Time Follower's Vision: A Teleoperation Interface with Past Images

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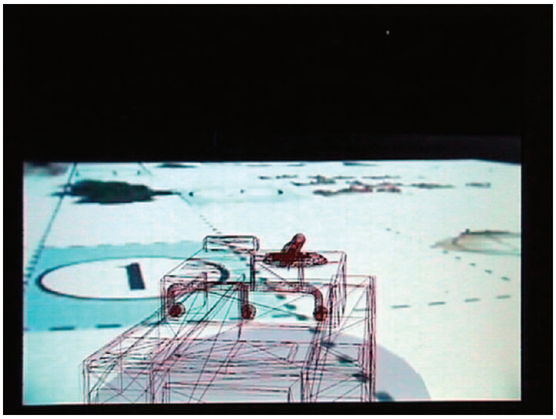
Time Follower's Vision is a mixed-reality-based visual presentation system that captures a robotic vehicle's size, position, and environment, allowing even inexperienced operators to easily control it.

Autonomous robots provide a variety of enhancements and improvements to daily life, and research of this class of robots continues to advance worldwide. However, for applications like medical treatment, search-and-rescue missions, and interpersonal communication, the optimal approach is generally a robot with advanced movement capabilities but a nonautonomous control mechanism.

A nonautonomous robot requires an operator to control it, so an efficient human interface system is essential for good performance. For robotic systems controlled via telexistence,[1,2] the operator performs remote tasks dexterously with the physical feeling of being in a surrogate robot working in the remote environment (see the "Teleoperation Interfaces" sidebar for more information on this topic). Although efficient operation systems that enable the operator to sense the remote environment exist, they require large-scale and high-cost equipment. Furthermore, operators require extensive training to adequately presume the vehicle's position and orientation from limited information.



1 Snapshot of Time Follower's Vision.

Our technique solves these problems by producing a virtual image using mixed reality technology and presenting the vehicle's surrounding environment and status to the operator. Figure 1 shows a snapshot of the system in use. Therefore, even for inexperienced operators, the vehicle's position and orientation and the surrounding situation can be readily understood. In this article, we implement a prototype system and evaluate its feasibility.

Camera image of teleoperated robots

Researchers have developed teleoperated rescue robots for search-and-rescue missions within unknown disorderly regions such as collapsed buildings, post-earthquake debris, and natural disaster sites.[3]

Figure 2 shows a photograph of a rescue robot. An egocentric view camera capturing the first-person viewpoint is typically installed in such simple remote control vehicles. By observing the camera image without an efficient human interface system, the operator tends to misinterpret the robot's position and direction, which in turn reduces the probability of achieving critical mission objectives.

Figure 3 shows the image captured by the egocentric view camera mounted on the vehicle. It's difficult for an operator not accustomed to the vehicle to estimate the vehicle's position and direction and the distances to a target strictly based on camera images from the first-person viewpoint. The exocentric view camera physically installed can be effective in such situations. However, to appropriately attach an exocentric view camera, the vehicle needs to be larger. Such a large body often disturbs the vehicle's activity. Therefore, it's more effective to provide a virtual exocentric view.

Another problem with an egocentric view camera is that it only shows an image of the environment from the vehicle's current position. However, when the vehicle advances forward, a previous image captures more environmental

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Teleoperation Interfaces

Numerous studies of teleoperated robots[1] exist. In fact, researchers have advocated the concept of telexistence as a superior method to perform remote control operation by effectively using a human's skills.

Although an operation system that enables the operator to feel the environment is extremely efficient, it typically assumes ideal conditions to obtain and transmit sensory information. To enable teleoperation in practical situations, like with a large delay, Ferrell and Sheridan[2] proposed using a supervisory control that prepares the projected model in the remote location on the operator side and presents an undelayed image of the model. Moreover, Tachi et al.[3] developed a simulator that prepares the model of the real world for adapting to challenging environments like in the midst of smoke. The technique for remotely controlling a robot using such model-based VR technology was used in the Mars exploration[4] mission with considerable success. These remote control systems construct the polygonal model of a complete 3D world, and the operator can control a robot by issuing commands to the model.

Another notable technology finding increasing use in robotic teleoperation is an extension to VR called mixed reality, or augmented reality, which integrates a virtual environment into the real world. This technology is based on the image-based rendering technique, in which polygonal models are rendered onto a real image texture, as a method of compositing a real image to computer graphics. The navigation is actively studied in the virtual environment by using image-based rendering techniques.[5-7] In a study of navigation in a virtual environment, researchers reported that a bird's-eye view is effective for intuitive operations.[8,9] The bird's-eye view is a kind of third-person viewpoint, which plainly presents the operated object and information on the surrounding environment, in contrast to a first-person viewpoint, which renders only objects within the user's field of view.

We believe that we can dramatically improve the operativity of a teleoperated vehicle (with a mounted camera that moves in the real world) through a simple and robust system using mixed reality technology, without requiring a complete model of the real world.

