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A Comparative Evaluation of Automatic Sampling Methods

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Abstract: **-** Preparation of Digital Terrain Model is one of the necessities of geometric sciences, especially Geographic Information Systems (GIS). The first step in this process is sampling, which is one of the most effective aspects on the accuracy of the final model. Various types of sampling methods have been introduced and implemented in the previous years. These methods are of a wide range that can be categorized based on different aspects. Nowadays, due to the large size of the data produced and the impact of IT sciences on all technical issues, automatic sampling methods have gained special significance and wider utility in comparison with methods requiring human involvement. This study introduces automatic sampling methods and evaluates them comparatively. The advantage of the employed comparison is using an equal number of points for comparison to make sure the final accuracy depends on the sampling method and not on the number of the points. To add to the precision of the comparison, all the process was conducted on samples including flat terrains, terrains with slight slopes and mountainous areas. All the details such as sampling, triangulation, locating control points within the triangulation grid, and interpolation are completely implemented in this research. In the next step, the errors yielded by various statistical criteria are analyzed and the methods are then evaluated using these criteria. The methods are finally analyzed and their strengths and weaknesses are discussed.

Keywords: **-** *Digital Terrain Model, Random Sampling, Systematic Sampling, Contouring, Profiling, Incremental Sampling, Statistical Criteria.*

I. INTRODUCTION

Digital Terrain Model is a continuous, mathematical and digital representation of a real or virtual object and its surroundings [1], which is commonly used to produce topographic maps [2]. The simple structure and availability of DTM makes it a favorable tool for land use planning, feature extraction, hydrological modeling, civil engineering, forest management, bird population modeling, and producing maps of polar ice layers, flood control, route design, large-scale map making, and telecommunications [3-7]. Such extensive utility of DTM attaches much significance to it.

The quality of a DTM depends on the following aspects [5, 8]: specification of input data, interpolation procedure, and specification of the terrain.Fisher and Tate [9] argue that the first two items are of error nature, on the contrary, the third should be counted as an item increasing uncertainty.

The first and most important action in modeling a terrain is specifying a number of points that determines the quality and quantity of input data [5, 10]. This action is of two main steps: sampling and measuring. Sampling concerns with selection of points and measuring relates to coordinates of the points [11]. Three important criteria for determining the points are density, accuracy and distribution of the points. The accuracy criterion concerns the measuring step and the other two, the density and distribution, relate to sampling. Density and distribution completely depend on the specification of the terrain. For instance, three points would suffice to sample a completely flat terrain such as a plain. While sampling from a mountainous area requires very dense control points with appropriate distribution; otherwise, the obtained DTM would not match the real terrain. Accuracy is the most important of the aforementioned criteria, which is of the most effectiveness on the model. The accuracy criterion must of course be taken into consideration along with cost and efficiency so as to maintain an economic and operational method [12]. There are multitudinous methods of sampling and ample studies have been conducted on selecting the best method in different conditions. Due to recent advances in data collection technologies such as aerial photography, digitalization technology of paper topographic maps, radargrammetry, Synthetic Aperture Radar (SAR) Interferometry, LIDAR, and GPS (and similar systems), data gathering has been facilitated and sped up such that manual sampling methods are not capable of catching up with the enormously fast data production methods. Thus, automatic methods are of great significance. Considering the wide range of automatic methods, it proves important to know what method in what condition is appropriate; that is, what method can yield the most accurate results by spending the least possible time and performing the least possible calculations.

We have studied and evaluated various methods in this paper. The important aspect of this study is sampling of an equal number of points in all methods. This ensures that the resultant precision in models will be only due to the method and not the quantity of points.

As DTM has been widely used in geosciences, many researches have been conducted on its various aspects. One of the important researches was conducted by Li [13]. He had three objectives in mind: 1) assessment of DTM accuracy by means of contour line with and without feature points; 2) assessment of DTM accuracy by means of regular grid with and without feature points; 3) assessment of DTM accuracy by means of regular grid and contour line with and without feature points. In the first two modes, he has utilized standard deviation for comparison and has reported the optimization percentage for each of the modes and with regard to the type of uneven terrains. In the third mode also, the author has proved a relation between the distance of contour line and the regular grid for achieving a similar accuracy. In another research, the author has studied the distance between contour lines for using this method for forming DTM. In this study, the author, after studying many terrains with different unevenness, concludes that the distance of contour lines affect the final accuracy of the model significantly. Also feature points are of positive effect on the accuracy of the model; that is, the more the distance of contour lines, the more its effect on the accuracy of the model. Also, the less the unevenness of the terrain, the more the effect of contour line on the decrease of accuracy of the model.

