# Development of Low-Cost Compact Omnidirectional Vision Sensors and their applications

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**Abstract**
Omnidirectional vision sensors, which have been proposed in 1970, are recently studied in Computer Vision and Multimedia research. This paper discusses features of previously developed omnidirectional vision sensors and their problems in the design. Further, this paper proposes designs of low-cost and compact omnidirectional vision sensors and their new applications. The author considers utilization of omnidirectional vision sensor will be a key issue in Computer Vision and Multimedia applications.

**Keywords**: Omnidirectional vision sensor, Omnidirectional Image, Visual surveillance, Multimedia, Robot vision.

# 1 Introduction

Physical agents living in complex environments, such as humans and animals, need two types of visual sensing abilities. One is to gaze particular objects with a precise but small retina, the other is to look around the environment with a wide but coarse retina. Both visual sensing mechanisms are required for realizing robust and flexible visual behaviors. Especially, the omnidirectional visual information obtained by looking around is necessary to monitor wide areas and to avoid dangerous situations.

On the other hand, cameras developed for TV broadcasting so far have been used for monitoring systems and vision systems of robots in previous computer and robot vision studies. The standard TV cameras, which have a limited visual field of about 30 - 60 degrees, can be used to observe local areas, but it cannot observe wide areas. In order to extend the TV camera applications and develop robust and flexible vision systems like animals, a special cameras which can take omnidirectional visual information is needed.

Such *OmniDirectional Vision Sensors* (ODVSs) (or omnidirectional cameras) is proposed by Rees [10] in the patent submitted to US government in 1970. Then, Yagi [12], Hong [2] and Yamazawa [13] developed again in 1990, 1991 and 1993, respectively. Recently, Nayar [7] has geometrically analyzed the complete class of single-lens single-mirror catadioptric imaging systems and developed an ideal ODVS using a parabola mirror.

In the previous works, the researchers developed the ODVSs for the purposes to prototype themselves and to investigate properties of *the OmniDirectional Images* (ODIs) taken with the ODVSs. Therefore, the developed ODVSs were not so compact and their costs were expensive. This paper discusses features of previously developed ODVSs and their designs, then proposes ideas to solve problems of the previous ODVSs.
Based on the discussions, this paper also shows designs *for low-cost and Compact ODVSs* (C-ODVSs). Further, novel vision systems realized by using multiple C-ODVSs are discussed.

# 2 Previous works

## 2.1 Omnidirectional vision sensors

### The history

The original idea of the ODVSs using a mirror in combination with a conventional imaging system has been proposed by Rees in the U.S. Patent No. 3, 505, 465 in 1970 [10] (see Fig. 1(c)). The idea is to use a hyperboloidal mirror for acquiring an ODI that has a single center of projection. That is, the ODI can be transformed into normal perspective images.

In 1990, progress of computer technologies enabled real-time process of vision data and researchers made again several types of ODVSs as vision systems for computers and robots. Yagi and Kawato [12] made an omnidirectional vision sensor using a conic mirror (see Fig. 1(a)). Hong and others [2] made an omnidirectional vision sensor using a spherical mirror (see Fig. 1(b)). Their purpose was to navigate mobile robots with the ODVSs. The omnidirectional vision of a robot is convenient for detecting moving obstacles around the robot and for localizing itself. Then, Yamazawa and others [13] made again an ODVS by using a hyperboloidal mirror. By utilizing the merit of the hyperboloidal mirror that the ODI can be transformed into perspective images, they proposed a monitoring system with the ODVS.