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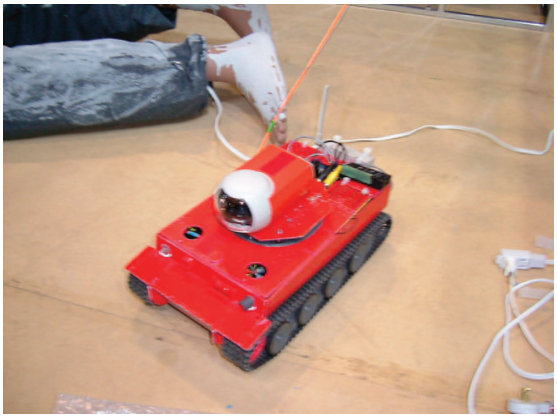
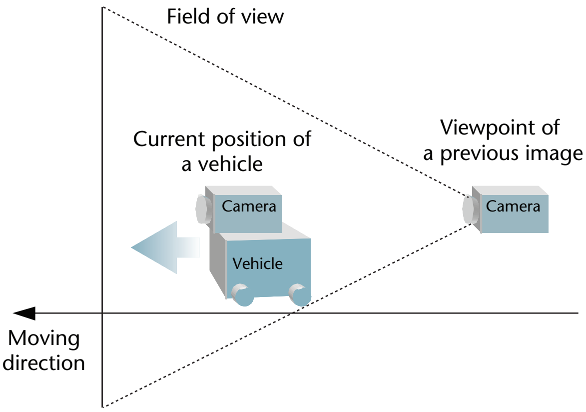
information on the vehicle than a current image. This image's viewpoint contains the current vehicle's position, as Figure 4 (next page) shows. If a previous first-person camera image is used, a comprehensible third-person perspective image can be presented to the operator.

By using mixed reality, even without constructing a model of the complex environment, we can achieve a controllable visual presentation by superimposing the vehicle model on the real image in the rendering stage. Although this system is readily available when



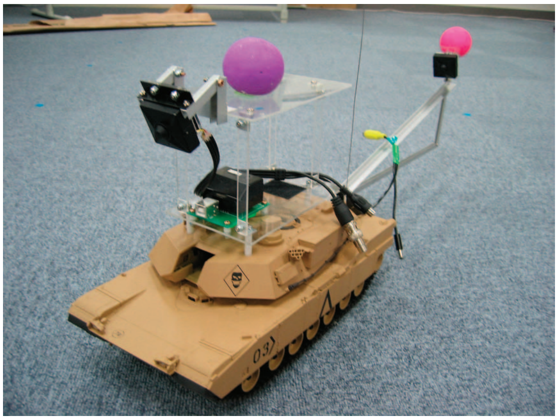
2 Rescue robot with an egocentric view camera.

3 Image captured from a teleoperated robot.



4 **Virtual exocentric viewpoint using a previous image.**

5 **Operator using Time Follower's Vision.**



6 **Experimental system hardware.**

the environment is static, problems arise when the environment is dynamic because of disparities between the current environment and the camera image. However, situations with rescue robots generally exclude significant ground motion, so the environment is nearly static and this technique is still practical.

System overview

Time Follower's Vision is a visual presentation system that captures a robotic vehicle's size, position, and environment, allowing even inexperienced operators to control it with ease.

We achieve this by using a simple camera and presenting the captured image with a conventional display like a computer monitor, where the operator controls the robot by looking at the image presented on-screen (see Figure 5). With an exocentric viewpoint, even if the vehicle and the camera parameters change, the operator is not disoriented by the operation because the vehicle's size and position are apparent.

Through this technique, the image captured by the vehicle's camera during remote-control operation is stored in a database along with time and position information. The system searches for the optimal image data within the database, which provides information on the vehicle's current position and environment. The image is selected by an evaluation function that considers the field of view, camera position, and vehicle position. After an image has been selected, the system maps a model of the vehicle to the chosen image and generates a viewpoint that gives the operator the impression of actually being behind the vehicle. Finally, we developed the human interface so that anyone can perform the control easily by viewing the vehicle and its environment.

This method might be useful for situations where the delay is large or the transmission rate is slow because the system can display an appropriate image to the operator to communicate position information even if the image is updated only occasionally.

Hardware

As a prototype remote operated vehicle, we used a Tokyo Marui 1/24 scale M1A2 Radio Control Model, as shown in Figure 6.

Table 1 shows the system specifications. To capture images necessary for remote control, we used a USB 2.0 video capturing unit (Novac NV-UT201) and an egocentric camera installed on top of the vehicle.

Moreover, to perform a comparison with existing methods, we placed a rear exocentric view camera with the same specifications as the egocentric view camera 50 cm behind the vehicle. We used an OKK QuickMAG IV video-based position tracking system to measure the vehicle's position and angle.

