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Coaxial optical structure for iris recognition from a distance

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Abstract. Supporting an unconstrained user interface is an important issue in iris recognition. Various methods try to remove the constraint of the iris being placed close to the camera, including portal-based and pan-tilt-zoom (PTZ)-based solutions. Generally speaking, a PTZ-based system has two cameras: one scene camera and one iris camera. The scene camera detects the eye's location and passes this information to the iris camera. The iris camera captures a high-resolution image of the person's iris. Existing PTZ-based systems are divided into separate types and parallel types, according to how the scene camera and iris camera combine. This paper proposes a novel PTZ-based iris recognition system, in which the iris camera and the scene camera are combined in a coaxial optical structure. The two cameras are placed together orthogonally and a cold mirror is inserted between them, such that the optical axes of the two cameras become coincident. Due to the coaxial optical structure, the proposed system does not need the optical axis displacement-related compensation required in parallel-type systems. Experimental results show that the coaxial type can acquire an iris image more quickly and accurately than a parallel type when the stand-off distance is between 1.0 and 1.5 m. [DOI: 10.1117/1.3582850]

Subject terms: iris recognition from a distance; pan-tilt-zoom-based iris recognition system; coaxial optical structure.

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1 Introduction

Biometrics is a human authentication technique based on human physiological or behavioral features, such as the iris, face, fingerprint, signature, and gait. It has advantages over other authentication methods, such as passwords and radio-frequency identity (RFID), because there is no need for users to remember or possess a token. Iris recognition is one of the most reliable methods among the biometric recognition techniques due to its high level of accuracy.[1]

Although iris recognition has great potential, conventional iris recognition systems have significant constraints in the image-acquisition process, including a short stand-off distance, small capture volume, and long residence time.[2,3] To solve these problems, some researchers have proposed unconstrained systems for iris image acquisition. These can be divided into two categories:[2] portal-based systems[4–6] and pan-tilt-zoom (PTZ)-based systems.[7–13] The portal-based system looks like a metal detector used by airport security, on which several high resolution mega-pixel cameras are installed. When a person passes through the portal at a normal walking speed, the cameras capture the assigned area, and one of them tries to acquire a good-quality iris image.[4] This removes some of the constraints by capturing the iris image while the person is moving. However, the capture volume of the system is still small and the total system is inevitably large in the physical dimension. A PTZ-based system installs a camera equipped with a zoom lens on a pan-tilt unit (PTU), and uses an additional camera to detect and track the user. The camera on the PTU is called an iris camera and the additional camera is called a scene camera.[7] When a user stands within the capture volume, the system directs the iris camera to the user's eye using the PTU, and captures a high-resolution iris image using a zoom lens. This system mainly aims at improving the user's convenience by providing a relatively large capture volume.

Existing PTZ-based systems can be divided into two types, separate types[7–10] and parallel types,[11–13] according to the way in which the iris camera and scene camera are combined.[2] The separate type consists of a fixed scene camera and a PTU-mounted iris camera. However, even when the scene camera precisely detects the user, the user's three-dimensional (3D) location could not be determined if the distance between the scene camera and the user is not measured. Therefore, the iris camera needs to use additional information, such as the user's face size, to reduce ambiguity, and then needs to search for the user's eye within a certain range of direction. To make searching easier, some systems use light-stripe projection (LSP)-based range estimation,[7] stereo vision-based range estimation,[8,9] and multiple cameras with a hierarchically ordered field of view (FOV).[10] The parallel type installs two cameras on a PTU, with their optical axes aligned in parallel. Although the scene camera and the iris camera are directed by the PTU simultaneously, they cannot

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be very close together, which means the target object (i.e., the iris) is located in different positions on the iris camera's image, depending on how far away the object is. As the FOV of the iris camera is very narrow and the distance to the user is relatively small, we cannot ignore even a small displacement of the two cameras.[12] In particular, the estimated distance to the user inevitably contains errors, which we need to compensate for by searching within a candidate zone.

This paper proposes a PTZ-based iris recognition system, in which the iris camera and the scene camera are combined in a coaxial optical structure. The proposed system is similar to the parallel type in that the two cameras are installed on a PTU. However, the two cameras are placed orthogonally, and a cold mirror is inserted between them such that the optical axes of the two cameras become coincident. The optical path of the iris camera passes through the cold mirror, while the optical path of the scene camera is folded perpendicularly by the cold mirror. Due to the coaxial optical structure, the proposed system does not need optical axis displacement-related compensation: when the scene camera detects the user's eye and directs its optical axis to the eye, the optical axis of the iris camera is directed to the user's eye simultaneously. Since the proposed system installs illuminators on the PTU, the FOV of the illuminator could be reduced. Therefore, the power consumption and size of the illuminator could also be reduced. The proposed system has three advantages over existing PTZ-based systems. First, direction control of the iris camera is simple and robust, because it does not use the distance to the user. Second, the system can be implemented using two low-cost cameras. Since the iris camera can be directed precisely to the user's eye, the camera's FOV does not need to be wide therefore, a high-resolution camera is not required. Finally, the calibration between the scene camera and iris camera is intuitive and easy.