Nayar and Baker [7] theoretically analyzed imaging systems using mirrors and developed an ideal ODVS using a parabola mirror and a telecentric lens. The ODVS using a hyperboloidal mirror can generate an image taken from a single center of projection in combination with a standard perspective camera. However, it has a demerit that one of the two focal points of the hyperboloid has to be set on the camera center as shown in Fig. 1(c). This demerit makes it difficult to design the ODVS. On the other hand, the imaging system proposed by Nayar and Baker does not have such a demerit since it is using the telecentric lens as shown in Fig. 1(d). As known well, the parabola mirror has a focal point for light which is parallel to the main axis of the parabola mirror. Further, the imaging system is superior in acquisition of non-blurred images and it can eliminate internal reflections of a hollow cylindrical or spherical glass which supports the mirror.

### Another method to acquire ODIs

The ODVSs using mirrors acquire ODIs in real time. However, the resolution is not so high. In order to acquire high resolution ODIs, methods swiveling a camera have been proposed by Sarachik [11] and Ishiguro [3]. The original idea has been given by the panorama camera which takes panoramic scene photographs by swiveling a slit camera. For taking images in static environments, this method is very effective and it is being recently used in multimedia applications. Another problem of the ODVSs is control of camera parameters, especially control of iris. In the method to swiveling a camera, the camera observes local environments, but the ODVS observes a wide environments and the ODI taken with the ODVS contains various intensities. Therefore, the camera used in the ODVS need a wide dynamic range.

As discussed here, the ODVS which can take ODIs has several advantages against the previous vision sensors, but it has also two major demerits, the low resolution and the requirement of a wide dynamic range. With current CCD sensors, it is difficult to obtain high resolution ODIs and its dynamic range is not so wide. We need to improve the CCD itself.

## 2.2 Omnidirectional images

**The history**
The origin of the methods to acquire the ODIs was a panoramic camera which takes omnidirectional photographs though a slit filter attached in the front of the camera lens while swiveling the camera. Zheng and Tsuji [14] used this idea with a CCD camera. The image obtained by arranging image data along a vertical line on the image center is called *Panoramic Image*. They analyzed the features of the panoramic images and proposed applications for mobile robot navigation. When the camera moves along a circular path in the method for acquiring panoramic images, an ODI is obtained. The ODIs is a cylindrical projection and it can contains precise angular information if the camera precisely moves.

Early studies on the ODIs were mainly done by Nelson, Zheng and Ishiguro. Zheng and others [14] proposed a *Circular Dynamic Programming* for identifying features between two ODIs. The circular dynamic programming robustly finds correspondences by iterating a conventional dynamic programming method based on the periodicity of the ODIs. Ishiguro and others [3] proposed two types of *Omnidirectional Stereo*. By rotating a camera along a circular path, motion pallarax is observed by tracking feature points on the image plane and omnidirectional range information can be obtained. This stereo method does not have any blind spots outside the circular path. Another stereo is realized with two ODIs taken at different locations. Although the method using two ODIs has a problem of feature identification, it can obtain more precise omnidirectional range information.

**The optical flow field**
The flow field of ODIs is also interesting properties. Nelson and others [8] analyzed the flow field of the Gauss sphere retina and proposed methods to estimate camera motion parameters. On the other hand, Ishiguro and others focused upon just the FOEs and proposed methods to precisely navigate mobile robots [3] and to estimate robot motion parameters [4] based on the important feature of the ODIs that two FOEs, FOE and FOC, are observed in the flow field and the angle between them is 180 degrees.

**The periodicity**
An ODI is a periodical signal around the rotation axis. That is, Fourier transform of the ODI does not require window functions. This means the transform is precise and efficient data compression is enable for the ODIs. By Fourier transform, an ODI is divided into magnitude components and phase components. The magnitude and phase components depend on location of the ODVS and the direction of the reference axis of the ODVS, respectively.

Based on the magnitude and phase components, mobile robot navigation that does not refer to the internal sensor data can be realized [5]. First, the robot moves randomly in the environment and takes ODIs at various locations. Then, it executes Fourier transform for the ODIs and divides them into magnitude and phase components. By comparing the magnitude components of the ODIs, positions where the ODIs are taken can be estimated. The positions cannot be precisely estimated but it is topologically correct. The map that represents the topological positions of the observation points can be used for the robot navigation. Here, in order to use the map, the robot needs to know the its direction against the environment. The direction can be estimated from the phase components of the ODIs. That is, the robot can memorize locations as a map and navigate itself by using it only with the ODVS.

