Utilization of Robotics Technology in the Tokyo 2020 Games

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Abstract

Various projects were implemented for the Olympic and Paralympic Games Tokyo 2020 to realize the Games' vision of "the most innovative Games in history, bringing positive change to the world". This article introduces the various initiatives implemented by Toyota Motor Corporation in the "utilization of robotics technology", which is a part of these projects.

Keywords : Tokyo 2020 Games, Autonomous mobility, Remote control, Communication network

1. Introduction

The Tokyo 2020 Robot Project Working Group was established by TOCOG, Toyota Motor Corporation, Panasonic Corporation, and experts to communicate to the world how robots will accompany people and be helpful in various situations at the Olympic and Paralympic Games Tokyo 2020 (hereinafter referred to as "Tokyo 2020 Games"). This article introduces the technical outline of each project.

(1) Torch relay project by telepresence robots (T-TR1 and T-TR2)
(2) Tokyo 2020 mascot robot (MR) to support spectators
(3) Planning for spectator support using the Human Support Robot (HSR)
(4) Field Sport Support Robot (FSR) to support competitions

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1.1 Torch Relay Project by T-TR1 and T-TR2

The T-TR1 and the T-TR2 are telepresence robots that project images of a person from a remote location that are realistic enough to make that person appear right in front of you. The robots combine communication devices such as a camera, microphone, display, and speakers with a mobility platform to move around as your own alter ego from a remote location. The concept is to provide an opportunity for those who cannot come to the venue or those with a special interest in the event to participate virtually and communicate with each other. As a specific project, we aimed to connect the torch in the torch relay as if the runners who could not participate in the event at the site were there.

1.2 MR-based Spectator Support Project

The basic concept of this project was to achieve realistic remote spectating by utilizing the technology cultivated through the development of a humanoid robot (T-HR3) and to provide a new way to enjoy the Games without mobility restrictions. This is based on the "school collaboration spectating program" that would provide opportunities for all public and private schools in Tokyo wishing to watch the Games at the venues.

On the other hand, some children are not eligible for the spectating program due to mobility restrictions such as severe disabilities or illnesses. We aimed to provide these children with the opportunity to feel the atmosphere of the venues through robotics technology.

During the reexamination of the event planning due to the postponement of the Games by one year, we had an in-depth discussion about what MR could do to make the children smile who are restricted in many aspects, such as school events, due to the coronavirus disease 2019 (COVID-19). As a result, we made significant changes in the MR specifications, aiming to significantly improve the quality of the user experience, such as having the Games mascots "Miraitowa" and "Someity" pop out from the digital world in a realistic size and dance with the children.

(1) Static display in the athletes' village
(2) Seats-for-future-stars project (venues ⇔ special-needs schools)

1.3 Spectator Support Project by HSR

The HSR spectator support project was designed to provide a stress-free spectator experience for wheelchair spectators at the National Stadium. The project combines the robot's autonomous motion technology with human remote-control technology to guide the robot from the entrance to its seat, collect trash, take commemorative photos, and solve other problems (Figure 1). The robot is characterized by its ability to operate in large areas where many people pass by and the fact that multiple robots combining autonomous operation and remote control can operate simultaneously.

1.4 Competition Support Project by FSR

The FSR was developed as a robot to assist the throwing and rugby sevens while working close to people (Figure 2). In the track and field events, FSR used AI and robotics technologies to carry and autonomously transport the objects that were thrown and recovered by officials, thereby helping to reduce recovery time and reduce the physical burden of the officials, and in the rugby sevens, the FSR autonomously delivered and dropped the ball by a mechanism at the center of the field immediately before kick-off to help make the games run more smoothly.

Figure 1 Spectator Support by HSR

Figure 2 Competition Support by FSR (©2021-International Olympic Committee-All Rights Reserved)

The system consists of a Lidar, cameras, batteries, and other components with an autonomous driving mode, a person-following mode, a mode to avoid collisions with objects, a manual driving mode, and an emergency stop mode.

For the Tokyo 2020 Games, the following two points were emphasized in the development and operation of the system.

① To return objects that are thrown to athletes as quickly as possible.
② To reduce the distance for the officials by even a single step.

2. Communication Infrastructure

2.1 Overall Overview

In the robot projects (1), (2), and (3) mentioned above, it was necessary to operate the robot from a remote location via a communication network, so with

