Plant maintenance and dismantling work support based on three-dimensional scanning technology

ISHII Hirotake

Graduate School of Energy Science, Kyoto University, Yoshida Honmachi Sakyo-ku Kyoto-shi, Kyoto 606-8501, Japan (hirotake@ieee.org)

Abstract: Recent progress of computer vision and micro-fabrication technologies has greatly reduced the cost and difficulty of three-dimensional modeling of maintenance and dismantling work environments. The model building process is so simple and inexpensive that models can be updated frequently, meaning that we can believe that the model represents the current work environment properly. This assurance enables us to conduct maintenance and dismantling work computer simulations with higher reliability, which might change the methods used for maintenance and dismantling work. The models, which are useful for work procedure planning and evaluation, training, and information sharing among workers, can be a basis for providing safe and efficient maintenance and dismantlement of nuclear power plants. This article presents recent progress of three-dimensional scanning technologies and their possible application to enhance safety and efficiency during plant maintenance and dismantlement.

Keyword: three-dimensional modeling; work procedure evaluation; training; virtual reality; augmented reality

1 Introduction

Information and Communication Technology (ICT) has advanced continuously over the last few decades, thereby enhancing the safety and efficiency of plant maintenance and dismantling work of nuclear power plants [1, 2]. This tendency is expected to continue also in the coming decades, but its pace will increase. A new technology called “Real-Time Dense Surface Mapping” has emerged recently, which scans surrounding environments and easily and quickly builds three-dimensional models of them as “a cloud of three dimensional points” [3, 4].

Scanning technologies have been available for many years, but they remained too expensive for use in actual maintenance and dismantling work because they were designed solely for industrial use, employing expensive components such as laser emitters and sensors. Moreover, they require much time to scan large areas such as industrial plants and nuclear power plants.

These issues can be resolved using a new type of camera, a Red, Green, Blue and Depth (RGB-D) camera, which became available for general consumers in 2010. The RGB-D camera can capture depth images of an environment in addition to RGB color images, as a normal color camera does. From its images, one can ascertain the depth of each pixel: how far the environment’s surface is from the camera position. The RGB-D camera target users are general consumers, for whom the RGB-D camera is intended to be used as an interface for family video games or human-computer interaction. The RGB-D camera is much cheaper than legacy scanning technologies because of economies of scale. Moreover, it is much smaller: it can be attached to a worker’s helmet.

Massively parallel computing is now available on mobile computers. The performance of Graphics Processing Units (GPU) has become higher than that of Central Processing Unit (CPU). The GPU’s energy consumption per unit of computational power is much less than in years past. General-Purpose computing on GPU (GP-GPU) can be used on mobile computers for various computing tasks. This change enables the execution of massive processing in real time, making it possible to use a normal RGB camera as a sensor for scanning work environments and for solving large global optimization problems to build their models.

Furthermore, an open source programming library that is useful for processing point clouds has

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developed in recent years, making it easy to apply many processing methods to remove noise, merge point clouds, and convert point clouds into polygons.

These technological and economic changes are expected to improve the safety and efficiency of plant maintenance and dismantling work. This article describes a state-of-the-art three-dimensional scanning technology, its applications, and its impact on the safety and efficiency of plant maintenance and dismantling work.

2 Three-Dimensional Scanning Technologies

Several technologies are useful to obtain three-dimensional shape models of environment as a collection of three-dimensional points called a "point cloud". One conventional means to obtain point clouds is to use a laser emitter and a sensor to measure the time delay of a laser beam traveling between the emitter and the target surface, or the phase difference between the outgoing laser beam and the reflected one. This technology provides extremely accurate and dense point clouds, but the scanning system is extremely expensive and large. Another way to obtain point clouds is Structure from Motion (SfM) [6], which uses a conventional camera, image processing, and mathematical techniques such as triangulation and bundle adjustment [7]. This technique has been developed mainly in the field of computer vision to recognize environments and has been applied recently to build a feature database used for estimating the camera position and orientation. SfM requires an image series captured at different positions and orientations, which means that the user must move the camera unnaturally. SfM also presents a shortcoming in that it can provide only a sparse point cloud in which the number of points is small and the distances among points are long, as shown in Fig. 1. It is also a problem that the accuracy and stability of SfM depends strongly on the degree of texturing of the environment. The SfM result degenerates when the appearance of the environment is too simple or complex, or has high repeatability. Therefore, SfM is unsuitable for use in obtaining three-dimensional shape models of the work environment.

