Technical Paper

Applying Model-based Development to Performance Development of Hydraulic Excavators Using 1DCAE

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The requirements for construction machinery are becoming more sophisticated year by year, and the systems are becoming larger and more complex. Komatsu is aiming for efficient development even in large and complicated systems by applying model-based development to vehicle performance development. This paper reports an application example of using 1DCAE for the performance development of a hydraulic excavator, and also introduces examples of further utilization of 1DCAE such as a simulator.

Key Words: *MBD, 1DCAE, Hydraulic excavator, Model, Performance, Simulation, Simulator*

1. Introduction

The automotive industry is facing a major transformation called CASE *1, which includes electrification and automation. Thorough efficiency improvement of automobile development, which is becoming more sophisticated and complicated, is indispensable; the importance of efforts in model-based development (MBD), which performs the development and performance evaluation process by virtual simulation, is expanding [1]. MBD is a method that is expected to shorten the development period and improve the software quality by utilizing the simulation function based on the model in the development of embedded systems, and from there, the scope of application has been expanded and it has been applied to the development of the entire system. Komatsu, like the automobile industry, started MBD from the development of embedded systems and is currently promoting it in-house to improve the efficiency and quality of development by virtually performing the feasibility of vehicle performance development at the concept design stage of the upstream process of vehicle development.

In the past, when the systems were not as large and complicated as they are today, desk study was enough to develop them. However, now that the system scale has become large and complicated, it has become difficult to carry out sufficient preliminary examinations only by simple desk studies, and it is becoming often to notice problems only after use of actual vehicles. Thus, Komatsu started to use the MBD process shown in **Fig. 1** also in vehicle performance development, to sufficiently identify issues and take countermeasures in a virtual environment before starting actual manufacturing.

This paper introduces an example of applying model-based development to the performance development of a hydraulic excavator using 1DCAE in the following **Section 2. Section 3** introduces excavation simulation using AGX Dynamics, sensory evaluation, a simulator that can be boarded by humans, and further utilization.

*1 CASE: Connected, Autonomous, Shared & Service, Electric

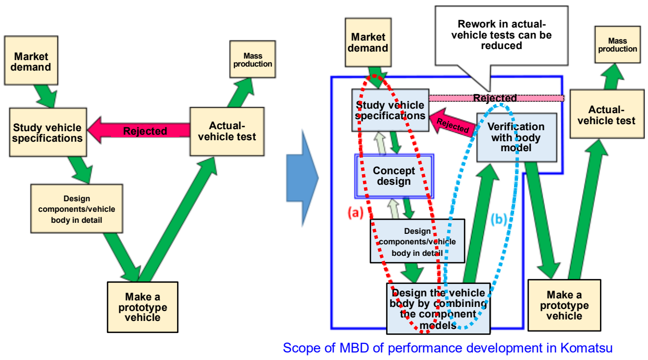


Fig. 1 MBD process in Komatsu

2. Performance development with 1DCAE

1DCAE is a design method that enables proper product design at the upstream stage of product development by enabling evaluation and analysis of the functions of the target product before designing the structure in product design [2]. While showing examples, this section describes the concept of the MBD process that uses the 1DCAE method being performed in Komatsu.

2.1 MBD process in performance development

The purpose of MBD in performance development is to improve the quality of design with enough pre-study before the performance evaluation using the prototype vehicle (hereinafter "the performance test") by adopting the process within the blue frame in **Fig. 1** and utilizing the 1DCAE model (hereinafter "Model"). The MBD process in Komatsu consists of two phases:

(1) Concept Phase (**Fig. 1**, flow **(a)**)

The vehicle development department determines the vehicle specifications from the market demands, assigns functions to the components to achieve these specifications, and organizes the required specifications for the component development department.

(2) Verification Phase (**Fig. 1**, flow **(b)**)

The results of the detailed design performed (component performance characteristic values) by the component development department are fed back to the Model to evaluate the feasibility of the vehicle specifications assumed at the Concept Phase. If it is feasible, the process will be proceeded to the performance test phase using the prototype vehicle; otherwise, the components will be redesigned, and/or the vehicle specifications will be revised.

