**Dimensional X-ray CT in Japan, development, application and standardization**

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**Abstract**

It is beyond question that dimensional X-ray Computed Tomography systems (DXCT) have been playing an important role in digital engineering. Although the development and applications of DXCT is advanced in Europe, new and original efforts have been started also in Japan. The history of development and current situation of DXCT, Japan’s and NMIJ’s activities, and measurement standard and industrial standards relevant to DXCT will be explained.

**Keywords:** dimensional X-ray CT, metrological standard, industrial standard, ISO, JIS, international comparison, high-energy X-ray CT

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**1 Introduction**

I won’t explain what a dimensional X-ray Computed Tomography system (DXCT) is or its role to be played in manufacturing process nowadays particularly in digital engineering, since most participants of this conference must know them very well. The development and applications of dimensional X-ray CT is well advanced in Europe, and Japan is trying to catch up with Europe. However some original attempts have been started in Japan. The development and standardization of DXCT will be reviewed in this article with focusing on Japanese situation.

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**2 Situation in Japan**

**2.1 History and overview**

In European countries development of DXCT by manufacturers and recognition and applications of DXCT in industries are far ahead compared to in other areas in the world. In Japan DXCT is hardly awared and no scientific conferences like iCT has taken place to the best of my knowledge. I participated in the seminar organized by BAM and PTB in 2009, where few presentations were made from Japan and United States. It means that only Japan is not behind, rather only Europe is ahead. In Figure 1, development of the instruments, measurement standard, and industrial standard on DXCT in Europe, United States, Japan, and Asia are reviewed. Of course some advanced users in Japan have started using DXCT. Total number of the instruments already installed is still very few. It is obvious DXCT will be used widely, however the dissemination may not be so drastic. The reasons for this difficulty can be considered as follows.

- Expensiveness
- Demanding legal procedure to use X-ray
- Distrust on its usefulness
- Unsatisfied specification
- Lack of standards, etc.
Figure 1: World trend on industrial dimensional X-ray CT.

In response to a request from Ministry of International Trade and Industry of Japan, Prof. Hiromasa Suzuki of Tokyo University and delegations from National Metrology Institute of Japan (NMIJ) of National Institute of Advanced Industrial Science and Technology (AIST) visited several manufacturers in Germany to survey on the application of non-contact coordinate measuring machines (CMM) in digital engineering.

We summarized non-contact CMM and DXCT were practically used in Europe and concluded it was necessary to disseminate these instruments for industries. After that we have been organizing small seminars and writing review articles in order to raise awareness.

2.2 Development of CMM - from point to line, plane, and volume

Coordinate measuring machine (CMM) has a long history. Because any geometrical parameters can be calculated with the aid of a computer, its usage is becoming more and more.

CMMs have been measuring ‘points’ with a contact probe for a long time since its onset. CMMs that measured points are most accurate, and therefore indispensable for the applications that need accurate measurement. Also there are many applications for which only point measurements are sufficient. However the largest disadvantage is its slow measurement. Discrete and sparse measurement points cannot satisfy the requirements for most applications in digital engineering.

After years CMMs equipped with scanning probe heads have emerged, which are capable of measuring ‘lines’, however the measurement points haven’t been drastically more.

Next CMMs having non-contact probes have appeared in the market. ‘Point’ measuring non-contact probe has a capability of measuring soft objects or those which cannot be touched, while there is no intrinsic difference with contact probes. On the contrary non-contact probes which can measure ‘planes’ by making use of a laser scanning or fringe projection carried out a revolution in digital engineering. Other principles including photogrammetry or standalone non-contact instruments without CMM moving frame have also been developed.
Eventually X-ray CT was released, which has a function of measuring ‘inside’ or ‘volume’ of specimen in addition to those surfaces. This is the history that many European manufacturers have traced. In short, DXCT is a CMM equipped with ‘X-ray CT probe’, which can measure ‘volume’ as well as external surfaces. This history is illustrated in Figure 2.

2.3 Development of X-ray CT – from medicine to inspection and metrology

On the other hand, X-ray CTs have been developed as medical instruments from its invention. The important functions required as medical instruments are

- how clear low contrast objects, i.e. human bodies, can be observed,
- how fast human bodies, whose motions cannot be stopped, can be scanned, and
- how small X-ray exposure can be achieved.

