Proceedings of the 2006 IEEE/RSJ
International Conference on Intelligent Robots and Systems
October 9 - 15, 2006, Beijing, China

Evaluation of HBP Mirror System for Remote Surveillance

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Abstract— **The HBP (Horizontal fixed viewpoint Biconical Paraboloidal) mirror is an anisotropic convex mirror that has a property of inhomogeneous angular resolution about azimuth angle. In this paper, we investigate the effectiveness of the HBP mirror system for remote surveillance. We developed a real remote surveillance system that is constructed by the HBP mirror system mounted on an electric cart. Through the surveillance experiments, surveyors usually looked almost front views, and they paid attention to interesting objects only when the cart approaches them. Since the HBP mirror system has high resolution in frontal view, it seems to work well in the surveillance. We also constructed a simulational remote surveillance environment in order to quantitatively compare the HBP mirror system with a conventional omnidirectional mirror system under fair experimental conditions. As a practical task, we assumed object searching in a virtually constructed devastated area. We confirmed that objects can be detected earlier and with certainty by the HBP mirror system.**

I. Introduction

Mobile robots that work in various environments hostile to humans have been developed and actually applied in many cases. As technology advances, the working space for the robots changes from an artificial and rectilinear environment with many limited conditions such as an indoor office, to a natural and largely unknown environment such as an outdoor work space. Researchers have especially taken notice of seeking tasks and operating tasks for mobile robots in unusual conditions, like a devastated area, an ocean bottom or a lunar surface; places that humans can not or should not work because of the dangerousness in such conditions. Insufficient pre-information and an irregular workplace surface in such conditions complicate automating the mobile robot. In the most cases, the mobile robot is remotely controlled by a human operator. Thus, it is effective to mount a vision sensor on the mobile robot and use it for both navigation and collecting information.

A catadioptric omnidirectional imaging system constructed by a convex mirror and a camera pointing vertically toward the mirror[1], [2], [3] is compact and can acquire 360 degree observations at a video rate. These properties are superior to exploring an insufficient pre-information area. Being small size, light-weight and the omnidirectional observation without a camera rotation the imaging system is suitable for practical use. A wide range observation in real time can give views in any direction desired without time latency. Onoe et. al[4] used an omnidirectional video stream for real time telepresense. But the low angular resolution compared to a normal camera is a problem with the catadioptric imaging system, since an omnidirectional view is projected onto a single input image. This weakness is not desirable for either navigation or collecting information. For example, the early detection of obstacles and correct estimation of its position are very important for safe navigation in the case of remote control including the time latency in transmission. Dense observations are very importance for such tasks.

There are several attempts to overcome the low resolution problem. Srinivasan et. al[5] and Hicks et. al[6] designed special mirror for directly getting a panoramic image of a scene. Swaminathan et. al[7] proposed an iterative method for mirror shape designing. Aim of these proposals is to realize given projection from a scene to an image plane. On the other hand, for a vision of a mobile robot, we have developed the HBP (Horizontal fixed viewpoint Biconical Paraboloidal) mirror system[9]. The HBP mirror system smoothly realizes changes in angular resolution about azimuth angle by using an anisotropic special deformed mirror. We illustrated the geometry of the HBP mirror system, the distribution of its resolution and relevant mathematical influences such as obstacle detection based on an optical flow size and image warp. However, the properties and effectiveness have not been clarified when the HBP is mounted on a mobile robot and is used for an actual task.

So, in this paper, we investigate the effectiveness of the HBP mirror system as a vision sensor of a mobile robot. As the actual task, we assume object detecting by a human in a remote surveillance. We developed a remote surveillance system constructed by the HBP mirror system mounted on an electric cart. The cart drives around to acquire images of the scene, then the images are transmitted to a computer at a distance from the working space for surveillance. In

TABLE I

OBSERVATION DENSITY OF EACH DIRECTION FOR EACH IMAGING SYSTEM.

Imaging system	Normal camera	Isotropic omnidirectional imaging system	Anisotropic omnidirectional imaging system
Front	full	middle	high
Side	none	middle	low

order to quantitatively compare the HBP mirror system with a conventional omnidirectional imaging under fair experimental conditions, we also constructed a simulational remote surveillance environment. With using this virtual environment, we performed experiments about object detecting.

