

Analysis of Score Functions for the Automatic Registration of Terrestrial Laser Scans

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ANALYSIS OF SCORE FUNCTIONS FOR THE AUTOMATIC REGISTRATION OF TERRESTRIAL LASER SCANS

Christoph Dold and Claus Brenner

Institute of Cartography and Geoinformatics
Leibniz University Hannover
Appelstr. 9A, 30167 Hannover
christoph.dold@ikg.uni-hannover.de, claus.brenner@ikg.uni-hannover.de
http://www.ikg.uni-hannover.de

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ABSTRACT:

Terrestrial laser scanners are more and more popular, e.g. for surveying purposes, cultural heritage, city modelling or architectural applications. Usually different points of view are necessary to acquire an object completely. The task of finding the relative orientation between several scan positions is termed as registration. Research work in data driven methods for the registration of point clouds was frequently published the last decade. A distinction between coarse registration and fine registration has been drawn. We use a feature-based registration to search for a coarse orientation. The transformation parameters are calculated by establishing correspondences between extracted planes. An efficient search strategy delivers possible candidates. The focus of this paper lies in the verification phase that is responsible for picking the correct solution. A score function is used to evaluate the candidates of probabilistic solutions for the searched transformation. The goal of a score function is to get a reliable indication, which solution is best. Ideally, the score function attains its maximum for the correct solution and is significantly larger than the score of any wrong solution.

1 INTRODUCTION

In the operation of terrestrial laser scanners, two situations can be distinguished. The data acquisition is done statically from different points of view or a mobile platform is used for kinematic data acquisition. In the latter case a terrestrial laser scanner is usually operated with a combination of a GPS and inertial measurement unit and the data is directly registered using the measured orientation data. One advantage of such mobile measurement systems is the fast acquisition in a short time, but additional hardware is required and the recorded objects must be visible from the road. Vehicles equipped with a terrestrial laser scanner and extern sensors for direct georeferencing are presented for example by Kukko et al. (2007); Asai et al. (2007); Talaya et al. (2004). Furthermore a commercial system equipped with four scanners was developed for the acquisition of street surfaces and the close environment, which is used for the documentation of accidents and the planning of abnormal loads transport (Hunter et al., 2006).

Static laser scanning is mainly done for surveying applications, a detailed data acquisition of objects from any point of view is possible. Each scan position S_i defines a local coordinate frame. The task of the registration is to find a transformation (rotation and translation component) between different scan positions. An euclidean transformation (rigid body) between two scan positions S_1 and S_2 is defined for any corresponding points $\mathbf{x}_1, \mathbf{x}_2 \in \mathbf{R}^3$ with the points \mathbf{x}_1 in S_1 , \mathbf{x}_2 in S_2 by the formula:

$$\mathbf{x}_1 = \mathbf{x}_2' = \mathbf{R}\mathbf{x}_2 + \mathbf{t}, \quad (1)$$

where \mathbf{R} is a 3×3 rotation matrix, and $\mathbf{t} \in \mathbf{R}^3$ the translation vector. For finding the correct values for \mathbf{R} and \mathbf{t} different approaches exist. A method, which is usually supported by commercial software packages for laser scanning data acquisition and processing, is to use corresponding points in S_1 and S_2 . Such

points must be measured manually by an operator or are defined by artificial targets. A drawback of this method is the manual interaction and the additional time exposure for distributing and scanning the targets. Providing point correspondences, the unknown transformation parameters from equation 1 are derived by the minimization of $\sum (\mathbf{x}_1 - \mathbf{x}_2')^2$. Closed form solutions for the more general case of a similarity transformation have been given by Sansò (1973) and Horn (1987).

Many research groups aim at solving the registration task fully automatically without the need of artificial markers or external sensors. Various data-driven registration algorithms have been proposed in the past decade. A distinction has been drawn between *coarse registration*, where the rotation is determined within few degrees and a similarly small translational tolerance is achieved, and *fine registration* for fine tuning of the transformation parameters (Campbell and Flynn, 2001).

