used for the acquisition

  The image scale determines the accuracy of the location for building points. For an image scale of 1:13,000 a grid spacing of 0.5 m is generally adequate. For a scale of 1:5,000 an increment of 0.25 m is sufficient.
- the *image contents*, e. g. low-density areas, city centre, industrial area, etc.
- the *time and date of the overflight*

  From the moment of the overflight one can conclude if the possibly visible trees have been deciduous or not. In the case of deciduous trees the ground points of the buildings are harder to register.
- the *purpose of the acquisition*

  From the purpose of the acquisition one can infer about the demanded degree of the generalization if this quantity is unknown.
- the *period of time* which has been placed to the contractor's disposal for the acquisition (hours worked).
- the *acquisition system* used
- ...

The itemized meta information can be complemented arbitrary and can be documented in a project file to be started. Furthermore, this information can be added to a log file. In doing so decision makers (customer and/or contractor) see the quality measures and the corresponding meta information in conjunction.

2.3 Decision Procedure

For the decision if a contract is accomplished or not a hierarchical approach is suggested: First of all the global quality measures, especially the quality rate, are examined starting with the 3D measures. If these values are insufficient, a cause study can be initiated with the help of the local quality measures. These refer to one-family houses or apartment buildings and can be displayed as colour-coded quality maps of the scenes (e. g. red-yellow-green). If the data is georeferenced, the quality map can be overlaid to an ortho photo.

3 IMPLEMENTATION

3.1 Data Structures

In the following the used structures for the vector and raster data will be explained briefly. A survey of established data representations give (Mäntylä, 1988) and (Foley et al., 1990).

Boundary Representation. The evaluation system uses a boundary representation *(b-rep)* which describes an object by the boundaries (vertices, edges, faces) of its surface, cf. (Foley et al., 1990). This representation consists in the simplest case of a list of 3D coordinates representing the vertices of the object and a list of plain polygons representing the bounding faces. The polygon lists contain indices to the coordinate list of the vertices.

The proprietary data formats of the acquisitions systems have to be converted into this boundary representation by specific input routines. By doing so the integrity of the building representations has to be checked. A valid representation exists if the model is unambiguous, closed and complete. In case of the CyberCity-Modeler format e. g. the building is represented by its roof and its walls. The ground plane has to be added in order to get valid boundary representations.

Hashing. The part of the screened volume which is occupied by buildings is of primary interest for the computations. Since this set is usually much smaller than the total screened space, the information can be stored by tables. An approach for the searching in tables is based upon the so-called *hashing* (Sedgewick, 1992). It allows the direct referencing to values in a table by executing arithmetic transformations which map a key into a table address. Hashing is a good example for the compromise between time and memory requirements. The required amount of memory can be estimated a priori. Therefore the simple method of *linear probing* can be used here.

In the following the memory requirements for a hash table and a spatial enumeration of the whole space will be compared. The computations refer to the storage of region numbers for every grid point. Thereby a region is a connected component of the screened volume. Let V be the number of volume elements specified by the cell size. If the maximal number of regions is 2^{16} = 65,536 two bytes are sufficient to store the labels. For a complete storage of all region labels $S_{\text{full}} = 2V$ byte are necessary. The length of the corresponding hash table is $N = 1.5qV$ with an occupancy factor q for the screened volume and a factor 1.5 of additional storage for the storage of collisions. With 2^{32} possible keys (4 byte) and 2^{16} possible values (region labels, 2 byte) the storage requirement for the hash table is $S_{\text{hash}} = 1.5qV(4+2)$ byte. With a chosen data type of 4 bytes for the keys and occupancy factor of $q = 0.22$ a maximal volume of $V_{\max} = 2^{32}/(1.5q) = 1,3 \cdot 10^{10}$ voxel can be treated.

The comparison reveals that with an occupancy rate of $q < 22\ \%$ the storage of region numbers in hash tables is favourable. With the application on hand this is always the case. For the difference and intersection sets the occupancy factor is actually clearly smaller.

3.2 Filling of Volume Elements

For symmetry reasons we choose the grid points to represent the mid points of the volume elements or cells. Each grid point has to be tested if it is inside or outside a building part. Practical all grid points lying inside the bounding box of a building part have to be tested. Note, that the bounding boxes can be nested. A point lying outside one building part can lie inside another building part. Furthermore, the building parts can penetrate each other, which is often the case modelling dormer windows.

For each grid point an outgoing ray is defined and checked if this ray intersects the bounding faces of the building part. If the number of intersections is divisible by two without remainder the point lies outside the building otherwise inside. First of all it has to be checked if the ray intersects the planes in which the bounding faces are embedded. If so, it has to be checked if the intersection point lies inside or outside of the plain polygon of the face.

