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Synthesized Scene Recollection for Vehicle Teleoperation

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In this paper we propose an innovative view synthesis method for vehicle teleoperation, a synthesized scene recollection method, which provides the operator with a bird's-eye view image of the vehicle in an environment which is generated by using position and orientation information of the vehicle, stored image history data captured by a camera mounted on the vehicle, and the CG model of the vehicle. This method helps the operator to easily recognize the situation of the vehicle even in unknown surroundings and enables the remote operation ability of a vehicle to be improved. We also propose the different ways of presenting the synthesized bird's-eye view images to an operator. This method is mainly based on two technologies, vehicle positioning and image synthesis. To realize self-contained system of the proposed method we use scan matching of the scan data of a laser rangefinder for vehicle positioning. Experimental results for a robot in 2D horizontal plane are shown.

Key Words: Teleoperation, bird's-eye view, image synthesis, positioning, scan matching

1. Introduction

Rescue robot systems have been actively investigated and developed after the great Hanshin-Awaji earthquake. It is hard to develop a full autonomous robot which can work for search and rescue tasks at real environments with current robot technologies and the system configuration such as a robot teleoperated by an operator is one of realistic solutions for rescue robot systems [1)–5)]. In robot teleoperation the robot remote control ability will improve when the robot operator can understand the robot surroundings and the robot situation.

Many works on vehicle teleoperation have been investigated. The system configuration of most of these works is that there is a camera mounted on a vehicle and an operator at a remote site controls the vehicle using camera information captured by the mounted camera. It is the well-known fact that the vehicle remote control is really hard for an operator only using mounted camera information with the system configuration without directly looking at the vehicle. One of the reasons of this fact is that it is hard to understand the vehicle itself and its surroundings situation by the information from the mounted camera images.

There are several methods have been proposed to overcome this problem in vehicle teleoperation such as the 3D model construction method for environment by obtaining the three dimensional data of unknown environments [6)], the teleoperation method with wide viewing angle images by multiple cameras and/or omni-directional cameras [7)], the teleoperation method with the reference view of the teleoperated vehicle itself [8)], and the teleoperation method by the vision support from the other robot [1)]. Even though these methods help a vehicle operator easily control the vehicle, these methods have some disadvantages such as it takes lots of processing time for the 3D model construction of unknown environments, it is hard to handle dynamically changing environments, and it would increase the cost, size, and/or weight of the system and the number of vehicles. In the work [9)] the scene images along the vehicle path are represented and recorded by panorama images for later use. On the other hand, in our work we propose the teleoperation method which can provide the bird's eye view image of the vehicle which is synthesized using the spatial-temporal information of images in real-time aiming to improve vehicle teleoperation ability in gradually but dynamically changing environments. We can overcome the above mentioned problems in teleoperation with this proposed method.

There is another issue in teleoperation such as the data communication issue: transmitting and receiving images which data size normally large will be large load for a communication network. In [10)] the prediction display and the force feedback which uses environment model are used to handle the time-delay when the teleoperation of a manipulator where the time-delay exists. The proposed method is the image-based method where no environment models are built. Even though this method will not directly handle the time-delay, we can select sending data contents according to the communication situation in this method and then we can use this method in the low bandwidth

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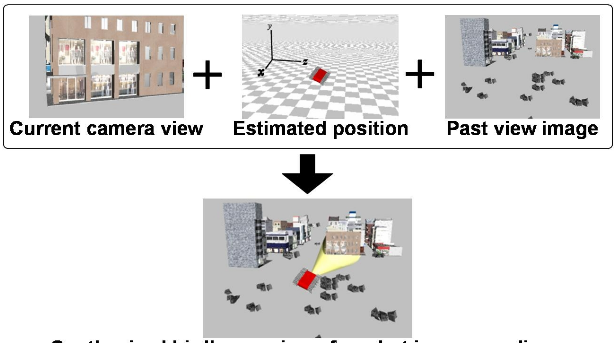


Fig. 1 Overview of bird's-eye view synthesis.

communication.