A well known algorithm for fine registration of 3D point clouds is the *Iterative Closest Point* (ICP) algorithm proposed by Besl and McKay (1992) and Chen and Medioni (1991). Two point clouds are oriented iteratively by minimizing the distance between corresponding points. Therefore corresponding points are searched and the transformation parameters are calculated alternately. The ICP algorithm requires initial values to avoid that the optimization ends up in a local minimum. Many variants of ICP were proposed, differing in the selection, matching, weighting and rejection of correspondences and the employed error metric. A survey of ICP variants is given by Rusinkiewicz and Levoy (2001). The algorithm is available in commercial software. Other examples for fine registration algorithms applied to 3D surfaces are *Least Squares Matching* (Gruen and Akca, 2005) or a matching method using *Signed Distance Fields* (Masuda, 2002).

The objective of coarse registration methods is to orient arbitrary positioned scans in space. General, robust and automatic methods for the coarse registration of point clouds acquired from

terrestrial laser scanners are still a discussed topic, although research is done since the first 3D sensors have been developed in the 1980s. Published methods can be divided in *global*, *local* and *feature based* methods. Global methods are straightforward and use global properties of the datasets such as principal axes (Chung et al., 1998) or the distribution of scan points (Ripperda and Brenner, 2005). On the other hand the local methods register datasets using only a descriptive subset of the point clouds. One example for a local registration method is the spin image technique. So called spin maps are created for local points by projecting surrounding points and then a matching of spin maps from different scan positions using standard image correlation technique delivers point correspondences for the calculation of the transformation parameters (Johnson and Hebert, 1999).

Feature based registration methods form a major group in coarse registration techniques. The transformation parameters are determined using extracted features from the scan data. In contrast to the global and local methods the data is interpreted and only few but meaningful features are extracted from the data. Depending on the type of extracted features the registration method may be point-based, line-based or extracted planes or other geometric primitives are used. For example Böhm and Becker (2007) extract point features from the intensity channel of laser scan images, Stamos and Leordeanu (2003) developed a line-based registration technique, planar patches are used by Hansen (2006) and planes, cylinders and tori are used by Rabbani et al. (2007), for example.

The remaining part of this paper is structured as follows. First, developed feature based registration methods are presented referencing to former publications of the authors. Such methods always include a search space for matching features and search strategies to find candidates for possible solutions are introduced. The focus of this paper is the selection of the correct solution from these candidates using a *score function*. Variations of score functions based on planar regions and also on the measured point cloud itself are presented. A test scene is shown and the proposed score functions are analysed regarding their effectiveness and reliability.

2 FEATURE BASED REGISTRATION

Feature based registration algorithms for coarse registration are generally divided into the following phases, whereas not all steps must be part of a registration algorithm:

- Feature extraction in the scan data,
- building a search space using the extracted features,
- calculation of possible transformations using a search strategy and
- verification of the correct transformation.

Our registration algorithms have been developed for built-up areas and are based on planes, since planar structures are dominant in urban districts. Therefore the first step is always the automatic extraction of planes from the scan data. A region growing algorithm based on a raster data structure was adopted for 3D laser scans (Dold and Brenner, 2004). The second step is then to establish correspondences between p_1 extracted planes in S_1 and p_2 extracted planes in S_2 . This leads to a complexity of the search space of

$$n = \binom{p_1}{k} \cdot \binom{p_2}{k} \cdot k! \quad (2)$$

possible combinations. The first two terms p_i over k are due to picking k planes from a given set. The permutations of the k identical planes must also be considered, which yields an additional factor of $k!$. To determine all six degrees of freedom of a transformation, three corresponding plane pairs are required. For $k = 3$, the combinations n are reduced by the factor two, since only triples of the same chirality need to be considered, because a right-handed normal vector triple from S_1 can only match a right-handed triple from S_2 . Nevertheless, for $p_1 = p_2 = 50$ plane patches the search space contains 1.15 billions combinations. An exploration of the whole search space and the verification of each solution is not possible, the search space should be reduced using constraints. One major problem is to select combinations from the search space without rejecting the ones that lead to the correct solution.

