Chapter 10
Dimensional and Morphological Measurements

Industrial X-ray CT scanners have been increasingly used to measure the internal and external dimensions and shapes of various industrial products and components, being used as *coordinate measuring machines* (*CMM*). There are currently products referred to as dimensional X-ray CT scanners, which are commercially available. Moreover, accuracy assessment methods have also been standardized.

Incidentally, modern industrial products have external shapes whose complexity cannot be fully expressed with a drawing alone and have fine internal structures, which can be controlled to a high degree of precision. As such, there is an increasing requirement for measuring and managing the dimensions and shape of end products, assuring product quality by determining its internal defects. Being able to conduct dimension and shape measurements of products in 3D enables a clear assessment of whether a product was created as designed and whether it conforms to standards. The internal structure of products and components, which otherwise have no means of measurement, are primarily assessed through cutting; however, a proper assessment is difficult to conduct for its required cost and effort. The role of X-ray tomography in this context is extremely significant. X-ray tomography also has the benefit of being able to assess external shapes accurately without being affected by various factors, which would otherwise be affected by conventional contact-based or optical-based dimensional/morphological measurement methods (e.g. light reflection from glossy surfaces, overhanging structures, surface roughness). Meanwhile, one cannot ignore the presence of various issues unique to X-ray tomography, such as the trade-off between sample size and spatial resolution, which was not an issue with conventional measurement methods (Sect. 7.5.1), as well as various noise unique to X-rays and artifacts. The various issues presented in this book should be duly considered while conducting 3D imaging to prevent them from becoming actual weaknesses of the X-ray tomography—a lesson that holds true for dimensional and morphological measurements as well.

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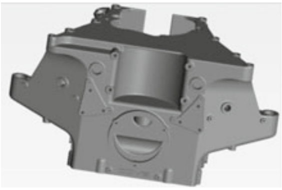
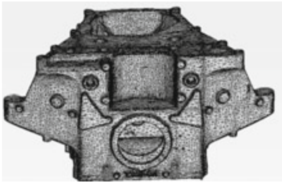
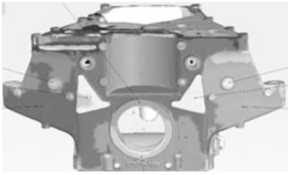


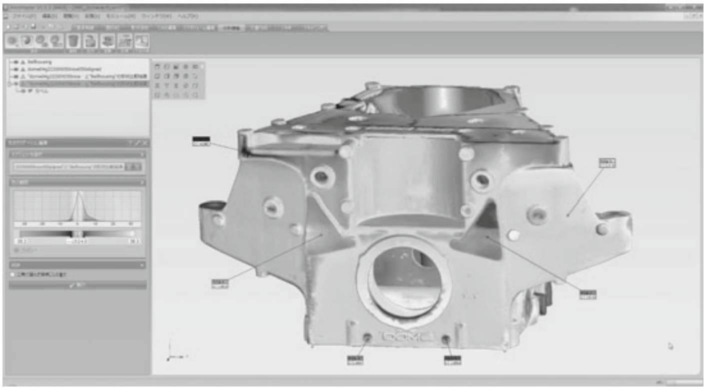
(a) Shape designed by means of the 3D CAD



(b) Polygon data of a casting obtained from the X-ray tomography



(c) Contour map representing shape error between the designed shape and a real product



(d) Appearance of analysis in (c) using a software for the reverse engineering (Computer screen)

Fig. 10.1 Example of reverse engineering using an X-ray CT scanner; analysis example using a Nihon Visual Science PointMaster V5.5 (courtesy of Katsuhiko Taki of Nihon Visual Science)