2.2 The way of thinking in the Concept Phase

In the Concept Phase, the requirements to be realized for the vehicle are modeled. For example, suppose that the vehicle development department has a requirement that the cylinder must move at a speed of V_{cyl} [m/s] that depends on the lever control. In this case, the Model is built with the assumption that information transmission between components is as shown in **Fig. 2**.

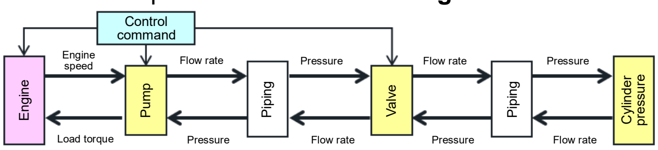


Fig. 2 Conceptual diagram of component-to-component transmission of information

When the pressured area on the driving side of the cylinder is A_{cyl} [m^2], the flow rate Q_{cyl} [m^3/s] required to move the cylinder at the required speed is calculated by Equation (1).

$$Q_{cyl} = A_{cyl} V_{cyl} \tag{1}$$

In addition, if Q_{cyl} [m^3/s] is considered as the valve passing oil flow rate, it can be expressed by Equation (2), and has the characteristic (**Fig. 3**) that is determined by the lever control quantity K_{lever} [%] and the differential pressure between the valve inlet and outlet ΔP_{vlv} [Pa].

$$Q_{cyl} = f(K_{lever}, \Delta P_{vlv}) \tag{2}$$

Here the pump pressure is P_p [Pa], the cylinder load pressure is P_{cyl_mi} [Pa], the pressure loss of the pipe connecting the pump and valve is ΔP_{ph} [Pa], and the pressure loss of the pipe connecting the valve and cylinder is ΔP_{ch} [Pa], then ΔP_{vlv} [Pa] can be expressed by Equation (3).

$$\Delta P_{vlv} = \left(P_p - \Delta P_{ph}\right) - \left(P_{cyl\_mi} + \Delta P_{ch}\right) \tag{3}$$

Since P_{cyl_mi} [Pa], ΔP_{ph} [Pa], and ΔP_{ch} [Pa] are determined by the posture of the work equipment and the characteristics of the hydraulic piping (such as volume and elasticity) incorporated in the vehicle, then, only P_p [Pa] can be controlled without changing the hardware. In other words, in order to move the cylinder at the required speed with existing hardware, the following two specifications need to be clarified:

- How to control the pump pressure
- The flow rate characteristics depending on the lever control quantity

Based on the above idea, in the Concept Phase, the vehicle development department conducts examinations as required for the vehicle specifications by using the Model and assigns functions to the components.

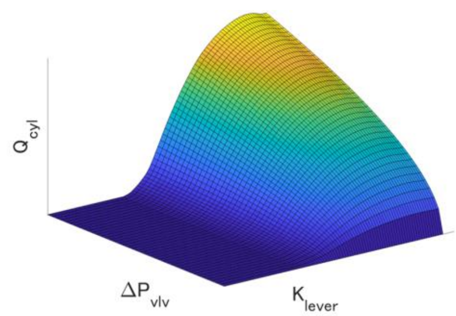


Fig. 3 Flow rate characteristics

2.3 The way of thinking in the verification phase

In the Verification Phase, the feasible performance is evaluated using the Model. The component development department designs components in consideration of the constraints of the own section and feeds back the feasibility of the required specifications from the vehicle development department. The vehicle development department reflects this feedback in the Model parameters and evaluates whether the targeted vehicle specifications determined at the Concept Phase have been achieved. If the evaluation result meets the required specifications, the process will be shifted to the performance test phase using the prototype vehicle. Otherwise, the vehicle development department requests the component development department to redesign it, reconsider the vehicle specifications, or change the function assignment to the components to achieve the specification target for the entire system.