Experimental software implementation

To assess the effectiveness of the proposed technique, we designed a simple software implementation. Using mixed reality, we composed the model and captured image. We accomplished the composition on a PC by capturing a real image with the camera and assigning it as a background image of 3D computer graphics. The PC had an Intel Celeron 1.4-GHz CPU with 384 Mbytes of RAM, Nvidia GeForce 4 Ti 4200 GPU, and Microsoft's Windows 2000 operating system. We used Microsoft Direct 9.0 SDK for the development of 3D computer graphics and Microsoft DirectShow to process captured images.

To provide an appropriate viewpoint, the method of selecting a background image is crucial to intuitive teleoperation. We developed this important processing capability as a custom DirectShow image stream filter.

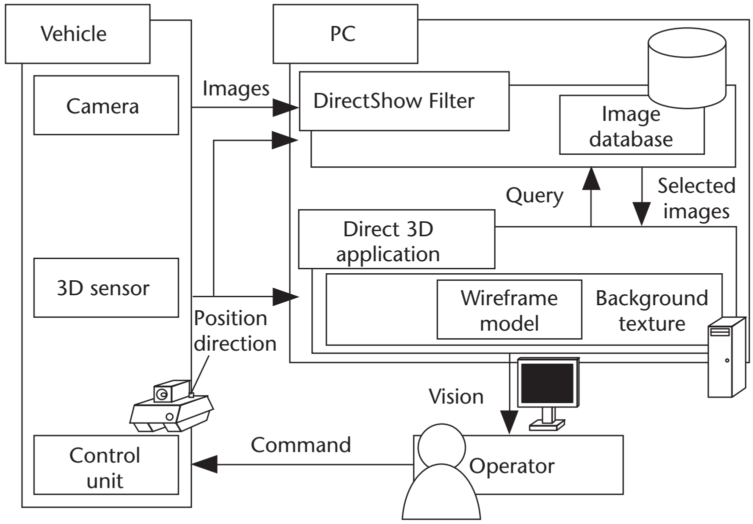
The database in this plug-in maintains time-stamped real images and position information. For this implementation, we evaluated three image selection methods, which we describe in the next section. The selected image is then forwarded to the Direct3D application, which draws 3D computer graphics as a texture image. By using the field of view and camera installation direction as well as vehicle position, body shape, and direction, the application can render the vehicle model on the texture at the same scale as the real world.

Figure 7 shows an architectural diagram of the software. According to this procedure, the system can show visual information that a human teleoperator can understand intuitively. In this system, the vehicle appears as a wire frame model with a shadow. Solid polygonal models have an occlusion region and are therefore often unsuitable for a teleoperating interface using image-based rendering.

Figure 8 shows the different rendering modes we considered. The wireframe models reduced the effects of occlusion, and the shadow proved effective in identifying the location, so we used this combination to render the vehicle. When there was no shadow, the vehicle seemed to be floating.

Table 1. System specifications.

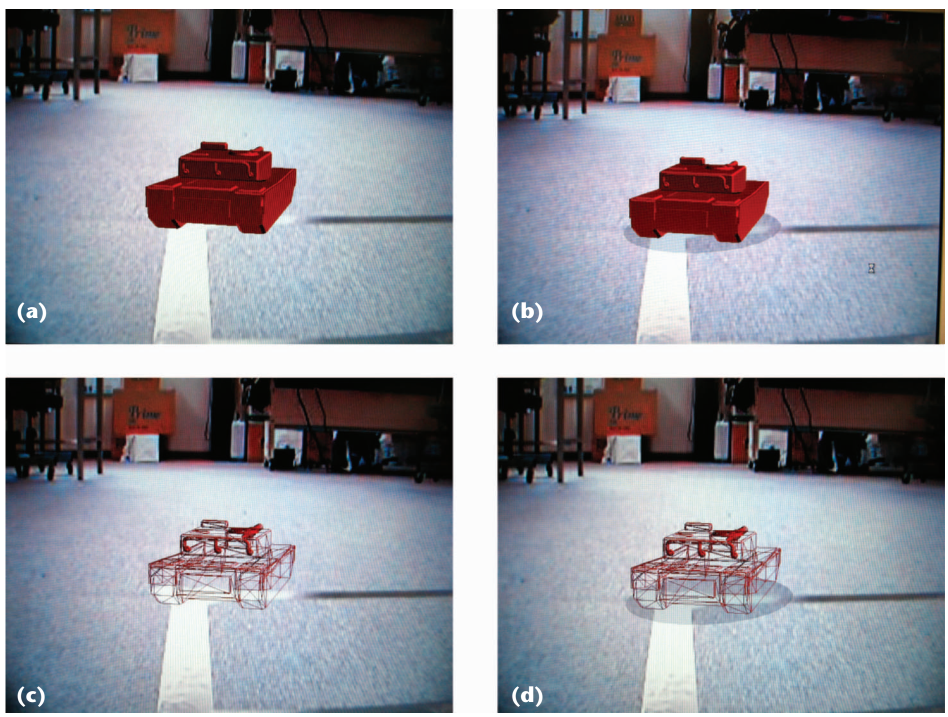
Parameter	Value
Vehicle size	152 (W) × 420 (D) × 135 (H) mm
Camera field of view	38 degrees
Video format	NTSC; 30 fps



7 Architectural diagram of our system software.

Image selection methods

In this study, we evaluated the effectiveness of the teleoperation interface with image-based rendering by assessing several basic image selection methods.