The representative application example of dimensional and morphological measurements is probably the measurement of the wall thickness and bore diameter of hollow components. The registration of 3D images of the obtained components and products and 3D CAD models using the methods discussed in Sect. 9.1 allows for the quantitative assessment of how much both components vary and in which locations. Figure 10.1 shows an implementation example of this. The product is a bell housing casting in an automobile. This type of assessment is particularly important during the trial manufacturing stage of the component or product, also when transitioning from trial production to mass production. Furthermore, the types of assessments mentioned above can be conducted when several components are assembled, as shown in Fig. 6.13, using X-ray tomography. Furthermore, the relationship between the performance and actual shape/production method of the product can be clarified by conducting various simulations using the measured 3D component morphology, which can, in turn, be used to optimize the morphology and control performance variability. In this manner, the 3D data provided by X-ray tomography matches extremely well with the design, analysis, and manufacturing process of industrial products based on current computer-aided design (CAD), computer-aided manufacturing (CAM), and computer-aided engineering (CAE).

A representative example, which requires internal defect measurements, is the detection of packing deficiencies, shrinkage cavities, porosity, and cracks in cast materials such as aluminum and injection-molding plastic materials. This enables efficient determinations, which not only eject components with the above-mentioned properties from the production line but also leave products with harmless defects in the production line. X-ray tomography-based dimensional/morphological measurements are also important in the configuration of new manufacturing processes, such as the production of components from 3D printers.

Industrial products with high accuracy and reliability have been pursued in the various fields of manufacturing industry. The active and efficient use of X-ray tomography should be promoted to ensure that these properties are maintained and developed in the future.

10.1 Device Technology

Figure 10.2 shows the characteristics of dimensional X-ray CT scanner device technology. Temperature control in the device (20 ± 0.5 °C [1]), vibration control, and positional stability due to a high-stiffness/low-thermal expansion stage [1] can be thought of as considerations unique to dimensional X-ray CT scanners. Temperature control is operated continuously over 24 h to regulate sample drift during startup. Furthermore, vibration control is included not only as control of the housing interior and exterior but at times in the assessment of the installation environment and its control. Next, the use of high-spatial-resolution detectors, microfocus radiation sources, and high-accuracy positioning stages is standard practice in obtaining high spatial resolution. As detailed in Sect. 7.5μ, the maximum spatial resolution of an X-ray CT scanner is constrained by the lowest accuracy among the various factors in X-ray tomography including the X-ray source, sample rotation stage, X-ray focusing elements in the case of an imaging optical system, and detectors. However, *accuracy* and *traceability* are more important than spatial resolution for the X-ray CT scanners as coordinate-measuring machines. In these cases, there are two factors associated with measurement accuracy: the deviation from the true value and the extent of data variation for each measurement. The positional stability of the focal spot and attachment of 2D measurement devices for correction and confirmation (e.g. laser interferometer) are important to ensure traceability. The voxel size must be accurately corrected for these cases. There are commercially available devices that automatically correct values and reflect this in the measured parameters. Some devices control the focal spot position in real-time so that it has no variation. High-energy X-ray sources and large-scale, high-accuracy, high-load-capacity positioning stages must be used particularly when large products or components are to be measured.

Two situations must be considered with regard to dimensional/morphological measurement: when relatively high-energy X-ray sources are used to measure large-scale components and products and when small-scale components and products must be measured with microtomography. As shown in Fig. 10.2, the device technology, in either case, is based on that described in Chap. 4, with no special cases in the basic

