Geometrical Modeling for Facility Management Systems Applying Surface Parameters

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ABSTRACT

Usually the acquisition of geometrical data for buildings is very expensive, as buildings are mostly parameterized by 3D point coordinates in CAD systems. For complex buildings this approach leads to large data sets with uncontrolled redundancy. Therefore geometry will often be disregarded for facility management systems or will be added just as descriptive information.

In this report it will be demonstrated that an economic solution to the task of geometrical data acquisition of buildings can be achieved by improving the data processing procedure rather than the data acquisition methods applied on site. The new approach is based on surface parameters and a strict modeling of the 3D topology. Thus the number of necessary parameters to be determined will be reduced considerably. The data model implies geometrical constraints by n:m-relationships between objects and parameters.

The data model affects the measurements to be made on site. For ordinary buildings, robust and easy to use measurement tools, like measurement tapes or hand hold laser distance measurement instruments, can be applied. Such observations can be collected by technician level workers.

The task of the surveying engineer will be to find a consistent result, exploiting the redundancy of the measurements to remove errors while transforming the data into a unique spatial reference frame. This task is a typical application of geodetic adjustment techniques which surveying engineers are used to.

ZUSAMMENFASSUNG

In vielen Fällen ist die Erfassung geometrischer Gebäudedaten sehr teuer. Diese Tatsache ist nicht zuletzt darauf zurückzuführen, dass die Geometrie in CAD-Systemen meistens durch 3D Punktkoordinaten parametrisiert wird. Bei komplexen Gebäuden führt ein solcher Ansatz zu großen Datenmengen und unkontrollierter Redundanz. Aus diesem Grund werden geometrische Informationen in CAFM-Systemen oft nicht berücksichtigt oder lediglich als beschreibende Daten mitgeführt.

Der vorliegende Beitrag zeigt, dass eine höhere Wirtschaftlichkeit der Gebäudeerfassung eher durch eine Verbesserung des Auswerteprozesses denn durch neue Aufnahmetechniken erreicht werden kann. Der vorgestellte Ansatz basiert auf einer Parametrisierung durch Flächenparameter und der strengen Trennung von Geometrie und Topologie im Datenmodell. Die Anzahl der für die geometrische Beschreibung des Gebäudes notwendigen Parameter wird dabei erheblich reduziert.

Das Datenmodell beeinflusst entscheidend die örtliche Messung. Für gewöhnliche Gebäude genügt der Einsatz einfacher Messmittel wie Zollstock, Messband oder Hand-Laserentfernungsmesser. Die Messung kann von angelerntem Personal durchgeführt werden.

Die eigentliche Aufgabe des Vermessungsingenieurs besteht in der Berechnung eines konsistenten Ergebnisses, wobei die im Beobachtungsmaterial vorhandene Redundanz genutzt wird, um Fehler zu eliminieren. Diese Aufgabe ist eine typische Anwendung der geodätischen Ausgleichungsrechnung.

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1 INTRODUCTION

The core problem of CAD systems or GIS is the question of how the geometrical information will be mapped. Considering geometrical information in general, two main classes should be considered. The first class contains the absolute geometry. Absolute means, that the position of an object is referenced to a global reference frame like a building coordinate system in a CAFM or, in the case of a GIS, to an official coordinate system. The second class contains the relative geometrical information like distances or angles.

Most CAD and GIS systems store only the first class, the absolute geometrical information. This class of information is unique and non-redundant. Relative geometrical information is only considered as a view of the absolute geometrical information. This is the classical view of the software engineer.

The view of the surveying engineer is different, however. In practical applications absolute geometrical information can not be observed directly, it is rather derived from relative observations. These observations are in general redundant and will contain contradictions. The contradictions in the observations are an expression of their stochastic properties. The task of the surveying engineer is to derive non-redundant and compatible absolute geometrical information from the observations. The tools used to achieve this are geodetic adjustment techniques. The result from the operation *adjustment calculation* is unique but not reversible. From a geodetic point of view absolute geometrical information is just a view at the relative geometrical information, the observations.

The difference between the classical software engineering view and the geodetic view with respect to geometrical information is fundamental. It is the task of geodetic science to overcome this shortcoming of the software engineering view. This will influence the further development of CAD, GIS and CAFM considerably. A prerequisite for the solving of this task is the integration of geodetic adjustment techniques into databases as operators to create views on the original observation data.