In this paper we propose this synthesized scene recollection method using real image data records. This paper is organized as follows: in the next section the synthesized scene recollection which improves the teleoperation ability is presented. In the following section the image synthesis method is explained. In the section four the vehicle position and orientation estimation method is presented and in the section five the implementation example of the vehicle teleoperation in the 2D plane is presented. Finally the paper is summarized by conclusion.

2. Bird's eye view image synthesis algorithm

The bird's eye view image synthesis method mainly consists of two technologies.

- Estimation of the position and orientation of the vehicle
- Image synthesis technique for bird's-eye view images using estimated position and orientation information of the vehicle and spatial-temporal information which are formerly captured real image data records

Overview of the bird's-eye view synthesis is represented in **Fig. 1**. The upper left, center and right pictures of **Fig. 1** are images currently captured by the camera, current position and orientation information of the robot, and the selected bird's-eye view like image of the robot from real image data records respectively. The bird's-eye view of the robot in its unknown surroundings shown in the bottom picture of **Fig. 1** is the synthesized image using above information and a CG model of the robot which is created in advance.

The vehicle operator can easily understand the situation of the robot and its unknown surroundings in the teleoperation using these composite images and the remote controllability will increase.

The algorithm for synthesizing the bird's-eye view images is as follows:

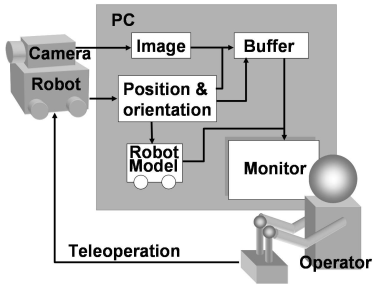


Fig. 2 System overview.

Bird's eye view image synthesis algorithm

(1) Obtain position and orientation information of the vehicle during operation (estimate position and orientation)

(2) Store images associated with position and orientation information of the mounted camera when they are captured to the buffer while the vehicle is moving (store image data records)

(3) Select an appropriate image from the stored real image data records according to the current position and orientation information of the vehicle and make the position and orientation of the selected image as the viewing position of the bird's-eye view image (select viewing position)

(4) Render the model of the vehicle according to the current position and orientation information of the vehicle and the selected viewing position (Render the vehicle model)

(5) Superimpose the model of the vehicle viewed from the selected viewing position onto the selected image from the stored real image data records (synthesize the bird's-eye view image)

(6) Repeat this procedure continuously

Here, (1) is realized by the estimation technology of vehicle position and orientation and (2)–(5) are realized according to the image synthesis technology. Overview of this system is shown in **Fig. 2**. Images captured by the mounted camera are stored in the buffer as bitmap images along with the associated position and orientation information of the camera when they are captured. The selection of the most appropriate viewing position is according to the position and orientation information of the mounted camera which is stored with the captured images in the buffer. As shown in **Fig. 3**, the selected image is used as the background image of the bird's-eye view image. This background image is not real-time one but it

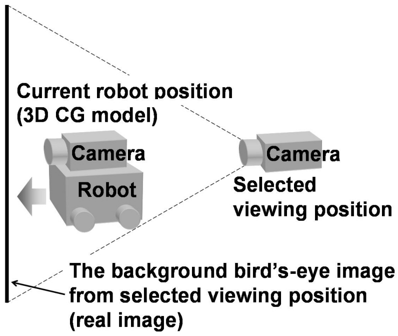


Fig. 3 Pseudo real-time view.

is a pseudo real-time one. Because of this system configuration it can handle dynamically changing environments in a pseudo real-time manner. Also this system does not require the construction of a 3D environmental model since this is an image-based method, and it does not take much time to synthesize the bird's-eye view image. Furthermore, since we can select sending data contents according to the communication situation such as the image data which has large data size is sent in low frequency and the vehicle position information which has small data size is sent in relatively high frequency in this method, this method can apply in low bandwidth communication. This method can prevent the operator from getting camera motion sickness by the providing bird's-eye and objective view images and reduce blind spots by presenting the vehicle model as the wire-frame model.

