Introduction of Products

Stereo Camera System for ICT Hydraulic Excavators

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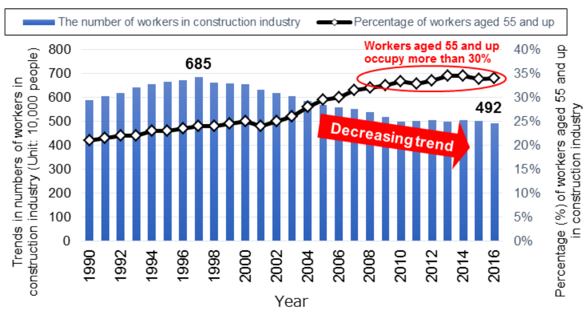
The labor shortage has become a serious problem in the construction industry, due to the decrease in the number of young new graduate employees and the retirement of the existing mature workers. In response to this situation, Komatsu launched a new service called "SMARTCONSTRUCTION" in 2015, which will improve productivity and safety at the construction sites leveraging its construction machinery with ICT technologies. The adoption rate of SMARTCONSTRUCTION is steadily growing spurred by i-Construction and ICT-aided construction, national programs promoted by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). In this paper, we introduce a stereo camera system that is newly developed to be implemented on ICT excavators for SMARTCONSTRUCTION.

Key Words: *ICT hydraulic excavator, Stereo camera, SMARTCONSTRUCTION, 3D point cloud data, Visualization of construction, Continuous shooting, i-Construction, Measuring construction result, KomEyeMonitor, KomEyeAR, Autonomous loading*

1. Introduction

Labor shortage has become a serious problem because of decrease in the number of construction machine operators and young graduate employees while the aging of existing operators is growing. In fact, the number of workers in construction industry has decreased from 6.85 million (in FY 1997, the peak year) to 4.92 million (in FY 2016), which is decrease of approx. 28%. Moreover, there is an ongoing situation in which more than 30% of them are aged 55 and up. (**Fig. 1**)



Reference: Ministry of Land, Infrastructure and Transport, *The Current condition of Construction Industry*

Fig. 1 Trends in the number of workers in construction industry

Under such a situation, nevertheless, the construction industry must take responsibility on construction and maintenance of the infrastructure. In addition, improvement of the productivity and safer work environment (hazard mitigation) are strongly required at every jobsite. In fact, the construction investment in Japan dropped down into approx. 41 trillion yen in FY 2010, but it seems in a tendency of recovery afterwards as the demand of construction industry is still really high. (**Fig. 2**)

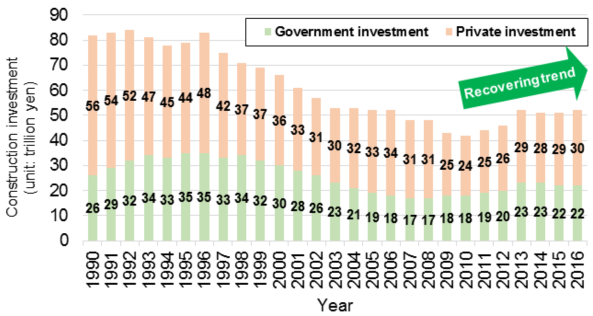


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Fig. 2 Trends in construction investment amount

Komatsu provided the construction jobsites with the ICT construction machines in which the latest technology were installed starting in 2013, and has worked on spreading ICT-aided construction methods. In addition, we took the customer's viewpoint into consideration and started offering a new service called the "SMARTCONSTRUCTION" in 2015 in order to improve productivity and safety at jobsites by utilizing ICT construction machines. The aim of this new service system is to realize the safe, smart and more productive jobsite by organically connecting all information of persons/machines/things through ICT technologies to make daily operations visualized. By using this service system, the movement of all things at the jobsites can be computerized and information about it is input into the system. Based on the information, workers can implement PDCA (Plan-Do-Check-Action) while reviewing each time and provide the actual working jobsites with the optimum construction plan.

2. Introduction of the Stereo Camera System

Komatsu developed the Stereo Camera System for ICT hydraulic excavators to visualize daily operations at construction jobsites.