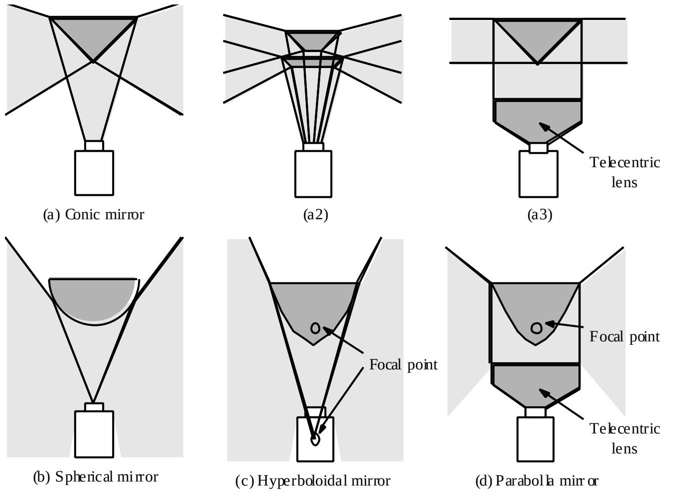


Figure 1: Omnidirectional mirrors

# 3 Designs of ODVSs

An ODVS is consists of two major components, a mirror which is symmetrical on rotation and an apparatus which supports the mirror. This section discusses merits and demerits on various designs of the two major components of previously developed ODVSs

## 3.1 Designs of mirrors

There are four types of the previously developed mirrors as shown in Figs. 1. Merits and demerits of the mirrors can be discussed from the following aspects:

Whether the mirror can generate an ODI which has a single center of projection (The ODI can be transformed to normal perspective images).

- How small the astigmatism of the optical system consisting of the mirror and a camera is.
- Whether the optical system uses a standard lens and camera.
- How large the vertical viewing angle is.

**Spherical mirror**
Generally, mirrors are made by depositing aluminum film onto a shaped glass. An important issue in the machining is how easy it is to process the glass. A normal lens is a part of a spherical glass, therefore it is easy to make spherical mirrors with the conventional lens process.

In addition to the merit in the machining, another important merit of the spherical mirror is the astigmatism. Comparing with other mirrors as shown in Figs. 1, the astigmatism is rather small since it can be considered as a flat surface near the optical axis of the camera (of course, it is not small in the peripheral). Further, as discussed in the next section, the spherical mirror does not require a long focal depth for acquiring a focused image. That is, the spherical mirror is superior to making low cost ODVSs which can acquire clear images.

However, the ODI acquired with the spherical mirror does not have a single center of projection and cannot be transformed into normal perspective images. The vertical viewing angle is also so large. Although the ODVS can observe over the horizontal plane, the image is distorted in the peripheral of the ODI.

### Conic mirror

A conic mirror is second to the spherical mirror in the easy machining. The feature of the conic mirror is to have normal reflection in the vertical direction. Therefore, it is easy to combine several mirrors. For example, stereo images can be acquired as shown in Fig. 1(a2). Further, the conic mirror enables a special optical system which observes horizontally in combination with a telcentric lens as shown in Fig. 2(a3).

However, the astigmatism is large and the ODI cannot be transformed into normal perspective images. Further, it needs a long focal depth to acquire focused ODIs. A spherical mirror has a focal point like a normal lens, on the other hand, the conic mirror does not have it and needs a lens which characteristics are near to them of a pin hole (the detail is discussed in the next section).

