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(54) EYE TRACKING USING IMAGE DATA

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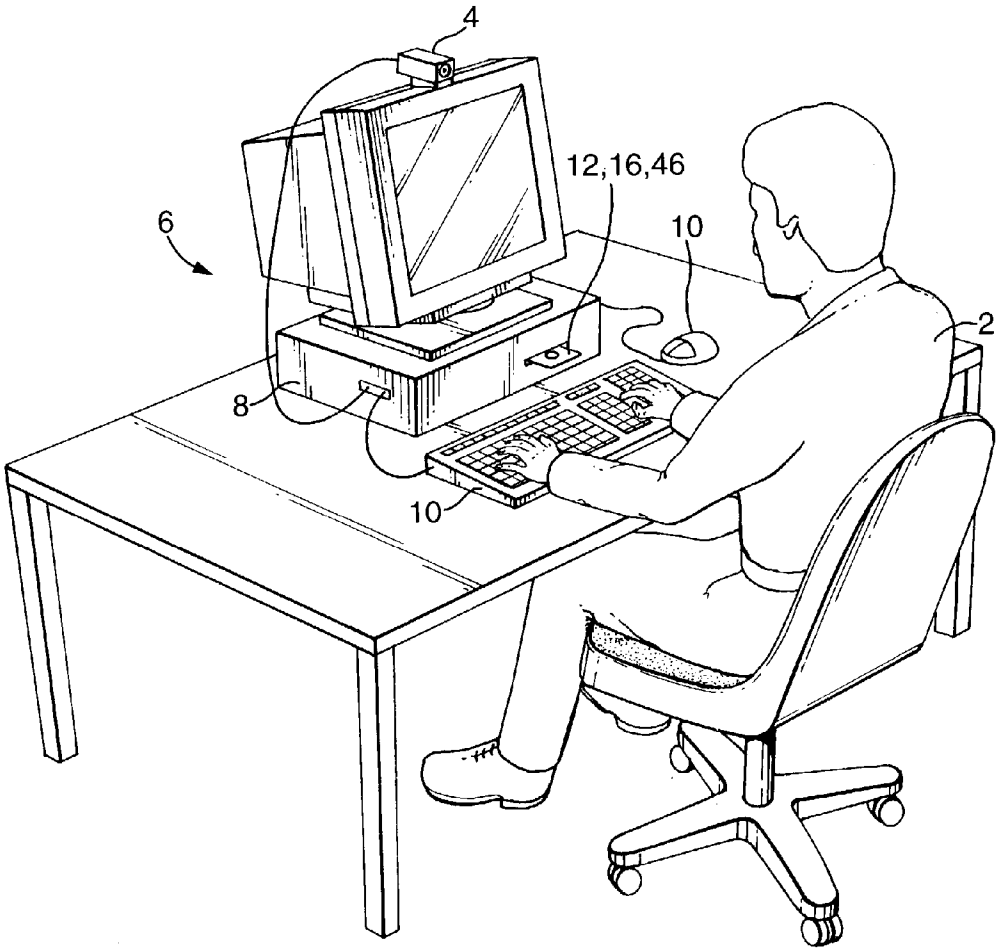
(52) **U.S. Cl.** **345/158**

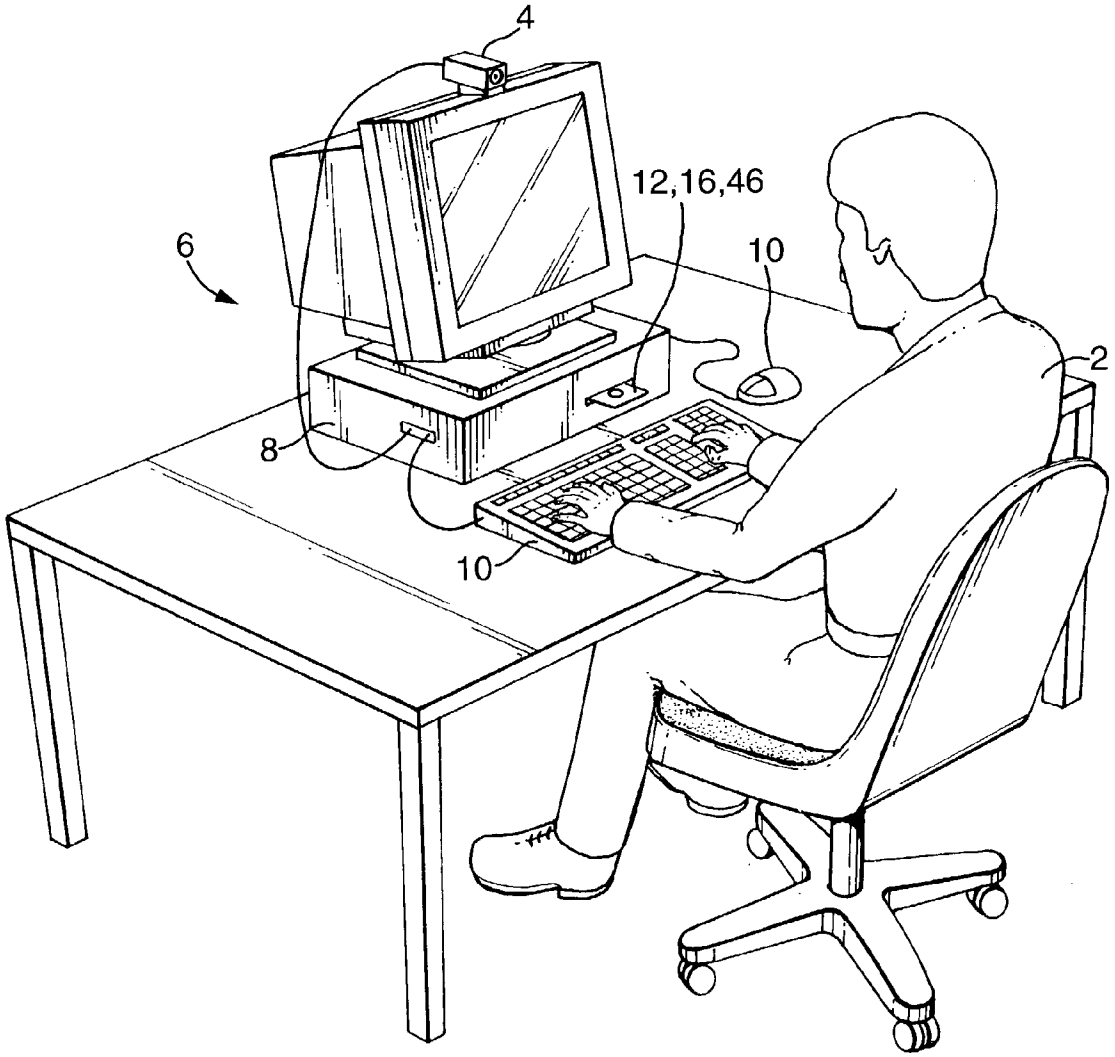
(57) **ABSTRACT**

In a computer processing apparatus **8**, frames of image data received from a camera **4** are processed to track the eyes of a user **2** in each image. A 3D computer model of a head is stored, and search regions are defined in the 3D space corresponding to the eyes and eyebrows. For each image, pixels within the projection of the search regions from the 3D space to the 2D image space are sampled to determine a representative intensity value for each of the search regions. Positions for the eyes in the 3D space are then calculated based on the determined values. The 3D computer model and search bands are moved within the 3D space to align the eyes with the calculated eye positions. In this way, when the next image is processed, the search bands project into the image from a head configuration determined from the previous image. This facilitates reliable and accurate eye tracking.