A second problem is the parametrization of absolute geometrical information. Conventional CAD systems are able to deal with graphical primitives like point, straight line or arc. The parametrization is mostly realized with point coordinates. But it is typical for buildings to have many geometrical constraints between these graphical primitives. There are for example coplanarity, parallelism or orthogonality. The coordinate approach leads to the problem, that it is necessary to formulate and to control a variety of additional consistency requirements. But even a modeling based on volumes in the common sense is not able to avoid completely uncontrolled redundancy in the geometrical data.

Therefore a project was initiated in the department of geodesy and adjustment techniques of the technical university of Berlin with the aim, to develop a system for the mapping of building geometry. It has the objective of realizing the following two principles:

- To represent absolute geometry as a view on observations using the operator *adjustment techniques*
- To parameterize the absolute geometry in a way that the data model automatically implies geometrical constraints

Another objective was to develop a system using established standards. The data and the data structures should be independent of the processing tools, so that it will be possible to develop different program modules accessing one database. For that reason the data modeling was carried out using a relational approach. In the present case a Microsoft® Access database is being used. The connection between database and program modules is realized using ODBC (open database connectivity).

For the different data processing tasks, for instance adjustment, topological consistency check or determination of proximity values, special modules were developed. The programming was carried out using an object oriented approach in the C++ language. *Figure 1* shows the general system architecture.

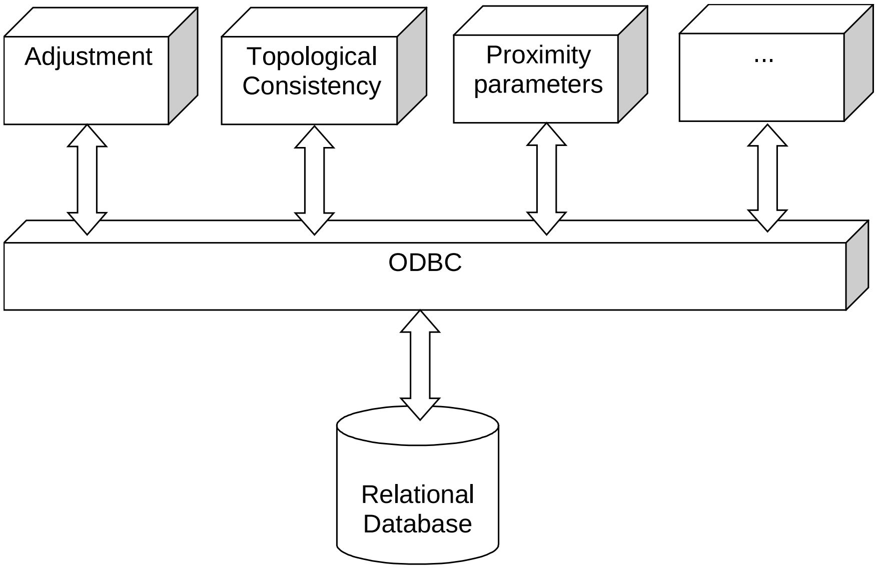

Figure 1: System Architecture

The sequence of development steps was inverse to the sequence of data processing. Thus the first and most important step was to develop the data model. This was followed by the modules for adjustment, proximity value determination, topological consistency checks and data acquisition. This paper will describe these steps in the same order as they were developed.

2 DATA MODEL

In the first stage only planes were used as elements to describe the geometry of a building. In a second stage higher order surfaces will be used, e.g. cylindrical, spherical or conical.

Before the actual data modeling, several requirements of the data model had to be formulated:

- Storing of observations as primary data
- Geometrical constraints to be included in the data model. There should be no necessity to formulate additional geometrical consistency requirements.
- No uncontrolled redundancy

- Strict separation of geometrical, topological and descriptive information

At the begin of the modeling process the question arose: “What is a corner?” The answer to this question depends on the point of view. In a geometrical sense a corner is the intersection line of two planes while under topological aspects it is an edge separating two meshes. The difference between these views is that a plane is characterized by geometrical attributes as components of its normal vector and its orthogonal distance to the origin of the coordinate system, while a mesh carries no geometrical information at all.

Why is it advisable to model these two views separately? When considering a building, one will find that the floors in many rooms are represented by one plane. This applies also in the case of ceilings or for walls standing in one line. In all these cases different meshes are associated with one and the same plane, which leads to a 1:n-relationship type in the data model between the object classes *planes* and *meshes*.

In the resulting data model a room is just a topological object, with meshes for boundaries. In the topological part of the data model, object classes of four different dimensions exist: space (3-cell), mesh (2-cell), edge (1-cell) and node (0-cell). There are three subclasses of the class *space*: *room*, *wall* and *external space*. A mesh associating a wall with a room or external space represents the surface of a wall. If it associates two rooms then it represents a door, and in the case of associating a room and external space, it is a window or a door to the outside.

