EXTENDED GAUSSIAN IMAGES FOR THE REGISTRATION OF TERRESTRIAL SCAN DATA

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ABSTRACT

Terrestrial laser scanning instruments are coming more and more into operation. Up to now vendors of laser scanners mainly use manual or semi-automated registration techniques combined with artificial targets to register single scans. The automatic matching of multiple scans without additional targets is still a research topic in the field of terrestrial laser scanning. Many different proposals and algorithms have already been presented to solve this task. Nevertheless, a strong demand remains for fast and robust algorithms for the registration of multiple scans. The problem is difficult to solve and the process is often divided into two stages. First a coarse matching is done in order to determine a pre-alignment of the scanned surfaces. Then a fine matching algorithm is used to achieve more accurate results. Robust algorithms like the well known iterative closest point (ICP) algorithm and lots of variants already exist for the fine matching, whereas the existing methods for the pre-alignment of the scan data are often rudimental and limited. In this paper a proposal for automatic registration of terrestrial laser scanning data using extended Gaussian images is introduced. The method is placed in the coarse matching stage of the registration process and can be used to determine the rotation component between different scan positions. Therefore normal vectors of local or segmented planes of the input data are used.

1 INTRODUCTION

The use of terrestrial laser scanners for object acquisition is increasing. With laser scanners a dense and accurate three-dimensional point cloud of the surface of an object is recorded. For example the instruments are used for monitoring measurements, documentation of historic buildings and monuments and also terrain surveying. Also large urban areas are surveyed with terrestrial laser scanners (GEODATA Ziviltechnikergesellschaft mbH, 2005). One problem in the data acquisition process is the registration process of multiple scans. Single scans from different scan positions are registered to a local coordinate frame defined by the instrument. For data processing the scans must be transformed into a common coordinate frame. This process is termed as registration.

Mobile systems, where the laser scanner instrument is mounted on a car, often use external sensors, for example GPS/INS systems, for tracking in order to achieve orientation data (Talaya et al., 2004). But when using a scanner in combination with a simple tripod for surveying of single or difficult to access objects, a couple of scan positions are usually registered by using artificial markers. This registration technique is usually supported by the operating software of commercial terrestrial laser scanners. Different markers as spheres, retro-reflective cylinders or plane markers are used as tie points between the scan positions. A drawback is the additional required survey time for the registration process. The reason is that the markers must be distributed in the field before scanning. Then the markers must be identified manually or semi-automatically in each scan position and have to be scanned with a high resolution in order to achieve a sufficient accuracy for the position of the tie points. The proportion between the required time for scanning and preliminaries for the registration are almost equal. Due to this drawback, automatic matching methods for multiple scans are proposed and analyzed by many research groups. The intention is to have fast, robust and quasi automatic methods for registration, which can be carried out in the field as far as possible.

2 RELATED WORK

Due to the large point clouds that laser scanners provide and difficulties in existing matching methods with the handling of such large datasets, the industry typically uses separately scanned markers to solve the registration problem. Many research groups aim at improving the registration process of terrestrial laser scans, so the topic is actively discussed in the field of terrestrial laser scanning and 3D modeling. Various matching algorithms without the need of artificial markers have already been proposed. The presented methods are usually calculating features, which are derived from the scan data and matched afterwards. Thereby either only few significant features are extracted from the scan data or lots of less significant features are derived. The used matching strategy is then adapted to the derived features.

Kern (Kern, 2003) describes different registration methods using retro-reflective markers or spheres, which are detected automatically. He also discusses the registration without reference markers and mentions that the determination of corresponding objects in different point clouds is a complex process.

Bae and Lichti (Bae and Lichti, 2004) propose a method for the registration of partially overlapping point clouds using geometric primitives and neighborhood search. The change of geometric curvature and normal vectors of the surface formed by a point and its neighborhood are used to determine the possible correspondence of point clouds.

A registration method in three steps is presented in (Liu and Hirzinger, 2005). First a segmentation is performed and then the matching is divided in a coarse and fine matching algorithm. For the coarse matching a matching tree is used to find the best pre-alignment between different scan positions. The method is particularly suitable for indoor rooms.