### Hyperboloidal mirror

The machining of a hyperbolidal mirror is difficult, but it has a single center of projection. An ODI taken with the hyperboloidal mirror can be transformed to normal perspective images, cylindrical images, and so on. Further, if the curvature is small, the astigmatism is not so large.

The hyperboloidal mirror is the best for optical systems using normal cameras. However, it has a serious demerits that the design is not so flexible since the focal point of the hyperboloid needs to be set on the camera center.

### Parabola mirror

An ideal optical system can be realized with a parabola mirror and telecentric lens. The optical system has a single center of projection and the astigmatism is small for a small curvature. Further, the parabola mirror is the best for acquiring focused ODIs.

The telecentric lens also brings two merits. Since the projection is orthogonal, the distance between the mirror and the lens can be set flexibly in the design and the lens eliminates internal reflections of a glass cylinder or sphere which supports the mirror (the detail is discussed in the next subsection).

However, it is a demerit for making a compact and low-cost system to use the telecentric lens. The telecentric lens is generally expensive and the size is not so small.

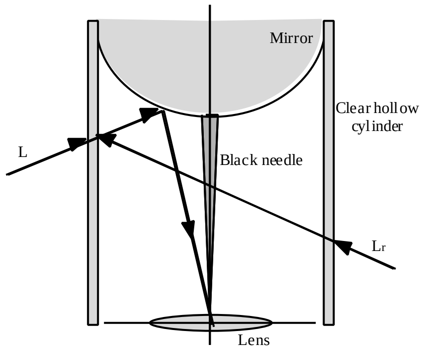



Figure 2: Elimination of the internal reflections with a black needle

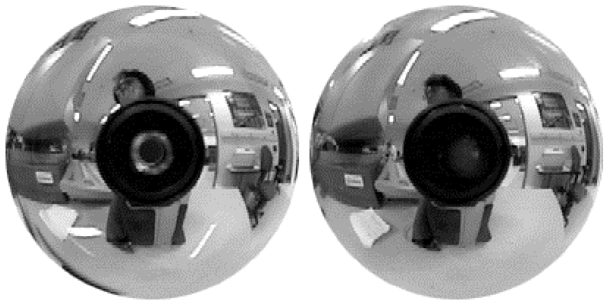


Figure 3: Experimentation on internal reflections

Table 1 summarize features of the four mirrors. In the table, the focal depth means the range in which the camera should be able to acquire non-blurred images for the mirror. The vertical viewing ranges are based on our experience. -90 degrees and 0 degrees are directions to observe downward and horizontally, respectively. From the view point of applications, a summary is given as follows:

**[Spherical mirror]**

ODVSs using spherical mirrors are suitable for observing objects which locate in the same height as the ODVSs or acquiring clear ODIs of objects locating under the ODVS. Further, since the cost of machining is low, the mass production can be performed.

| | Machining cost | Astigmatism | Focal depth | Vertical viewing range | Single center of projection | Lens |
|---|---|---|---|---|---|---|
| Spherical mirror | Low | Small | Short | -90 … 10 | No | Normal |
| Conic mirror | Low | Large | Long | -45 … 45 | No | Normal |
| Hyperboloidal mirror with a small curvature | High | Small | Short | -90 … 10 | Yes | Normal |
| Hyperboloidal mirror with a large curvature | High | Large | Long | -90 … 45 | Yes | Normal |
| Parabola mirror with a small curvature | High | Small | Short | -90 … 10 | Yes | Telcentric |
| Parabola mirror with a large curvature | High | Large | Short | -90 … 45 | Yes | Telcentric |