The stereo cameras mounted outside operator's cab on an ICT hydraulic excavator take photographic images of the construction site. The images are then processed into the 3D point cloud data by using a dedicated electronic controller. These generated 3D point cloud data are transmitted to cloud service "SMARTCONSTRUCTION CLOUD" via the internet together with camera images. (**Fig. 3**)

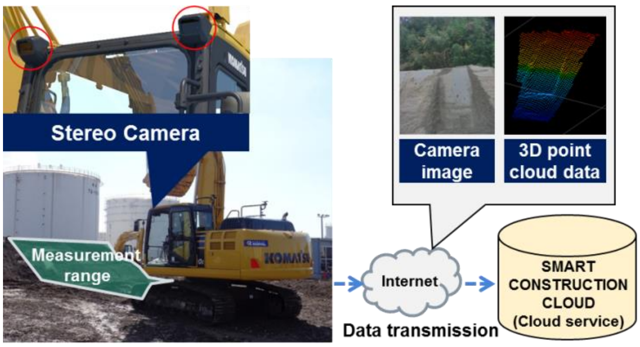
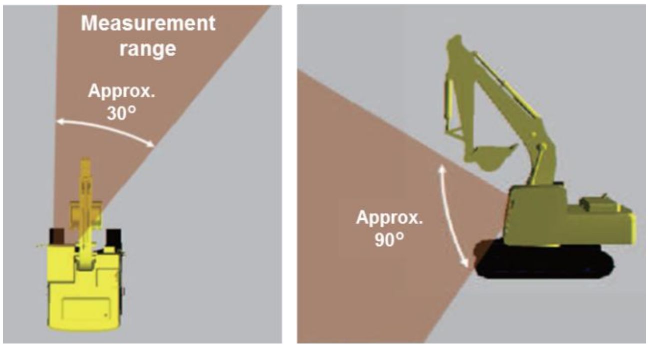


Fig. 3 Overview of the Stereo Camera System

The Stereo Camera System for ICT hydraulic excavators is comprised of two sets of stereo cameras, which shoot the upper view and lower view respectively. The measuring range is up to approx. 20 meters in the forward direction, approx. 30 degrees in the horizontal direction (**Fig. 4** (a)), and approx. 90 degrees in the vertical direction (**Fig. 4** (b)).



(a) Horizontal direction (b) Vertical direction

Fig. 4 Measurement range of the Stereo Camera System

This Stereo Camera System can also monitor the progress of construction jobs which are performed by non-ICT construction machines and workers at jobsites. Therefore, it can visualize daily progress of construction at the whole jobsite, by combining with terrain data which are obtained from moving paths of ICT excavator's bucket cutting edge.

The 3D point cloud data acquired by these stereo cameras are transmitted to cloud service called "SMARTCONSTRUCTION CLOUD", which workers can get access to from any jobsite and with any terminal device. The transmitted data updates the daily progress of construction. The figure of construction progress shows the earth cut portion and the earth filled portion by different colors, and their two-dimensional and three-dimensional images can be displayed. It is also possible to show any cross section of the land, which enables the workers to confirm the construction progress. (**Fig. 5**)

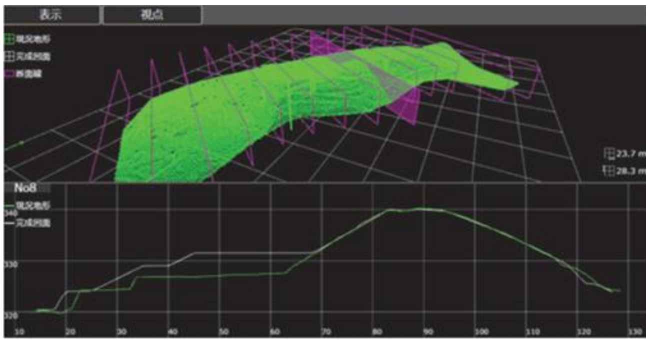


Fig. 5 Construction progress display as a cross section

2.1 Principle of the Stereo Camera (Triangulation)

The stereo cameras take images of the objects, using two cameras in the same way a person sees a thing and measures the distance to an object. The *D* for distance to an object is calculated with (Formula 1), using the positional deviation (disparity) Z of the pixel positions in the image planes of the same object which is shot with right and left cameras. (**Fig. 6**)

$$D = \frac{B \times f}{Z} \qquad \text{(Formula 1)}$$

where *B* is the distance (baseline length) between the right and left cameras, and *f* means the focal length of the camera.