Another registration algorithm divided in a coarse and fine matching stage is presented in (Mian et al., 2004). The authors present an automatic correspondence technique for pairwise registration of different views of a free-form object. They define local 3-D grids over the object's surface and represent the surface inside a grid by a fourth order tensor. The derived tensors are matched using a correlation technique. The solution is refined using a variant of the ICP algorithm.

Rietdorf (Rietdorf, 2004) also describes different registration methods and presents a marker free registration method using identical planes. Therefore he installed a special indoor test field with calibrated planes. The transformation parameters between several scan positions within the test field are calculated in one adjustment.

Wendt (Wendt, 2004) uses an operator for feature extraction, which detects features in point clouds as well as in photogrammetric images. Features are first extracted in the images and then evaluated with the point clouds. To match the features the stochastic optimization principle of Simulated Annealing (Metropolis Algorithm) is used.

This paper is a contribution to automatic matching methods without artificial markers. The proposal uses extended Gaussian images of distributed normal vectors for determining the rotation component between different scans. The paper is organized as follows: First the extended Gaussian image is shortly introduced in general. Then the matching strategy is presented. Several examples are used to explain the behavior of the algorithm. The paper concludes with a summary and an outlook to future work.

3 EXTENDED GAUSSIAN IMAGE

Extended Gaussian images are useful for representing the shape of surfaces. A detailed description of extended Gaussian images is given by Horn (Horn, 1984). An extended Gaussian image is based on a unit sphere. Vectors are shifted to the origin of the sphere and projected on the surface.

For this purpose the surface of the sphere is divided into different regions. This process is called the tessellation of a sphere. Therefore a geometric solid is used as an approximation for the sphere with the condition that each vertex

(a) 20 faces (b) 80 faces (c) 320 faces

Figure 1: Tessellation of a sphere, Gaussian spheres

lies on the surface of the sphere. The faces of the solid can be subdivided in a way that again each vertex lies on the surface of the sphere. The more often the faces are subdivided, the higher is the refinement and the unit sphere is more and more approximated. Suitable basic solids for the tessellation are for example an icosahedron, octahedron or tetrahedron. Figure 1 depicts the tessellation of a sphere using an icosahedron as basic solid in different levels of refinement.

3.1 Gaussian spheres used for registration

In this context the extended Gaussian image is used for the registration of multiple scans. Therefore normal vectors are derived from the segmentation of single scans and are mapped on a sphere. For each scan position one sphere is created. The matching is done by investigating the distribution of the normal vectors on the Gaussian sphere.

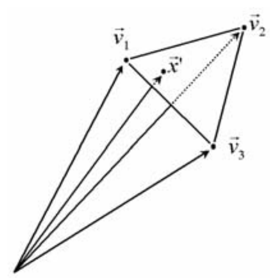


Figure 2: Mapping of a vector to a face on the sphere

A sphere is tessellated in a given level and the normal vectors are sorted into the respective face on the sphere's surface (figure 2). The verification of the correct face, in which a normal vector is mapped, is done by the following linear combination:

$$\vec{x} = \lambda_1 \cdot \vec{v_1} + \lambda_2 \cdot \vec{v_2} + \lambda_3 \cdot \vec{v_3} \tag{1}$$

The vector $\vec{x}'$ in figure 2 represents a normal vector that is projected on one face of the sphere. The vectors $\vec{v_i}$ define the vertices of one face of the Gaussian sphere. If the values λ_1, λ_2 and λ_3 of the linear combination given in equation (1) are positive, the vector $\vec{x}$ lies within the tetrahedron spanned by the vectors $\vec{v_1}$, $\vec{v_2}$ and $\vec{v_3}$. $\vec{x}'$ defines the point of intersection between $\vec{x}$ and a face of the Gaussian sphere. The values of λ_i are computed by:

$$\begin{pmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{pmatrix} = \begin{pmatrix} v_{1_x} & v_{2_x} & v_{3_x} \\ v_{1_y} & v_{2_y} & v_{3_y} \\ v_{1_z} & v_{2_z} & v_{3_z} \end{pmatrix}^{-1} \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix} \tag{2}$$

Using these formulas an extended Gaussian image is calculated for each scan position. The result is a surface of a sphere, which faces contain a different number of assigned normal vectors. The distribution of the vectors on the sphere can be matched and the rotation component can be determined using the Gaussian spheres. An example of an tessellated sphere with distributed normal vectors is depicted in figure 3 in section 4.2. The number of assigned normal vectors is visualized using a color scale from blue to red. The blue color represents faces containing only few vectors, whereas red faces contain a high number of assigned vectors.

