Application of Airborne Laser Technology to 3D Cadastre

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Key words: Airborne laser scanning, 3D cadastre, matching.

SUMMARY

Growing demand for an efficient land use above and below the ground is motivating cadastre and land management systems to move from traditional 2D systems toward three-dimensional ones. A major concern in realizing the 3D cadastre vision is the development of efficient methods for the attachment of the third dimension to the existing 2D systems. In this regard airborne laser technology that offers direct acquisition of dense and accurate 3D data in the rapid turn-around time offers a very suitable mean to meet this objective. Finding ways to harnessing laser technology to nourish the other seems therefore only natural. The transformation of surface data into objects and shapes is, however, not as immediate and requires studying several aspects in more detail. Whereas developing methods to process LiDAR data is an active research field, little is reported about utilizing this technology for cadastral purposes. We identify three major aspects that should be studied in some detail. The first one is fundamental and concerns elements of accuracy, co-registration of the two datasets and required point density. The second one concerns recognizing objects and their shapes in relation to cadastre purposes, and the third one concerns the integration of the data with the existing databases. The paper presents a methodology and an algorithm for integrating airborne laser scanning data and existing 2D cadastral system. We demonstrate the integration over a residential area comprising several high rising buildings with varying shapes, open areas, etc. A special attention is paid to elements of accuracy and co-registration between the datasets a topic of great importance in terms of consistency. Results highlight the processes involved in realizing the idea of transforming laser data into cadastral information.

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1. INTRODUCTION

The shortage of land and the growing demand for an efficient land use above and below the ground are shifting cadastre and land management systems from traditional 2D systems towards three dimensional ones. It is agreed upon by many researchers that in the cadastre of the future will location of parcels and their boundaries will be determined in 3D space (Kaufman and Steudler, 1998; Stoter, 2000, Benhamu and Doytsher, 2003). The realization that rapid urban and land development requires more effective utilization of space has led the Survey of Israel (SOI) and the Technion–Israel Institute of Technology in 1996 to initiate a joint research forum that was followed by a PhD research primarily aimed at analyzing the 3D cadastre as a technology base for spatial management and registration of real estate properties. Results of this research have then led the Israeli Ministry of Finance to form and fund a governmental sponsored research and development group hosted by the SOI that will provide recommendations for the formation of 3D cadastre in Israel. The rationale of this project was that above and below the ground, planning and development activities can be considerably accelerated by guaranteeing the property rights of the owners. Results and conclusions of this research are given in Shoshani et al., 2004.

A major concern in realizing the 3D cadastre vision is the development of efficient methods for the attachment of the third dimension to the existing 2D systems. In this regard airborne laser technology that provides means for the extraction of dense and accurate 3D information of physical surfaces offers the most natural solution. By direct range measurements to surfaces Light Detection and Ranging (LiDAR) provide a ready made 3D description of the scanned regions thus allowing the assignment of the elevation component of the cadastral databases. Compared to land surveys that are localized and mapping from aerial photography which is labor intensive LiDAR data allow a fully automated process for the incorporation of the third dimension over wide land coverage via airborne laser scanning surveys. The detailed description of the terrain and the objects on the terrain facilitates the detection and mapping of objects with distinct "surface" signature. Therefore, not only the terrain height but also the objects height and their shape can be extracted from the LiDAR data for the cadastral information.

Whereas developing methods to process LiDAR data is an active research field, little is reported about utilizing this technology for cadastral purposes. Analysis of what constitutes such integration gives rise to three main aspects that should be studied in some detail. The first one is fundamental and concerns elements of accuracy, co-registration of the two datasets and required point density. The second one concerns recognizing objects and their shapes in relation to cadastre purposes, and the third one concerns the integration of the data with the existing databases. Laser datasets are merely a set of points that sample the scanned surface. They contain no semantic information that enables one to group or identify them by the type of object they were reflected from. Therefore before adding the height component to 2D objects one must ensure that correct height is assigned to the given points or objects.

The paper presents an algorithm for integrating airborne laser scanning data and existing 2D cadastral system. It demonstrates the integration over a residential area comprising several high rising buildings with varying shapes, open areas, etc. Special attention is paid to elements of accuracy and co-registration between the datasets a topic of great importance in terms of consistency. Results highlight the processes involved in realizing the idea of transforming laser data into cadastral information.

