DIGITAL TERRAIN MODELS IN DENSE URBAN AREAS

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ABSTRACT

In this paper we consider the problem of DTM extraction in dense urban areas. To this aim, we need valuable and reliable data in the tiny open areas among buildings, and a suitable algorithm to reconstruct the terrain discarding these same structures. So, we compare first LIDAR and aerial photogrammetry by evaluating the relative accuracy of the three-dimensional reconstructed surface in the small open areas in the town center. Then, we characterize the digital terrain model (DTM) of the whole town using a filtering and building detection approach. It comes out, as expected, that the best filter width depends on the terrain and built structure characteristics, and we show that, after training on test areas comprising all possible combination, it is possible to obtain highly precision DTMs filling the built areas with surrounding terrain without significantly affecting the open areas.

1 INTRODUCTION

Historical centres in European Towns are often crowded with buildings, grouped in small or large blocks and separated by very narrow roads. This situation provides a formidable challenge to Digital Terrain Model extraction tools, both automatic and semi-automatic. Indeed, in this area we have bunches of points only in a few parts of the area, and the definition of the digital terrain model (DTM) should be considered by interpolation or substitution techniques. This, in turn, requires that these points must be detected with extreme precision in the 3D space to provide a sufficient basis for the extraction of the surrounding areas.

Usually these points can be retrieved by using automatic or semi-automatic photogrammetric tools, and, recently, by LIDAR systems. Current laser ranging systems allow measuring terrain points at approximately one point each 0.5 x 0.5 m^2 and a vertical accuracy in the order of 0.3 m and are therefore suitable for this task.

A first aim of this work is to make a quantitative evaluation in a dense urban area of the two techniques, (LIDAR and aerial photogrammetry) by computing the relative accuracy of the three-dimensional reconstructed surface in the small open areas of a dense town center.

A different but related problem of the LIDAR approach is that you need to restrict your measurements to the true terrain areas to retrieve DTM from DSM. In some sense this problem is similar to the extraction of the soil in forested areas. Indeed, the histogram technique introduced in [1] and the algorithm used in [2] are very similar in the concept, assuming that on an area of a "reasonable extension", ground points and tree/building points constitute two disjoint sets and these two sets are characterized by significantly different values of the average height. The problem is the dimension of the "reasonable extension", which heavily depends on the structure of the forest (or the city center).

The second part of this paper is devoted to the definition of a strategy to understand which is this "reasonable dimension" in a urban environment, and if it is possible to adopt a strategy to choose the parameters of a terrain point extraction procedure similar to the one discussed in [1].

2 DATA SET AND DTM EXTRACTION ALGORITHMS

For this work, a LIDAR data set has been acquired on the town of Pavia and its immediate neighbourhood in mid-November 1999 with the Toposys sensor, produced and operated by the German company Toposys, installed on a plane of an Italian company called CGR, Compagnia Generale Ripreseaeree. The flight height was around 850 meters (with the exception of two cross stripes, flight at halved height); the Toposys sensor is able to acquire, flying at that height, approximately five points per square meter, so that the one-meter grid which is usually delivered to the customers, and that we used, can be calculated with a good reliability. Up to now the Toposys instrument isn't able to measure the reflected signal intensity, so it gives pure geometric data and it can acquire first pulse or last pulse alternatively. Therefore, to test all the operational capabilities of the sensor, three different acquisitions have been performed: they are shown in Table 1. The German company delivered to us the gridded data, with 1 meter cells, as well as the so called raw data, that is, sparse points measured by the sensor. Aerial photogrammetric images were acquired during the same flight and scanned at 1200 dpi resolution, allowing a scale ratio of 1/5600 and a ground pixel size of 12 cm.

On the same area we were able to provide a large number of Ground Control Points (GCPs), in many test areas. So, we were also able to make a quantitative evaluation of the original DSM as well as the DTM extracted. This, in turn, allowed us to compute the *systematic* and *random* elevation errors ($\bar{z}$ and σ_z) and determine how the range of the input parameters of each DTM extraction algorithm could be related to the topographic characteristics of the terrain. To this aim, GCPs must be computed with extreme precision: on our test areas they were measured by means of differential GPS techniques or manual photogrammetric analysis by an expert operator.

We individuated four test areas, each covering a 400 x 400 pixel square (corresponding to 160000 m^2), shown in figure 1. In test areas (1) and (2) reference data were obtained by GPS techniques and belong to topologically flat structures, like tennis or basketball courts. In particular, the first area contains the playground near the college called "Collegio Borromeo", the second one is situated near the railway station of Pavia Porta Garibaldi. Ground control points for test areas (3) and (4) were obtained by means of photogrammetric techniques and refer to a small bay in the Northern bank of the river at the border of the town and the central area near Piazza della Vittoria, respectively. All these test areas were selected following two criteria. First of all, the availability of measurements to compare with, but also the capability to cover all the topographic features which are present in the area, from residential to industrial to central areas of the town, as well as artificial or natural features of the ground. By this choice, we were able to test the DTMs in different situations of terrain topography as well as building densities. In section 4 we will evaluate only test areas (1) and (4), due to the limited space.