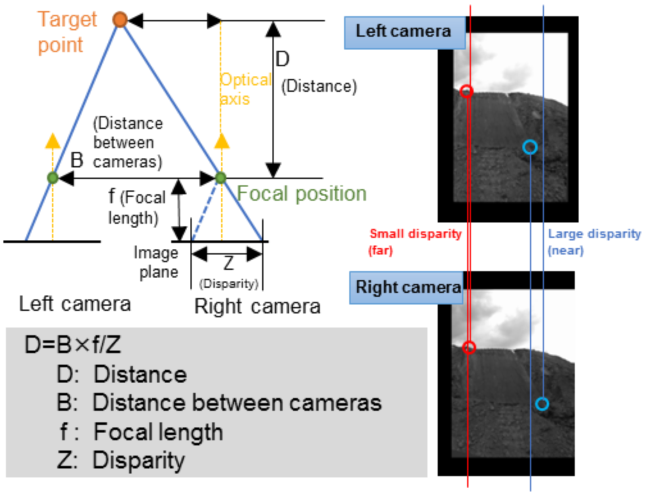


Fig. 6 Principle of Stereo Camera

2.2 Stereo Processing

A distance to the object *D* is easily calculated from a disparity *Z*, the distance between two corresponding points in the left and right image of a stereo pair. A disparity for each pixel is calculated by stereo matching with several preprocessing, such as undistortion and rectification.

2.2.1 Undistortion

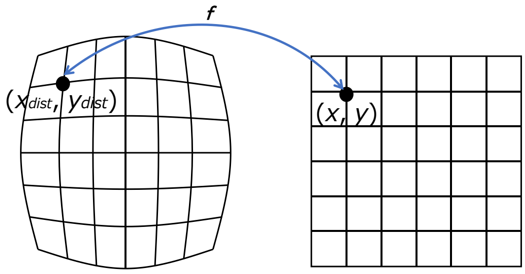
Because the camera lens has a radial distortion, the straight line is distorted by its curve as shown in **Fig. 7** (a) and it is difficult to accurately obtain a disparity *Z*. Therefore, undistortion is necessary to remove the radial distortion before calculating a correct disparity value.

The radial distortion is defined by the formulas below (Formula 2 and Formula 3), where the coordinate (x_{dist}, y_{dist}) indicates the position in the image before undistortion, the coordinate (*x*, *y*) indicates the position in the image after undistortion, *r* is a radius from the center of the image to the pixel position (x_{dist}, y_{dist}), and *k* indicates the distortion coefficient which shows the degree of the radial distortion.

$$x = f(x_{dist}, r, k) \qquad \text{(Formula 2)}$$
$$y = f(y_{dist}, r, k) \qquad \text{(Formula 3)}$$

Note that the distortion coefficient *k* is calculated individually when manufactured because each camera has a different coefficient.

After applying (Formula 2) and (Formula 3) to every pixel on the camera image, the camera image with distortion can be converted into the image without distortion. **Fig. 7** (a) and **Fig. 7** (b) respectively show before and after undistortion.



(a) Before undistortion (b) After undistortion

Fig. 7 Example of undistortion

2.2.2 Stereo Rectification

It takes time to search for the pixel position where the feature of the object image shot by the left camera matches that of the image shot by the right camera. Therefore, it is necessary to convert the corresponding pixels in right and left cameras into the same line to obtain the distance. This conversion is called “stereo rectification”.