II. HBP MIRROR SYSTEM

A. Mirror design

Generally, the camera and convex mirror of a conventional catadioptric omnidirectional imaging system are usually arranged as shown in Fig. 1. It has uniform angular resolution about azimuth angle because the shape of the convex mirror is defined by rotating a curvature around the optical axis of the camera. We deformed a paraboloidal mirror based on “simple stretching” and “focal point shifts” ideas, and constructed the HBP mirror that has biased resolution. A normal perspective camera uses a camera’s entire image plane for a very limited filed of view, while a general omnidirectional imaging system distributes it uniformly according to azimuth angle. On the other hand, the HBP mirror system allocates larger resources of the image plane to important directions, rather than a relatively unimportant direction. Table 1 shows the resolution distribution properties of each imaging system. The equations for the HBP mirror shape and mirror-camera projection are as follows:

$$\begin{cases} X = t\cos\theta \\ Y = t\sin\theta \\ Z = \frac{2D(\theta)-a}{2L(\theta)^2}t^2 - \frac{D(\theta)-a}{L(\theta)}t - \frac{a}{2} \\ L(\theta) = ab\sqrt{\frac{\tan^2\theta+1}{a^2\tan^2\theta+b^2}} \\ D(\theta) = ab\sqrt{\frac{a^2\tan^2\theta+b^2}{a^4\tan^2\theta+b^4}} \end{cases} \qquad \begin{cases} x = X \\ y = Y \end{cases} \tag{1}$$

where X, Y, Z are axes of three dimensional Cartesian coordinates, t, θ are a polar description of the XY plane, and x, y represent a coordinate of an input image plane in the camera, respectively. a, b are elliptic coefficients deciding the shape of the horizontal section at Z=0, which determines the amount of the anisotropic property the mirror has. When a is equal to b, the mirror is not deformed and the above equations described a conventional paraboloidal mirror system. Since the horizontal section of the HBP mirror is the shape similar to an ellipse, it also effectively uses a rectangle of an input image plane such as 4:3 or 16:9 aspect ratio.

Figure 2 shows an overview of the prototype HBP mirror system with design coefficients a=28mm, b=38mm and Fig. 3

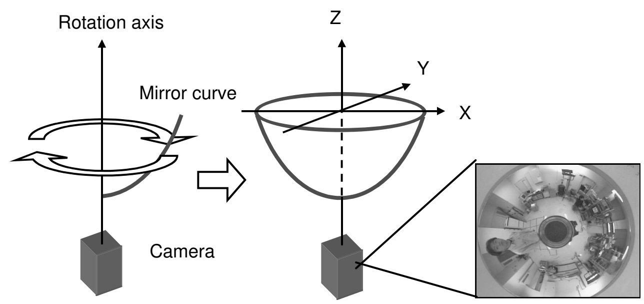


Fig. 1. An example of a conventional omnidirectional imaging system with a convex mirror. It consists of a camera and a rotational convex mirror. The optical axis of the camera is aligned to the mirror’s rotational axis.

shows an example of the input image. We used a panoramic mirror in order to translate from the orthogonal projection described in right term of Equation(1) to the perspective projection that a normal camera requires. The quantitative resolution changes shown in Fig. 4 indicate a higher angular resolution at a 0 degree azimuth angle than at 90 degree. Though the HBP mirror has a lower longitudinal(horizontal) resolution at 90 degree than the paraboloidal mirror, the latitudinal(vertical) resolution is higher than it, which shows that there is little spatial resolution difference between the two imaging systems.

B. Image transforming for display

Direct display of distorted input images of the omnidirectional imaging sysytem gives an uncomfortable feeling to the operator. So the input image should be transformed as if it is taken by a normal camera. The view direction and view angle determine the area to be displayed in the input image, and the geometry of the omnidirectional imaging system decides the image transformation, respectively. But, in the case of the HBP mirror system, much computational time is needed to solve the inverse of Equation(2). So, the ray-point correspondences for an each view are calculated in advance, and stored as image transforming tables. For display, it is only necessary to read data from the table, depending on the current view direction. With this method, an operator can immediately look the desired view.

Since the HBP mirror system does not have a single view point, its image warping can not be completely corrected. However, its influence is very small in practical uses[9], so we ignore the influence of multi viewpoints.

III. REMOTE SURVEILLANCE SYSTEM WITH HBP MIRROR

A. HBP mirror system as a vision sensor for a mobile robot

If the high resolution area of the HBP mirror corresponds the direction of a robot’s moving path, an operator can obtain high resolution images in this direction. For mobile robot navigation and surveillance of a scene, dense observation in the moving direction is important. Because obstacles that the robot must certainly avoid tend to appear in the direction of movement. Interesting objects that the operator wants to detect earlier also tend to appear in that direction. But it

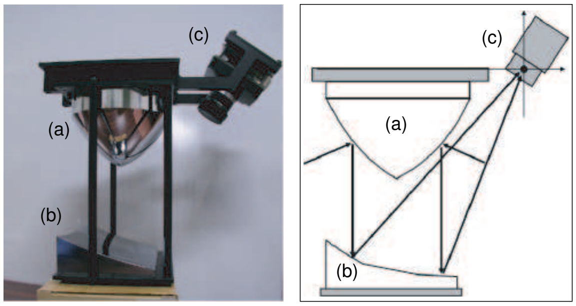


Fig. 2. Prototype of the HBP mirror system and its geometry model. A ray from a point in a scene is reflected by the HBP mirror(a) and reflected again by a parabolic mirror(b) to concentrate on a perspective camera(c).

