Technical Paper

Teleoperation System for Ultra-large Hydraulic Excavators

Jun Morinaga

Komatsu demonstrated the teleoperation in Las Vegas, Nevada, at MINExpo2021. From the console installed in the exhibition hall, we remotely controlled the PC7000-11, ultra-large hydraulic excavator located in Arizona more than 650 kilometers away from the exhibition hall. The PC7000-11 loaded soil to autonomous vehicle "Innovative Autonomous Haulage Vehicle". This paper reports on the teleoperation system.

Key Words: *Teleoperation, Automated action, Unmanned operation, Augmented reality, Hydraulic excavator, Autonomous dump truck*

1. Introduction

In 2008, Komatsu launched an autonomous dump truck operation system called Autonomous Haulage System (hereafter "AHS") for commercial applications, a first in the industry segment. Since then, the system has been adopted at a total of 21 mines in four countries, with a cumulative truck population of 600 units as of December 2022. To further advance the goal of unmanned mining operations, Komatsu has developed a teleoperation system for the PC7000-11 ultra-large hydraulic excavator, which was demonstrated at MINExpo2021 by loading soil onto an autonomous dump truck called the "Innovative Autonomous Haulage Vehicle". This paper discusses the teleoperation system that was demonstrated at the expo.

Fig. 1 Scene from the demonstration

2. Overview of the teleoperation system

2.1 Concepts and the system

The teleoperation system is designed to remotely operate hydraulic excavators to load materials onto autonomous dump trucks at AHS operation mines. The hydraulic excavators are equipped with cameras, sensors, wireless transmitters, and other related equipment. The teleoperation console is located a long distance away from the mine. The teleoperation system offers the following new values to society and the market.

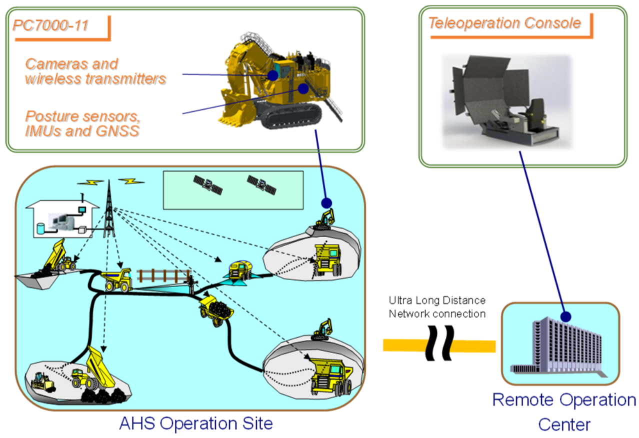

Fig. 2 Concepts

(1) Enhanced safety
- Implementation of unmanned mine worksites

(2) Improved productivity
- Minimal downtime between operator work shifts and during rest periods
- Provision of operation assistance to operators

- Additional cameras and augmented reality (hereafter "AR") offering better monitoring of the worksite than operators on the machine
- Efficient mine production control and operator training using huge data gathered by the teleoperation system

(3) Work style reform

- Provision of a comfortable work environment for operators
- Creation of opportunities for a wide range of people to work in the mining industry

(4) Reduced cost

- Reduction in operator recruitment costs for mines located far away from populated areas

2.2 System architecture

2.2.1 Hydraulic excavator (PC7000-11)

The PC7000-11 was chosen as the remotely-controlled hydraulic excavator as it is not only a perfect match for the dimensions of the autonomous dump truck being loaded, but is also equipped as standard with a fully electronic vehicle control system. The PC7000-11 can be controlled remotely when it is retrofitted with a teleoperation kit, a set of electronic devices including cameras, sensors, wireless transmitters, and dedicated controllers.

Fig. 3 PC7000-11 retrofitted with a teleoperation kit

2.2.2 Teleoperation console

The teleoperation console was developed by Immersive Technologies (hereafter "Immersive"), which manufactures and markets the operator training simulator for the PC7000-11, by harnessing its numerous technologies and know-how acquired through the development of training simulators. The teleoperation console mainly consists of the following units.