The stereo rectification is a process of regenerating images so that the images taken by the cameras which are physically not located in parallel will be in a pseudo-parallel state, for the purpose of narrowing the area to be searched for the pixel with the corresponding feature. Before performing this processing, a calibration is performed to obtain the inner parameters (the focal length, the pixel pitch, and the center position of pixels of each camera) and the outer parameters (the relation of positions/postures between the right and left camera). The stereo rectification is then accomplished by generating a rectified image plane based on the above parameters and generating an undistorted image in this image plane. (**Fig. 8**)

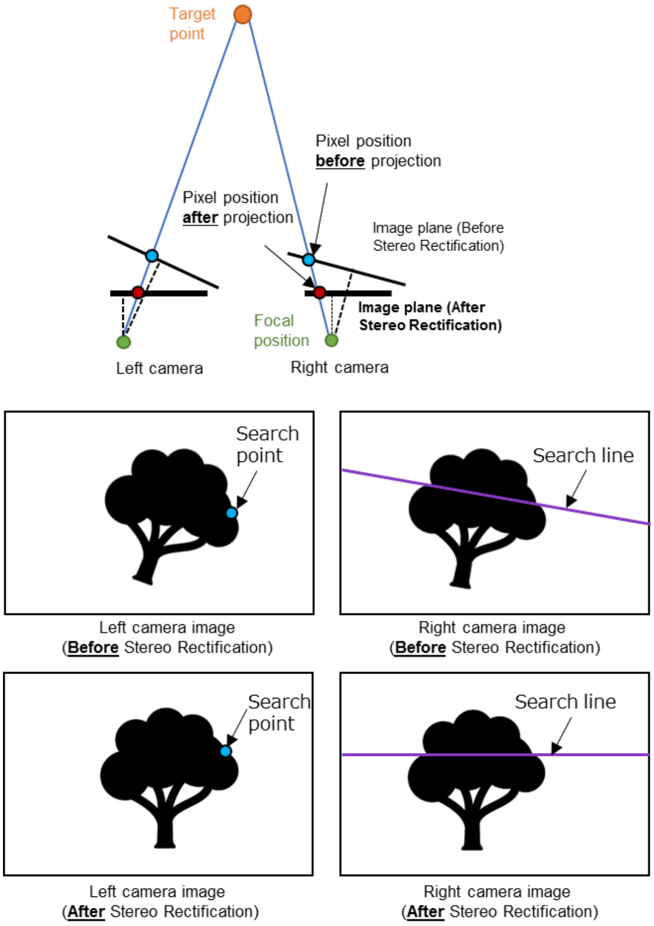


Fig. 8 Stereo rectification

2.2.3 Stereo Matching

Stereo matching is performed to search for corresponding pixels in the right and left camera images by scanning the rectified images taken by both cameras.

Since the images taken by right and left cameras are in a parallel state after the stereo rectification, the corresponding pixels of the right and left camera images exist on the same horizontal line. Therefore, it is enough to search only this line for the corresponding pixels when searching for a pixel in the left camera image (hereinafter referred to as a "search pixel") from the right camera image. In the stereo matching, the right camera image is searched for pixels corresponding to the search pixel, by referring to the pixel value in the area around the search pixel and the calculating the degree of similarity. (**Fig. 9**)

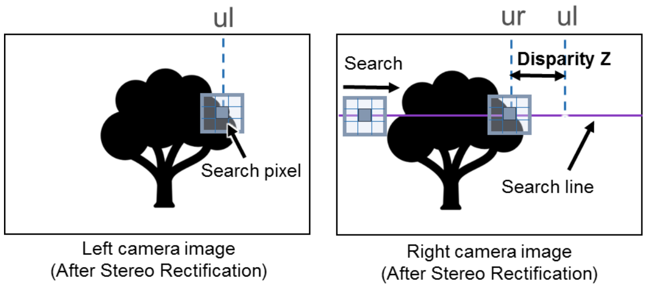


Fig. 9 Stereo matching

2.3 Generating 3D Point Cloud Data

Three-dimensional camera coordinate data provided by stereo processing are converted into jobsite coordinate system to be generally used in the construction jobsites.