2.4 Effects of MBD

The conventional performance development required a large number of man-hours and costs because it relied on the pass/fail judgment in performance tests, multi-level parts were prepared, and parts replacement was repeated until the performance tests were passed. In addition, measurements were limited to only the locations where significant design changes have been made from the existing vehicle due to the limitation of the test man-hours and the number of measuring equipment owned. For this reason, when a problem occurred, it was often impossible to obtain data on the estimated cause, and the present condition was not fully understood. Therefore it was only possible to take measures whose effects were estimated by simple desk studies. As a result, the design was often changed by following precedents such as comparison with other models. Measures tended to result in excessive quality because it was usual to ensure a sufficient safety margin. This was one of the factors that increased the cost of products. In the future, the functions required for hydraulic excavators are expected to be more sophisticated and the system will be even more complicated; there is concern that the number of evaluation items will be enormous. Therefore, in the future, it will be difficult to establish the vehicle specifications in terms of both cost and quality through the conventional performance development based on performance tests of prototype vehicles.

By contrast, in MBD, all the components for one vehicle are connected on one Model, and we can confirm the physical quantities related to performance as time series data. Utilizing these pieces of data for the design evaluation or the identification of the cause of problems can reduce the man-hours for performance tests and the cost of test parts. The following is an outline of the result of applying MBD to the development of hydraulic excavator as an example. First, **Fig. 4** shows the functional model of the vehicle. This model was made by MATLAB/Simulink for the hydraulic components (e.g. controls, valves, pumps), work equipment mechanism, and swing mechanism, and by GT-SUITE for the engine. This model enables functional evaluation of work equipment and swing operations. This model is used to evaluate the vehicle behavior and determine the required specifications for components from the Model parameters.

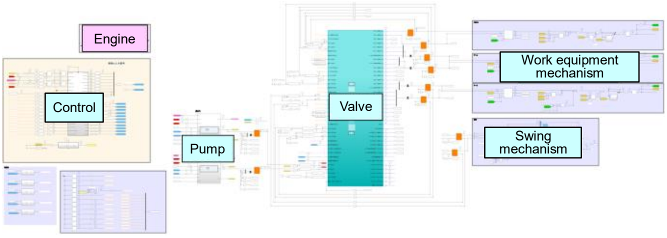


Fig. 4 Vehicle model

The following explanation presents an example of designing the swing reversal prevention function. When the hydraulic excavator stops its swing, the effect of inertia causes a swing reversal phenomenon (**Fig. 5**). Since the swing reversal quantity affects operability and ride feeling, suppressing the swing reversal is the purpose of the function. For this purpose, a swing reversal prevention should be incorporated in the hydraulic component. To design this function based on conventional performance testing, we had to go through a process that needs a lot of cost and man-hours. For going through this process, we had to prepare parts of several patterns, repeat parts replacement and measurements, and finally select the best one. By contrast, in MBD, the difference in behavior can be immediately checked as time-series data simply by rewriting the presence/absence of the relevant function and/or the characteristic value on the Model.

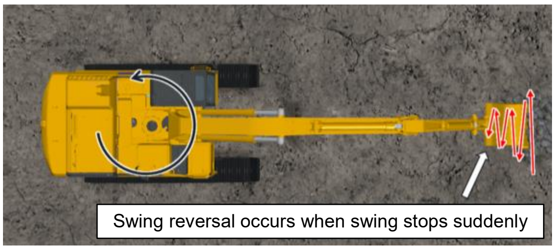


Fig. 5 Swing reversal phenomenon

Figure 6 shows a comparison of swing motion results with and without the swing reversal prevention function. It expresses the difference in the swing reversal quantity (i.e. bucket cutting edge movement amount), and we could confirm the effectiveness of the function without using an actual vehicle.

