URBAN 3D MODELLING USING TERRESTRIAL LASER SCANNERS

G. Boström, M. Fiocco, J.G.M Gonçalves, V. Sequeira

European Commission - Joint Research Centre I-21020 Ispra, Italy vitor.sequeira@jrc.it

Commission V, Working Group V/4

KEY WORDS: Urban, Three-dimensional, Laser scanning, Registration

ABSTRACT:

This paper describes a technique for 3D Reconstruction of large outdoor areas using terrestrial laser scanning. It presents the paradigm for automated 3D registration and requirements of the positioning and orientation subsystem to handle fully automatic 3D registrations. It analyzes the different problems and difficulties associated with such type of environments, including the analysis of scanning non-static objects (e.g. trees, persons) and other difficulties like scanning in narrow-street environments. Finally, the paper presents the results for a final triangulated model having contributions from both terrestrial scan data/images as well as aerial DSM data/images.

1. INTRODUCTION

There is a growing interest for the 3D reconstruction of large environments such as entire city centres. Applications of such models include Cultural Heritage, Cadastral Mapping, and City Planning. Previous work in this area includes (Asai et al., 2005; Iavarone and Vagners, 2003) using terrestrial laser scanners to reconstruct local areas and a few buildings. Moving vehicles equipped with laser scanners and/or cameras has been investigated by (Früh and Zakhor, 2003; Boström et al., 2004; Zhao and Shibasaki, 2003; CityGrid, 2006). This technique can cover a large area in a limited amount of time due to the moving acquisition platform. However, the accuracy can not fully compete with a fixed terrestrial laser scanner. Spatially, the moving platform technique has pro's and con's. While the scanning is always performed perpendicularly against the moving direction, this technique certainly gives a strong contribution in complex environments but the spatial resolution is very much related to the speed of acquisition hardware.

For a less detailed but more rapid reconstruction other techniques are used like LIDAR or TLS-sensor based airborne data, see work from (Gruen *et al.*, 2003). These techniques alone do not provide complete 3D models as do not acquire data from the house facades.

This paper concentrates on the paradigm for robust registration of large quantities of data on a non structured outdoor large environment. The results of the proposed technique are illustrated on the 3D reconstruction of the city centre of Verona. The objective was to perform a realistic 3D Reconstruction of the area with sub-centimeter local surface accuracy. The covered area is around 250 x 300 meters. In order to acquire this amount of data in an efficient manner a vehicle equipped with all hardware to perform rapid transfer, scanning, and storage was used.

The scanning strategy was to stop the vehicle for some minutes, acquire the local domain 3D covering range up to 53 meters as well as images together with the local position and orientation, then moving to the next suitable scanning position. This procedure should then be repeated as long as more scanning area haven't been covered.

A total amount of 63 scans have been acquired resulting in about 700 million point measurements. The total scanning time was 9 hours. The scanning was performed using a Z+F Imager 5003 Laser scanner. The position and headings were registered by GPS (Global Positioning System) and IMU (Inertial Measurement Unit) subsystems. A digital camera mounted on the scanner mechanics was used to acquire the colour images used for texturing the model.

The following section presents the proposed Paradigm for automatic scanning and processing of urban areas. This is followed by a brief description of the hardware used for the case study. The last two sections present results from an experiment with position and orientation robustness in natural scanning environments and results for a meshed and textured 3D Model.

2. PARADIGM

Ideally, we would like to perform the acquisition by some automated means; maybe by using an autonomous robot, directly sending the raw data including accurate orientation and position of the scanner device to a computer taking care of the registration of the acquired data to previously registered amount of 3D data. Thereby iteratively building the final model.

The steps involved in this concept, which denoted the automatic registration paradigm can be sketched as follows:

- 1. Define a global coordinate system.
- 2. Acquire a scan.
- 3. Retrieve the position of the acquisition system as well as the final 3 degrees of freedom by using the INS sub-system.
- 4. Pre-process the data to compute important scan information such as local surface normals, correct for holes, local point quality etc.
- 5. Compute a relative transformation relative to the global coordinate system.
- 6. Register the acquired scan onto the previous registered scans.
- 7. Attach the recently acquired and registered scan to the list of registered scans.
- 8. Acquire colour images, re-project and blend the list of images to a complete images covering the current acquisition.
- 9. Continue from p.2 as long as more further area needs to be modelled.

The above structure is applied to build a complete data-set having an accurate position and orientation registration using as little manual interaction as possible and without using any artificial markers or targets either for pre-registration or registration purposes.

