TERRESTRIAL LASER SCANNING FOR AREA BASED DEFORMATION ANALYSIS OF TOWERS AND WATER DAMNS

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Abstract: Laserscanners have so far not frequently been used for high precision engineering geodesy measurement tasks, such as deformation monitoring, since the technical specifications of most laserscanners do not fulfil the accuracy requirements in such applications. The paper describes methods which allow for the use of laserscanners in this field. The methods are based on the analysis of highly redundant unstructured point clouds which represent the surface of objects. The precision potential in these applications is not limited by the single point accuracy of laserscanners, since surface elements derived from a large number of points are used for deformation analysis. The practical example presented here is the determination of the bending line of a television tower. Finally an outlook on future work - the analysis of deformations on water dams – will be shown.

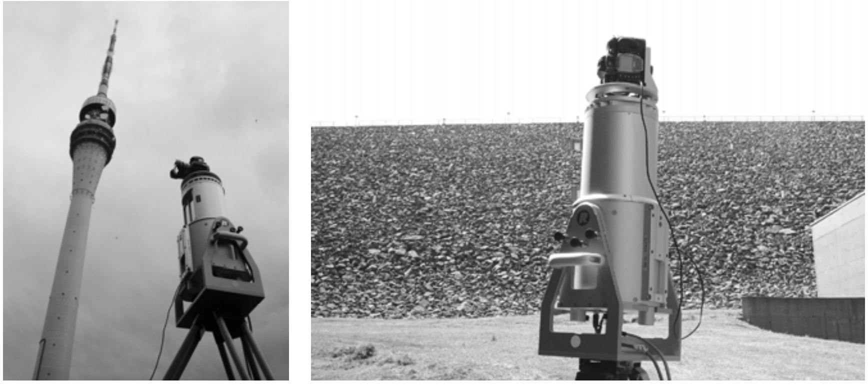


Figure 1: Laserscanner Riegl LMS-Z420i for deformation analysis of towers and water dams

1. Introduction

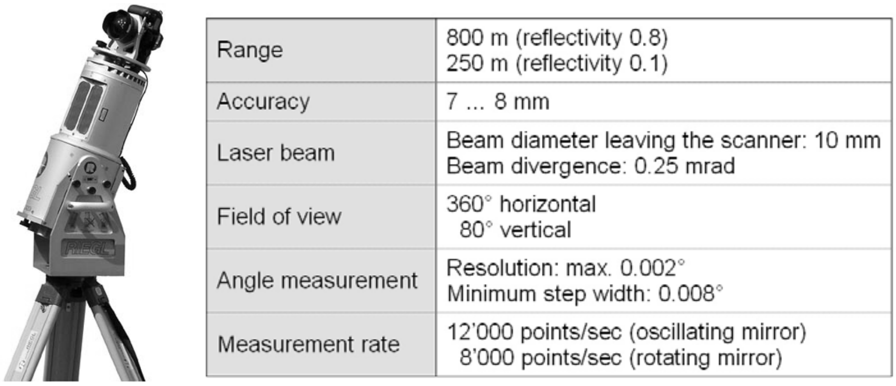
Metrological monitoring of large structures, in particular towers, bridges or water dams, is an important subject, since such objects might cause an immense damage in case of a malfunction. Measurement devices and techniques in this field are mainly based on the monitoring of discrete points. Besides photogrammetric techniques (e.g. [8]), for the recording of surfaces nowadays laser scanners are used, which acquire dense point clouds in very short time. However, laserscanners have hardly been used for high precision building monitoring tasks, since their single point precision is mostly not sufficient. HESSE & STRAMM [4] already describe possibilities and challenges of laserscanners in deformation measurement applications with two example projects, an underwater tunnel and a water lock gate which show surface deformations due to water pressure. Further investigations of laserscanners in deformation applications are shown in Girardeau-Montaut et. al. [3] and Lindenbergh et. al. [7]. Hesse et. al. [5] presents the deformation analysis on a wind energy turbine by investigating the amplitude spectrum of time series of laserscanning data.

In the research presented in this paper techniques have been developed and tested which allow an area based analysis of the deformation, going beyond the single point accuracy by deriving deformation parameters from a large number of points representing the surface under the assumption of mainly stochastic parts in the single point error budget. A similar approach for the accuracy enhancement of 2D profiles extracted from laserscanner point clouds is presented in Bienert [2].