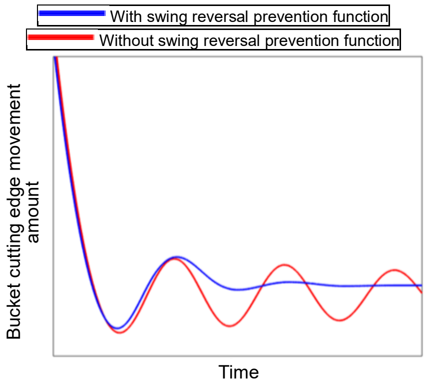
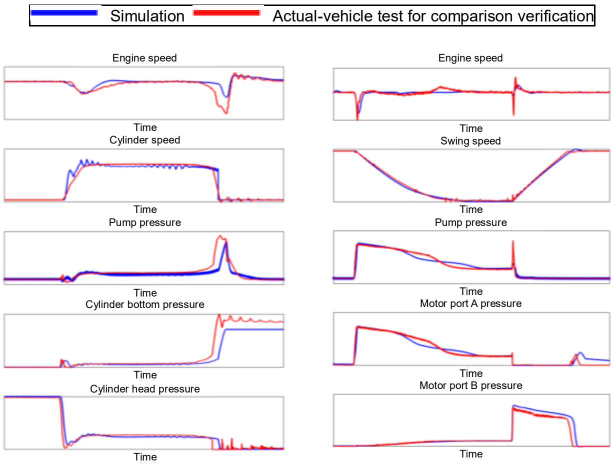


Fig. 6 Comparison between simulation results

2.5 Model accuracy

Figure 7 shows a comparison between the results of work equipment / swing operation simulations and the results of actual-vehicle tests, which were conducted for this comparison and verification.



(a) (b)

Fig. 7 Data comparison between simulations and actual-vehicle tests

The **Fig. 7 (a)** charts show the comparison results of operating the work equipment only, and the **Fig. 7 (b)** charts show the comparison results of performing swing operation only. In both **Fig. 7 (a)** and **Fig. 7 (b)** charts, the simulation results and the data from the actual-vehicle tests are in good agreement in terms of the engine speed, actuator speed, pump pressure, actuator port pressure. It means that this Model has sufficient accuracy for design studies.

3. 1DCAE model utilization examples

Section 2 described the vehicle performance development using the Model. **Section 3** describes further utilization of the Model, including an excavation simulation (**3.1**), simulation for sensory evaluation (**3.2**), and also presents an application example of a simulator built for desk study of sensory performance (**3.3**). In hydraulic excavators, digging performance and sensory performance are priority performances because they are directly linked to productivity and furthermore marketability, where "sensory performance" refers to the characteristics based on the operator's subjective evaluation. On the other hand, neither a firm design method for digging performance nor sensory performance has been established. At present, designing of the digging performance and sensory performance are done by adjusting and brushing up based on past experience and performance test results. Measures like this kind of personal and symptomatic treatment are an issue in promoting development efficiency, and in order to solve it, we are working on building an environment using 1DCAE as described in the previous section. The process by which we are studying is a step-by-step study process where the vehicle specifications related to digging performance and sensory performance are clarified at the concept design stage, and then reflected in the respective component specifications using 1DCAE.

3.1 Excavation simulation

Hydraulic excavators are required to operate smoothly without large fluctuations in speed or stoppage of the work equipment due to load fluctuations during excavation. To satisfy this requirement, the following items must be properly designed: digging force that can withstand the soil load, weight balance that enables stable excavation, and efficient bucket shape and link mechanism. However, we have been unable to make desk studies fully including the effects of soil characteristics at present. So far, Komatsu has conducted excavation simulations using the Discrete Element Method (DEM); however, although the DEM generally has high calculation accuracy, it requires much calculation time, so it is unsuitable for situations where simulations must be repeated many times for try and error of many ideas, like the concept stage. Thus, we needed to create a system to examine the vehicle specifications that improves the digging performance at the conceptual stage, and break down them into the specifications for the individual components.

This study performed an excavation simulation using AGX Dynamics [3], a physics engine with a module to model and simulate soil deformation (hereinafter, AGX Dynamics and AGX module are collectively referred to as AGX). AGX soil models are broadly divided into static models based on soil mechanics and dynamic models based on powder mechanics and multibody dynamics. The area in which an external force acts on the static model and exceeds the permissible value is switched to the dynamic model. The advantages of AGX are: By minimizing the range of dynamic models with high computational costs, the calculation speed is faster than that of the general DEM model, and real-time calculation is also available although it depends on the model scale. In addition, the soil model has many parameters that affect mechanical properties such as the density, viscosity, friction coefficient, and Young's modulus, and can express various soil properties by combining parameters.