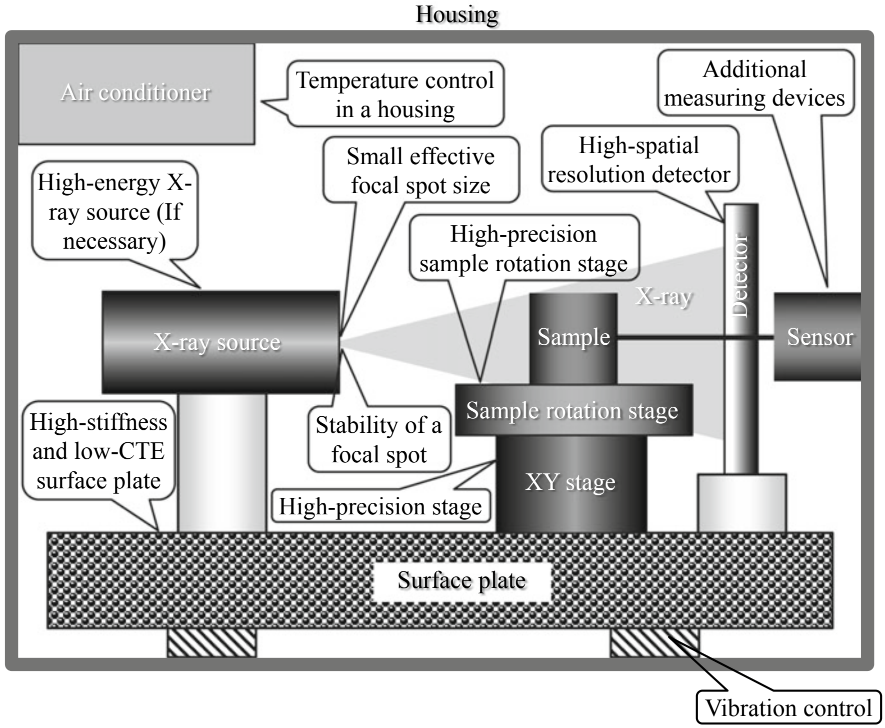


Fig. 10.2 Summary of the important elements regarding the device technologies in a dimensional X-ray CT scanner according to component machine (ten categories in the balloons)

principles and rules of X-ray tomography or its various component devices. In other words, dimensional and morphological measurements according to the performance of each X-ray CT scanner can be conducted without necessarily using a machine referred to as a dimensional X-ray CT scanner if the relationships between the methods (i.e., various constitutive devices, reconstructions, various image processing techniques) and the image quality of 3D images (i.e., spatial resolution, noise, and contrast) are sufficiently understood through this book and if some additional considerations are made with regard to the heat drift and vibrations of the sample. In addition to the aforementioned consideration of the hardware, a major point of difference between dimensional and imaging X-ray CT scanners is perhaps the support from various user-friendly software and the assurance of accuracy. The former refers to support when simultaneously and rapidly assessing large numbers of measurement points, or when creating assessment reports. Furthermore, fast imaging and imaging analysis are necessary to support high throughput and the handling of samples by industrial robots when setting up production lines for in-line inspection to conduct a total inspection of products and components. The latter is discussed in the next section.

10.2 Measurement Accuracy

10.2.1 Standardization

International testing standards are present when using X-ray CT scanners for measurements. The reliability of an X-ray CT scanner as a coordinate measuring machine can be increased with the listing of the characteristics of the scanner as per international testing standards or with the regular maintenance and correction of the X-ray CT scanner. At present, we are still in a transitional stage concerning these types of viewpoints.

First, with regard to the testing standards of X-ray tomography itself, ISO 15,708–1:2017 provides a definition of the terminology used [2]; ISO 15,708–2:2017 provides general principles, devices, and samples [3]; ISO 15,708–3:2017 provides the operation of industrial X-ray CT scanners and the interpretation of the obtained images [4]; and ISO 15,708–4:2017 provides inspections of X-ray tomography including dimensional/morphological measurements and assessments of the device [5]. ISO 15,708–4:2017, in particular, also has descriptions relating to the accuracy of dimensional/morphological measurements [5].

Meanwhile, VDI/VDE 2617–13 [6] and VDI/VDE 2630–1.3 [7], which are the German test standards relating to dimensional/morphological measurements as of 2018, have also been applied to X-ray CT scanners outside of Germany. These are used as guidelines for applying ISO10360, which are the ISO standard for accuracy assessments of coordinate measuring machines, to dimensional X-ray CT scanners. Furthermore, VDI/VDE 2630–1.1:2016–05 [8] includes entries on basic items and definitions, and VDI/VDE 2630–1.2:2016–07 [9] includes entries on influential quantities relating to the morphological measurements conducted with X-ray CT scanners. Using these standards enables the comparison of different X-ray CT scanners based on the definitions in performance assessments of dimensional X-ray CT scanners and standard devices. According to Matsuzaki, the issue of whether there are any problems with the application of these standards has been a subject of international debate [1].