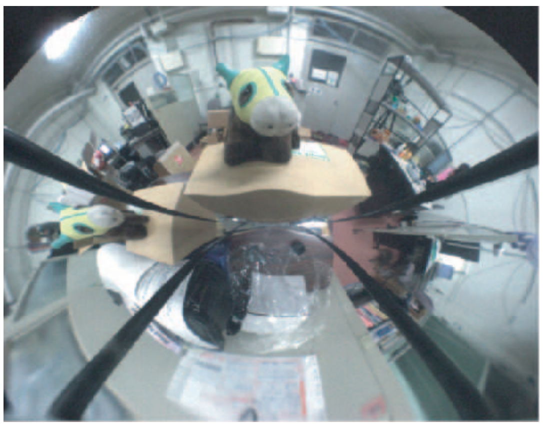


Fig. 3. An example of input image taken by the prototype HBP mirror system shown in Fig. 2. Two horse plushies are same size and located at same distance(200mm) from the mirror in real scene, however they are projected as different size.

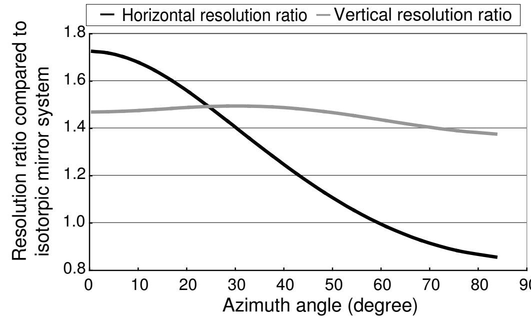


Fig. 4. Resolution changes of the HBP mirror system expressed as a ratio to the resolution of a paraboloidal mirror system. Black line and gray line show longitudinal resolution and latitudinal resolution, respectively.

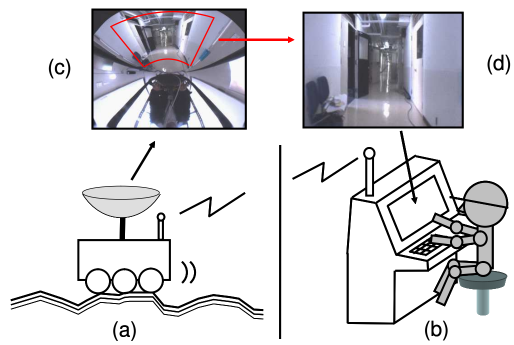


Fig. 5. Outline of the remote surveillance system. (a) mobile robot with a catadioptric omnidirectional camera. (b) surveillance at distance place. (c) input image. (d) transformed image for display.

is problem not to be able to look other direction such as side direction. We should be able to observe any direction. Since the HBP mirror system satisfies above two requirements - omnidirectional observation and detail observation in the moving direction, it is suitable for a vision sensor of a mobile robot.

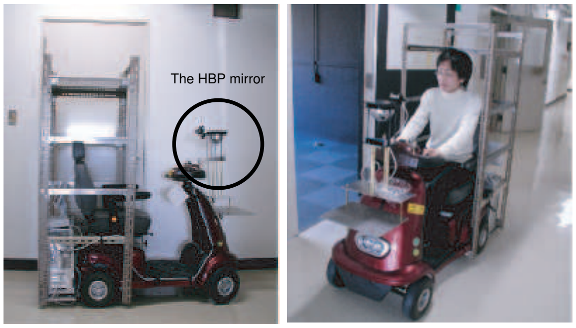
B. Development of surveillance system

A remote surveillance is one of application that suitably uses the properties of omnidirectional imaging system. It is constructed as shown in Fig. 5. The omnidirectional imaging system mounted on the mobile robot acquires omnidirectional images of the scene and the captured images are transmitted to an operator through a network. Since the captured images cover an omnidirectional scene, the operator can immediately look the desired view in any direction.

Based on the construction described in Fig. 5, we developed a real remote surveillance system with the prototype of the HBP mirror system mounted on an electric cart (Fig. 6). In this paper, we want to demonstrate effectiveness of the HBP mirror system when it is used for surveillance, not for such as driving. So we assume that a driver actually rides on the cart to drive it.

C. Surveillance experiment

We performed surveillance experiments with using the above constructed system under an actual environment. The cart drove through an indoor scene as shown in Fig. 7 to transmit captured images. Surveyors looked these captured scenes with freely panning their view direction at a distant place. The average velocity of the cart is about 2.0 km/h and driving distance is about 70m. Figure 7 is an example of the results. The curved line and the short lines with dots in the figure represent the trajectory of the cart and view directions of the surveyor at each time, respectively. In the most case of the surveillance, the surveyor looked almost frontal view following driving of the cart. When the cart goes through a narrow space such as doors, he also looked frontal view. As we expected, the frontal view is important in the case of remote surveillance. On the other hand, when the cart approaches the opened doors and drives near obstacles in the room C, the surveyor looked them. This indicates that since he was interested in inside of the rooms and the obstacles, he took attention to them. We confirmed that the surveyor effectively use the view of the HBP mirror system that has biased resolution, with changing his view direction according to purposes.