Geometrical information is stored in two higher level classes: *planes* and *observations*. The planes contain the absolute geometry while the observations contain the relative geometry. Observations will be described in section 3. The geometry of a building will be completely mapped by planes. Points with absolute coordinates no longer exist as primary data. They are generated automatically by the intersection of three planes. A list of nodal coordinates can easily be created as a view of the topology together with the planes. *Figure 2* shows a SQL statement generating a coordinate list of the nodes. The `SELECT` phrase realizes the calculation of the coordinates by Cramer’s rule.

```
SELECT  P.Knoten,

        E1.x*E2.y*E3.z+E2.x*E3.y*E1.z+E3.x*E1.y*E2.z-E3.x*E2.y*E1.z-
        E2.x*E1.y*E3.z-E1.x*E3.y*E2.z AS d,

        (E1.d*E2.y*E3.z+E2.d*E3.y*E1.z+E3.d*E1.y*E2.z-E3.d*E2.y*E1.z-
        E2.d*E1.y*E3.z-E1.d*E3.y*E2.z)/[d] AS x,

        (E1.x*E2.d*E3.z+E2.x*E3.d*E1.z+E3.x*E1.d*E2.z-E3.x*E2.d*E1.z-
        E2.x*E1.d*E3.z-E1.x*E3.d*E2.z)/[d] AS y,

        (E1.x*E2.y*E3.d+E2.x*E3.y*E1.d+E3.x*E1.y*E2.d-E3.x*E2.y*E1.d-
        E2.x*E1.y*E3.d-E1.x*E3.y*E2.d)/[d] AS z

FROM    (([Knoten 3 Ebenen] AS P INNER JOIN [Ebenen-Werte] AS E1 ON
        P.E1.Ebene=E1.Ebene) INNER JOIN [Ebenen-Werte] AS E2 ON
        P.E2.Ebene=E2.Ebene) INNER JOIN [Ebenen-Werte] AS E3 ON
        P.E3.Ebene=E3.Ebene

WHERE   E1.d Is Not Null AND E2.d Is Not Null AND E3.d Is Not Null
```

Figure 2: SQL statement generating a coordinate list

Planes are represented by a vector polynomial of degree one:

$$\mathbf{n}^{\mathrm{T}}\mathbf{x} + d = 0 \tag{1}$$

In this equation **n** means the normalized normal vector, **x** the position vector and *d* the orthogonal distance from the coordinate origin. For a unique solution it is necessary to enforce the length of the normal vector to be 1. This can be achieved by the introduction of a strongly weighted observation in the adjustment model.

Walls, floors and ceilings are very often parallel or orthogonal to each other. Information about parallelism is mapped such that both planes are associated with one and the same normal vector. Therefore, it was necessary to introduce normal vectors as a separate object class. Orthogonality is mapped in such a way that the normal vectors of orthogonal elements are associated with the same parameters. By swapping the position of two parameters in a normal vector together with a change in one of their signs effects a rotation of 90° or 270°. Changing both signs effects a rotation of 180°. Therefore, a separate class for orientation parameters was defined. The normal vector class contains only the signs and the pointer to the orientation parameters. Orientation parameters can have either fixed or unknown status. This status determines its role in the adjustment. For example, the orientation parameters of a horizontal floor normal vector will be fixed with $\mathbf{n}^{\mathrm{T}} = (0,0,1)$.

The parameter sharing approach presented here reduces the number of necessary geometrical parameters compared to an absolute coordinate representation considerably. In the example presented in Section 6 90% less parameters were needed. Geometrical constraints, such as point and straight line coplanarity, as well as the parallelism and orthogonality of planes or straight lines are included in the data model.

3 OBSERVATION TYPES AND ADJUSTMENT

As mentioned, the absolute geometry is stored in the class *planes* while the relative geometry is stored in the class *observations*.