3. Image synthesis method

In this section the image synthesis method which realizes the bird's-eye view image synthesis algorithm is explained. The core technology is the selection of the viewing position. There are two types of selections such as the fixed bird's-eye viewing position and the moving bird's-eye moving position. This viewing position selection can be extended to the manual selection by an operator.

3.1 Image synthesis by fixed bird's-eye viewing position

In this method the viewing position is fixed and the same image used as the background image. Synthesized images viewed from the fixed point is provided to an operator.

Fig. 4 shows the one of examples of the vehicle teleoperation by the fixed bird's-eye view image synthesis [(1)]. **Fig. 4** (a) shows the used robot in the experiment. **Fig. 4** (b) shows the direct image from the mounted camera on the robot. **Fig. 4** (c) shows the synthesized images using the fixed background image which is viewed from the fixed position and the current position and orientation information of the robot. The images that are shown in the same columns in **Fig. 4** are the same time images. It can be seen that it is hard to understand and recognize the situation of the robot in its surroundings as well as its environment by only using direct images from the mounted camera in **Fig. 4** (b).

It can be said that it is easier to understand the situation of the robot in its surroundings by using the synthesized images by the proposed method in **Fig. 4** (c) rather than the direct images from the mounted camera.

3.2 Image synthesis by moving bird's-eye viewing position

For this moving viewing position teleoperation method we will propose four different types of teleoperation methods as follows:

(1) Real-time image teleoperation
(2) Constant time delay image teleoperation
(3) Fixed distance image teleoperation
(4) FOV evaluated image teleoperation

3.2.1 Real-time image teleoperation

This method uses the direct images that are captured by the camera mounted on the robot and displays those images to an operator for the teleoperation. This is the most basic teleoperation method.

3.2.2 Constant time delay image teleoperation

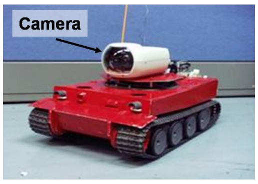
This method uses the images that are captured before in a set time limit from the current time in the buffer and displays those images to an operator for the teleoperation. These displayed images will realize a viewing position behind the current position of the robot.

In this method a memory space which can store the constant time amount images is prepared in the buffer. The oldest image in the buffer is used as a background bird's-eye view image and associated position and orientation information of the image is used as a viewing position. Every time the current frame image is inserted into the buffer the oldest one is erased. The current frame image up to the before set time frame image is constantly stored in the buffer.

3.2.3 Fixed distance image teleoperation

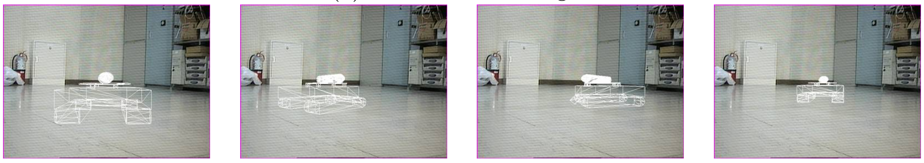
This method uses the images that are captured at the position which is a fixed distance away from the current position of the robot and displays those images to an operator for the teleoperation. Although in the previous constant time delay teleoperation, when the robot stops

(1) The image process is conducted in off-line and the vehicle position and orientation information is measured by the external sensor in this example.



(a) Robot.

(b) Actual camera images.



(c) Synthesized images by the proposed method.

Fig. 4 Example of fixed viewing position synthesis.

the background bird's-eye view image catches up to the current position image and the bird'-eye view image of the robot is unable to be obtained, this never happens in this method. A position at a fixed distance away from the current position of the robot is calculated and an image which is captured from the closest position from it is selected from the buffer as the background bird's-eye view image.

3. 2. 4 FOV evaluated image teleoperation

This method is composed by adding the property that the model of the robot can always be seen in the synthesized image to the fixed distance image teleoperation.