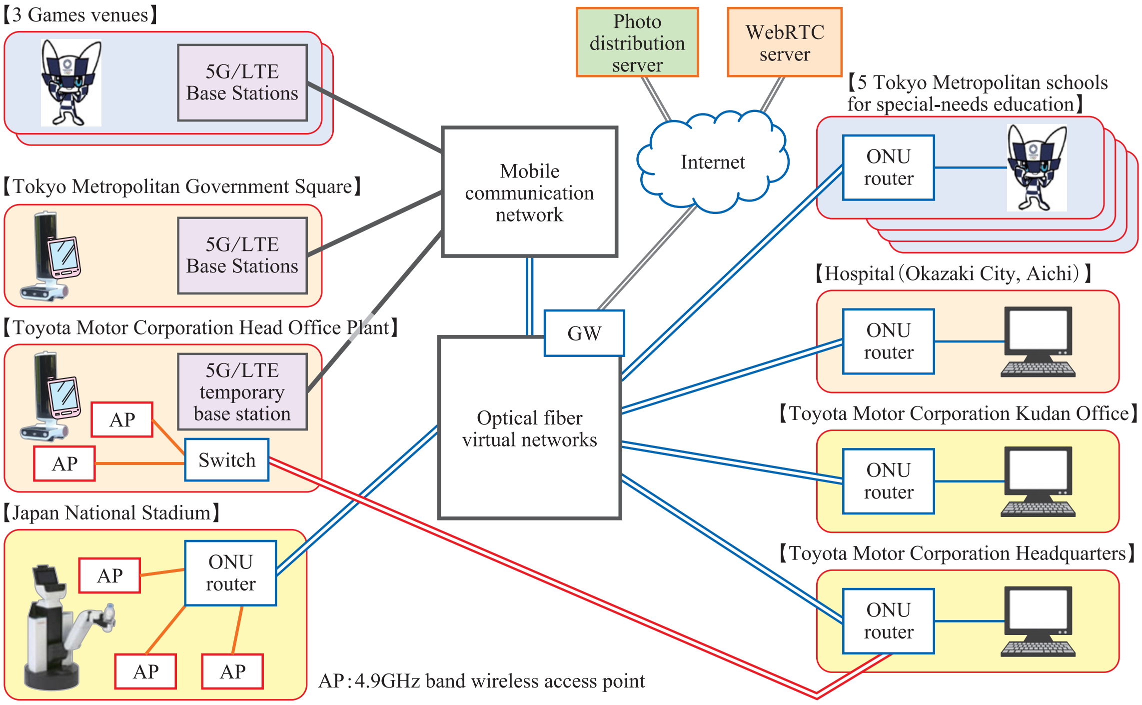


Figure 3　Complete Overview

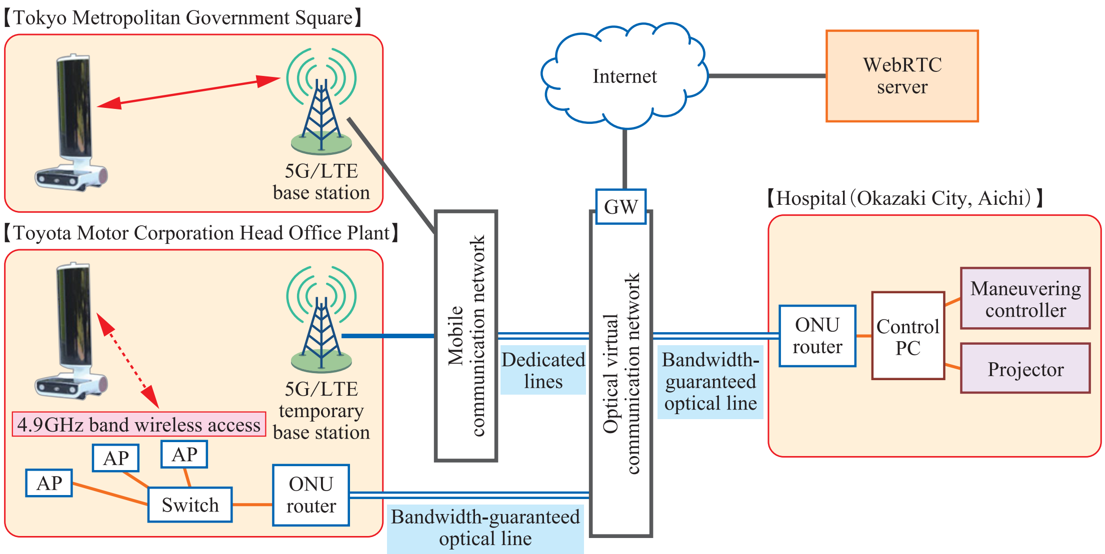


Figure 4　Overview of Communication Infrastructure Technology in the T-TR1/T-TR2 Project

the cooperation of the NTT Group, we built a dedicated network using a closed area optical network and commercial 5G mobile network services. In places where commercial 5G mobile network services were unavailable, we used a 4.9 GHz band wireless access system (JRC JRL-849AP2/E) in combination with a local radio (Figure 3). Project (4) used LTE mobile network service and a 169 MHz band radio developed for this competition as local wireless communication.

2.2 Overview of Communication Infrastructure Technology in T-TR1 and T-TR2 Planning

The plan to remotely control a robot on the wheelchair from a hospital in Aichi Prefecture to run as a torchbearer was realized by connecting the operator side o a bandwidth-guaranteed optical fiber line and the robot side to a commercial 5G mobile network. Video, audio and control data were communicated using an external connection service that supports the WebRTC