Length measurement errors and probing errors representing local measurement errors are the subjects of the ISO (international standardization) relating to performance assessments of dimensional X-ray CT scanners [10]. The latest standardization trends should be studied and used.

10.2.2 Uncertainty in Measurement Accuracy

The assessment of *uncertainty in measurement accuracy* relating to the various above-mentioned component devices, post-measurement reconstruction, and 3D image handling is discussed here. In addition, standard devices for the assessment of dimensional and shape measurement characteristics in X-ray CT scanners are briefly discussed. Various factors relating to imaging hardware, measurement environment, sample, measurement conditions, reconstruction, and various image processing that may influence measurement accuracy are comprehensively listed in Table 10.1. It is important to consider in advance, what the major influences are and what can be ignored in measurements conducted by the researcher.

Traceability can be guaranteed if there is a standard device whose shape and size are known in advance and its measurements periodically conducted and reflected in the dimensional/morphological measurements. This refers to whether the measurement results can be verified to be the same each time and whether the X-ray CT scanner accurately revises based on measurement results or corrects the measurement data. This requires that the shape and size of the standard device are measured and confirmed using another coordinate measuring machine or another X-ray CT scanner with an effective spatial resolution and accuracy that is considerably higher than the X-ray CT scanner being used for dimensional/morphological measurements. Furthermore, measurements must be repeatedly conducted and the variation in results must be statistically assessed to assure reproducibility.

Standard devices of various forms are used. Representative examples, shown in Fig. 10.3, include the forest gage, where multiple spheres are supported by stays and standing close together, and step cylinder, which is a hollow cylinder with multiple steps. The spheres can generally be measured to assess probing error. The dimensional error can be assessed by measuring between the two points whose distances are known in advance. The forest gage is designed so that multiple data can be simultaneously obtained. Furthermore, the step cylinder considers how changes in material thickness influence measurements, as well as the verification of internal structure assessment by measuring the opened holes in the interior.

The difference between the maximum radius R_{max} and minimum radius R_{min} when the sphere diameters are measured are assessed as a *form probing error* in VDI/VDE 2630–1.3. Furthermore, the deviation from the true diameter value determined in advance is assessed as the *size probing error*. Sphere size and measurement methods, as well as error calculation specifications, are stipulated here. A standard device in which four spheres are arranged and attached to a cylinder is used to measure the distance between spheres with regard to distance error.

VDI/VDE 2630–2.1 describes a method for assessing error U during measurement using the corrected standard device. Here, U is expressed as follows, based on various causes of error [11]:

$$U = k\sqrt{{u_{cal}}^2 + {u_p}^2 + {u_w}^2 + {u_b}^2} \tag{10.1}$$

Here, u_{cal} is the uncertainty when calibrating the standard device using the 3D measurement method, u_{p} the uncertainty related to the reproducibility of the measurement method, u_{w} the uncertainty caused by the sample and the variation in its production process, and u_{b} the uncertainty due to the measurement method procedure. Furthermore, k is a coefficient that varies with the confidence interval, with $k = 2$ at a 95.45% confidence interval.

Table 10.1 Various factors which can influence the measurement accuracy of dimensional X-ray CT scanners and their classifications

Category	Sub-category	Cause
Apparatus	X-ray source	Drift
		Ageing
		Poor fixation
		Beam hardening
		Tube voltage
	Positioning stage	Alignment of a rotation axis
		Shortage of load bearing capacity
		Eccentricity
		Surface runout
		Cyclic positioning accuracy
	Detector	Alignment in beam direction
		Angular alignment
		Planarity
		Sensitivity/Dynamic range
		Spatial resolution
		Noise characteristic
		Pixel size (Poor calibration)
Environment	Housing/surface plate	Temperature
		Stiffness
	Installation environment	Vibration
Observation object	Sample	Chemical composition
		Size
		Deformation
		Drift
		Surface roughness
		Poor fixing
		Beam hardening
Condition	Measuring condition	Number of projections/exposure time
		Magnification and its calibration
		Selection of a filter
Post processing	Reconstruction	Cone beam artifact
		Reconstruction filter
	Image processing	Filtering
		Various image processing