(1) Large monitor

The size of monitor, the number of monitors, and the layout can be adjusted to suit the model and/or application.

(2) Seat and console

All of the controls are made of the same materials that are used for the corresponding controls on the PC7000-11 to ensure the operator feels as if he/she is operating the excavator. The layout of the pedals and joysticks is also identical to that on the excavator.

(3) Control unit

High-performance CPUs and GPUs are used for the control unit, which is an advantage of the office environment over the worksite. The worksite limits the mountability of high-performance units on the excavator.

(4) Administrator monitor

Administrators and trainers can view current performance and past data of operators at any time. Settings can be made on the monitor for the size and layout of AR and operation assistance information.

Fig. 4 Teleoperation station (Entire view)

Fig. 5 Seat and console

3. Teleoperation system functions and performance

3.1 Overview

While offering a range of benefits including enhanced safety and comfortable work environment for the operator, Teleoperation system is known to produce lower productivity than the conventional operation on board [1]. Productivity of the former is said to be half that of the latter [2].

The development of the teleoperation system started with the creation of simulation environment for teleoperation using Immersive's existing simulator for operator training. Teleoperation parameters including visibility from the simulator, image quality, and camera image latency were set up and benchmarking conducted to identify factors contributing to lower productivity and the degree of their contribution. Based on the findings, new system parameters and functions thought to promise higher productivity were added and the effects of those additions were investigated on the simulator. The above procedures allowed trial and error to be run in shorter cycles than would have taken when conducted on board. In addition, the control unit platform for the simulator was almost identical to that for the teleoperation console, which made it possible to export the operation assistance information and other functions refined on the simulator to the teleoperation system in nearly the original form.

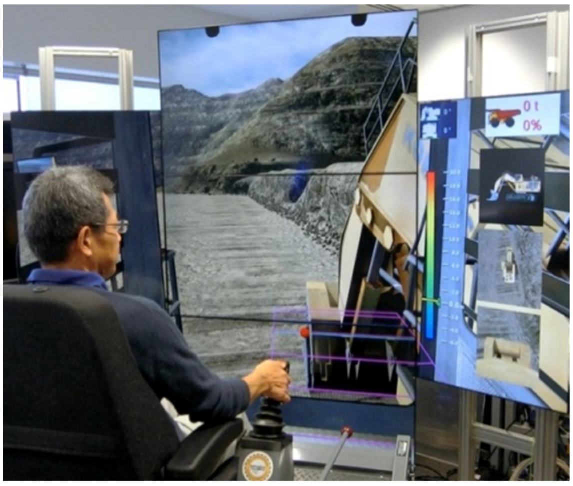

Fig. 6 Simulator testing

Following the trial and error and refining stages on the simulator, the final system was built using the actual machine and tested on the actual machine in the test facilities. The test found that the teleoperation system with additional functions incorporated in the development process achieved 37% higher productivity than the system without the additional functions, with the hourly loading work rate of the improved system being nearly the same as that of operation on board. The following paragraphs provide a detailed explanation of the system's functions.