 GOOGLE-SAMSUNG EXHIBIT 1020

Fig.1.



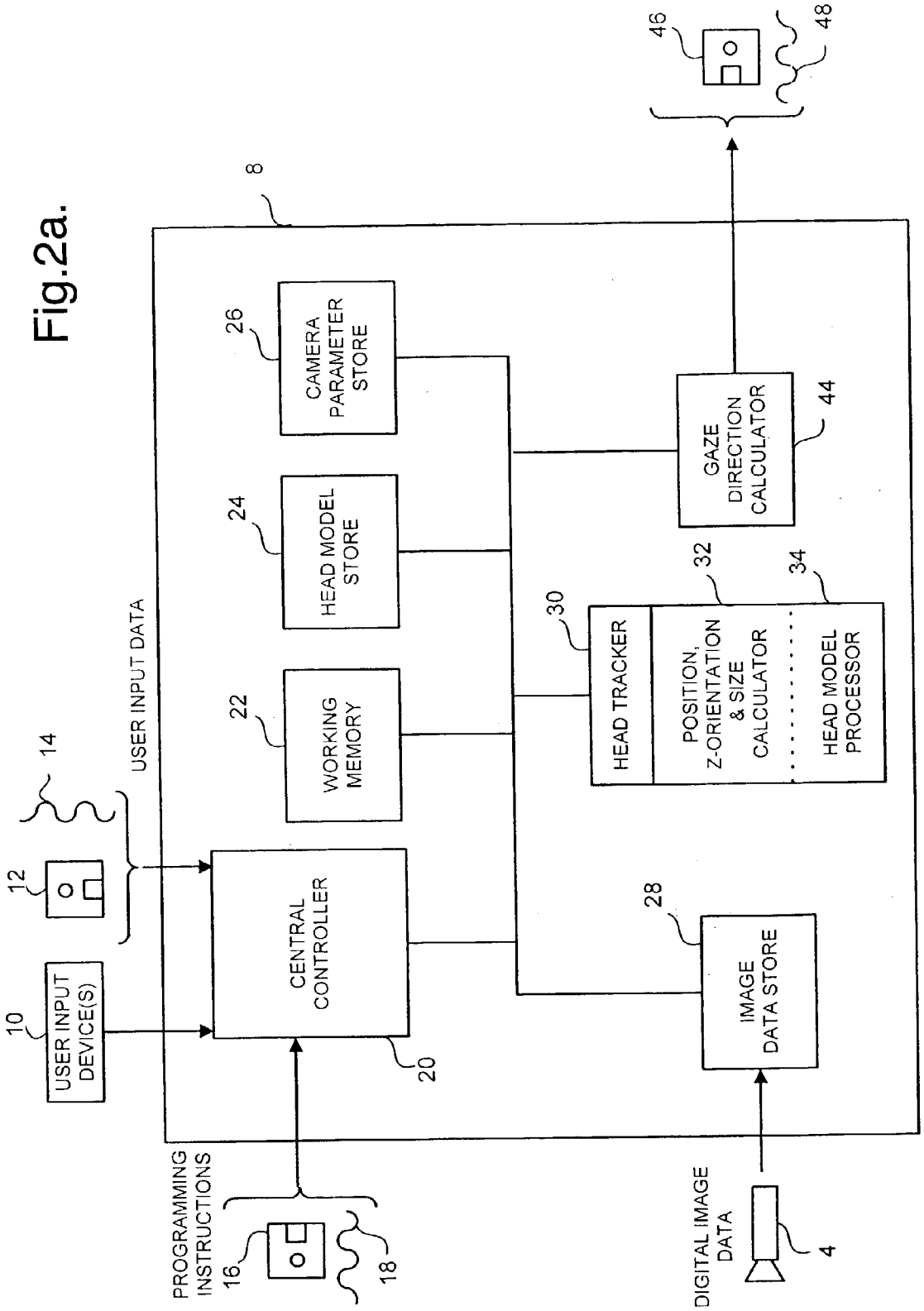


Fig.2a.
8
USER INPUT DEVICE(S)
10
12
14
USER INPUT DATA
CENTRAL CONTROLLER
20
WORKING MEMORY
22
HEAD MODEL STORE
24
CAMERA PARAMETER STORE
26
PROGRAMMING INSTRUCTIONS
16
18
IMAGE DATA STORE
28
HEAD TRACKER
30
POSITION, Z-ORIENTATION & SIZE CALCULATOR
32
HEAD MODEL PROCESSOR
34
GAZE DIRECTION CALCULATOR
44
46
48
DIGITAL IMAGE DATA
4

Fig.2b.