Table 1: Comparison between various mirrors

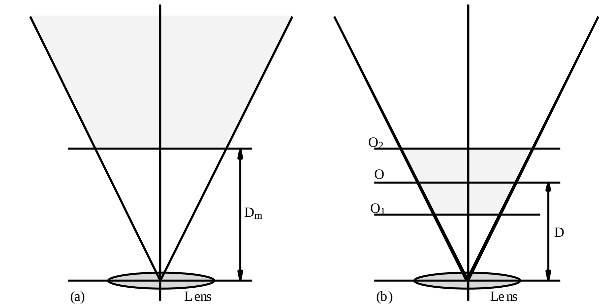


Figure 4: Focal depth of a camera

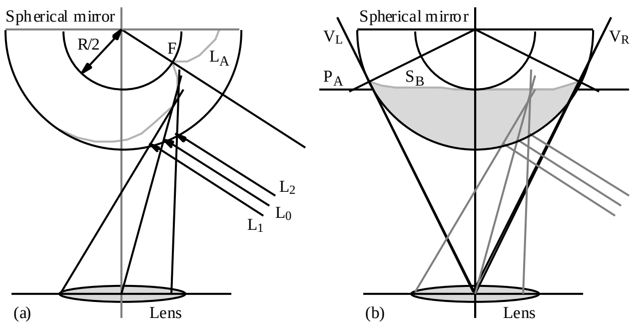


Figure 5: Focusing on a spherical mirror

**[Conic mirror]** The conic mirror is useful for acquire ODIs of which vertical visual field is limited.

**[Hyperboloidal mirror]**
In combination with a normal lens, the mirror can generate ODIs which can be transformed to normal perspective images. Therefore, it can be applied to monitoring applications.

**[Parabola mirror]**
The machining cost and the cost of the telecentric lens is, generally, high. However, it is an ideal optical system to acquire ODIs.

## 3.2 Design of supporting apparatuses

Another important component of the ODVS is apparatus which supports the mirror as shown in Fig. 1. For the supporting apparatus, there are two requirements:

1. Eliminating internal reflections by the supporting apparatus.
2. Precise surface finish for acquiring non-distorted ODIs.

In previous works, the following three types of the supporting apparatuses were used:

- Clear cylinder made from glass or plastic
- Clear sphere made from glass or plastic
- Clear cylinder/sphere and a telecentric lens

Many types of ready-made clear hollow cylinders made from glass and plastic are available and the surface precision is high. However, the clear hollow cylinder has a serious problem of internal reflections as shown in Fig. 2. One of the ideas to solve this problem is to use a telecentric lens. Since the optical array of the telecentric lens is parallel to the surface of the cylinder, there is no projections of the internal reflections on the ODI.

Another idea is to support the mirror with a clear hollow sphere of which center locates on the focal point of the mirror. This idea has been proposed by Yamazawa and others [13] and applied to an ODVS using a hyperboloidal mirror. However, the problem is in the precision of the surface. Generally, precise machining for the clear hollow sphere is very difficult.

As discussed here, there are two solutions: clear hollow cylinder with a telecentric lens and clear hollow sphere with a hyperboloidal mirror. But, these can be applied to particular ODVSs. More general idea is needed. The next section proposes such an idea.

# 4 Trial production of C-ODVSs

Based on the discussion in the previous sections, this section proposes low-cost and compact ODVSs (C-ODVSs). The author considers ODVSs which can be used in various applications should satisfy the following requirements:

1. Small size including the camera
2. Low machining cost
3. Small astigmatism
4. Short focal depth
5. Using standard lenses and cameras

For the requirements, the authors originally developed the following two methods:

- General optical mechanism to eliminate the internal reflection.
- A method to make mirrors from metal.

## 4.1 Eliminating internal reflections

From the view point of precision, the clear hollow cylinder is the best, however, it has a problem of internal reflections. And further, utilization of the telecentric lens make the size of the ODVS large and the cost is also high.

An idea to eliminate internal reflections by the clear hollow cylinder is to equip a black needle along the main axis of the cylinder. As shown in Fig. 2, the light which is reflected by the internal surface of the clear hollow cylinder and then passes through the camera center closes the main axis of the cylinder. Therefore, the black needle equipped along the main axis completely eliminates internal reflections. The idea is very simple but very effective as shown in Figs. 3. In Fig. 3(a), several double projections of fluorescent lamps are observed. On the other hand, the ODI taken with the black needle does not have such double projections as shown in Fig. 3(b).