2. INCORPORATING 3D LASER DATA TO THE 2D CADASTRE

Modeling the third dimension for objects above and below the ground is particularly complex when cadastre is concerned as the nature of 3D cadastre exceeds beyond geometric modeling. Our discussion is limited to the incorporation of the height component of above the ground into the 2D cadastral data. Such incorporation can be implemented in several ways in varying levels of detail. A basic question that is raised is whether elevation should be measures as relative height with respect to the ground or in absolute orthometric values with respect to the national coordinate reference frame (Stoter and Gorte, 2003). Whereas relative heights are more intuitive (as objects are measured with by their heights or depth) absolute heights are more rigorous in the sense that objects have their absolute coordinates, similarly to the parcel boundaries that are given in planimetric coordinates. The absolute representation is not influenced by surface definitions or changes and is therefore preferable to the relative representation. Nevertheless, the vertical position of an object is yet incomplete without knowledge of the reference surface, namely the terrain. The combination of the object height and the surface provide a description of the 3D location of the object in space, both absolutely (in the sense of absolute coordinates) and relatively, with respect to the ground. Incorporation of the surface component into the cadastre can be applied in several ways. We list here three alternatives:

- Adding a *z*-value of the turning points of the parcels boundary as derived from the laser data into the 2D cadastre. This approach preserves the original 2D cadastre but supplements it with another field for the height.
- Extending the definition of the parcel boundary into 3D. Here turning points are considered in all three dimensions. This approach features the three dimensional shape of the parcel boundary, but does not alter the prevailing parcel boundary representation.
- Maintaining the ground laser points within to the parcel boundary to describe the terrain within the parcel (Stoter and Gorte, 2003). This representation is maximal and incurs a cost of maintaining a large volume of data to describe the terrain within the parcel.

The current recommendations Israeli 3D cadastre research and development group opts towards the first alternative. They suggest assigning a *z*-value to each turning point in the parcel and sub-parcel boundary definition (Shoshani et al., 2005). The sub-parcel boundary (e.g., a building in the parcel) will be defined as a function of the object coordinates and safety distances surrounding the objects.

To allocate the *z* component to the cadastre direct assignment of LiDAR derived heights may prove inadequate when positional offsets between the datasets exist. Such offsets may lead to positional and vertical inaccuracies and inconsistencies. Therefore, the attribution of the heights to the parcel boundary requires co-registration of the two datasets so that no horizontal displacement exists between the two. Sources of errors that lead to positional inconsistency are to be found in both datasets. The significant among them may be attributed to the quality of the graphical cadastre, a term coined in Doytsher et al., 2001 to describe the current status of a large section of the computerized cadastre in Israel. Many of the cadastral blocks in Israel exist(ed) in the form of paper drawings (considered as analogue cadastre) and suffer from both drawing inaccuracies and the effect of paper deformation over time. Thus far their transformation into digital form is limited in large to their digitization (thus considered graphical cadastre); errors in the graphical cadastre can reach up to the level of a few meters (Doytsher et al., 2001). On a lesser scale positional errors also can be noticed in laser altimetry data. Ignoring random errors (which are around the single decimeter level) systematic 3D offsets are sometimes noticed in the data. Such offsets can reach the level of a few decimeters within the data unless eliminated by a 3D strip adjustment (Filin and Vosselman, 2004). It is noted that the different characteristics that the two dataset have – cadastral data as a vectorial dataset whereas laser data sample of the surface as a function of the laser scanner properties– suggest that offsets that are within the sampling interval are very likely to remain unnoticeable. In cases where errors exceed the sampling rate our goal is to register the datasets to achieve consistency. To do this we separate the process into three steps: i) detection of objects common to both datasets and matching their shape, ii) transformation of the two datasets by some transformation method, and iii) integration of the two datasets so that the height component is embedded into the 2D cadastral data.

3. DETECTION AND RECONSTRUCTION OF CORRESPONDING OBJECTS

As the laser points do not contain semantic information that identify the objects from which points were reflected, correspondence has to be based on objects that can be inferred from the laser data and exist in the cadastre data. Figure 1 that shows a cadastre map of a suburban area demonstrates that buildings are the most suitable candidates upon which the registration can be based. Notably a registration based on the parcels boundaries or turning points would have been the best solution (in fact in such case no transformation would have been needed at all) however, in many cases these boundaries have no distinct height signature and therefore cannot be considered reliable/general candidates for the registration.

