FILTERING OF DIGITAL ELEVATION MODELS

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ABSTRACT

A digital elevation model (DEM) created by automatic image matching or laser scanning – also named as LIDAR, includes a not negligible number of points, not located on the terrain surface but on buildings or vegetation or even mis matching. The manual refinement of such a DEM is time consuming. In general, points located not on a continuous surface that can be differentiated, have to be identified and removed. A Digital Filtering Technique to be applied to the automatically acquired DEM-data is presented. The strategy is based on Linear Prediction of stationary random function after trend removal. The filtering was applied to photogrammetrically acquired DEM-data via automatic digital correlation techniques. Different terrain compositions like buildings and canopy density; terrain roughness; grid sizes; photo scales have been investigated

The system can also be used in connection with DEM acquired through LIDAR. For both applications very acceptable results have been achieved.

INTRODUCTION

Digital Elevation Models (DEM*)* acquired using photogrammetric correlation techniques or LIDAR have the disadvantage that the resulting modelation surface may not represent the bare terrain but the visible surface including vegetation and buildings, the so called Digital Surface Model (DSM).

The first step to be done after data acquisition is the removal of the points not belonging to the terrain. An automated method based on linear prediction has been developed and applied. The method and results are explained.

DIGITAL ELEVATION MODEL FILTERING

The elimination of points not belonging to the terrain surface is known as Filtering. There are several methods or procedures for interpolation and filtering. Among them are:

a) Splines approximation
b) Shift Invariant Filters
c) Linear Prediction
d) Morphological Filters

Although Morphological Filters are the most frequently been applied, Linear Prediction is a very robust methodology for the filtering of Digital Surface Models. It is based on the following concepts:

Let us consider the following three random functions $l(u)$, $s(u)$, and $r(u)$, such that

$$l(u) = s(u) + r(u)$$

The observable function is $l(u)$ and $r(u)$ represents the noise, $s(u)$ is called the signal. Interpolation and filtering are therefore the problems of finding an estimate $s\,(u_o)$ of the random function $s(u)$ at $u = u_o$, when a discrete set of a function *values* $l(u_1), l(u_2),\ldots l(u_n)$ from a given realization $l(u)$ are given.
The favored estimate is such that its results from a linear combination of $l(u)$, or:

$$s_o = s(u_o) = a^t\, l$$

With: $a^t = [a_1, a_2,\ldots a_n]$ is a vector of coefficients and

$l = [l(u_1), l(u_2),\ldots, l(u_n)]$ is the vector of given data values,

that means, the estimated value is a linear combination of the given data values. This is particularly important for those cases where a function cannot be or it can be extremely difficult to be represented in an analytical form, i.e., *Digital Terrain Models*.
It can be proven that filtered signal value $s_o = s(u_o)$ is:

$$s_o = s_{sol}\, S_{ll}^{-1}\, \boldsymbol{l} \qquad (1)$$

With:

$s_o =$ predicted or filtered value of the signal at $u=u_o$

$s_{sol} =$ is a vector containing the cross-covariance between signal s at $u=u_o$ (s_o) and observations l_i. (equals to covariance between signals s_i and s_o)

$S_{ll} =$ Covariance matrix

$\boldsymbol{l} =$ Vector of centered measurements

The covariance matrix is constructed from the covariance function that has the general form:

$$COV = A \bullet e^{-\left(\frac{\overline{PiPk}}{B}\right)^2} \qquad (2)$$

This expression states that the covariance between two points P_i and P_k is dependent on their reciprocal distance. If the points are close to each other, then the covariance is high. The covariance tends to zero with growing distance between points. A is the vertex value of the function and consequently is the covariance for zero distance. B represents a scale factor for the width of the covariance function. These parameters are known or they are to be determined by an analysis of the data.
A fundamental prerequisite for the application of a covariance function is the removal of the trend from the given observations or signals. Only in this case the covariance between points will only be dependent on their reciprocal distances and in such a case we will be handling *stationary random functions*. The elimination of the trend is accomplished by using a low degree polynomial or a moving plane. The result of this trend separation is the vector $\boldsymbol{l_i}$ that contains the centered points of measurements. These values $\boldsymbol{l_i}$ describes the deviations of the sample-measured points from the moving pane or the low degree polynomial.
Finally we can conclude that the elements of the covariance matrix $\mathbf{C}_{ll}$ are in fact the covariance values between the point measurements. The main diagonal elements are the variances of the signals (centered point measurements after trend removal) and the off-diagonal elements are the covariance values corresponding to formula 2. That is:

$$\mathbf{C} = \begin{bmatrix} V_{ll} & (P_1P_2) & \ldots & C(P_1P_n) \\ C(P_2P_1) & V_{ll} & \ldots & C(P_2P_n) \\ . & & . & . \\ C(P_nP_1) & C(P_nP_2) & \ldots & V_{ll} \end{bmatrix} \qquad (3)$$

As mentioned before, a fundamental prerequisite for the application of a covariance function is the removal of the trend from the given observations or signals. Depending on the terrain type, i.e., flat, rolling mountainous, the elimination of the trend is carried out via the use of a moving plane or a 2^{nd} order polynomial surface.

$$Z_i = a_0 + a_1 X_i + a_2 Y_i \qquad (4) \qquad \text{or}$$
$$Z_i = a_0 + a_1 X_i + a_2 X_i^{\ 2} + a_3 X_i Y_i + a_4 Y_i^{\ 2} \qquad (5)$$

For the computations of the coefficients of (4) or (5) the area covered by the DEM is divided into a mesh of equal size. Based on the actual distribution of the points in the DEM to be filtered, the dimensions of the square grid are computed such as to have best distribution possible within the mesh. For the processing of the points of a particular mesh (processing unit = 1 mesh), the points located in the 8 surrounding meshes are considered. In this way, the moving plane (or low degree polynomial) coefficients are computed using the points located in the 9 contiguous meshes (area of consideration), via least squares. See Fig. 1

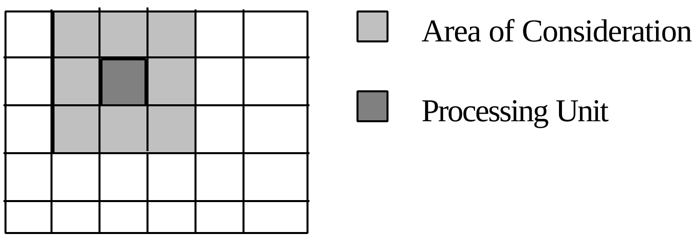

Figure 1

The trend removal is based on the tilted plane (or a 2^{nd} order polynomial surface) in the area of consideration resulting in the centered measurement values l_i.
Assuming a normal distribution of those l_i values their standard deviation (σ_z) is computed and a multiplication factor (*fac*) is derived for the computation of a threshold or tolerance factor (T_z).

$$T_z = fac\ \sigma_z \qquad (5)$$

All those points within the corresponding processing unit whose deviations (i.e., centered measurement values *li*) are exceeding the above tolerance (T_z) are excluded. The trend separation is repeated in a loop until no more defective heights are recognized by the system. The erroneous heights of the processing mesh are deleted from the records. The erroneous heights of the neighboring patches (i.e., area of consideration) are kept for the computations of the next patch. They only remain unconsidered for the current patch.
Figure 2 shows the above-explained iterative process of trend removal and elimination of erroneous height values when a tilted plane is used.