(a) (b)

Fig. 6. The HBP mirror system mounted on an electric cart for remote surveillance. (a) overview of the cart. The HBP mirror system is fixed at the front of the steering wheel (even if a driver steers, the HBP mirror system does not rotate). (b) driving scene for surveillance.

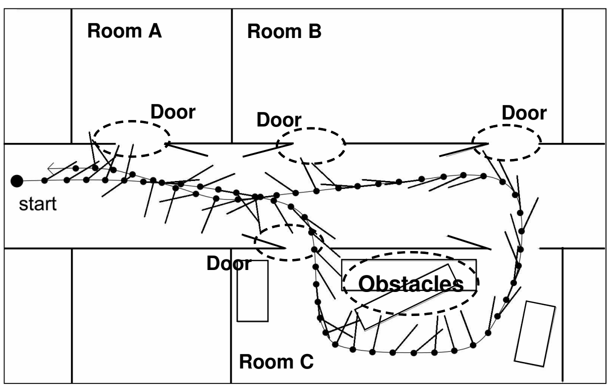


Fig. 7. Experimental scene in which the cart with the HBP mirror system drove. The scene is constructed by a passage and rooms. Doors of the room A, B and C are opened for the surveyor to be able to look in. The cart starts driving from the left edge of the figure, then goes into the room C including some obstacles and goes out to return to the starting point, described by a curve. Dots with short lines describe positions of the cart and the view direction of the surveyor at that time, respectively.

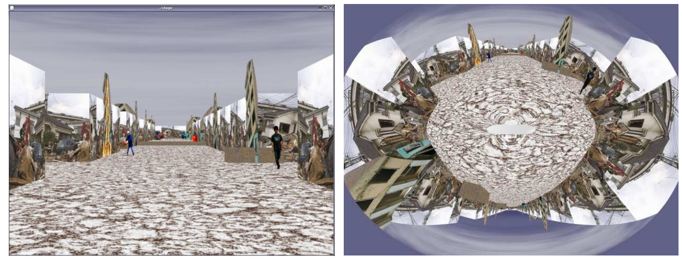
IV. Development of virtual remote surveillance environment

A. Need of a virtual remote surveillance environment

In the above section, we confirmed the practicality of the HBP mirror system when it is used for the remote surveillance. But quantitative advantage is not compared with conventional omnidirectional imaging systems. An experiment with the remote surveillance system in a real situation has much ambiguity, such as the experimental environment changing with time, different routes at each experiment, and hardware noise. We want to equalize the experimental conditions through the experiments. So we developed a virtual remote surveillance environment with a virtually constructed scene and the imaging system. In this way an experiment can be easily replicated with same conditions. We now discuss a task setting, a target scene, image generation by ray-tracing, and surveillance types.

B. Task setting

We assume that the operator searches an area devastated by an earthquake using this remote surveillance system. This



(a) (b)

Fig. 8. An example of virtually constructed devastated scene. (a) taken by a normal perspective camera model. (b) rtaken by the HBP mirror system model.

is appropriate, since researchers have recently paid much attention to the use of robots that can collect information in devastated areas for such as lifesaving, preventing the expansion of the disaster and recoveries of the affected area. But going into a devastated area is dangerous for humans; therefore, it is desirable to do it using robots rather than humans.

The types of the robot are categorized into the three groups depending on the size of the target area. Aircraft and balloon type robots such as in [10] are suitable for wide range observations. Spider and crawler type robots such as in [11], [12] are suitable for burroing into narrow space. Here, we detail a driving type robot that can be categorized in middle range observation. We therefore assume that a wheel type mobile robot with an imaging system drives through a devastated area to find and detect interesting objects as information arising out of a disaster.

The concrete experimental task is that an operator surveys a view given by an omnidirectional imaging system in order to detect interesting objects. We call this task “object searching task”. If the HBP mirror system well works in the searching task, it will be able to detect objects earlier and more certainly than a conventional isotropic omnidirectional imaging system.

C. Target scene

We constructed the target scene simulating a devastated area as follows. The scene consists of constant width roads, destroyed buildings and objects that an operator must detect. The objects are fire disasters, disaster victims and obstacles. The mobile robot does not freely move with an operator’s driving, but moves along a planned route in the scene. An example of the scene with textures of real destroyed buildings shown in Fig. 8(a) is taken by a normal perspective camera model.

D. Image generation by ray-tracing

A projection of a catadioptric omnidirectional imaging system is non-linear. Furthermore the projection of the HBP mirror system is more complex. To correctly simulate the projection, it is necessary to calculate each non-linear correspondence between the ray in the three dimensional scene and the point on the image plane. For this calculation, a ray-trace technique that can perfectly simulate the geometry between a scene and an imaging system is suitable. We used POV-Ray, which is a ray-trace software. It can generate images of a complex imaging system like a catadioptric camera. Although POV-Ray does not completely simulate optical properties such as focus and blur, we consider that these shortcomings are not a serious problem because we can avoid the problem with one step in the design of the mirror shape. As POV-Ray needs a lot of time to generate images, the images were set up as an image sequence in advance. An image shown in Fig. 8(b) is an example of the generated images with using the HBP mirror model.