8 Rendering modes. Solid polygonal model (a) without and (b) with a shadow. Wireframe model (c) without and (d) with a shadow.

Selection methods 1 and 2

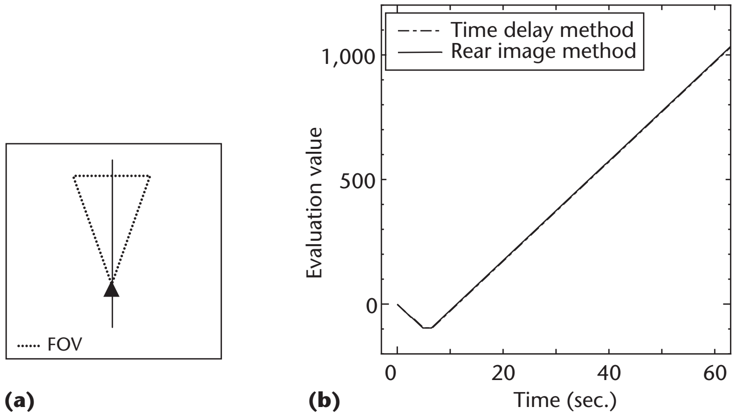
The image selection method influenced the operativity of the vehicle. Here, we describe two primitive image selection methods and their implementation. The camera images in the database have time stamp information as well as the camera's position and direction information. Thus, selecting an image is tantamount to selecting a viewpoint. The database stores 200 frames of previous images, which is a limitation imposed by the hardware and software environment. We established an image update tolerance parameter to omit the update of the database when the vehicle has stopped. This detection depends on the tolerance parameter of position and orientation.

Selection method 1 selects a fixed time-delayed image from the database. The system evaluates the time-stamped record of the image preserved in the database and selects the image nearest to the specified time. Thus, the vehicle model will be displayed on the fixed time-delayed image. This method is a simple implementation. Because the selection image changes directly according to time, this method exhibited the smoothest transition between image selections.

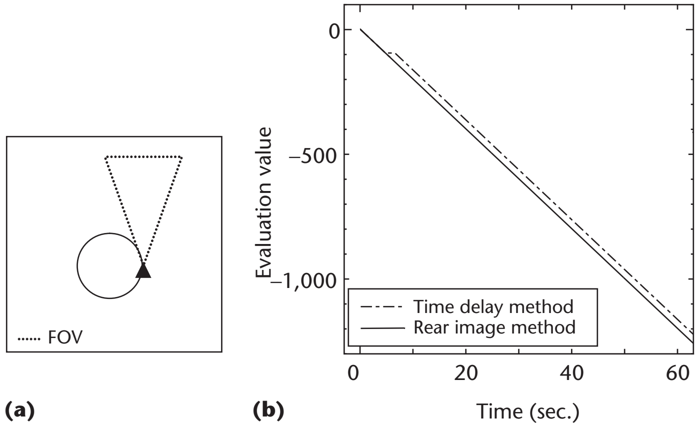
Selection method 2 requests the viewpoint that is a certain distance directly behind the vehicle. The system calculates the coordinate by the vehicle's current

Table 2. Parameters of the software simulation.

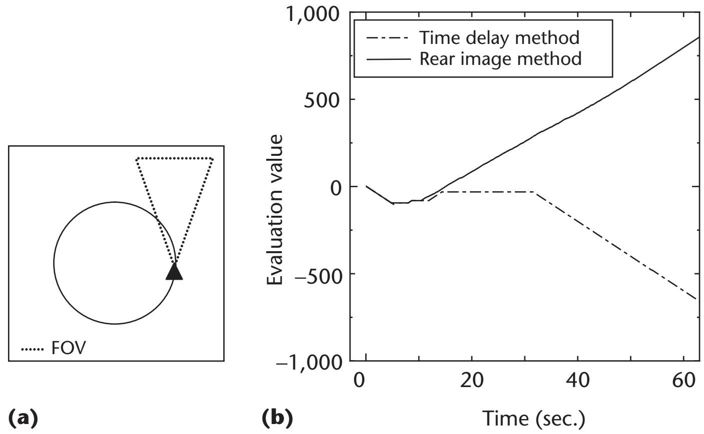
Parameter	Value
3D computer graphics frame rate	20 fps
Database capacity	200 frames
Image update tolerance	2 cm, 0.5 degree
Time delay of method 1	7.5 sec.
Specified distance of method 2	1.5 m



9 Forward advancement.



10 Circle with a 1.0-m radius.



11 Circle with a 2.0-m radius.

position and direction and selects an image that is the nearest to the coordinates in the database. The request queries only the coordinates and not the image-related information in the database. When there is no corresponding image close to the coordinate, the direction of the request is equal to the current direction, so the system selects a real-time image, such as after the vehicle turns. During the vehicle's rotation, if showing the traveling direction offers better operativity, this method should have good results in an actual field experiment.