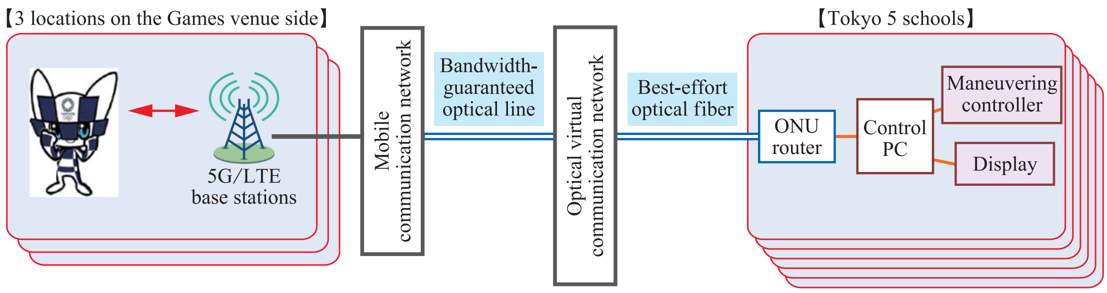


Figure 5 Overview of Communication Infrastructure Technology for the MR Project

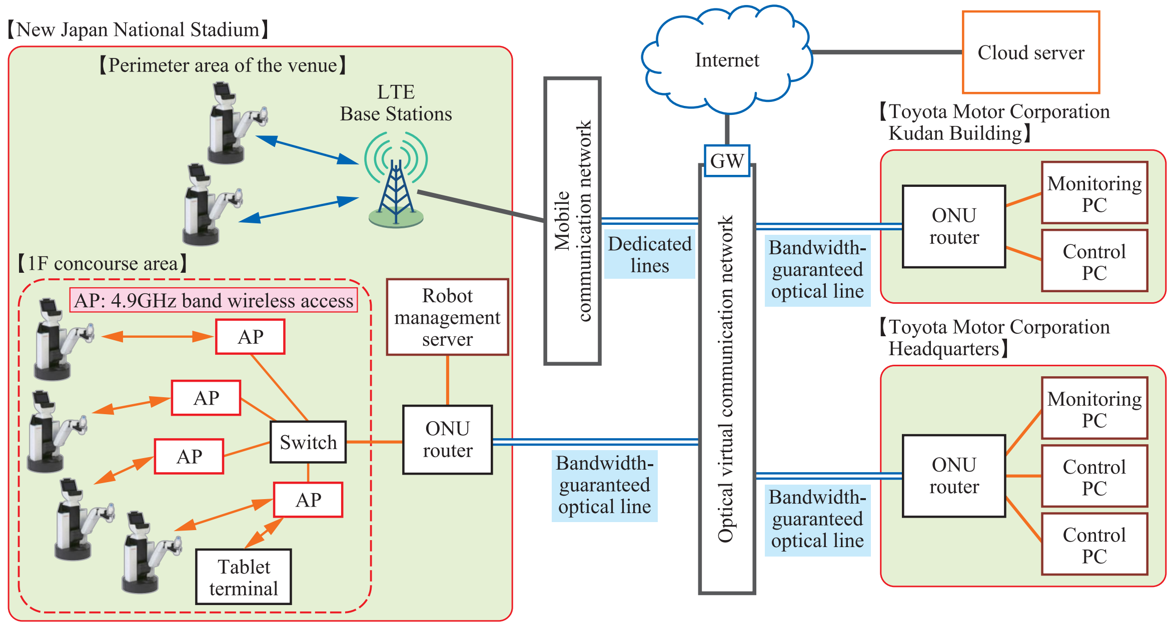


Figure 6 Overview of Communication Infrastructure Technology in the HSR Project

protocol via a security gateway (Figure 4). A 5G/LTE gateway terminal (IDY IR-730B) for small embedded products was built into the robot to ensure high reliability in high-temperature environments. An access point for the 4.9 GHz wireless access system was also installed as a backup line on the Toyota Motor Corporation Head Office Factory side.

2.3 Overview of Communication Infrastructure Technology in MR Project

Remote viewing using robots was realized by connecting schools/hospitals in Tokyo to the Games venues, connecting the control devices at the schools/hospitals using closed optical fiber lines, and connecting the robots installed at the Games venues using commercial 5G mobile networks (Figure 5). Video data from the robot camera were sent from the Games venues to the school side, and control commands were sent from the school side to the robots to realize remote control.

A compact 5G communication modem (TELIT FN 980 m) and a dedicated antenna were installed in the robots.

2.4 Overview of Communication Infrastructure Technology in the HSR Project

The robots at the National Stadium from Aichi Prefecture (Toyota Motor Corporation Head Office) and Tokyo (Toyota Motor Corporation Kudan Office) were remotely controlled by connecting the venues with a bandwidth-guaranteed optical line. In the National Stadium, the necessary number of access points for the 4.9 GHz wireless access system was installed to cover the entire area within the robot moving area of the 1F concourse (Figure 6). In addition, due to the decision to make the entire stadium spectator-free due to the declaration of a state of emergency as part of the

COVID-19 infection control measures, a small LTE gateway terminal (IDY IR-720B) was built into the robot and used.

The WebRTC protocol was used for bi-directional communication for video, audio, robot control, sensor information, etc.

2.5 Overview of Communication Infrastructure Technology in the FSR Project

We used the proprietary 169 MHz radio system for robot control and emergency stop. This radio system could operate 10 units/ch, and four radios on the control side and four radios on the robot side were all operated on the same frequency and used jointly.

2.6 Summary of Communication Infrastructure

This time, we built a dedicated closed network considering security aspects and the communication necessary for remote control/operation, emergency stop, of the robots were successfully and securely operated.

This time, a dedicated closed network was constructed considering security, and the communication necessary for remote control/maneuvering and emergency stop of the robot was successfully and securely operated.

However, since the line quality of the communication network fluctuates constantly, there was a lack of consideration for fluctuations on the robot system side, which posed some problems with stable operation.

Although the number of high-speed, large-capacity and low-latency means of communication will increase with the evolution of communication technology, we believe that further innovation is required to stabilize the remote operation of robots, and we plan to promote research and development for the same.

3. Key Technological Elements of Each Robot

3.1 Key Technologies in T-TR1 and T-TR2

3.1.1 Development to Enhance the Sensation of Being in Remote Locations

A system was constructed to enable a user to operate a robot using the wheelchair usually used by the user. The system configuration is shown in Figure 7. The wheelchair speed is identified by outputting parallel values from the left and right encoders positioned on the chassis are converted to angular values by an interface (I/F) device and input to the Portal-PC at the remote location via the Web USB protocol. The client application running on the Portal-PC generates straight movement and turning commands based on the values obtained by the I/F device. A TWILIO API is used to transmit these commands to the robots via the internet.