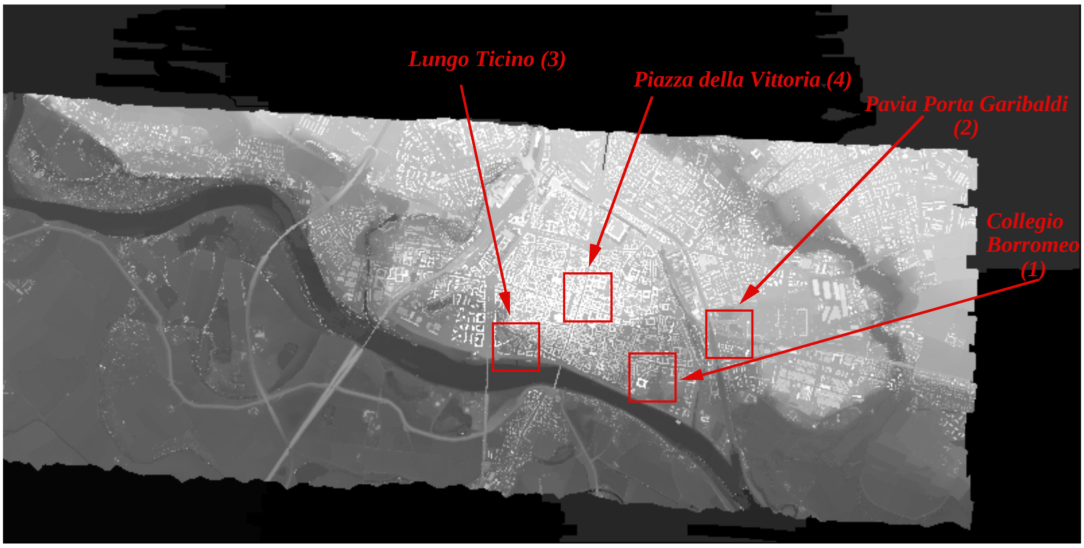

Figure 1: A bidimensional representation of the LIDAR data set over the town of Pavia, Northern Italy. The squares represent the four test area used to train the DTM extraction algorithms in this research.

	T_1	T_2	T_3
Points measured in a second	80000	80000	80000
Scan lines acquired in a second	625	625	625
Acquisition mode	LP	FP	LP
Flight height	850 m	850 m	400 m
Plane speed	70 m s-1	70 m s-1	70 m s-1
Scan semiangle	7°	7°	7°
Scan line length	209 m	209 m	98 m
Distance between two points on the same line	1.66 m	1.66 m	0.78 m
Distance between homologous points belonging to two consecutive lines	0.11 m	0.11 m	0.11 m
Average density (points per square meter)	5.47	5.47	11.63

Table 1: Main parameters of the laser flights over Pavia.

As for the algorithms, we considered two different approaches to extract DTM from the original LIDAR data. They are based on three-dimensional data filtering by means of convolutional or morphological kernels (Lohman *et al.*, 2000). The workflow of these algorithms requires a first DTM estimate by means of a low pass or a morphological filter. Buildings are then individuated by thresholding the difference between the original DSM and the estimated DTM. Then the built areas are extracted and filled in the original digital surface model (DSM) using the mean height value around them or the first DTM estimate (in the low-pass and morphological case, respectively). Finally, the large buildings are extracted using the histogram technique in Hug and Wehr, 1997, where the height histogram is computed and the highest peak is associated to these structures, provided that their area is sufficiently large to justify their survival to the first processing step. To correctly apply the procedure, we need to know the kernel size that reduces as much as possible the DTM errors with respect to GCPs. Moreover, it turns out that the histogram techniques is extremely sensible to the window size where the heights are considered, and that it is difficult to define an unique size if a very rugged terrain is considered. Moreover, it is necessary to observe that, when we have buildings near steep terrain areas, the results of the histogram technique depend on the kernel size used for the first part of the procedures. Since each kernel has a different smoothing effect, this might produce an apparently similar histogram, where the threshold computed using the technique in Hug and Wehr, 1997, is actually slightly different.

So, even this very short outline of the algorithms highlights he need to provide some hints on the input parameters of the filtering procedure, as well as the dimension of the areas used to discriminate between terrain and buildings in the histogram approach. This point has been studied, for instance, in Morgan and Tempfli, 2000, where adaptive filtering has been conceived, with a morphological approach using a window whose width is ruled by sloping parameters. However, the window size and the so called "height bandwidth" in this algorithm have still to be decided from a priori knowledge of the area. What we want to discuss in this paper is if we can test the parameter choice in a few test areas and apply this values to the overall urban area.

3 LIDAR AND PHOTOGRAMMETRIC DTM COMPARISON IN SELECTED AREAS

As mentioned in the introduction, the need to provide accurate terrain height in open areas inside built area and especially city centres requires first an evaluation in selected parts of out data set of the relative accuracy of the LIDAR data with respect to the above mentioned photogrammetric DEM.