The object used for the analysis is a television tower, where the goal of the research was to determine the bending line and its accuracy. As a first step the point cloud was cut into thin layers and projected onto 2D planes in different height levels. Then a circle-fit algorithm was applied to these planar point clouds, where the centre points of the circles have a much higher precision than the original laser scanner points. The connection of centre points obtained at different height levels represents the bending line.

2. Laserscanner Riegl LMS-Z420i

The laserscanner used for the investigations was a Riegl LMS-Z420i (Fig. 2). This time-of-flight scanner provides a range of max. 800 m and is therefore well suited for recording large objects in applications such as architecture, as-built surveying and city modelling. The 3D point coordinate precision is ca. 7 – 8 mm (cp. [9]), and the scanner covers a 360° × 80° field of view. The system includes a digital camera (Nikon D100), which can be used to colorize point clouds or to texturize triangulated surfaces.



Range	800 m (reflectivity 0.8) 250 m (reflectivity 0.1)
Accuracy	7 ... 8 mm
Laser beam	Beam diameter leaving the scanner: 10 mm Beam divergence: 0.25 mrad
Field of view	360° horizontal 80° vertical
Angle measurement	Resolution: max. 0.002° Minimum step width: 0.008°
Measurement rate	12'000 points/sec (oscillating mirror) 8'000 points/sec (rotating mirror)

Figure 2: Laserscanner Riegl LMS-Z420i

2.1. Accuracy tests

In order to analyse precision potential of the instrument, several preliminary investigations were carried out (cp. [9]). One is the investigation of the standard deviation of point clouds representing a plane. For this purpose a metal plate (ca. 1 m²), which was put up in front of the laserscanner, was scanned. Then a plane adjustment was applied and the standard deviation of the point cloud was investigated. The test was split into an indoor test with a range up to 30 m and an outdoor test with a range of 50…900 m. The results of both tests are visualized in Fig. 3. It shows that the standard deviation of the point clouds recorded with the

Riegl LMS-Z420i is less than 10 mm in the closer range and up to 18 mm in the farer range. The characteristics of the noise turned out to be perfectly gaussian.

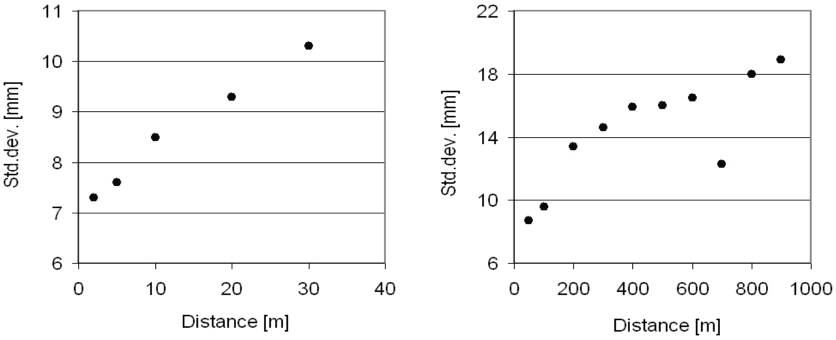


Figure 3: Standard deviation of plane adjustment depending on the measurement distance

2.2. Point cloud registration

In deformation monitoring applications the orientation of measurement data is a crucial point. Laserscanner point clouds can be registered using surface based algorithms, such as ICP (iterative closest point) or using algorithms which base on discrete points. If the measurement task requires an absolute orientation of the laserscanner data, in most cases control points have to be used. In this case, it is of particular interest how accurate the control points can be detected. In order to investigate this, a retro-reflecting target was shifted stepwise horizontally, vertically and in depth direction. The scanner software is able to measure the target centre with mm-accuracy applying an intensity-weighted centroid operator on multiple points covering the target. The deviations between target and actual shift are listed in table 1, which shows that signalized points can be measured at a precision much better than single point precision, with the planimetric coordinates better than the depth coordinate.