## 4.2 Making mirrors from metal

Standard process to make mirrors from glass is iterative polishing of a glass block and coating with aluminum. Therefore, it takes much time and cost for making a mirror of which curvature is large.

Another method is to make the mirrors from metal by using a precise NC machine. The major problem in this case is the precision of the surface. In order to make a precise mirror, careful selection of metal materials and control of the NC machine are required. With several trials, the author and others have determined to use brass as the metal material and obtained empirical knowledge to precisely control the NC machine.

After the machining with the NC machine, coating is performed. Aluminum coating is precise but expensive. Therefore, in spite of aluminum coating, the author has performed iterative thin chrome plating and determined the number of the iteration through many trials.

## 4.3 Focusing of ODVSs

For previously developed ODVSs, cameras which have a short focal length are used in order to focused ODIs. That is, the mirror is attached with the closest distance Dm on condition that the camera acquires focused images for objects locating at infinity, as shown in Figs. 4(a). And the minimum size of the ODVSs is restricted with the closest distance Dm. For example, it is difficult to find a ready-made camera which has the closest distance of 10 cm.

For making smaller ODVSs, the mirror needs to be attached with a shorter distance. Actually, the focal depth (or object depth) of standard lens is not zero, and if it is possible to set all focal planes of the mirror for all objects locating with various distances in the focal depth $O_1$-$O_2$, the ODVS can acquire focal ODIs with the mirror attached with a close distance D from the camera as shown in Fig. 4(b).

Let us consider the focal planes of a spherical mirror. As well known, the parallel light is focused with the spherical mirror but the focal point is not single. The focal point describes an epicycloid $L_A$, which pass through the point F, for the parallel light $L_0$, $L_1$ and $L_2$ in a direction as shown in Fig. 5(a). In Fig. 5(a), R is the radius of the spherical mirror. Therefore, images of all objects locating various locations are focused within the gray region encircled with the surface of the spherical mirror and the surface $S_B$ as shown in Fig. 5(b). In conclusion, if the focal depth covers the gray region, the camera focuses clear images for all objects through the spherical mirror. Especially, in the case of the spherical mirror, the gray region almost locates between the horizontal plane on $P_A$ and the surface of the spherical mirror. In cases of the hyperboloidal and parabola mirrors with little curvatures, they can be considered to be identical with the spherical mirror. However, in cases of the conic, hyperboloidal and parabola mirrors with large curvatures, the gray region is extended along the surfaces of the mirrors and the camera needs a long focal depth for focusing clear ODIs. In order to making compact ODVSs, the spherical mirror is the best selection.

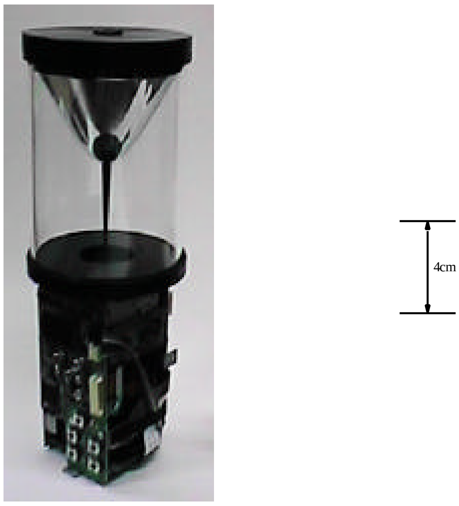
Proper camera selection is also an important issue. For making compact ODVSs, a cameras which has a short distance of Dm shown in Fig. 4(a) is required. As such a camera, SONY EVI-330 which is a camera component of a standard handy video recorder SONY HandyCam is one of the proper selections. Although the size is not so compact the distance Dm is less than 10 cm. In order to make more compact ODVSs, more compact cameras are required. Recently, many such cameras are available, but their distance Dm is not sufficiently short. For designing ODVSs with such compact cameras, the spherical mirrors can be used with the idea shown in Fig. 4(b).