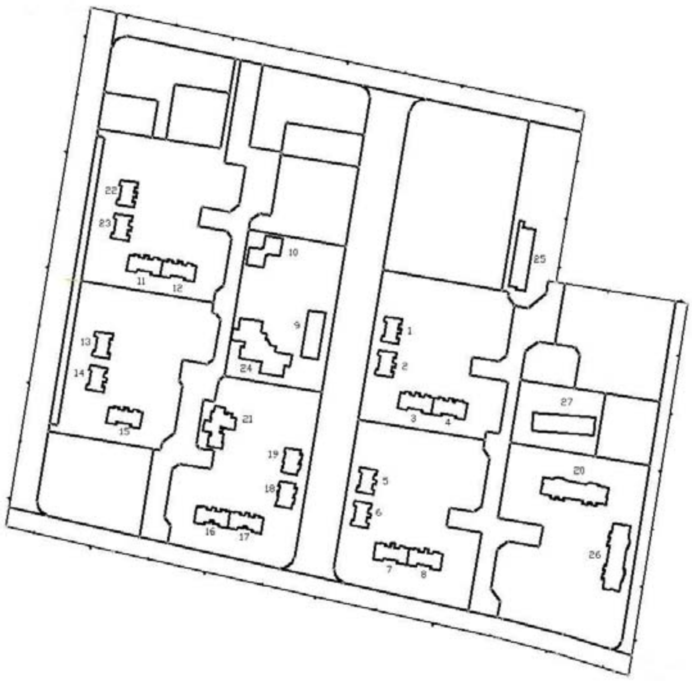

Figure 1: Cadastral map

Building Detection –detection of buildings in laser data has been researched quite extensively in the past (see e.g., Vosselman and Dijkman, 2001; Rottensteiner and Briese, 2002; Abo-Akel et al., 2005) and is likely to remain so in the near future. For registration purposes building detection per se is only a mean to an end; our algorithm does not aim to detect and reconstruct building shapes which is usually complex and computational expensive, but rather to borrow the relevant parts. The first observation that simplifies the algorithm is that the current problem is rather localized as it concerns detecting buildings that exist both in datasets. Therefore, buildings appearing the cadastre maps guide the detection of building in the LiDAR point cloud; "LiDAR buildings" that have no cadastral counterparts have no contributions. With the assumption that the offset between the building boundary and the laser "building" points does not exceed the size of the building (namely there is an overlap between the building related laser points and the cadastre based building contour) the algorithm finds first laser points within the building polygon and analyzes them further. The points are first thresholded to separate roof related points from other points. The region that is formed by the thresholded points is then extended (via height criterion) to detect the rest of the building/roof reflected points. A plane fitting is then applied to identify the roof and points that are on and above the roof level (may arrive from structures on the roof) are considered the roof related laser points.

Building reconstruction – the literature shows that building reconstruction focus mostly on the detection of the roof parts (mostly roof faces) and on the agglomeration of those parts into a volumetric building model. The buildings that are usually studied feature complex roof shapes (heap roofs, cross hipped roofs, dormers, etc.) but relatively simple boundaries that follow the shape of the roof parts. In this regard it is quite ironic that with flat roofs that are generally simple to detect and reconstruct (usually reduced to a plane fitting) the boundary can be quite complex and difficult to define. In densely populated metropolitan areas that are characterized by the existence of many high-rising buildings flat-roof buildings are prevailing type of buildings as the cadastral map in Figure 1 illustrates. Figure 1 also shows many of the buildings are characterized by many turning points that form a rather complex shape to reconstruct. With a medium point density (app. a points per 1.4 m^2) the reconstruction of the building shape turns error prone and relatively unpredictable. Figure 2 illustrates the reconstruction of a typical building. The reconstruction is based on the detection of straight lines via the application of the Hough transformation on the boundary laser points of the building.