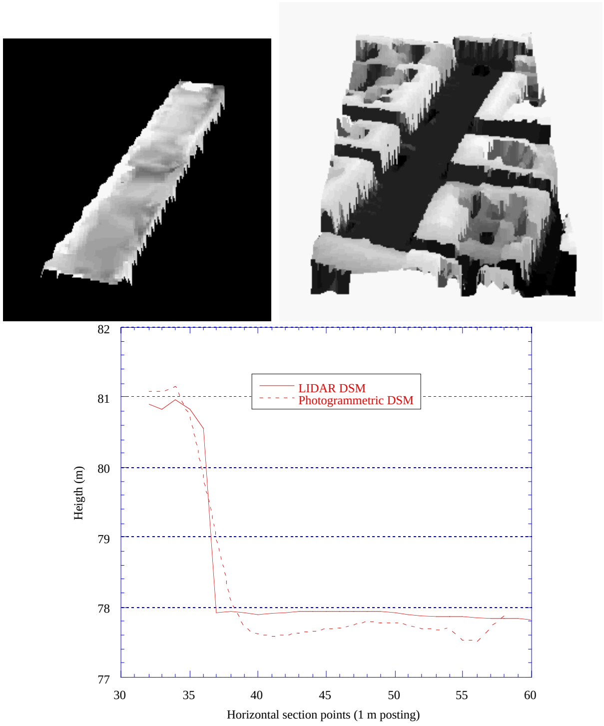

Figure.2: 3D view (on top) of the Photogrammetric and LIDAR DSM of the part of Piazza della Vittoria, where control points by analytical photogrammetry were available. Lower graph is a horizontal section of both DSMs for quantitative comparison.

Their high accuracy and reliability make the heights of the manually extracted photogrammetric points very useful as ground truth values for the LIDAR DTM. However, it is also evident that no suitable data set of GCPs will be available by photogrammetric techniques in a reasonable time, because analytical photogrammetry is a manual operation. Moreover, geometric problems due to the limited terrain areas visible in stereo views in urban zones where buildings are very dense prevent this approach to be effective other than to provide accurate reference for control points.

4 DTM EXTRACTION IN TEST AREAS

Before discussing how the DTM extraction procedures should be tuned to provide the best results in the test area, it is useful to anticipate part of the problems we will see in the results. This in order to explain the criteria used to test the algorithms in the selected areas. Sometimes, in the following graphs we will see that the altimetric values of the DTMs *inside* the building are different from those *outside* it. The causes for such behaviour are many and different. For instance, if the values inside are higher than outside, this could be due to a wrong width dimension for the filtering window, or to the variability of the terrain surrounding the structure. In some cases, this is also due to parts of the buildings at different (lower) height than the major built structure, with a non-negligible area, like terraces or porches.

Therefore, as a general rule to understand if the DTM extraction procedure has been truly successful, we will consider not only the ground control points presented in the previous section. We will also take into account a more qualitative but surely interesting approach, looking at DTM sections and

A detailed analysis of the relative strengths and drawbacks of the two techniques have been already considered for extra-urban areas in *Casella et al.*, 2001, where a section of the main embankment of the river Ticino South-West of the town has been extensively studied. The conclusions were that a skilled and trained operator is able to reconstruct DTM geometry by using stereo pairs with a similar (or even superior) accuracy than the LIDAR instruments. However, the time required is extremely limiting with respect to the point number that could be made available. On the other hand, automatic extraction of photogrammetric DTM by commercial software fails in characterizing the true terrain slope, with mean absolute deviation still more than 1 meter in the best case.

We want to provide here a similar discussion for a selected area inside the city centre, where we were able to extract a sufficiently reliable photogrammetric DTM. In figure 2 we provide a 3D view and a section of a part of Piazza della Vittoria as it can be seen using the original LIDAR and the photogrammetric DSM. We note that the two DTMs are very similar as for the capability to characterize the flat square terrain, and the systematic error (nearly 20 cm) and the small random error are both evident.

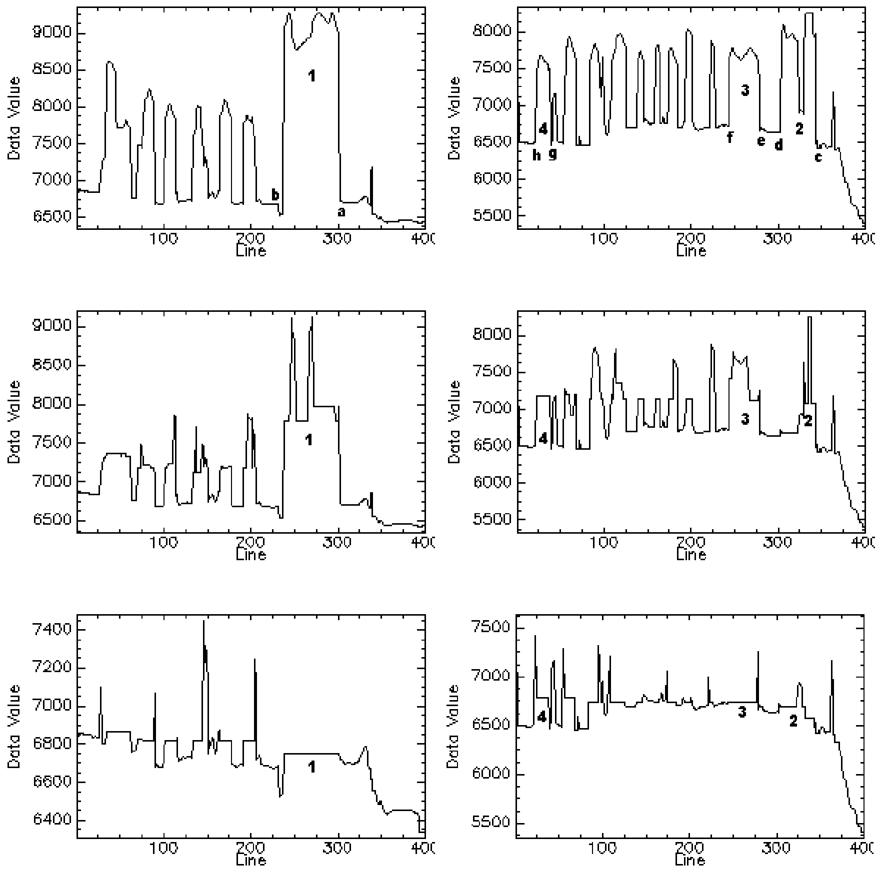

Figure 4 : From top to bottom: sections Y1 and Y2 in the initial DSM, and after low-pass filtering with a kernel size of 10 and 100 m, respectively.