The camera coordinate data (x_c, y_c, z_c) of the measured point are converted into the jobsite coordinate data (x_g, y_g, z_g) by (Formula 4), by using transformation matrices *R* and *T*, which are derived from positional information provided by GNSS receiver mounted on ICT hydraulic excavator, machine body posture angles obtained by IMU, and the camera set position and angle on the machine which are obtained by calibration. (**Fig. 10**)

$$\begin{pmatrix} x_g \\ y_g \\ z_g \end{pmatrix} = \boldsymbol{R} \begin{pmatrix} x_c \\ y_c \\ z_c \end{pmatrix} + \boldsymbol{T} \qquad \text{(Formula 4)}$$

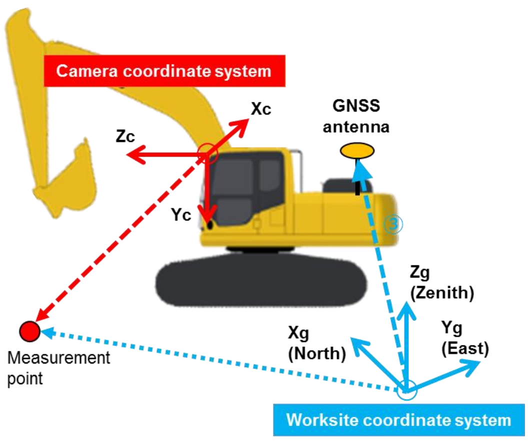


Fig. 10 Conversion to jobsite coordinate system

Finally, the 3D point cloud data shown in **Fig. 11** can be obtained.

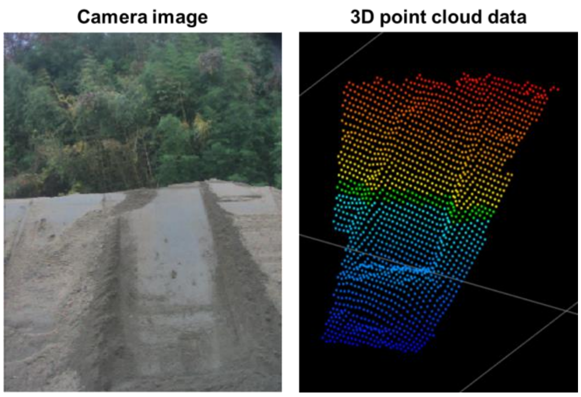


Fig. 11 3D point cloud data obtained by Stereo Camera

2.4 Continuous Shooting

When the machine is in a stationary condition, the Stereo Camera System can measure the range of approx. 20 meters in the forward direction, approx. 30 degrees in the horizontal direction, and approx. 90 degrees in the vertical direction by pressing the shoot button. In addition, the Stereo Camera System has a function of continuous shooting, which expands the measuring range of a single shooting action by swinging the machine body.

The continuous shooting function enables continuously measuring 3D terrain data while the machine is in a swing movement by pressing down the shoot button at the start and end of swinging operation. Moreover, it is equipped with a sound guidance function to navigate the operator to make operation easier.

This continuous shooting function has also enabled shortening the time for measuring, because measuring the terrain in front of the construction machine can be performed in a single shooting operation, which had conventionally been required to be divided into several times. (**Fig. 12**)

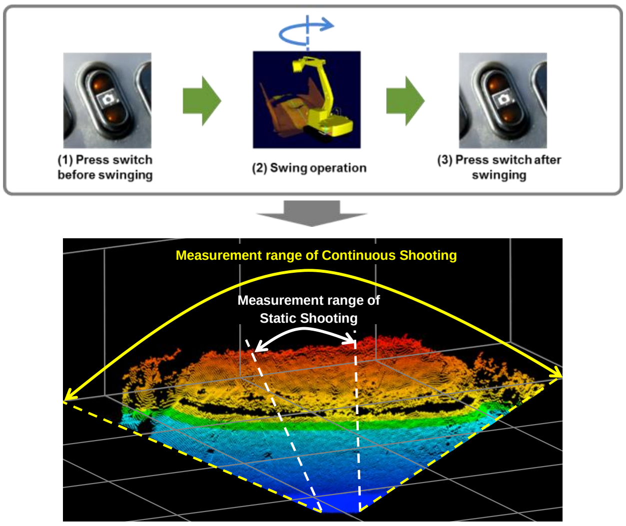


Fig. 12 Operation flow of continuous shooting and its measurement range

2.5 Cooperation with the KomEyeMonitor Application

A new application, "KomEyeMonitor", enables the operator to see which area of the jobsite the camera is shooting at on the tablet monitor.