As the years go by, the availability of high-energy X-ray enables CT to be used for observation and inspection of industrial products. Since the size of tumors and defects are of interest to the manufacturers for medical or inspection purposes, they have been trying to improve measurement accuracy, however no CTs existed which guaranteed the measurement accuracy (see Figure 3).

In recent years, those X-ray CTs that guarantee measurement accuracy have been developed. Peripheral technology that underpins the development of X-ray CTs is improved. Highly reproducibility and resolution of measurements make X-ray CTs possible to be used for metrology
purpose. This is the history that many Japanese X-ray CT manufacturers have traced. In brief, DXCT is an X-ray CT that has an additional metrology capability. As a result, a CMM equipped with ‘X-ray CT probe’ and an X-ray CT equipped with metrology capability are the same. Nevertheless the differences in the histories and points of views of DXCT in Europe and Japan bring the differences in the usage and standardization of DXCT. Through the survey described above and activities in ISO committee, we confirmed the difference.

3 Research in NMIJ

3.1 Introduction of NMIJ

NMIJ (National Metrology Institute of Japan) belongs to AIST (National Institute of Advanced Industrial Science and Technology) and is responsible for establishing, maintaining, and supplying national measurement standards. Counterpart institutes of NMIJ exist in all countries, such as BEV (Bundesamt für Eich- und Vermessungswesen) in Austria and PTB (Physikalisch-Technischen Bundesanstalt) in Germany. NMIJ consists of 17 divisions that are taking care of all measurement standards including physical standards, chemical standards, and legal metrology. Length and dimensions division is conducting various research activities covering from length standard to hand tools and also providing calibration services.

3.2 Dimensional X-ray CT developed by NMIJ

Different from the Japanese history of DXCT explained in 2.3, length and dimensions division has been researching on conventional CMM. In accordance with the history of CMM shown in 2.2, we started a research on non-contact CMM about ten years ago and recently on X-ray CT. Research topics on X-ray CT itself is not covered while assessing measurement accuracy is our main topic that is in line with the mission of NMIJ.

The motivation we started research on X-ray CT is the non-existence of DXCT made by Japanese companies. We have collaborated with Shimazu Corporation that is one of the leading X-ray CT manufacturers to make DXCT (see Figure 4). This is the first DXCT made by a Japanese company to the best of our knowledge. Its detail specification will be described below.

![Figure 4: External view and structure of the Dimensional X-ray CT ‘inspeXio SMX-225CTS’ developed by NMIJ in collaboration with Shimazu Corporation.](image)

This instrument (inspeXio SMX-225CTS) is a modified version of Shimazu’s ready-made model inspeXio SMX-225CT. As easily can be inferred from the model number, the voltage of the X-ray source is 225 KeV.

DXCT requires good reproducibility compared to conventional X-ray CT. A metrological frame made of granite is used like high performance CMM so that good temperature stability and measurement
reproducibility can be attained. The sample stage moves between the X-ray source and the detector. A linear motor having small motion error and good positioning accuracy is used. In the future, the displacement of the sample stage should be measured with measurement traceability. At the moment, the readout of the linear encoder is used. The most important motion mechanism is the rotary stage on which the measurement sample is placed. Radial error motion of the rotary stage will cause a blur in the observed images. A high precision rotary table made by Aerotech, Inc is installed; whose radial error is less than 1 µm.

To achieve good temperature stability, the instrument enclosure is equipped with an air conditioner. Both the instrument and measurement samples can be kept at 20 °C, and therefore high measurement reproducibility can be expected. Since the temperature is set at 20 °C that is a standard temperature in length measurements, no temperature compensation is needed due to the deviation of the standard temperature. As a consequence small measurement uncertainty can be anticipated.

A flat panel image detector (1024 × 1024 pixels, 20 × 20 cm) is used. Its image distortion is smaller than ordinary image intensifier’s, so that small measurement uncertainty can be obtained. In addition its dynamic range is larger. Consequently high contrast images can be captured which enables accurate edge detection.