E. Surveillance type

In the remote surveillance situation, there are some types of surveillance. We prepared two types of surveillance as follows. One is a searching with a freely pan-tilting view.Though an operator can freely change the available view to look over the scene, the view direction seems to be mostly front. Because it is dangerous for the operator not to be able to look the front view. Therefore, using this type of surveillance, overlooking seems to be a rare case. We expected that early detection of the obstacles would become obvious.

The other is searching with a fixed panoramic view. In this case, we make up a single wide image that covers from a front to a side view. The panoramic image is divided into sub images to be shown on LCDs.Since the view of the operator can not cover all of the panoramic image at once, attention mainly seems to influence detection. For instance, it may often be case that when the operator pays attention to a particular object, another object goes past. This type of surveillance does not lead to accurate evaluations by an imaging system, but it demonstrates a situation that more realistically simulates searching and surveying.

F. Whole construction of the virtual remote surveillance

Our proposed experimental remote searching system constructed by the above components works as shown in Fig. 9. An input image corresponding to the present time is transformed into a image for display according to direction of the surveyor's view. In the case of the fixed panoramic view, this view direction does not move. Figure 10 shows examples of displayed images of each omnidirectional camera and in each view direction. A paraboloidal mirror system having constant resolution about azimuth angle produces the same density in the front and side. In contrast, the HBP mirror system produces bias dense images between these views.

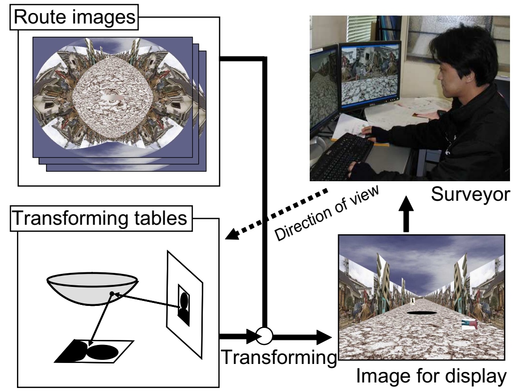


Fig. 9. Whole process flow of the simulational environment.

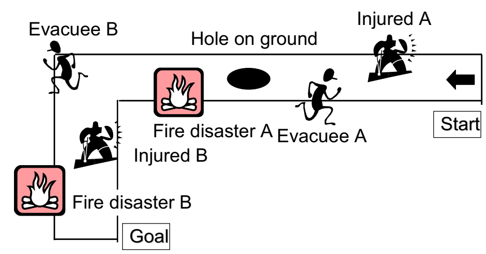


Fig. 11. Virtually constructed route used in the experiment with a freely pan-tilting view.

V. Experimental results

A. Experiment with the freely pan-tilting view

We undertook a virtual searching simulation in which test subjects detect objects in the virtual devastated area, as shown in Fig. 11. The subjects were eight students of our laboratory. Each subject tries twice with the paraboloidal mirror system and the HBP mirror system with its design coeffeicients $a = 35mm, b = 50mm$. Each subject surveys through the virtual devastated area in order to detect interesting objects (fire disaster A/B, injured A/B, evacuees A/B and a hole in the ground). To control the robot's movements, the operator can use the keyboard to just start/stop the robot driving along the planned route at a constant velocity. When a subject correctly detects an object, the distance from the robot is recorded as the "object detecting distance". If the subject overlooks the object and goes past, it is an "overlooked object". In the second round of the test, subjects tended to get better scores than in the first one because of the learning effect. To weaken this effect, a reverse route and/or flip horizontal images are used in the second round test.

1) results of the overlooked objects: In all the recorded data, there were only two overlooking episodes in the "Fire disaster A", that both occurred when subjects used the paraboloidal mirror system. There was nothing overlooked when subjects used the HBP mirror system (all objects were detected). Since the "Fire disaster A" represents a smaller fire than the "Fire disaster B", it tends to be assimilated into the background, which could have induced the overlooking episodes.

A subject with a paraboloidal mirror system tends to overlook a small object because of the low angular resolution in all directions. However, the HBP mirror system with its high angular resolution to the front has the possibility of detecting objects appearing in front of it. This is the main reason why there was nothing overlooked with the HBP mirror system. Thus, we consider that the HBP mirror system works more effectively than the paraboloidal mirror system in respect to