## 4.4 Developed C-ODVSs

Based on the above discussions, the author have developed four types of C-ODVSs as shown in Fig. 6. Each of the C-ODVSs has the following features.

**[C-ODVS with a hyperboloidal mirror]**
The second from the left in Fig. 6. A hyperboloidal mirror with a large curvature is used. The vertical viewing range is about 270 degrees. A black needle is attached for eliminating the internal reflections. It is designed for SONY EVI-330 and the overview is

Figure 6: Four types of C-ODVs




(a) C-ODVS with a hyperboloidal mirror (b) Ultra C-ODVS with a spherical mirror

Figure 7: C-ODVs with cameras

shown in Fig. 7(a).

**[C-ODVS with a spherical mirror]**
The third from the left in Fig. 6. It is designed for SONY EVI-330. The height and diameter are 15 cm and 7cm, respectively.

**[Ultra C-ODVS with a hyperboloidal mirror]**
The first from the left in Fig. 6. The curvature of the mirror is small for acquiring clear images and the viewing range is about 190 degrees. It is designed for a camera of RF Co. Ltd. The height and diameter are 3 cm and 4 cm, respectively.

**[Ultra C-ODVS with a spherical mirror]**
The fourth from the left in Fig. 6. It is designed for a camera of RF Co. Ltd. and the overview is shown in Fig. 7(b).

Fig. 8(a) and (b) show ODIs taken by the C-ODVS with a hyperboloidal mirror and the C-ODVS with a spherical mirror, respectively.

# 5 Applications of ODVSs

## 5.1 Multimedia applications

Figure 9: Distributed vision system for recognizing human behaviors

In the recording of round table meeting scenes, the previous camera cannot acquire images which contains faces of all participants. The ODVS attached at the center of the table makes it possible. Nishimura and others [9] used the ODVS for recognizing human gestures in round table meetings. Their approach can be extended for several applications. For example, indexed database of round table meetings with the simple human behavior recognition and tele-conference systems which enable communication between groups can be considered.

## 5.2 Monitoring applications

The ODVS with a hyperboloidal or parabola mirror can be used in spite of the conventional camera system using a pan-tilt gaze controller. The ODI taken with the ODVS can be transformed into perspective images taken in any directions. Although there exist several problems, especially the resolution of the images, the ODVSs can be used as gaze control camera systems. The systems with the ODVSs is very compact and it can change the gaze direction in real time with a powerful computer.

The ODVSs have a demerit of the low image resolution, therefore the author considers ODVSs should not be used as TV cameras, but as vision sensors. As an application in which ODVSs are used as vision sensors, a moving object tracking system using multiple ODVSs can be considered [6]. Fig. 9 shows an overview of the system.

The use of multiple ODVSs solves the following problems of vision systems with the wide viewing range.

1. The wide environment can be covered with a smaller number of ODVSs.
2. The ODVSs can be observed each other, therefore the relative positions of the ODVSs can be precisely estimated with error minimization methods, such as a least square method.
3. Extended trinocular vision, namely {\it N-ocular vision} can be realized. With the N-ocular vision, multiple ODVSs can robustly identify objects between the ODIs.

The robust and real-time tracking system can be developed by using constraints of the environment in addition to the above fundamental merits. For example, this system can be used for human behavior recognition. Previous research approaches for human behavior recognition focused upon rather local behavior, such as facial expressions and gestures. The system which recognizes global behaviors of humans in a room gives useful information to the previous system for recognizing local behaviors. In the case where ODVSs are used as vision sensors, the approaches to use many ODVSs are promising and C-ODVSs are useful for such applications which require many number of ODVSs.