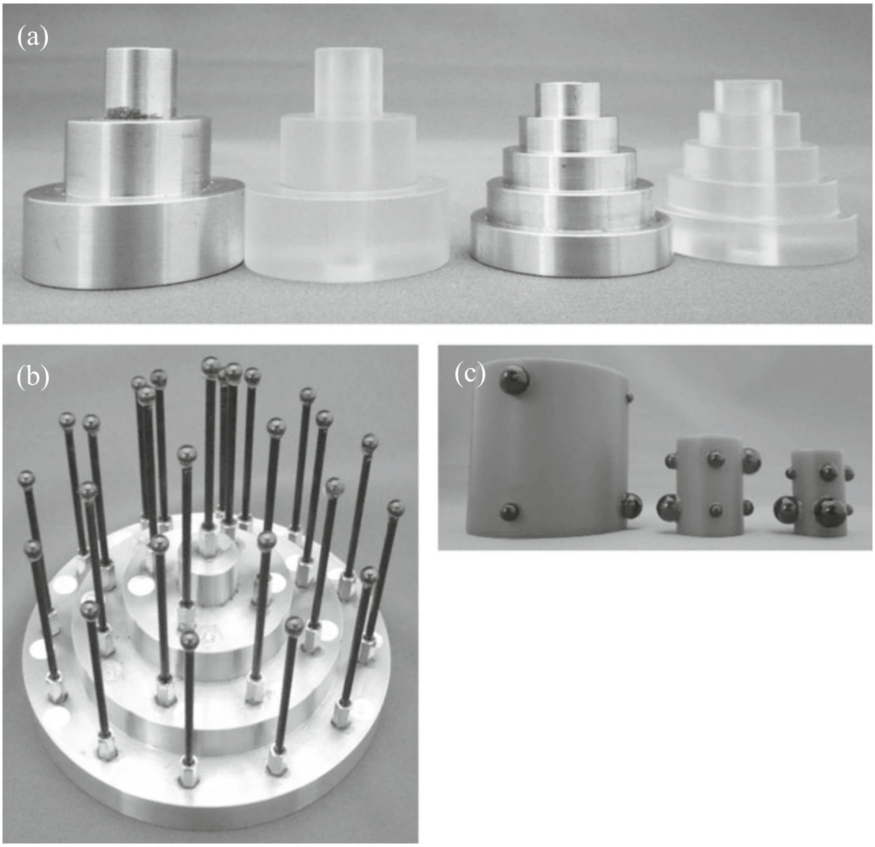


Fig. 10.3 Standard devices used for measurement accuracy assessments of the dimensional X-ray CT scanner: **a** step gage, **b** forest gage, and **c** is a device made independently by Mr. Takahashi (courtesy of Yuichi Takahashi of the Gunma Industrial Technology Center)

Table 10.1 does not include u_{cal}. Meanwhile, other factors cover a lot of ground in actual practice, as shown in Table 10.1, and the substantial meaning of Eq. (10.1) must be sufficiently understood by carefully examining the X-ray CT scanner, measurement conditions, sample, and data processing methods. For example, Jiménez et al. applied the method in Eq. (10.1) on microtomography devices [12]. They expressed u_w and u_b as follows [12]:

$$u_w = \sqrt{{u_{w_1}}^2 + {u_{w_2}}^2} \tag{10.2}$$

$$u_b = \sqrt{{u_{b_1}}^2 + {u_{b_2}}^2} \tag{10.3}$$

Here, u_{w_1} is the uncertainty related to the variation in the mechanical properties of the sample and u_{w_2} is the uncertainty related to the variation in the thermal expansion coefficients of the sample [12]. Furthermore, u_{b_1} is the uncertainty related to temperature fluctuations during measurement and u_{b_2} is the uncertainty related to surface position specification [12]. According to them, u_{cal} is equal to approximately 2.5–2.7 μm when an optical coordinate measuring machine is used, accounting for the largest share of U. This is followed by u_{p}, which is measured 10 times and is approximately 0.5–1.8 μm. Meanwhile, Kraemer et al. similarly investigated measurement uncertainty using a microtomography device with a focal spot size of 8 μm [13]. These results showed that a result similar to Jiménez was obtained when distances between spheres with a diameter of 2 mm were measured; however, u_{b} was considerably larger at 8.2–13.2 μm when the sphere diameters were measured.