2.1 Geometrical constraints

A significant reduction of the number of combinations in the matching process is achieved, if geometrical constraints are used. Attributes are derived from the planar patches, which make it possible to establish the correspondences by comparing derived attribute values. Terrestrial laser scanner provide 3D coordinates for each measured point, from which undistorted geometric features can be derived from different points of view. We extracted features such as area, boundary length, height-to-width ratio of a minimum bounding box and intensity values (Dold and Brenner, 2006). Then the matching algorithm first compares the attributes of each extracted plane from S_1 and S_2 , totally $p_1 \cdot p_2$ comparisons must be done. Two features are regarded as similar, if the difference is below a threshold. Plane pairs are ranked by the number of compatible features leading to a list $L = \{C, (e_i, e_j)\}$, where e_i and e_j are candidates for plane correspondences and C is a counter indicating the number of similar features. The transformation parameters are finally derived from combinations of pairs with a high counter.

The drawback of this method is that the feature computation is not sufficiently reliable. Especially if scan positions are further apart, occlusions and differences in sampling density can lead to different feature values. The correct solution may be pruned as well from the search space, if the feature attributes cannot be matched.

2.2 Heuristics based on the orientation of planar patches

Another algorithm preselects suitable patches for the calculation of the transformation parameters regarding to the orientation of planar patches. A sensible criterion for optimal plane triples would be that the error to determine \mathbf{t} in equation 1 is minimized. This happens when all normal vectors of the selected plane triple are perpendicular. Thus the triple product that results in the volume given by the parallelepiped of the normal vectors is calculated for all combinations of each scan position (Brenner et al., 2008; Dold and Brenner, 2006).

In the matching step, the obtained lists containing $\binom{p_1}{3}$ plane triples from S_1 and $\binom{p_2}{3}$ plane triples from S_2 are sorted according to the triple product value in decreasing order. Corresponding plane triples must show a similar triple product value and planes with large triple products are selected from the list

first. Combinations with three plane pairs that fulfil the criteria are assigned. The transformation parameters are computed and verified based on a score function which counts the matching planes. The transformation is then accepted or rejected depending on the returned value of the score function.

Since the best score is not known in advance, as it depends on the (unknown) overlap, we implemented a voting scheme. Instead of testing all triple combinations, iteration stops as soon as the same transformation is found for a predefined number of times. This reflects the assumption that correct triple assignments lead to one and the same transformation, whereas wrong assignments lead to many different transformations. In the voting, only transformations with a minimum score (usually, 40% of the total number of planes) take part.

A drawback of this method is that the maximum value for the triple product is scene dependent. If no plane triples with a high triple product are present in the scene, the lists will contain triple products with lower values and the probability of having triples with similar triple product values increases quickly. In consequence, the search space increases as well and many combinations leading to a wrong transformation must be tested.

2.3 Angle constraints for the selection of planar patches

In order to form a more selective and scene independent criterion, we also investigated the use of the three angles enclosed by the three normal vectors instead of the triple product (Brenner and Dold, 2007). Candidates for the transformations parameters are ranked in a priority list, but are not verified by a score function. The idea is, that a plane triple or pair can only match, if the enclosed angles between the normal vectors are similar. The determination of the transformation parameters can be split into a separate determination of the rotation and translation component. The rotation is fully determined using two pairs of normal vectors. With 50 extracted planes in both scans, equation 2 yields three million possible combinations for $k = 2$, whereas the number of plane pairs with a compatible angle is considerably lower. In a test scene introduced in Brenner and Dold (2007), only about 3-5% of all combinations remained after adopting the angle constraint.

In the next step the rotation component is calculated for each combination with compatible angles and the computed rotation parameters are sorted into histogram bins for the rotation angles (ω, ϕ, κ) . The bins are ranked regarding to highest bin count and yield candidates for the rotation component. The correct rotation parameters are usually represented within the first bins.