"KomEyeMonitor" displays images taken by the upper and lower cameras that are transmitted via wireless communication from the controller of the Stereo Camera System.

Moreover, it can show the conditions of controller as well as the image area where the 3D point cloud data is generated by the Stereo Camera System. (**Fig. 13**) This "KomEyeMonitor" can be used by downloading from Google Play Store or App Store.

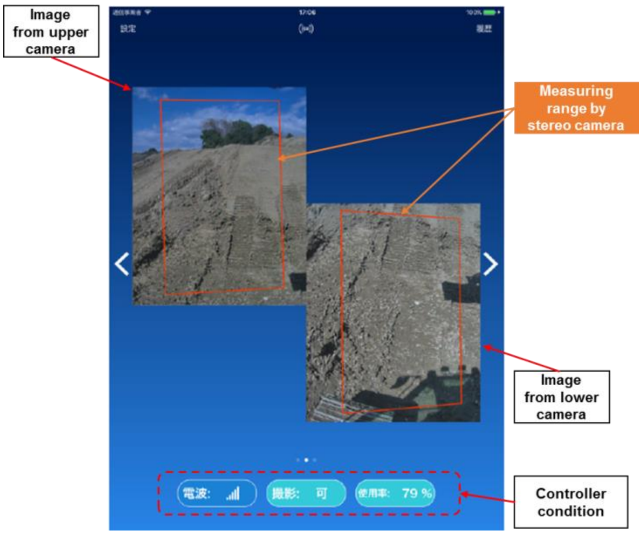


Fig. 13 Tablet application "KomEyeMonitor" display screen

3. Efforts Toward i-Construction

In order to promote i-Construction, Ministry of Land, Infrastructure and Transport introduced a system in which partial payment can be made based on the construction result. (**Fig. 14**) If this method of partial payment based on construction result becomes popular, the financial status (cash flow) of the construction companies are expected to be improved. Moreover, the quality of construction job is expected to be improved since the partial result of inspection reflects the next construction plans.

The Stereo Camera System developed by Komatsu for ICT hydraulic excavators was registered as a measuring device for measuring construction results, together with terrestrial laser scanner, aerial photographic survey device by UAV, and total station system.

This measuring device for measuring construction result requires use of actual measurement data and measurement accuracy in both elevation and horizontal ranges of 200 mm or less. Therefore, Komatsu additionally implemented this processing for measuring construction result into the cloud service “SMARTCONSTRUCTION CLOUD” in order to satisfy this requirement, which made it possible to measure up to 20 meters in the forward direction.

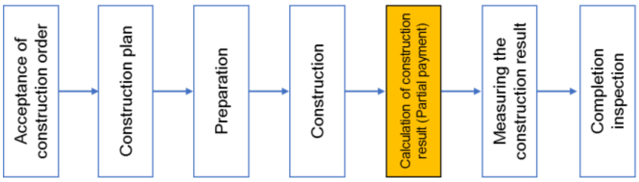


Fig. 14 Flow of partial payment based on construction result measurement

4. Action Plans in the Future

We will strive to expand the range of applications of this Stereo Camera System, not only for visualization of daily construction jobs but also for other purposes in future.

4.1 Application Example 1: KomEye AR

The workers became free from ground survey work during the construction job and finishing stake work which had been required conventionally thanks to spreading ICT-aided construction method, which resulted in a significant improvement in construction efficiency at the jobsites. On the other hand, due to the loss of finishing stake which was very common at actual jobsites conventionally, the complaints came up from the jobsite workers, saying that it is difficult to find the actual location of the construction site corresponding to the three-dimensional data of the construction drawings. This is because the finishing stake, which is no longer performed at construction jobsites due to the spread of the ICT-aided construction method, used to be a clue to imagining a state of the terrain at the completion of the construction.

