

Omnidirectional Sensing and Its Applications

Yasushi YAGI[†], *Member*

SUMMARY The goal of this paper is to present a critical survey of existing literature on an omnidirectional sensing. The area of vision application such as autonomous robot navigation, telepresence and virtual reality is expanding by use of a camera with a wide angle of view. In particular, a real-time omnidirectional camera with a single center of projection is suitable for analyzing and monitoring, because we can easily generate any desired image projected on any designated image plane, such as a pure perspective image or a panoramic image, from the omnidirectional input image. In this paper, I review designs and principles of existing omnidirectional cameras, which can acquire an omnidirectional (360 degrees) field of view, and their applications in fields of autonomous robot navigation, telepresence, remote surveillance and virtual reality.

key words: *omnidirectional camera, multiple sensing camera, panoramic view, omnidirectional view, computer vision*

1. Introduction

In humans, peripheral vision informs us that something is going on, however, our peripheral acuity is not good enough to tell us what it is precisely. A central zone in the retina, called the fovea centralis, handles high-quality vision and is used for understanding the detail of an object. The view field of binocular vision is approximately 6 degrees. To recognize the whole shape of an object, peripheral vision with a wide view field is used for combining local fovea images observed by eye movements. This shows that sensing with a wide field of view is one of the important factors for human perception.

For navigation, robot vision must generate a spatial map of its environment for path planning, obstacle (possibly moving) avoidance, and finding candidates of interesting objects. For this purpose, a detailed analysis is not necessary but high speed and rough understanding of the environment around the robot is required. If considered from the standpoint of machine perception, applications such as autonomous navigation, telepresence and so on, need the field of view as wide as possible. Thus, a real-time omnidirectional camera, which can acquire an omnidirectional (360 degrees) field of view at video rate, could be applied in a variety of fields such as autonomous navigation, telepresence, virtual reality and remote moni-

toring. There have been several attempts to acquire omnidirectional images using a rotating camera, a fish-eye lens, a conic mirror and a spherical mirror. Over the past 15 years, researchers in computer vision, applied optics and robotics have investigated a number of papers related to omnidirectional cameras and their applications. In particular, since the mid 1990's, research for applying omnidirectional vision to telepresence, virtual reality, remote monitoring and surveillance have rapidly increased in number.

In this paper, I review designs and principles of existing omnidirectional cameras, which can acquire an omnidirectional (360 degrees) field of view, and their applications in fields of autonomous robot navigation, telepresence, remote surveillance and virtual reality.

2. Omnidirectional Sensing

Approaches for obtaining omnidirectional images can be classified roughly according to structure into the following three types; use of multiple images, use of special lenses and use of convex mirrors. Another criterion of omnidirectional sensor classification is whether it has a single center of projection or not. A single center of projection is an important characteristic of an omnidirectional sensor. It makes easy generation of any desired image projected on any designated image plane possible, such as a distortion free perspective image or a panoramic image, from an omnidirectional input image. This easy generation of distortion free perspective or panoramic images allows the robot vision to use existing image processing methods for autonomous navigation and manipulation. It also allows a human user to see familiar perspective images or panorama images instead of an unfamiliar omnidirectional input image.

2.1 Use of Multiple Images

2.1.1 Rotating Camera System

A straightforward approach for obtaining omnidirectional images is to rotate the camera around vertical axis as shown in Fig. 1 (a) [1]–[3]. The camera rotates around with constant angular velocity. Vertical scan lines are taken from different images and stitched together to form an omnidirectional image. The horizontal

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[†]The author is with the Department of Systems and Human Science, Graduate School of Engineering Science, Osaka University, Toyonaka-shi, 560-8531 Japan.

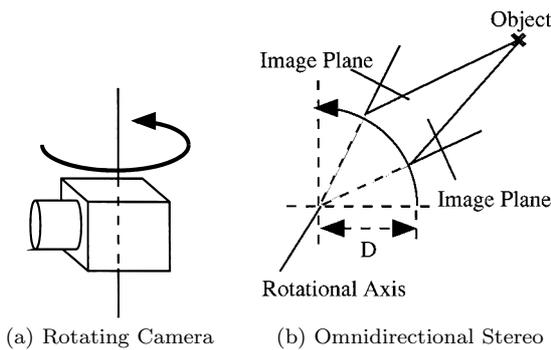


Fig. 1 Rotating camera system.

resolution of an obtained omnidirectional image is dependent not on the camera resolution, but on the angular resolution of the rotation. Therefore, an advantage of this method is that we can acquire a high-resolution omnidirectional image if the camera is controlled precisely. A single center of projection can be made by an exact alignment of the rotating camera axis and the center of the projection. However, this method has a disadvantage that it requires a rather long time to obtain an omnidirectional image, which restricts its use to static scenes but not to dynamic or real-time applications. Barth developed a comparatively fast panoramic imaging system by rotating a vertical line scan camera around a vertical axis [4]. Krishnan and Ahuja developed another idea to improve the performance of the acquisition time of a panoramic image [5]. They rotate the camera around the vertical axis with a regular angle and obtain a panoramic image by connecting a sequence of images at each pan position. A useful advantage of a rotating camera is that omnidirectional range data can be acquired while the camera is rotating if the focal point of the camera is at a certain distance from the rotational axis as shown in Fig. 1 (b) [6], [7]. Two panoramic images are obtained by arranging vertical lines through each slit at the sides of the image sensor. Coarse range data can be acquired by matching similar lines between both panoramic images.