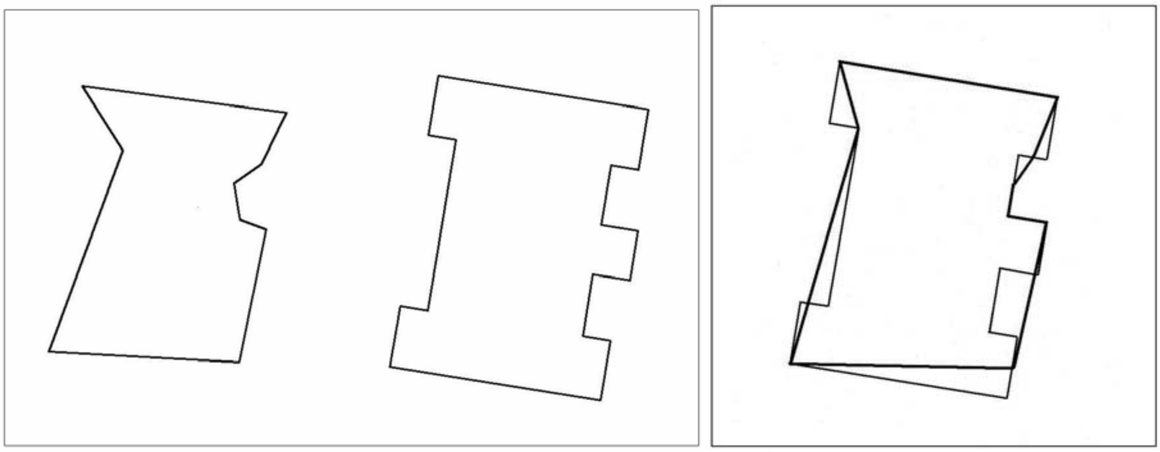

Figure 2: Potential reconstruction of building shapes for complex boundaries and medium point density, (left) the actual building and its reconstructed shape one by the other; (right) the actual building and its reconstructed shape overlaid one on top of the other.

Figure 2 indicates that the reliability in reconstructing the bounding polygon of complex buildings from point cloud medium density is questionable. Even when an orthogonallity constraint is applied the algorithm does not manage to reconstruct the actual shape of the building. We therefore conclude that matching cadastre based building and LiDAR reconstructed building by their shape, offers a very fragile strategy that relies on the data density and implicitly assumes a simple shape of the building contour.

Matching and translation computation – to match the two datasets and compute the offsets we take a different approach – instead of shape association, which is sensitive to the point density, our association is based on comparing the laser "building" points to the building depiction as is given by the cadastre. Choosing this approach offers several advantages, i) it is attentive to the characteristics of the different datasets, ii) it is insensitive to the point density, and iii) its implementation is simple. Our hypothesis is that when the laser data and the cadastral data will be co-registered the maximal number of laser points that describe the building will fall inside the building polygon. Therefore, instead of search of a transformation that matches the shape of the buildings our algorithm searches for a transformation that maximizes the number of points that fall inside the polygon. To achieve this association the building related points are shifted in the *xy*-plane at predefined intervals and the shift that maximizes the number of points in the polygon determines the shift between the building related points and the building description in the cadastre data. More formally

$$\Phi\{\Delta x^*, \Delta y^*\} = \arg\max_{\Delta x, \Delta y}\{\#(q_i(\Delta x, \Delta y) \in p_i) \mid -\Delta x_{bound} < \Delta x < \Delta x_{bound}, -\Delta y_{bound} < \Delta y < \Delta y_{bound})\}$$

$$\forall i = 1,2,\ldots,n \qquad (1)$$

where $q_i(\Delta x, \Delta y)$ are the laser points of a given building, i, under translation Δx, Δy, and p_i, the bounding polygon of the building. The offsets are computed for each building independently of the others.

The search for maximal number of points is performed in a cross-correlation like procedure (shifting the points by an interval in each test). The binary nature of the graphical data, i.e., inside a polygon or outside a polygon, does not allow the generation of computational models (e.g., in the form of least square matching) that will maximize a function in an analytical form.