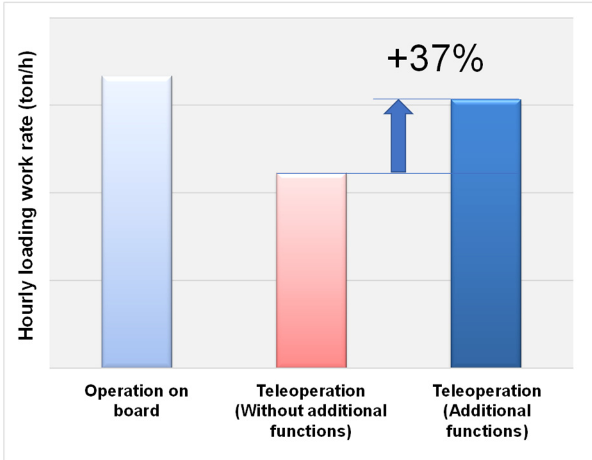

Fig. 7 Productivity of the actual machine

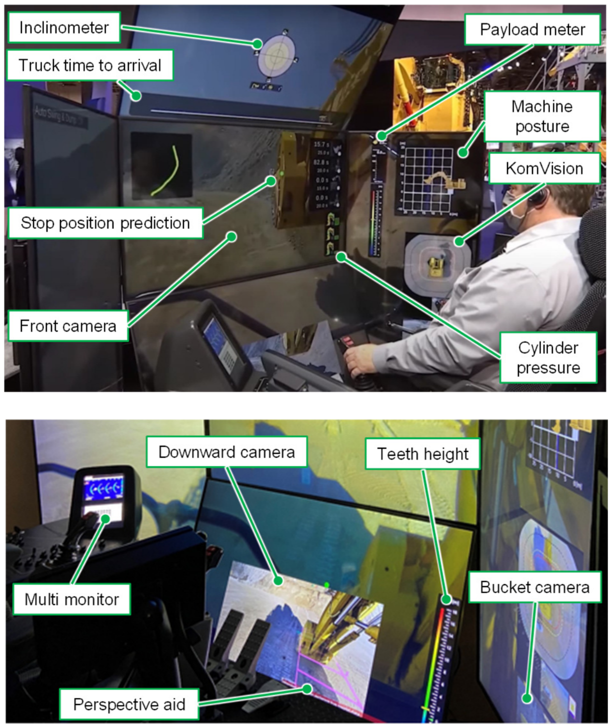

Fig. 8 Teleoperation console on the actual machine

3.2 High-quality camera image with low transmission and latency

The review and testing on the simulator discussed earlier found that the standard sequence of operation could be performed even with the front camera image, which should provide the operator with the view on a par with that on board, set to HD resolution. However, operators did not rate the sensory performance highly, stating that they experienced stress during operation due to the unclear image. Another concern raised was the difficulty in clearly recognizing the size of gravel and the condition of soil at the digging area, which may make it difficult for the operator to differentiate between the ore they are looking for and ordinary soil just by viewing the image.

Possible solutions include increasing the camera performance (resolution), and using more cameras and compositing the images. However, high performance cameras capable of withstanding severe mining conditions such as ambient temperature, vibration and dust have limitations in terms of cost, availability and interchangeability. In addition, image needs to be transmitted over the air over a long distance to the teleoperation console, which necessitates an upper limit on the size of the video data sent (transmission quantity). Video data can be compressed further to make its size smaller. However, this in turn makes the compression and decompression time longer, resulting in higher image latency and lower productivity.

Following the above consideration, it was decided to increase the resolution by using a full HD front camera and, for video data compression and uncompression, adopt hardware encoding and decoding using exclusive image processing IC chips in place of the conventional software encoding and decoding.

As opposed to the HD camera and software encoding and decoding option, this conclusion offers a combination of higher resolution (full HD as opposed to HD), minimum increase (+53%) in the size of video data transmitted and reduction in time taken (-50%) to compress and uncompress video data.

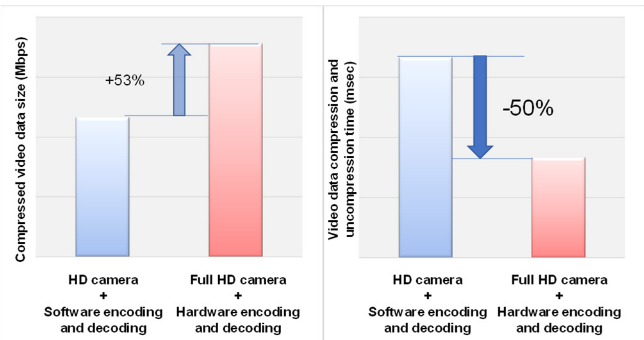

Fig. 9 Lower image latency

3.3 Enhanced visibility

With the front camera in the cab, the teleoperation system offers visibility that matches the visibility on board. A downward facing camera that offers images around the tracks and a bucket camera that offers images of soil in the bucket were additionally installed on the excavator. Images of those additional cameras are laid over the front camera image on the large monitor, eliminating the need to install additional monitors and maintaining the enhanced visibility through the large monitor.