evaluating how the terrain profile matches our request to have transactions as smooth as possible between non-built and built areas in the same zone.

Figure.3: The raster map (on the left) and a bidimensional representation of the LIDAR height values (on the right) for the test area near the Collegio Borromeo.

4.1 First test area (Borromeo): flat terrain with large/ sparse buildings

As already said, the first test area is located near the University College called "Collegio Borromeo", whose green park is visible in figure 2 in the lower part of the images. In the same figure we show on the right a bidimensional representation of the LIDAR data (lighter areas correspond to higher elevation values, as usual). On the left, instead, there is the same part of the town as it is represented on the raster map of the town of Pavia (1:2000 scale). In the same figure we have highlighted the playground where the ground control points were recorded during the GPS measurement campaign, while the two green lines correspond to the sections that we will consider in the following to compare the DTM estimate inside and outside the buildings. Section denoted as "Y1" give us information on the college building and the GCP test area. Section "Y2", instead depicts more densely placed buildings at the left in the figure. Note that, beyond the control zone the main structure of the college is the nearly square building at the lower left, with a large internal ground.

As a first note, we should consider that the original LIDAR DSM provides for this area a min-max difference around 5 meters. So, we may label this test area as a "flat area with large/sparse buildings".

Then, we need to consider the difference between the original LIDAR data and the GPS control points. The systematic and random errors for this set are $\bar{z}$ = 31.5000 cm and σ_z = 2.3452 cm, respectively. Since the algorithms used for DTM extraction aim at labelling building structures without changing the laser estimates on the "natural" terrain surface, these values are exactly the same also for the DTM, for any window width and any filtering choice. Indeed, the GCPs are on a flat playground, and no change in this area is expected between the DSM and the DTM. However, as we will see in a moment, there is a further processing step that we need, to complete the DTM procedure, which has the disadvantage to change the original elevation data.

So, this step does not give us any hint on the investigated matter. Still, it gives us a strong validation results, because we can compare the error values with those found in Casella, 2001 which is an extensive evaluation of the laser scanning precision on the same data set. In that work, the author finds that the systematic error should be placed in the range between 25 and 30 cm, while random error is around 5 cm. We should note that the values presented in the previous paragraph are extremely similar as for the systematic error, but they seem better for the random part. However, this is an effect of the fact that GCPs are, in this test, very near one to the other, and differential GPS allows better reducing the random error in elevation measurements.

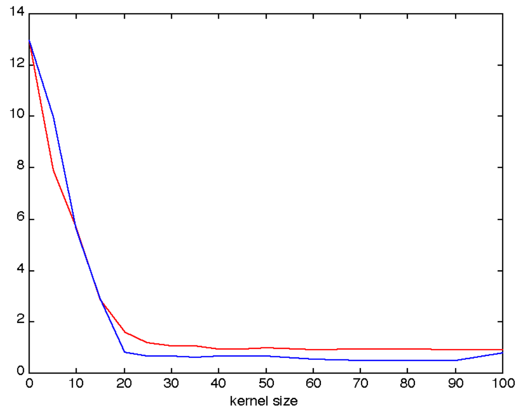

Figure 5: Mean square error between the elevation data *inside* and *outside* the buildings, computed using the data in section Y1, with respect to the filtering window width (in meters). Lower values at higher kernel sizes for morphological DTM.

Now, even if filtering does not affect the playground area, it changes the results in the building area. In figure 4 we show sections Y1 and Y2 (on the left and the right, respectively) in the original DSM as well as in two DTMs obtained with a low-pass filter and different window width (10 and 100 pixels, corresponding to 10 and 100 m). The numbers in the sections help identifying the different buildings (number 1 is the Collegio Borromeo). The letters in the first row sections, instead, correspond to point just outside the buildings (not changed by the DTM extraction procedures). In section Y1 the