Hardwares originally developed by Shimazu are also used, such as an image reconstruction hardware, which makes use of GPU, and an X-ray source whose focus size in 4 µm. Only a simple error compensation of the motion stage is utilized. Full parametric error compensation should be introduced in the future. Although originally developed image reconstruction software is installed, a commercial image handling software VG Studio Max is used, and dimensional measurement function of this software is also used. Figure 5 shows an example of dimensional measurement. The left figure shows the diameter of a sphere made of ruby whose radius is 2.5 mm in different position and days. The scattering of measurement results, i.e. reproducibility, is within ±1 µm, which successfully demonstrated the excellent performance of this instrument. The right figure shows the length measurement error. Although no scaling correction has been applied prior or posterior the measurements, the error is around 10 µm. It means this instrument can be called a dimensional X-ray CT.

Figure 5: An example of measurement results by NMIJ’s dimensional X-ray CT. Left: radii of a sphere measured in different positions and days are plotted. Scattering of the result, i.e. reproducibility, is less than 1 µm. Right: length errors with respect to the measurement length.

4 Standardization

4.1 Effectiveness of standardization

Demonstrating its outstanding performance will increase the sales of the instrument. However without presenting objective evaluation customers won’t be convinced and cannot use the instrument for
quality control purpose with relief. Standardization is useful for both manufacturers and customers. The effect brought by the standardization is summarized as follows.

Manufactures can show their superiority over competitors by objectively assessing the performance of their products. In addition, by evaluating their own products according to the standardized procedures, they can see the position of their products in the market and may identify their problems to improve the performance of their products.

Customers are able to compare and select products whose specifications are really needed for them without being confused by the brand names or rumors. They are also able to use the products with relief since the performance of the products is clearly expressed or guaranteed by standardized procedures.

4.2 Measurement standards

By the way there are two standards, i.e. measurement standards and industrial standards. Many people mixed up them.

Measurement standard means a calibration chain from the definition of units to practical shop floor measurement. Measurement standards are maintained and supplied by National Metrology Institutes (NMI) in each country. Correct measurements underpinned by correct measurement standards facilitate high quality industrial activities and safe daily lives.

The calibration chain explained above is called metrological traceability. Measurement standards and metrological traceability may be considered synonyms. In addition calibrations are always accompanied by measurement uncertainties, which secures the reliability of measurements. On the other hand the existence of too complicated uncertainties may impede the diffusion of traceability systems. Appropriate uncertainty treatment is essential. In the field of DXCT, uncertainty estimation will also be a key topic.

4.3 Industrial standards

A companion of measurement standards is industrial standards. It is also called document standards. When we simple say standards, it means industrial standards in most cases. There are international standards such as ISO and IEC, and domestic standards JIS in Japan, ASME in United State, VDI/VDE in Germany and so on.

The merits explained in 4.1 are mostly applicable for industrial standards. Industrial standardization brings merits both for manufacturers and users.

Industrial standards are categorized into two kinds. The first one is ‘product standards’ specifying the requirements which the products must conform. Product standards are for fundamental products for which interchangeability is important.

The second one is ‘procedure standards’ specifying the procedures to test the performance of the products. The specification that the products must conform is not defined in most cases, while the impartial test procedures and conditions to test the products are specified. By comparing the test results and the specification the manufactures shows in the product catalog, the conformity of the product may be evaluated.

Concerning state-of-the-art products, defining the principle and specification may prevent the technological development. The users are happy to know whether the specification is satisfied or not.

4.4 ISO 10360 series

The standard that defines the test procedure of coordinate measuring machines is ISO 10360 series: Geometrical product specifications (GPS) - Acceptance and reverification tests for coordinate measuring machines (CMM) -. Since product standard is not suitable for CMMs that is a high functional products, this standard is one of the procedure standards. Neither measurement principle nor accuracy to be satisfied is stated. The manufacturer should show them in the product catalog as a
Maximum Permissible Error (MPE). The customer who purchased the CMM believes the specification is satisfied and performs the acceptance test. This series of ISO define impartial and practical test conditions and procedures that are not advantageous for any of manufacturers and customers.

Figure 6 shows the structure, history, and brief contents of ISO 10360 series. The part numbers and the progress of publications directly reflect the development history of CMM explained in 2.2

Part 2 provides the procedure of assessing the measurement errors when one-dimensional length standards are measured. This part 2 is a basis of all consecutive parts. CMM is not an instrument to measure one-dimensional length but capable of measuring any geometrical features. It is, however, unrealistic to test all functions, hence the objective of this standard is to make it clear the practical performance of the instrument with a least effort. Specifically five gauge blocks of different sizes are measured in seven different positions and orientations three times, namely 105 measurements in total. From 105 measurement results, the conformance of MPE is verified.