Next, on the robot side, the robot application running on the Upper-PC for communication mounted on the upper part of the main unit obtains these command values, which are converted to Robot Operating System 2 (ROS2) Topic via the WebSocket protocol and transmitted to the Lower-PC for mobility control

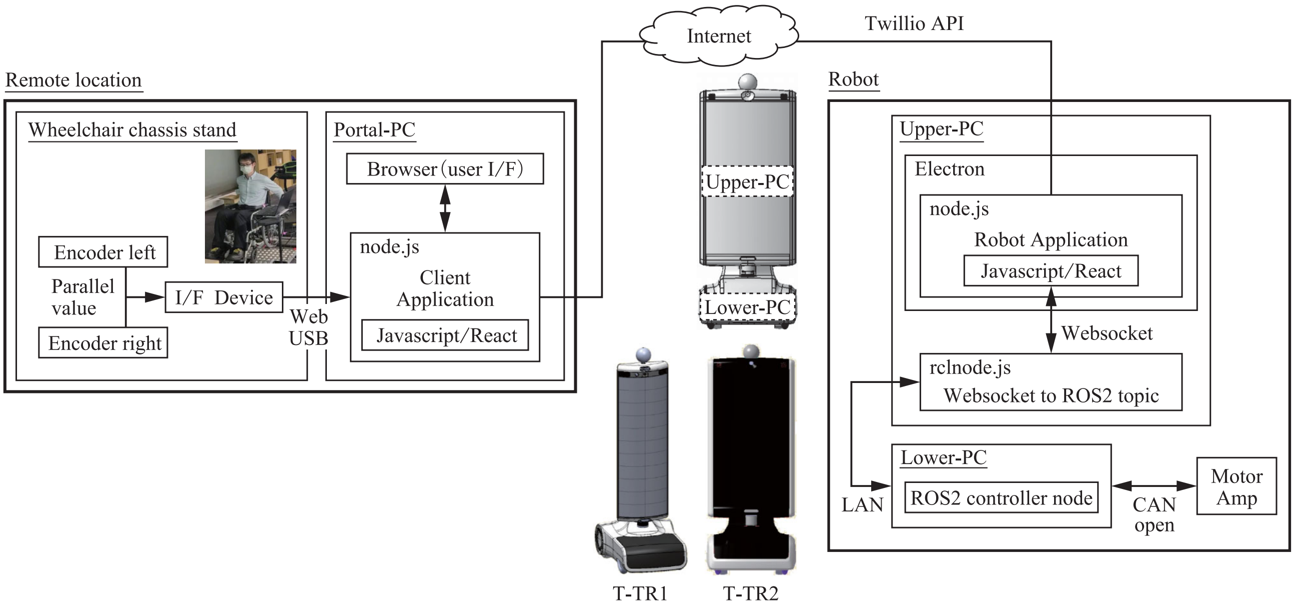


Figure 7 System Configuration for Wheelchair Operation

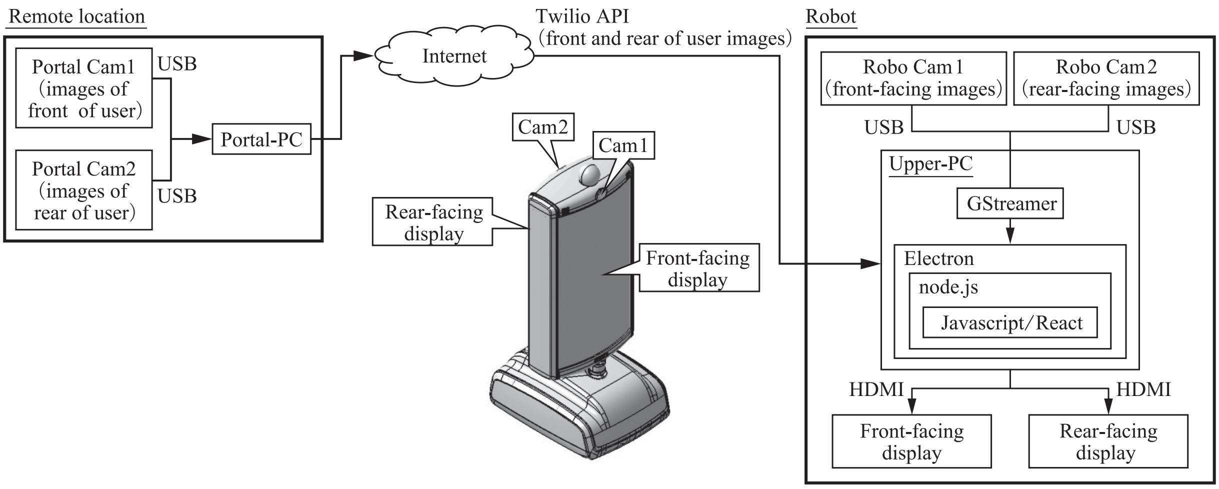


Figure 8 System Configuration to Enhance the Impression That a Person in a Far-away Location Is Present

mounted on the lower part of the main unit. Lower-PC then converts the command values to the CAN Open protocol and transmits the values to the motor amplifier.

With the above hardware and software configuration, we could confirm that the robot can move forward and turn via the internet. However, when confirming operations using the actual robot, it was found that delicate control of the robot using only the remote Portal-PC was difficult due to delays in internet communication, the responsiveness of the motor amplifier, the condition of the road surface, and other factors. As a result, control from a remote location was restricted to movement in a straight line only. If the robot strays off course, a safety operator close to the robot will override the remote control with a signal from the 920 MHz wireless controllers to correct the robot's position.

3.1.2 Development to Enhance the Impression that a Person in a Remote Location is Present

We have developed a system that composites images obtained from the cameras mounted on the robot with images of the remote user to effectively project the remote user onto the robot and enhance the impression that the remote user is present. In particular, since the T-TR2 is equipped with displays on the front and rear sides of the robot, by synthesizing images of the remote user with images obtained from the robot cameras, we aimed to create the impression as if the user were running in the torch relay. The system configuration is shown in Figure 8.

The displays are mounted on the front, and rear surfaces of the robot, and two cameras are mounted on the top of the robot at the front and rear. The images from the front-facing camera are shown on the rear-facing display, while the images from the rear-facing camera are shown on the front-facing display.

The remote side also had two cameras installed, Portal Cam1 and Portal Cam2, to capture images of the front and rear sides of the remote user. The Portal-PC recognizes and extracts the user from the images obtained from Portal Cam1 and Portal Cam2 based on the Background Matting method[(1)] to improve the accuracy of compositing the image of the remote user with the background image.