Software simulation

We identified the effective region of the image selection methods through software simulation. Table 2 shows the major parameters of this simulation.

Evaluation method. In this simulation, we evaluated the visual presentation of the vehicle moving along a specified trajectory based on the following standards: The evaluation value increases when the whole of the vehicle is rendered, remains constant when only part is rendered, and decreases when the vehicle is not rendered at all. This evaluation confirms only whether the vehicle model is drawn using the viewpoint selected in each trajectory and does not evaluate the quality of operativity. This simulation is significant because the characteristic of this technique appears when the vehicle's position and posture are presented to the operator as visual information.

Simulation results. The evaluation value increases if the entire model of the vehicle is drawn as previously mentioned, so for straight advancement such as that shown in Figure 9, the evaluation value is always increased because both methods can see the vehicle in view. In contrast, when turning in a small radius, the evaluation value doesn't improve because the current position of the vehicle doesn't enter previous fields of view. Figure 10 shows the result of the vehicle moving in a circle, and Figure 11 shows the result of the vehicle moving in a larger circle. The values increase in some situations because the vehicle's position enters a previous view when the radius is large. Figure 12 shows the result of the vehicle turning a corner after it goes straight. Initially, the value increases for all methods as the vehicle proceeds forward; afterwards in turning, the value decreases using the primitive methods.

The primitive selection methods do have some weaknesses. In the case of turning the vehicle in a small radius, the rear image method tended to select a real-time image because it requires that the direction be the same as the vehicle, so the evaluation value decreased greatly. Moreover, when the vehicle stops, the time delay method cannot handle such a situation, because according to the passage of time, the viewpoint catches up with the current position. In the next section, we propose a supplementary selection method.

Selection method 3

The field-of-view method selects the viewpoint that always shows the vehicle model in the visual display. To select a viewpoint, the system uses an evaluation function as shown in Equation 1 to compare the viewpoint of an image with the vehicle's current position and direction:

$$Val = \frac{|\theta|}{\theta_{\mathrm{FOV}}} + \frac{|d - d_{\mathrm{spec}}|}{d_{\mathrm{spec}}} + Val_{\mathrm{correction}} \quad (1)$$

The variables represent the following:

- *Val* is the return value of the evaluation function.
- q is the vehicle's current angle to the center of the viewpoint.
- q_{FOV} is the half angle of the field of view.
- *d* is the distance between the current position of the vehicle and the position of viewpoint.
- d_{spec} is the specified distance, determined by the viewing angle and the camera's installed position and posture.
- $Val_{\mathrm{correction}}$ is the negative correction values to the images selected in the past.

The system applies the function one by one to stored images, and then selects the viewpoint with the smallest value. According to this procedure, the system selects the viewpoint so that the vehicle model is displayed near the center of view.

This evaluation function provides a simple metric to select the appropriate images based on predefined user parameters. To reduce viewpoint changes, the operator can control the vehicle with the stable viewpoint. When the value of distance or angle exceeds 1.0, the current vehicle position is considered to be outside any preserved field of view, so the system selects a real-time image instead. During the vehicle's rotation, if the presentation of motion is better than showing the traveling direction, this method will produce good results.

Field experiment

In this experiment, human subjects evaluated the system's actual operativity and sense of immersion by completing a survey afterward. We verified the real-time egocentric camera view and exocentric camera view and the three proposed methods. We thus obtained an objective assessment and a subjective evaluation of our technique. We equipped the vehicle used in the actual experiment with a caterpillar track wheel, so only small radius rotations could be performed. This had a significant influence on the presented image.

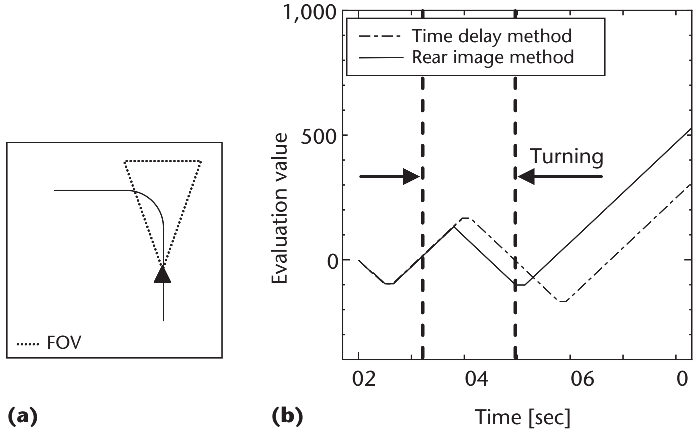
Experimental method

We subdivided the experimental environment into 50-cm units, as shown in Figure 13. The subjects were directed to stop sequentially—from destination 1 to 4. All subjects were adult males between 21 and 25 years old, with little to no experience in teleoperation. The subjects operated the vehicle with only the visual presentation system. The field was not seen directly by the subjects.