To compute the translation component three plane pairs are required, because of restrictions to the position of planes in space. Since we obtained lists with two plane pairs from the first step, we simply pick pairs of quadruples from the bins using the RANSAC principle (Fischler and Bolles, 1981). From the four plane pairs the translation component is calculated in a least squares manner and the matching planes were counted using an inexpensive score function, which compares the plane equations and counts the hits. Again the achieved solutions (rotation and translation) are ranked according to the hit count. As a result we get only a few possible solutions and a selective, but computational more expensive score function can be applied to test for the correct solution.

3 VERIFICATION WITH SCORE FUNCTIONS

A crucial point in a registration algorithm is always the verification step. In this phase of the algorithm a decision must be made,

whether a solution is regarded as correct or incorrect. Since a search delivers many different solutions, the computation time of the verification step must be short, but the score function should also be selective and therefore the complete measured data should be used if possible. We implemented different score functions, which are described in the next sections.

3.1 Compatible planes score

A computational inexpensive score function that was also used in the described search strategies is the comparison of the plane equations. A plane equation $\langle \mathbf{n}_1, \mathbf{x} \rangle + d_1 = 0$ and a transformed plane equation $\langle \mathbf{n}'_2, \mathbf{x} \rangle + d'_2 = 0$ are regarded as similar, if the directions of their normal vectors and their distances to the origin are similar. This can be expressed as

$$\begin{aligned} \langle \mathbf{n}_1, \mathbf{n}'_2 \rangle &\geq \theta \\ |d_1 - d'_2| &\leq \delta \end{aligned}$$

where θ and δ are thresholds for the normal vector angle and the distance to the origin. The advantage of this score function is the small number of comparisons to compute, if p_1 and p_2 are the number of extracted planes in S_1 and S_2 , only $p_1 \cdot p_2$ comparisons are required.

To define appropriate thresholds we investigated the computed score value with different datasets and known transformation parameters. A series of tests on datasets with known overlap were performed using increasing values for the thresholds. As a result the thresholds $\theta = 2^\circ$ and $\delta = 0.15m$ were chosen. With these thresholds the score values represented the overlap of the scans, but are still selective.

3.2 Compatible points score

The aim of this score function is to determine the overlap between two scans by counting similar points. All points of the scan to register are transformed and the similar points in the other scan are counted. In comparison to the planar patch score function, more computation is required, because instead of comparing only a few extracted planes, millions of points must be processed. In contrast to the planar patch score, the point based score reflects that many points supporting a large planar area also have a greater influence in the calculated score than a single plane.

We implemented a data structure using voxel elements with a predefined size for an efficient nearest neighbour search. Therefore the 3D point cloud of the reference scan is overlaid with a three-dimensional voxel raster and the points are sorted into the voxel. To find corresponding points, the indices of a voxel are calculated for each transformed point of S_2 and a similar point is searched only in the respective voxel. To ensure that the nearest neighbored points are actually detected, either the neighbored voxel must be also searched, or all points from the reference scan are sorted not only into their associated voxel but also into all neighbored voxels. Note that the last possibility will increase memory requirements, since each point is stored in 26 additional boxes.

This data structure is also useful to thin out point clouds. Instead of saving several points within the voxels, only one averaged point is saved. The voxel size defines the resolution of the reduced data. When computing the compatible points score first the data structure is created for both scans, the reference scan and the one to register, and then only the reduced point cloud is transformed and the nearest points are searched.