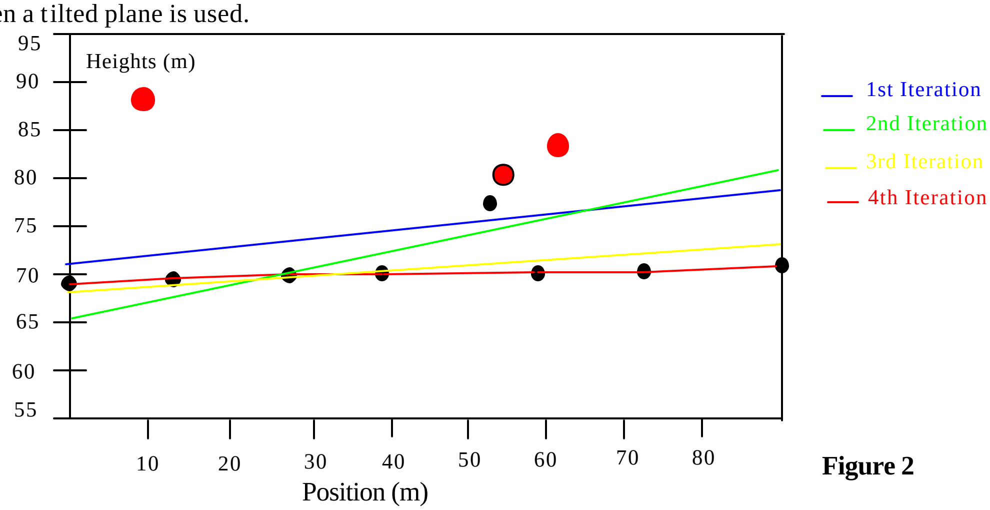

Figure 2

The figure 2 shows a typical terrain height-profile. It consists of 10 points, three of which are blunders. The inclination of the moving plane, represented by the colored straight lines, varies considerably with the iterations. Four iterations are needed in the example, until the moving plane stabilizes and fits as best as possible the terrain surface and no more blunders are identified. The standard deviation decreases drastically from iteration to iteration with the removal of the largest blunders to the smallest.
Once the trend is removed the Linear Prediction can be applied making use of a Covariance Function with the following form:

$$C(PiPk) = A \bullet e^{-1.30103\left(\frac{\overline{PiPk}}{B}\right)^2} \qquad (6)$$

The parameters A and B are parameters of the function. A is the vertex-value of the signal-covariance function. It is a filter factor for the normed covariance function. It specifies the relationship between random and systematic components of the height discrepancies (i.e., centered measured heights l_i). A value A = 1.0 (in the program limited to 0.99), means no random errors are available. The parameter B is scale factor for the width of the function and represents the distance at which the influence of points is reduced to 5%. On the other hand its value also limits the width of the mesh for the local prediction.
The interpolated surface is defined as in equation (1) where the main diagonal elements of the covariance matrix contains variances $\boldsymbol{V_{ll}}$ = 1, meaning all measurements are regarded as being of the same accuracy. As the vertex-value A have been found to be appropriate at 0.7, interpolation and filtering are possible. The higher the vertex-value of the function is, the smaller the variance s_l^2 is, and smaller is the filtering effect (See Figure 3).

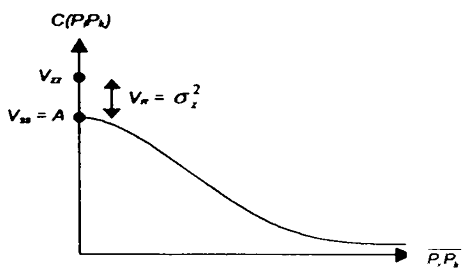

Figure 3.
Covariance Function

The differences between the centered measured values at each DEM point and the predicted value according to formulae (1) are computed. Once again assuming normal distribution of the above discrepancies, their corresponding standard deviation (σ_{zp}) is computed. A multiplication factor is introduced in the program for the calculation of a threshold or tolerance value (T_{zp})

$$T_{zp} = fac\ \sigma_{zp} \qquad (7)$$

If the computed discrepancies are exceeding the threshold, the corresponding DEM points are also eliminated in a loop fashion.