Images from the surround view camera system “KomVision,” a standard equipment on the standard machine, are also displayed on the large monitor.

3.4 Improved spatial awareness

At the teleoperation console, front camera images are shown to the operator on five large monitors. While those monitors are three-dimensionally arranged, the images themselves are two-dimensional. In addition, the images on the monitor are not as fine and vivid as those gained through the eyes of the operator on board. Those factors contribute to reduced spatial awareness such as poorer recognition of depth in comparison with operation on board, eventually leading to reduced operability.

To ensure spatial awareness at the console matching that of the operator on board, the teleoperation system adds the following auxiliary information to the screen images using AR and other technologies.

(1) Perspective aid

The range of bucket movement in the direction of depth and the current bucket teeth position are laid over the ground in the screen image.

(2) Machine posture

Machine posture seen from the side of the vehicle is displayed on the monitor. When a dump truck is stationary at the loading position, it is also displayed to allow the operator to intuitively grasp at a glance the distance and height of the bucket from the dump truck.

(3) Teeth height

Teeth height from the ground is displayed in a bar graph near the bucket. This information, together with the machine posture, provides three-dimensional, at-a-glance indication of the bucket position.

3.5 Offsetting the loss of body sensory information

When on board the excavator, the operator receives not just visual information but body sensory information including vibration, sound, and vehicle inclination. When at the console of the teleoperation system, the operator operates the controls based on images on the monitor, having difficulty in grasping the conditions of the vehicle through senses other than sight.

That said, teleoperation can offer the operator comfortable environment to work in for no other reason than the lack of vibration, sound, vehicle inclination, and other body sensory information. Operator fatigue may then be reduced and, as a result, increased productivity can be expected. Therefore, the best option is to give the operator body sensory information, not in the same way as when the operator is on board the machine, but in ways that are not stressful to the operator.

(1) Inclinometer

Vehicle inclination is displayed in plain graphics.

(2) Sound system

In-cab sound is collected by microphones and transmitted to the teleoperation console where it is replayed on the sound system. The operator can grasp the load and other conditions of the machine by the sound of the engine and hydraulic system. The sound system has the sound volume control.

3.6 Other operation assistance information

(1) Payload meter

Detailed graphic information is provided to the operator, including the dump truck's truck nominal payload, current truck payload and current truck remaining capacity, and the hydraulic excavator's last bucket payload. In addition, when the loaded weight exceeds the upper limit of the dump truck, the current truck payload bar graph turns red and the overload message appears on the monitor.

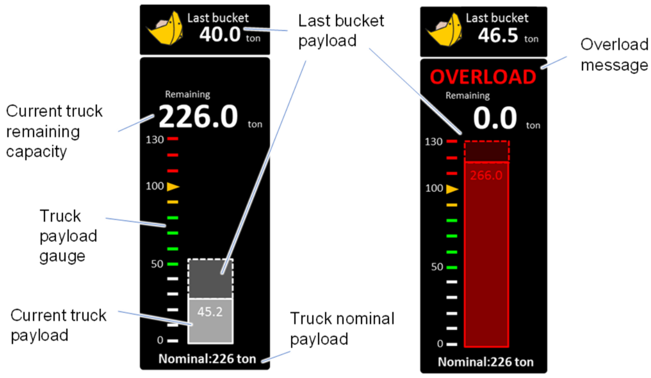

Fig. 10 Payload meter

(2) Stop position prediction

The position at which the operator should stop swinging is calculated based on data including the image latency, current swing speed and machine posture, and the calculated position is then displayed as a small AR dot in the front camera image. When the dot reaches the position at which swinging should be stopped, the operator at the console should immediately control the swing joystick back to neutral, which causes the machine to stop swinging at the desired position. This feature enables the operator to perform efficient swing operation without being affected by image latency and reduced spatial awareness associated with teleoperation system.

