Development of a novel gauge filled with resin for X-ray CT

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Abstract

X-ray computed tomography (CT) systems have been widely used for three-dimensional (3D) measurements in the engineering field. Therefore, verifying X-ray CT systems with full traceability is necessary to ensure accurate measurements. Measurement errors of X-ray CT systems are evaluated using a reference gauge whose geometry is calibrated using 3D measuring systems with higher accuracy. Thus, this study developed and characterized a novel reference gauge for X-ray CT systems, comprising spheres embedded in a cylindrical resin.

Keywords: X-ray CT, Calibration, Verification, Three-dimensional measurement

1 Introduction

There is a high demand for X-ray computed tomography (CT) systems to investigate industrial products' external and internal three-dimensional (3D) geometry. Verifying X-ray CT systems is important when used for research, development, and quality management in the manufacturing field. In addition, the X-ray CT systems are verified using reference gauges calibrated by other 3D measuring systems. Geometries of the gauges, such as 3D positions or distances, are measured using an X-ray CT system, and the measured values are compared with reference values.

Various reference gauges have been proposed. Requirements for the reference gauge include traceability and small uncertainty. For example, one reference gauge has some ruby spheres as measured elements supported by ceramic shafts [1]. Hence, *artefacts* can be generated in the X-ray CT data because ruby spheres and ceramic shafts are overlapped in some transmission images but not in others. As a result, *artefacts* may cause measurement errors of the X-ray CT system and affect the verification of the system. Another reference gauge has steel spheres on a cylindrical body made of carbon fibre tubes [2,3]. Thus, the position measurement performance of the system can be verified only within the cylindrical shell area.

All positions in the measurement volume of the X-ray CT system must be measured. However, a reference gauge for an X-ray CT system that generates no *artefacts* and measures any position has not been developed Therefore, we proposed the concept of a novel reference gauge for X-ray CT systems [4].

2 Novel gauge filled with resin for X-ray CT as the reference standard

The proposed gauge has some spheres embedded in a cylindrical resin (Figure 1), which is epoxy mixed with a curing agent. The spheres are made of silicon nitride, and their radii are 1.5 mm. The most important design of the gauge is that the cross-section images of the gauge measured using an X-ray CT system have no *artefacts,* and all positions in the measurement volume of the X-ray CT system can be measured. The gauge is designed according to the following four points: first, the influence of *artefacts* is reduced in cross-sectional images of X-ray CT systems because the cylindrical shape aids the constant transmission of X-rays at any rotational position. In addition, each sphere is placed at a different height to avoid overlapping between the projected spheres. Second, the spheres can be placed arbitrarily in the resin. Third, various gauge sizes are desirable, depending on the source-to-object distance affecting the magnification range of the X-ray CT system. Fourth, small gauges (<40 mm) are available. Finally, the gauge can be made at a low cost.

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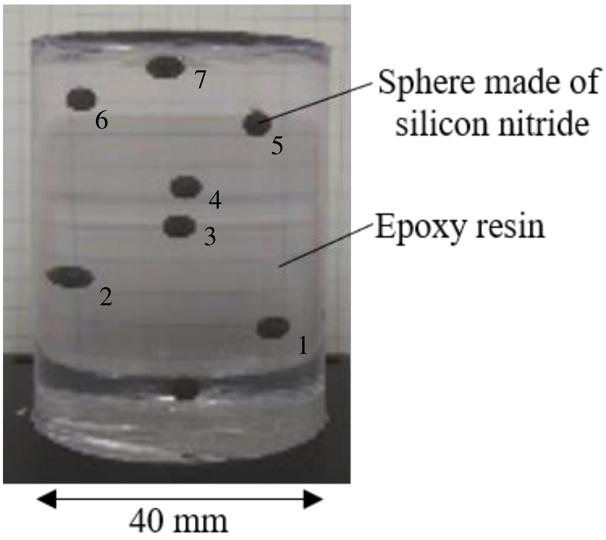


Figure 1: Gauge filled with resin.