In order to achieve good final results and minimise user interaction some rules have to be applied. First of all, it is wise to pay some attention to the first activity and the first scan to be defined registered. The first position should in fact be taken from a well know position e.g. covering geodetic control survey points or in case this is not possible making sure that a good quality GPS position is guaranteed. If one would blindly assume the position from the GPS subsystem to be the truth, and in fact it is not, this will lead to a constant extra shift needed for all subsequent scans being registered. The probability of a registration failure increases and for some scans this results in a too large misalignment leading to an unwanted, but necessary manual corrective action. Another, maybe yet more important aspect is the orientation acquired from the INS. The effect for an error in the heading will in fact increase as we move away from the original scan. A small orientation error of say 0.5 degrees in all 3 euler angles would result that a scan to be registered some 200 meters further along a street will be translated some 2.5 meters. Figure 1 shows the effect of a used erroneous heading when chained scan data are to be registered.



Figure 1. INS-Heading error consequence in chained scan registrations.

There is an user interaction which seems unavoidable in some cases. The activity in p.6 above, the 3D registration, fails. There can be a number of different reasons why this would happen. One would be the consequence of selecting a first scan with too low position and orientation accuracy. Other causes might be temporarily bad data being acquired from thew the GPS or INS subsystems. This is especially common in urban environments in narrow streets making it impossible to maintain a tracking of sufficient number of satellites or when facades build multiple paths for the GPS detector. Other maybe less common problems relates to the INS being sensitive to large amounts of metallic surfaces. For instance, stopping in the close vicinity of a large metal rod like a iron-cast streetlight, would probably yield a poor INS dataresponse. A last common situation for a failure of registration exists in the situation where the scanned structure consists of narrow openings such as extremely narrow passages where simply the number of data overlapping is limited.

2.1 Robust registration

The scan data acquired in a vivid urban area, at any time of the day, will contain moving "ghost" objects which do not fit into a static model. The unwanted objects such as pedestrian, vehicles and other movable structures are being modelled in one scan while in another scan they might be gone or displaced. These types of structures might affect the automatic registration binding wrong objects to one another. Another, maybe more important aspect when it comes to robust registration, is the existence of varying dense objects such as trees and bushes. Such objects will result in a quickly changing surface structure in the scan. A significant amount of this data originates from trees will be removed and being invalidated by the pre-processing step. See (Fiocco *et al.*, 2005) for a suitable pre-processing algorithm removing a large portion of these data-sets. However, there might still be some surfaces remaining from trees and other varying objects locking false point-pairs to each other.

In order to define a robust registration for large-scale urban data we propose some modifications on the well known Iterative Closest Point (ICP) algorithm and previous adaptations (Besl and Mc-Kay, 1992; Rusinkiewicz and Levoy, 2001). The modifications, further described below, are the handling of potential random variations in the scene and adaptations to the algorithm to manage large scale data-sets.

Weighting by surface normal In order to tackle the problems with trees and random objects, we have introduced a weighted version of the ICP, where the point-pair weights comes from the dot product of the local surface normals, eq. 1. The weight will, if not completely invalidating the point-pair, at least reduce the implication on the final result significantly. Figure 2a shows a scan from a busy street. The colouring of the points in the same scene, figure 2b, are based on the registration-point pair weights (black represents a weight of 0 and a white colour represents an ideal weight of 1). In the left part of the figure one can see a section of trees and to the right in the figure there is a house facade. The weight of the point-pairs in the tree section are reduced by the normal dot-product being more random, i.e. greyed in the figure, and the ground data and facade are kept with a nearly nonsuppressed weight factor due to the rigidity of these surfaces. A number of point-pairs are identified throughout the figure as black dots. These are related to temporary objects as humans and of very small objects such as lamp-posts, pillars, etc.

$$w_{i} = \begin{cases} \hat{n_{i}} \cdot \hat{n_{r}} & \hat{n_{i}} \cdot \hat{n_{r}} \ge 0\\ 0 & \hat{n_{i}} \cdot \hat{n_{r}} < 0 \end{cases}$$
(1)

Adaptive search distance In order to cope with the situation with varying pre-register quality, where some scans are very well aligned by the initial values from the GPS/INS subsystem, we have introduced a adaptive maximum search distance. This means that before the actual iterative procedure, a looping is introduced for increasing search distance. The looping starts with a minimum search distance, D_{min} , and finalizes when a pre-defined sufficient number of point-pairs have been found, N_{pp} . For each search loop we increase the current search distance by a factor of 2. For well pre-registered scans or during a second loop of already registered scans, the maximum search distance can be as low as 0.2 meters and consequently, further point-pairs are directly considered as outliers. For other scans, having rather un-accurate pre-registration values, the search distance can reach a pre-defined maximum search distance, D_{max} . Typical values which we are using in our search for optimum search distance is, $D_{min} = 0.1, D_{max} = 4$ and $N_{pp} = 25\%$ of total reference points.