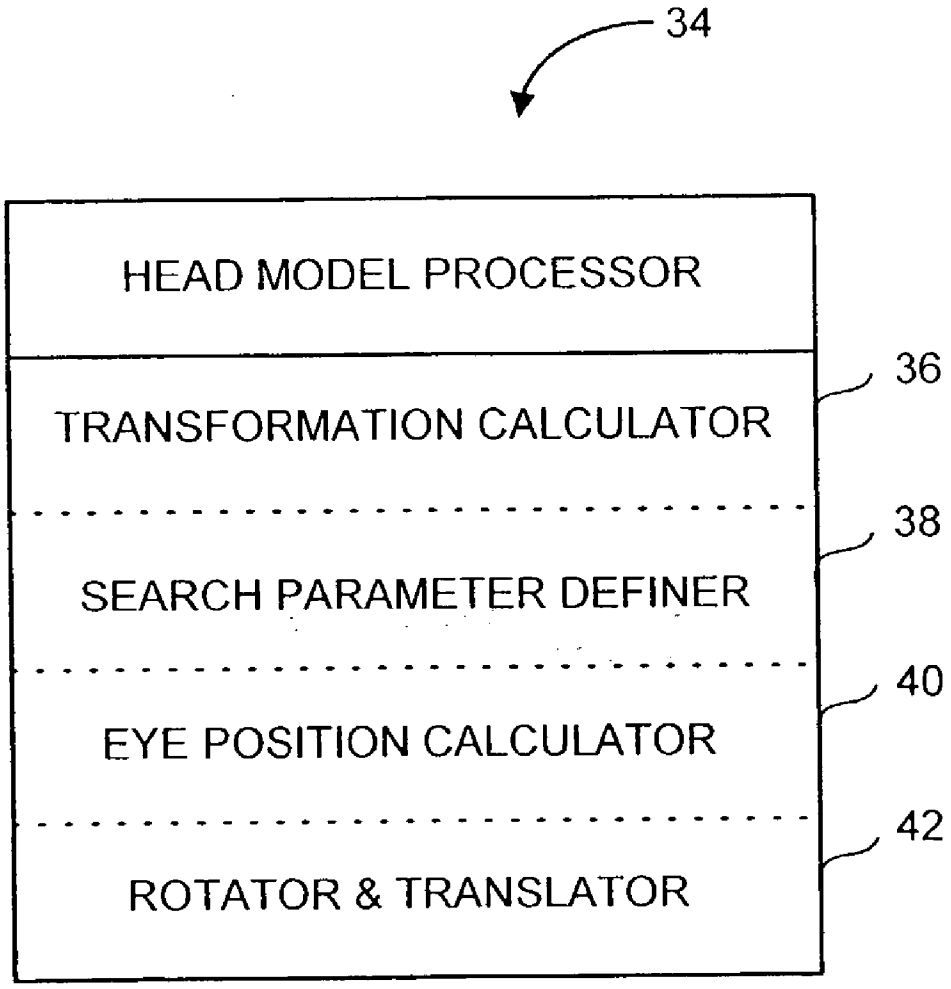

34
HEAD MODEL PROCESSOR
TRANSFORMATION CALCULATOR
36
SEARCH PARAMETER DEFINER
38
EYE POSITION CALCULATOR
40
ROTATOR & TRANSLATOR
42

Fig.3a.

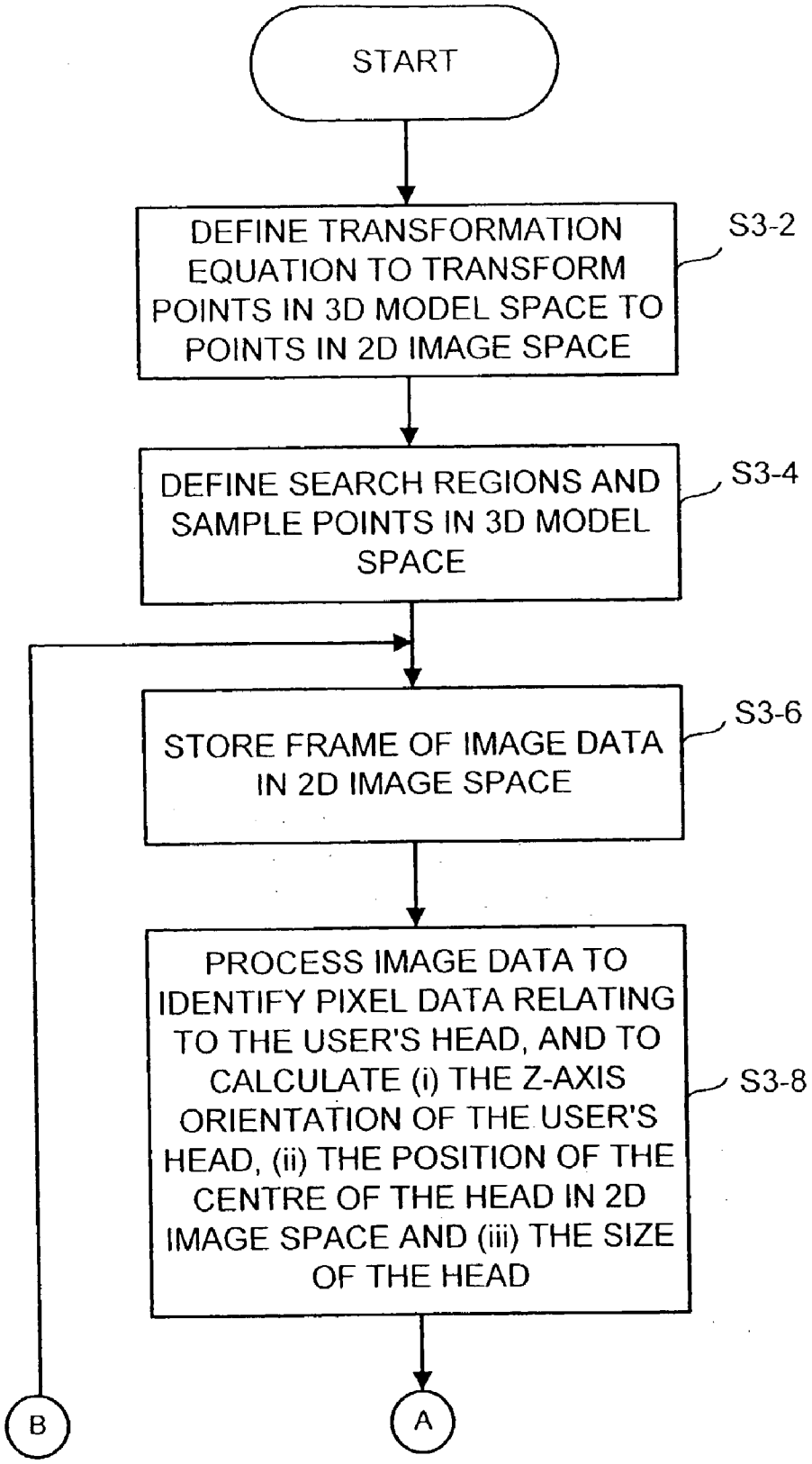

START
DEFINE TRANSFORMATION EQUATION TO TRANSFORM POINTS IN 3D MODEL SPACE TO POINTS IN 2D IMAGE SPACE
S3-2
DEFINE SEARCH REGIONS AND SAMPLE POINTS IN 3D MODEL SPACE
S3-4
STORE FRAME OF IMAGE DATA IN 2D IMAGE SPACE
S3-6
PROCESS IMAGE DATA TO IDENTIFY PIXEL DATA RELATING TO THE USER'S HEAD, AND TO CALCULATE (i) THE Z-AXIS ORIENTATION OF THE USER'S HEAD, (ii) THE POSITION OF THE CENTRE OF THE HEAD IN 2D IMAGE SPACE AND (iii) THE SIZE OF THE HEAD
S3-8
B
A

Fig.3b.