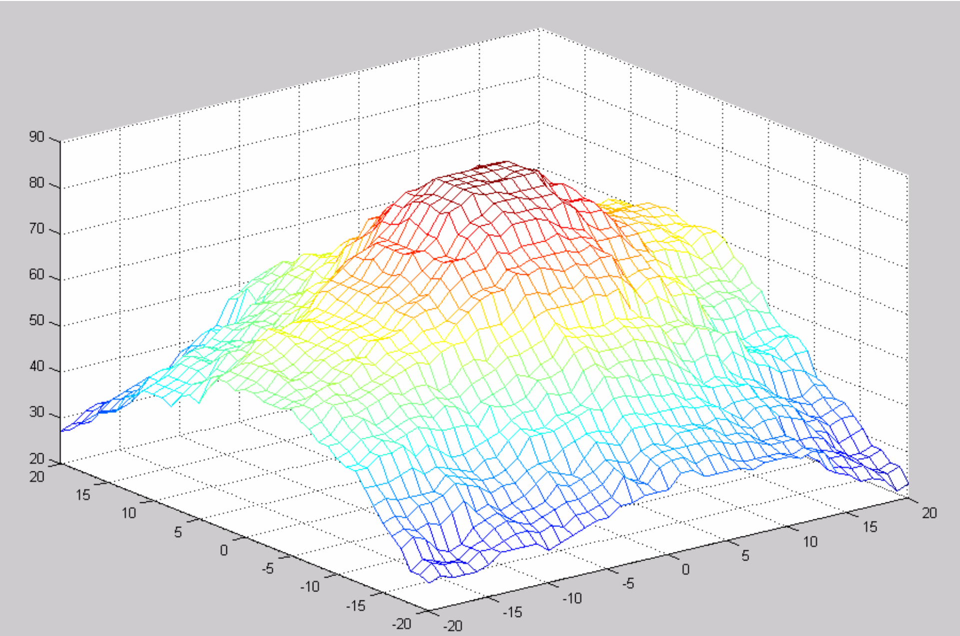

Figure 3: Offsets map

Figure 3 shows the graph of number of points vs. the shift in *x* and *y* for a given object, the units on the *xy* plane give the integer multipliers with which the offset steps (set to 25cm) were multiplied. Figure 3 shows the existence of a distinct peak that maximizes the translation between the two datasets. A bi-quadratic surface that is fitted to the "cross correlation" like map allows the determination of the optimal offset. Figure 4 shows the result of the offsets between the two datasets. As can be seen a clear and distinct offset between the two datasets can be noticed. Notice that for the two buildings that are presented here the offsets are in different direction. The result of this computation is the recording of the shift in *x* and *y* for the given building.

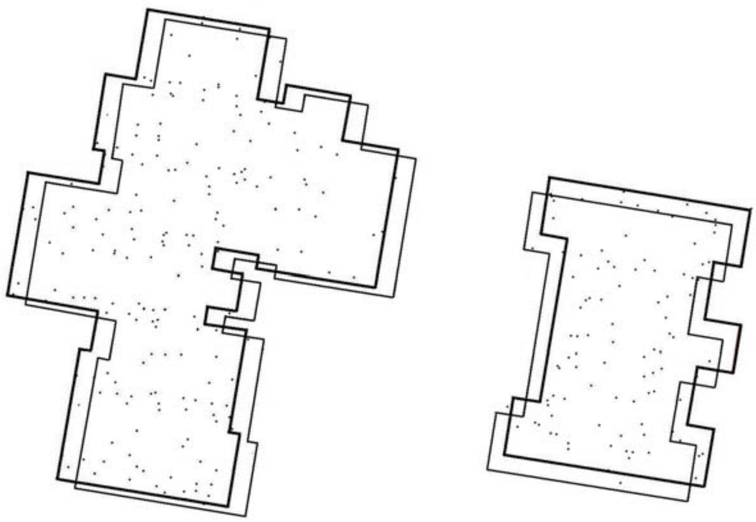

Figure 4: Offsets between the location of the cadastral buildings and their counterpart laser points