Horizontal shift			Vertical shift			Depth shift		
$\|\Delta S\|_{target}$ [mm]	$\|\Delta S\|_{actual}$ [mm]	Deviation [mm]	$\|\Delta S\|_{target}$ [mm]	$\|\Delta S\|_{actual}$ [mm]	Deviation [mm]	$\|\Delta S\|_{target}$ [mm]	$\|\Delta S\|_{actual}$ [mm]	Deviation [mm]
5	5	0	5	6	1	5	4	-1
10	10	0	10	10	0	10	7	-3
15	15	0	15	14	-1	15	12	-3
20	19	-1	20	20	0	20	18	-2
25	24	-1	25	24	-1	25	23	-2

Table 1: Point measurement precision on a retro reflecting target

In a further practical test the registration of a point-cloud, based on 15 retro-reflecting targets used as control points, were investigated. The standard deviation of the registration resulted in 2.1 mm, which is ca. 4 times better than the single point accuracy. This value, however, indicates a limitation for the detectability of absolute deformations. Registration algorithms based on surfaces instead of targets (e.g. [1]) – applied on surfaces in the non-deformation area – might have the potential to increase the registration accuracy beyond this value.

3. Television Tower

The Dresden television tower was built in 1963-1966. The height is 252 m and the diameter at the bottom is 9.40 m. The baseplate is situated 5.5 m beneath the ground surrounded by granite stone and has a diameter of 21 m. Up to a height of 167 m the tower consists of a ferroconcrete construction. Today it is used for telecommunication purposes and it is not publicly accessible.

Since the construction of the tower, geodetic measurements have been conducted annually. One is the trigonometric surveying of the vertical bending line by horizontal and vertical angle measurements from two orthogonal viewing directions. With the trigonometric measurements absolute movements as well as daily amplitudes can be detected. Furthermore, precise leveling at the towers bottom and hydrostatic leveling in the cellar are carried out annually in order to analyze the detected deformations.

In the following, the determination of the tower bending line from terrestrial laserscanner data will be described. The geodetic measurements will be used as reference measurements.

Figure 4: Television Tower

3.1. Practical work

In order to get an absolute orientation a traverse was measured with a total station considering the reference points in the surrounding of the television tower (Fig. 5). In the local surrounding of 4 possible laserscanner stations (close to point 1000, 3000, 6000 and 10000) retro-reflecting targets were distributed which were included into the object's reference system additionally. The laserscanner software is able to detect these retro-reflecting targets fully automatic and determines the target centre with mm-accuracy applying an intensity-weighted centroid operator. Thus, the laserscanner positions were oriented in the absolute reference system (cp. 2.2.).

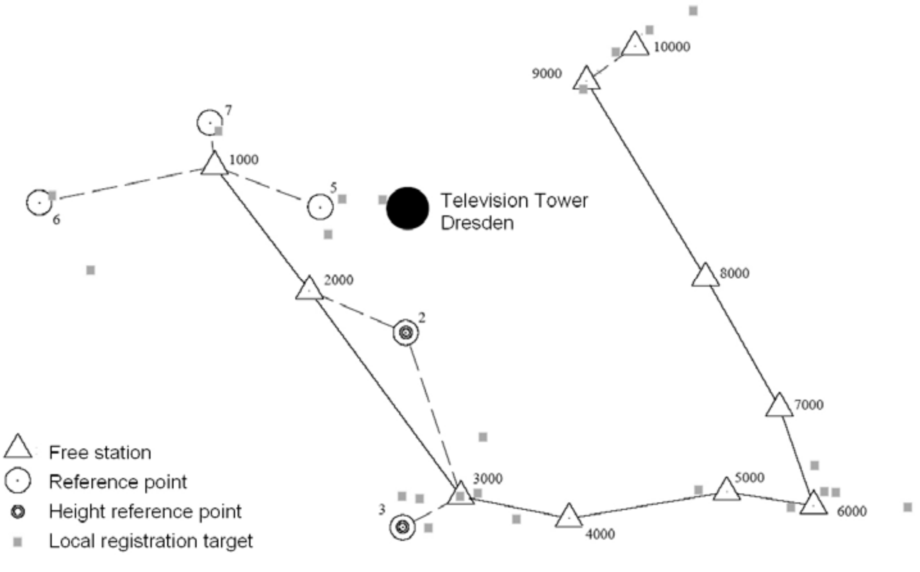


Figure 5: Network diagram

For practical reasons only one of the four laserscanner position was used (close to point 1000) for the determination of the bending line. The other laserscanner positions were only used to generate a 3D model of the television tower.