The direction of the ray can be chosen arbitrarily in principle. An alignment with the height-axis however is advisable, which circumvents many intersections with the vertical building walls.

3.3 Calculation of Disjoint Sets

Binary Sets. For the calculation of the quality measures union, difference and intersection sets have to be determined. These result from the application of the well-known Boolean operations on bit patterns (cell occupancy) of the screened data sets. For the test and the reference data set $\mathcal{T}$ and $\mathcal{R}$

$$\mathcal{T}_i \cup \mathcal{R}_i = \mathcal{T}_i \cap \mathcal{R}_i + \mathcal{T}_i \setminus \mathcal{R}_i + \mathcal{R}_i \setminus \mathcal{T}_i \tag{5}$$

holds.

Connected Components and Correspondences. For the computation of the local quality measures the connected components have to be determined which constitute the smallest spatial units. These are for inner-city areas the apartment buildings and for low-density areas one-family houses. The determination of the connected components and their labelling can be done e. g. according to (Lumia et al., 1983) in 2D and 3D. Thereby the *disjoint set* data structure can be expoited (Cormen et al., 1990) storing the region labels into a hash table.

The assignment of labels to the regions is rather random for each set. Thus for each apartment building the corresponding subsets have to be determined according to (5). The mapping can be done by assigning the corresponding unions $\mathcal{R}_i \cup \mathcal{T}_i$ to every subset. Thus for every apartment building i the sets

$$\{\mathcal{T}_i \cup \mathcal{R}_i, \quad \mathcal{T}_i \cap \mathcal{R}_i, \quad \mathcal{T}_i \setminus \mathcal{R}_i, \quad \mathcal{R}_i \setminus \mathcal{T}_i\} \tag{6}$$

are available for the further computations.

4 EXPERIMENTAL TESTS

4.1 Data Sets

Several data sets have been examined with different contents, such as a fairground or low-density residential areas. The presented results are focussing upon on a test site which has been acquired both with the InJect acquisition system and with the CyberCity-Modeler. The scene shows apartment buildings. Fig. 1 shows a ground plan as overview. Fig. 2 shows clippings from the 3D visualization of the vector data. If the scene has been captured by the same operator is unknown. The assignment of test and reference has been random for these data sets since no statements about the accuracies have been known a priori. The CyberCity data set has been chosen as reference data set $\mathcal{R}$ — the InJect data set as evaluation data set $\mathcal{T}$.

The volume of the test site is 531 m × 347 m × 25 m $\approx$ 4,600,000 m^3. The data sets have been rastered with a cell size of 0.5 m × 0.5 m × 0.5 m which yields a total number of 1,062 × 693 × 50 = 36,798,300 volume elements.

The two acquisition systems offer different methods for the registration of building ground points. While in the InJect system the ground points have to be registered explicitly, the ground points in the CyberCity-Modeler result from an intersection of the building walls with a digital elevation model. In the test data set on hand this difference can be disregarded since the scene is very flat and all ground points have nearly identical heights.

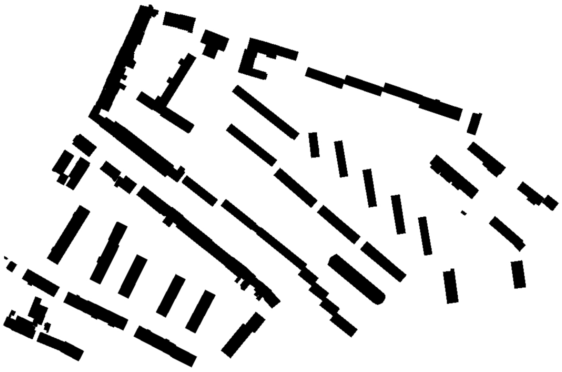

Figure 1: Test site: apartment buildings of a residential area with a size of about 530 m × 350 m.

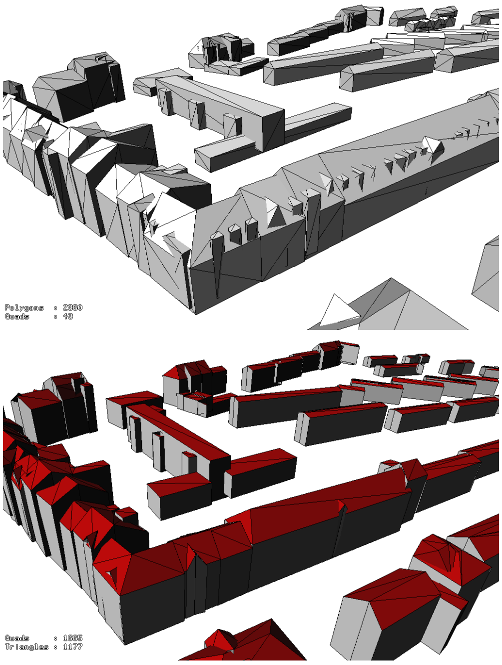

Figure 2: clippings of the InJect data set (top) and the corresponding CyberCity data set (bottom).