3 X-ray CT measurement of the gauge

We measured the sphere's center-to-center distance of the gauge filled with resin by X-ray CT, using XDimensus300s (Shimadzu Corporation). The measurement error of the sphere's center-to-center distance declared by the manufacturer is (3.8 + L/50) µm (L in mm). The air temperature inside the system cabinet is maintained at 20°C. Figure 2 shows the 3D volume data and cross-section image of the gauge. *Artefacts* introduced from the overlaps mentioned above cannot be observed. Because the *artefacts* tend to be introduced at the polar caps of the sphere, the parts are excluded from the sphere's fitting area.

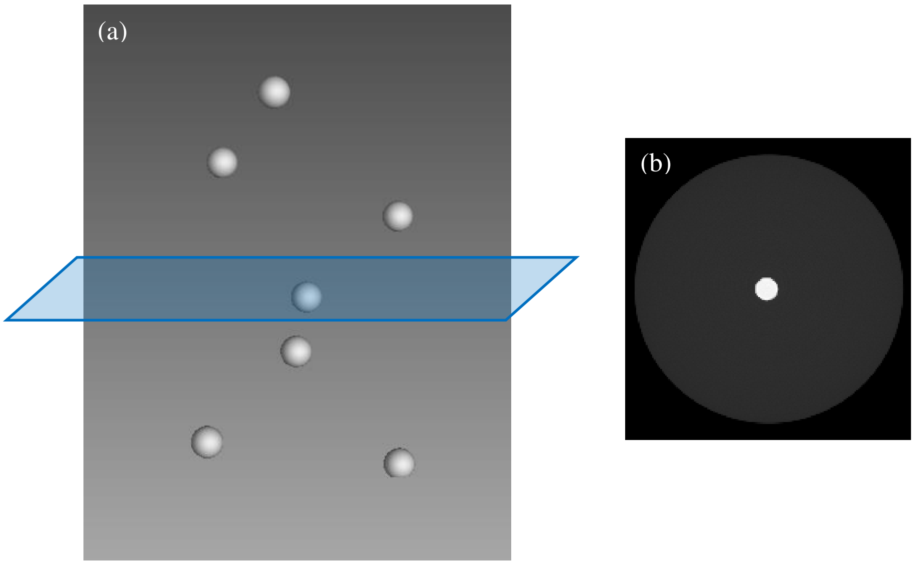


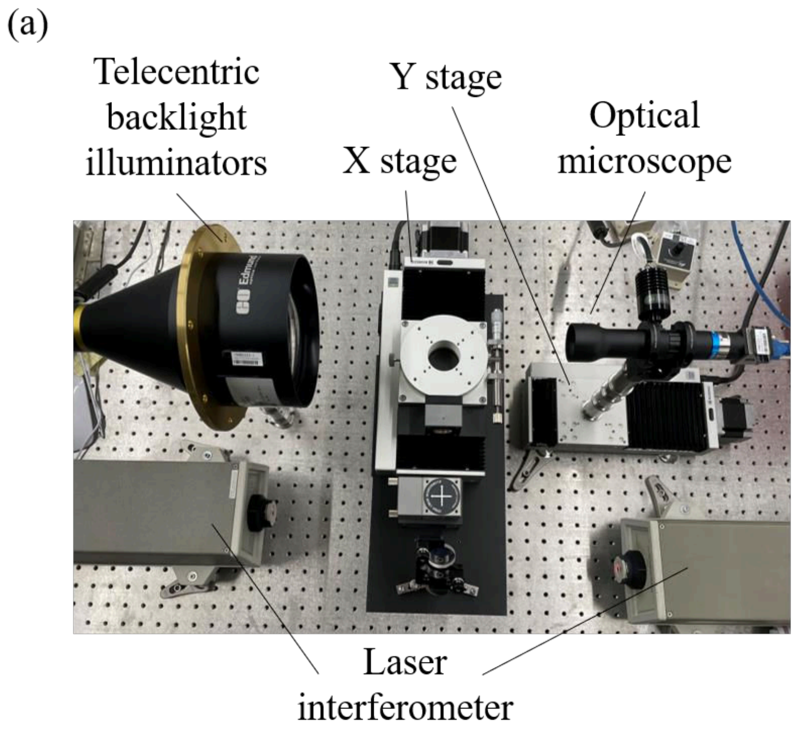
Figure 2: (a) Three-dimensional volume data of the gauge. (b) Cross-sectional image on the highlighted plane in (a).