This type of score function requires as parameters the size of the voxels and a threshold for the maximum distance between two

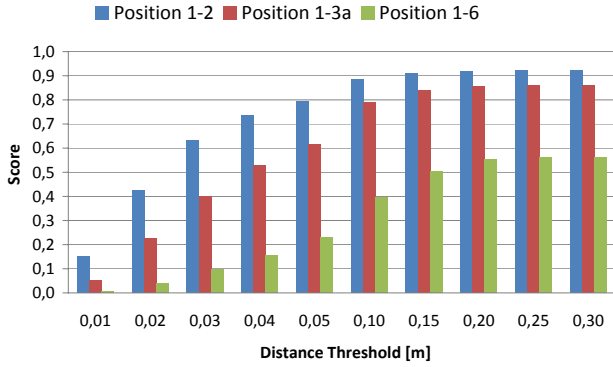


Figure 1: Result of the compatible points score for different distance thresholds. The score was calculated between scan positions with different overlap.

points, which are regarded as corresponding points. Test series showed that small voxel sizes are most efficient when comparing voxels with multiple points, because of the computation time for finding the nearest point within one voxel. The results are shown in figure 1. The optimum distance threshold was derived by calculating the score between scan positions with different overlap¹ for various distance thresholds. For small distance thresholds the score function does not obtain its maximum, which is equivalent to the overlap. As a result a threshold of $\delta = 0.15m$ was chosen. The next two score functions are also point based, but they simplify the search for correspondences and are therefore less computationally expensive.

3.3 Simple box score

This score function is similar to the compatible points score with an averaged point per voxel. Again the reference scan is overlaid with a voxel raster - to differentiate between the other score functions the term box is used in this case. Instead of saving a point with the coordinates x , y and z in a voxel, only a boolean value indicating the occupancy of the box is saved. The box flag is set true, if at least one point is located within the box. For the transformed points of the scan to register it is only checked, if the point lies within an occupied box.

The box raster size defines up to which distance a transformed point has a valid corresponding point and is therefore defined to $d = 0.15m$. The advantage of this score function is, that it requires less memory and the decision, if a transformed point has a correspondent point is very fast.

3.4 Score based on points and local normal vectors

The idea of this score function is to include also the direction of normal vectors from points. Therefore a local plane is estimated for each point using its neighbored points and compatible points only count for the score function, if both, the point and also the assigned normal vector are compatible. The voxel raster data structure (cf. section 3.2) is used to search for corresponding points.

The voxels contain now an additional vector for each point. The purpose of this additional criterion is, that only accurate measured points and points with a correct orientation of their normals contribute to the score value and as a result the score function is more selective.

Figure 2 shows an intensity image and the respective point cloud (thinned out by factor 10) with local estimated normal vectors.

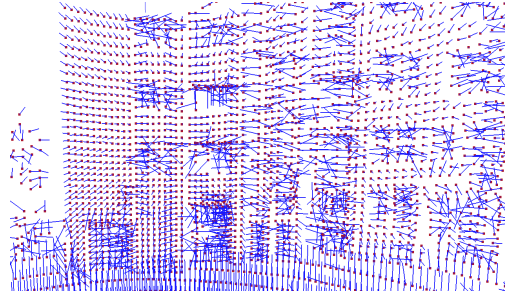


Figure 2: Intensity image (top) and point cloud with local estimated normal vectors (bottom).

The normal vectors of neighbouring points on the wall and from the ground point into a similar direction, whereas the measured points on window surfaces or edges are scattered in all directions. This is because of erroneous measurements of such objects, a laser beam may be reflected from the window pane or from inside.

3.5 Scan raster score

This score function is also based on the measured point cloud and the scan raster is used as data structure. Since terrestrial laser scanners deflect the laser beam stepwise in vertical and horizontal direction, a regular scan pattern with constant angle increments is achieved. The measured point coordinates (x, y, z) are stored within a raster model and each point can be transformed into polar coordinates (ϑ, φ, r) . If the start-, stop-angles and the angle increments of the scan are known, the position of a point measured in S_2 related to S_1 is easily obtained. Figure 3 shows the principle of the data access.

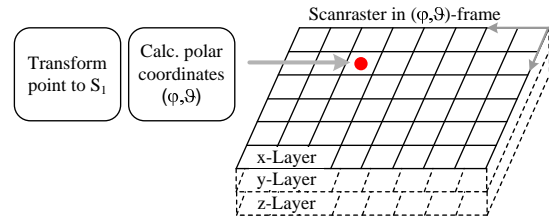


Figure 3: Data access principle using polar coordinates and the scan raster.