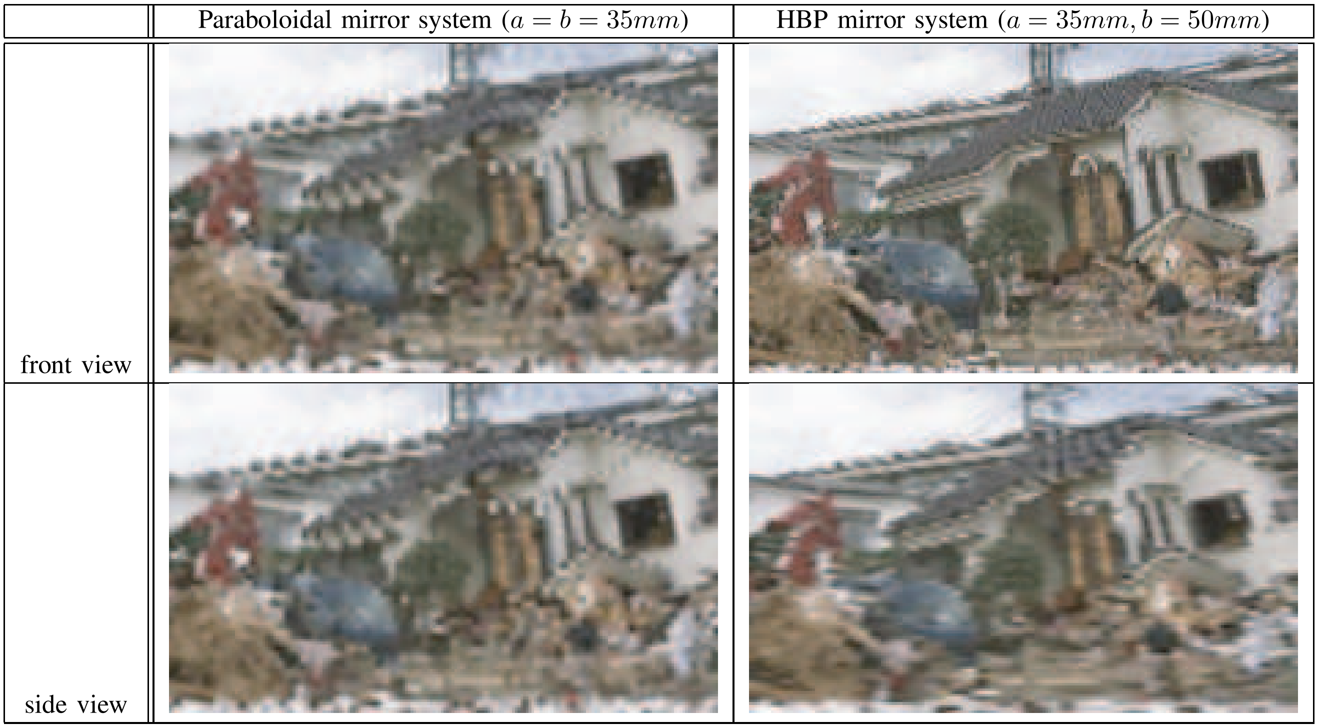


Fig. 10. Examples of the displayed images for each omnidirectional imaging system and direction. In a paraboloidal mirror system, the front and the side views have the same density. In the HBP mirror system, the density of the front view is higher than that of the side view.

TABLE II

AN EXAMPLE OF EXPERIMENTAL RESULTS. VALUES ARE OBJECTS DETECTING DISTANCES.

Objects	InjuredA	EvacueeA	Hole	FireDisasterA	EvacueeB	InjuredB	FireDisasterB
Paraboloidal mirror system	3	10	13	6	13	5	10
HBP mirror system	5	19	20	7	18	6	12

not overlooking objects.

2) results of detecting distance: For the quantitative evaluation, we define the effectiveness in the seeking task as that shown by the object detecting distance. Table 2 represents the detecting distance results for one subject. A large value in the table means the earlier detection of the object. To compare the effectiveness of the two imaging systems, we defined the following detecting scores.

$$D_{ratio} = \frac{D_{hbp}}{D_{paraboloidal}} \quad (2)$$

where D_{hbp} and $D_{paraboloidal}$ denote the object detecting distances for each imaging system. A larger D_{ratio} than 1 means that the HBP mirror system can detect objects earlier than the paraboloidal mirror system. D_{ratio} values calculated for each subject and each object are shown in Fig. 12, and the average ratios for each type of the objects are shown in Fig. 13, respectively. In most cases the values are larger than 1; and moreover, the average score of all subjects overtakes 1 in any object. This result shows the effectiveness of the HBP mirror system compared with the paraboloidal mirror system in the earliness and certainty of object detecting. We can see that the scores for the "Hole" and the "Fire disasters" are relatively low, and that of the "Injured" and the "Evacuees" are high in Fig. 13. Since the "Hole" and the "Fire disaster" have distinguishing color, the high resolution property not very effects the detecting, we think. On the other hand, the colors of the "Injured" and the "Evacuees" are similar to those of the background. So subjects must detect these using the shapes and/or textures of the objects. The high resolution images from the HBP mirror system seem to well work in this case, and result in good scores.