We can calculate the projected position and size of a vehicle which locates in the three dimensional space in an two dimensional image from the camera position and orientation, the camera parameters, the vehicle position and orientation. There might be a chance that no stored image has the current vehicle position image in it. In this method the selection of the background image is conducted according to the projected position and size of a vehicle in an image. At first, the preferable relative position between the vehicle and the viewing position is provided. This preferable relative position can be determined according to the camera parameters and the vehicle size. Next, one of the stored images which viewing position and the current vehicle position is the closest to the preferable relative position is selected as the background image.

All the position and orientation information of the mounted camera associated with the stored images in the buffer is used in this method. It is evaluated whether or not the robot is in the FOV by using this position and orientation information along with the viewing angle of the camera. Insertion of the captured images into the buffer occurs when the robot moves specified distance or specified rotation angle. The stored images in the buffer are not captured consecutively. They are captured from the sparsely spread position of the robot motion.

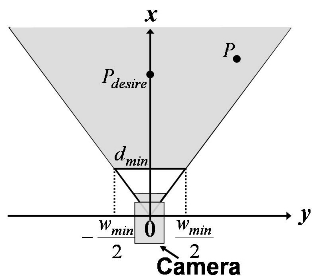


Fig. 5 Top view of Field of View.

The detailed explanation of the proposed method assuming a vehicle is moving in the two dimensional plane is presented below.

The FOV of the mounted camera can be represented as shown in **Fig. 5**. This is the top view of the FOV. The origin is the position of the camera. The heading direction of the robot is the same as the x-axis direction of the coordinate system and the y-axis is orthonormal to it. Points in the colored area in **Fig. 5** can be seen from the mounted camera. θ_w rad is half of the horizontal viewing angle. The side view of the camera is shown in **Fig. 6**. Here, θ_h rad, θ_p rad, and H_c mm are half of the vertical viewing angle, the camera pitch angle, and camera height from the ground respectively. The viewing area S can be represented by d_{min} and w_{min} in **Fig. 5** as follows: $S = \{(x, y)|x \geq d_{min}, y \leq \frac{w_{min}}{2d_{min}}x, y \geq -\frac{w_{min}}{2d_{min}}x\}$. Here, d_{min} mm is the minimum distance between the point which can be seen from the mounted camera and the projection point of the camera position. It can be obtained as follows:

$$d_{min} = \frac{H_c}{\tan(\theta_p + \theta_h)} \tag{1}$$

$$w_{min} = 2\,\frac{d_{min}}{\cos(\theta_p + \theta_h)}\cos\theta_h \tan\theta_w \tag{2}$$

The preferable relative position between the vehicle and the viewing position which is determined according to the camera parameters and the vehicle size is provided.

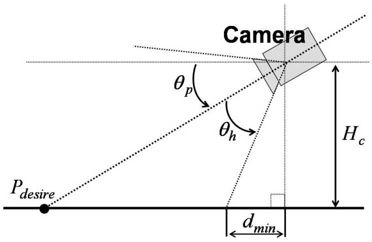


Fig. 6 Side view of the camera configuration.

P_{desire} is the position of the vehicle which locates this preferable position in the xy plane and the current vehicle position is represented by P. The background in this method is selected as follows: first images such as $P \in S$ are selected from the buffer and the image whose distance between P and P_{desire} is the shortest is selected as the background image.

3. 2. 5 Background image update

The update frequency of the background images in each teleoperation method should be adjusted according to the vehicle traveling velocity, surroundings, and so on.

One of the guideline for the determination of this background image update frequency can be the error distribution of the relative position and orientation between the past and the current vehicle position such as the background image is updated when the error grows the specified magnitude while managing the relative position and orientation error distributions. This would be the future work.