Zhou and Liu [7] studied the effectiveness level of data accuracy, grid size, grid direction, and complexity of the terrain in the error distribution pattern in the calculation of the morphologic properties such as size and slope direction. In a more recent study by the same researchers [14], the role of terrain unevenness on variables of DTM such as slope and aspect was investigated. They concluded that the accuracy of slope and aspect has a reverse relationshipwith the slope of terrain. Also, the slope and aspect has extreme reverse dependency on unevenness. Fisher and Tate [9] have explained the grid data errors by the difference between the obtained value and the real value (incorrect height values, height values with wrong location, locations without data and etc.)

Bonk [15] evaluated the effect of arrangement of input points in random and grid sampling methods. He also studied the effect of the number of points in the size and spatial distribution of DTM errors. Aguilar, Aguilar [16], having studied the accidental method of DTM sampling, concluded that the accuracy of this method has great dependency on input data concentration. Höhle and Höhle [17] studied the number of appropriate points required for quality control of DTM. Their focus was upon the issues where the histogram of errors is symmetric and where errors exist in the data. Zandbergen [18] studied DTMs from a hydrological perspective, i.e. the water flow on DTMs should resemble the water flow on the real earth. He concluded that little and shallow pits are more likely to occur than deep and large pits. It has also been pointed out in this paper that selection of an extreme threshold for identification of unreal pits leads to considerable number of errors and field operations are needed for their identification.

II. MATERIALS AND METHODS

1.1. Sampling theory

From a theoretical perspective, 3-dimensional surfaces are comprised of an infinite number of dimensionless points. If the complete information of all points of a surface is needed, then all points should be measured, which is impossible; that is, modeling surfaces such that the modeling matches the reality 100% is impossible. In practice, when the height of a point is measured, it represents a neighboring area. Thus, a surface can be modelled by a finite number of points. The key point is that since it is impossible to provide a model matching a surface 100%, thus a sufficient number of points should be measured to obtain appropriate accuracy. The main aspect of sampling is using the best points for sampling.

1.2. Sampling from different perspectives

Points on a surface can be studied from different aspects such as statistics-based, geometry-based, and feature-based that are introduced briefly in this section [11].

1.2.1. Statistics-based

From a statistical viewpoint, a surface is comprised of an infinite number of points constituting the statistical population. To study a statistical population, the sample space must be evaluated. To choose the members of a sample space, the samples must be selected through either random or systematic methods. In random selection of samples, points are random variables and are sampled accidentally; thus, considering this mechanism, the probability of selection of different points may be different. However, in systematic sampling, the points are chosen specifically such that the probability of their selection is 100%. Systematic sampling is often performed through grid selection of points [11].

1.2.2. Geometry-based

From a geometric viewpoint, the surface of a terrain can be modeled by different geometric patterns, either regular or irregular. Regular patterns can be divided into two groups: one-dimensional and two-dimensional. Profiling and contouring are types of geometric sampling that are regular only in one dimension. In contouring, the height dimension and in profiling, the dimension parallel to x, y, or a combination of them is fixed. In fact, the output of the contouring is the cross-section of x-y and the output of profiling is the cross-section of x-z or y-z [11].

1.2.3. Feature-based

From a feature-based perspective, the surface of the terrain is comprised of a finite number of points whose data may vary based on their position. Thus, surface points consist of feature-based and random points. The feature points are relative extremes of the surface of the terrain, such as hills and valleys. These points not only are of height, but also provide valuable topographic information about their surroundings. The lines connecting these points are called feature lines including ridge, thalweg, etc. [11].

1.3. Different types of automatic sampling

This section introduces different types of automatic sampling. These methods will be implemented and compared with each another in the following sections.

1.3.1. Random sampling

According to this method, some points are selected randomly and their heights are measured. As mentioned in 1.2.1, the likelihood of being selected is equal for all points. A demonstration of random sampling is illustrated in Figure 1-A.

1.3.2. Systematic Sampling (grid-based)

Points in this approach are sampled with a fixed interval in both directions. An example of systematic sampling is illustrated in Figure 1-B.