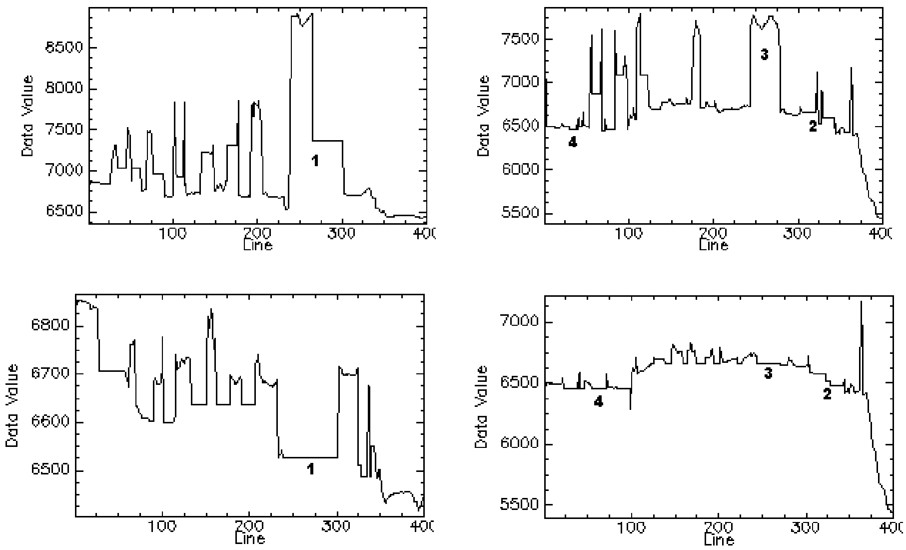

Figure 6: From top to bottom: sections Y1 and Y2 after morphological filtering with a kernel size of 10 and 100 m, respectively.

playground area correspond to the flat portion line numbers between 350 and 400.

Looking at this figure, we may first note that there are points where in both DTMs it is evident an error, or at least a different elevation value with respect to what expected (for instance, the two peaks over object #1). This situation could be labelled as “noise” and will be considered in next paragraphs. The second consideration refers to the low-pass filter window width. No doubt that the second choice (a larger width) corresponds to better results. To have a quantitative evaluation of this effect, we computed the mean value of the terrain around each structure, and compared it with the mean value inside the same structure. This is, as already discussed, a different but equally valuable way to discriminate between effective and useless DTM results. In particular, the mean value of the terrain height in the points characterized by a letter is compared with the mean elevation value of the points referring to a structure (i.e. numbers in the sections of figure 3), and the mean square difference is given as a numerical value of this assessment process. The graph in figure 4 represents this error as a function of the window width (called from now on *kernel size*). Since the result shown in figure 3 for the low-pass procedure is valid also for morphological filtering, we report in figure 5 both mean square differences. It is interesting to note that the behaviour is similar, and that for both approaches an unbearable change is obtained with kernel size lower than 20 m. More in detail, the error is 108 cm for a kernel size of 25 m, while it lowers to 95 cm for a kernel size greater or equal to 40 m. Using morphological filtering, instead, we obtain an error of 82 cm already with a kernel size of 20 m.

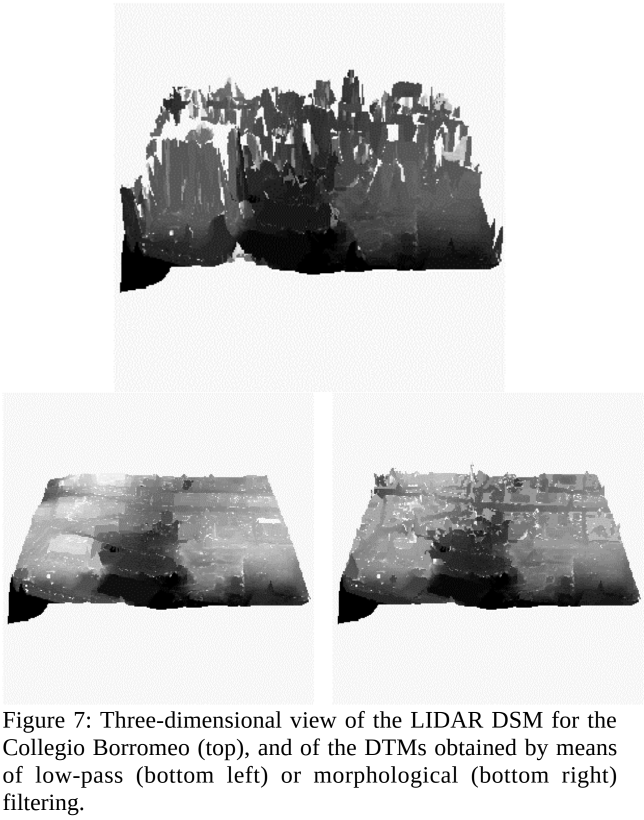

Figure 7: Three-dimensional view of the LIDAR DSM for the Collegio Borromeo (top), and of the DTMs obtained by means of low-pass (bottom left) or morphological (bottom right) filtering.

In figure 6 we show the DTM results for sections Y1 and Y2 using the morphological approach. By comparing figure 6 and 4 we should say that the former provides a smoother terrain inside the building structures (this is more evident looking at Collegio Borromeo and to building #4 in section Y2), confirming the graph in figure 5.

So, as a final statement for this point, the best achievable DTM seems to be the one with kernel size higher than 40 m for low-pass filtering and 25 m for morphological filtering. This means, by the way, that there is no simple relationship between the mean building area and the filtering window width. At least, this strongly depends on the filtering approach.

Finally, in figure 7 we show the original DSM and the DTMs obtained by means of low-pass filtering (kernel size = 100 m) or morphological filtering (kernel size = 25 m). It is evident that the building extraction software works better with larger filtering width, and therefore buildings are individuated and removed in the left image better than in the right one.

In other words, the two different DTMs present different advantages and drawbacks. The low-pass one has a larger number of “noisy parts” and a better characterization of the built structure, especially on their borders. The morphological DTM, instead, shows less local problem but also a lower definition of the built areas. Therefore, both models need a further refinement, as already noted.