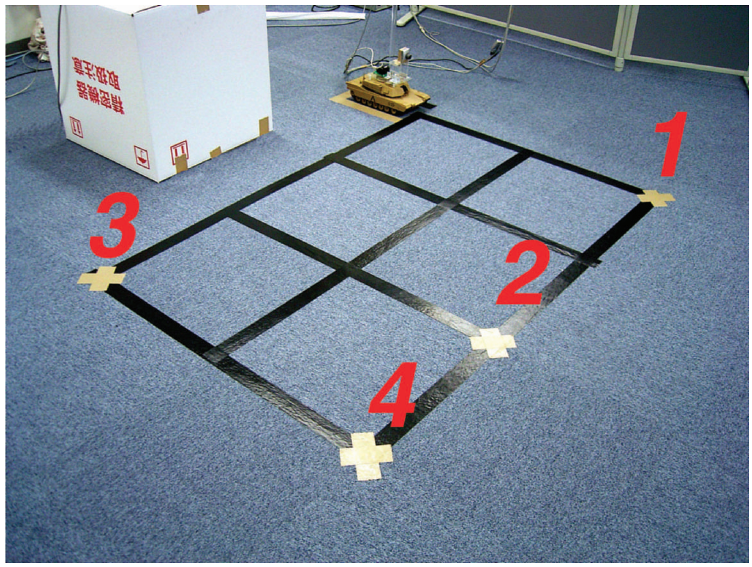
We instructed the subjects of the following priorities:

- Stop the vehicle as accurately as possible at the destination.
- If it doesn't compromise the accuracy, complete the route as fast as possible.

The subjects answered the questionnaire without knowing how close the actual vehicle approached the destinations after the operation. Table 3 shows the major parameters of this experiment.



12 **A 90-degree rotation with a 1.0-m radius.**



13 **Experimental environment field.**

Table 3. Experiment parameters.

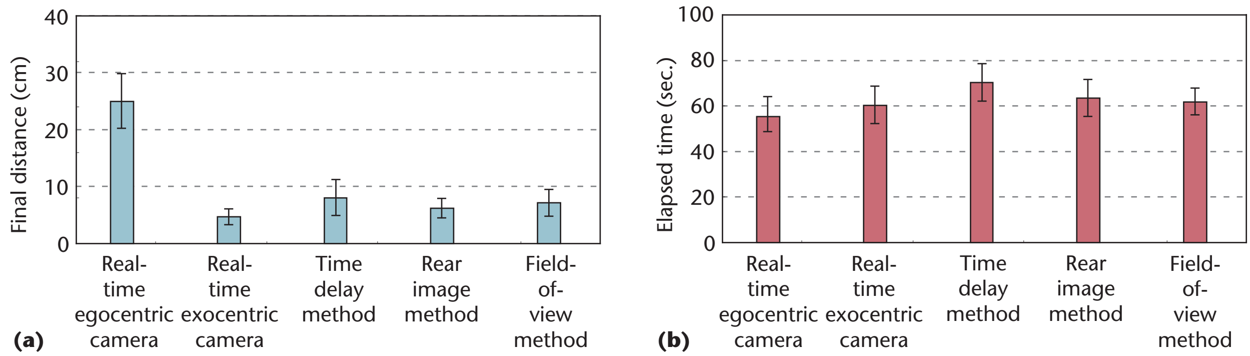
Parameter	Value
Database capacity	200 frames
Image update tolerance	2 cm, 0.5 degree
Time delay of method 1	5.0 sec.
Specified distance of methods 2 and 3	1.0 m
Selection correction value of method 3	–0.3 (attenuates with five frames)

Objective results

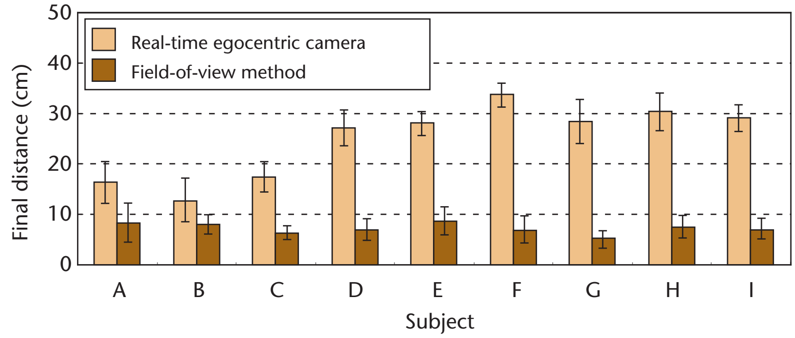
Table 4 and Figure 14 (next page) show the results of using each method. The elapsed time is the mean value

Table 4. Final distance and elapsed time of each method.