1.3.3. Sampling with one dimension fixed

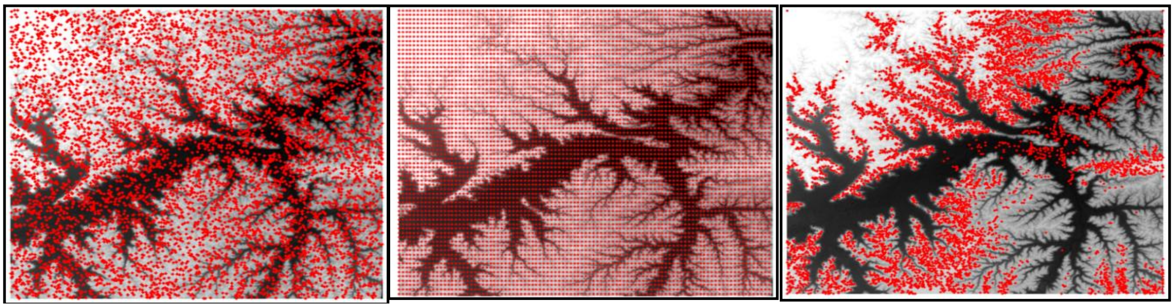
As discussed in 1.2.2, each of the x, y, and z dimensions is considered as fixed and move on the other two dimensions. In photogrammetry, fixing the z value and moving on the map produces points having the fixed height. These points make lines that are called contour lines. This approach is shown in Figure 1-C. By fixing x, y or a combination of them, profiles are produced that an example is shown in Figure 1-D.

1.3.4. Sampling with two fixed dimensions

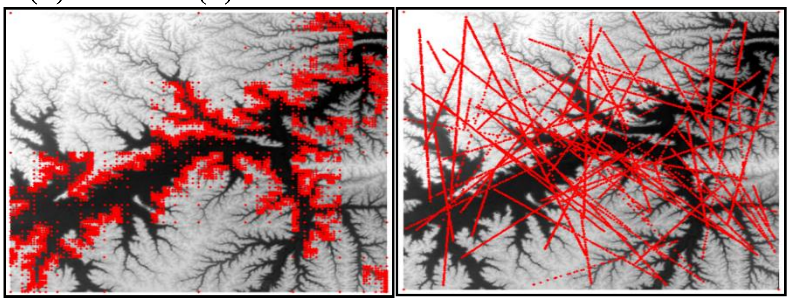
In this method, two x and y dimensions are kept fixed that is called regular grid. The major disadvantage of this method is that it requires a large amount of samples to ensure all important points such as slopes and topographic changesare sampled. To resolve this issue, a procedure is added to the method. The resultant method is called incremental sampling. It works by grid sampling where the grid distance decreases incrementally. First, a very coarse grid is performed. Then, using a certain criterion, a calculation is run for each cell individually to determine whether it is necessary to decrease the grid lines in the cell or not. In the positive case, a new grid network is formed within the cell according to a certain procedure (for instance four points or nine points are selected in each cell) and this procedure continues. The criterion determining the progress within the cells can be either the second derivative of the height of the points, parabolic distance or any other criterion [19]. This method is depicted in Figure 1-E. Although incremental sampling has resolved data overload, it still suffers from the following weaknesses [11]:

- Data overload around sudden changes in topographic points;
- Some features may be ignored in the initial steps of gridding;
- The path may become too long and thus decrease the efficiency of the algorithm.

There is another method called ROAM, which is introduced by Mark, Wolinsky [20]. The principles of this method is similar to those of the incremental method. The only difference is that in the ROAM, the grid cells are divided in the form of triangles instead of squares. The procedure is like that of incremental method according to which square-shaped divisions are formed in the first step. Then, if the condition of breaking the square is correct, a diameter of square is drawn and two right isosceles triangles are formed. From this step onwards, whenever the condition of triangle is correct, a line is drawn from the angle of the right side to the opposite side and two other right isosceles triangles are formed [21]. This method cannot be considered as an irregular method such as triangulation because all triangles are right isosceles triangles.



(A) (B) (C)



(D) (E)

Figure 1 - Types of Sampling Methods: A) Accidental; B) Systematic (Grid); C) Contour Line; D) Profiling; E) Incremental.

III. RESULT AND DISCUSSION

Figure 2 shows the flowchart of comparison of aforementioned automatic sampling methods. The whole process is conducted in this study for three different terrain types, namely almost flat, with gentle slope and mountainous. It is noteworthy that the numbers of captured points are equal so that the obtained results indicate only the efficiency of the method and not the difference in the number of input points. In fact, one can view the issue from this perspective that how accurate the information is yielded by different methods of sampling with an equal amount of input. In the next step, the DTM is created for all different samples by means of Triangular Irregular Network (TIN) and their accuracy and precision is assessed using control points. The results are then interpreted. For reconstruction of the terrain, the Delaunay triangulation is used that yields the best performance among other triangulation methods [22], although other methods such as Wavelet TIN and Irregular Network Merge and Triangulation also exist [23, 24]. Figure 3 shows triangulations conducted in a mountainous region.