Part 3 is related to the scanning, i.e. the measurement of ‘lines’. Part 4 concerns CMM equipped with a rotary table. Part 5 is a standard used for testing a performance of a probe independently. Whole measurement performance of a conventional CMM can be tested by performing both Part 2 and Part 5 tests. Part 6 treats a software test. Part 7 is for CMM equipped with an imaging probe, i.e. the measurement of ‘planes’ and Part 8 is for that equipped with an optical distance sensor. Part 9 is used for testing CMM having multiple different type probes. Standards up to Part 9 have already been published.

All standards up to Part 9 are assumed to apply for conventional Cartesian coordinate CMM. On the other hand, all standards after Part 10 are used for non-Cartesian coordinate CMM: Part 10 for laser trackers, Part 11 for X-ray CT, and Part 12 for articulating arm CMMs. In Part 11, the measurement target is expanded to ‘inside’.

4.5 ISO standards used for dimensional X-ray CT

The concept of ISO 10360 series is to divide the structure of CMM into a frame and a probe and to assess their performance separately. Some tests may be additionally done to see the inherent functions of specific measurement principles.
The same concept holds for DXCT. A gauge consists of an array of many spheres, which is named ‘forest’, is measured to evaluate scale errors and distortion of the measurement volume (see Figure 7). A larger sphere is also measured to assess the probing performance like Part 5.

![Figure 7: Forest gauge used for the acceptance test of dimensional X-ray CT.](image)

An inherent function of X-ray CT is a capability of the inside of workpieces. VDI/VDE makes use of a stack of cylinders having different diameters, which is named ‘step cylinder’ (see Figure 8). A hole is drilled in the center of the cylinders. If measurements are performed correctly, the hole looks like a cylinder. Actually it looks like a cone due to different penetration lengths of X-ray. The deviation of the cone from the cylinder indicates the capability of measuring ‘inside’.

![Figure 8: Photograph and structure of a step cylinder gauge used for assessing internal measurement capability of dimensional X-ray CT.](image)

ISO 10360-11 has been being discussed in ISO/TC 213/WG 10. The discussion is controversial and it is stopping at Working Draft stage. The reason of this standstill is due to a strong objection for assessing the measuring capability of inside from Germany. We suppose this assertion comes from an idea that DXCT is one of CMMs, i.e. the primary requirement for DXCT is a capability of measuring geometrical features of sample surfaces and the capability of measuring inside is additional. Even when measuring the sample surface, DXCT has a capability of capturing 3D image at one time, which is a more advantageous function than conventional CMMs’. On the other hand, Japanese primary requirement for DXCT is a capability of measuring inside because DXCT is an evolutionary form of X-ray CT. Although as explained in 2.3 the resultant instruments by Japanese and German approaches are the same, the actual ways of using and evaluating instruments are slightly different. This slight difference is a large barrier in standardizing the acceptance test of DXCT. Opinions by Japanese and Germany have been in parallel and the standard is still in its Working Draft stage. As a gauge whose shape and measuring procedure both of us can agree, a hole plate was proposed. It is based on an idea that both external and internal measurement capability can be assessed...
by the hole plate. From the meeting held in September 2013 to that in February 2014, a hole plate manufactured by PTB is circulated to verify the feasibility of this proposal. Figure 9 shows the hole plate used for this international experiment.

![Figure 9: Holeplates used for the international experiment organized by ISO/TC 213/WG 10. Two different size holeplates are circulated.]

4.6 Japanese Industrial Standard (JIS)

The members of ISO are ‘member bodies’, which are organizations belong to each member country. Japanese member body is Japan Industrial Standards Committee (JISC) founded under Ministry of International Trade and Industry (MITI). Actual standardization activities are entrusted to other organizations. Concerning TC 213 Japanese Standards Association (JSA) is committed. Independent from the domestic committee organized by JSA, AIST is running a consortium on DXCT. It is an open organization to which most Japanese large CT manufacturers and import agents belong. Members of the domestic committee organized by JSA are mostly from CMM community and there are few experts on DXCT. A lot of proposals in standardizing DXCT are raised from the consortium of AIST and sent to ISO committee through the domestic committee of JSA.