2 Hardware Structure and Specifications

To show the advantages of the proposed system, we implemented a PTZ-based iris recognition system, which could operate both as a coaxial type (coaxial mode) and a parallel type (parallel mode) system. We installed one scene camera, one iris camera, and two illuminators on a PTU. The iris camera is equipped with a telephoto zoom lens. The zoom and focus position of the lens is controlled by a small step motor. When the system operates in coaxial mode, the scene camera faces upwards, and its light path is folded by a cold mirror, as shown in Fig. 1. When the system operates in parallel mode, the scene camera points in the same direction as the iris camera, as shown in Fig. 2. The system is designed so that it has the same capture volume, both in parallel and coaxial mode. Figure 3 shows the capture volume specifications: width = 0.9 to 1.2 m, height = 0.7 to 0.9 m, and depth = 0.5 m (i.e., the stand-off distance = 1.0 to 1.5 m). The system can be switched between coaxial and parallel mode by adding a cold mirror and rotating the scene camera.

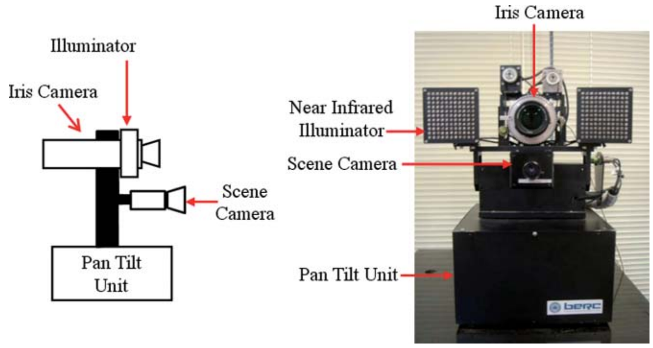

Fig. 2 Hardware structure of parallel-type system.

The scene camera uses a charge-coupled device (CCD) with 640 × 480 resolution, video graphics array (VGA)-grade, and captures visible light range images. The scene camera is equipped with a fixed focal length lens, with a focal length of 6 mm. The iris camera uses a CCD with 1024 × 768 resolution, extended graphics array (XGA)-grade, and captures near infrared (NIR) range images. The iris camera is equipped with a telephoto zoom lens, with a focal length that can change between 50 and 250 mm. To acquire a good quality iris image (i.e., 200 pixel/cm)[14] when the stand-off distance is between 1.0 and 1.5 m, the system controls the focal length of the zoom lens in the range between 85 and 127 mm. The cold mirror used in the proposed coaxial type system reflects visible light with a reflectance rate above 90%, and passes NIR light with a transmission rate above 85%.[15]

3 Operating Software

3.1 *Software Architecture*

As shown in Fig. 4(a), the operating software of the proposed system consists of five phases: face detection, eye detection, pan-tilt control, distance estimation, and zoom-focus control. In the case of the parallel type system, we would have to add

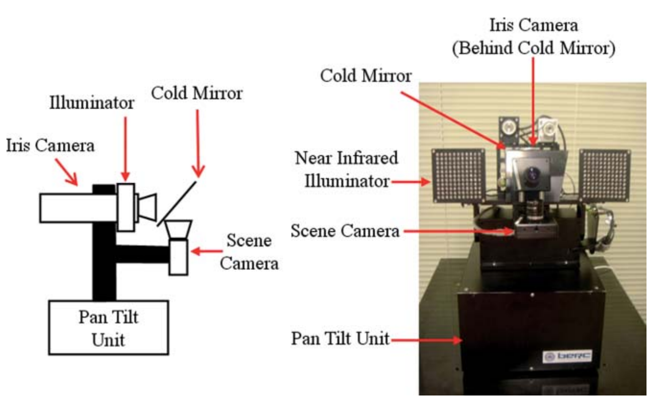

Fig. 1 Hardware structure for the coaxial-type system.

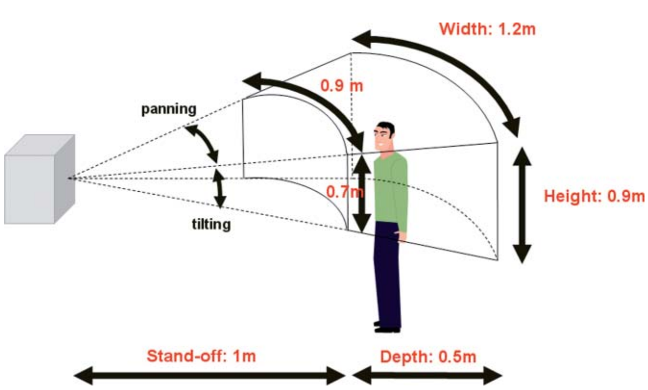

Fig. 3 Capture volume of the iris recognition system.