To compute the score between two scans, first each point \mathbf{x}_i in S_2 is transformed and then the polar coordinates and the respective raster element in S_1 are derived. The corresponding point is simply picked from the raster using the polar coordinates. If the distance between the transformed point \mathbf{x}'_i and the selected point of S_1 is below a predefined threshold, the points are regarded as corresponding. Tests with different thresholds for datasets with known overlap resulted in a selection of $\delta = 0.15m$ as distance threshold.

¹see also figure 4, the complete dataset is introduced in section 4

4 RESULTS AND DISCUSSION

As an example we selected a densely built-up area in the historic district of Hannover, Germany. The scan positions were placed systematically along a trajectory with a spacing of approximately 5 meters. The scans have been acquired using a Riegl LMS-Z360I scanner, which has a single shot measurement accuracy of 12 mm, field of view of $360^\circ \times 90^\circ$ and a maximum range of ≈ 200 m. At 0.12° step width, a full scan results in a maximum of $3000 \times 750 = 2.25$ million scanned points, of which in the test scene, 1.9 million are valid on average. In total, we acquired 20 scans, of which 12 were taken approximately upright and another 8 with a tilted scan head. The tilted scans were acquired at the same positions as the upright scans. Fig. 4 shows all 12 scan locations in a cadastral map, where tilted scans are marked with an 'a' suffix.

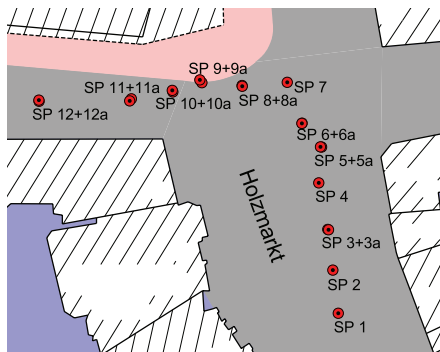


Figure 4: Placement of scan positions shown in a cadastral map. Tilted scan are marked with an 'a' suffix.

The introduced score functions have been applied to the dataset using pairs with scan position one and all others. The histograms in figure 5 show the resulting score values for the reference transformation. As expected the score decreases for scan positions being farther apart. The score based on compatible points is computational expensive but yields the highest score values, which corresponds approximately to the overlap of the scans. The scan raster and simple box score is also based on similar points, but the calculation is faster (factor ≈ 5 and factor ≈ 8 respectively), whereas the score for the scan raster methods decreases rapidly for positions far apart. This is due to constant angular increments of the scans. The compatible planes score produces good results, but exceeds for some combinations the overlap of the scans that implies a non-realistic score value. The points and normals score function implements the hardest criteria and therefore leads to lower but more stable score values.

To evaluate how selective the score functions are, we took possible solutions from our search methods and calculated the score and the deviation from the reference solution. To visualize the deviation we differentiate into a rotation and translation error. The translation error is defined by the euclidian distance between current and reference solution. For the rotation error we express the rotation component using quaternions, in this case a rotation is defined by an rotation axis and one rotation angle around this axis. The rotational error is then regarded as the difference of this rotation angle between the current and reference solution. Figure 6 shows the calculated score as function of the rotational and translational deviation for the combination of the scan positions one and six for the compatible planes score function. Beside the maximum depicted in the rear corner also other peaks exist.