Ishiguro built a multiple vision agent robot system which consisted of four cameras rotating independently of each other. These cameras can be used for either omnidirectional imaging or active vision sensing [10].

In any case, although precise azimuth information is available in the omnidirectional view obtained by a rotating camera, the time-consuming imaging prevents its application to real-time problems. Another disadvantage of rotating cameras is that they require the use of moving parts. It is not suitable for robot application.

2.1.2 Multiple Camera System

One natural method without rotating is the use of multiple cameras. A researcher at Bell lab. AT & T

built a panoramic imaging system by using four conventional TV cameras and four triangular mirrors [11]. Researchers at the Nara Institute of Science and Technology developed a high-resolution omnidirectional stereo imaging system that can take images at video-rate [12]. The sensor system takes an omnidirectional view by a component constructed of the six cameras and a hexagonal mirror, which is designed so that the vertical lens centers of six cameras are located at a fixed point in the mirror images. Therefore, an obtained omnidirectional image satisfies the relation of a single center of projection. Stereoscopic view can be built by aligning two symmetrical sets of the component on the same vertical line. As with Benosman's system [9] described in Sect. 2.3.6, such a configuration reduces the 2-D stereo matching problem to a 1D one. The system can acquire a high resolution and single viewpoint image at video-rate, however, they pointed out that alignment and calibration among each of the six cameras are difficult and not complete yet. Furthermore, it is difficult to build a compact system because acquisition of twelve cameras needs the same number of AD converters or recorders.

2.2 Use of Special Lenses

2.2.1 Fish-Eye Lenses

A fish-eye camera, which employs a fish-eye lens instead of a conventional camera lens, can acquire a wide-angle view as much as a hemispherical view, in real-time. Morita proposed a motion stereo method for measuring the three dimensional locations of lines by mapping an input image on the spherical coordinates [13]. Researchers at the University of Cincinnati applied a fish-eye camera to mobile robot position control by using given targets [14]–[17] and following lines [18], [19]. The camera, however, can obtain good resolution only for the ceiling but poor resolution on the side view and the ground. This means that the image obtained through the fish-eye lens has rather good resolution in the center region but has poor resolution in the peripheral region. Image analysis of the ground (floor) and objects on it is difficult because they appear along the circular boundary where image resolution is poor. Furthermore, it is difficult to generate a complete perspective image, because fish-eye lenses do not have the single center of projection property.

2.2.2 Panoramic Annular Lenses

Fish-eye lenses are a good commercial optics for applying to wide view visualization, but unsuitable for computer vision because they do not satisfy the relation of the single center of projection. Greguss has proposed an optical lens system that can acquire a distortion free panoramic image [20], [21]. The optics of the proposed

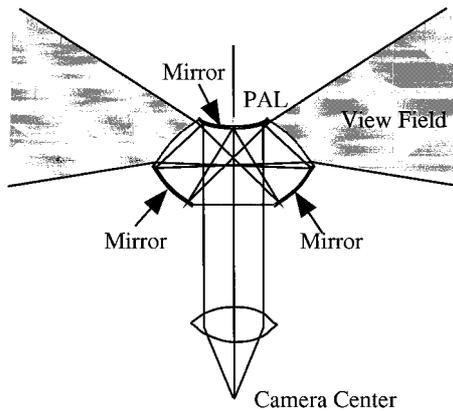
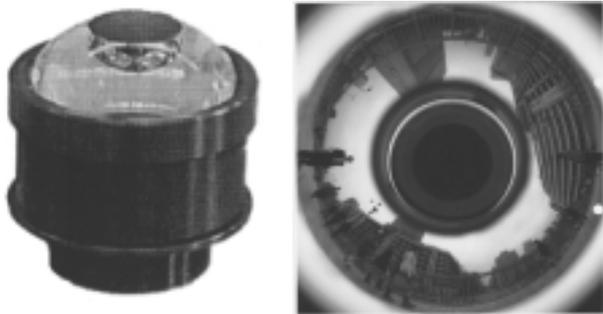


Fig. 2 An optical relation of PAL.

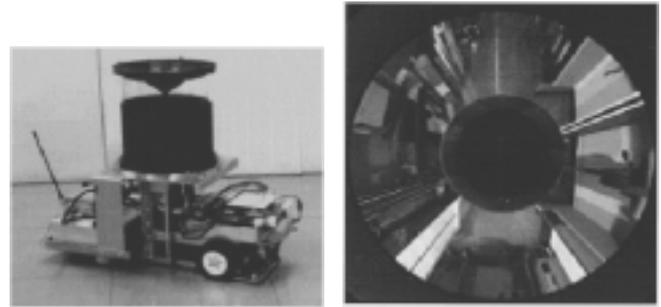


(a) A prototype (b) An example of input image
Fig. 3 PAL.

system, named Panoramic Annular Lens (PAL), consists of a single glass block with two reflective and two refractive planes as shown in Fig. 2. Therefore, PAL optics does not have to be aligned and can be easily miniaturized. On the other hand, other omnidirectional imaging optics has to align several optical elements. Figures 3 (a) and (b) show a prototype of PAL optics and an example of an input image, respectively. Furthermore, PAL can be used for not only all round data acquisition and recording but also panoramic visualization. They reproject the panoramic images recorded by a PAL optic or computed according to the ray tracing laws of the PAL optic. A disadvantage of PAL optics is that it is difficult to increase the view field of tilt angles.