3.2. Bending line determination method

The conventional geodetic measurements for bending line determination use discrete points attached to the tower's surface. Annual measurements of these targets allow for the deformation analysis of the tower with respect to a zero epoch. The reconstructed tower axis is represented by those discrete points.

The idea of the proposed method is to use unstructured laserscanner point clouds representing the surface of the tower. For this purpose the point cloud, recorded from one position, was cut into more than 15 thin layers in different height levels (Fig. 6) with a thickness of ca. 5 cm, to ensure that enough points will be used for the determination of the tower axis. Afterwards the points of each layer were projected onto 2D planes. The mathematical basis for the intersection of point clouds with an intersection plane is explained in detail in [6].

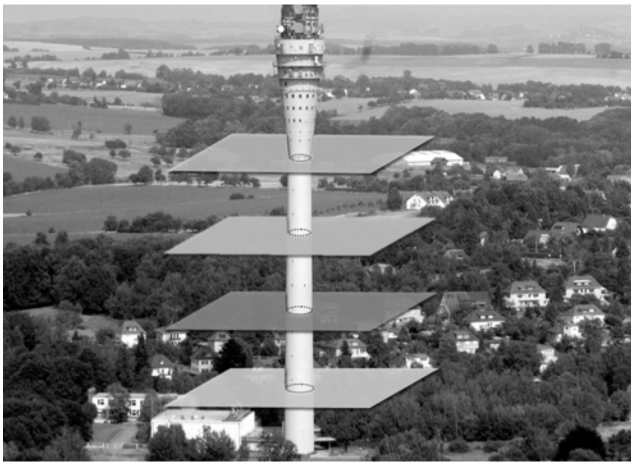


Figure 6: Cut of the point cloud into thin layers and projection onto 2D planes

On each 2D layer a circle-fit algorithm was applied to the planar point clouds, where the square sum of the radial distance of each individual point to the circle is minimized:

$$d_i = \sqrt{(x_i - x_M)^2 + (y_i - y_M)^2} - R \qquad \sum d_i^{\,2} \rightarrow \min \tag{1}$$

The result of this algorithm is the centre point and the radius of the tower in different height levels (Fig. 7). In case of a homogeneous surface the precision of the centre points of the circles should have a much higher precision than the original laserscanner points. The connection of centre points achieved from different height levels represents the bending line.

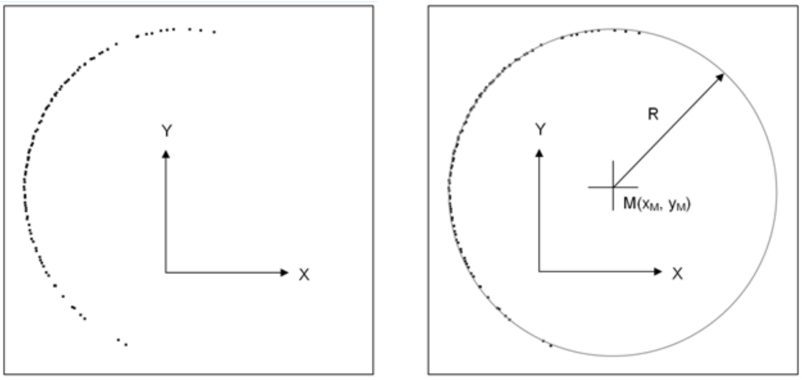


Figure 7: 2D Point cloud and circle fitting

This method can be applied fully automatically. The main advantage of the method is fast data acquisition and processing as well as the description of the bending line by an arbitrary number of intersection planes, where each intersection represents the surface by a large number of points.

3.3. Results

The results of the circle fitting of a selection of point cloud intersections are summarized in table 2. The average precision of each laserscanner point is ca. 8 mm, with some points having a deviation of up to 3 cm. Taking this into account, the standard deviation of the centre point coordinates have a higher accuracy than the original laserscanner points, as supposed. However, the accuracy of the fitting algorithm seems to be two times better in y-direction than in x-direction. This can be explained by the lateral and depth precision characteristics of the laserscanner. To achieve homogeneous and higher accuracy, at least two orthogonal laserscanner views would be required. This seems unrealistic, as - strictly spoken - both datasets should be recorded simultaneously by two instruments in order to avoid blurred results due to the movements e.g. caused by temperature changes.