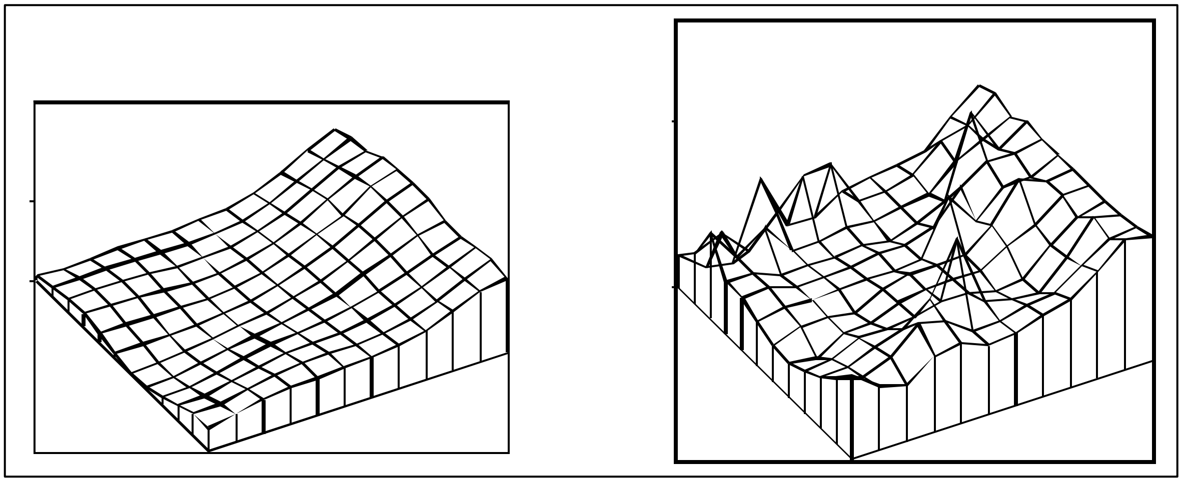

Figure 4. Surface of Prediction **Corresponding real height values**

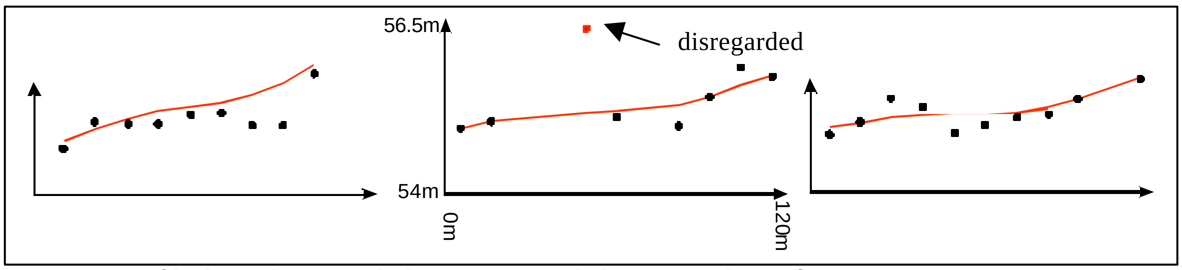

Figure 5. profile through area including a point not belonging to the surface
(left: left hand profile, center: center profile, right: right hand profile
red line = surface of prediction in these profiles based on the area,
points = real height point)

DETERMINATION OF THE THRESHOLDS

One of the most important aspects of the above theoretical explanations is the determination of the *fac* values (factor values of formulas 5 and 7) or the termination of the threshold for accepting or rejecting the height values. In general this is based on the frequency distribution of the height differences against a reference parameter or value (i.e., neighbored point, linear or polynomial fitting in profiles and in a reference area, and prediction). *The determination of the threshold is finally based on test results – that means the empirical level of probability that the height value is belonging to the surface or not.*