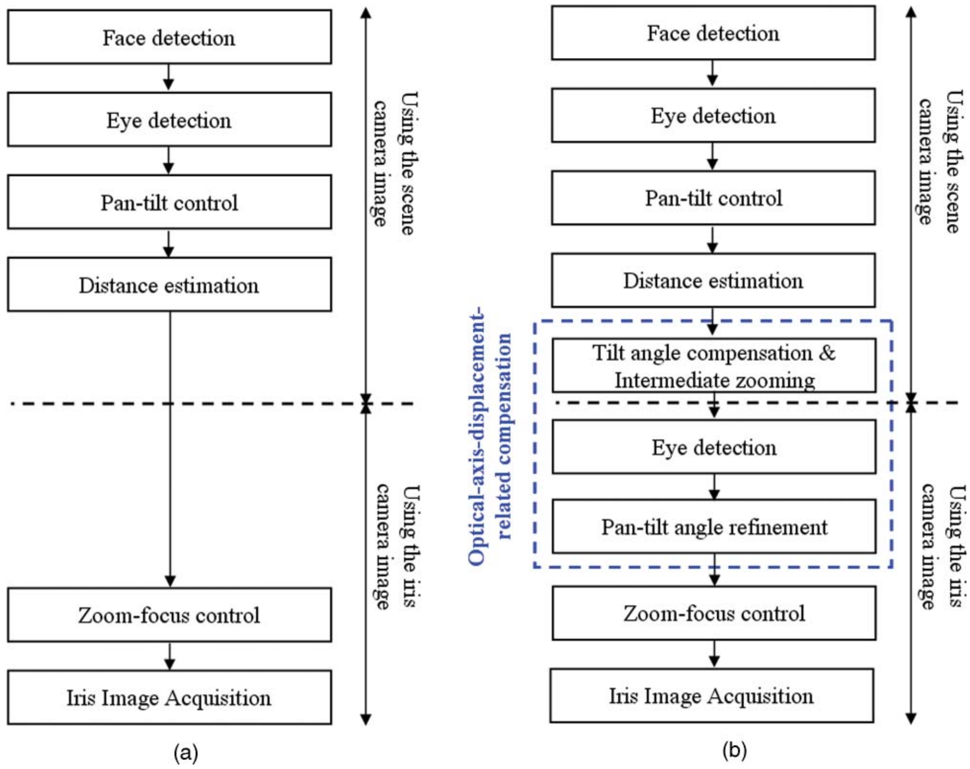

Fig. 4 Flowcharts for iris image acquisition: (a) coaxial type and (b) parallel type.

optical axis displacement-related compensation between the eye detection and zoom-focus control phases, as shown in Fig. 4(b).

The scene camera monitors the frontal area, and detects the user's face using Viola–Jones' general object detection method, called AdaBoost-based face detection.[16] Then, the system begins to search the face area in order to detect the user's eye. AdaBoost-based eye detection localizes the user's eye within the search area.[17,18] Once the system detects the user's eye, it determines the pan and tilt angle of the PTU. By setting this pan and tilt angle, the system is able to direct the scene camera to the user's eye. Using a geometrical model of face size with respect to distance, the system estimates the distance to the user. In our proposed system, the iris camera is directed to the user's eye at the same time as the scene camera. By comparison, the parallel-type system only directs the iris camera to the user's eye after the additional pan-tile control. In the final phase, the system controls the zoom and focus position of the telephoto zoom lens to acquire a good quality iris image.

3.2 *Distance Estimation*

The distance estimation is derived from the geometrical relationship between object size H and image size h, assuming a thin lens model and a constant face size. Figure 5 shows the thin lens model, which defines the relationship between the focal length, f, lens to object distance, u, and the lens-to-image plane distance, v, as shown in Eq. (1).[19] We can also rewrite the equation in terms of v, as shown in Eq. (2).