The simulation model imports the shape data from the 3D CAD data, and the constraint conditions such as links and cylinders are set (**Fig. 8**). The specification values of the target vehicle are input for the weight, center-of-gravity, and inertia information about the components. The mechanism and weight balance of the vehicle are expressed in the above way.

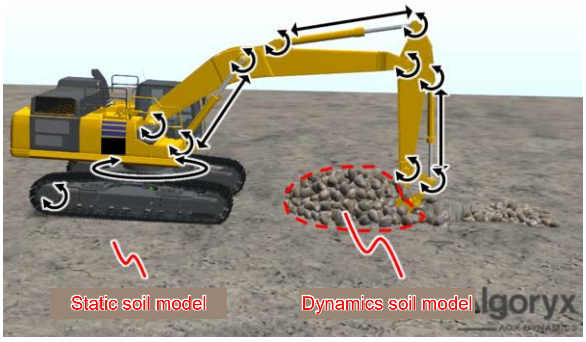


Fig. 8 Soil and vehicle body models

The vehicle model moves according to the expansion/contraction and rotation movements of various actuators such as cylinders, swing motor, and travel motors. Time-series data can be set for the operator input (control quantity) of the simulation model. This enables it to be available for evaluation using field measurement data as input. The control quantity is converted into the target displacement or target driving force before it acts on each actuator, and calculations are made based on the constraint conditions of vehicle, weight, inertia, and soil reaction force. The above is the overview of the simulation model.

From here, we will introduce an excavation simulation on flat ground as an example. To compare and examine the vehicle body load fluctuation in excavation, we prepared two soil characteristics with different hardness and verified the differences in load between the two levels. We acquired time-series data of the arm cylinder load as an index of the vehicle body load. The control quantity in time series was set and input in sequence; thus, the control quantities between the two soil characteristics were identical. **Figure 9** shows the simulation results.

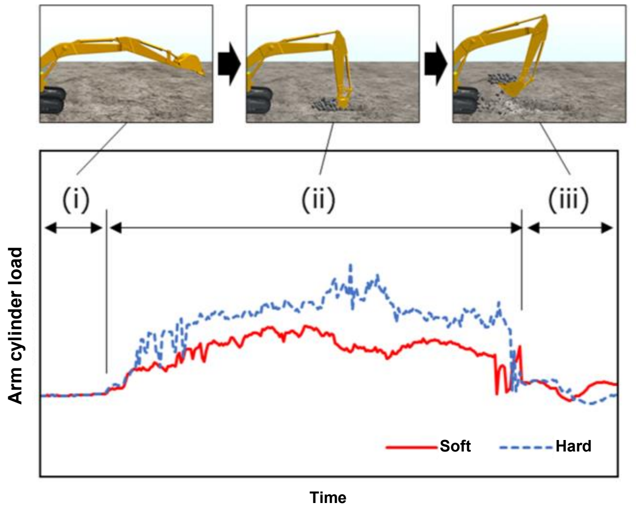


Fig. 9 Arm cylinder load time-series data

In **Fig. 9**, we divided the time-series waveforms into three sections of **(i)** to **(iii)** based on the soil-bucket contact condition before examining them. At the beginning of the simulation, since it was before the bucket came into contact with the soil; the cylinder load maintained a relatively low value (**Fig. 9, (i)**). After the bucket cutting edge penetrates into the ground, the arm cylinder load increases in soil-deformed sections due to the soil reaction force (**Fig. 9, (ii)**). During the process of removing the bucket cutting edge from the ground, the cylinder load decreases (**Fig. 9, (iii)**). From the simulation results, we confirmed the process in which the load changes from moment to moment due to the interaction with the soil. Then, focusing on the difference between soil levels, we also confirmed that the cylinder load during excavation in hard soil remains relatively high compared to that in soft soil, that is, the cylinder load changes depending on the soil property.