2.3 Use of Convex Mirrors

The basic idea of using a convex mirror is that a camera is pointed vertically toward a convex mirror with the optical axis of camera lens aligned with the mirror's axis. By setting the axis of the camera vertical, we can acquire a 2π view around the camera in real time. However, the anisotropic property of the convex mirror,



(a) A prototype (b) An example of input image
Fig. 4 COPIS.

known as spherical aberration, astigmatism, etc [22], results in much blurring in the input image of the TV camera if the optical system is not well designed. For instance, the curvature of the conical mirror across a horizontal section is the same as that of the spherical mirror. If the camera lens has a large relative aperture, the rays coming through the horizontal section from the object point do not focus at a common point, an effect known as spherical aberration. Curvature of the conical mirror on the vertical section is the same as that of a planar mirror while that on the horizontal section is the same as that of a spherical mirror, hence, the rays reflected through vertical or horizontal planes focus at different points. Thus, to reduce blurring and to obtain a clear picture, one needs an optical system that can cover focus points from both optics. In particular, a careful design is needed when using a single convex mirror.

2.3.1 Conical Mirror

An image obtained by the conical mirror has good resolution in the peripheral. Yagi developed the omnidirectional image sensor, named COPIS, for guiding navigation of a mobile robot, together with an image processing method (See Fig. 4 (a)) [23], [24]. As shown in Fig. 4 (b), it provides a panoramic view around the sensor. Mapping of the scene on to the image by COPIS involves a conic projection causing vertical edges in the environment to appear as lines radiating from the image center. The vertical lines provide a useful cue in a man-made environment, such as room, and corridors, containing many objects with vertical edges; for example, doors, desks and shelves. If a line is vertical, it appears radially in the image plane, as shown in Fig. 5. Thus, COPIS can easily find and track the vertical edges by searching consecutive images for radial edges. A serious drawback of COPIS is that it does not have a focal point (a center of a viewpoint). Therefore, it is impossible to generate a distortion free perspective image from an input omnidirectional image.

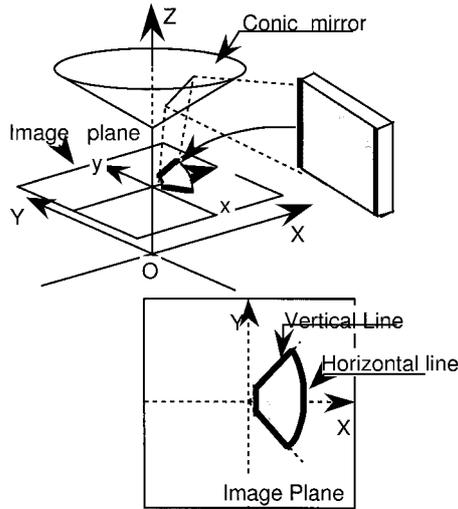


Fig. 5 Conic projection.

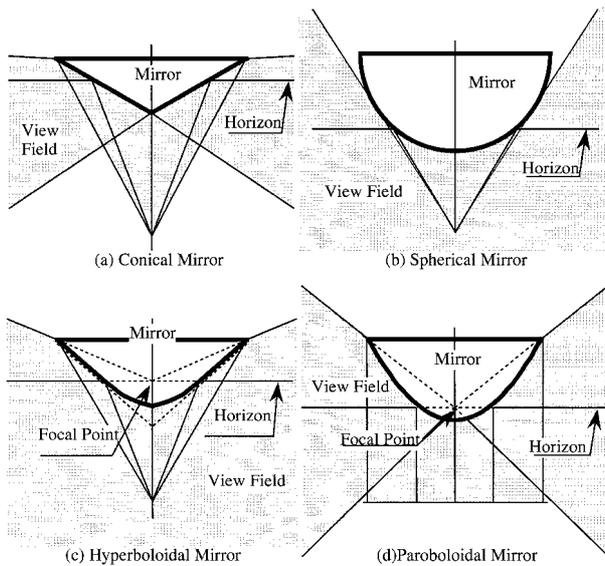


Fig. 6 Field of view.

2.3.2 Spherical Mirror

Similar to the fish-eye lens, an image obtained from spherical mirror has rather good resolution in the center region but poor resolution in the peripheral region. As shown in Fig. 6, a spherical mirror yields an image of the environment around it and its field of view is the widest among sensors with convex mirrors [25], [26]. A wide view is useful for locating the robot along its route. Hong proposed a method for navigating a robot by using appearance change of features on the horizon [25], [27]. However, the geometrical relation of the single center of projection is not satisfied.