We got noticed inconsistency of technical terms used by the members during the discussions in the consortium. The members agree to coordinate the technical terms before DXCTs become widespread, and it will accelerate the dissemination more rapidly. We compiled the glossary of technical terms related to X-ray CT and AIST proposed it to JISC. It was published in 2013 as JIS B 7442 Industrial X-ray CT systems – Vocabulary (see Figure 9) [1]. Unfortunately the explanations of the terms are only written in Japanese, but the terms are in Japanese-English bilingual. All JIS standards are published in English version later, although they are not formal versions. The English version JIS B 7442 will be available soon.

![Figure 9: JIS B 7442 Industrial X-ray CT systems - Vocabulary (Cover page and examples of terms).]
5 High energy X-ray CT

5.1 High energy X-ray CT

Compared to the high-function of X-ray CT, its structure is very simple, and by this reason there are many manufacturers. Most of them are making cone beam type X-ray CTs that make use of low energy X-ray source up to 225 KeV. Some manufacturers are using middle energy X-ray CT up to 1 MeV to make cone beam or fan beam type instruments.

In contrast, only a few manufacturers are utilizing high energy X-ray sources. In Japan, Hitachi is a leading company of high energy X-ray CT and most high energy X-ray CT installed in Japan are made by Hitachi. Although we don’t have information on the spread of high energy X-ray CT in other countries, it is Japanese characteristic situation that many high energy X-ray CT are being used.

The penetration of high energy X-ray is overwhelming. As shown in Figure 10, 12 MeV X-ray CT can measure samples up to 40 cm size made of steel and 1.5 m size made of aluminum. Whole large size parts such as an engine block can be measured. There are a lot of applications that cannot be performed without high energy X-ray CT.

![Figure 10: Schematic view and measured size of a high-energy X-ray CT. Photos from Hitachi, Ltd. website (http://www.hitachi.co.jp/products/power/xct/).](http://www.hitachi.co.jp/products/power/xct/)

5.2 Japanese national project

Measuring large samples with high resolution is a universal subject for all measuring technology. Japan has started a national project to make a challenge to this subject. Also in Germany a national project to make a huge size X-ray CT is running. The planned X-ray CT in Japan is not so large as Germany’s. Our objective is to measure large industrial parts with high resolution.

Among many factors influencing the resolution of X-ray CT, the largest one is the focus size of the X-ray source. As the edges of transmission images have unsharpness whose size is almost the same of the focus size of X-ray source, higher resolution than the focus size cannot be achieved. In general, as the energy is higher, the focus size becomes larger. Energy and focus size of X-ray source are in a tradeoff relation. High energy, which can measure large parts, and high resolution cannot be compatible. This relationship is illustrated in Figure 11. The top-right is the area to be developed.
Almost all high energy X-ray CT are making use of linear accelerators (LINIAC, LINAC) as X-ray sources which is not free from the trade of between the energy and focus size. Instead we are going to use a small size synchrotron by the name of MIRRORCLE (see Figure 12) [2]. A Bremsstrahlung radiation from the small synchrotron is used, which is not a synchrotron radiation from a large ring accelerator. A high energy and small focus size X-ray is radiated from the MIRRORCLE so that large parts can be observed with high resolution. This project has started from 2013 for three years term. It will be in experimental operation in 2015, and the detail of this instrument will be reported at that time.

Figure 11: New X-ray CT to be developed.

Figure 12: Structure and whole view of the micro size high-energy X-ray source MIRRORCLE. Photos from Photon Production Laboratory, Ltd website (http://www.photon-production.co.jp/).

6 Conclusions
X-ray CT are sophisticated but simple instruments, and therefore a flood of manufacturers exist. However there is not many dimensional X-ray CT which can perform reliable dimensional measurement. Concurrently with the technical improvements by the race of development all over the world, it is necessary to make a pair of measurement standard and industrial standard. It enables the customers to purchase and use dimensional X-ray CT with relief, resulting in the improvement of the quality of the products made by the dimensional X-ray CT users.

The development and utilization of dimensional X-ray CT is advanced in Europe compared to in other parts of the world. We expect better dimensional X-ray CT will be developed through a global competition and collaboration. Then end users will also benefitted through the satisfaction of dimensional X-ray CT users.
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