As mentioned at the beginning of the section, this simulation is available to determine the vehicle specifications according to the soil characteristics by computing the load in excavation. Then, based on the vehicle specifications to be achieved, we will be able to design the digging performance of the vehicle in the steps of examining the specifications of each component while utilizing 1DCAE.

3.2 Simulation for sensory evaluation

Next, this section describes simulation for sensory evaluation. One example of sensory performance is the quality of operability (good/poor) that the operator feels. Taking the sense of work equipment speed as a specific example of operability, this has been evaluated sensuously, unlike quantitatively evaluating the work equipment speed. We believe that the process of breaking down such sensory elements into quantitative design standards and evaluation criteria is essential for achieving sensory performance development on the desk. **Figure 10** shows the design steps of the sensory performance that we think of.

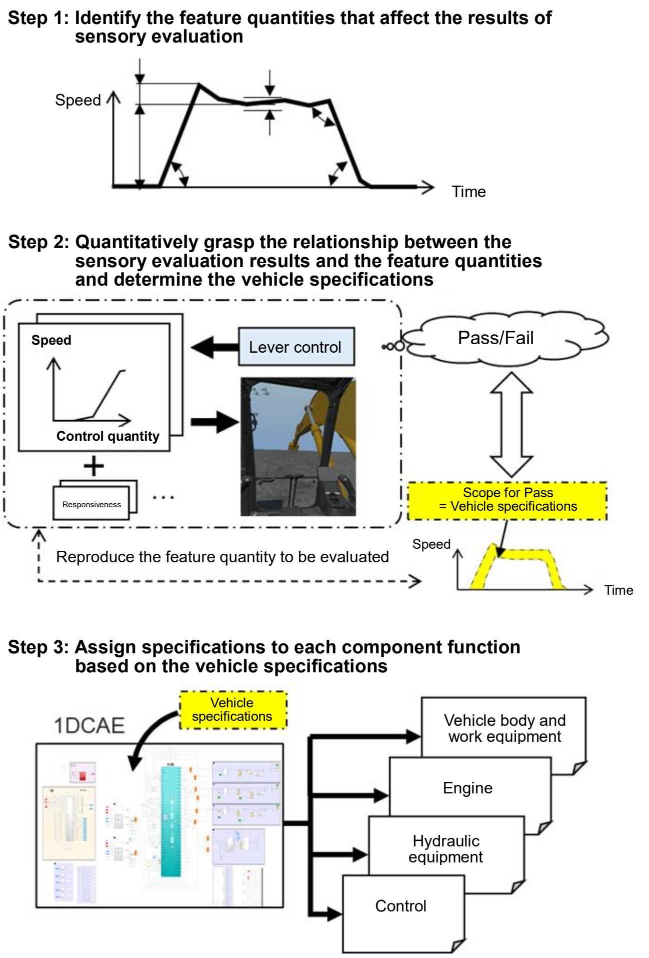


Fig. 10 Sensory performance design steps

To clarify the relationship between the results of sensory evaluation and the feature quantities in **Fig. 10**, an evaluation experiment must be conducted with the feature quantity as a variable. In this case, conducting evaluation experiments on the actual vehicle is impractical in terms of time because a huge number of experiments are required: There are a huge number of experimental levels due to the combination of types and quantities of features, fine-tuning of the hardware and software is required to change the feature quantity on the actual vehicle, and even if experiments are conducted on vehicles with exactly the same performance, the evaluation results will differ depending on the evaluator.

This paper addresses a real-time simulator constructed so that the operator can experience the sense of speed virtually. In a simulated environment, it is easy to change the feature quantities, and it is possible to verify performance items that are difficult to evaluate with an actual vehicle due to technical and safety restrictions. Thus, a simulator is also useful for considering the ideal specifications of the vehicle. To reproduce the feeling of boarding an actual vehicle, the simulator is required to have real-time performance and visual reality. In this study, focusing on the real-time performance of AGX, we used it for the physical calculation section of the simulator. We also ran AGX on the Unity game engine, to reproduce more realistic images. The images were projected onto commercially available VR goggles or monitors. When they were projected onto a monitor, the operator's eye points were fixed. A set of joysticks, or virtual levers that came with the VR goggles, was used as the control interface. **Figure 11** shows the simulator configuration. **Figure 12** shows an image from the operator's perspective in order to present the simulator boarding image.