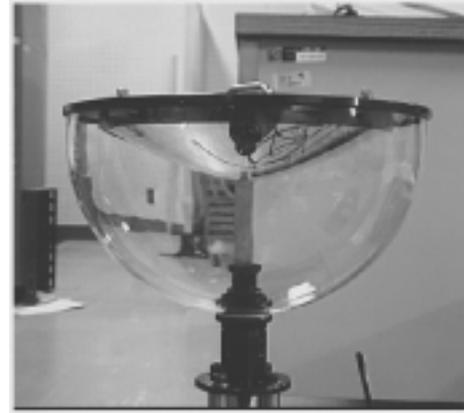


Fig. 7 A prototype of HyperOmniVision.

2.3.3 Hyperboloidal Mirror

A hyperboloidal mirror yields an image of the scene around its axis. We can observe the images generated using a TV camera with its optical axis aligned with the hyperboloidal mirror’s one, as shown in Fig. 6 (c). Yamazawa, et al. have proposed an omnidirectional image sensor using a hyperboloidal mirror. Its name is HyperOmni Vision [28], [30] (See Fig. 7).

Mounting HyperOmniVision on a robot so that optical axis is vertical, we acquire a 360-degree view around the robot. HyperOmni Vision maps a scene onto the image plane through a hyperboloidal mirror and a lens. This mapping is called “hyperboloidal projection.” The hyperboloidal mirror has a focal point, which makes possible easy generation of any desired image projected on any designated image plane, such as a perspective image or a panoramic image, from an omnidirectional input. This easy generation of perspective or panoramic images allows the robot vision to use existing image processing methods for autonomous navigation and manipulation. It also allows a human user to see familiar perspective images or panorama images instead of an unfamiliar omnidirectional input image deformed by the hyperboloidal mirror.

The hyperboloid has two focal points (O_m, O_c). The camera center is fixed at one of the focal points. As shown in Fig. 8 (a), a hyperboloidal mirror yields the image of a point in space on a vertical plane through the point P and its axis. Thus, the point P at (X, Y, Z) is projected onto the image point p at (x, y) such that

$$\tan \theta = \frac{Y}{X} \tag{1}$$

This means that the angle in the image, which can be easily calculated as Y/X shows the azimuth angle θ of the point P in space. Also, it can be easily understood that all points with the same azimuth in space appear on a radial line through the image center. This good feature is the same as a conic or spherical projection.

Therefore, with a hyperboloidal projection, the vertical edges in the environment appear radially in the image and the azimuth angles are invariant to changes in distance and height. Here, the hyperboloidal mirror has a special feature. Let's consider the straight line that connects the point P in the real world and the point that the ray from the object point reflects at the hyperboloidal mirror. This line passes through the focal point O_m regardless of the location of the object point P . It means that the image taken by HyperOmni Vision can be easily transformed to a cylindrical panorama image or a common perspective image, where the origin of the transformed coordinate systems is fixed at the focal point O_m . Therefore, one can obtain an omnidirectional image of the scene on the image plane with a single center of projection O_m . Figures 8(c) and (d) show examples of a panorama image and a perspective image converted from the input omnidirectional image (b).

Let us consider the view field of the hyperboloidal mirror and the resolution of the omnidirectional image obtained. The image obtained using a spherical mirror has rather good resolution in the central region (down view), but it has poor resolution in the peripheral re-

gion (side view). Figure 6(b) shows an example of the view field of the image sensor with a spherical mirror. The view field of HyperOmni Vision is the same as that of a spherical mirror, however, the resolution of HyperOmni Vision is limited by the asymptote of the hyperboloid, thus the upper angle of HyperOmni Vision is the same as that of a conical mirror. The lower angle of conical mirror is limited by the vertex angle of the conic mirror, thus a conic mirror can not look its foot as shown in Fig. 6(c). However, the lower angle of HyperOmni Vision is not limited. HyperOmni Vision has both advantages of conic and spherical mirrors.

2.3.4 Paraboloidal Mirror

Another optic, which has the relation of a single center of projection, was proposed by Peri and Nayar [31], [32]. They use a paraboloidal mirror. A concave paraboloidal optics is frequently used to converge an incoming set of parallel rays such as a paraboloidal antenna. Basically their idea is same as the paraboloidal antenna. In the case of a convex paraboloidal mirror, all rays from the environment reflect at the mirror and run parallel to the rotating axis of the paraboloidal mirror. A straight line that extends the ray from the object point in the environment passes through the focal point regardless of the location of the object point. Therefore omnidirectional imaging with a single center of projection can be done by setting a camera with orthographic projection such as a telecentric lens or zoom lens in front of the paraboloidal mirror. They made a video conference system, named OmniVideo, and generated the perspective image of a desired viewpoint [31]. The view field of the paraboloidal mirror and the resolution of the omnidirectional image are just between the hyperboloidal mirror and the spherical mirror (See Fig. 6(d)). Mathematically, curvatures of these mirrors are represented by

$$Z = \frac{cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}} \quad (2)$$

where z -axis is the rotating axis of the convex mirror, c is the curvature, r is the radial coordinate in lens units and k is the conic constant. The type of the mirror is represented by the conic constant; $k < -1$ for hyperbolas, $k = -1$ for parabolas and $k = 0$ for sphere. Comparative analysis of omnidirectional cameras with convex mirrors was done by Baker and Nayar [33].