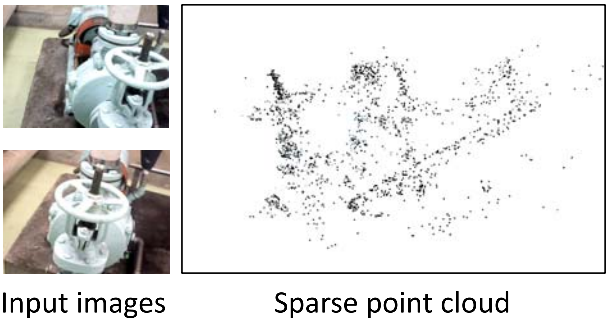

Fig.1 Sparse point cloud built with SfM.

In recent years, new technologies have emerged that can obtain three-dimensional models of environment easily and cheaply. An RGB-D camera, which can provide "depth" images in addition to normal color images, projects an infrared random dot pattern onto the environment, as shown in Fig. 2, and captures its reflection on the environment surface with an infrared camera located at a slightly different position from the infrared projection source. The distance from the camera at each random dot projections is calculable from the dot pattern distortion. The depth images can be captured just as they can be with a normal video camera. The projection and depth measurements are done 30 times per second. The resolution of the depth image is not high compared to that of conventional scanning technology; the most widely used depth camera (Kinect; Microsoft Corp.) has a 640×480 resolution. However, sub-pixel three-dimensional points of the environment are obtainable by connecting sequential depth images.

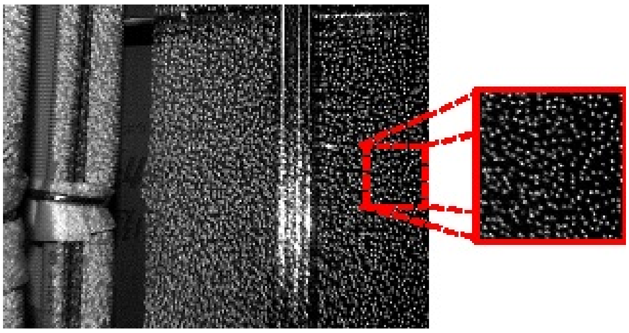

Fig.2 Random dot projection for depth measurement.

KinectFusion [3] builds a dense point cloud from sequential sparse depth images by estimating the position and orientation difference between the depth images with the Iterative Closest Point (ICP) algorithm [8] and merging them into single point cloud. These processes can be done in real time when massively parallel computing is available. Therefore, we can obtain three-dimensional models in real time merely by capturing depth images in the work environment.

Massively parallel computing transforms a conventional camera to a three-dimensional scanning sensor. Dense Tracking and Mapping (DTAM) [4] is a method that uses massively parallel computing on GP-GPU to obtain three-dimensional models in real time from sequential conventional camera images. The surface of instruments in a work environment is smooth. The apparent color of identical point of the environment is fundamentally the same even if the point is viewed from different positions. These assumptions are useful to estimate the three-dimensional surface shape of the environment by solving a large global energy optimization problem. An important disadvantage is that the camera must be moved unnaturally in order to use DTAM. Nonetheless, the three-dimensional scanning method, which requires only a single conventional camera, is a promising technique because its cost continues to decline.

A key limitation is that both the depth camera and DTAM can obtain surface shape information as a point cloud only in a small area. To build models for a large area, it is necessary to merge multiple point clouds into a single point cloud and convert them into polygon models. In recent years, many algorithms have been proposed to remove noise, merge multiple point clouds and convert point clouds into polygon models. Figure 3 shows point clouds obtained at different positions, while Fig. 4 shows a merged point cloud with the ICP algorithm. Implementing these algorithms was a time-consuming task, but an open source library called the Point Cloud Library (PCL) is available [5]. PCL is maintained and updated by active worldwide community members. The latest algorithm is quickly included in the library immediately after a new algorithm is proposed.