## 5.3 Mobile robot navigation

Other major applications of the ODVS are in mobile robot navigation. The wide viewing range is useful for predicting collisions with moving obstacles. Yagi and others [12] proposed a method to avoid collisions with moving obstacles by continuous observation with the ODVS. In the case where both the robot and obstacles move along linear paths with constant velocities and they collide each other, the viewing angle from the robot to the obstacles is constant. By feeding the viewing angle to the steering, the robot can avoid the collision.
The ODIs are also useful for memorizing particular locations. Hong and others [2] proposed a method for image-based homing. The robot memorizes the goal location with a vertical edge image observed by the ODVS. Then, the robot goes from a distant location toward the goal by comparing input images with the memorized image. This approach is interesting as a method which shows rich properties of ODIs.

Further, ODVSs can be used for other functions of robots, such as pose stabilization and so on. The author considers the most serious problem of previous vision-guided mobile robots is in the limited visual field of the vision sensors. The ODVSs are expected as key tools for solving such difficulties.

# 6 Conclusion

In this paper, the author has discussed features of previously developed omnidirectional vision sensors and proposed designs of low-cost and compact ODVSs. Further, their novel applications have been briefly discussed. Although a few problems are still remained for the ODVSs, the author considers utilization of omnidirectional vision sensor will be a key issue in Computer Vision and Multimedia applications. The detailed information on the ODVSs is in http:// www.pluto.dti.ne.jp/~accowle1/index.html.

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# References

1. D. H. Ballard, Reference frames for animate vision, Proc. Int. Joint. Conf. Artificial Intelligence, pp. 1635-1641, 1989.
2. J. Hong, and others, Image-based homing, Proc. Int. Conf. Robotics and Automation, 1991.
3. H. Ishiguro, M. Yamamoto and S. Tsuji, Omni-directional stereo, IEEE Trans. Pattern Analysis & Machine Intelligence, Vol. 14, No. 2, pp. 257-262, 1992.
4. H. Ishiguro, K. Ueda and S. Tsuji, Omnidirectional visual

information for navigating a mobile robot, Proc. IEEE Int. Conf. Robotics and Automation, pp. 799-804, 1993.
5. H. Ishiguro and S. Tsuji, Image-based memory of environment, Proc. Int. Conf. Intelligent Robots and Systems, pp. 634-639, Nov. 1996.
6. H. Ishiguro, T. Sogo and T. Ishida, Human behavior recognition by a distributed vision system, Proc. DiCoMo Workshop, pp. 615-620, 1997. (in Japanese)
7. S. K. Nayar and S. Baker, Catadioptiric image formation, Proc. 1997 DARPA Image Understanding Workshop, pp. 1431-1437, 1997.
8. R. C. Nelson and J. Aloimonos, Finding motion parameters from spherical flow fields, Proc. Workshop on Computer Vision, pp. 145-150, 1987.
9. T. Nishimura, T. Mukai and R. Oka, Spotting recognition of gestures performed by people from a single time-varying image, Proc. Int. Conf. Robots and Systems, pp. 967-972, 1997.
10. D. W. Rees, Panoramic television viewing system, United States Patent No. 3, 505, 465, Apr. 1970.
11. K. Sarachik, Characterizing an indoor environment with a mobile robot and uncaliblated stereo, Proc. Int. Conf. Robotics and Automation, pp. 984-989, 1989.
12. Y. Yagi and S. Kawato, Panoramic scene analysis with conic projection, Proc. Int. Conf. Robots and Systems, 1990.
13. K. Yamazawa, Y. Yagi and M. Yachida, Omnidirectional imaging with hyperboloidal projection, Proc. Int. Conf. Robots and Systems, 1993.
14. J. Y. Zheng and S. Tsuji, Panoramic representation for route recognition by a mobile robot, Int. J. Computer Vision, Vol. 9, No. 1, pp. 55-76, 1992.