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}, \tag{1}$$

$$v = \frac{fu}{u - f}. \tag{2}$$

In the thin lens model, the object size (H) and its associated image size (h) satisfy a proportional expression, as shown in Eq. (3). We can also rewrite the equation in terms of h, as shown in Eq. (4).

$$v : h = u : H, \tag{3}$$

$$h = \frac{v \cdot H}{u}. \tag{4}$$

By substituting Eq. (2) into Eq. (4) and rewriting the equation in terms of u, we obtain Eq. (5). From this, we see

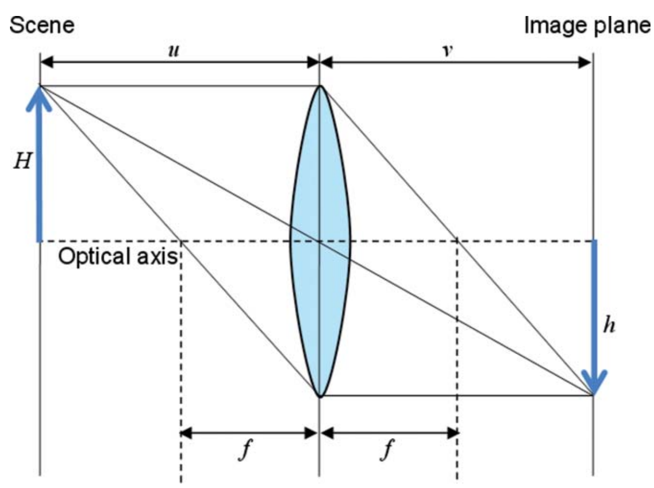

Fig. 5 Thin lens model.

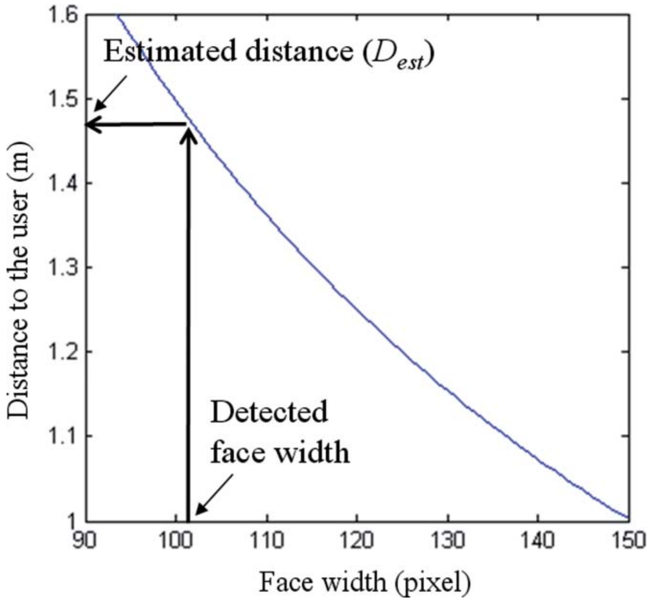

Fig. 6 Distance to the user estimated from the face size detected by the scene camera.

that the lens to object distance, u, is inversely proportional to the image size, h, with a constant offset. As the scene camera uses a fixed focal length lens, and H is assumed to be constant, we can estimate the distance to the user (u) from the face size (h) directly, as shown in Fig. 6. Since we can detect the left and right border of a face in a robust way, thanks to the strong vertical edges of the face and the upright facial pose, we use the face width as the face size.

$$u = \frac{fH}{h} + f. \tag{5}$$

3.3 *Zoom-Focus Control*

Zoom-focus control is a procedure that sets the zoom and focus position of the telephoto zoom lens to the optimal value that will enable the camera to acquire a good-quality iris image. The zoom-focus control consists of two phases, namely the initialization phase and the refinement phase.[7]

The initialization phase finds the zoom and focus position, assuming that the system has estimated a precise distance to the user. Since the zoom position is related to the magnification power of the zoom lens (the requirement is 200 pixel/cm), we can determine this beforehand. Therefore, we initialize the zoom position using a table that maps a distance to a zoom position. If we know the distance to the user and the zoom position, we can also determine the focus position in order to acquire an in-focus image. From previous experiments, we have recorded the focus positions corresponding to all possible distance-zoom position pairs. Therefore, we are also able to initialize the focus position using a table that maps a distance to a focus position.

The refinement phase is a search process that finds the focus position that maximizes the focus measure of the acquired iris image. We use the focus measure proposed in Ref. 20, which has a maximum value (generally approximately 100) when the iris image is in focus. The initial position of the search process is established by subtracting the maximum error of the distance estimation from the estimated distance,