Important features of these new technologies are that the necessary sensors are small and cheap. For DTAM, a conventional cheap and small camera is useful to capture images for processing. The depth camera (ex. ASUS Xtion PRO LIVE), which costs less than 300 US dollars, weighs about 170 g inclusive of cables. Therefore, all workers can use helmet-mounted three-dimensional scanning devices, enabling frequent updating of three-dimensional environment models.

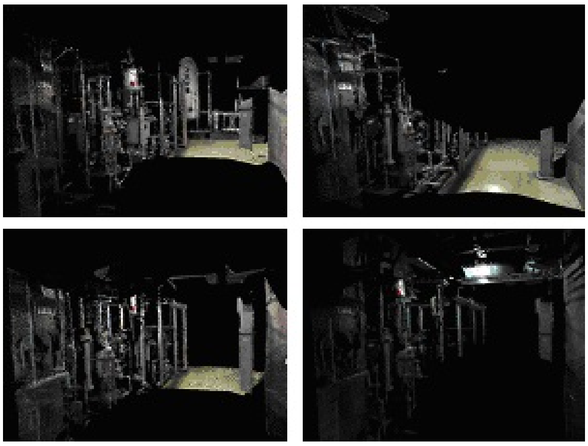

Fig.3 Point clouds obtained at different positions.

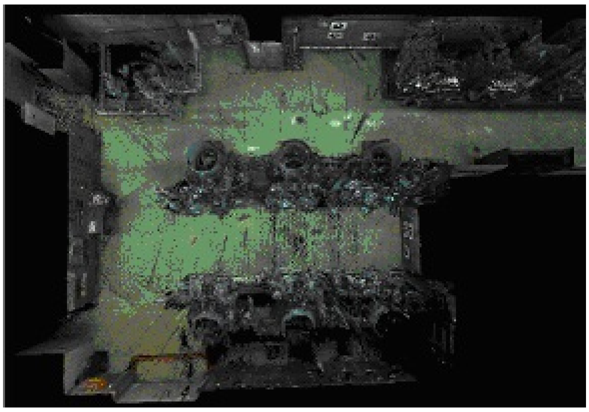

Fig.4 Point cloud merged with ICP algorithm
(Top view of the room).

Three-dimensional Computer Aided Design (CAD) models of nuclear power plants were built when the plants were newly designed. However, they were not updated frequently owing to the fact that manual updating of models is expensive. Even if the models are updated, a possibility exists that the update will be done incorrectly, with models that are not representative of the current work environment. Therefore, we were unable to rely on the models to support the safety of critical tasks. Using the new three-dimensional scanning technologies enables frequent updating with an interval of hours or minutes, providing extremely high accuracy and reliability. The accuracy can be improved from sub-meter to centimeter order. This qualitative change of models can support various applications for supporting maintenance and dismantling work.

The current limitation of these new three-dimensional scanning technologies is that they can only obtain surface models for a small area at once, due to the limitation of memory and computational power of the mobile computer. Nevertheless, it can be predicted confidently that CPU and GP-GPU performance will increase by increasing the number of processing cores, even if it is difficult to increase the clock of cores. The cost of memory will continue to fall, at least in the next decade, by upgrading manufacturing processes. Therefore, these limitations can be expected to be overcome in several years.

3 Maintenance and Dismantling Work Support using Environment Models

When three-dimensional models that represent the current work environment properly are available, various simulations and calculations related to maintenance and dismantling work are possible. These simulations might change the methods of nuclear power plants maintenance and dismantling work. This section introduces examples of plant maintenance and dismantling work support using environment models.