Tower Height [m]	x_M [m]	σx_M [mm]	y_M [m]	σy_M [mm]	R [m]	σR [mm]
0	7.625	6	6.093	3	4.604	6
10	7.638	5	6.098	2	4.486	4
20	7.654	4	6.116	2	4.381	4
30	7.640	5	6.125	2	4.249	4
40	7.646	5	6.157	2	4.129	4
50	7.645	6	6.165	3	3.997	5
60	7.642	7	6.199	3	3.873	6
70	7.661	11	6.205	5	3.760	10
80	7.701	9	6.204	4	3.644	7
90	7.749	8	6.217	3	4.142	6

Table 2: Circle fitting results of epoch 1

Figure 8 shows the determined circle centre points split into X- and Y-component. Obviously there is a deviation between the tower axis and the vertical coordinate axis of ca. 20 cm at a height of 150 m. At first a misalignment of the horizontal orientation of the laserscanner was supposed. A comparison with trigonometric measurements from 1968 to 1991 (Fig. 9), however, confirmed the tilting of the television tower partly.

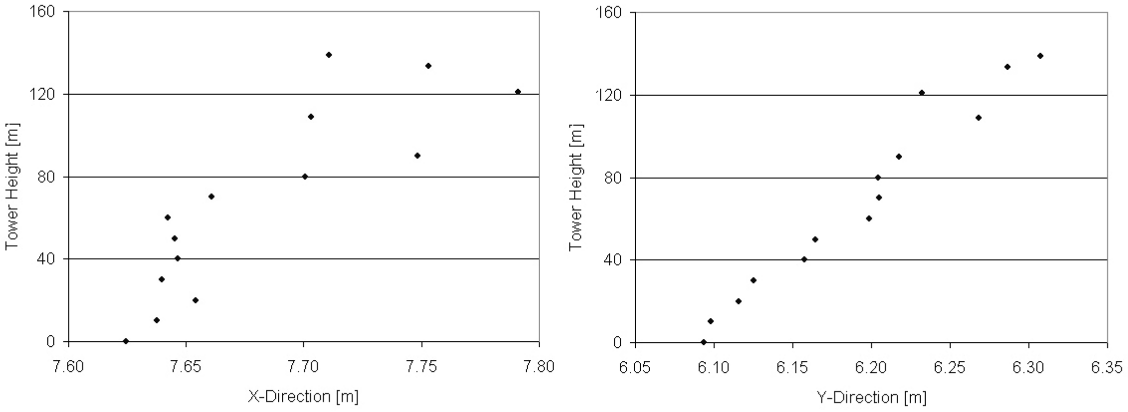


Figure 8: Extracted tower axis of epoch 1

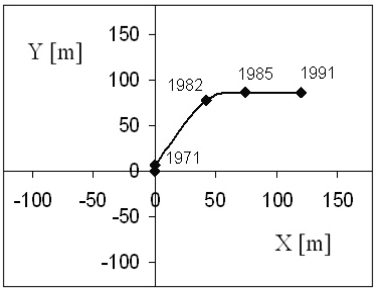


Figure 9: Geodetic measurements 1968-1991

Finally the difference between the tower axes of two epochs, which were measured with a time difference of ca. 4 hours, was calculated. In this time the temperature changed and the sun started to shine on the tower's surface from southern direction. Therefore deformations were expected mainly in y-direction. This is confirmed by the difference between the two bending lines of the two epochs split into the x-direction and the y-direction (Fig. 10). While no significant difference is noticeable in the east-west direction (X), a change of ca. 13 mm per 130 m is visible in north-south direction (Y).