The images displayed on the robot are captured by the two cameras mounted on the robot via the GStreamer framework to the upper-PC. At the same time, the images of the front and rear of the user captured by the Portal Cam1 and Portal Cam2 cameras on the remote side are acquired via the internet. On the front display of the robot, the image behind the robot is cropped and used as the background image for the front display, and the front view of the user at the remote site is composited and displayed. On the rear display, the image in front of the robot is cropped and used as the background image for the rear display, and the back view of the user is composited and displayed.

3.2 Key Technologies in MR

3.2.1 Emotional and Facial Expressions

In the new model, we aimed to significantly improve the physical expressiveness and the quality of appearance of the mascots (Figure 9) while maintaining the mascots' lovability. Each arm and leg has 6 degrees of freedom, enabling a variety of bipedal walking and

Figure 9 Appearance of MR (©2021-International Olympic Committee-All Rights Reserved)

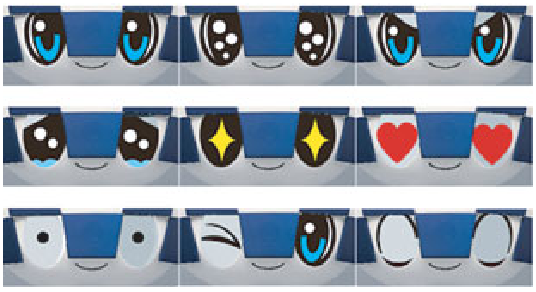


Figure 10 Various Emotional Expressions by Stationary Display (©2021-International Olympic Committee-All Rights Reserved)

dancing steps. For further improvement of expressiveness, we increased the number of joints on the waist and neck, and the mascots' height was increased by only about 5 cm despite adding a total of 8 degrees of freedom.

In addition to physical expressions with a wide range of DOFs, the mascot robots also feature emotional expressions by animating the eyes (Figure 10).

The eye area is designed to be prominent on the robot's face with high curvature. Flexible OLED displays are bent into a two-dimensional curved surface and mounted on the robot's face to display natural eye expressions. A thin acrylic lens protects the display surface with a two-dimensional curved inner surface and a three-dimensional curved outer surface. In addition to the excellent color reproduction of the display, the curved surface provides a wide viewing angle to enhance the visibility of emotional eye expressions.

The exterior uses a soft shell made of Agilus30, a rubber-like material fabricated by a 3D printer. The hardness of the soft shell varies depending on the part of the body, with the hard and soft parts molded as a single

Figure 11 Soft Skin of MR (©2021-International Olympic Committee-All Rights Reserved)

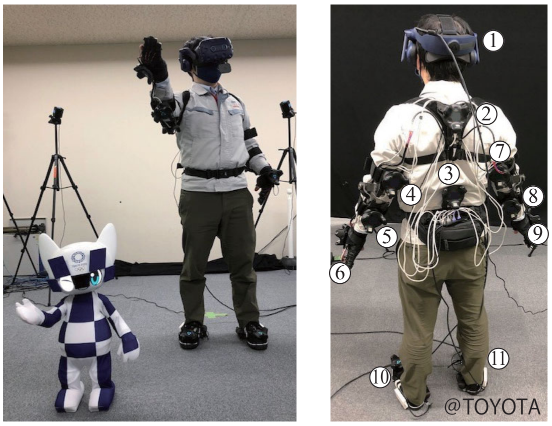


Figure 12 MR Maneuvering (©2021-International Olympic Committee-All Rights Reserved)

piece, which enables various movements even in areas where three degrees of freedom are concentrated, such as the hip joint and a wide range of motion while maintaining the outlines of "Miraitowa" and "Someity". In addition, superior high-performance polyester fabric is used as soft skin over the entire body, covering the joints to achieve a realistic appearance (Figure 11).

The use of soft shells and soft skins not only improves the appearance of the robots but also allows for a maximum range of motion of the joints despite the extremely short leg length, resulting in the robots having a high level of physical expressiveness.

3.2.2 Remote Control System

In pursuit of realistic motion for the mascot robots, a special remote-control method was adopted where the robot reflects the operator's movements in real-time (Figure 12). This control application converts the position and posture of the upper body based on the position and posture information from the VR equipment (11 tracker devices, including the headset) worn by the operator, handling the differences in physicality (size and joint range of motion) between a human and the robot. Furthermore, the position and posture commands are corrected according to the robot shape to prevent

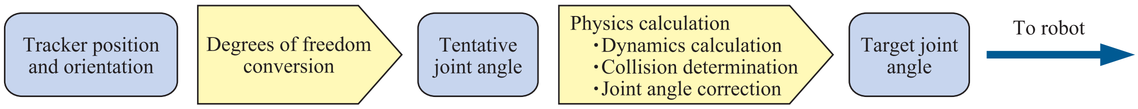


Figure 13　Conversion Process from Human Motion to Robot Motion

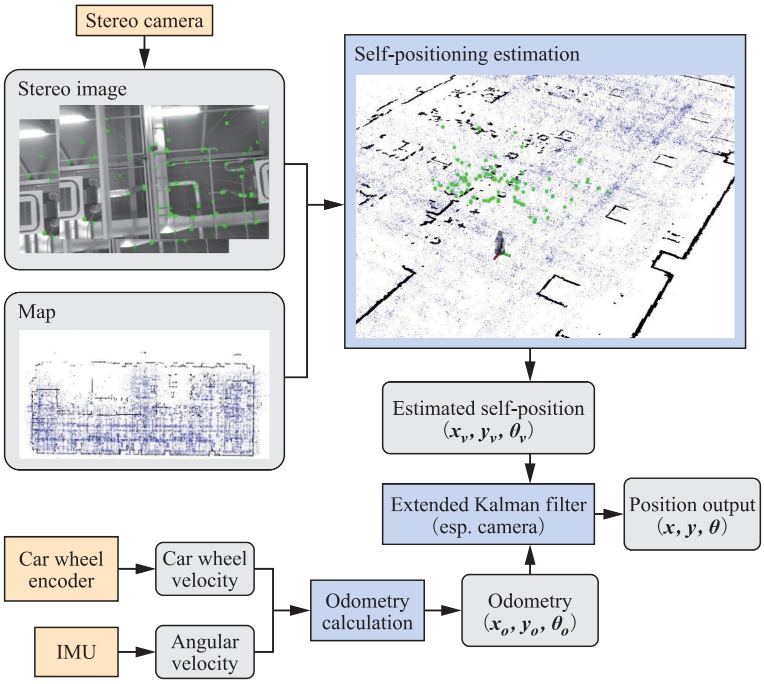


Figure 14　System Configuration for Self-position Estimation

self-interference and transmitted to the robot side as a target command (Figure 13).