In this step, 500 check points are selected accidentally. Then, using the random walk algorithm, the triangle containing the point is discovered and then the height is calculated for each sampling method using inverse distance weighting (IDW) [25]. According to a research conducted by Chaplat et al., the inverse distance weighting has functioned much better than other methods such as Ordinary Kriging (OK), Universal Kriging (UK), Multiquadratic Radial Basis Function (MRBF), and Regularized Spline with Tension (RST) [10]. On the other hand, complicating the procedure using these methods as well as other methods such as combined method of linear and nonlinear interpolation [26] will be of no avail to the objective of this study. In the next step, the difference between the calculated height and the real height as well as the obtained results are analyzed by L1 Norm, L2 Norm and standard deviation [4, 27]. As the errors of DTM depend on the type of the terrain, all calculations of this study are performed for three different types of terrain – almost flat, gentle slope, and mountainous [27, 28]; Table 1 shows the results.

It is worth to note that these values are not of any validity in regard with absolute value and are only utilized for comparison of different methods.

As blunders may exist in different points, errors are purified using 2.5-Sigma test and the above statistical analysis has been rerun and the results are presented in Table 2.

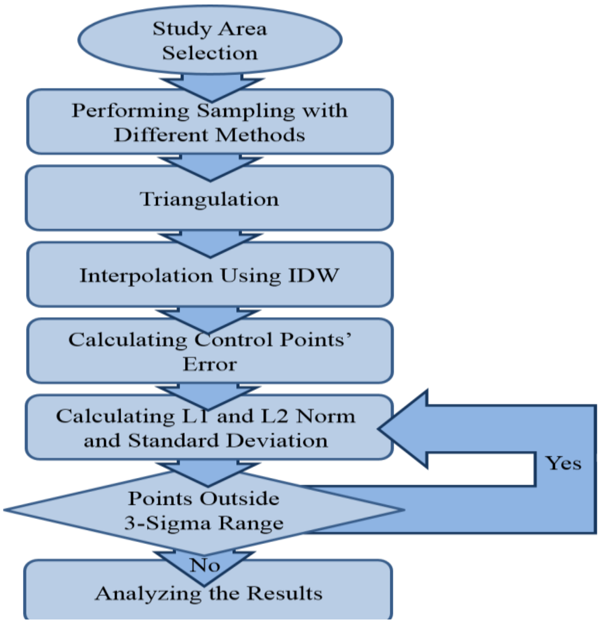


Figure 2: Flowchart of comparison of automatic sampling methods mentioned in this study