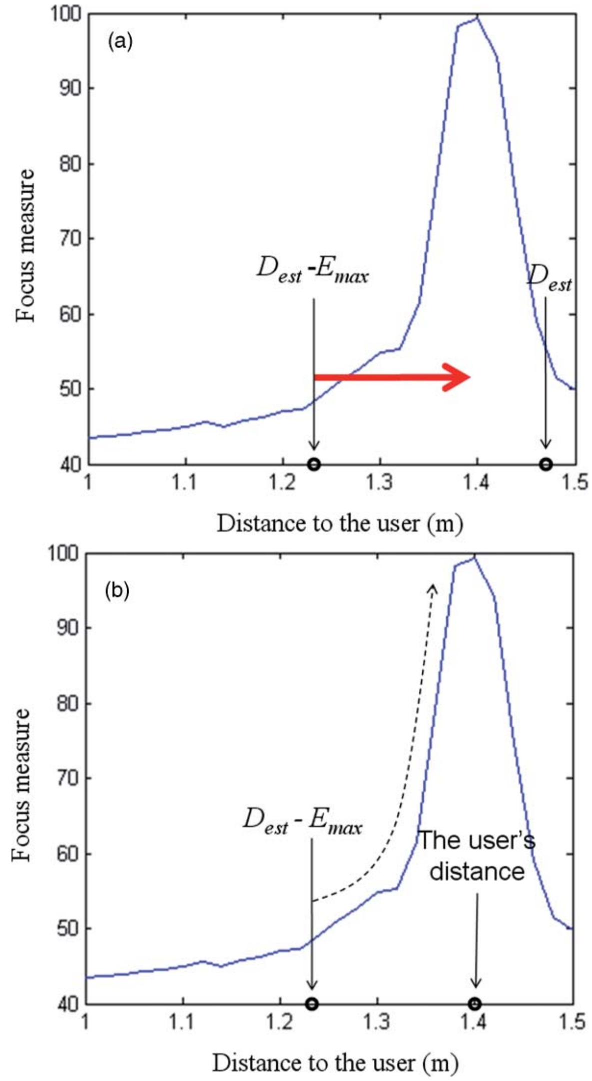

Fig. 7 Focus control of the iris camera: (a) initial position and (b) hill climbing-based optimization.

as shown in Fig. 7(a). In Fig. 7, the x-axis is the distance to the user, because it is more descriptive and has a one-to-one relationship with the focus position, as explained previously. The variable D_{est} denotes the estimated distance and $E_{\max}$ denotes the maximum error. Figure 7(a) shows an example in which a user stands at a distance of 1.4 m, and the system estimates the distance as 1.47 m (the face width measures 102 pixels). Using the initial position, the system repeatedly changes the focus position in order to increase the focus measure, until it reaches a peak, as shown in Fig. 7(b). This repetition is a type of hill climbing-based optimization.

3.4 *Optical Axis Displacement-Related Compensation for the Parallel Type*

In the parallel type, because of the displacement of the optical axes, the iris camera is directed to a point below the user's eye when the scene camera is directed to the user's eye. Therefore, to direct the iris camera precisely to the user's eye, the system must adjust the tilt angle, taking into consideration the distance of the user from the camera. This optical axis displacement-related compensation of the tilt angle can be derived from a simple geometrical analysis. If Y_{offset} denotes the optical axis displacement in metric units, and D_{est} denotes the estimated distance to the user in metric units, the PTU tilt angle should be increased by θ, as shown in Eq. (6).

$$\theta = \tan^{-1}\left(\frac{Y_{offset}}{D_{est}}\right). \tag{6}$$

When the distance to the user is estimated using only the scene camera image, there is inevitably an error in the estimation, and the tilt angle compensation is not precise. In the worst case, the iris camera could be directed to a point far from the user's eye, in which case the user's iris might not even be in the iris camera image. To address this problem, the system conducts the tilt angle compensation twice. First, it adjusts the tilt angle in an approximate way using the scene camera image, and then it adjusts the tilt angle a second time, more precisely, using the iris camera image. In other words, after the tilt angle compensation using the scene camera image, the zoom position is set to an intermediate value in order to confirm the location of the user's eye. In our implementation, the focal length of the intermediate zoom is 60 mm, which enables the iris camera to capture a 130% wider scene when the user is at the closest distance, namely 1 m. Using the iris image, which definitely contains the user's iris region, the system adjusts the pan-tilt angle again. After the additional compensation, the parallel type applies the same procedures as the coaxial type.

4 Experimental Results

To prove that the direction control of the proposed system is simpler and more robust than the parallel type, we compare the iris localization error in the iris camera image and the time required to acquire a good-quality iris image in the two systems. In addition, to ensure that the acquired iris image is of a good quality, we evaluate the performance of the iris recognition when acquiring iris images with the proposed system.

4.1 *Iris Localization Error*

The iris localization error is defined as the root mean square (rms) of the distance between the detected iris center and its ground truth, in pixel units, after completing the pan-tilt-zoom control. To compare the iris localization errors between the coaxial type and parallel type systems, we repeat the iris image acquisition 250 times (= 10 persons × 5 positions × 5 times) for each system type, and record the detected iris center coordinates. The user's positions used in the experiments are evenly spread over the defined capture volume, as shown in Fig. 8.