2.3.5 Dual Convex Mirrors

A difficulty of design for omnidirectional imaging using mirrors is focusing. The anisotropic property of the convex mirror, known as spherical aberration, an astigmatism, etc., results in much blurring in the input image of the TV camera if the optical system is not well designed. It is, usually, hard to reduce aberration

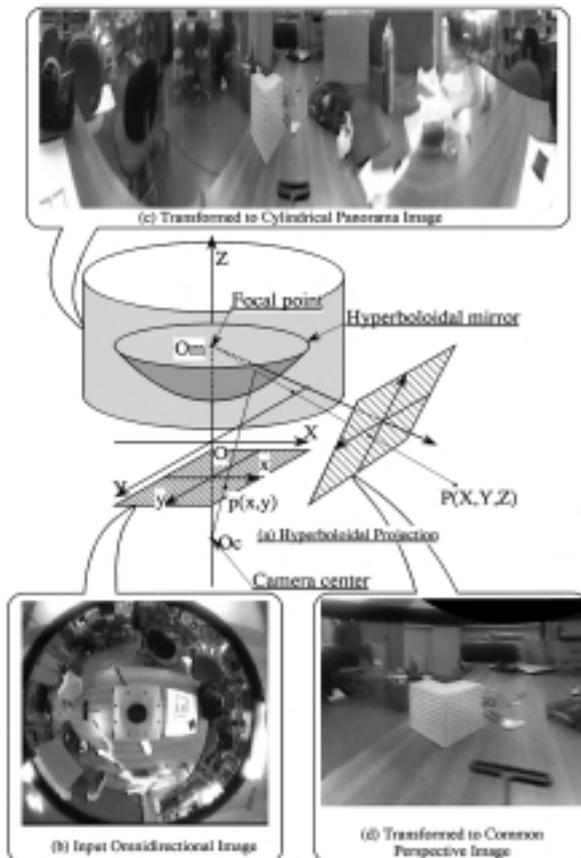


Fig. 8 Hyperboloidal projection and examples of transformed images.

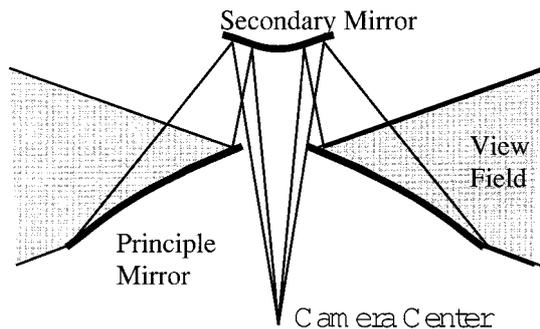


Fig. 9 Optics of dual convex mirror.

by a single reflective mirror. Takeya etc have designed optics like a reflecting telescope, which consists of two convex mirrors, to minimize blurring influence [34]. As shown in Fig. 9, a ray from the object point is reflected at the principle mirror. Then, the reflected ray is reflected at the secondary mirror and focused on the image plane. Curvatures of both mirrors are optimized for minimizing the blur on the image plane. A fundamental configuration of optics is similar with panoramic annular lenses [21], but the optics does not satisfy the important relation of distortion-free.

2.3.6 Omnidirectional Stereo

Ishiguro and Tsuji have proposed an omnidirectional stereo system which uses two panoramic views [6], [7]. Two panoramic images are obtained by arranging vertical lines through each slit at the sides of the image sensor. Coarse range data can be acquired by matching similar lines between both panoramic images. Murray generalized the above approach according to a principle of structure from known motion [39]. Kang recovered the 3 dimensional data of the scene from panoramic images at different points, by using techniques of 8 points structure from motion and multibaseline stereo [40]. Godber developed a panoramic line-scanning range system by using two vertical line scan devices mounted parallel to a vertical axis at a certain distance [8].

Benosman proposed a different type of panoramic line-scanning range system, with two line scan devices having the same rotational axis and arranged as one on top of the other. A single point lies on the same vertical line in both high and low panoramic images, therefore, it reduces the 2-D matching problem to a 1D one [9]. One of the earliest works to measure panoramic ranging system by setting two cameras up and down is done by Saraclik [1]. She used it for determining the size and shape of the room and estimating the location of the robot.

Researchers at the Nara Institute of Science and Technology developed a high-resolution omnidirectional stereo imaging system that can take images at

video-rate as mentioned above [12]. The system can acquire a high resolution and single viewpoint image at video-rate, however, they pointed out that alignment and calibration among each six cameras are difficult and not complete yet. Furthermore, it is difficult to build a compact system because acquisition of twelve cameras needs same number of AD converters or recorders.

A unique panoramic stereo system was investigated by Bogner [26]. He set a bi-convex lobed mirror in front of the camera. A point in the environment reflected at both lobes and focused at different positions on the image plane. Southwell et al have developed a similar panoramic stereo system. Furthermore, they made real-time hardware for remapping an input image to a panoramic image [38]. Disadvantage of these system is that ranging precision is not so good because of a short length of stereo baseline and poor resolution of the inner omnidirectional image.