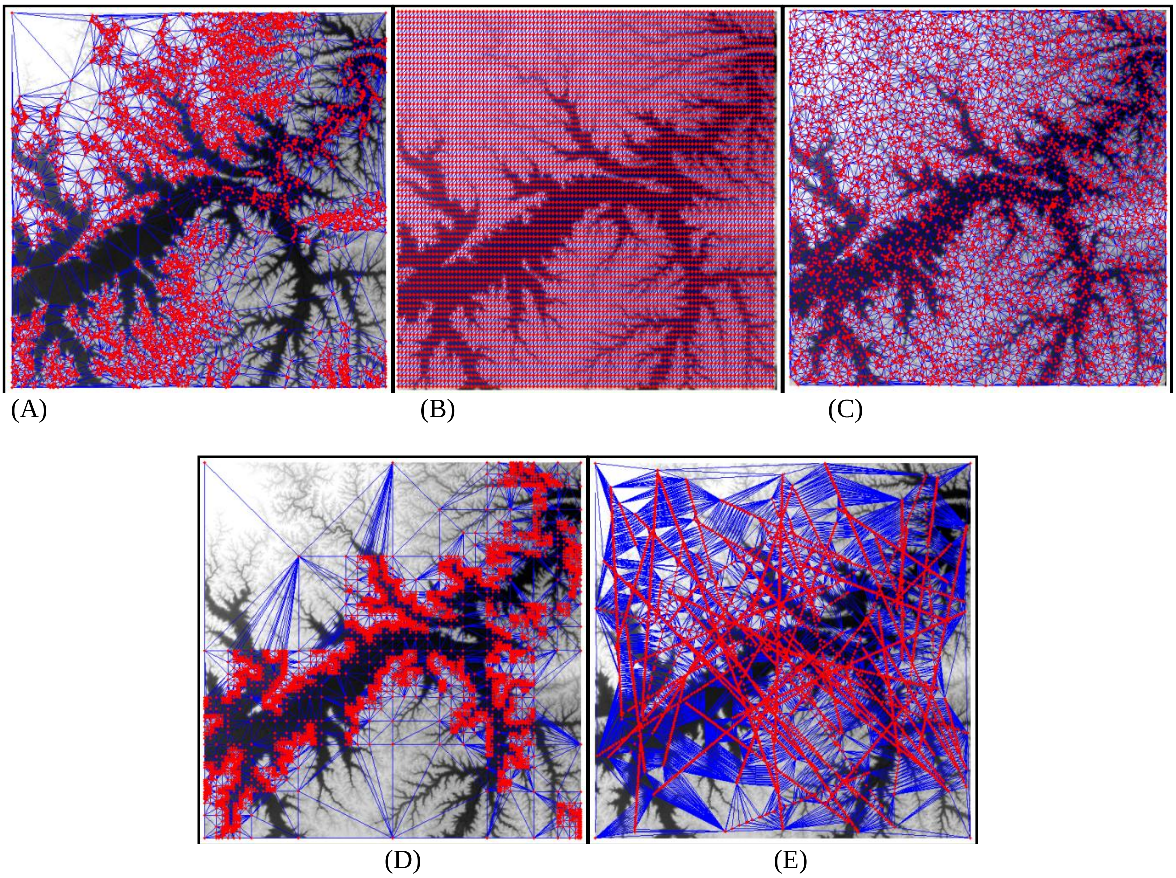


Figure 3: Triangulation conducted on captured point by means of different methods:
A) Accidental; B) Systematic; C) Contour Line; D) Profiling; E) Incremental

To show the impact of errors in each method, the percentage of improvement for statistical values after removal of errors is presented in Table 3.

Table 1: Statistical evaluation of height errors by means of different methods for different terrains

Sampling method	Terrain	Random	Systematic	Contouring	Profiling	Incremental
L1 norm	Flat	4.45	3.57	9.6	6.28	11.38
	Gentle slope	10.21	10.14	12.33	11.24	13.67
	Mountainous	35.76	26.87	28.61	37.46	25.65
L2 norm	Flat	0.19	0.07	-6.02	-1.06	0.72
	Gentle slope	-0.24	0.72	0.78	-0.72	1.3
	Mountainous	-33.19	-24.26	-11	-30.12	-19.4
Standard deviation	Flat	10.17	9.63	13.98	14.27	20.39
	Gentle slope	15.7	14.84	17.18	16.56	18.51
	Mountainous	47.16	41.71	40.91	49.34	38.15

Table 2: Statistical evaluation of height errors by means of different methods after removal of blunders

Sampling method	Terrain	Random	Systematic	Contouring	Profiling	Incremental
Number of blunders omitted	Flat	16	11	8	20	9
	Gentle slope	11	15	16	15	11
	Mountainous	13	19	11	18	22
L1 norm	Flat	3.14	2.59	8.87	4.18	9.64
	Gentle slope	9.03	8.98	10.9	9.92	12.63
	Mountainous	31.7	21.43	25.99	32.52	20.25
L2 norm	Flat	-0.2	-0.11	-6.39	0.07	-0.7
	Gentle slope	0.1	0.4	1.35	0.02	0.86
	Mountainous	-29.1	-18.7	-7.99	-27.8	-13.7
Standard deviation	Flat	5.82	4.96	12	7.72	13.87
	Gentle slope	12.62	12.41	14.49	13.79	16.3
	Mountainous	40.18	31.19	35.87	39.85	27.69

Table 3: The percentage of improvement of statistical values after removal of blunders

Sampling method	Terrain	Random	Systematic	Contouring	Profiling	Incremental
L1 norm	Flat	29.61	27.49	7.47	33.44	15.21
	Gentle slope	11.56	11.4	11.56	11.76	7.58
	Mountainous	11.35	20.21	9.15	13.19	21.03
L2 norm	Flat	-7.4	-77.11	-6.24	-92.74	3.32
	Gentle slope	56.46	44.81	-73.17	96.8	34.11
	Mountainous	12.44	22.81	27.4	7.69	29.28
Standard deviation	Flat	42.74	48.46	14.19	45.89	32.01
	Gentle slope	19.6	16.41	17.09	16.72	11.93
	Mountainous	14.18	25.27	12.31	19.23	27.41

Due to the considerable difference in mean and standard deviation in some of the methods, the removal of errors by 2.5-sigma method has been continued up to the point that no data is removed. The results are presented in Table 4.