Finally, we summarized this from the viewpoint of the relationship between uncertainty and spatial resolution of the 3D image. The effective pixel size of the 3D image in the case of Jiménez was 8 μm and the spatial resolution of the 3D image was estimated to be at most 16 μm based on the sampling theorem. In contrast, the uncertainty was 5.6–7.0 μm, which is less than half of the spatial resolution. The effective pixel size in the case of Kraemer et al. was 13 μm and the maximum spatial resolution value was 26 μm. The uncertainty at this point was 2–5 μm for the distance between the spheres, which is 10–20% of the spatial resolution but 16–26 μm for the sphere diameter, which is at a level similar to the spatial resolution. In this manner, it should be noted that the uncertainty could vary by a factor of 10 even with the identical sample by changing the measurement location.

These studies show that the standard device must first be calibrated to a high level of precision. Next, it must be understood that the factors, which dominate uncertainty vary for each case, and the physical elements, which bring about these factors, should be understood at the level shown in Table 10.1. Finally, the uncertainty level brought about by these factors should be understood if possible. Care must also be taken as this uncertainty can vary considerably from the effective spatial resolution of the X-ray CT scanner or 3D image, which is relatively easy to determine.

10.3 Reverse Engineering

Reverse engineering is a production method that involves decomposing and analyzing industrial products including software; understanding the material and thermomechanical heat treatment of that product, the shape and functionality of constituent components, and the materials specifications; and actively applying these aspects for production. For example, a business can purchase a product from another company, decompose it and thoroughly analyze it to create a similar product. Alternatively, it can use the product's technology to design or develop an original product. However, this chapter focuses on reverse engineering in the narrow sense of conducting the 3D imaging of industrial products with X-ray tomography, applying the obtained digital data to production. For example, the outer shells of automobiles are created with multiple complex curved surfaces, unlike those from several decades ago. Even if these are rendered with CAD, humans cannot completely capture this shape in a monitor. With this in mind, the external appearance of the automobile is created using a clay model and once the designer corrects this with human perception, this is measured to create 3D data, from which a metal mold is created. Production is enabled if this metal mold is used, and CAE-based analysis is enabled if 3D data are used.

Figure 10.4 shows a flowchart of reverse engineering and the necessary elements in X-ray tomography for conducting reverse engineering; Fig. 10.5 shows application examples. Among these, CAE can conduct a variety of measurements, including structural analysis, solidification analysis, fluids, heat transfer, electromagnetic fields, and diffusion of elements. Explanations relating to STL files and structural analyses were provided in Sect. 8.6; however, further discussions on CAE or CAM are beyond the scope of this book and are therefore omitted.

The same consideration afforded to the thought processes and points of caution regarding 3D imaging, which have been discussed up until now mainly in Sect. 6.7, is necessary for 3D imaging. In other words, the size of the industrial products and components to be examined, and their average atomic numbers (taking voids into account) must be considered when selecting the necessary X-ray CT scanner and X-ray energy to be used during imaging, taking field of view and transmissivity into account. X-ray CT scanners equipped with the compact electron accelerators