This threshold is depending also upon the settings or type of terrain we are dealing with, that is flat, rolling or mountainous and on its homogeneous or non-homogeneous characteristics. Thus, in a flat area we should expect a different frequency distribution than in a mountainous area – which is of course overlapped by the accuracy of the height determination itself. In a non-homogeneous area the thresholds have to be more on the save side because the frequency distribution is based on the mixed areas – so also in the mountainous part it is not advisable to remove points just based on the threshold of the frequency distribution based on flat / rolling / mountainous characterization – of course this will cause a high level of acceptance for the flat part of a non-homogenous area, that means the system will accept points that may not belong to the surface. As the decisions are based on probabilities, it is not possible to avoid totally the errors type 1 and 2, that is to accept points not belonging to the surface / remove points belonging to the surface. Nevertheless, this is minimal since the probability decisions are based on a high number of supporting points, hence non-depending upon one individual point.

In addition to the general task of eliminating DEM points not belonging to the surface it is also a question of the later use of the DEM. For a better and smooth representation of contour lines the final height values can be smoothened based on the relation of neighboured points. The selection of the corresponding reference surface and the kernel size is based on the type of terrain. Thus a tilted plane and a 3 (3*3) kernel is recommended for flat terrain’s whereas for an undulated or very undulated area a neighbourhood of 5 (5 * 5 points) together with a polynomial surface is adequate. A larger neighbourhood may be used for the generation of more smooth contour lines.

THE PROGRAMS DTMCOR AND RASCOR

Based on all above theoretical explanation, the Institute for Photogrammetry and GeoInformation of the University of Hannover developed the Programs DTMCOR and RASCOR. DTMCOR can be used in connection with the filtering of DEM-TIN type of point distribution whereas RASCOR is more efficient for DEM-Grid layouts. These two programs are used in the daily photogrammetric operations of the company.

EXPERIMENTAL TESTS

Samples of DEM's automatically acquired using digital correlation techniques have been filtered using DTMCOR and RASCOR. Three different terrain areas have been used, namely:

Area Type A: Flat Terrain with some bushes and large number of buildings / houses. DEMs Grid of 20, 30 and 50 feet. Photo Scale 1”=350’ (1:4,200)

Area Type B: Undulated Terrain with bushes and buildings / houses. DEMs Grid of 40, 60 and 80 feet. Photo Scale 1”=660’ (1:7,920)

Area Type C: Very Rough Terrain with very dense bushes and buildings / houses. DEMs Grid of 40, 60 and 80 feet. Photo Scale 1”=660’ (1:7,920)

Table 1 shows the results

Terrain Type	Photo Scale	Grid Size [ft]	Total No. of Pts.	Total Eliminated	Trend Elimin.	L.P. Elimin.	Type I Error	Type II Error
A	1”=350’	20	49,771	19.75%	17.42%	2.33%	Negl.	Negl.
		30	22,052	18.22%	16.21%	2.01%	“	“
		50	7,875	15.51%	13.78%	1.73%	0.12%	0.22%
B	1”=660’	40	41,698	39.91%	39.33%	0.58%	0.78%	0.72%
		60	18,507	37.24%	36.53%	0.71%	0.92%	0.79%
		80	10,395	36.67%	36.15%	0.52%	0.93%	0.87%
C	1”=660’	40	42,735	47.72%	46.93%	0.79%	Negl.	0.56%
		60	18,995	43.64%	43.20%	0.44%	“	1.57%
		80	10,666	37.71%	37.20%	0.51%	0.78%	1.88%

Table 1. Results of Filtering applied to different DEMs

A close look of Table 1 reveals:

1 For a given terrain coverage the smaller the grid size or distance between DEM points the larger the number of filtered (eliminated) points is. This is understandable since with smaller grid size the greater are the chances for the extracted points of not belonging to the terrain.

2 Regardless of the type of terrain being filtered, the greater number of removed points is due to the trend removal and acceptable minimum and maximum value of the DEM points in the area of interest.