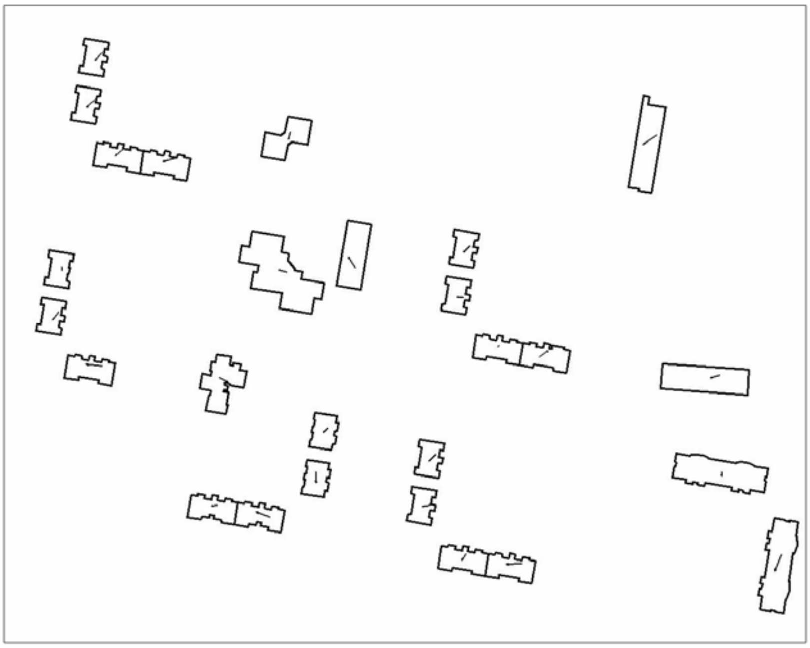

Figure 5: Offset map between the building related laser points and the cadastral building boundary

Application of the same offset computation strategy for all buildings in the cadastre leads to the creation of an offset graph for the overall area in concern. Figure 5 shows a map of the offsets as they were computed to the buildings that were given Figure 1. The offsets map the disagreements between the datasets.

4. TRANSFORMATION OF THE DATASETS

The choice of a transformation model for the registration is largely between a global model that is either conformal (shape preserving) or affine (including sheer transformation), and a local transformation. A global transformation represents a process, in which the offsets that are measured represent observations with stochastic properties. The estimation of the transformation parameters provides the best fit solution and leaves some unexplained offsets for each "observation" in the form of residuals. Consequently, the transformation will not reduce the offsets completely. With the current problem no knowledge about the deformation process that created the offsets exists and therefore an affine model is as good as any other model proposed. Furthermore, our concern here is not with finding a best fit registration but with one that minimize the offsets that were computed and consider this offset as an indication for the offsets in the nearby surrounding. Therefore, the transformation model that is chosen is a deterministic model that is based on local transformations. Observing the type of offsets in Figure 5 shows that the locally they feature consistency in direction and generally in magnitude, however, globally no consistency in the directions can be noticed.

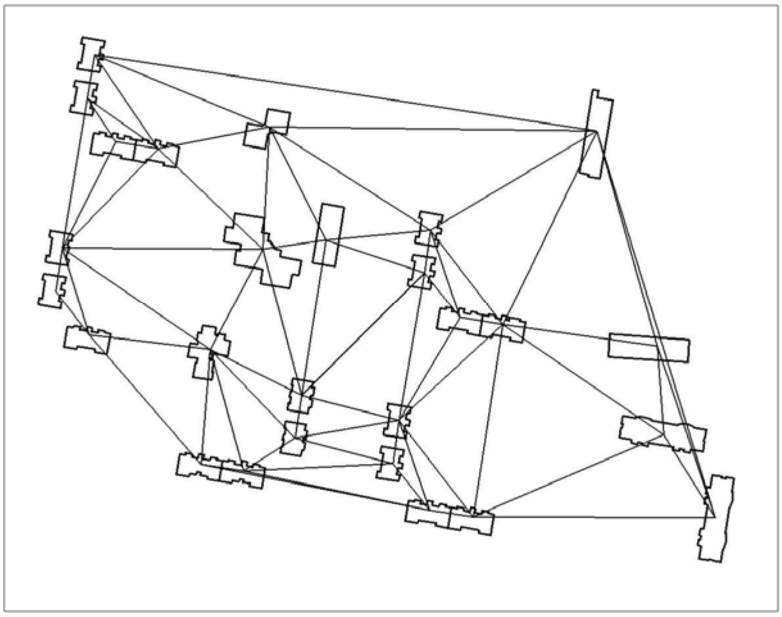

Figure 6: Triangulation formed by the centroids of the corresponding buildings

Local transformations are computed by a space partition into triangular cells. The centroids of the reference buildings serve as the nodes for the triangulation. The transformation strategy is based a Piecewise Linear Homeomorphic (PLH) transformation, known also as rubber sheeting, to transform the data in a manner wherein topological relations between objects are maintained (White and Griffin, 1985, Saalfeld, 1985).