3.1 Estimation of waste volume and weight

Models obtained using three-dimensional scanning technologies include size information of the environment. Therefore, it is possible to measure the length of arbitrary parts of nuclear plants by measuring the length of corresponding parts of the models. This length information is useful for estimating the volume and weight of waste associated with dismantling activities. For example, by choosing a part of a pipe and by measuring its length and radius, the pipe volume can be calculated. By summing up the volumes, we can estimate how many waste boxes are necessary to store the waste from dismantling activities. Furthermore, it is possible to estimate the weight of that waste when the pipe thickness and pipe material are known. Therefore, it becomes possible to estimate how many workers are necessary to convey the waste, or which type of crane is necessary to lift up a waste box. It is also possible to ascertain which part of the dismantling target should be cut to enable workers to convey them safely. Therefore, it becomes possible to estimate and evaluate the method of dismantling that minimizes the worker load thereby maximizing efficiency.

3.2 Training and work content explanation

When three-dimensional models of the work environment are available, it is possible to conduct maintenance and dismantling training using virtual reality technology. Trainees can be immersed in virtual space built with the obtained three-dimensional models and can conduct various works activities to understand the methods of maintenance and dismantling work. Virtual reality-based training system has been used since the 1990’s, but the virtual environments were built based on models that were produced manually. The models were not sufficiently detailed. It was also difficult to update the models when the real work environment was modified. Therefore, virtual reality-based training was applicable only for novice workers to understand the fundamental tasks related to maintenance and dismantling work. However, it becomes possible to apply virtual reality-based training to more realistic tasks when three-dimensional models of the work environment are easily available. The virtual reality-based training can produce a more realistic view of the work environment. Trainees can understand not only the work itself, but also their surrounding environment more accurately. Figure 5 presents an image captured using a real camera and an image rendered with a point cloud. Results show that realistic images can be rendered with a point cloud obtained using three-dimensional scanning technology. Realistic three-dimensional models can also be used for directors to explain work contents to workers at a toolbox meeting. When the director explains the work contents and procedures with the rendered realistic view of the work environment, the workers can readily understand the explanation. It is expected that the efficiency and safety will improve.

Real camera image

Image rendered with point cloud

Fig.5 Comparison between a real camera image (top) and a rendered image (down).

3.3 Spatial clearance verification for waste conveyance and temporary placement

When the model accuracy is sufficiently high, it becomes possible to detect collisions between transported objects and the environment during conveyance and to ascertain how to convey them without collision. Simulations of this kind are extremely useful when the passage is too narrow to accommodate the transported waste and when the clearance for temporary placement is insufficient.

Figure 6 shows a spatial clearance verification system for supporting dismantling work at a nuclear power plant developed in a joint research project between Fugen Decommissioning Engineering Center and Kyoto University [9]. The system is useful to conduct simulations of transportation and placement of wastes in actual work environments intuitively using augmented reality technology. The most important feature of the system is a function that detects collisions between virtual wastes components and the actual work environment. The system uses three-dimensional models of waste and the environment for augmented reality superimposition of the waste and collision detection. The system is intended to be used by two workers: a cube operator and a system operator. The cube is used to indicate the three-dimensional position and orientation of the virtual waste. The worker can input the path of the conveyance to the system by operating the cube. The system recognizes the position and orientation of the cube in real time. A three-dimensional model of the waste is then superimposed on the camera image. When the virtual waste collides with the work environment, the collision position is shown as portrayed in Fig. 7. Areas highlighted in yellow and red color show the collided part of the virtual waste and work environment, respectively. The workers can understand which part might collide by referring to the colored part of the waste and the environment.

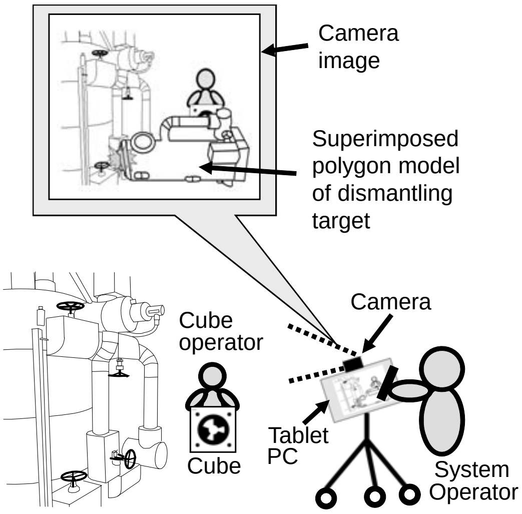

Fig.6 Conceptual image of spatial clearance verification system using augmented reality.