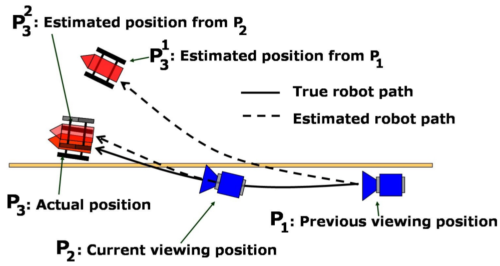
4. Estimation of vehicle position and orientation

4. 1 Position and orientation estimation for image synthesis

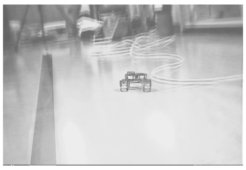
In the previous section several viewing position selection method for the image synthesis is presented. The vehicle relative position and orientation information between the current and past is enough for this image synthesis and we might not need the vehicle global position and orientation information.

The dead reckoning is the useful integral type vehicle position and orientation estimation method where the GPS sensor can not be used. The well-know problem of the dead reckoning is the error accumulation. This proposed method can work with the relative position and orientation information and suppress the effect of the accumulated errors.

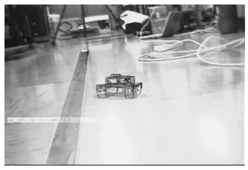
The concept images which represent the effectiveness of the image synthesis based on the relative position and orientation are shown in **Fig. 7**. In **Fig. 7** (a) the dark thin solid line represents the actual vehicle path. The vehicle traveled from P_1 through P_2 and reached P_3. The dashed lines represent the estimated vehicle paths and the light colored thick solid line represents the reference path.



(a) Schematic figure of the relative positioning teleoperation.



(b) Synthesized view from P_1.



(c) Synthesized view from P_2.

Fig. 7 Only some accurate relative positioning is required in this teleoperation method.

The estimated relative position of the vehicle from P_1 is P_3^1 because of the accumulated error. The synthesized image using the previously obtained image at P_1 and this estimation can be seen in **Fig. 7** (b). The vehicle position is far from the acctual position in the image. On the other hand, the estimated position of the vehicle form P_2 is P_3^2 and the accumulated error is smaller than before. The synthesized image using the image obtained at P_2 and this estimation can be seen in **Fig. 7** (c) and this image represents the better current vehicle real situation. Since this method updates the background image to the new one which obtained closer position to the current vehicle position, the effect of the error accumulation is suppressed.

In this paper we use the position estimation method which uses scan matching of the laser scanner measurement as the vehicle position estimation method which does not depend on the external sensor.

4. 2 Robot positioning using scan matching

4. 2. 1 Scan matching

In scan matching two scan data from a laser rangefinder (LRF): a reference scan, R_n, and an input scan, S_n are used to determine the relative rotation, dR, and the relative translation, dt, of the LRF position. This relative rotation and translation are the same as the ones of the robot position. The ICP (Iterative Closest Point) algorithm [11) 12)] which is based on the least square registration is a well known algorithm for local scan matching. In this paper we use the ICP algorithm for scan matching and to determine the relative rotation and translation of the robot position.

The algorithm used in this paper for scan matching in 2D horizontal plane is as follows:

Scan matching algorithm

(1) *Determine closest point pairs*

Find a closest point $r_i \in \mathbb{R}^2$ in the points of the reference scan data, R_n, which corresponds to each point $s_i \in \mathbb{R}^2$ for all the points in the input scan data, S_n.

(2) *Suppress bad closest point pairs*

Ignore closest point pairs (s_i, r_i) of the input and reference scan data whose point distances $|s_i - r_i|$ are larger than the specified threshold distance δ.

(3) *Subtract centroids of the scans from the scan data*

Calculate centroids of each scan, s_c and r_c. Subtract corresponding centroid from all the closest point pair (s_i, s_r).

$$s_c = \frac{1}{N}\Sigma s_i \qquad r_c = \frac{1}{N}\Sigma r_i \tag{3}$$

$$s'_i = s_i - s_c \qquad r'_i = r_i - r_c \tag{4}$$

Here, N is the number of the closest point pairs.