3 The contribution of the linear prediction (see column L.P. of Table 1) to the removal of non terrain points is more effective in the flat terrains (see terrain type A) and more over in the terrains with large open areas, like the one used in our experimental tests. This is expected because the linear prediction it is able to detect and eliminate points that are floating or buried in the terrain.

4 Regardless of the type of terrain, photo scale, grid size, etc., the output of a filtered DEM has type I errors (points belonging to the bare terrain but removed) and type II errors (points not belonging to the terrain but kept). Nevertheless the number of errors are dependent on the terrain type, the grid size and the quality of the correlated and matched points. Thus, filtered DEMs of flat terrains with high point density (grid size of 20 and 30 feet in our example) do have a negligible number of type I and type II errors. This because with high point density, majority of frequencies of the terrain are captured and any deviation (i.e., buildings, trees, boshes, poles, etc.) from the dominating frequencies are modeled with high reliability and removed.

5 Filtered DEMs of very rough terrains with very dense forest (terrain type C of our example) do have a negligible number of type I errors for high point density (40 and 60 feet in our example) and an increasing number of type II errors for larger grid sizes. The type II errors can be explained by the poor quality of the correlation in areas of low or uniform contrast such as the forest areas. There, the correlated and matched points can be uniformly floating over or buried into the ground. Consequently, they cannot be recognized by the system as anomalies and are kept as points belonging to the terrain. The negligible amount of type I error is due to the high density of points that allows the modeling of the majority of dominating frequencies of the surface been sampled.

6 The photo scale has no influence on the efficiency of the filtering technique.

7 Through visual inspection of the filtered DEM, it has been noticed that the type I and II errors are mainly located in the range of the geomorphologic and break lines that have not been sampled. These lines demarcate the abrupt changes of the slope of the terrain and if they are not included in the filtering scheme, it is not possible to model the dominating frequencies contained within those lines with high reliability.

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Figure 6. Filtered DEM – remaining points after filtering