5. RESULTS

The PLH transformation provides a mapping between the cadastre and the LiDAR datasets. It is primarily aimed at the computation of the parcel turning points transformation from the cadastre into the LiDAR reference system. Heights are determined by the computation of the triangle that contains the transformed *x*, *y* coordinates of the parcel turning point. In a similar fashion computing the height variation along the parcel boundary will be carried out by traversing the triangulation along the line defining the boundary. Heights for the above the ground sub-parcel objects are defined as the maximum height of the laser points that define the object.

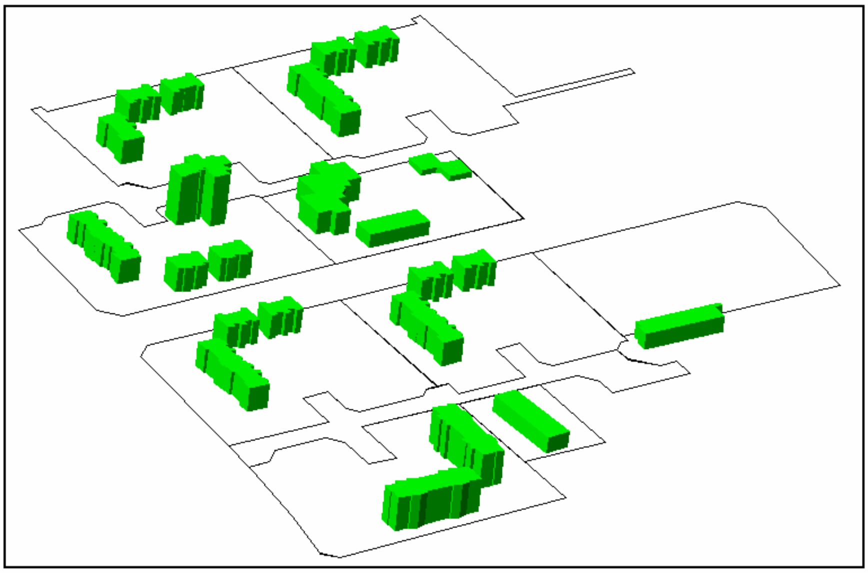

Figure 7: Integrated LiDAR data and 2D cadastre

The algorithm was applied to a sub-block consisting of 21 parcels with 27 buildings (see Figure 1). The threshold based detection algorithm has managed to detect the actual building related laser points for most of the buildings in the dataset. The detection encountered a problem with low buildings that were surrounded by trees. The simple threshold that was applied collected also tree reflected points, which in turn affected the plane fitting (see Section 2.1 - building detection). A surface segmentation model (see Filin, 2002) will manage separating vegetation from solid surfaces. The computation of the displacements revealed offsets on the order of up to 2.5 meters in position. Computation of the offsets was carried out by a "grid search" algorithm in which offsets separated by predefined intervals. The offset map is given in Figure 5 and Figure 6 shows the partition into local triangular cells. Results of the application of the algorithm are given in Figure 7. The turning points of parcels in the Figure maintain calculated height and so are the building polygons.

6. CONCLUSIONS AND FURTHER WORK

The wide land coverage that airborne laser scanning technology provides offers a very suitable mean to support the formation of a 3D cadastre for above the ground objects. The paper addressed the problem of accuracy and consistency in the registration of the two datasets. It described a fully automatic algorithm that detected and matched corresponding objects between the dataset and inserted height values into the 2D cadastre. The magnitude of the offsets manifested the need for securing the co-registration of the two datasets.

Improvement of the algorithm lies mostly in the building detection algorithm and handling of pathological cases where building size and shape in one dataset is very different than its depiction in its counterpart. Assuming that the matching of the features (now implemented in the form of translations only) should not be extended into potential scale and rotation modeling we plan to develop safeguards that will allow us to detect and eliminate such cases.

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BIOGRAPHICAL NOTES

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