4 PROPOSED REGISTRATION METHOD

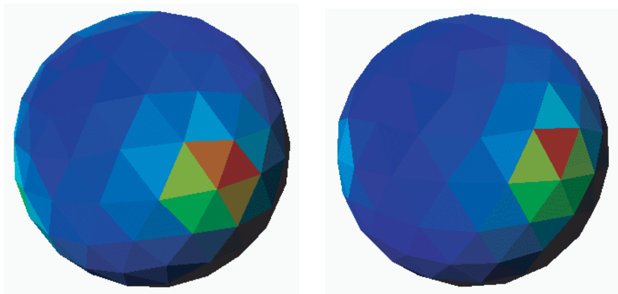
4.1 Segmentation of the scan data

Input data for the matching method are normal vectors of segmented planes of the scan data. Such vectors can be generated in different ways. One method is to segment scan data into planar regions, every region yields one normal vector. For the extraction, a region growing algorithm has been adapted to terrestrial scan data (Dold and Brenner, 2004). The principle in general is to define a seed region first. From this initial region all neighboring points are investigated and it is checked, if they fit to the seed. Rules for the fitting process are used to decide whether the investigated point is added to the seed or not. A region grows until no more neighboring points are added to the region. Then a new seed region is selected from the remaining points and the process starts from the beginning. All steps are repeated, until all points are assigned to a region, all possible seed regions have been used or a predefined maximum number of regions is reached. Usually the number of regions per scan is limited, so only a manageable amount of vectors must be handled later in the matching process.

Another method is to estimate a mass of local regions per scan without any classification. Therefore a window operator is shifted over the scan data and a local plane is estimated using the scan points within the window operator. Thereby a normal vector can be calculated for each scan point except for the boundary points. The quality of the result depends on the size of the operator and the data itself. A normal vector is calculated in any case, also if the window operator is shifted over edges or noise in the data. The advantage of this method is the short time requirement of the algorithm for deriving the normal vectors. But the high number of generated normal vectors must then be processed in the following matching step, so the profit in the time requirement may be reduced or even nullified for the whole registration process.

4.2 Matching strategy

It is assumed that different, but overlapping scan positions containing the point clouds $\{P_1..P_n\}$ are given. From these point clouds sets of regions (clusters) $\{C_1..C_n\}$ are derived by using an extraction method described in section 4.1. Then for a each cluster of normal vectors a Gaussian sphere $\{S_1^l..S_n^l\}$ with the tessellation level l is calculated and the normal vectors of the clusters $\{C_1..C_n\}$ are mapped on the spheres. Now each face of a sphere contains a certain number of assigned normal vectors. Figure 3 shows an example of colorized Gaussian spheres visualized with a color scale for the number of mapped vectors. Theses spheres can be matched in a way that the colored surface fits best. A matching algorithm determines the rotation angles ω, ϕ and κ, which define the rotation component between two scan positions.



(a) Scan 1 (b) Scan 2

Figure 3: Colored Sphere

The rotation matrix, which transforms the points from one scan into the coordinate frame of another is given by:

$$R = R_{\omega\phi\kappa} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \qquad (3)$$

The elements of the rotation matrix are functions of the three rotation angles ω, ϕ and κ. The explicit functions of the elements are given for example in (Kraus, 1997).

The rotation angles between two scan positions are determined with a straight forward searching technique. The sphere S_1^l is set as reference and the other spheres $\{S_2^l..S_n^l\}$ are registered to the coordinate frame of the first one. In the search all possible triples of rotation angles are considered as a possible solution. Therefore all elements of the clusters with normal vectors $C_2..C_i$ are transformed using each feasible rotation triple. Then the transformed normal vectors are mapped on a Gaussian sphere and finally the reference sphere from the first scan is compared with the currently created sphere. The comparison is done by matching the number of normal vectors assigned to the respective face of the sphere. Since the Gaussian spheres can be calculated in a low level with only 20 (level 1) or 80 (level 2) faces, an approximate result for the rotation between two scans is achieved quickly. Only a few triples of angles have to be used to find the best corresponding spheres in a low tessellation level. In higher levels the search is limited since start values are given and the results get more and more accurate. Summarized, the whole registration process is realized with the following steps:

1. Generate a cluster of normal vector lists C_i by planar extraction from each scan position

2. Start with a tessellation level of the Gaussian sphere with the level $l = 1$ or $l = 2$
3. Calculate the Gaussian spheres S_i^l in level l and map the normal vectors on the tessellated sphere
4. Match the spheres in level l
5. Increase l and proceed with step 3 until a solution is determined or a predefined maximum level of tessellation is reached

The main problem of the method is the matching step. There the Gaussian spheres are compared with each other and the spheres, which fit best to the reference sphere must be identified. The characteristic of a sphere is given by the number of normal vectors mapped to one face of the sphere. A criterion for the similarity between two spheres must be defined to obtain a predication of the correspondence quality. Therefore the following criteria may be used:

1. Sum of the difference of normalized number of vectors per face

$$\Delta d_1 = \sum_{i=1}^{n} \left| \, ||N_{S_1^l}(i)|| - ||N_{S_2^l}(i)|| \, \right| \tag{4}$$

$$\frac{1}{\Delta d_1} \longrightarrow max$$

2. Sum of the square difference of normalized number of vectors per face

$$\Delta d_2 = \sum_{i=1}^{n} \left(||N_{S_1^l}(i)|| - ||N_{S_2^l}(i)|| \right)^2 \tag{5}$$

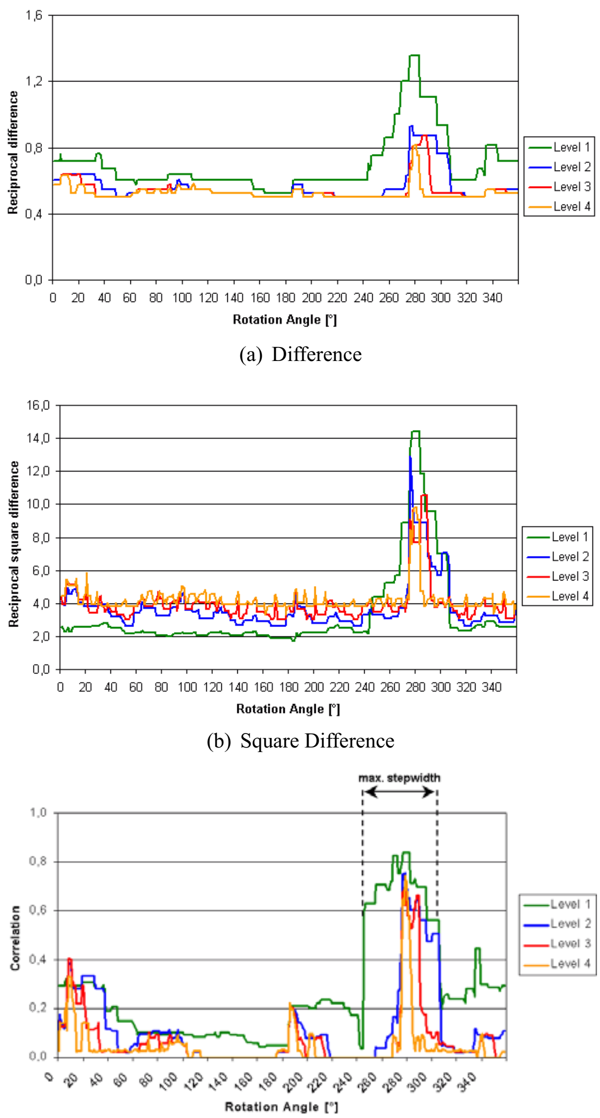
$$\frac{1}{\Delta d_2} \longrightarrow max$$