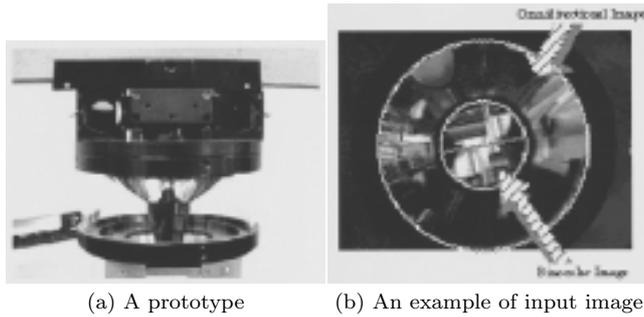
2.4 Multiple Sensing Camera with Omnidirectional View and Local View

Tasks of an autonomous mobile robot can be classified into two categories: navigation to a goal and manipulation of objects or communication with other robots and people at the goal. For navigation, the robot needs to estimate its own location relative to the environment, find unknown obstacles and generate a spatial map of its environment, for path planning and collision avoidance. For this purpose, a detailed analysis of the environment around the robot is required. Omnidirectional sensing is suitable for this purpose as it can view 360 degrees in real time. On the other hand, for object manipulation or human communication, a limited field of view is sufficient but high resolution is required (namely local view) for detailed analysis of an interesting object.

Although a local perspective image can be generated from an omnidirectional camera, resolution of the omnidirectional camera system with a single camera is not sufficient for this purpose since an omnidirectional view is projected onto an image with a limited resolution. An omnidirectional camera with multiple cameras [12] can meet both requirements, however, it has the difficulty of alignment and calibration among the multiple cameras.

To perform each subject effectively, different sensing functions are required for the vision system because their specifications such as image resolution, visual field of the sensor and speed of data acquisition differ. Thus, as with human perception, multiple sensors and hybrid sensing are necessary for performing more tasks, more efficiently and more reliably.

One practical sensor, named the multiple image sensing system MISS, was developed by researchers at Osaka University [30], [35]. They combined two differ-



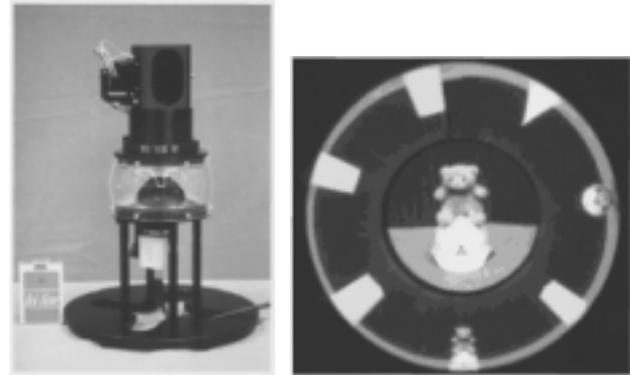
(a) A prototype (b) An example of input image

Fig. 10 Multiple image sensing system MISS.

ent types of optics on a single conventional TV camera; an omnidirectional camera and binocular vision. The omnidirectional camera by using a conic mirror can observe a 360-degree view around the robot in real time. It is suitable for observing global information around the robot, however, the geometric property of the conic mirror results in much distortion in the input image of the camera. On the other hand, although the view field of binocular vision is restricted by the visual angle of the lens, it can acquire fine stereo images, and it is useful for understanding the spatial configuration of the environment. Such multiple image sensing systems can be easily reduced size and weight. Compactness and high performance are also important factors for a mobile robot. Figures 10(a) and (b) show a prototype of the multiple image sensing system MISS and an example input image, respectively. It has three components: optics of an omnidirectional imaging system, a binocular vision adapter and a tilting optical unit for changing the viewing direction of the binocular vision. MISS has a fast tilting unit for viewing an interesting object but not a panning unit since panning can be done by rotating the robot itself. The omnidirectional image obtained by the conic mirror has a better resolution of azimuth angle in the peripheral area than that in the center region. For example, the resolution of azimuth angle is approximately 0.25 degrees in the peripheral area of the image whereas it is approximately 1 degree at the circumference of a 60 pixels radius from the image center. In particular, the central region of the omnidirectional image has poor resolution of azimuth angle. The shape of the conic mirror is improved from a circular cone to a frustum of a cone. The hole in the center region of the frustum is utilized for binocular vision imaging. Binocular vision products an image including stereo images on the center region of a single image plane. The peripheral region of the image plane is used for omnidirectional sensing.

Researchers at Mitsubishi Electric Corp. have proposed a similar multiple imaging sensor for a television communication system, which combines an omnidirectional camera with not binocular vision but a single view camera as shown in Figs. 11(a) and (b) [36].

Researchers at Osaka University have proposed a



(a) A prototype (b) An example of input image

Fig. 11 Multiple imaging sensor.



Fig. 12 Cooperative robot system with omnidirectional vision and binocular vision.

practical multiple imaging system which consists of hyperboloidal omnidirectional camera and active binocular vision which has much degree of freedom for observation [37]. Actually, the system consists of two robots; a main robot with an omnidirectional image sensor and a small robot with an active binocular vision as shown in Fig.12. The small robot is set on a stage of the main robot and can freely change its viewing direction because degree of freedom is an important factor for flexible human-robot interaction. The sensor is used for finding and tracking persons around the robot and focusing attention on an interesting person.