The “noise” problem is related to small parts of the buildings or vegetation that have not been discarded by the previous steps. As already noted, this is indeed the case for complex structures and should be corrected. Therefore, we implemented a final low-pass filtering step on the first DTM approximation, with a window size that now should be investigated in order to change as few as possible the terrain parts untouched by the previous processing steps. To individuate the optimal kernel size, we computed the systematic and random error $\bar{z}$ and σ_z, as a function of the kernel size (figure 8).

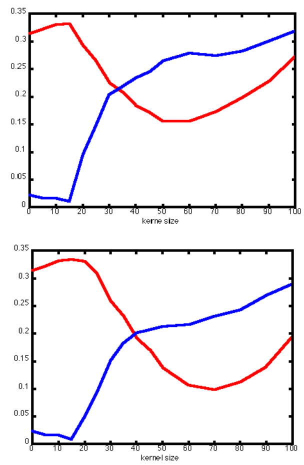

Figure 8: The absolute value of $\bar{z}$ (decreasing curves) and σ_z (increasing curves) after the final low-pass filtering step applied to the first DTM approximation in figure 7 as a function of the kernel size. The upper graph refers to low-pass DTM, the lower one to morphological DTM.

The behaviours in figure 8 are very similar for both DTMs, as expected. In particular, the absolute value of $\bar{z}$ tends to increase with larger kernel sizes, because the effect of small noisy area expands to the surrounding terrain. Instead, σ_z almost constantly decreases because of the smoothing effect of the filter. In both images the best value to reduce the systematic error is around 15 m, while for random errors the best range is between 50 and 70 meters. The two curves intersects somewhere in the middle of the 20÷40 range, suggesting that the best compromise for both error measures is 30 meters.

Applying this choice, we obtain the final DTMs, shown in figure 9.

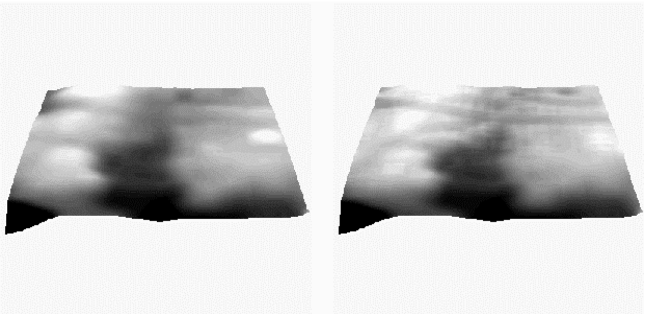

Figure 9: Final DTMs, after the final low-pass filtering with kernel size of 30 m.

3.2 Fourth test area (Piazza della Vittoria): city center

One more test area to be considered is a part of the city center, crowded with buildings and with small, short streets bordering building blocks. We focus on the main square of the old town and the surrounding built structures.

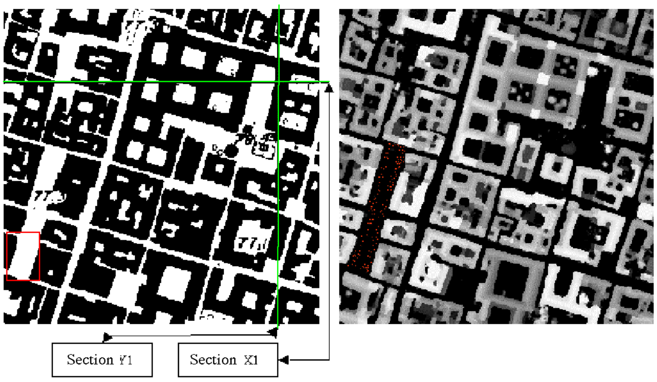

Figure 10: Raster map and LIDAR DSM of the 4th test area.

In figure 10 we show the map and the LIDAR DSM of this area, together with the locations of sections X1 and Y1, which are used to characterize building profiles after the DTM extraction. Moreover, we have highlighted the area where the GCPs have been measured. The points have been characterized by means of photogrammetric techniques, since their location do not allow to provide GPS measurements with sufficient reliability, due to the building surrounding the square.

A first analysis of the DSM height values in the area provides a max-min difference of about 8 m, due to the presence of the buildings. Indeed, this is a flat area, with no terrain slope. As for the section analysis, we should note that in this dense urban area the best result is obtained by means of the morphological filtering approach, while the low-pass technique provides an overestimate of the terrain inside the buildings, due to the insufficient smoothing effect of the filter. Indeed, partially covered, internal courts, whose effect is evident in the sections in figure 11, characterize the buildings. These parts are not easily evaluated by means of the histogram technique, if the first DTM approximation maintains information on the built structures. This effect is larger with low-pass than morphological filtering, and leads to worse building extraction in the histogram analysis and, finally, to worse DTM approximations. Quantitatively, we have systematic and random errors of 1.99 cm and 33.04 cm, respectively for the low pass DTM. This shows a good reduction of the systematic height shift but a consistent enhancement of the random errors, due to terrain fluctuations that are not real ones. Instead, the morphological DTM has for the random error a value near to the original one. A graphical evaluation of this effect may be obtained looking at section Y1 and X1 profiles in figure 19.