3. Correlation of number of vectors between the spheres

$$Corr = \frac{< N_{S_1^l}, N_{S_2^l} >}{||N_{S_1^l}|| \cdot ||N_{S_2^l}||} \tag{6}$$

$$Corr \longrightarrow max$$

For analyzing these methods, the critera between two Gaussian spheres were calculated only for the rotation angle κ. The other angles ω and ϕ where fixed at their correct value. The angle κ was incremented with a step width of one degree, and for each value the Gaussian sphere was calculated and compared with the reference using the described criteria. Therefore the data set, which will be introduced in section 5, is used. The charts depicted in figure 4 show the calculated values indicating the similarity of the spheres for each criterion and for each angle between 0 and 360 degrees. Chart (a) shows the result for the normalized difference, (b) for the normalized square difference and (c) for the correlation criterion. The values describing



(a) Difference

(b) Square Difference

(c) Correlation

Figure 4: Correlation between two spheres depending on one rotation angle

the similarity of the Gaussian spheres have also been calculated for different levels of tessellation. In level one the tessellation consists 20, in level two 80, in level three 320 and in level four 1280 faces. The levels are distinguished by different curves within one chart.

The curves for level one show a wide maximum. This is because the normal vectors are mapped to only 20 faces on the Gaussian image. But even there the sector, where the correct solution lies in, is detected clearly. For the next higher levels the peaks in the curves are pointed out more exactly. The identified angle corresponds to the correct value of the rotation angle. The experiments also showed that the correlation criterion or the normalized square difference criterion is most suitable to detect the peaks. The simple difference criterion tends to blurred peaks at a high tessellation level, so that it may be difficult to detect the correct solution. For this reason, the use of the square difference and correlation criteria is selected for further investigations and experiments. Another result of the test can be read off the chart in figure 4. The step width of the rotation angles in the straight forward search can be determined for each tessellation level. For example in level one an increment between 20° and 30° for the rotation angles would be sufficient to detect the peaks. This results in only a few triples of angles for the first tessellation level, where the Gaussian sphere must be calculated and compared with the reference sphere. In the next higher levels the step width is reduced and the approximate solutions of the precedent calculation are used as initial values. This technique ensures a fast and efficient search.

In some cases the determination of the correct rotation angles with only using the number of normal vectors per face as matching criterion failed. Therefore the matching strategy has been improved and another additional matching criterion is also used to enhance the correlation values between the spheres. A suitable attribute therefore is the area of an extracted plane that supports the matching result. If planes are extracted from the scan data, it is also possible to derive the area of the segmented plane from the 3D scan data. Therefore all scan points assigned to a plane are projected on the plane and then the convex hull of these points is determined. The convex hull defines the boundary of the plane and the area of the plane is calculated from the boundary points using the area formula by Gauss (Gruber, 1998). The area of each plane is then added to the faces of the Gaussian sphere as additional attribute. If more than one normal vector is situated within one face, the area values are added. In the matching process the correlation of the area between the spheres is calculated and merged with the correlation of the number of normal vectors. So the quality and reliability of the correlation is stabilized.

5 PRACTICAL EXPERIMENTS AND RESULTS

Terrestrial laser scanner instruments acquire 3D points directly at a high scanning rate usually by measuring the time of flight of the laser pulse and polar angles of the laser beam. The derived coordinates are then available in a local coordinate frame referred to the scan position of the instrument. Because of this fact there is no restriction for the orientation of the laser scanner instrument, so multiple scan positions may be chosen freely in space. Thus, there is no need to setup a laser scanner instrument horizontally as with other geodetic instruments. The field of view of the scanner may be adapted to the object, which is acquired with the scanner by using tilt mounts of the laser scanner instrument.

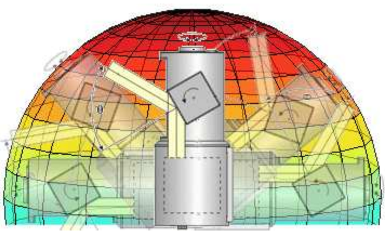
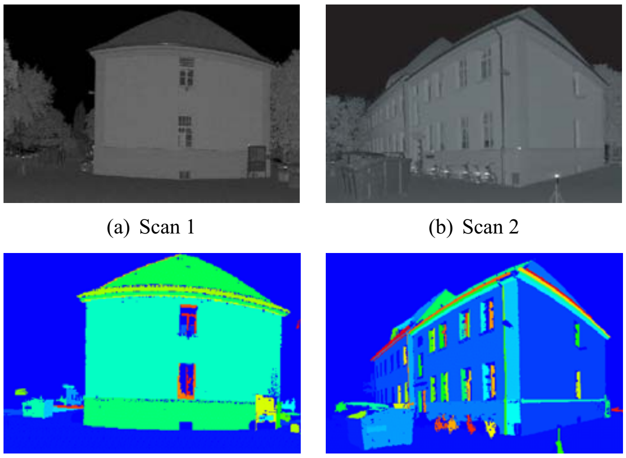