3. Applications

Real-time omnidirectional cameras can be applied to a variety of fields such as autonomous navigation, telepresence, virtual reality and remote monitoring. We will describe examples of applications for robot navigation,

remote viewing and surveillance systems.

3.1 Autonomous Robot

Advantages of omnidirectional sensing is not only wide view angle but also special properties such as invariability of azimuths, circumferencial continuity, periodic characteristic, symmetric characteristic and rotational invariant. Most previous works use these special properties.

Since the vertical lines in space appear as radial lines through the image center in an omnidirectional image, they can be robustly detected. The characteristic that the angle in the image coincides with the azimuth angle of the point in space is also used for efficient estimation of 3-D position of vertical lines.

Yagi has proposed a method for navigating a robot by detecting the azimuth of each object in the omnidirectional image [41]. The azimuth is matched with a given environmental map. The robot can precisely estimate its own location and motion (the velocity of the robot) because the omnidirectional camera can observe a 360 degrees view around the robot, even when all edges are not extracted correctly from the omnidirectional image. Under the assumption of the known motion of the robot, environmental maps of the real scene are successfully generated by monitoring azimuth changes in the image. Several researchers used this property for robot navigation [42]. Delahoche et al have proposed the incremental map building method based on the exploitation of the azimuths data given by an omnidirectional vision and by an odometer [43]. The robot position estimation and map updating are based on the use of an Extended Kalman Filter.

Forward and backward features along the moving direction of the robot show constant azimuth angles while the robot moves straight. By using this property, Ishiguro proposed a strategy, based on path-centered representation, for map generation [45], [46]. Furthermore, environmental representation, called T-Net, for robot navigation was proposed. A T-Net consisting of the paths represents rigid structure and keeps relations between local area (environmental map) [47].

The other important task for navigation is obstacle avoidance. Yamazawa has estimated motion of a robot and detected obstacles using the inverse perspective mapping on the floor [44]. The image transformed an input image to a perspective image, whose optical axis is perpendicular to the floor, is the same as that of inverse perspective mapping on the floor. As apparent shapes of features on the floor are constant in the image, it is easy to establish correspondences among the features in consecutive images by a simple matching method. Thus, motion estimation of the robot and obstacle detection can be done robustly. Yagi has proposed a method where the objects moving along collision paths are detected by monitoring azimuth changes

of vertical edges. Confronted with such objects, the robot changes velocity to avoid collision and determines locations and velocities [24].

While navigating to a goal, omnidirectional views are used for localization, collision avoidance and finding candidates of interesting objects such as landmarks. However, generally, the resolution of the omnidirectional image is not sufficient for further analysis of the object. Effective observation was done by using the multiple image sensing system MISS [35]. Since vertical lines can be robustly detected in the omnidirectional image and their 3-D locations can be obtained by motion stereo of the omnidirectional image sequence, the 3-D location of vertical edges of the unknown object are used for attention control of the binocular vision. Furthermore, by integrating merits of omnidirectional and binocular vision, MISS can generate an environmental map and estimate egomotion of the robot from both sensory information sources without assumption of the exact known motion of the robot [48].

A general technique for estimating egomotion is presented by Nelson and Aloimonous [49]. To estimate egomotion with 6 DOF, this technique requires optical flows on three orthogonal great circles on spherical coordinates. Egomotion is determined by iterative calculation, so the computational cost is high. Gluckman and Nayar have estimated 6 DOF of the egomotion of the camera by using their omnidirectional camera, however, estimation error is not so small [50]. In the case of mobile robot navigation, the egomotion of the robot is usually caused by joggling due to unevenness in the ground plane. Under the assumption of the ground plane motion of the robot, Yagi has robustly estimated the rolling and swaying motions of the robot from omnidirectional optical flows by using special characteristics; 1) The radial component of optical flow in an omnidirectional camera has a periodic characteristic and is invariant to the ground plane motion of the robot. 2) The circumferential component of optical flow has a symmetric characteristic [51]. In addition, the image interpolation technique was used for computation of egomotion from two panoramic images [52].

Memory based navigation is a common approach for visual navigation. The basic operation is the comparison between present sensorial inputs and previous memorized patterns. It is easy to directly relate the robot action and sensory data without the geometrical model. Zheng's robot memorized the side of scene of a route by a panoramic view while it moved along the route [53]. Matsumoto et al.'s robot memorized the whole front view image at reference points along the route for visual navigation [54]. The correspondence between present input images and previous memorized images were established by using a DP matching method and a correlation method, respectively. However, these methods need a large amount of memory for memorizing the route. Therefore, to reduce memo-

rising data, Ishiguro has proposed a compact representation by expanding it into a Fourier series [55]. Each input image is memorized by the coefficients of the low frequency components. His approach is simple and useful for navigation in a real environment. Aihara et al compressed memorized data by KL transformation [56]. Most of these previous memory-based approaches memorize relations between the apparent features (image) at reference points. Apparent features are useful information for finding correspondence between the current position and memorized ones and for estimating orientation of the robot. However, apparent features at the reference point do not directly represent the robot action against the environment and the spatial relation between the environment and the robot. An approach proposed by Yagi, memorized by a series of two-dimensional Fourier power spectrums of consecutive omnidirectional images at the horizon while the robot moves to the goal position [57]. The method can directly represent the temporal and spatial relations between the environment and the robot. In addition, neural network have also been used for scene understanding [58], [59].