(4) *Calculate the correlation matrix*

Correlation matrix H can be obtained as follows:

$$H = \Sigma r'_i s'^T_i \tag{5}$$

(5) *Calculate the small relative rotation and translation*

The SVD (Singular Value Decomposition) of the correlation matrix H is as follows:

$$H = UDV^T \tag{6}$$

Here, D is the diagonal matrix which has the singular values of H as its diagonal elements. U and V are the orthonormal matrices in which the left and right singular vectors corresponding to the singular values of H are aligned as the column vectors. The small relative rotation, $\mathrm{d}R$, and translation, $\mathrm{d}t$, can be obtained using the matrices U and V as follows:

$$\mathrm{d}R = VU^T, \quad \mathrm{d}t = r_c - \mathrm{d}Rs_c \tag{7}$$

(6) *Move the input scan by* $(\mathrm{d}R, \mathrm{d}t)$

Move the input scan data by the obtained relative rotation and translation $(\mathrm{d}R, \mathrm{d}t)$.

(7) *Repeat this procedure continuously*

4.2.2 Robot positioning

The total rotation and translation of the robot can be obtained by accumulating the small relative rotation, $\mathrm{d}R$, and translation, $\mathrm{d}t$, at each time step. We calculated the robot position using scan matching as following algorithm:

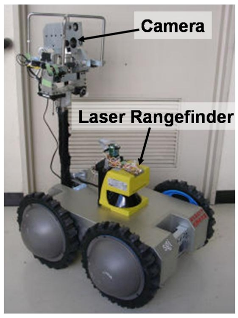


Fig. 8 A four-wheeled rescue robot FUMA with RS4-4.

Robot positioning algorithm

(1) Take the first scan at the initial position of the robot and register the scan data as the reference scan. Following scans are used as input scans unless the specified conditions are met.

(2) When the next scan is obtained, use the scan as the input scan and do scan matching with the registered reference scan. The relative robot motion (relative rotation and translation) will be obtained.

(3) Calculate the current robot position by adding the obtained relative robot motion to the position of the robot where the reference scan was registered.

(4) Update reference scan when the robot translates the specified distance or rotates the specified angle.

(5) Go back to (2) and repeat this procedure continuously.

It should be noted that since we have the robot position information and the scan data from that robot position, we can generate a 2D horizontal map by combining these information and stitching each scan data according to the robot position information in some accuracy. This position and orientation estimation method is the integral type position estimation method which has the error accumulation since the reference scans are updated.

4.3 Robot positioning experiment

4.3.1 Experimental setup

The experimental environment is the flat two dimensional plane and the developed four-wheeled rescue robot platform called FUMA [13] which is shown in **Fig. 8** is used as the experimental mobile robot. The RS4-4 (Leuze) is used as a laser rangefinder and it is mounted on the FUMA as shown in **Fig. 8**. The RS4-4 can scan in the range of 190 degrees in angle and 50 m in distance in front of it. Its resolution is 0.36 degrees in angle and 5 mm in

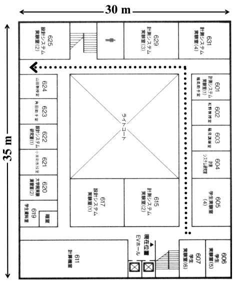


Fig. 9 Sketch map of the environment.

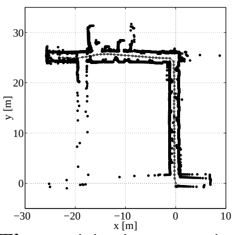


Fig. 10 The positioning experiment result.

distance. It uses the 905 nm infrared laser and its scanning rate is 40 msec/scan.

4. 3. 2 Positioning experiment

We have conducted a positioning experiment using the RS4-4 mounted on FUMA. Each parameter is set as follows:

- The number of scanning point at one scan: 133 (every 1.44 degrees)
- Distance threshold between closest point pairs: 500 mm
- Scan matching sampling rate: 100 msec
- Update condition of a reference scan: motion difference of 200 mm in distance and/or 5 degrees in angle

These parameters are obtained experimentally. All process in the position and orientation estimation including scan matching can be executed in real-time.