Initial flexibility in search distance During the initial iterations of the ICP registration, we allow the search distance to slightly increase from its initial value. This makes it possible to further bring in point-pairs which were almost unaccounted for in the previously mentioned adaptive search distance optimization. This increase in search distance allows for rather badly aligned scans to be registered since the search opens up for rather distant point-pairs. However, there are 2 important sub-rules which makes the iteration not to hit local minimums. 1). The increase in search can never exceed a certain pre-defined largest allowed search distance. 2). The increase in search distance in the iterative procedure is only accepted for the first iterations.



(a) One reference scan with colour



(b) Corresponding point-pairs in registration with weight colour

Figure 2. A scan registration position shown with two different colouring. Trees and other minor details are suppressed (grey or black in weights image).

Management of large quantities of data In order to automate the registration of a sequence of scans we have defined a strategy for the progression of registering all input scan data. If the registration succeeds based on some criteria, this scan is added to an ever increasing group of registered scans. As the number of registered scans increase, the amount of data to be managed increases. There are two selection mechanisms which optimizes the points needed for a robust registration. The first mechanism relates to the selection of contributing registered scans and the second relates to suitable sub-sampling. As a new scan is to be registered, we select the scans potentially contributing to the scan registration by selecting, based on bounding-box extension, here defined as \Box_i for the ith scan, the sum of the already registered scans cut with the scan bounding box to be registered, \Box_s . Finally, we get the bounding box to be used in the registration, \Box_{reg} . All scans intersecting this box will partly contribute to an as good registration as possible. This procedure is described in eq. 2. Figure 3 shows a scan bounding-box to be registered in green, each scan bounding-box in the vicinity coloured red and black. The scan bounding boxes contributing to the registration, i.e. having an existing area in the registration bounding box are coloured red. The final search bounding box are composed of the union of all part boxes. This bounding box is shown in blue.

$$\Box_{reg} = \bigcup \sum_{i} \left(\Box_i \cap \Box_s \right) \tag{2}$$

The second mechanism to manage large quantities of data relates to the selection of sub-sampling. If the scan acquisition is dense in a specific area, we may have a large amount of registered scans all assumed to be contribute to the best possible registration of a scan. The laser scanner hardware currently on the market can easily produce very dense point clouds where each scan has some 50 million points. If we have some 5 contributing scans in a registration, clearly, not all of these 250 million points can be con-



Figure 3. Bounding boxes of scans. Scan to be registered (green), contributing scans to the registration (red) and the final registration bounding box (hashed blue).

sidered. Our approach is to define a maximum number of contributing reference points and by counting the number of points that remains in the registration bounding box, \Box_{reg} , we can select a sub-sampling for each scan which randomly picks scan points in the bounding box evenly from all participating scans. Typical values for the maximum number of scan points to be considered lay in the range of 10-100 million points.

3. ACQUISITION HARDWARE

For the case study presented in the paper, we have used a vehicle equipped with all the necessary devices to scan and at the same time acquire the scanning position and orientation in world coordinates (see figure 4). Apart from the accurate laser scanner, we have used a Real-Time-Kinematics GPS (RTK-GPS). This device is able to produce centimeter resolution position accuracy in ideal situations in connection to a RTK-based reference station. We have used a connection between the rover on the vehicle and a fixed station infrastructure provided by the city.

In order to predict the attitude, roll & heading for the scanning hardware, an INS has been used. The INS has an input for a GPS-antenna in order to feed an internal filter-processor with position estimates. However, for these experiments, the INS subsystem was working in a 3-axis mode.

In order to acquire accurate colour photos of the scanned scenario, we have used a digital colour camera mounted on the laser scanner hardware which made it possible to acquire images covering fully 360 horizontal degrees.

All the peripheral components were attached to a portable computer for automatic operation. The movable scanning platform was battery supported to cope with 9 hours of continuous scanning.

4. RESULTS

4.1 Data acquisition

During a 9 hour scanning session, a total number of 63 scans were acquired around the city centre of Verona. The area covered contains many old houses and historical structures. In many places, the street-width was as low as 5 meters while the facades



Figure 4. Laser acquisition hardware.

exceeded 10 meters in height. In these situation, the GPS quality significantly becomes reduced due to a low visibility towards the satellites. Clearly, some scan acquisition would suffer from the this fact. The positions that were used for scanning can be seen as small coordinate axis in figure 5. The axis show the vehicle orientation during acquisition.