Figure 9 shows the detected iris centers, in which each dot depicts a detected iris center. Since the iris camera uses XGA resolution, the image center (512, 384) is the ground truth of the iris center. Considering that the radius of an iris is about 100 pixels in the iris camera image, we can depict the area of the iris center, guaranteeing that the whole iris is captured, by using a rectangle that is smaller than the image boundary. In Fig. 9, two rectangles with dotted lines, labeled as the VGA case boundary and the XGA case boundary, indicate when the iris camera is VGA grade and XGA grade, respectively. Figure 9(a) shows the detected iris centers when the system operates in coaxial mode. Here, it is noticeable that all iris centers are located inside the VGA case boundary. This means that a VGA-grade camera is sufficient

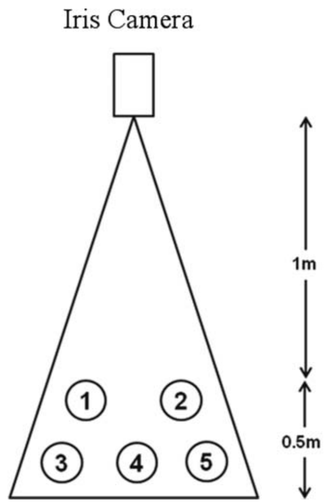

Fig. 8 User's positions for the performance evaluation.

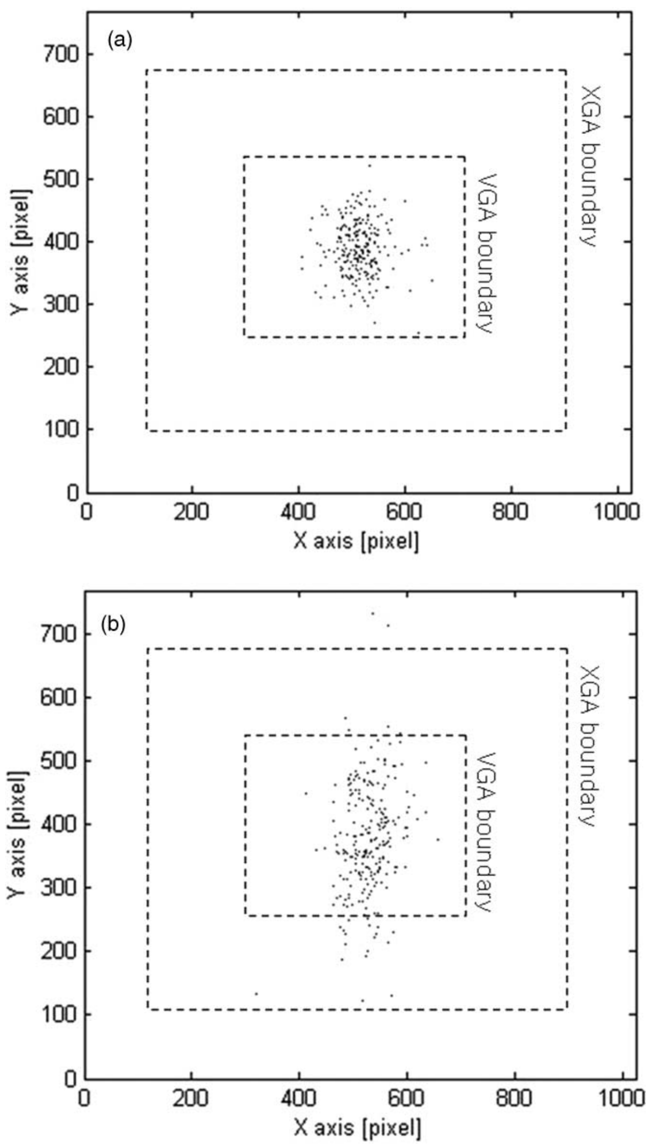

Fig. 9 Detected iris centers: (a) coaxial type and (b) parallel type.

Table 1 RMSE of iris center.

	x-axis (pixels)	*y*-axis (pixels)
Coaxial type	46	49
Parallel type	52	175

for coaxial type operation. Figure 9(b) shows the detected iris centers when the system operates in parallel mode. Since the detected iris centers scatter vertically, some of the acquired iris images fail to contain the whole iris area: 10% in the VGA case, and 0.8% in the XGA case. Table 1 shows the root mean square error (RMSE) of the detected iris centers. Here, we see that the y-axis RMSE values of the two types are significantly different, while the x-axis values are almost the same. In particular, the y-axis RMSE of the parallel type is three times larger than that of the coaxial type.

There are three major causes of iris localization errors: an optical axis alignment error, an eye detection error, and a tilt angle compensation error. The first and second cause is common to the two types, but the third cause applies only to the parallel type. After evaluating the effect of each cause, we deduce that the large differences in y-axis RMSE values are the result of the tilt angle compensation error.