Figure 5: Half sphere defines range of rotation angles

The instruments are usually not mounted upside down, so the range of the rotation angles is restricted within a hemisphere as depicted in figure 5. The angles ω and ϕ range from -90° to +90° and the angle κ ranges from 0° to 360°. The rotation angles are iteratively determined by the searching strategy described in section 4.2.

The practical results of this proposal are shown for example with a recorded dataset using a Riegl LMS Z360i laser scanner instrument. The registration in the example is limited to two scan positions. The object was scanned from different points of view and the registration technique with artificial markers was applied. Thus reference values for the transformation parameters of the scans are available. The reference rotation angles were determined on the basis of the components r_{ij} of the rotation matrix (cf. equation 3), which are given by the used data acquisition and registration software. The scanner was not setup horizontal exactly, but also no tilt mount was used to scan the object. Therefore the angles ω and ϕ are close to zero.



(a) Scan 1 (b) Scan 2

(c) Segmented scan 1 (d) Segmented scan 2

Figure 6: Example dataset

The acquired scene contains a facade of a building scanned from different positions. The scans overlap each other partly. The recorded point clouds are depicted in figure 6, part (a) and (b). Planar regions were extracted automatically from the scan data and the size of the areas were calculated and used as additional attribute for the matching. The result for the segmentation of the scan data in planes is also depicted in figure 6, part (c) and (d). The normal vectors and the area size of the planes as additional attribute are mapped on the Gaussian spheres.

The search technique starts with using a large angle increment and a low tessellation level for the first iteration in order to achieve an approximate solution quickly. Thereby, in practice a Gaussian sphere containing 80 faces (level two) and an angle increment of 20° is suitable and yields a sufficient solution for the first iteration. The result are various candidates of rotation angles. The calculated fit value describing the similarity provides a measure for the matching result. Afterwards the result is refined by further iterations. The searching area is limited and the step width of the angles is reduced. Four iterations have been processed and the angle increment of the last iteration was

0.1°. The determined values of the rotation angles and also the reference values are listed in table 1.

	$\omega[°]$	$\phi[°]$	$\kappa[°]$
Reference Values	-3.05	0.16	-82.09
1. Iteration	-15.00	0.00	-67.50
2. Iteration	-2.00	-2.00	-82.00
3. Iteration	-4.00	0.00	-83.50
4. Iteration	-4.50	-0.10	-83.20

Table 1: Rotation angles after registration process

The correct solution is not exactly detected, the values even get worse at the last iterations for the angles ω and κ. But nevertheless the method yields a coarse solution, which can be used as input for a subsequent fine alignment of the laser data. A well known method is the iterative closest point algorithm (Besl and McKay, 1992) and its variants.

6 SUMMARY AND OUTLOOK

In this paper a novel approach for the determination of the rotation component between different scan positions for registration purposes is proposed. The method uses extracted normal vectors from terrestrial scan data and maps them on an extended Gaussian image. The generation of Gaussian spheres for different levels of details, the mapping of the normal vectors and the described matching strategy was implemented. The distribution and accumulation of the vectors may be visualized by colorized faces of the Gaussian image (cf. figure 3). Such colorized spheres of different scan positions are matched using attributes like the the number of vectors sorted into one face of the sphere and the area of extracted planes. The functionality of the algorithm was investigated by a straight forward search technique and an example was given.

The presented work shows that it is possible to use extended Gaussian images for registration in general. The major advantage of the Gaussian spheres is the fact that various levels of tessellation can be used. Thereby a fast convergence of the matching process and different stages of accuracy are achieved. In the future further investigations of the algorithm's functionality will be made using other datasets. Also a method for determining the translation component between different scan positions must be added to the proposed registration method. Then an iterative fine alignment can be applied to the registration process by using for instance a variant of the ICP algorithm.

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