Figure 5. Capture points and vehicle orientation shown as small coordinate axis on the global aerial model.

4.2 Perturbation analysis

In this section an analysis is performed regarding the stability for natural variations in accuracy of used GPS/INS subsystem. Especially in urban areas, one sometimes must accept less-qualitative GPS position-readings. The error-sources are ranging from limited visibility towards the upper hemisphere resulting in a limited number of satellites being tracked. Another source of introduced errors is multipaths which occur for signals bouncing on facades or other vertical objects.

By running the same sequence of registrations, continuously building the registered scan group, the scan to be registered was perturbed from its ideal registered position. By changing the perturbation both for rotation and/or translations in different steps, it was possible to generate a result matrix with conclusions about the allowed variation in position and inclination accuracy.

In table 1 we can see the perturbations that have been introduced.

R[deg]	0	2	4
T [m]			
0	100%	100%	80%
0.1	100%	97%	94%
0.2	100%	100%	80%
0.4	100%	100%	94%
0.8	94%	89%	77%
1.6	77%	80%	71%
3.2	60%	57%	54%

Table 1. Registration success rate as a function of perturbation in position and orientation.



Figure 6. Registration success rate as a function of perturbation in position and orientation

In the horizontal direction, the maximum rotational perturbation, R, affecting all three rotation directions with a random value within the limits. In the vertical direction, a random translational perturbation, T, was introduced affecting all 3 axis. The values represent the percentage of successful registrations when the perturbation was applied to a subset of 35 scans. As it can be seen, the success-rate declines as larger perturbations are applied. Figure 6 shows the same information graphically. Along the X-axis, we have the translational disturbance and the 3 histogram graphs represent 0, 2 and 4 degrees of perturbation respectively.

In order to generate a simulated effect of a sequential registration process, something needed to be done with failed registrations. Consequently, when this happens due to either difficult scanning situations and/or bad automatic pre-registrations from noisy GPS/INS values, a manual interaction is needed. In order to take care of these situations, an ideal transformation was applied to all scans that failed in order for the sequential registration to be able to continue. For successful registrations however, the found transformation was used for further sequential scans. The conclusions from this study can be summarized as follows:

- The registration process is rather sensitive to rotational disturbances. The reason for this is most likely that our scan data is rather complex, not having a distinct isolated surface, rather a large amount of part surfaces residing from facades, vehicles, trees, fountains and other naturally varying objects.
- The registration copes with rather large disturbances for the position accuracy provided that the rotational error is low. However, based on the operation of the INS which only uses the Earth magnetic field, one would need to accept some degrees of deviation.
- For an overall automatic success-rate of some 90%, we need a GPS/INS subsystems that work with angular error of less than 2 degrees at the same time as the GPS having a position error of less than 0.5 meters.



Figure 7. Ghost surfaces, marked yellow, comes from the lightmodulated phase shift measurement technique (the origin of the scan is under the white arch).



Figure 8. Acquired high-resolution texture over the area from airborne scanning

4.3 Meshing

Typical laser range scans from outdoor environments come with a lot of noise and bad measurements. Random noisy measurements are sometimes detected in open air due to either particles in the sky or random noise in the scanner detector system. An operation of filtering low reflectance values and mixed points removes most of the unwanted ghost points. Nevertheless, some manual editing is regularly necessary to remove and clean points that are still considered "real" after filtering.

One example of this type of effect can be seen in figure 7, where the yellow part close to the arch in the center of the image relates to the limitations of the scanning technique. Here, the detector has been able to acquire information from more than, $r_{max} = 53m$, which is the max distance of the scanner. Consequently, this measurements are being folded into the valid distance range, $r_{ghost} = r_{true} - r_{max}$, due to the used phase-measurement technique.

The terrestrial scans have been meshed with a multi-resolution triangulation of the range surface as described by (Sequeira *et al.*,



Figure 9. DSM meshed with a uniform triangulation technique, with automatic filtered triangles over discontinuities.



Figure 10. Final Triangulated model showing the ancient Arena and the front of the "Palazzo Barbieri"

1999). The texture is generated from the re-projection of 7 overlapping photos on each individual scan.

The facade triangulated model based on the registered terrestrial scans were combined with a triangulated aerial DSM resulting in a photo realistic and geometrically accurate 3D model. The aerial DSM was acquired with a LIDAR.