4 Calibration of the gauge filled with resin

The previous used gauges developed are calibrated using tactile coordinate measuring machines (CMMs); however, the proposed gauge cannot be measured using tactile CMMs, because spheres are filled with resin. On the other hand, image measurement machines might be available for existing contactless measuring machines that can measure the novel gauge. The image measurement machine observes objects from above through an optical microscope, then X and Y coordinates of spheres in the gauge can be measured. However, the gauge must be laid down to measure Z coordinates as the means of the image measurement machine. As mentioned below, the measurement for which the gauge is laid down is not preferable. Therefore, we developed a novel measuring system that can measure the gauge from the side.

<u>Optical measuring system of the proposed gauge</u>

Figure 3 shows an actual and schematic measuring system we developed. The measuring system comprises X and Z stages, an optical microscope and two laser interferometers. The novel gauge is set on a rotary stage in conjunction with the X and Z stages. This is because the measurement from the two sides by turning the gauge 90° is needed to measure the 3D coordinates of the gauge's spheres. The moving distance of the X or Z stage is measured using each laser interferometer. The optical microscope can move on a Y stage for focalization. A telecentric lens is used in the optical microscope because the image sphere size is left unchanged with sphere displacement.



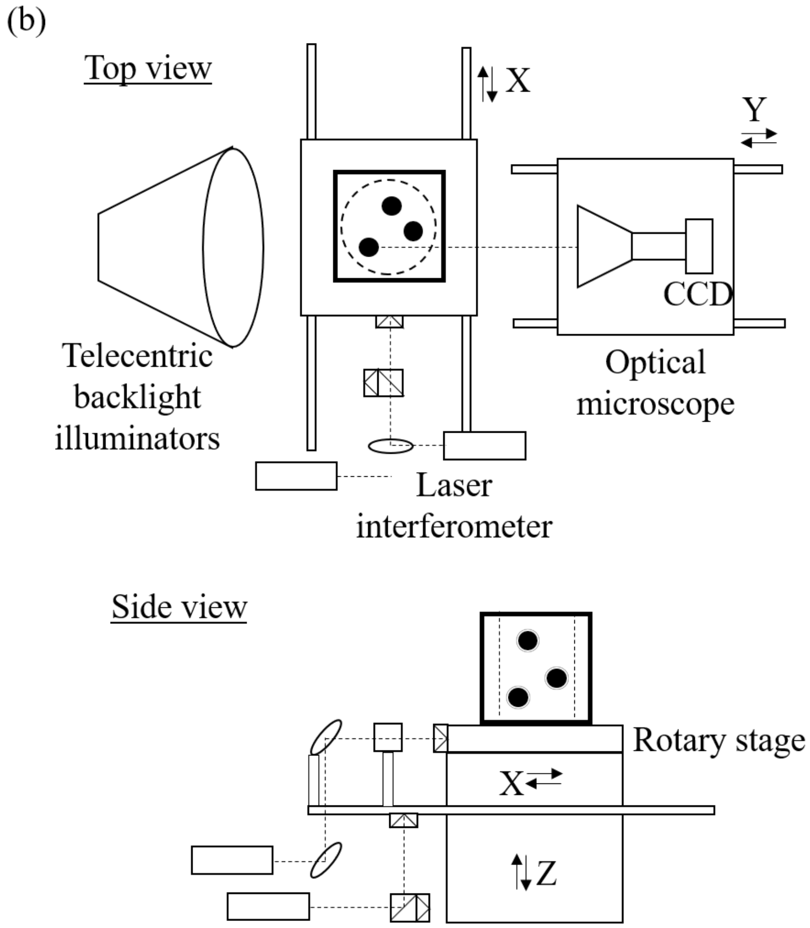


Figure 3: (a) Actual and (b) schematic measuring system we developed.