The robot autonomously performs feedback control to maintain its balance while following the instructed joint, position and posture information in real-time. The operator can intuitively operate the robot as if they were controlling it from within since the operator receives audiovisual information recorded by the robot's onboard camera and microphone that is reproduced through the head-mounted display. In addition, the headset's eye tracker acquires information on the operator's pupil movement and eye-opening and closing, which is reflected in the robot's eye animation in real time. When the robot spots a person, it first follows the person with its eyes and then turns to face the person, enabling natural interaction. These remote-control functions allow the operator to act as a performer and control the mascot robot.

3.3　Key Technologies in HSR

3.3.1　Mobility Technology

General autonomous mobility algorithms using 2D Lidar face a problem in that the accuracy of self-position estimation is significantly reduced in a dynamic environment where many people pass by. For this reason, we developed a method for stable self-position estimation by pointing the camera to the ceiling, which is less susceptible to dynamic objects (Figure 14).

Self-position estimation is performed by mapping the feature points obtained from the images of the stereo camera pointed at the ceiling to a map, which is a set of feature points. The odometry calculated by combining the outputs of the HSR wheel encoder and IMU is fused with an extended Kalman filter and output as the final self-position. The following improvements were made regarding feature point-based Visual SLAM[(2)].

(1) To eliminate the influence of dynamic objects such as people during mapping, the self-position estimation results from 2D Lidar are highly accurate in static environments and were input as reference values for the optimization process.

(2) Maps created at different times were synthesized to cope with changes in lighting due to time

variations. Combinations satisfying the criteria for self-location estimation performance were selected and synthesized from test data multiple times.

(3) To improve the recovery rate when self-position estimation fails, only a certain area from the map was used for matching, centered on the self-position immediately before the failure.

A map of the actual National Stadium is shown in Figure 15. The blue dots in the figure are feature points obtained from the ceiling stereo camera. Figure 16 shows the relationship between the movement locus and the self-position estimation error, and Figure 17 shows a histogram of the estimation error. The root mean square error (RMSE) of the self-position estimation was 0.084 m, and the 3σ range of the error was 0.19 m, indicating that a highly accurate self-position estimation was achieved.

3.3.2 Remote Control System

The remote operator controls the robot's head, arm, and carriage using a mouse or device connected to a PC for remote control (Figure 18).

The remote-control screen features an autonomous movement function and a 3D view. When moving along a predetermined route, the robot moves autonomously by specifying a destination. This function is used for movement within the concourse of the National Stadium. On the other hand, the game controller is used to maneuver the robot around the wheelchair spectator seats. The 3D view displays a composite of static structures such as pillars and dynamic information such as surrounding obstacles and people recognized by the robot (Figure 19). The robot uses a wide-angle camera mounted on the robot while maneuvering to see wheelchair spectators and a 3D view to grasp obstacles in the vicinity. The viewpoint in the 3D view can be freely moved, allowing the user to zoom in to see obstacles near the robot in detail or to see the approximate location of obstacles using zoom out (Figure 20).

The robot is equipped with the following safety features to prevent collisions with people due to erroneous operation, allowing the robot to be remotely controlled with peace of mind. ① An imitation function