Figure 14 shows the early detection probability results. For example, in respect to the detection scores for "Injured A" in Fig. 14, only subject 4 has a less than 1, while the other seven subjects have scores of more than 1. This means that earlier detection occurred in just 12.5% of the tests using the paraboloidal mirror system, but in 87.5% using the HBP mirror system. Thus the HBP mirror system works far more effectively (over 90%) than the paraboloidal mirror system for "Injured" and "Evacuee" detections.

B. Experiment with the fixed panoramic view

In the previous experiment, we evaluated the ability of the HBP mirror system for earlier object detecting by mainly focusing on the front view. Here we evaluate the effectiveness

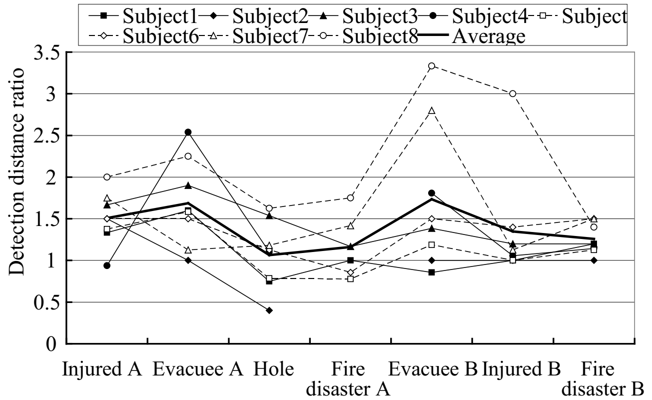


Fig. 12. D_{ratio} values for each subject and objects. Thin lines with markers show each experimental subject's value, and thick black lines without markers show the average of those values, respectively.

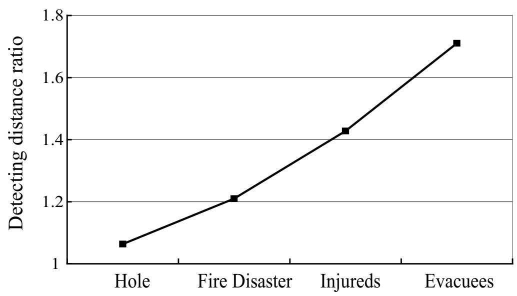


Fig. 13. Average value of the each object type in Fig. 12.

of the HBP mirror system when the operator simultaneously looks over a wide range view including that to the front and a side. This condition is assumed to be similar to a practical searching mission. Then we assume a scene with cross roads and place objects not only on the main route but also on roads crossing the route as shown in Fig. 15. We considere that with a panoramic view, the operator would pay attention to various points. Objects to be detected are persons (walking, with a child, injured, calling help and extinguishing a fire), fire disasters (a burned building and a burned house), and obstacles for navigation (a step and a hole in the ground). Subjects are ten students of our laboratory. Each subject tries twice as same as the previous experiment. During the test, the imaging system switches in a chronological order to reduce the learning effect. In the second round test, the switching is reverse order of that in the first round. Therefore total time of display by each imaging system are same. In this experiment, imaging systems, the way of recording the object detections, the computer used for the experiment and the method of driving the robot are the same as in the previous experiment with the freely pan-tilting view.

1) results of the overlooked objects: As noted above, the surveillance with the fixed panoramic view includes factors other than the difference of the imaging systems. Thus evaluations for each object type such as in the previous experiments

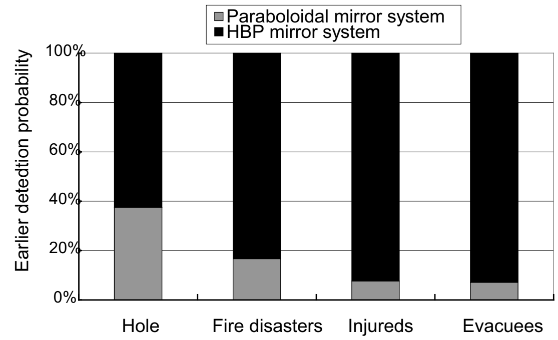


Fig. 14. Earlier detection probability. The graph represents which imaging system detects earlier for each target type. For instance, in the case of the fire disaster, a paraboloidal mirror system has about 18% probability of earlier detection, and an HBP mirror system has about 82%.

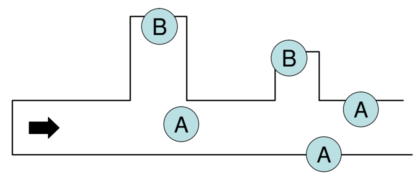


Fig. 15. Part of the virtually constructed route used in the experiment with a fixed panoramic view. (A) objects on the main route. (B) additional objects on a road, an alley, crossing the route.

have large variances. We evaluated the results for all the recorded objects instead of dividing it into each object type. Overlooking results of objects are shown in Table III. In the results shown in Table III, the incidents of overlooking are very few and the number of detected objects from each imaging system are similar. Since the spatial resolutions of the side view of the two imaging system is similar as described in Section II-A, almost the same incidents of overlooking are seen in both imaging systems. The objects in alleys often suddenly break out from behind buildings when the robot is close enough to it. This appearance will attract the attention of the operator, and so tend to prevent it being overlooked. On the other hand, there are many incidents of overlooking of objects on the main route. These objects are in the range of vision for long sequences, but the variation is small because the closing of the distance is just gradual. We consider that since the operator paid attention to another object, there was an ignorance of the small variation. Comparing the number of incidents of detection in each imaging system, we can see that the HBP mirror gives more certainly detection than the paraboloidal mirror.