Conversion of the gauge's shape

To measure the novel gauge from the side optically, it is necessary to convert the gauge's shape. The gauge is cylindrical to aid the constant transmission of X-rays at any rotation position. However, in the case of the optical measurement, the laser is refracted, and the shapes of the spheres in the gauge are distorted in the direction of X or Y. Therefore, the X and Y coordinates of the sphere cannot be measured. Some spheres in the gauge appear like ellipses from the side because of the above problem (Figure 1). In order to not introduce the refraction, we converted the cylindrical shape of the gauge into a rectangular shape. Concretely, the cylindrical gauge is put through a rectangular frame hollowed out cylindrically and made of the same resin as the gauge (Figure 4 (a) and (b)). Furthermore, the gap between the gauge and the frame is filled with an immersion oil whose refractive index equals that of the resin. As a result, the sphere coordinates can be measured from the side optically. If the gap is not filled with immersion oil, spheres at the edge cannot be seen from the side because they are totally reflected. Thus, conversion of the gauge's shape and immersion oil is necessary to measure the gauge from the side optically. That is why image measurement machines observing objects from above is difficult to measure the gauge. However, Figure 4 (c) shows the rectangular gauge made using the frame and immersion oil. Slight thin lines are seen at the side of the cylindrical gauge, but its cylindrical surface is almost invisible.