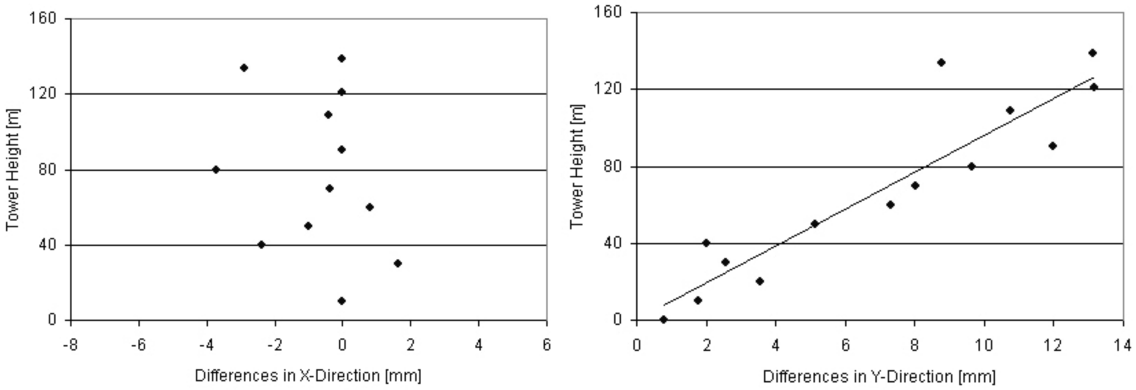


Figure 10: Difference between tower axis of epoch 1 and 2

4. Applications on water dams

Another investigation will be carried out on two water dams, one with a loose stone surface (Lichtenberg, Germany) and one with a concrete surface (Rauschenbach, Germany) (Fig. 11).

Figure 11: Water dams Lichtenberg (left) and Rauschenbach (right)

The dam Lichtenberg shows a bulge in the surface. The size and the shape of this bulge shall be detected. Since this is a laminar deformation, the benefit of the information density delivered by a laserscanner over the time-consuming conventional measurement of many discrete points has to be examined. In order to further analyse the potential of laserscanners, the dam Rauschenbach with its more regular surface will be also included into the investigations.

The idea of deriving structural deformation information from laserscanner data is again to improve the precision of single laserscanner points by considering the surrounding of a point, i.e. a group of points representing a surface element. In the most simple case, this surface element might be a small planar patch (dam Rauschenbach); in a structure with higher complexity (dam Lichtenberg), elements could be described by a triangulation. It is also possible to reduce the complexity to a 2D analysis by replacing surface elements by profile lines (similar to the method applied to the television tower). If the accuracy of a single point recorded with a laserscanner is 7…8 mm, the accuracy of the position and orientation of surface elements will usually be much better. The easiest description of a surface element is the centre of gravity of points belonging to this element and in case of a plane the direction of the surface normal. For complex 3D-shaped surface elements such as a stone the orientation may be obtained from a principle axis analysis applied to a segmented point cloud.

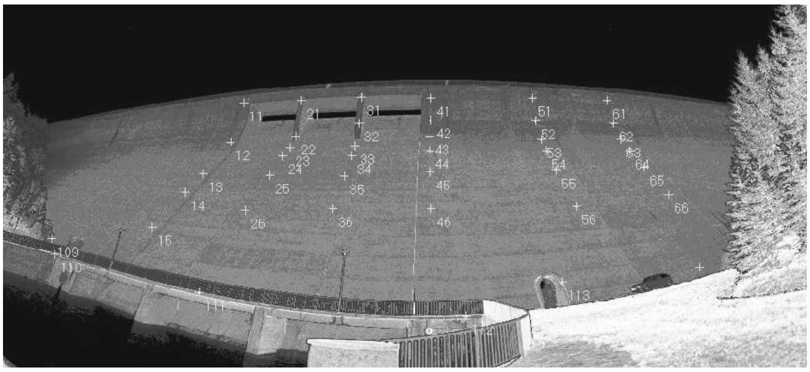


Figure 12: Intensity image of dam Rauschenbach incl. check points

5. Outlook

The presented investigations show the potential of laserscanner data in monitoring applications and may widen the application field of monitoring techniques, though they do not claim to substitute proven methods. There are some improvements which should be considered in future investigations. For example particular attention should be directed to the geometric referencing of the laserscanner, because most laserscanners do not offer the option to level the device. Furthermore the accuracy and longterm calibration stability of laserscanners is not as good as the accuracy of conventional tacheometers.

The next step on the way to automatic deformation measurement will be the automatic segmentation of surfaces of one epoch into structural surface elements. The same surface element will be selected in a second epoch. The points belonging to these elements will be used to fit a parameterised primitive (plane, sphere, spline surfaces) into this point cloud. The size of these sub-segments has to be adapted to the characteristics of the object at hand. The comparison of the parameters of the primitives in both epochs allows drawing conclusions about the deformation (global and local) of the object. The results may be visualized in images with a coloured scale, indicating the deformation values.

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