4.2 Results

Raster and Labelling. Table 2 summarizes statistics for the pixel and voxel sets. Figure 3 shows a clipping from the screened data set exemplary. The dormer windows of the saddleback roof can be seen clearly with the spatial resolution of 0.5 meters. In fig. 4 the difference set $\mathcal{R} \setminus \mathcal{T}$ can be seen. The building walls appear as outlines in parts darker than the remaining volume. Therefore, with the InJect system the operator has registered the buildings of this scene wider than with the CyberCity modeller.

After the screening the differences, unions and intersections of the bit sets have been calculated. Then the connected components have been determined. Note, that the regions are three-dimensional. Regions which are not adjacent in 3D might be adjacent in a projection during a visual inspection.

Quality Measures. Table 3 summarizes the various global quality measures according to section 2.2. Fig. 5 shows the quality rates ρ_q for each apartment building in the 2D and 3D evaluation. The values are grey level decoded. Dark grey values depict high quality rates whereas light grey values depict low qualities

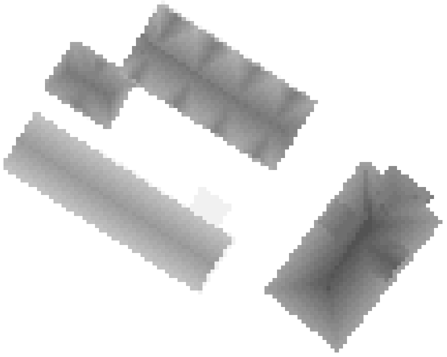

Figure 3: clipping of the screened data set. Picture elements in dark grey represent more volume than picture elements in light gray.

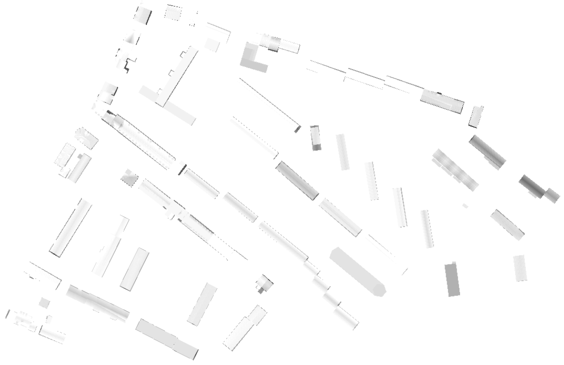

Figure 4: Voxel set $\mathcal{R}\backslash\mathcal{T}$. Picture elements in dark grey represent more volume differences than picture elements in light gray.

rates. A more convenient representation results with the help of a traffic lights colour map: Good quality rates are denoted green – bad qualities red. Values in-between can be denoted yellow with a user-defined threshold. The comparison of 2D and 3D shows that the quality rates of the 3D evaluation tend to be worse than those of the 2D evaluation. The reason might the different accuracies in position and height of the acquisitions.

In the bottom right corner of the data set one can make out a building missing in the CyberCity data set. This building can be recognized in the images of the volume differences (fig. 4) and in the quality evaluation (fig. 5, light grey). The quality rates for apartment buildings or one-family houses in terms of the corresponding areas or volumes (fig. 6) show that some small buildings with worse qualities contribute to the poor global quality rate.

Storage Requirements and Running Time. Table 4 summarizes the essential storage requirements for a data set. The number N represents either the number of volume elements (voxel) or the number of area elements (pixel). The density q of the occupancy, needed for the memory allocation of the hash table, is for areas about 0.5 and for volumes about 0.15. Six bytes each are necessary for an entry in the hash table — 2 bytes for the value (region number) and additional 4 byte for the key (position in the grid). The factor 1.5 represents the reserve to avoid collisions addressing of the table elements. The total storage requirement results from the sum of the storage requirements for the sets $\mathcal{T}$, $\mathcal{R}$, $\mathcal{T} \cup \mathcal{R}$, $\mathcal{R} \cap \mathcal{T}$, $\mathcal{R}\backslash\mathcal{T}$ und $\mathcal{T}\backslash\mathcal{R}$ — each for volumes and areas.