In the experiment the robot moved along the L shape path drawn by the dotted line from the start point at the bottom right corner to the goal point at the top left corner as depicted in **Fig. 9**. **Fig. 9** is a schematic figure of the floor where the experiment was conducted.

The positioning experiment result is shown in **Fig. 10**. The small circle dots denote the position of the robot and the big dark dots the point on the objects around the path which form the map around the path where the robot has traveled. As shown in **Fig. 9** and **Fig. 10** the position of the robot can be obtained by scan matching using the LRF.

5. Implementation of the synthesized scene recollection

The proposed method is implemented on FUMA. The two dimensional flat plane is assumed as the experimental environment. The previously explained scan matching is used as the position estimation method and the FOV evaluated image teleoperation method for the image synthesis.

One of the examples using the FOV evaluated image teleoperation method in real-time is shown in **Fig. 11**. This is the scene of the FUMA after traveling total 25 m translation and 420 degrees rotation. The images in **Fig. 11** are taken at the same time. (a) is the image of the FUMA taken from the external camera which shows the reference of the scene. (b) is the image from the camera mounted on the FUMA. (c) is the synthesized image of FUMA in the environment by the proposed method. As shown in **Fig. 11** it can be said that the synthesized image is well representing the situation of the robot in the environment even though it is hard to understand the robot situation in the environment by the image (b) which is taken from the camera mounted on the FUMA.

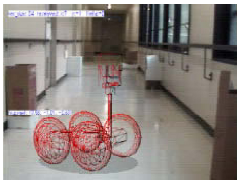
The other example using the FOV evaluated image teleoperation method in real-time is shown in **Fig. 12**. The viewing positions are selected automatically according to how close the model of the robot can be seen in the image area. The snapshots of the experiment are represented from the left to the right and from the upper row to the bottom one as time goes by. It can be said that the situation of the robot in the surroundings of the remote site can be understood with ease and this helps the operator to control the robot.

Since this method does not require to obtain image data which data size is usually large in high frequency, it can be applied in the low bandwidth communication and since it is the image-based method which does not require any environment model, it can work in real-time and also can handle dynamically changing environments in a pseudo real-time manner.

There are some other advantages of this method such as: this method can reduce blind spots by presenting the vehicle model as the wire-frame model. Even though there is noise in the current image, we can select a less noise clearer image from the stored images in the buffer for the background image and can suppress effect of the noise. Also since the background images are selected from the discretely stored past images, it has an effect of filtering the high frequency oscillation comparing with the provid-

(a) External camera image of FUMA.

(b) Direct camera image.



(c) Synthesized image.

Fig. 11 One scene of FUMA at the experiment.

ing direct camera images to an operator. This method can prevent the operator from getting camera motion sickness by providing the less oscillation bird's-eye and objective view images. This method not only can be applied to vehicle teleoperation but also can be applied to any other applications for a moving object.

6. Conclusion

In this paper we have proposed a novel teleoperation method for a mobile robot, the synthesized scene recollection method using real image data records and the effectiveness of this method which based on the relative position is presented. The self-contained implementation example of the method with the positioning by scan matching of a laser rangefinder's scan data is presented. The proposed teleoperation method enables an operator to easily understand and recognize the situation of the robot in its surroundings which leads to the improvement of the remote controllability. It can be said that this self-contained implementation of the proposed method made the progress for the realistic application of the method such as a rescue activity use.

In our future work we will extend our implementation of the method to the three dimensional environment with some three dimensional robot positioning method. The implementation of the three dimensional robot positioning in unstructured environment is important. Incorporation of the robot positioning only with single camera [14] will enables the compact and less expensive implementation of the system. These would be our future work.

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Fig. 12 Example of FOV evaluated image teleoperation.

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