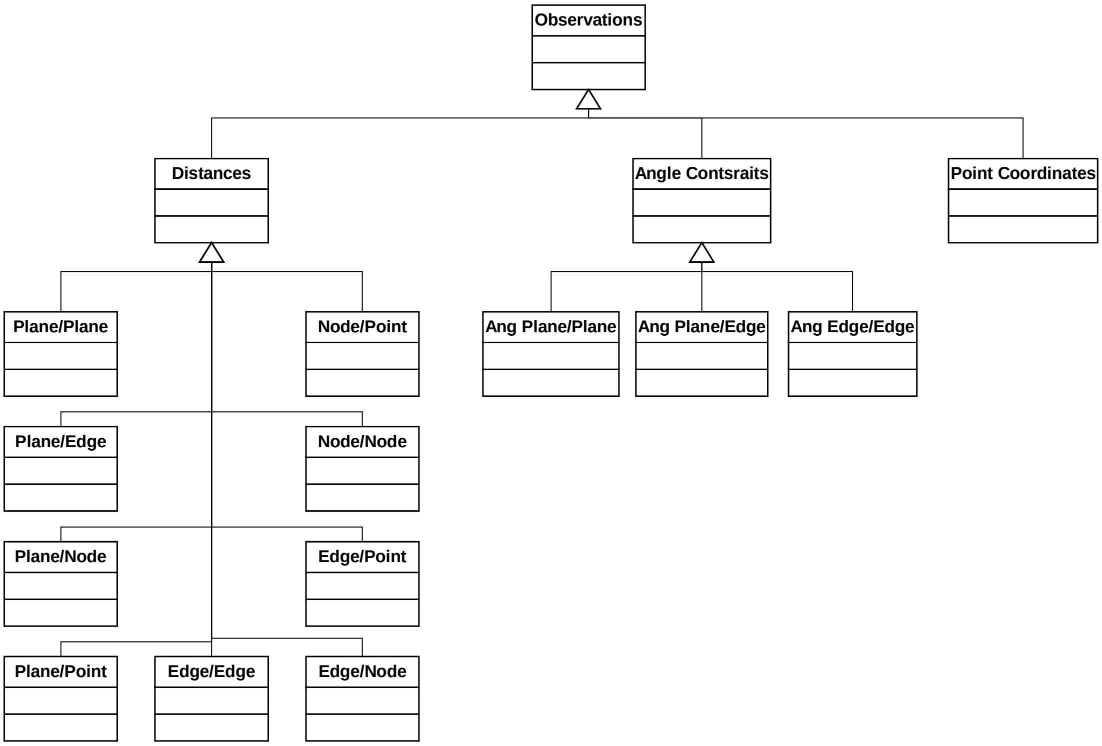

Figure 3: Object Class Model

shows the object class hierarchy of the observations. Distances are always the shortest distance between two elements. If the associated elements are of type plane or edge, they have to be parallel. The accuracy of a distance observation is characterized by its standard deviation.

Angular constraints are necessary where it is not possible to express orthogonality or parallelism between two elements by using the same normal vector parameters. In the adjustment these constraints are modeled by strongly weighted observations.

A special observation type is *point coordinates*. The element *point* exists in the data model only as an observation rather than as absolute geometry. Points will be used to introduce tachymetrical or photogrammetrical measurements to the adjustment model. In general only a few points are necessary to define the outside frame of a building and to avoid error propagation.

The adjustment is formulated as an indirect adjustment problem. The unknowns are the parameters of the planes namely the components of $\mathbf{n}$ as rotation and the parameter d representing the translation. Observations are distances, coordinates, angular constraints and the norm of the normal vectors to enforce the value 1.

4 PROXIMITY PARAMETERS

Before performing the adjustment, it is necessary to calculate proximity values for the unknown parameters. It is important to consider that the observations might contain many blunders, especially when less skilled workers provide the measurements. Therefore, the algorithm for proximity value calculation should be robust and should provide blunder detection methods. The best way to fulfill these requirements is to formulate the task as a linear adjustment problem.

The first step in the proximity value calculation is the grouping of planes by their normal vectors. An ideal regular building, for example, has exactly three groups of planes: parallel to the *xy*-plane (horizontal), parallel to the *xz*-plane (vertical) and parallel to the *yz*-plane (vertical) of a building coordinate system. In these groups the parameter *d* of each plane is determined by a 1D linear adjustment calculation, analogous to a leveling network.

In the second step the absolute orientation parameters of the single normal vector groups is determined. The intersection of the vertical edges of a group with the *xy*-plane results in a group of points. These point groups can be referenced to local 2D coordinate systems. Between the different groups identical edges exist as identical points in the *xy* -plane. Using these identical points, the local 2D systems can be transformed to the global building system by an interconnected similarity transformation, which is also a linear adjustment problem. Because of the scale factor, the norm of the normal vectors will not be exactly 1 after this calculation, but it is a sufficient approximation for the final adjustment.

In the third and final step the remaining parameters will be calculated in a classical sequential manner.

5 DATA COLLECTION AND DATA MANIPULATION

It was the aim of the project to develop a system which makes it possible to survey a complete building using simple tools such as meter stick, measuring tape or hand held laser instrument. The smallest data unit to store in the database is a complete surveyed room. A room will be accepted as completely surveyed if it is topologically consistent, if all topological elements are geometrically determinable and if no blunders have been detected.