Objective Parameters	Real-Time Egocentric Camera	Real-Time Exocentric Camera	Time Delay Method	Rear Image Method	Field-of-View Method
Final distance (cm)	24.8	4.7	8.0	6.2	7.2
Elapsed time (sec.)	55.3	60.2	70.2	63.4	61.8



14 **Colored bars show (a) the average final distance and (b) average elapsed time of each method. Error bars denote the standard deviation.**



15 **Colored bars show the average final distance of each subject. Error bars denote the standard deviation.**

of 27 trials (nine subjects with three trials). The final distance is the average over 108 targets (27 trials include four destinations, respectively).

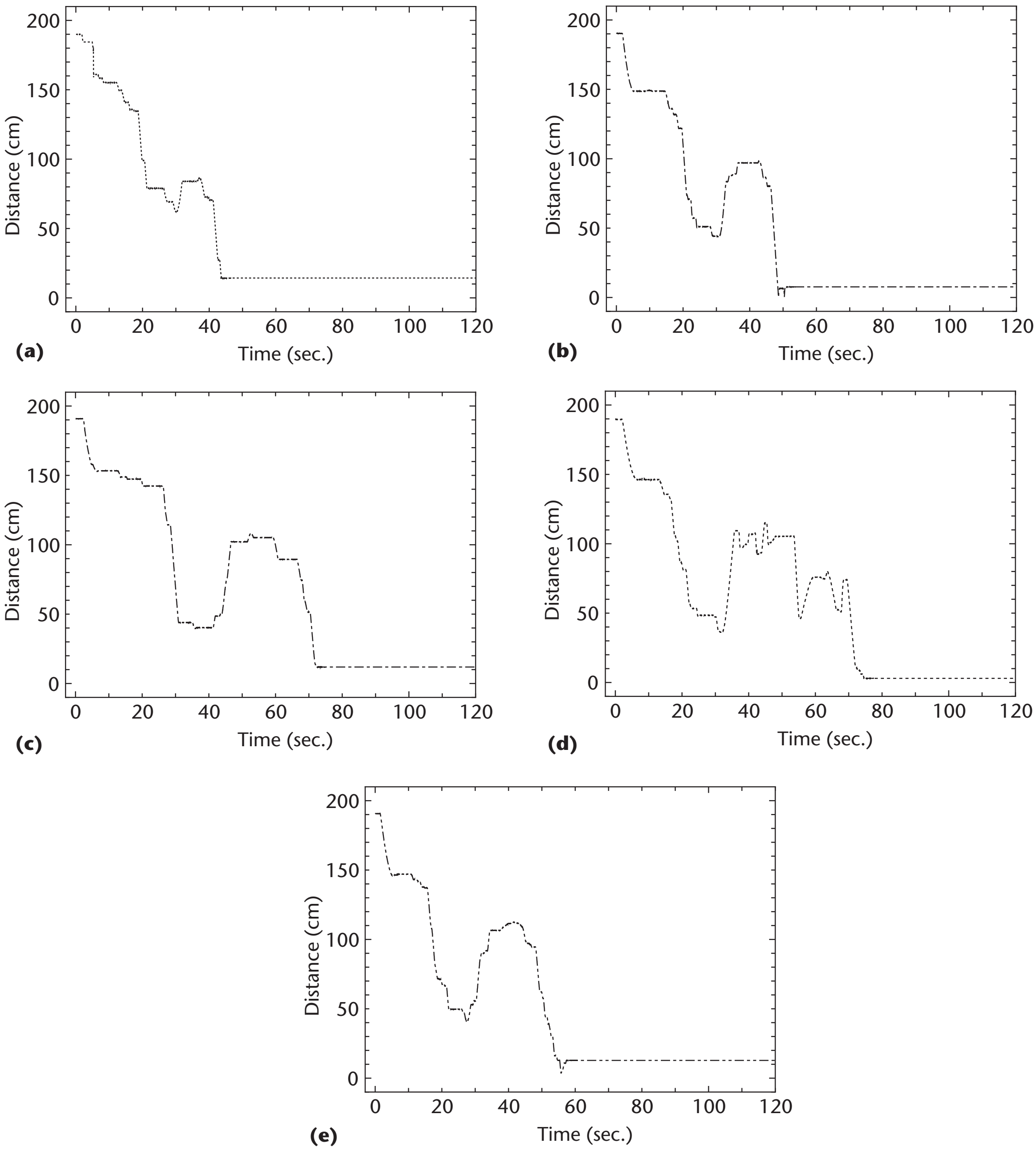
Naturally, the real-time exocentric camera view shows the best result in the final distances. The grid of this experiment field might have affected the good result. Using every proposed method, the distances from the targets were significantly reduced compared with the real-time egocentric camera view. The final distances of the three proposed methods were almost the same. However, the differences in elapsed time reveal the usability difference. The time delay method took the most time because the subject took a long time to confirm the effect of operation when the viewing area did not include the vehicle's current position.