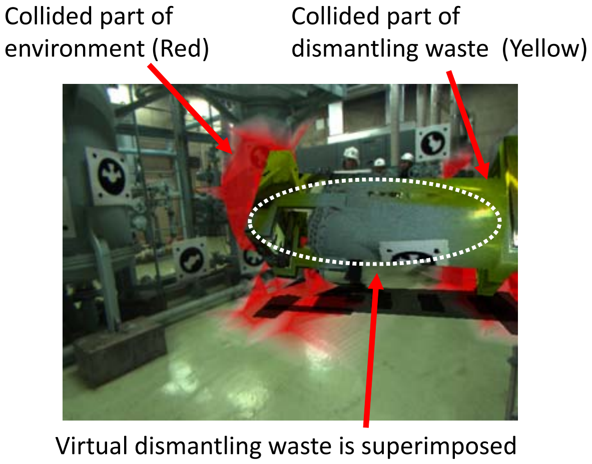

Fig.7 Visualization of collided part.

3.4 Maintenance information management

A model of the whole plant, if available, can be useful as a basis for the management of plant maintenance information. All instruments in a real plant presumably exist in the environment model. Each real instrument corresponds to a part of the environment model. Plant instrument management can be simplified when the status information of each instrument and its maintenance history are related directly to a corresponding model of the instrument. In a conventional manner, the current status of each instrument is indicated with tags pasted on the real instrument to inform the status to workers and to record the status and history in a maintenance database. This mode of management leads to disagreement between the maintenance database and the real status of the instruments. After introducing the management via the model of instruments, the workers can access the information of each instrument merely by indicating the real instrument and can record the maintenance history directly into the model of each instrument.

4 Improvement of elemental technology

Accurate models of the work environment are also useful to improve the performance of elemental technologies to realize the systems described above. One important aspect is the improvement of tracking, which estimates the position and orientation of something in real-time. To provide useful location-aware information to the workers on site, it is necessary to estimate the position and orientation of workers in real time. One technical candidate is marker-based tracking [10]. Marker-based tracking uses specially designed markers which are pasted in the environment or tracking targets as shown in Fig. 8. Position and orientation of camera are estimated using image processing and mathematical calculations. Although the marker-based tracking can provide very accurate tracking, it demands much preparation and might obstruct the work itself. The number of markers pasted in the work environment can be reduced when natural feature based tracking is available. Three-dimensional models of the work environment are useful for the natural feature based tracking. Images captured with a conventional color camera can be compared to images generated by rendering the models to estimate the position and orientation of the real camera relative to the models as shown in Fig. 9. Depth images obtained using the depth camera can also be compared with depth images generated from the three-dimensional models.

Another important application of point clouds to improve elemental technology is an accuracy prediction of the natural feature-based tracking. When the whole model of the work environment is known, it is possible to conduct tracking virtually at the position where the camera possibly exists and to evaluate the performance of the tracking in advance (as shown in Fig. 10). We can know the area where tracking tends to fail because the degree of texturing of the area is either too great or too slight by the simulation. In this case, for example, we can paste markers in an area to improve the tracking accuracy and stability. It is possible to improve the tracking accuracy and stability using a scanned model of the work environment.

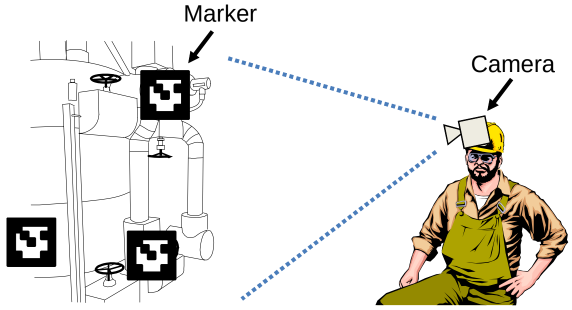

Fig.8 Configuration of marker-based tracking.