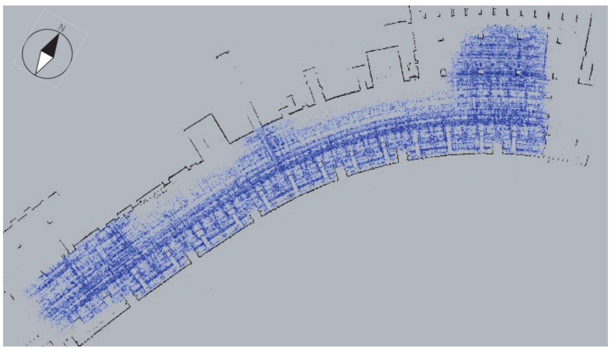


Figure 15 Map Created by VSLAM

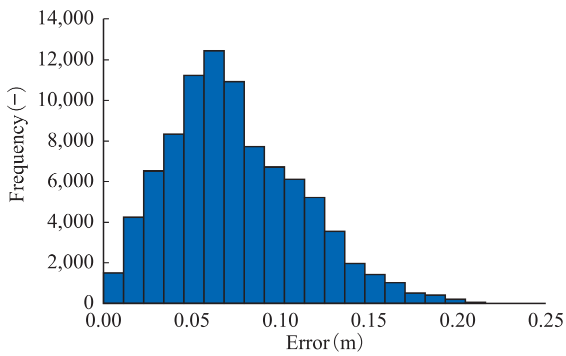


Figure 17 Histogram of Estimation Error

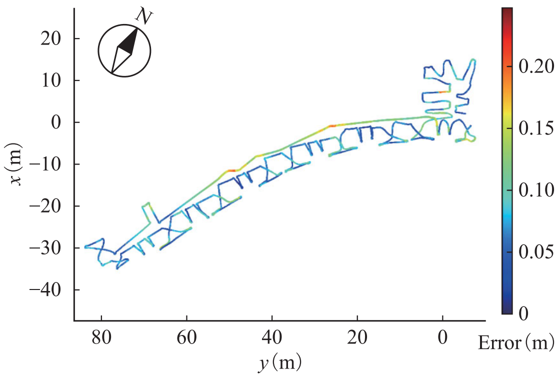


Figure 16 Relationship between Movement Trajectory and Estimation error

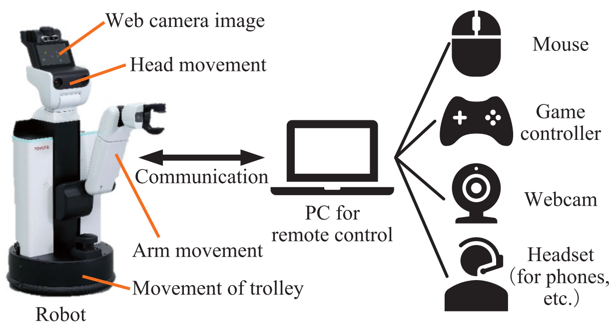


Figure 18 Remote Control System

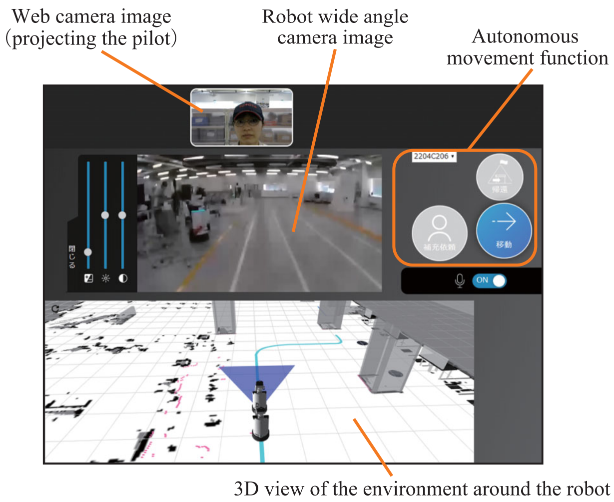
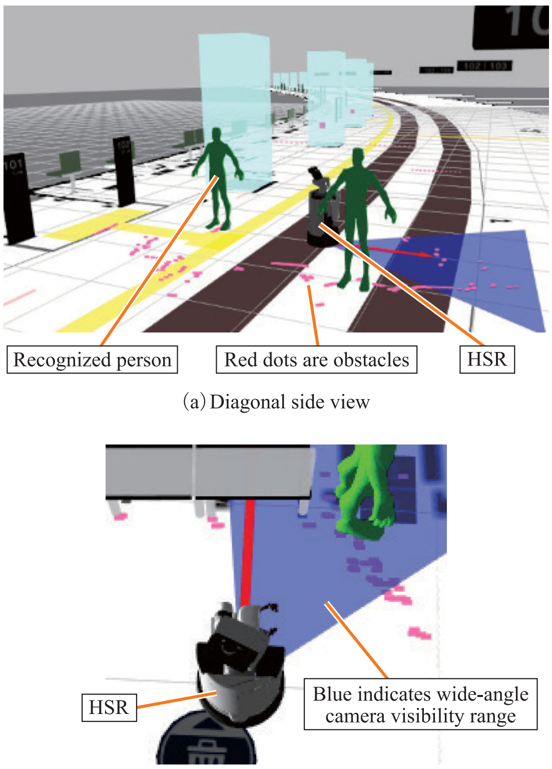


Figure 19　Control Screen Used by the Remote Operator



(a) Diagonal side view

(b) Enlarged view from above

Figure 20　3D View of Obstacles in the Vicinity

that automatically adjusts the direction of movement so that the robot follows the shape of the obstacle. This function is mainly effective for static obstacles. ② A virtual bumper function automatically stops the robot before physical contact with an obstacle that the imitation function cannot avoid. This function is mainly effective for dynamic obstacles.

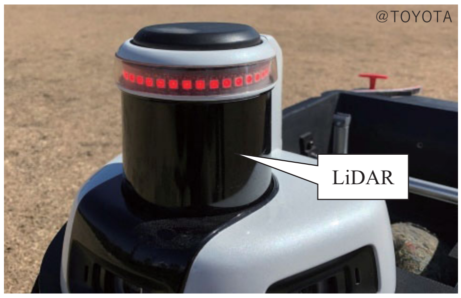


Figure 21　Lidar

3.4　Key Technologies in FSR

This section introduces “Autonomous driving” and “Person-following” from among the five modes of “Autonomous driving”, “Collision avoidance”, “Person-following”, “Manual driving”, and “Emergency stop”.

3.4.1　Autonomous Driving

At the return position, the official working with the FSR covers the touchless switch at the top of the FSR by hand to activate autonomous driving mode.

In autonomous driving mode, information about the distance travelled obtained from the vehicle speed sensors installed at the rear wheels, information about the location of the FSR obtained by comparison between a prepared map of the Competition Venue and the shape of the Competition Venue measured by lidar during FSR operation, and Real Time Kinematic-Global Navigation Satellite System (RTK-GNSS) information are combined to estimate the position of the FSR and guide it to the target destination.

The New National Stadium, the venue for the throwing events at the Tokyo 2020 Games, has a maximum distance of approximately 130 meters between the walls of the competition field. Therefore, the FSR was equipped with a 200-meter-class Lidar to ensure reliable measurements (Figure 21).

Vehicle speed sensors of the hall integrated circuit (IC) type are attached to the FSR rear differential joint cups. These sensors are synchronized with the tire rotation to output four pulses per rotation. The FSR speed is calculated from the sensor information on both the left and right wheels to improve accuracy and realize fail-safe operation.

The FSR is capable of nine degree-of-freedom (DOF) acceleration. This function utilizes an acceleration sensor installed on the vehicle control interface board “Moab”, kept in the rear ECU box.