Focusing on the standard deviation (see the error bars in Figure 14) of the final distance, the variance of the real-time egocentric camera view presentation appears large. To determine whether the difference originated in individual differences in the subjects or varied as a whole, we measured the average and the standard deviation of the final distance of each subject as shown in Figure 15. This figure shows the results of the real-time egocentric camera image and the field-of-view method, and the value is based on 12 data points (three trials with four destinations each).

In the real-time egocentric camera view, the standard deviation for each individual was small among the subjects, although the average varied greatly. It was clear that the variance appearing in the real-time egocentric camera view depended on the individuality of the subjects. On the other hand, the deviations among the subjects decreased under the proposed techniques such as the field-of-view method. The results show that subjects with little experience could also perform appropriate operations via these methods.

Moreover, to discuss this experimental result, it's necessary to pay attention to the relation of the time passage and the traversed distance. Figure 16 shows a sample of the time passage and distance for each method. The distance along the ordinate axis indicates the gap of the position at destination 4. The vehicle begins advancing from the starting point (190 cm), arrives at destination 1 (150 cm), advances to destination 2 (50 cm), then moves to destination 3 (100 cm), and finally stops near destination 4 (0 cm).

In the real-time egocentric camera view, there was a tendency for the distance to fall short (see Figure 16a). This depends on the recognition of the vehicle reaching the front of the destination, because the subjects were unfamiliar with the camera's specifications. In this method, the time until stopping is short although the distance is great.



16 Time passage and distance for each method: (a) Real-time egocentric camera, (b) real-time exocentric camera, (c) time delay, (d) rear image, and (e) field of view.

In the real-time exocentric camera view, the operator stops the vehicle without hesitation. So, Figure 16b shows a simple line.

In the time delay method, a waiting time is needed to confirm the vehicle's traveling direction when rotating. This waiting time increases the mean value of the elapsed time as Figure 16c shows.

In the rear image method, the viewpoint often changes to the real-time egocentric camera view during rotation. So, the operator is confused, and the graph of the distance in Figure 16d shows the blur.

The elapsed time was short for both the field-of-view method (Figure 16e) and the real-time egocentric camera view. However, the field-of-view method had a shorter distance, and subjects perceived it to be superior in this experiment.

Subjective results

For the subjective evaluation, after the first experience, we asked the participants the following questions to evaluate the operational feeling:

1. Was the position of the vehicle comprehendible?
2. Was the vehicle's surrounding environment comprehendible?
3. What are your impressions of the vehicle's operability using the interface?

From the results of the real-time egocentric camera view, the performance metric demonstrated that the position of the vehicle was not well understood, but the feeling of the operativeness was mixed. The real-time exocentric camera view had good results for every ques-

Through our teleoperation interface, we expect remote-controlled robot technology to become more accessible and enhance our daily lives.

tion and in the absence of physical constraints, this view is an optimal interface for control because it can also correspond to a dynamic environment.

In the time delay method and the rear image method, the answers showed individual preferences, but from the performance in the objective evaluation it was evident that the comprehension of the position and environment seemed to improve.

The field-of-view method was consistently the best result in the proposed methods. It had favorable results in the ease of understanding the position of the vehicle and the environment, because this method succeeded in drawing the vehicle model as much as possible in the augmented field of view.

Discussion

Robots operating in extreme environments should be more compact than the one used in our experiment. The proposed methods don't need any larger vehicles. The field-of-view method showed nearly identical results to the physical exocentric view camera in the objective and subjective results, so it was the best view selection method among the proposed methods.

On the other hand, the time delay method showed poor results because this method pauses before it presents the captured image, regardless of whether the vehicle model can be drawn. The viewpoint changes according to the time passage, so if the vehicle stops and makes a small turn, it becomes difficult to control.

When subjects rotated the vehicle using the rear image method, a large change in viewpoint occurred, which caused confusion for the subjects. Therefore, the vehicle was often controlled in the wrong direction. This confusion is perhaps the result of the loss of sight of the direction by an automatic switch in the viewpoint. The field-of-view method showed good results compared with the rear image method in the subjective results, perhaps because the capability to confirm the vehicle's posture during rotation was more important to operativity than seeing the traveling direction. However, when the field is not static, the traveling direction might have to be synchronized accordingly. In such an environment, it seems that the real-time camera view is necessary for our proposed teleoperation interface.

Because the vehicle's posture and position are clearly shown by the computer graphics model on the real image, operators can still perform appropriate control actions even if they don't know the camera's state, the installation position, or the vehicle's size.

We observed that the subjects tended to lose the vehicle's position when the viewpoint changed significantly. This confusion occurred often when switching to the real-time viewpoint. To solve this problem, we plan to add superimposed 2D map information based on the measured position information.

Through our teleoperation interface, we expect remote-controlled robot technology to become more accessible and enhance our daily lives. ■

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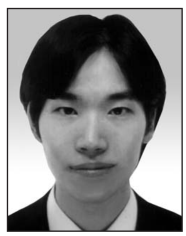

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