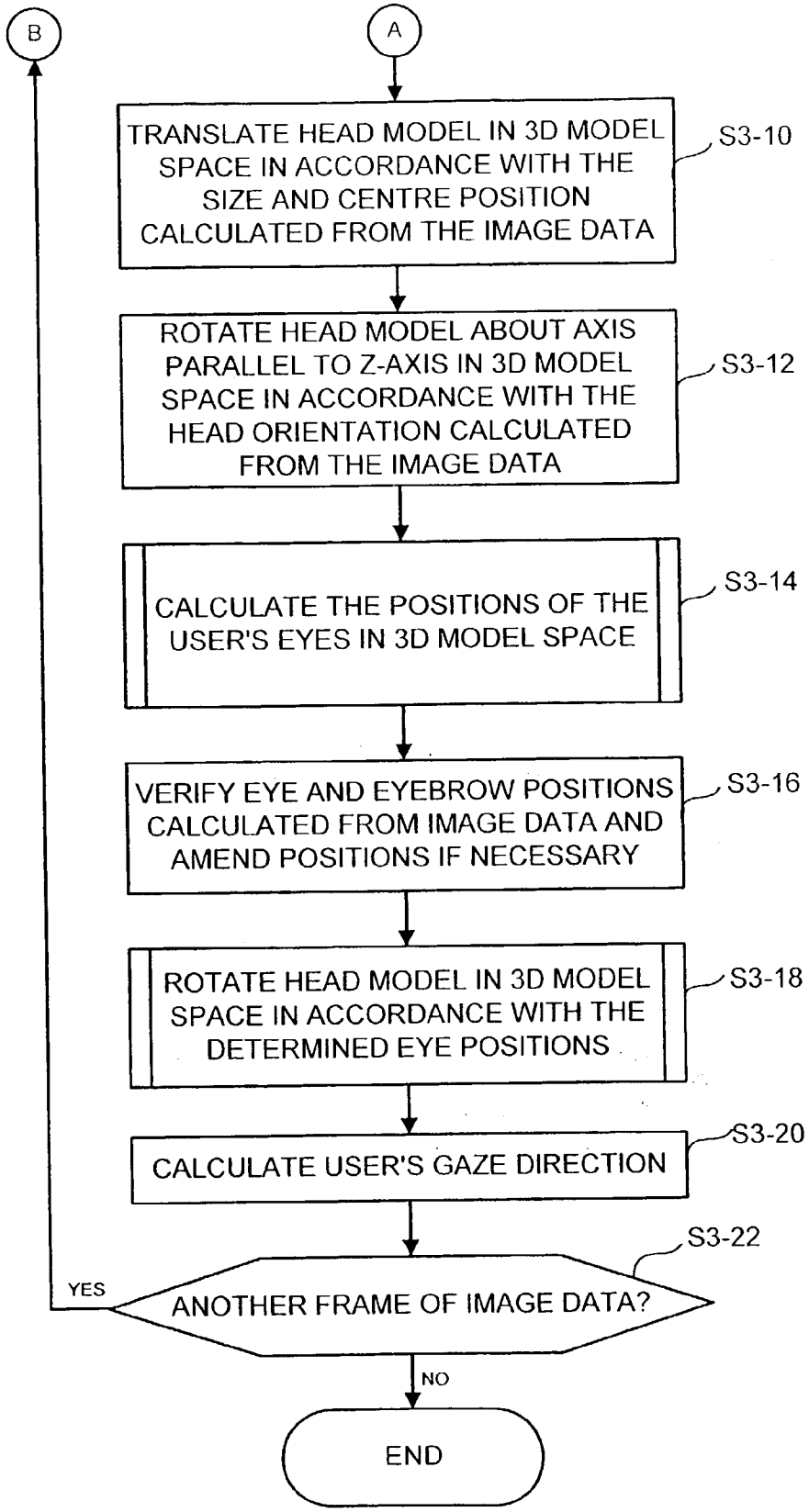

B
A
TRANSLATE HEAD MODEL IN 3D MODEL SPACE IN ACCORDANCE WITH THE SIZE AND CENTRE POSITION CALCULATED FROM THE IMAGE DATA
S3-10
ROTATE HEAD MODEL ABOUT AXIS PARALLEL TO Z-AXIS IN 3D MODEL SPACE IN ACCORDANCE WITH THE HEAD ORIENTATION CALCULATED FROM THE IMAGE DATA
S3-12
CALCULATE THE POSITIONS OF THE USER'S EYES IN 3D MODEL SPACE
S3-14
VERIFY EYE AND EYEBROW POSITIONS CALCULATED FROM IMAGE DATA AND AMEND POSITIONS IF NECESSARY
S3-16
ROTATE HEAD MODEL IN 3D MODEL SPACE IN ACCORDANCE WITH THE DETERMINED EYE POSITIONS
S3-18
CALCULATE USER'S GAZE DIRECTION
S3-20
S3-22
YES
ANOTHER FRAME OF IMAGE DATA?
NO
END

Fig.4.

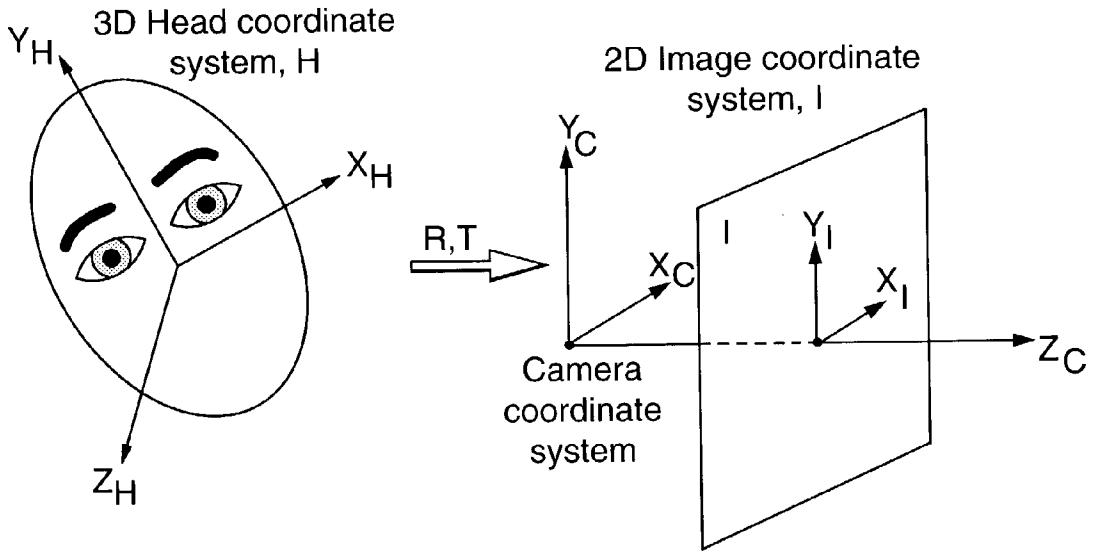
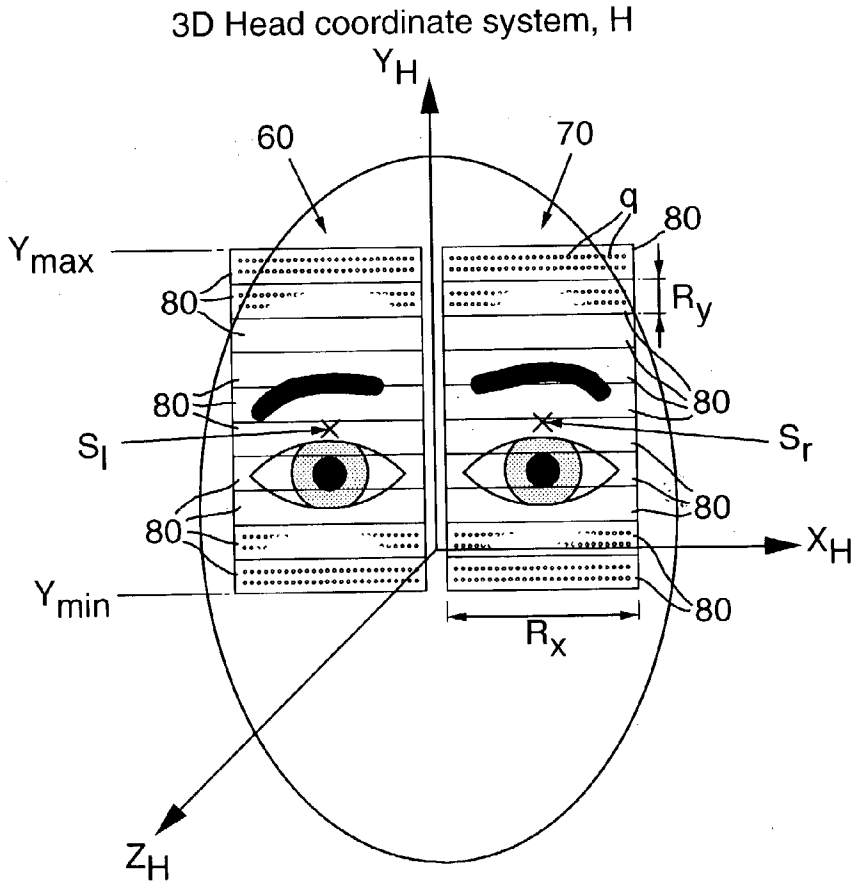