Table 4: Evaluation of statistical errors of heights by means of different methods after repetitive removal of errors up to the point that no data is removed

Sampling method	Terrain	Random	Systematic	Contouring	Profiling	Incremental
Number of iterations	Flat	11	11	3	12	14
	Gentle slope	11	7	5	7	3
	Mountainous	5	15	4	7	7
Number of blunders omitted	Flat	137	134	14	175	65
	Gentle slope	67	58	38	50	20
	Mountainous	44	109	20	56	67

L1 norm	Flat	0.93	0.71	8.65	0.79	6.93
	Gentle slope	6.51	6.99	9.68	8.08	12.08
	Mountainous	25.42	9.62	24.78	25.45	14.31
L2 norm	Flat	-0.1	0.04	-6.66	-0.01	-1.42
	Gentle slope	-0.21	-0.22	1.55	-0.03	59
	Mountainous	-22.87	-7.76	-8.11	-21.16	-7.4
Standard deviation	Flat	1.3	1.02	11.54	1,14	9.47
	Gentle slope	8.4	9.11	12.44	10.74	15.51
	Mountainous	32.17	13.86	33.94	30.77	18.55

IV. CONCLUSION

Considering the different tables presented in the previous section, the following points can be concluded about different sampling methods as the results of this study:

- The systematic method can be considered as the most appropriate method, as it yielded the best result in the most of the selected statistical variables. This can be explained by the homogeneous distribution all over the area in question that led to a decrease in the number of errors all over the area.
- Contouring is of the least accuracy as the selected points are on several limited contour lines leading to a large number of flat triangles in the triangulation process. Formation of flat triangles decreases the performance of IDW to nearest neighbor interpolation. On the one hand, as shown in Figure 1-C, the distribution of points is not homogeneous and in some spots due to the fact the points are distant, the formed triangles are so large that interpolation is of no use and erroneous (Figure 2-C). Furthermore, due to the large value of standard deviation obtained through 2.5-sigma test, the erroneous points cannot be removed.
- As illustrated in Table 3, the greatest improvement after 2.5-sigma test have been witnessed in all variables in the incremental method. This indicates the accuracy of the method, despite presence of some errors. As pointed out in section 4-4, one of the weaknesses of this method is the issue that many features are lost when the grid distances are still large. This has been shown in Figure 2-E where triangles are very large in many occasions and many features within the grid have been ignored.
- The profiling method chooses the points on direct lines, thus the resultant triangulations will resemble spider webs, as illustrated in Figure 2-D. That is, triangles are drawn to a certain direction and lose their equilateral form. Therefore, high accuracy cannot be expected.
- The random method, like systematic method, is of good distribution i.e. the points are distributed equally and evenly. This method is ranked second after the systematic method.
- Considering many features are not seen in methods with poor distribution, adding feature points will have a significant effect on the accuracy of methods [12]. With regard to the great accuracy optimization in the incremental method with error removal, this method is expected to experience the greatest optimization after adding the feature points.
- Contouring, profiling and incremental methods have been evolved through time. That is, many researchers have made great efforts to improve them. Thus, it is possible that after such optimizations, the obtained results may better the results obtained in this study.

We attempted to compare the automatic sampling methods in this research. The studied methods included: random, systematic, contouring, profiling and incremental methods. This study was based on equal conditions for compared methods; that is, accuracy has been evaluated while an equal number of points have been captured during sampling. This way, the most efficient method, the one which yields to a more accurate DTM with the same equal cost, is identified. The variables that were taken into account in this study for comparison were L1 norm, L2 norm and standard deviation. To decrease the impact of studied variables, 2.5-sigma test was utilized for discovering and removing blunders. According to the obtained results, the systematic method and contouring method have the highest and lowest accuracy, respectively, in all studied variables. The random method has ranked second after systematic method. The low accuracy of contouring method is due to the great number of flat triangles, which in fact nullify the efficiency of interpolation. The weakness of the incremental method, as predicted in the study and pointed out by other researchers, was loss of feature points in the initial steps of segregation.

This research work can be considered as a step forward in this field as it has dealt with this issue with a data and input approach. In practice, the results of this research can be of great use for selection of optimum model in special conditions.

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