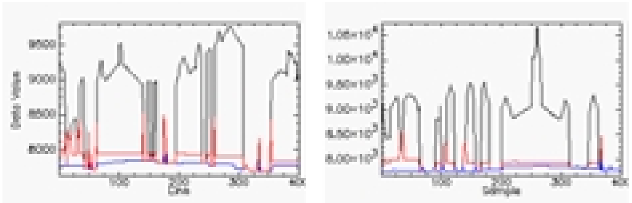

Figure 11: Section Y1 (left) and X1 (right) profiles in the original DSM of the fourth test area (tèop curve), the low-pass DTM (middle curve) and morphological DTM (bottom curve).

Finally, in figure 12 we give a three-dimensional representation of the original DSM (upper image) in comparison with the low-pass (left) and morphological (right) DTMs, before the final low-pass filtering step.

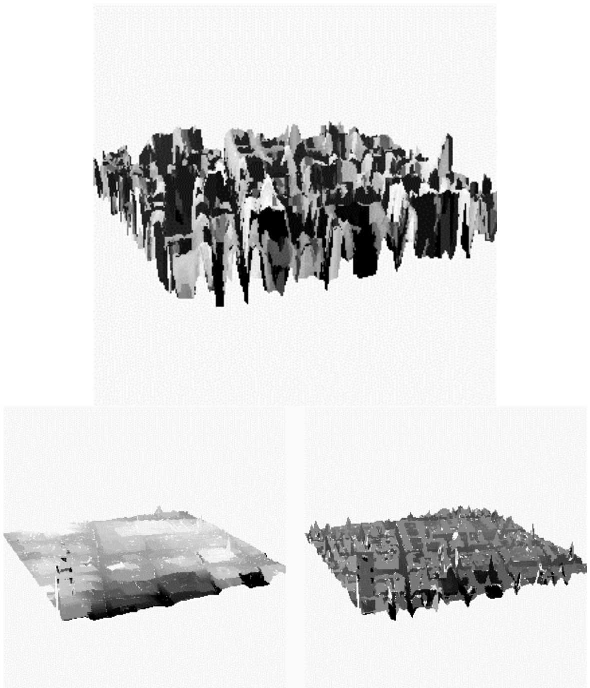

Figure 12: Three dimensional view of the original LIDAR DSM for the Piazza della Vittoria test area, together with the morphological DTM (lower left, kernel size = 25 m) and the low-pass DTM (lower right, kernel size = 100 m).

5 DTM EXTRACTION FOR THE WHOLE URBAN AREA

After the discussion of the previous section, it seems that filtering approaches followed by histogram evaluation are able to provide a sufficiently precise DTM of the whole urban area, since there is a strong similarity between the kernel size values that provide the best results in all our four test areas. Therefore, we implemented a complete DTM extraction for the whole area depicted in figure 1, with three different choices: low-pass filtering with kernel size of 25 or 100 m and morphological filtering with kernel size of 20 m.

Figure 13: Low-pass DTM (kernel size = 25 m).

Figure 14: Low-pass DTM (kernel size = 100 m).

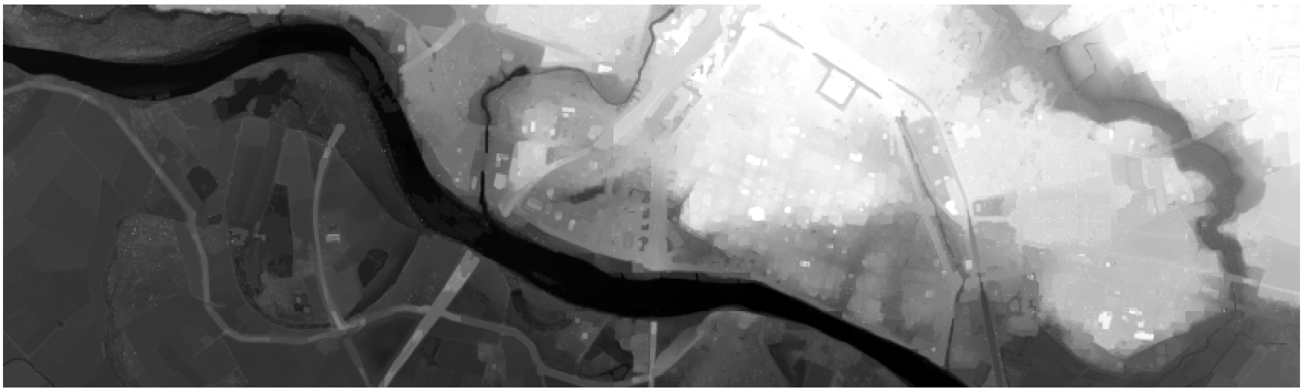

Figure 15: Morphological DTM (kernel size = 20 m).

As expected, the use of smaller kernel and low-pass filter provide smaller errors in the natural structures (like embankments) East of the town. However, in dense built areas the effect of this filter is not completely satisfying, leaving to slightly different values inside the building areas than outside them. Instead, low-pass filtering with a larger kernel helps in these areas, but tends to cancel natural features that may be of interest.

The best compromise in this sense is obtained by means of the morphological filtering approach, with small kernel size as suggested by all test areas analysis. In this case we obtained a good extraction results, both in the city center and in the areas outside the town. Moreover, given the reduced kernel size, even the computation time is lower.

This analysis is confirmed by the inspection of a horizontal section of the DTMs, shown in the following figure for the best low-pass in the urban area (100 m) and the morphological DTMs. Note that the city center area is comprised between samples 3500 and 4500.