(3) Cylinder pressure

The pressure in each hydraulic cylinder is displayed in the bar graph and in the color associated with the predetermined threshold. This allows the operator to intuitively grasp the load on each hydraulic cylinder during excavation, enabling the operator to control the joysticks in ways that minimize fuel consumption and maximize productivity.

(4) Truck time to arrival

Using the AHS system and data communication, the expected time for autonomous dump trucks to arrive at the hydraulic excavator at the loading site is calculated based on data on the trucks' routes, current speeds, route congestion and other related parameters, and the calculation for each truck is then displayed. On the monitor, all of the dump trucks on their routes to the hydraulic excavator are represented by their icons, which move from the left to the right of the screen as their time to arrival nears zero. This information enables the operator of the hydraulic excavator to know in real time the remaining time to the next arrival, helping him/her efficiently carry out prior leveling and other preparation for the next loading session.

3.7 Semi-automatic digging and loading

Digging and loading operation consists of four phases: digging, swing and hoist, dumping, and swing and boom down. Of the four phases, Komatsu automated the following three and incorporated the automated processes in the teleoperation system: swing and hoist, dumping, and swing and boom down.

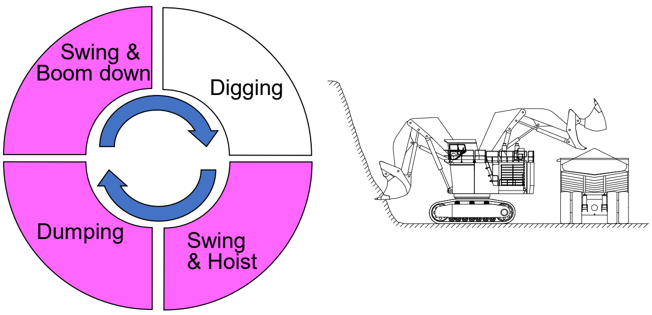

Fig. 11 Digging and loading operation (Automated phases in pink)

The semi-automatic digging and loading is enabled by the following technologies.

(1) Recognition of dumping location

This can be calculated based on the accurate positioning data on autonomous dump trucks.

(2) Recognition of machine posture and current bucket position

This has been calculated based on the aforementioned information provided to the operator.

(3) Output of work equipment operation from the controllers

This technology has been incorporated in the teleoperation system.

As suggested above, the semi-automatic digging and loading feature was made available by incorporation in the teleoperation system rather than by physically adding dedicated devices.

3.8 Hydraulic cylinder stroke end cushioning

When a hydraulic cylinder rapidly reaches the end of its travel (stroke end), large sound and shock are generated, possibly shortening the service life of the vehicle and on-board equipment or leading to failures.

When on board the machine, the operator typically operates the controls carefully to avoid generating unpleasant sound and shock. At the teleoperation console, the operator, due to image latency and reduced spatial awareness associated with the system, can often tend to control the joystick until it hits the stroke end, and to avoid this, controls the joystick so carefully as to reduce productivity. Some operators may operate the joystick while not caring much about hitting the stroke end as the sound and shock are not something uncomfortable to him/her.

Considering the above, Komatsu added a feature, which automatically restricts the flow of fluid commanded by the operator at the console immediately before the cylinder reaches the stroke end based on the aforementioned machine posture data. Like the semi-automatic digging and loading feature, this feature also was made available by incorporation in the teleoperation system rather than by physically adding dedicated devices.

4. Utilization of teleoperation system data

4.1 Overview

Mining machines are generally an independent, closed unit, with only the vehicle data remotely monitored on Komtrax and other means.

The teleoperation system automatically sends huge volumes of operation data (on operator input, vehicle status, camera image, etc.) in real time to the remote, teleoperation console. The teleoperation console has less spatial restrictions than the cab on the actual machine, and therefore can accommodate large monitors. The teleoperation console is set up in an office environment better controlled than the cab on the machine, and therefore benefits from a wide choice of data storage methods and data processing computers to employ.