For a comparison of the score functions we select as an example the compatible planes and points-normals score function and

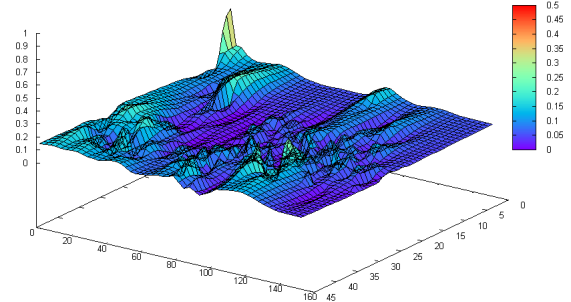


Figure 6: Compatible planes score functions of position combination 01-06. The correct solution is located in the rear corner of the image.

plot the computed score depending on the deviation from the reference. The correct solutions are on the left side of the figures, the rotational error is the depth-axis and the translational error is plotted to the right. (cf. figure 7). Whereas the compatible plane score is more scattered, the point-normals score is for most of the tested candidates almost zero. The point-normals score function is more sensible to wrong solutions, but unfortunately the maximum is not attained for the correct solution. Symmetries in the scene and the different density of the laser scanning data lead to additional peaks in the score function.

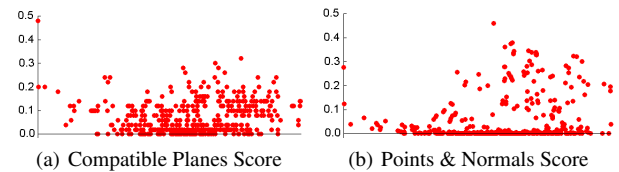


Figure 7: Computed score values for candidates of solution depending on the deviation from the reference.

5 CONCLUSIONS

Various score functions for the evaluation of possible candidates for solutions of a coarse registration for terrestrial laser scans have been introduced and differences between the functions are demonstrated. A fast but simple score function based on the comparison of plane equations was compared to a point and normal vector based score function. The results showed, that the function is more selective but vulnerable to symmetries in the scene. This is mainly because of the different acquisition density of terrestrial laser scanners depending on the measured distance. As a result the point-normals score function gets also peaks for shifted (but not rotated) solutions due. A point based score function with regular distributed points may overcome this disadvantage and also decrease computation time.

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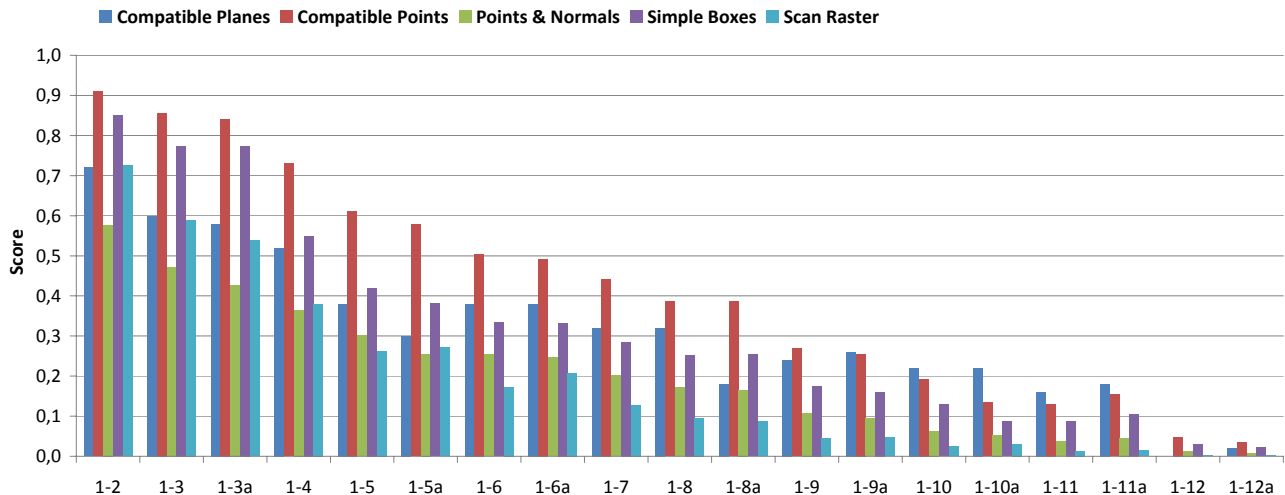


Figure 5: The histogram shows the score (computed with the reference transformation) of the introduced score functions for combinations of scan position one with all others.

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