“KomEye AR” was developed, in response to the workers’ demand, as a substitute for the clue at the construction jobsites, whose role was taken by finishing stake devices conventionally. AR technology allowed the machine operator at the jobsite to see an expected completion image and current progress of his/her job, by displaying the three-dimensional design data over the image shot by stereo cameras. (**Fig. 15**)

Fig. 15 Tablet application “KomEye AR” display screen

4.2 Application Example 2: Autonomous Loading

Introduction of ICT excavators with stereo camera system made the high-level of visualization of construction sites come true. Now we are moving on to the next step beyond.

Komatsu made an exhibition at CEATEC JAPAN 2018 for the first time to introduce the new challenges taken up by its SMARTCONSTRUCTION under the theme of safer, more productive and smart construction jobsites of the future. (**Fig. 16**)

Fig. 16 Komatsu’s exhibition booth for CEATEC JAPAN 2018

As one of the main exhibits, we performed actual machine demonstration that an ICT hydraulic excavator with stereo camera system automatically loaded a dump truck at Komatsu IoT Center Tokyo, Komatsu’s test field 8 km away from CEATEC JAPAN 2018 exhibition site in Makuhari-city. The demonstration was relayed live from the IoT Center to the exhibition site. (**Fig. 17**)

Fig. 17 Autonomous loading demonstration at CEATEC JAPAN 2018

The Stereo Camera played the role of "eye" in the system and was used for perception and visualization of the situation. The 6DoF (Degrees of Freedom) pose of the dump truck vessel was recognized from stereo camera images leveraging the latest AI technologies and the result was passed to the control system that took the overall control of the autonomous loading. (**Fig. 18**)

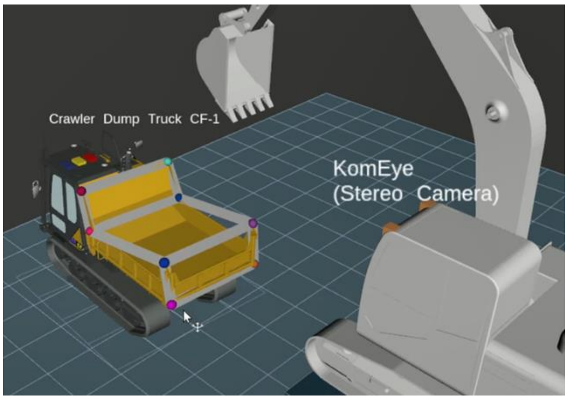


Fig. 18 6DoF dump truck vessel pose estimation

5. Conclusion

In this report, we introduced the function and its applications of the Stereo Camera System which we started introducing into ICT hydraulic excavators. The Stereo Camera System makes it possible to visualize construction work carried out not only by ICT construction machines, but also by many other non-ICT construction machines and workers at the jobsites. By using the cloud service "SMARTCONSTRUCTION CLOUD" at any jobsite and with any terminal device to unify management of 3D point cloud data obtained from the Stereo Camera System and 3D data obtained from ICT construction machines, the progress of daily construction work can be visualized.

Furthermore, we developed "KomEye AR", which displays the three-dimensional data of the construction drawing over the image taken by the stereo cameras by applying the Stereo Camera System. This enabled the machine operator at the jobsite to see an expected completion image based on the three-dimensional data of construction drawings, which were lost from the construction jobsites due to the spread of the ICT-aided construction method.

We believe that in the future we can contribute to the realization of the attractive construction jobsites and increase in the number of construction industry employees by widening the range of application of the Stereo Camera System and continuing to provide solutions while taking customers viewpoints into consideration. In addition, we will strive to grade up our solutions step by step to improve the productivity and safety, and to realize the "fully-automated" construction.

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[A comment from the authors]

Komatsu has provided the construction jobsites not just with ICT construction machines, but also with a new service called "SMARTCONSTRUCTION" in order to improve productivity and the safety at construction jobsites through contemplating how ICT construction machines should be applied while taking the customers' perspective into consideration.

We will continue to find out the problems together with customers through visiting their jobsites and to offer our solutions to them, and will strive to realize the slogan "Even safer, even more productive and even smarter worksites in the future". We believe that such activities will support the construction industry which plays the roles of infrastructure development and its maintenance, and that they can then contribute to our society.