As mentioned earlier, the control unit platform for the teleoperation console is almost identical to that for the training simulator manufactured and marketed by Immersive. Therefore, data from real remote teleoperation and that from virtual operation using a simulator are compatible with each other.

This shows that the teleoperation system is a highly expandable and versatile data platform for mining operation.

Komatsu actively sought attention to that point at MINExpo2021 through demonstration. Some of the data utilization features promoted at the expo are discussed below.

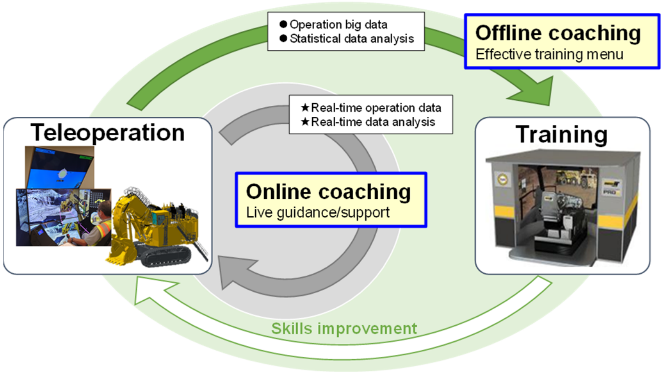

Fig. 12 Utilization of the teleoperation system data (Concepts)

4.2 Online coaching

The teleoperation console is equipped with a feature, which analyzes and processes teleoperation data in real time and lays the end product as operation guidance to the operator over the camera image in an easy-to-view area on the large monitor.

(1) Cycle time

Joystick operation and work equipment actions are analyzed, based on which the time taken (cycle time) for each of digging, swing and hoist, dumping, and swing and boom down is displayed. Displayed below the actual cycle time for each phase is the target cycle time set by the mine administrator. Any actual cycle time that exceeds the target value is displayed in red to intuitively warn the operator that he/she is getting behind.

(2) Bucket teeth trajectory

The path of the bucket teeth during digging action is displayed, with a thicker line for a slower action. The operator can evaluate the smoothness of his/her digging action based on the path shape and line thickness, and use the data to try and achieve faster action of the bucket with higher filling rate.

(3) Undesirable operation warning message

When the operator makes an undesirable action, a message immediately appears, warning the operator against and not to repeat the action. Undesirable actions have points, which vary according to the type of action. Accumulated points of the day are also displayed with the message.

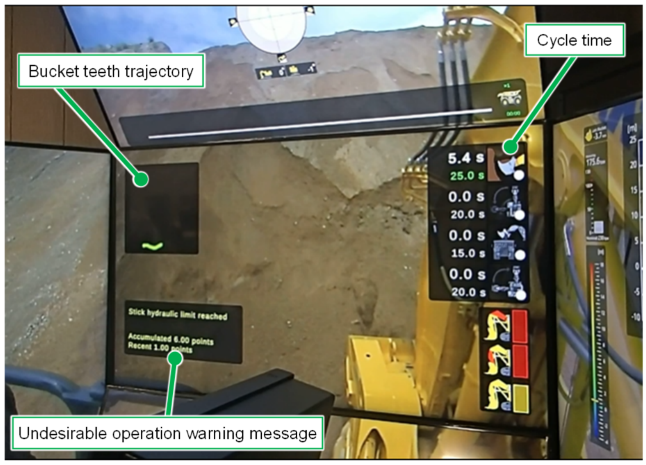

Fig. 13 Online coaching

4.3 Offline coaching

4.3.1 Playback data

All teleoperation data including on operation, vehicle status, and camera image is stored in the server. Mine administrators and operator trainers can access the stored and current data at any time on the administrator monitor. The data on undesirable actions and productivity by the operator, date and time is useful in identifying the cause of failures and accidents, formulating remedial measures for each operator and mining machine and making training menus. **Figure 14** shows the playback data screen.