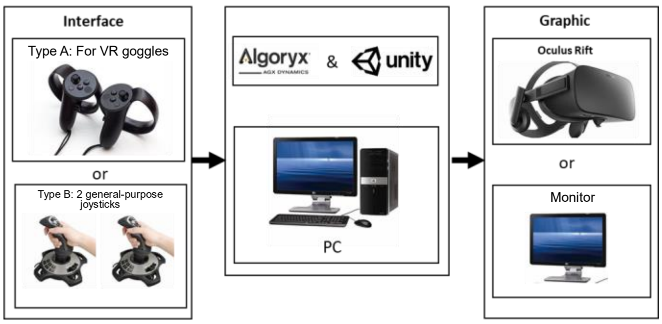


Fig. 11 Simulator configuration

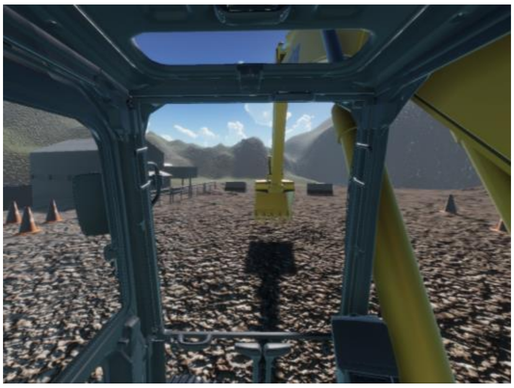


Fig. 12 Example of an image viewed from the simulator seat

The simulator operator can perform basic operations such as work equipment operation, swing, and travel through the control interface, and can see the movement of the vehicle in real time. Sensory evaluation experiments can be conducted by changing the simulator environment as desired because, as mentioned above, it can easily change the feature quantities such as steady speed / acceleration relative to the control quantity, delay, and dead time. It will enable us to study the specifications for the components based on the vehicle specifications using 1DCAE after determining these specifications from an evaluation experiment.

3.3 Examples of expanding the utilization of the simulator

As mentioned in the previous section, the simulator currently being constructed for sensory evaluation provides simulation by AGX Dynamics running on Unity, and can simulate basic operations of a hydraulic excavator such as dig, swing, and travel. We examined whether this hydraulic excavator simulator could be used for applications other than sensory evaluation. As a result, we found that it can be used for: (1) night visibility evaluation, (2) cab mock evaluation, (3) creation of around-view image, and (4) desk study of human detection logic. The following subsections outline examples of these application items.

3.3.1 Night visibility evaluation

On Unity, the external environment can be easily changed, and environments with poor visibility (e.g. nighttime, dusk) can be reproduced. This function can reproduce the night environment, enabling us to study the design of the on-board working lights.

On a vehicle model on Unity, we installed a light of the same characteristics at the same position as the mounting position on the actual vehicle and reproduced the night environment in the VR space (**Fig. 13**). It allows us to change the number of lights and check their effects during the simulation, and to easily change the installation position and characteristics of the lights as well. This function is effective for night visibility evaluation because the effects of lights, including the positional and quantity effects, can be evaluated while working in a night environment.

Fig. 13 Example of night visibility evaluation simulation

3.3.2 Cab mock evaluation

By using the Oculus Touch controllers that come with the Oculus Rift CV1 VR head mounted display (HMD), the actual hand position of the operator can be shown in the VR space. If the contact is set between the virtually displayed hand (hereinafter “virtual hand”) and the lever, you can grasp the lever with the virtual hand and operate the work equipment (**Fig. 14**). The area surrounded by the red circle in **Fig. 14** shows the virtual hand. Furthermore, by setting the contact between the virtual hand and various parts in the cab, it will be possible to consider the placement of the parts. The design inside the cab can be studied without using actual parts. This contributes to reduce rework after assembling actual parts. It can be said that this is an effective application of the simulator for improving design efficiency.