2) results of detecting distance: The method to obtain object detection distances $D_{paraboloidal}$ and D_{hbp} is the same as in the previous discussion. We made histograms of the all detection distances as shown in Fig. 16. In the histogram, horizontal axis describes classes of detection distances, and vertical axis describes the number of objects that are detected corresponding to each distance class, respectively. In respect to the results regarding objects in the alleys, there is a similar distribution between the HBP and paraboloidal mirror systems.

TABLE III

OVERLOOKINGS RESULTS. TOP) ABOUT THE OBJECTS PUT ON THE ALLEYS. BOTTOM)ABOUT THE OBJECTS PUT ON THE MAIN ROUTE.

overlooked	detected by the paraboloidal mirror	detected by the HBP mirror	total
5	128	127	260

overlooked	detected by the paraboloidal mirror	detected by the HBP mirror	total
63	204	234	500

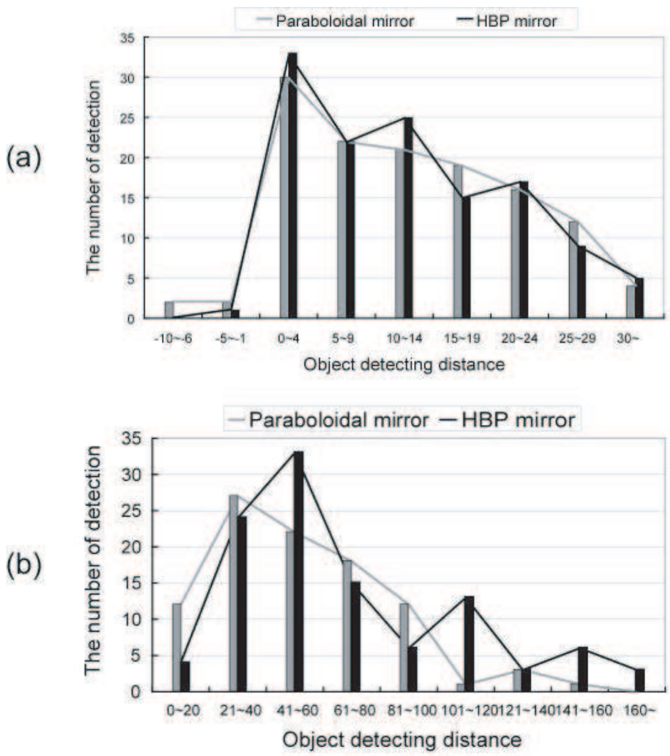


Fig. 16. Histograms of the detection distances. (a) detections of objects on the alleys. (b) detections of objects on the main route.

This means that the HBP mirror has almost same detecting ability as the paraboloidal one for a side view. On the other hand, in the results of objects in the main route, there are different distributions between the two imaging systems. While the paraboloidal mirror system has a distribution peak from 21 to 40 distance class, the HBP mirror system has a peak at a longer distance class, from 41 to 60. Furthermore many objects are detected at more than 101 distance when the operators use the HBP mirror system. Although we use a surveillance system with a fix panoramic view, and include factors other than the differences of the imaging systems, we confirmed that the HBP mirror system can detect objects with similar score for a side view, and it can detect objects earlier in a front view than can be done with the paraboloidal mirror system.

VI. CONCLUSION

In this paper, we confirmed the effectiveness of our HBP mirror system as a vision sensor of a remote surveillance system. We developed a real remote surveillance system with the prototype of the HBP mirror system mounted on the electric cart. The surveyor used the biased resolution view effectively with changing his view direction. We also constructed a virtual remote surveillance environment with a virtual devastated area and a catadioptric omnidirectional imaging system. This perfectly simulated the complex imaging system such as the HBP mirror system. By using the HBP mirror system, an operator can detect objects earlier and more certainly than in the case of using the paraboloidal mirror system, and not overlook anything. This demonstrates that the HBP mirror system with biased resolution is more effective than the paraboloidal mirror system with uniform resolution for seeking tasks.

In current implementation, images captured by the HBP mirror system were used for only surveillance, not used for navigation. The importance of surrounding observations for stably navigating a remote controlled mobile robot is confirmed by Nagahara et. al[8]. At the same time, high resolution frontal images is also important, we think. Because obstacles to be avoided seems to appear on the moving path of the robot. So the HBP mirror system that realizes to acquire both of omnidirectional image and high resolution frontal image seems to have advantage for driving a robot. We make a plan to evaluate the effectiveness of the HBP mirror system in the case of teleoperating the robot.

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