Fig. 14 Playback data

(1) Undesirable operation history

A list of undesirable actions that occurred during operation is displayed in chronological order. Clicking on each action causes the monitor to jump to the screen at the time the action was made. On the screen, the viewer can see how the operator made the action and how the event unfolded.

(2) Camera image selection buttons

Video from multiple synchronized cameras is available for playback. The viewer can see operation at a specific moment shot by multiple cameras by pressing their buttons.

(3) Slide bar

Sliding the bar will take the view to the corresponding time and the data and image at that specific time.

4.3.2 Statistical data processing

Operation data is automatically uploaded to Operator Performance Analytics (hereafter "OPA") run by Immersive for analysis. Analyzed data is then displayed as statistical data on the analysis results screen called the dashboard.

By accessing the statistical data, which is available in the form of tables and graphs, the mine administrator can grasp daily performance, mid- and long-term change in work rate, operation history by the operator and other parameters. Operator trainers can also use the statistical data to grasp specific operation patterns and skills of each operator and, based on the findings, plan effective simulator training menus.

Going forward, Komatsu envisions building a system whereby OPA and training simulators autonomously collaborate with each other and that the system automatically establishes training menus for each operator based on statistical data.

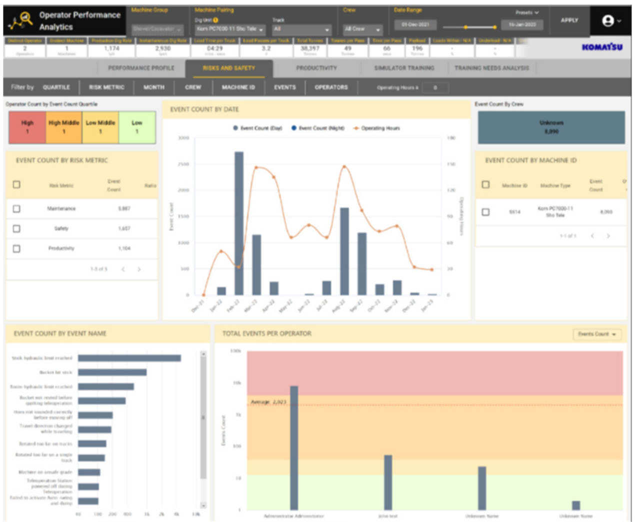

Fig. 15 OPA dashboard

5. Conclusion

At MINExpo2021, Komatsu held a total of six demonstrations, with every session so packed that some visitors were forced to keep standing. The teleoperation system development has been completed except for some functions. Trial operations will start soon at a customer site.

Acknowledgments

We would like to thank all those from the U.S., Australia, Germany, and Japan, who dedicated their energy and time en masse to making the teleoperation system available and the demonstrations successful.

References

[1] Masaharu Moteki, Nishiyama Akihiko, Shinichi Yuta, Hiroshi Ando, Sadanori Ito, and Kenichi Fujino, "Work efficiency evaluation on the various remote control of the unmanned construction", The 15th Symposium on Construction Robotics in Japan, O-21, 2015

[2] Yasushi Nitta, Osamu Matsuo, Shigeo Kitahara, Noboru Kuroda, Keiji Tamura, Takanori Shimoda, "A study of the application of ultra-long-range remote-controlled construction technology - A summary of ultra-long-range remote control experiment in Mt. Fugen in Unzen", The 13th Symposium on Construction Robotics in Japan, 2012

Introduction of the author

Jun Morinaga

Joined Komatsu Ltd. in 1992.

Field Automation Development Center, Development Division

[A comment from the author]

Global circumstances prevented me for a while from visiting the actual-machine test site in the U.S., forcing me to join the development project literally "remotely" from Japan. This gave me, often away from home on business trips, the opportunity to spend much more time with my family and to truly appreciate the value of teleoperation. I hope the teleoperation system discussed in this paper will bring more happiness to society in general and those working at mines in particular.