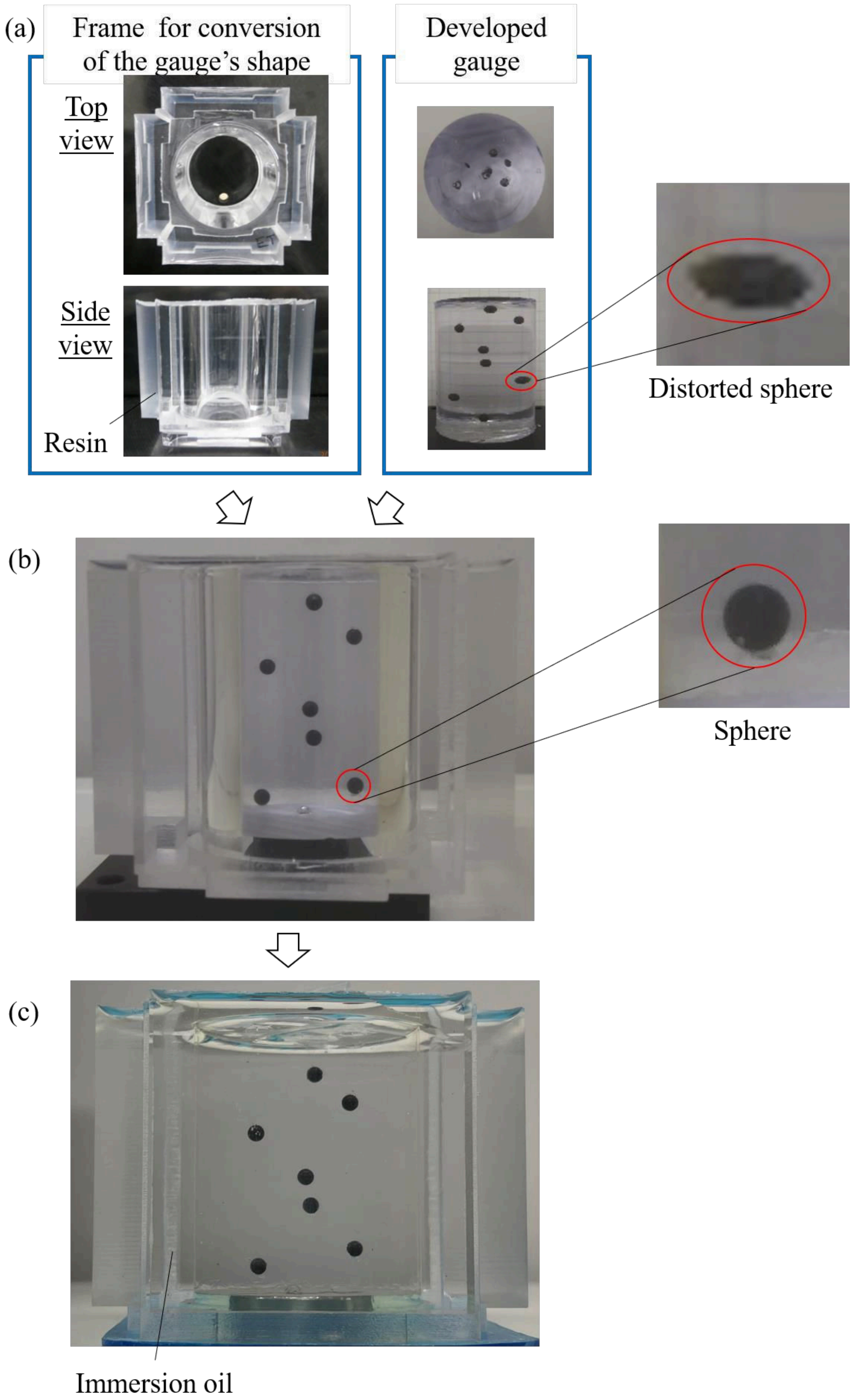


Figure4: (a) Frame and the developed gauge. (b) Conversion of the gauge's shape. (c) Rectangular gauge.

Measuring method of the proposed gauge

First, the rectangular-shaped gauge is set on the X and Z stage, and all spheres in the gauge are observed from the side using an optical microscope. Next, by adjusting the center position of the sphere and the center position of a microscope image, X and Z coordinates are measured using two laser interferometers. Nevertheless, exactly adjusting both positions is difficult. Therefore, we observed the sphere around the center position of the microscope image at the two slightly different positions, simultaneously recording X and Z coordinates using laser interferometers. Then, we analyzed the center position of the sphere from the two images. Next, by interpolating the relationship between the center position of the sphere and coordinates measured by laser interferometers, we calculated X and Z coordinates measured by laser interferometers when the center position of the sphere and microscope image is adjusted. Finally, 3D coordinates are determined by turning the gauge 90° and measuring each sphere position from another side perpendicular to the side.

5 X-ray CT and optical measurement results

We measured each sphere's center-to-center distance using the X-ray CT and the optical measuring systems we developed. Seven spheres are arranged in the measuring gauge, and the lower six spheres were measured because the highest sphere in the gauge cannot be observed using this measuring system. Here we numbered the spheres as shown in Figure 1. The center-to-center distance between two arbitrary spheres measured using the X-ray CT and optical measuring systems is defined as d_{ij}^{ct} ,d_{ij}^{opt} $(i \neq j, i, j = 1, 2, 3, 4, 5)$, respectively. Table 1 indicates the sphere center-to-center distance measured by the measuring systems, and Figure 6 indicates the deviation, $d_{ij}^{\mathrm{ct}} - d_{ij}^{\mathrm{opt}}$. As seen in Figure 5, There was no bias but variation. In addition, the relationship between the sphere center-to-center distance, d_{ij}, and the deviation, $d_{ij}^{\mathrm{ct}} - d_{ij}^{\mathrm{opt}}$, showed no correlation (Figure 6). The deviation, $d_{ij}^{\mathrm{ct}} - d_{ij}^{\mathrm{opt}}$, was from −0.154 mm to 0.256 mm. This study's results are the first we measured using the developed measuring system. Although, the deviation was large due to the measuring system being under development. For one of the factors, the flatness of the rectangular frame used for conversion of the gauge's shape is not high because this study's frame is made of the same resin as the gauge. For the poor flatness of the surface, each sphere position will be distorted in the optical measurement. The flatness of the frame needs to be equal to that of an optical flat. We have the solution for the problem. Other factors still remain. We will solve these problems and calibrate the developed gauge optically.

Table 1: Sphere center-to-center distance d_{ij}^{ct} and d_{ij}^{opt} measured by using the X-ray CT system and the optical measuring system.

	$j = 6$	$j = 5$	$j = 4$	$j = 3$	$j = 2$
$i = 1$	33.840	25.098	18.397	14.477	18.399
	33.884	24.970	18.287	14.405	18.554
$i = 2$	27.831	30.230	17.566	12.414	
	27.698	30.025	17.479	12.502	
$i = 3$	20.003	17.883	5.750		
	20.072	17.627	5.637		
$i = 4$	15.464	12.855			
	15.618	12.695			
$i = 5$	18.003				d_{ij}^{ct}[mm]
	17.975				d_{ij}^{opt}[mm]