3D Head coordinate system, H
Y_H
X_H
Z_H
R,T
2D Image coordinate system, I
Y_C
X_C
I
Y_I
X_I
Z_C
Camera coordinate system

Fig.5.


3D Head coordinate system, H
Y_H
60
70
q
80
Y_{max}
R_y
S_l
S_r
X_H
Y_{min}
R_x
Z_H

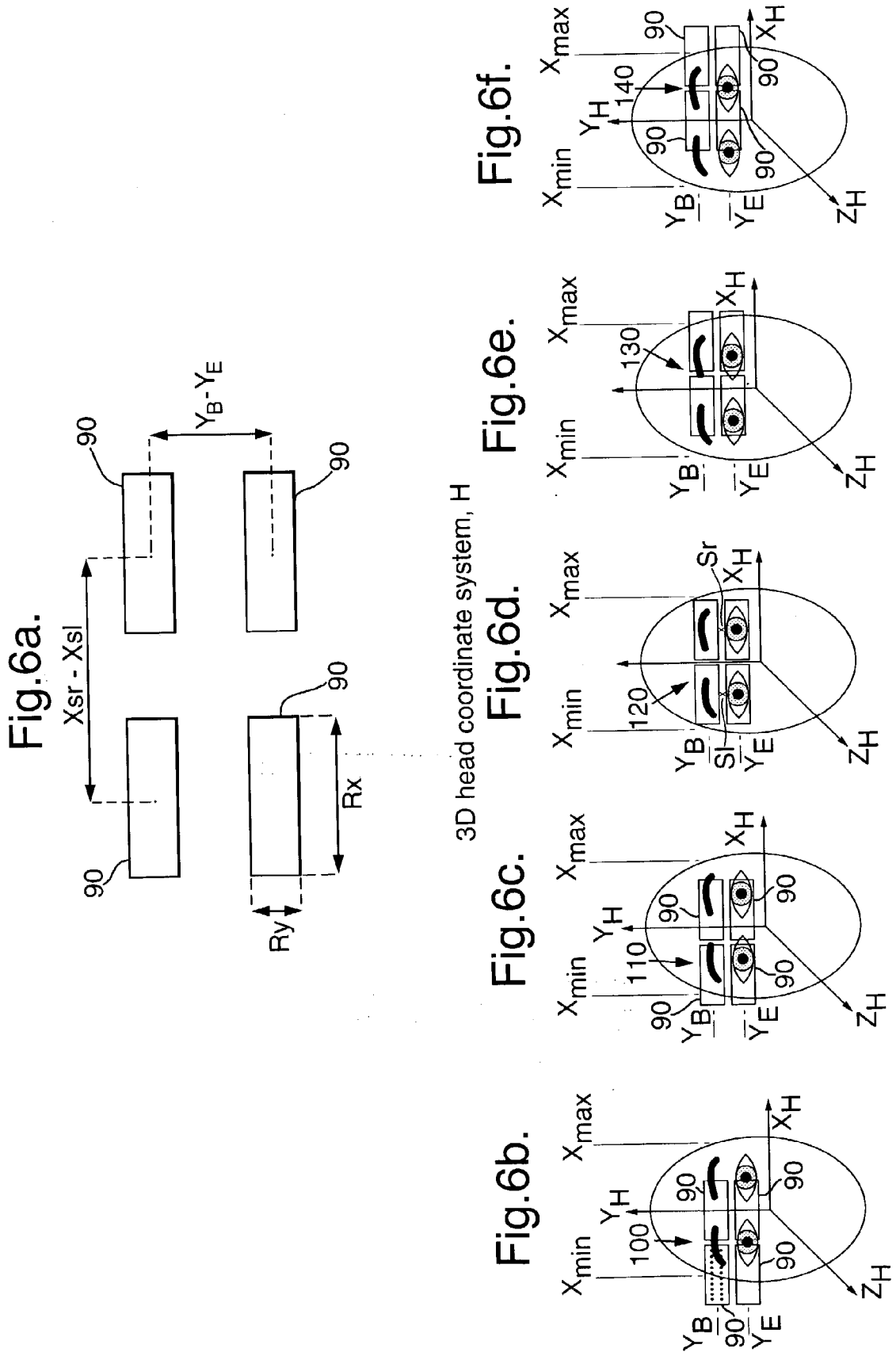


Fig.6a.
Xsr - Xsl
Y_B-Y_E
90
Ry
Rx
3D head coordinate system, H
Fig.6b.
Fig.6c.
Fig.6d.
Fig.6e.
Fig.6f.
X_{min}
X_{max}
Y_H
X_H
Z_H
Y_B
Y_E
100
110
120
130
140
Sl
Sr

Fig.7.