The Moab board is the most important control board

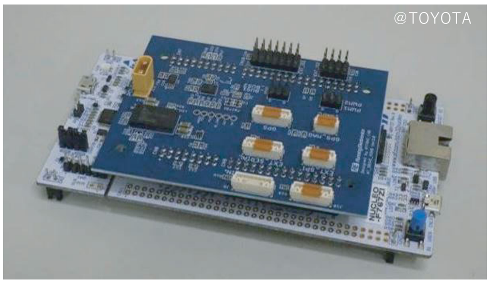


Figure 22　Vehicle Control Interface Board "Moab"

Figure 23　Heat Map Created by AI Analysis

in the FSR since it connects the drive control, steering, and autonomous driving systems. It was designed to emphasize reliability and features a simple microcomputer and input/output (I/O) devices. To prevent the FSR from rolling over when steered, the Moab board also incorporates an algorithm restricting the maximum steering angle following the vehicle speed (Figure 22).

In autonomous driving mode, the FSR operates along a pre-set route. The driving route was studied using AI developed by Toyota Motor East Japan, Inc. A heat map of the positions of the competition officials and camera crews was created using AI analysis of images taken by fixed-point cameras. Based on this heat map, the routes of the FSR were designed to avoid interaction with people as far as possible (Figure 23).

3.4.2　Person-following

In person-following mode, the FSR uses AI to drive on the field behind a event official.

The FSR is equipped with a commercially available C930 web camera manufactured by Logicool Co., Ltd. In this mode, the AI recognizes a competition official from RGB images obtained by the camera and creates a boundary. The target angle to the competition official is calculated using the center point of the boundary box. Next, the point closest to the FSR from a point group

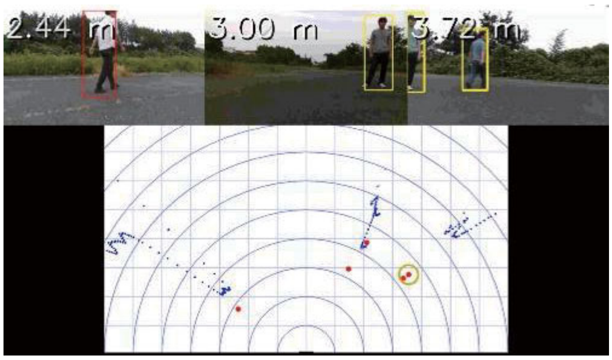


Figure 24　Boundary Box Formed by AI

created by the horizontal Lidar beam in the horizontal angle region defined by the boundary box is used as the distance to the competition official. The process described above is carried out for each frame, and the FSR is controlled to remain at a distance of three meters from the competition official (Figure 24).

By combining a web camera with AI and Lidar, we could realize the following function with compact and agile processing.

4.　Conclusion

The Robot WG was able to carry out its plans, albeit with some modifications in scale and content, in the face of repeated adversities, including the first-ever postponement of the Games due to the COVID-19, critical public opinion, and the fact that the Games were held without spectators. This was due not only to the members of the Robotics WG but also to the support and cooperation of the Organising Committee and Games volunteers, and we must thank all of them for their efforts.

The participation and cooperation of the volunteer staff members in all of the planning sites resulted from their shared desire to enliven the Games and make them even better. We believe that we were able to realize a project filled with smiles because we could look forward together.

Again, a large-scale demonstration event cannot be accomplished by an individual. It can only be realized with the cooperation of all parties involved, so finding as many people as possible to work together is desirable. What we feel is necessary for this is to recognize the diversity of ideas (tolerance and respect), to remember the spirit of cooperation (mutual aid), and to remember the spirit of gratitude and consideration. Finally, we would like to thank everyone involved for their understanding, cooperation, and guidance in progressing with this grand project. Thank you very much.

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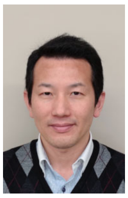
He graduated from the University of Mie in 1999, completed a master's course at the same university in 2001, and joined Fujitsu Computer Technology Limited in the same year. He joined Toyota Motor Corporation in 2009, where he was engaged in the development of partner robots. Currently belongs to the Connected Advanced Development Department. He is currently engaged in the development of next-generation vehicle cockpits.



MORIDAIRA Tomohisa

He graduated from the Tokyo Institute of Technology in 1996, completed the master's course at the same university in 1998, and joined Sony Corporation in the same year. He joined Toyota Motor Corporation in 2008, where he was engaged in humanoid robot development. Currently, he is engaged in the development of avatar robots and remote-control systems as a manager of Dynamic Robotics G, R Frontier Department.

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He received his B.S., M.S., and Ph.D. degrees in electronic engineering from Tohoku University, Sendai, Japan, in 1998, 2000, and 2003, respectively. From 2003 to 2007, he was a Research Associate at New Industry Creation Hatchery Center (NICHe), Tohoku University, where he researched algorithms, circuits, and systems for image compression, transmission, and recognition. In 2007, he joined Toyota Motor Corporation, Aichi, Japan. He is currently engaged in research and development of telepresence robot systems. Dr. Nakayama is a member of the IEEE Signal Processing Society and the IEEE Circuits and Systems Society.

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He graduated from the Faculty of Engineering, Faculty of Engineering, Department of Electronics in 1991 and joined Toyota Motor Corporation in the same year. Since then, he has been engaged in product design and production technology development of in-vehicle electronic components. Currently, he works at the Robotics Research Unit, R Frontier Department, Toyota Motor Corporation. He is engaged in research and development to realize remote service by robots using next-generation communication technology.

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He graduated from Keio University in 1992, completed the master's course at Keio University in 1994, and joined Toyota Motor Corporation in the same year. He was in charge of chassis design, mid-to-long-term R&D strategy planning, Toyota Motor Europe, and FSR development leader. Currently, he is engaged in overall technical development at Toyota Auto Body Co., Ltd.