The optical axis alignment error means that the iris localization error is caused by inexact hardware implementations, in particular, the inexact alignment of the two optical axes. In the coaxial system, when the scene camera is directed to a point such that the point's image is located in the center of the image, the point should also be located in the center of the iris camera image. During the optical calibration, the cold mirror is rotated minutely to meet the requirement in all ranges of distance. In the case of parallel type, when the scene camera is directed to a point such that the point's image is located in the center of the image, a point located below the point by the same displacement as the optical axes should be located in the center of the iris camera image. During the optical calibration, the installation of the iris camera is rotated minutely to meet the requirement in all ranges of distance. Even though the calibration of the parallel type is more difficult than that of the coaxial type because it has to ensure the calibration pattern is parallel to the image plane and vertically upright, the optical axis alignment error of the two types can be minimized to almost the same level, approximately 20 to 30 pixels.

The eye detection error means that the iris localization error is caused by the inexact result of the eye detection using the scene camera image. Even though the error is just 1 or 2 pixels in the scene camera image, it is magnified to between 20 and 25 pixels in the iris camera image. As the two types use the same eye detection method, the eye detection error is the same in both cases.

Finally, the tilt angle compensation error, which exists only in the parallel type, means that the iris localization error is caused by the inexact optical axis displacement-related compensation, calculated in Eq. (6). As the displacement, Y_{offset}, is constant, the error is caused mainly by the error in the estimation of the user's distance. By evaluating 600 test cases from 20 people, we observed that the error in the estimation of the user's distance is in the range of 70 to 95 mm, and its corresponding iris localization error is in the range of 130 to 150 pixels.

Table 2 Operation time of each step (Unit: second).

Step	Parallel type (s)	Coaxial type (s)
Eye detection and tracking in the scene cameara image	0.8349	0.8309
Decision of the user's standing	0.9312	0.8732
Tilt angle compenstion and intermediate zooming	0.2871	-
Eye centering in the iris camera image	0.1769	-
Initialization of zoom-focus position	0.6131	0.3237
Refinement of zoom-focus position	1.7021	1.7521
Total time	**4.5453**	**3.7799**

4.2 *Operation Time*

We recorded the time spent on each step while conducting the experiment explained in Sec. 4.1. Table 2 shows the time taken in each step. It is evident here that the total operation time of the coaxial type is less than that of the parallel type by 17%.

The second step named "decision of the user's standing," is required in order to confirm that the user is ready to be captured. This prevents the system from starting the zoom-focus control too early. If the system changes the zoom position for a high level of magnification while the user is moving, the iris camera could lose the user's eye, and the operation time could increase as a result. The step is implemented by checking whether the iris center is located within the central area of the iris camera image for longer than a threshold value. The third and fourth steps correspond to the optical axis displacement-related compensation. As they are needed only in the parallel type, we believe that they are the main cause of the operation time difference between the two types. Even though the fifth step is common to the two types, the operation time of each type is significantly different. This can be explained by the zoom position when the step starts. In the case of parallel type, the zoom position is set to the intermediate value, 60 mm, as explained in Sec. 3.4. In contrast, in the case of coaxial type, zoom position is set to the middle of the operating range, 106 mm. In other words, the parallel type needs a longer operation time so that it does not lose the user's eye by starting the zoom-focus control from a wider FOV.

4.3 *Iris Recognition Performance*

We confirmed that the proposed system could acquire good-quality iris images, as shown in Fig. 10. To ensure the acquired iris images satisfy the quality requirements,[14] we applied a general iris recognition system to the images and evaluated the performance. The iris recognition system consists of five steps: segmentation, eyelid detection, normalization, feature encoding, and matching.[20–24] The segmentation

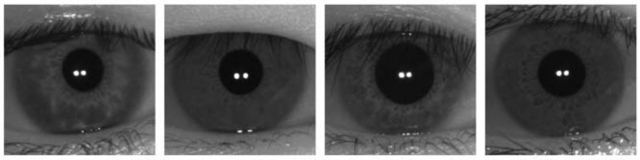

Fig. 10 Examples of iris images captured with the proposed system.

step detects the inner and outer boundary of the iris using a circular edge detector,[22–24] and the eyelid detection step extracts the exact border between the iris and the eyelid.[24] In order to eliminate differences in iris size due to optical magnification and pupil dilation, the normalization step converts the detected iris region into a rectangular image with a fixed size. The feature encoding step uses a generally used Gabor filter and outputs an iris code of 512 bytes. The iris code consists of quantized phase information of 256 bytes and a pixel-wise validity mask of 256 bytes. The matching step measures the similarity between the iris codes using the Hamming distance (HD), which is a value between 0 and 1. The HD threshold is set to 0.34 to minimize the equal error rate (EER).