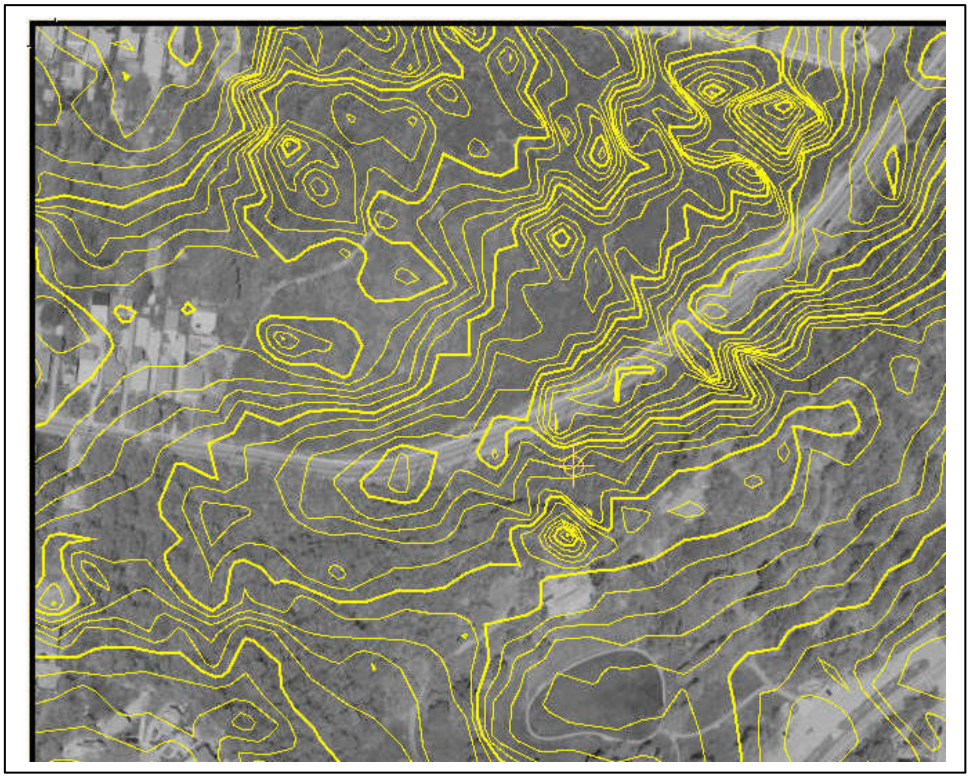

Figure 7. Contour lines from non filtered DEM

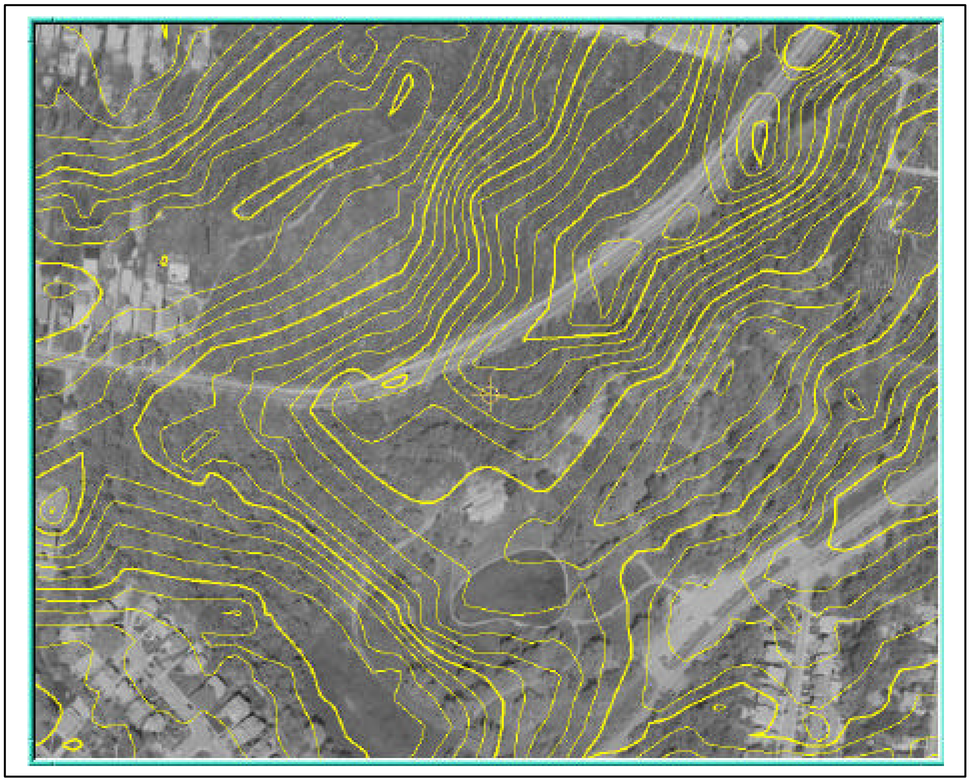

Figure 8. Contour lines from filtered DEM

Figures 6 shows a section of a DEM of terrain type B after filtering, superimposed to the aerial photo. It still includes some type II error points, specially matched points on top of dense tree areas. The contour lines in figure 7 do clearly show the errors of a non filtered DEM and figure 8 portraits the contour lines of the same DEM after filtering has been applied.

CONCLUSION

A very efficient method for filtering Digital Elevations Models has been presented. Based on the statistical analysis of the terrain data and simple statistical tools, the filtering model is able to identify and eliminate non terrain points automatically without the need of inspecting the stereoscopic model as it is commonly done in a digital editing process. Regardless of the type of terrain and terrain cover, the system it is not fool proof , that means there are type I and type II errors, i..e, points being eliminated while belonging to the terrain and vise versa. It is believed that the incorporation of break lines into the filtering system as non variant information will enhance the efficiency and reliability of the filtered data by minimizing even more of the type I and type II errors.

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