Figure 8 shows the aerial photo and figure 9 the triangulated aerial DSM together with the surface texture. The aerial scan was combined with the registered group of the 63 scans. The result as can be seen in figures 10 and 11 show a well registered city centre with natural colouring. The lower part of figure 11 shows some holes where no data was available and some star-shaped effects due to occlusions from construction barriers close to the scanning-position.

The final model is based on 9 million triangles and 64 texture images each having a resolution of 2549x1083 pixels. Figure 12 shows a detail of the model from the Arena.

5. CONCLUSIONS AND FUTURE WORK

This paper proposes an applied scan and registration paradigm for large terrestrial laser scanning projects. It details the procedure for a successful scan operation followed by a procedure for automatic scan registration without using any artificial targets. The proposed adaptation to the registration technique have proved to



Figure 11. Final Triangulated model from another viewpoint, showing the entire Colosseum-like Arena



Figure 12. Detail of the model covering one of the entrances of the Arena.

be more robust than the standard techniques when applied in natural urban environments.

An analysis of the robustness of the registration operation for laser based terrestrial scans has been performed. The effect of using an automatic pre-registration based on the readings from the GPS/INS subsystems was shown to give a very positive contribution for an automatic overall registration process. This is valid provided that the accuracy of the position and heading lies within roughly 0.5 meters and 2 degrees respectively.

The techniques for scanning and registration have been applied to 63 scans. A facade triangulated model based on the registered scans was constructed and combined with an triangulated aerial DSM resulting in a photo realistic and geometrically accurate 3D model.

Current work concentrates on the further analysis of the automated registration paradigm, including speed optimization. Regarding the final 3D modelling, efforts focus on enhanced filtering including noise detection, ghost data removal and better closing of eventual gaps.

ACKNOWLEDGEMENTS

The scanning in Verona was performed during daytime. Most of scan positions are in pedestrian areas and normally not accessible by a vehicle. The authors would like to thank the Comune di Verona for all the kind support and allowance to perform the scans in the limited access areas. Also, we are grateful for the assistance with the GPS data acquisition provided by Prof. Vassena and his group from University of Brescia, Italy. Finally, we would like to thank the Compagnia Generale Ripresearee S.p.A, Parma Italy, for providing us with aerial data and images.

REFERENCES

Asai, T., Kanbara, M., and Yokoya, N., 2005. 3d modeling of outdoor scenes by integrating stop-and-go and continuous scanning of rangefinder. In 3D-ARCH'2005: 3D Virtual Reconstruction and Visualization of Complex Architectures.

Besl, P. J. and Mc-Kay, N. D., 1992. A method for registrationpf 3d shapes. *IEEE Transactions on PAttern analysis and Machine Intelligence* 14(2).

Boström, G., Fiocco, M., Puig, D., Rossini, A., Gonçalves, J. G., and Sequeira, V., 2004. Acquisition, modelling and rendering of very large urban environments. In *Proc. of Second International Symposium on 3D Data Processing, Visualization and Transmission.*

CityGrid, 2006. http://www.citygrid.at/ (accessed 14 July 2006).

Fiocco, M., Bostrm, G., Gonalves, J. G., and Sequeira, V., Ottawa Canada, 2005. Multisensor fusion for volumetric reconstruction of large outdoor areas. In *Proc. of the 5th IEEE International Conference on 3-D Digital Imaging and Modeling*.

Früh, C. and Zakhor, A., 2003. Constructing 3d city models by merging ground-based and airborne views. *Special Issue of IEEE Computer Graphics and applications*, 52–61.

Gruen, A., Li, Z., and Wang, X., 2003. 3d city modeling with tls (threeline scanner) data. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Volume XXXIV-5/W10.

Iavarone, A. and Vagners, D., 2003. Sensor fusion: Generating 3d by combining airborne and tripod-mounted lidar data. In *3D-ARCH: 3D Virtual Reconstruction and Visualization of Complex Architectures*.

Rusinkiewicz, S. and Levoy, M., 2001. Efficient variants of the ICP algorithm. In *Proceedings of the Third Intl. Conf. on 3D Digital Imaging and Modeling*, pp. 145–152.

Sequeira, V., Ng, K., Wolfart, E., Gonalves, J., and Hogg, D., 1999. Automated reconstruction of 3d models from real environments. *ISPRS Journal of Photogrammetry and Remote Sensing, Elsevier* 54.

Zhao, H. and Shibasaki, R., 2003. A vehicle-borne urban 3-d acquisition system using single-row laser range scanners. *IEEE Transactions on Systems, Man and Cybernetics, Part B* 33(4), 658–666.