The surveying takes place in two steps; topological and geometrical. In the initial stage the room is a cube. The cube is a kind of a template. During the topological registration the operator modifies the initial draft by changing the length and width and by outlining the corners, doors and windows. If a door is to be defined, it is necessary to specify the identifier of the associated neighboring room. After the first step is completed, a topological consistency check is performed.

In the second step, the geometrical surveying, the model from the first step will be supplied with geometrical information. This is achieved by the measuring of distances and registration of angular constraints. The program checks if the parameters of all associated planes can be determined relative to a local coordinate frame. If this is the case the parameters will be calculated in the same way as described in Sections 3 and 4.

The data collection module also acts as the only permissible tool for data manipulation. It selects the data of one room from the database and provides an editing capability. After editing the, already described, consistency checking and geometry calculation procedures take place. If consistent the data is stored in the database again. To guarantee the consistency of the absolute geometric data, it is necessary to perform the steps up to the adjustment calculation.

6 VISUALIZATION

The visualization of single rooms is possible with the data collection module.
With the current implementation the visualization of a complete building is achieved with external programs. It is easy to export a nodal coordinate list and a list of edges in ASCII format. The external program produces a wireframe model of the building and provides functions to modify the view and to print. Export filters to DXF and VRML are planed.

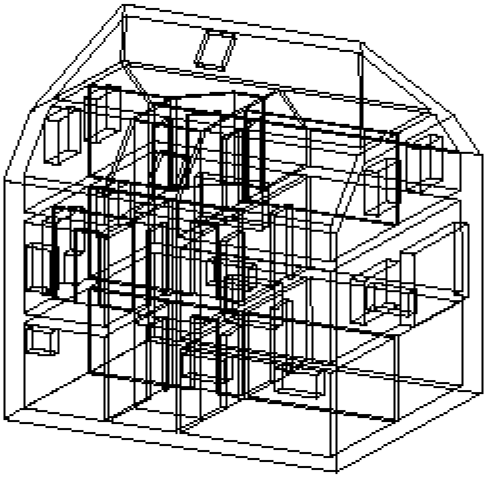

Figure 4: Wireframe Model of a Building

7 PERSPECTIVES

The data model can be extended to support surfaces of second order. These surfaces can be expressed by a vector polynomial of degree two:

$$\mathbf{A}^{\mathrm{T}}\mathbf{x}\mathbf{A} + \mathbf{n}^{\mathrm{T}}\mathbf{x} + d = 0 \tag{2}$$

The class of these surfaces contains spheres, ellipsoids, cylinders and cones. In almost all practically relevant cases the matrix **A** is orthonormal, so that it can be fully described by the parameters of its main axis transformation.
A special problem is the calculation of the intersection lines between these surfaces. This is because they can touch tangentially. The parameters of intersecting surfaces are random variables, which can lead to non-unique solutions. It seems sensible to introduce a special class of planes which realize these required unique solutions.
If the geometry of a building is very complex it can be necessary to use surveying techniques such as tachymetry, photogrammetry or laser scanning. The preprocessing of such data should be the task of a separate program module.
The philosophy of parameter sharing in the data model simplifies even the mapping of complex constructions. As an example a Romanesque crypt shall be considered. The ceiling consists of intersecting cylinders with horizontal axes. The axes are equidistant and

orthogonal. The radius of all cylinders is the same and can be expressed by one parameter. The normal vector **n** of the symmetric planes is the same for all parallel cylinders. The normal vector $\mathbf{n}_o$ of the symmetric planes of the orthogonal cylinders uses the same parameters as **n**. The lower bound of the arches and the upper bound of the pillars is one plane.

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BIOGRAPHICAL NOTES

Dr. Frank Gielsdorf, born 1960. Graduated in 1987 as Dipl.-Ing. in Surveying from Technical University of Dresden. Obtaining doctorate degree in 1997 from Technical University of Berlin. Since 1995 Assistant Professor at the Department of Geodesy and Geomatics, Technical University of Berlin.

Prof. Dr. Lothar Gründig, born in 1944. Graduated in 1970 as Dipl.-Ing. in Surveying and obtaining doctorate degree in 1975, both from University of Stuttgart. From 1970 to 1977, work as Assistant Professor and until 1987 senior research assistant at University of Stuttgart. Scientist at Scientific Center of IBM in Heidelberg on data bases 1984-1982 and guest scientist at Calgary University for 4 months in 1983. Since 1988 Professor of Geodesy and Adjustment Techniques at the Department of Geodesy and Geomatics, Technical University of Berlin.