Quantitatively, to characterize all these DTMs in a densely built part of the town, we provide here a comparison with a set of GCPs in a different part of the city center (Piazza del Duomo). The systematic and random error values are 0.20 m and 0.65 m for the original DSM, 0.14 m and 0.36 m for the low-pass DTM (kernel size = 25 m), 0.13 m and 0.32 m for the low-pass DTM (kernel size = 100 m), and 0.14 m and 0.38 m for the morphological DTM. As expected, all the DTMs have comparable good results outside of the buildings.

6 CONCLUSIONS

The present work provides a methodological approach to the extraction of digital terrain models in densely built areas. The idea is to use a filtering approach with a kernel size determined by means of a training step in some test areas.

Two filtering techniques, namely the low-pass and the morphological ones have been exploited, together with the

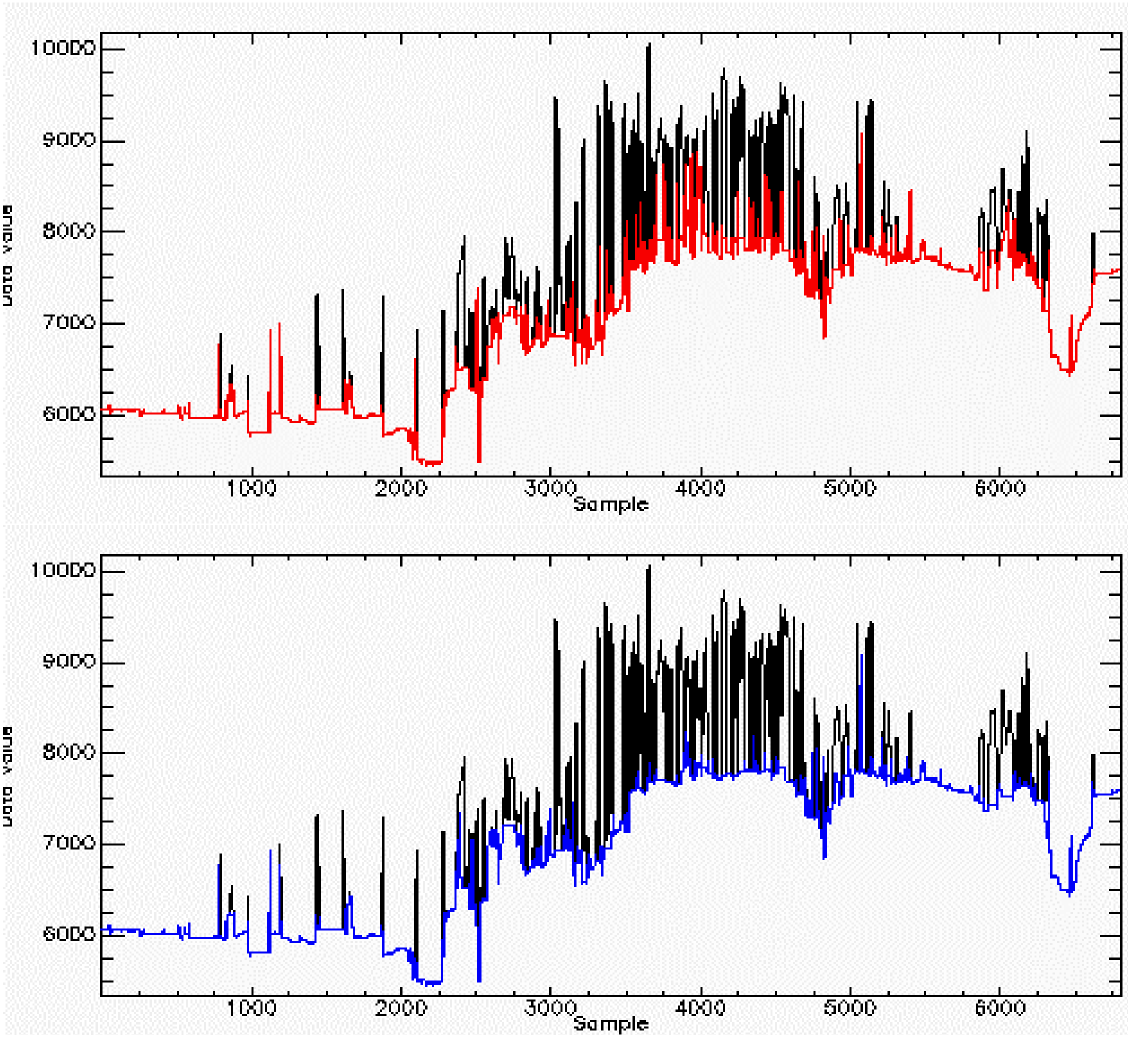

Figure 16: Comparison between the original DSM and the low-pass and morphological DTMs in a horizontal section of figures 14 and 15. In black the original DSM, in grey the low-pass and the morphological DTMs.

histogram analysis for building extraction, and reasonably good DTMs have been provided. The test area characterization proved to be an effective way to choose the input parameters of these techniques, and quantitative evaluations of the retrieved terrain height with ground control points have confirmed this assumption.

Future work will be dedicated to improve the procedure and determine a relationship between the values of the inpiut parameters and the structural characteristics of the buildings and the terrain features, so that no DTM extraction in test areas will be required, but only simpler information in the same zones.

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