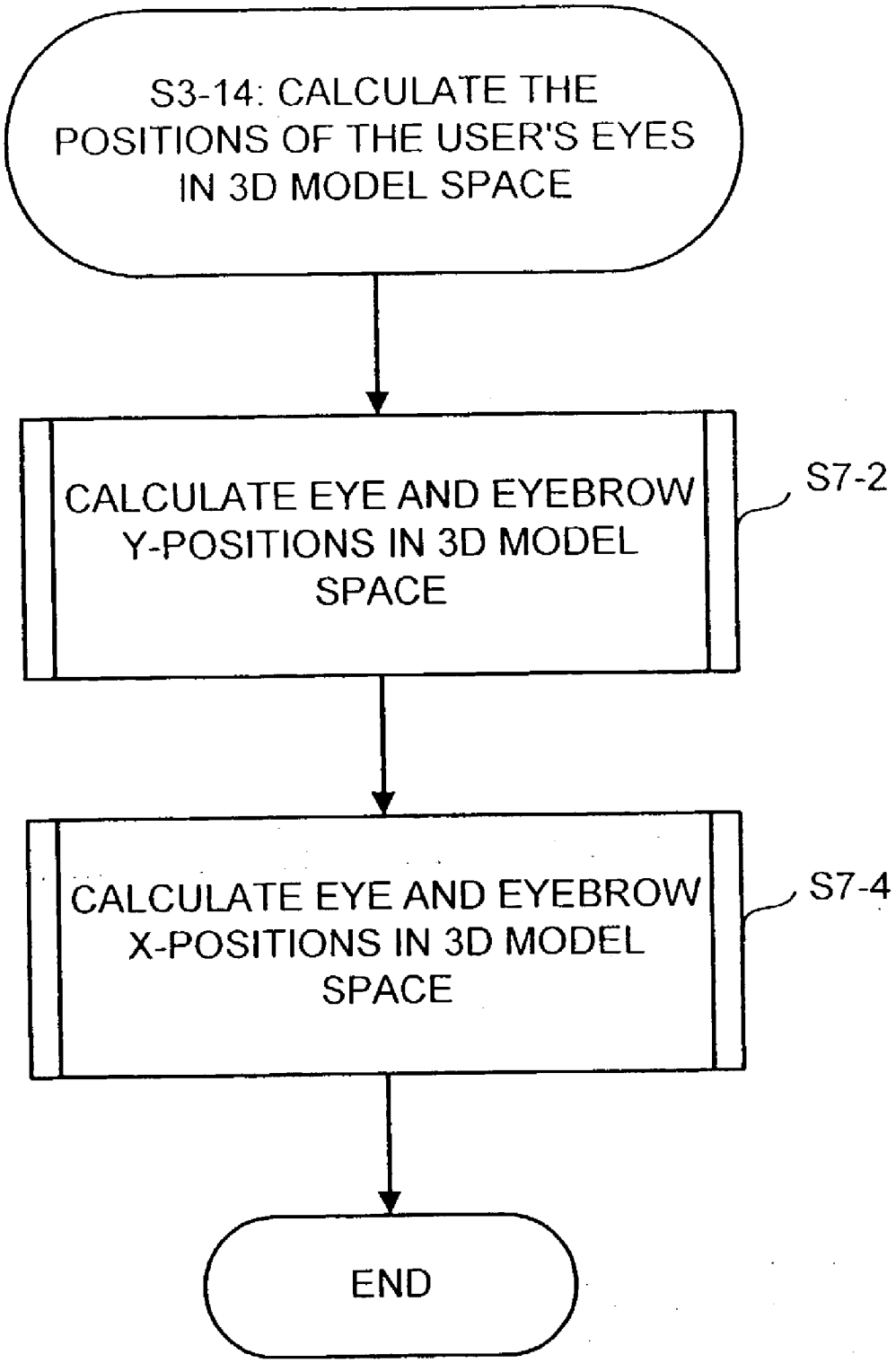

S3-14: CALCULATE THE POSITIONS OF THE USER'S EYES IN 3D MODEL SPACE
CALCULATE EYE AND EYEBROW Y-POSITIONS IN 3D MODEL SPACE
S7-2
CALCULATE EYE AND EYEBROW X-POSITIONS IN 3D MODEL SPACE
S7-4
END

Fig.8a.

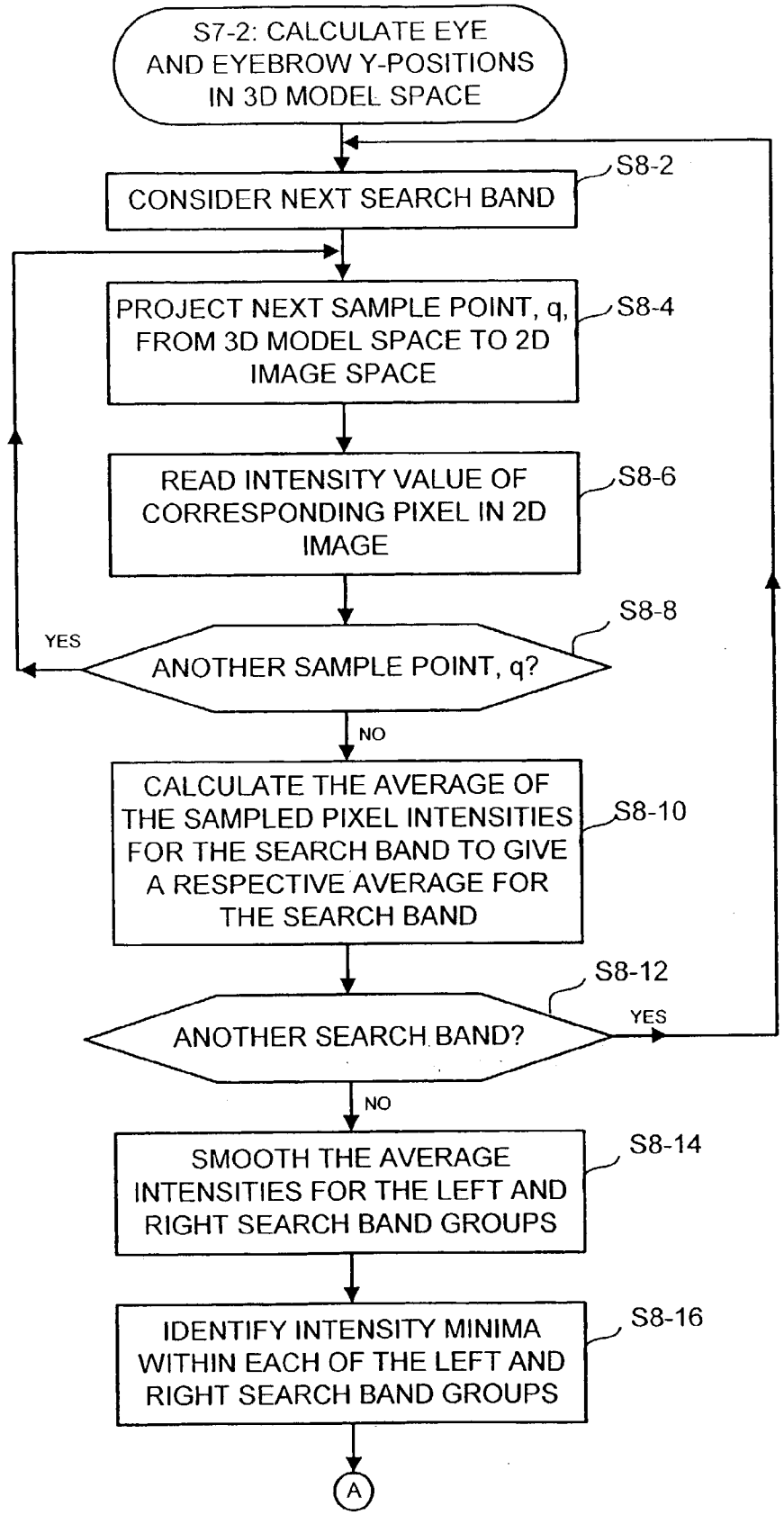

S7-2: CALCULATE EYE AND EYEBROW Y-POSITIONS IN 3D MODEL SPACE
CONSIDER NEXT SEARCH BAND
S8-2
PROJECT NEXT SAMPLE POINT, q, FROM 3D MODEL SPACE TO 2D IMAGE SPACE
S8-4
READ INTENSITY VALUE OF CORRESPONDING PIXEL IN 2D IMAGE
S8-6
ANOTHER SAMPLE POINT, q?
S8-8
YES
NO
CALCULATE THE AVERAGE OF THE SAMPLED PIXEL INTENSITIES FOR THE SEARCH BAND TO GIVE A RESPECTIVE AVERAGE FOR THE SEARCH BAND
S8-10
ANOTHER SEARCH BAND?
S8-12
YES
NO
SMOOTH THE AVERAGE INTENSITIES FOR THE LEFT AND RIGHT SEARCH BAND GROUPS
S8-14
IDENTIFY INTENSITY MINIMA WITHIN EACH OF THE LEFT AND RIGHT SEARCH BAND GROUPS
S8-16
A

Fig.8b.