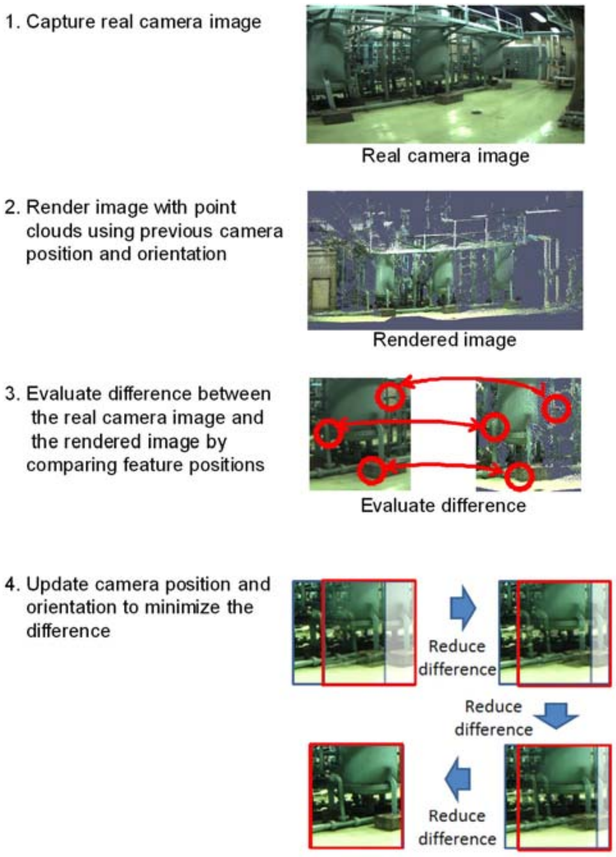

Fig.9 Estimation of camera position and orientation with comparison between real camera image and rendered image.

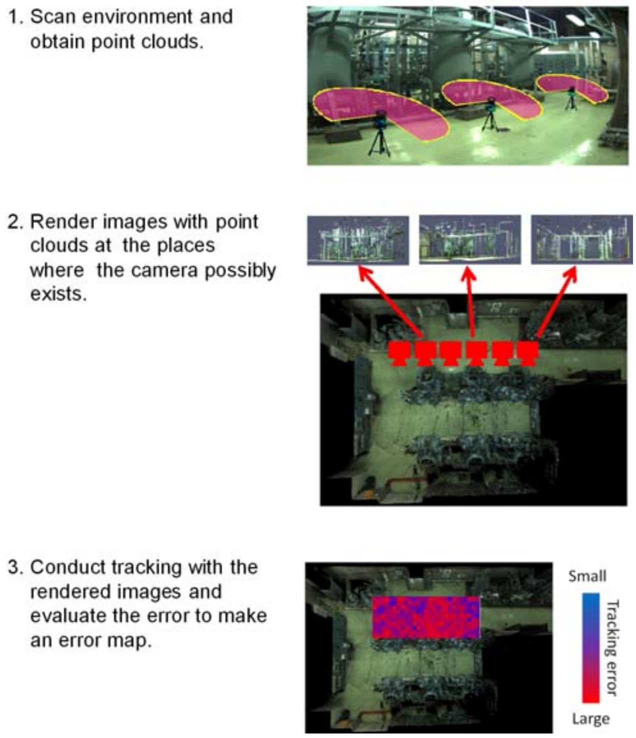

Fig.10 Tracking accuracy prediction using point clouds.

5 Summary

This article describes three-dimensional scanning technologies and their possible applications to plant maintenance and dismantlement. One reason as to why virtual reality and augmented reality are not widely used yet, is that the cost to build their contents is too great compared to their effects. New three-dimensional scanning technologies can bypass this problem. Once three-dimensional models of environment are built, they can serve as good contents supporting virtual reality and augmented reality systems. Three-dimensional scanning technology is now worthy of special attention.

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