	$\mathcal{T}$ CyberCity	$\mathcal{R}$ InJect	$\mathcal{T} \setminus \mathcal{R}$
building parts	175	221	—
regions 2D	54	102	897
3D	103	125	3,687
occupied pixel 2D	98,046	102,470	5,245
voxel 3D	1,768,110	1,929,064	184,260
density 2D	13.34 %	13,923 %	0.713 %
3D	4.81 %	5.24 %	0.501 %

Table 2: statistics for the pixel and voxel sets based on 735,966 pixel and 36,798,300 voxel.

quality measure	2D	3D
quality rate ρ_q	0.862	0.780
error type II β	0.051	0.096
branch factor ρ_b	0.104	0.128
miss factor ρ_m	0.057	0.116

Table 3: Global quality measures.

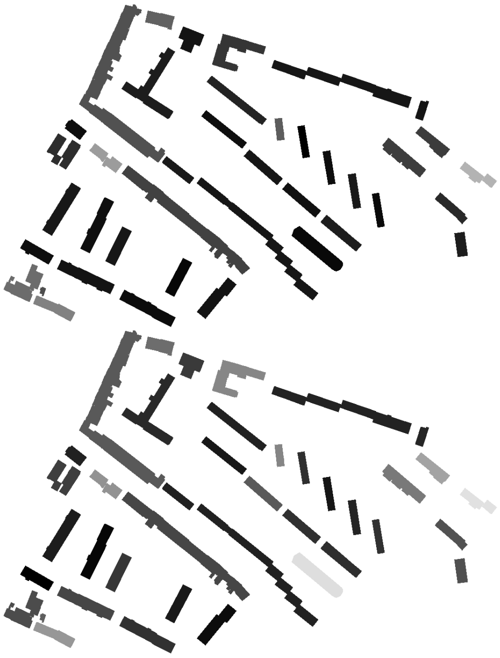

Figure 5: Quality rates for the 2D evaluation (top) and in the 3D evaluation (bottom). Good quality values are depicted in dark grey, bad quality values in light grey.

The running time of the program depends on the size of the data sets and the chosen cell size for the volume elements. The crucial operations are the filling of the volume elements and the determination of the connected components. The operations should be done by low-level routines. By doing so the running time lies in

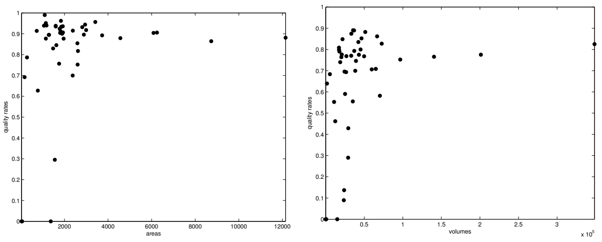

Figure 6: Quality rates for apartment buildings $\mathcal{T}_i \cap \mathcal{R}_i$ in terms of the corresponding areas (left) and the corresponding volumes (right).

information	data structure	storage requirement
cell occupancy	bit set	N bit = $N/8$ byte
region labels	hash table	$1.5 \cdot 6 \cdot q \cdot N \cdot$ byte

Table 4: Storage requirements for N area or volume elements. The density of the occupancy if q for the volume.

the magnitude of one hour for the presented data set.

5 CONCLUSIONS AND OUTLOOK

Conclusions. For the quantitative evaluation of photogrammetric building acquisitions an automatic system has been presented, which enables the contractor and the customer to check the compliance of the contractual specifications. Furthermore, the procedure allows the comparison of different acquisition systems and methods.

The evaluation is based on the comparison of a test and a reference data. This control sample should be representative for the acquisition task. For complex buildings the topology of building acquisitions may vary due to the operators notion or the acquisition system. Therefore, a screening of the scene has been suggested. The only parameter is the size of the cell which determines the spatial resolution and thus the precision of the derived quantities.

For the selection of reasonable quality measures criteria have been established and applied. To facilitate the work of the decision-maker a hierarchical decision procedure has been recommended, cooperating with the provided meta information. Additionally, the determined local quality measures of single apartment buildings or one-family houses allows the realisation of diagnostics if the primary criteria are not fulfilled. This visual inspection allows to distinguish between positional accuracy and completeness.

Outlook. Further investigations should take the magnitudes of the deviations into account. This can easily be done by the applications of weights taken from a distance transformation. In addition an error seam can be placed around the buildings taking the uncertainty of the geometric acquisition into account. For the screened data sets this error seam can be realized by a morphologic closing operation defined on binary images in 2D and 3D (Haralick et al., 1987). Furthermore, the attributes of the registered building parts should be taken into consideration. Perhaps only small buildings are missing for instance. This can be achieved by the generation of histograms. To avoid storage limitations which might appear with large data sets in high resolution the introduction of hierachical data structures like octrees is considered.

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