Fig. 14 Lever control with a virtual hand

3.3.3 Creating an around-view image

The KomVision Human Detection & Collision Mitigation System detects the approach of a person from the on-board camera images and avoids a collision with the vehicle. The situation around the vehicle and the positions of people are displayed on the monitor inside the cab. The displayed image is an around-view image combined from the on-board camera images. Focusing on this around-view image creation, we reproduced this function also in the virtual environment. This was achieved by linking Unity and MATLAB/Simulink, acquiring the on-board camera images with Unity, and combining the images into an around-view image using MATLAB/Simulink. The communication between Unity and MATLAB/Simulink was TCP/IP communication (**Fig. 15**). Since the camera position, orientation, and angle of view can be easily changed on Unity, installation of cameras to create around-view images can be studied even virtually.

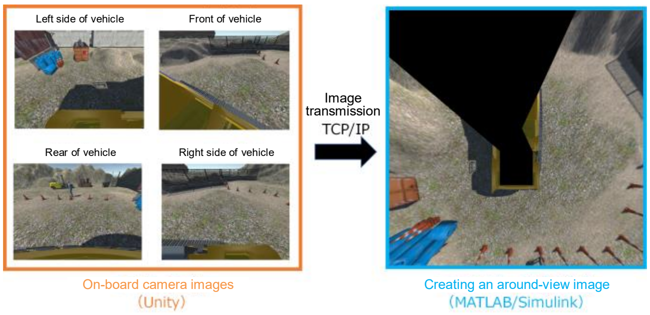


Fig. 15 Creating an around-view image

3.3.4 Human detection logic desk study

As mentioned in **3.3.3,** systems that detect people and avoid a collision are being installed in construction machinery as well. Thus, we also considered the use of this simulator for the study of the logic of human detection, etc. In this study as well, Unity and MATLAB/Simulink were linked like the around view creation explained in the previous section, and the human detection system designed by MATLAB/Simulink was executed for the camera images acquired by Unity. TCP/IP communication was used to send images from Unity to MATLAB/Simulink. As a result, as shown in **Fig. 16**, the model of the person who appeared in the camera image acquired by Unity is surrounded by a blue frame, which demonstrates that the system can detect the model as a person without any problem.

Fig. 16 Verifying the human detection logic

By using this simulator, people can be placed virtually in dangerous areas where people cannot actually walk due to a risk of possible accidents in tests using actual equipment. Therefore, it will be possible to study the functions of the human detection system in a safer environment.

4. Conclusion

In future performance development, it will be difficult for us to survive a fiercely competitive society unless we achieve our customers' desired functions ahead of our competitors. There is no doubt that manufacturing in a virtual environment using MBD will become more and more indispensable for the early realization of functions. For example, it would be very difficult to develop a lunar construction machine that cannot be easily evaluated with a real machine without using MBD. This will be one of the missions where MBD will be most utilized. The ultimate goal of MBD, which Komatsu is aiming for, is complete virtual development without using a prototype vehicle. Although we still have piled-up issues to be solved in order to reach that goal, we would like to steadily accumulate findings and achieve it.

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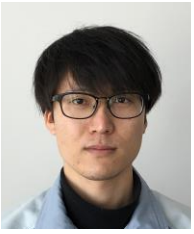

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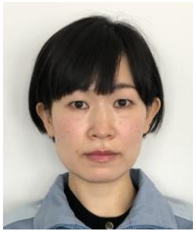

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[A comment from the authors]

MBD is an indispensable development technology for improving the vehicle performance, but through the activities of the MBD promotion project, we felt that it requires advanced skills and a lot of experience. Komatsu is focusing on training high skilled specialists as part of its development reforms. In the future, also regarding for MBD, we would like to develop specialists who are recognized not only internally but also externally.