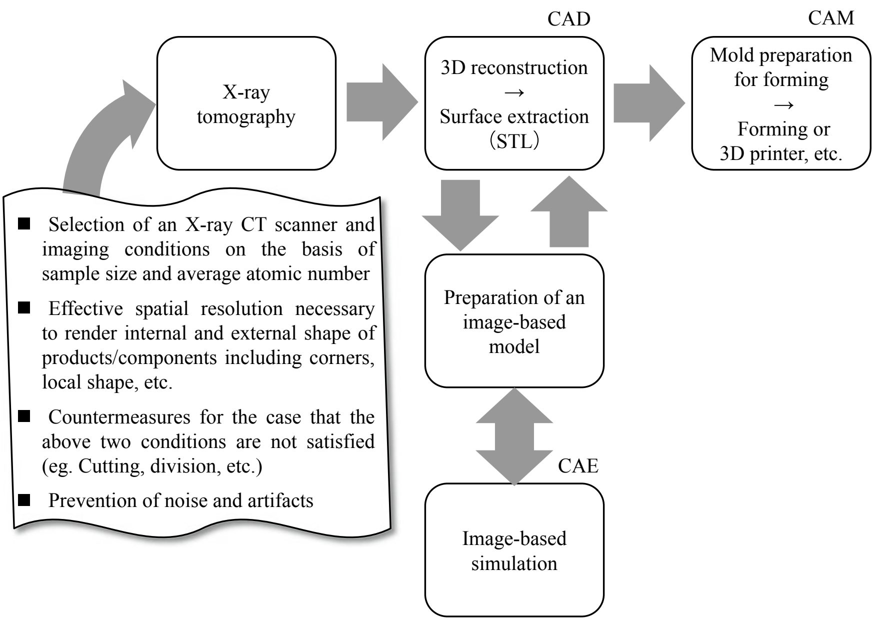
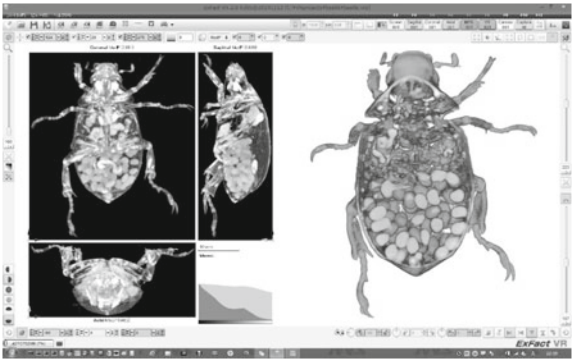
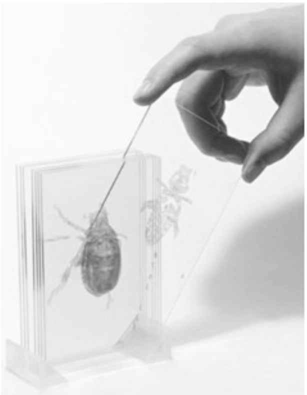


Fig. 10.4 Flowchart of reverse engineering using an X-ray CT scanner and a schematic summarizing the major points of 3D imaging

(a) Real object such as industrial products (In this case an insect specimen)



(b) Conversion into image data using the X-ray tomography. MPR (Left) and a 3D image (Right) using a 3D image rendering software



(c) A solid model based on the 3D image data that consists of stacked transparent thin plates

Fig. 10.5 Example of reverse engineering. Here, 3D imaging of an insect specimen instead of an industrial product or component is conducted and its surface is extracted, after which a 3D model was created using the 3D image data. Various production processes can be conducted, including metal forging and casting, plastic injection, and 3D printing (courtesy of Katsuhiko Taki of Nihon Visual Science)

discussed in Sect. 4.1.3 become necessary when the product or component size is large or when the material has a large average atomic number (e.g., iron). Next, the effective spatial resolution necessary for a 3D image is determined by considering the internal and external shape of the product/component, reproducibility of the pin-angle section, size and shape of the micro-section with the narrowest width, and the separability between the micro-sections. When transmissivity and spatial resolution are incompatible, some type of plan is required prior to 3D imaging such as cutting or assembly separation, as discussed in Sect. 6.7. Furthermore, as briefly discussed in

Sect. 8.6, the connectivity of the triangular mesh, the correction of distorted element shapes, and the control of the number of elements require immense amounts of time and effort. Other than this, the noise and artifacts that always accompany 3D imaging should be sufficiently determined in advance and should be eliminated as much as possible during the 3D image processing or segmentation step.

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