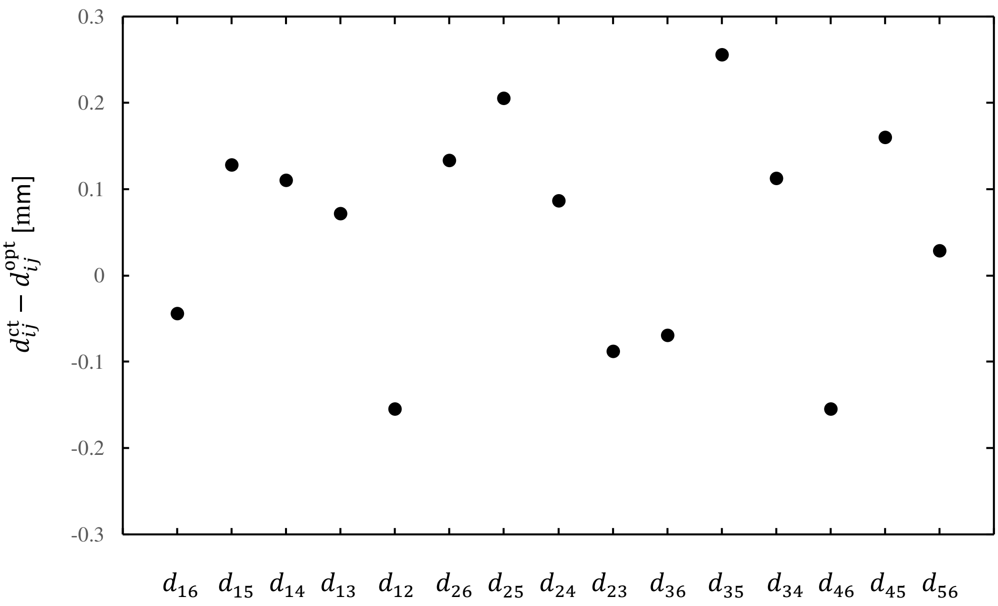


Figure 5: deviation $d_{ij}^{\mathrm{ct}} - d_{ij}^{\mathrm{opt}}$.

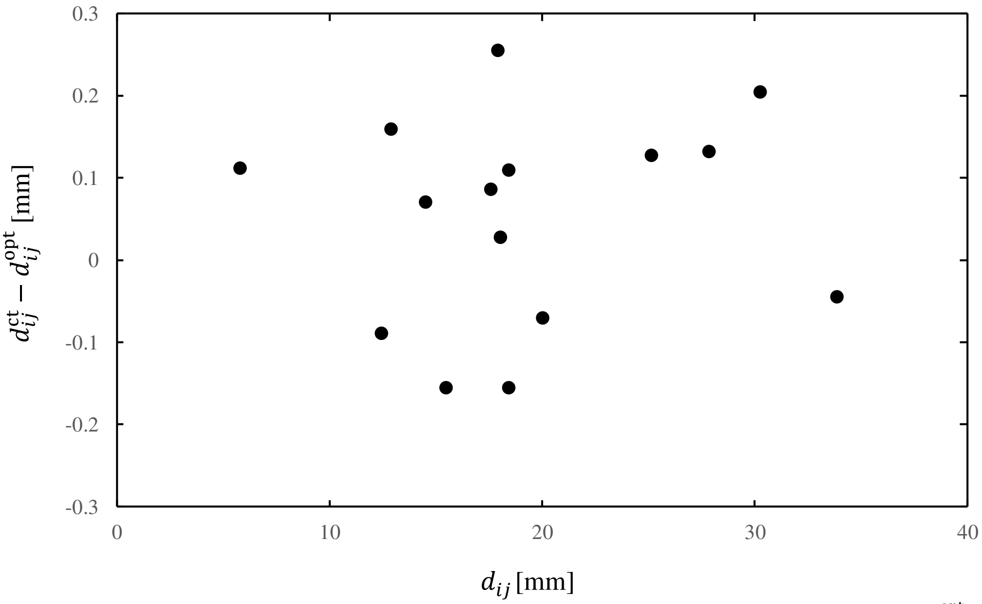


Figure 6: the relationship between the sphere center-to-center distance d_{ij} and the deviation $d_{ij}^{\mathrm{ct}} - d_{ij}^{\mathrm{opt}}$.

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