To evaluate the iris recognition performance, we measured the EER and the decidability index. In our experiments, we collected 300 iris images (10 persons × 30 times) using the proposed system. Before acquiring the iris image, all participants were asked to stand within the marked capture volume and stare at the iris camera. Figure 11 shows the HD distribution of the experimental samples. Here, we observe that the intraclass mode is explicitly separate from the interclass mode. The resultant EER measures 0.3%, as shown in Fig. 12. This indicates that the acquired iris images are good quality, as it is similar to that of Ref. 25 (EER = 0.17%), which is a contactless iris recognition system within a short stand-off distance of 25 cm. Another measure that indicates that the two modes are separate is the decidability index, d', defined in Eq. (7).[26] In Eq. (7), μ_1 and μ_2 denote the mean of the two distributions, and σ_1 and σ_2 denote the standard deviations of the two distributions. The resultant value of d' is 7.37, which is similar to that of Ref. 26 ($d' = 7.3$).

$$d' = \frac{|\mu_1 - \mu_2|}{\sqrt{\dfrac{\sigma_1^2 + \sigma_2^2}{2}}} \tag{7}$$

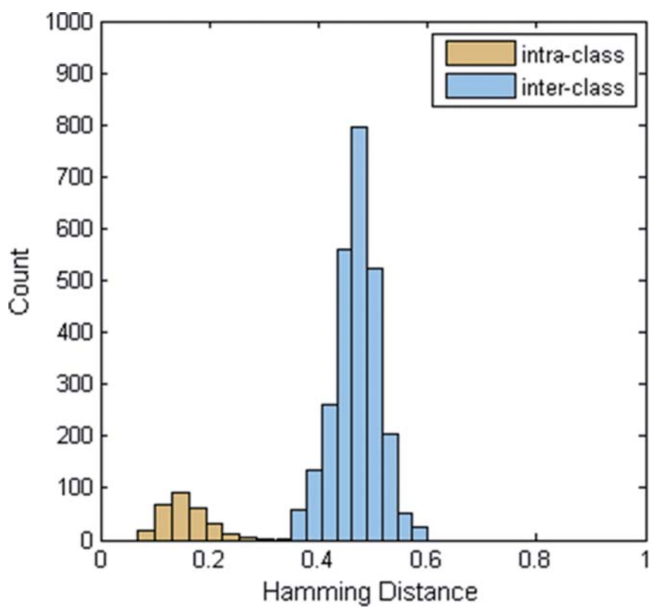

Fig. 11 HD distribution of the experimental samples.

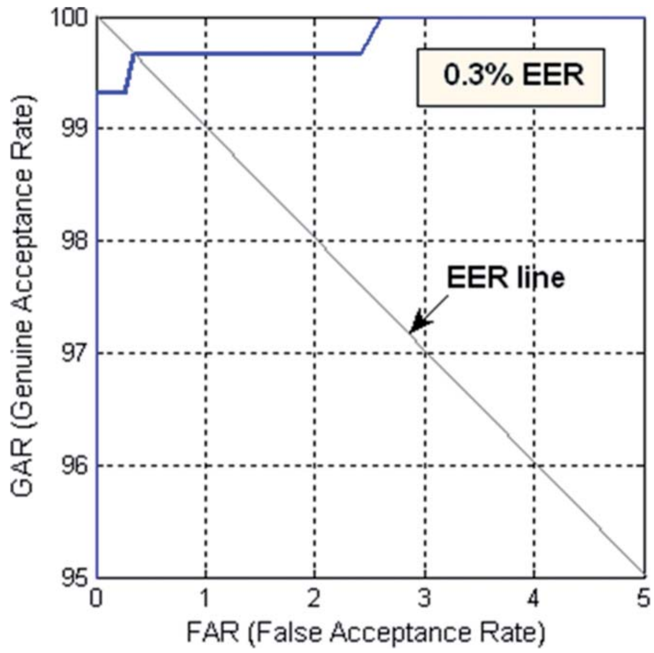

Fig. 12 Receiver operating characteristic curve and EER of the experimental samples.

5 Conclusion

This paper proposed a novel PTZ-based iris recognition system, in which an iris camera and a scene camera are combined in a coaxial optical structure and installed on a PTU. The two cameras are placed orthogonally to each other, and a cold mirror is inserted between them, such that the optical axes of the two cameras become coincident. When the scene camera directs its optical axis to the user's eye, the optical axis of the iris camera is simultaneously directed to the user's eye. The proposed iris system is expected to be more compact than the portal-based system and the separate-type PTZ-based system, because it does not require the large portal, separately installed scene camera, or any range measurement device. Furthermore, the proposed system is expected to be more robust and faster than the parallel-type PTZ-based system because the coaxial optical structure can eliminate the error-prone optical axis displacement-related tilt-angle compensation.

Experimental results confirm the following: 1. The iris localization error of the proposed coaxial type is smaller than that of the parallel type. 2. The proposed system can be implemented with two VGA-grade cameras. 3. The operation time of the proposed coaxial type is less than that of the parallel type by 17%. 4. The proposed system acquires good-quality iris images, with an EER of 0.3% and a decidability index of 7.37.

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