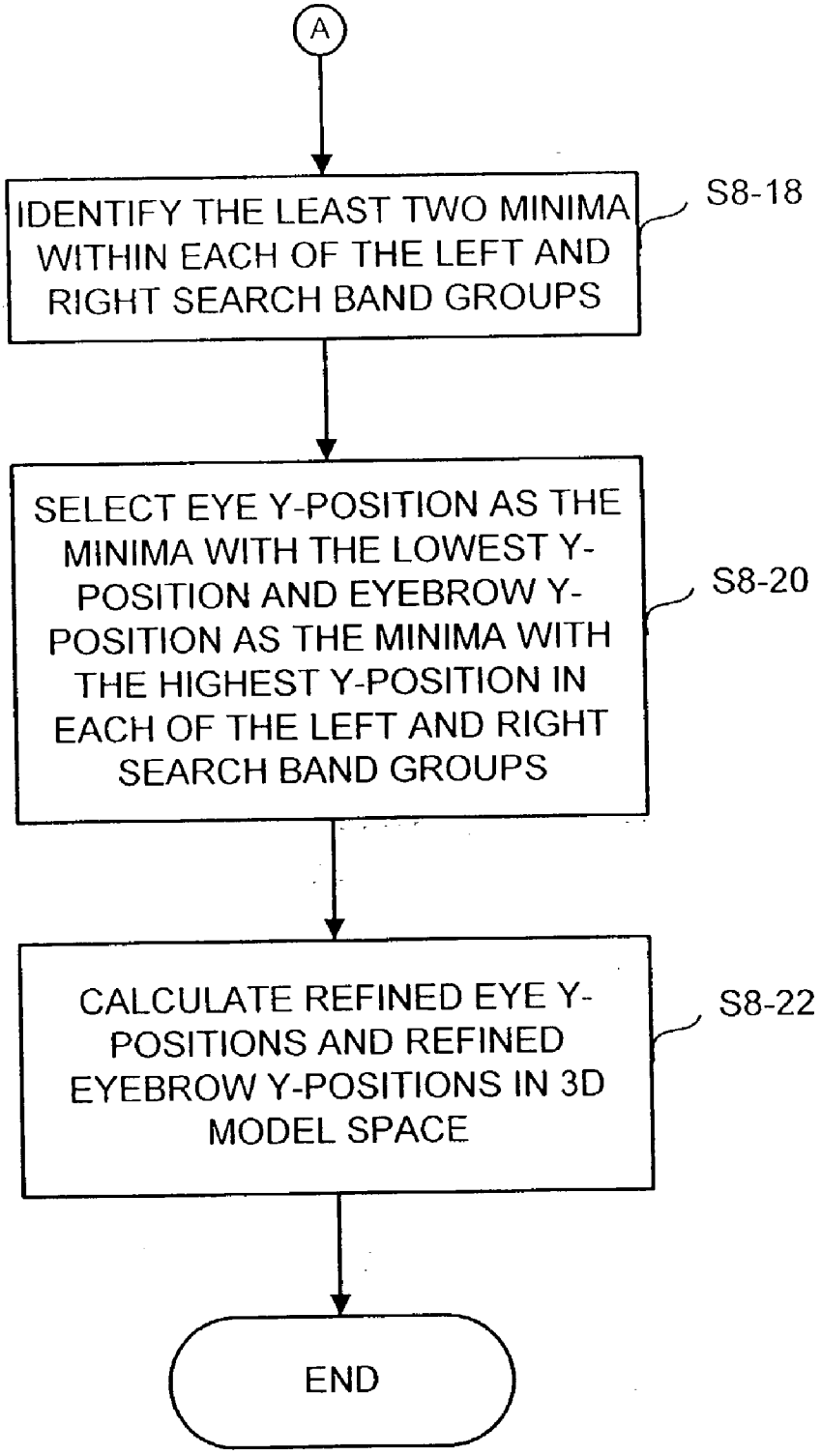

A
IDENTIFY THE LEAST TWO MINIMA WITHIN EACH OF THE LEFT AND RIGHT SEARCH BAND GROUPS
S8-18
SELECT EYE Y-POSITION AS THE MINIMA WITH THE LOWEST Y-POSITION AND EYEBROW Y-POSITION AS THE MINIMA WITH THE HIGHEST Y-POSITION IN EACH OF THE LEFT AND RIGHT SEARCH BAND GROUPS
S8-20
CALCULATE REFINED EYE Y-POSITIONS AND REFINED EYEBROW Y-POSITIONS IN 3D MODEL SPACE
S8-22
END

Fig.9.