From the standpoint of sensor fusion, several researchers integrated the sensor input from an omnidirectional vision sensor and ultrasonic sensor for visual navigation. For Bang, the ultrasonic sensor gives the range, and the vision sensor gives the azimuth of the edge feature [60]; and for Yagi, the vision sensor gives the azimuth of the edge, and the ultrasonic sensor the confirmation of free space between two vertical edges [41]. Wei fused color and edge information from the omnidirectional vision sensor with range data from an ultrasonic sensor on a metric grid-based representation [61].

As omnidirectional view around the robot can be acquired in real-time, it is easy to communicate among multiple robots. Several groups investigated multi agent robot system using omnidirectional cameras [62]–[64]. In addition, Basu and Greguss applied omnidirectional camera system for pipe inspection and endoscopy, respectively [20], [65].

3.2 Communication, Telepresence and Surveillance

A real-time omnidirectional camera could be applied in other fields such as telepresence, virtual reality and remote monitoring. Yagi et al described an autonomous guidance robot system with an omnidirectional camera HyperOmni Vision and ultrasonic range sensors [66]. The system can follow and navigate the observer to the desired position in the environment such as a museum or exhibition. The omnidirectional camera is used for localization of the robot and human tracking.

Peri et al developed the video conference system OmniVideo. They used omnidirectional camera with a paraboloidal mirror which has a property of single cen-

ter of projection, and generated the perspective image of a desired viewpoint [31].

Conventional virtual reality systems based on real images need to memorize panoramic or omnidirectional images at different view points with such images acquired by integrating overlapping images taken by a rotating camera [67], [68]. But they could not be applied to dynamic environments. Onoe et al have developed a telepresence system which realizes virtual tours into a visualized dynamical real world without significant time delay [69], [70]. Omnidirectional video is recorded in advance by a HyperOmni Vision mounted on the roof of a car or the top of a remote controlled robot which are manually driven on a public road and in a hallway, respectively. A viewer's head motion is measured by a 3D magnetic tracker attached to a head mount display. Then the perspective image is transformed from an omnidirectional input image and displayed onto the head-mounted display corresponding to the viewer's head motion in real time. Authors have investigated that multiple users can look around from a single viewpoint in a visualized dynamic real world in different directions at same time. However, the resolution of the transformed perspective image is too poor for monitoring details because the resolution is restricted by that of used camera (CCD). Therefore, development of high-resolution omnidirectional camera is required for such applications. For instance, high-resolution omnidirectional video surveillance systems may wipe the smiles off the faces of bank robbers.

4. Conclusions

In this paper, I have presented an extensive survey of omnidirectional sensing with applications. I have focused with cameras with panoramic or omnidirectional imaging and vision application to autonomous robot navigation, telepresence and virtual reality.

I give below a concise summary followed by conclusions in the same order as the topics in the paper.

Omnidirectional sensing: Approaches for obtaining omnidirectional images can be classified according to structure into the following three types; use of multiple images, use of special lenses and use of convex mirrors. Another criterion of classification of omnidirectional sensing is whether it has a single center of projection or not. Single center of projection is an important characteristic of omnidirectional sensing. It makes easy generation of any desired image projected on any designated image plane possible, such as a distortion free perspective image or a panoramic image, from an omnidirectional input image. This easy generation of distortion free perspective or panoramic images allows the robot vision to use existing image processing methods for autonomous navigation and manipulation. It also allows a human user to see familiar perspective images or panorama images instead of an unfamiliar

omnidirectional input image. The following existing systems can satisfy this property; a rotating camera system, a multiple camera system, use of a panoramic annular lenses, use of a hyperboloidal mirror and use of paraboloidal mirror.

Applications: Real-time omnidirectional cameras can be applied in a variety of fields such as autonomous navigation, telepresence, virtual reality and remote monitoring. I describe examples of applications for map generation, map or landmark based navigation, collision avoidance, egomotion estimation, memory-based navigation, robot navigation, pipe inspection, guidance robot, video conference system, remote viewing and surveillance system.

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Yasushi Yagi received B.E. and M.E. degrees in control engineering, in 1983 and 1985, respectively, and the Ph.D. degree in 1991, from Osaka University. In 1985, he joined the Product Development Laboratory, the Mitsubishi Electric Corporation, where he was working on robotics and inspections. In 1990, he was a Research Associate of Information and Computer Science, Faculty of Engineering Science, Osaka University. From 1993

to 1996, he was a Lecturer of Systems Engineering, Faculty of Engineering Science, Osaka University. In 1996, he was an Associate Professor of Systems Engineering, Faculty of Engineering Science, Osaka University. Since 1997, he has been an Associate Professor of Systems and Human Science, Graduate School of Engineering Science, Osaka University. From June 1995 to March 1996, he was an academic visitor of Department of Engineering Science, University of Oxford. Computer vision and robotics are his research subjects.