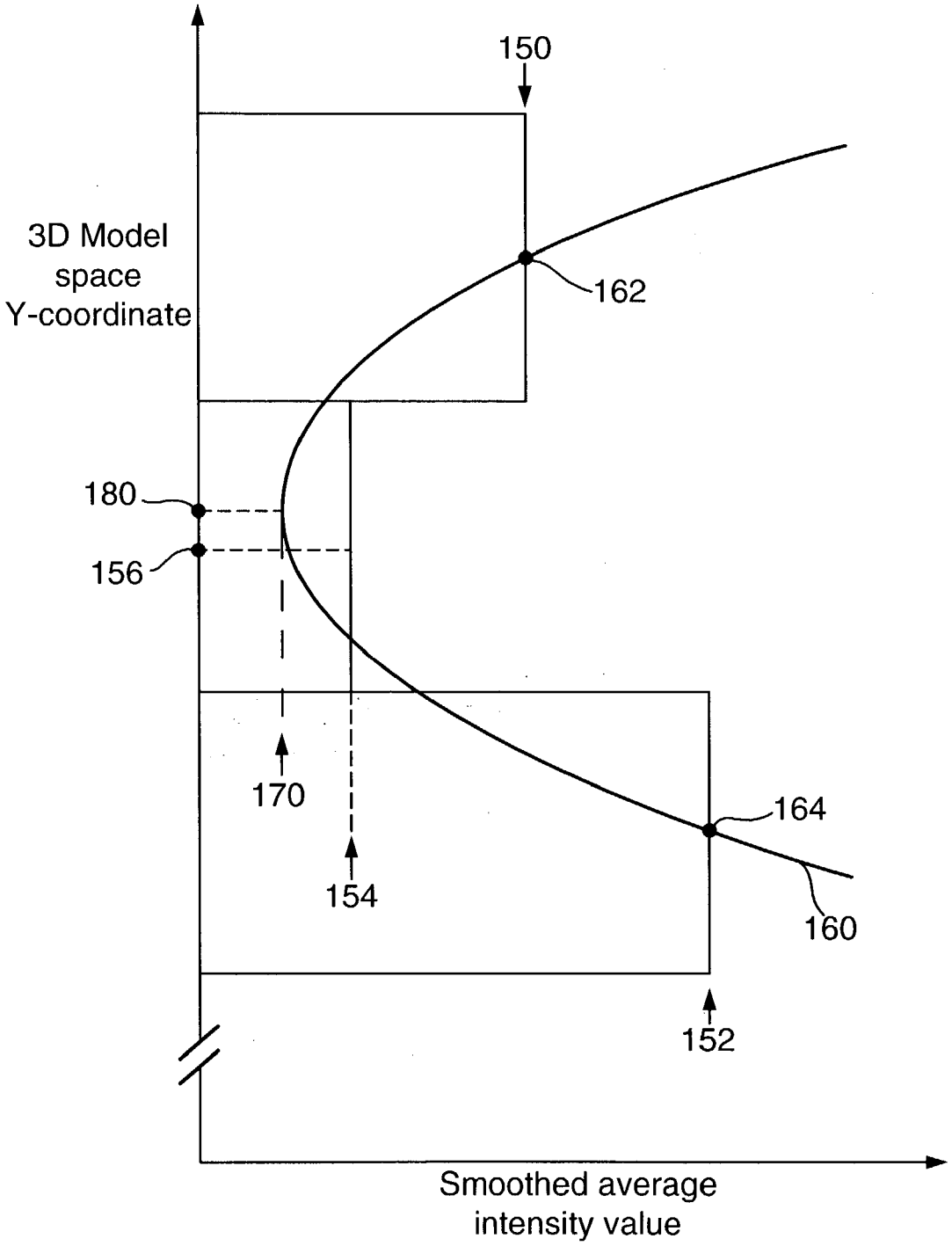

150
3D Model
space
Y-coordinate
162
180
156
170
154
164
160
152
Smoothed average
intensity value

Fig.10a.

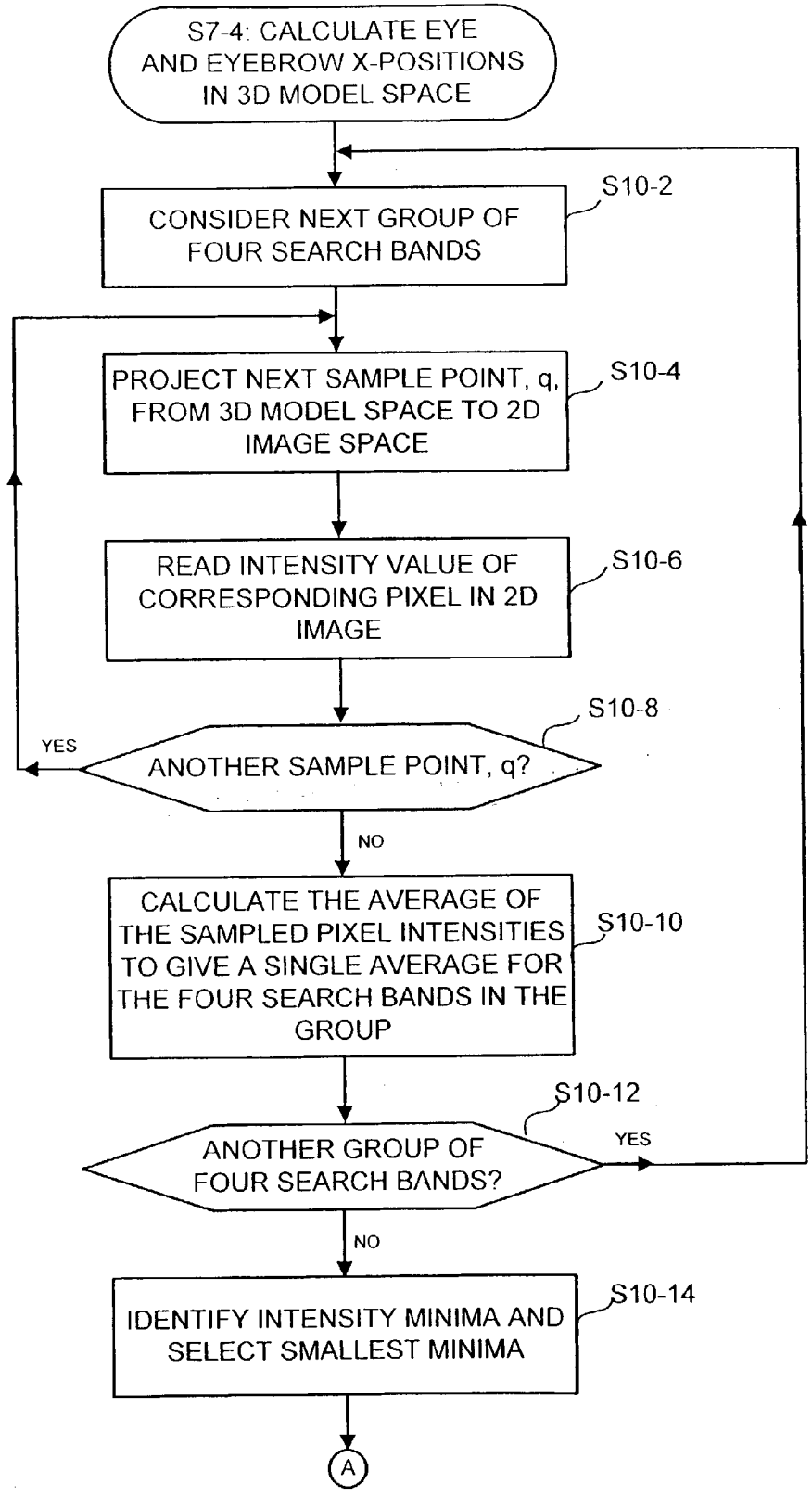

S7-4: CALCULATE EYE AND EYEBROW X-POSITIONS IN 3D MODEL SPACE
CONSIDER NEXT GROUP OF FOUR SEARCH BANDS
S10-2
PROJECT NEXT SAMPLE POINT, q, FROM 3D MODEL SPACE TO 2D IMAGE SPACE
S10-4
READ INTENSITY VALUE OF CORRESPONDING PIXEL IN 2D IMAGE
S10-6
S10-8
YES
ANOTHER SAMPLE POINT, q?
NO
CALCULATE THE AVERAGE OF THE SAMPLED PIXEL INTENSITIES TO GIVE A SINGLE AVERAGE FOR THE FOUR SEARCH BANDS IN THE GROUP
S10-10
S10-12
ANOTHER GROUP OF FOUR SEARCH BANDS?
YES
NO
IDENTIFY INTENSITY MINIMA AND SELECT SMALLEST MINIMA
S10-14
A

Fig.10b.

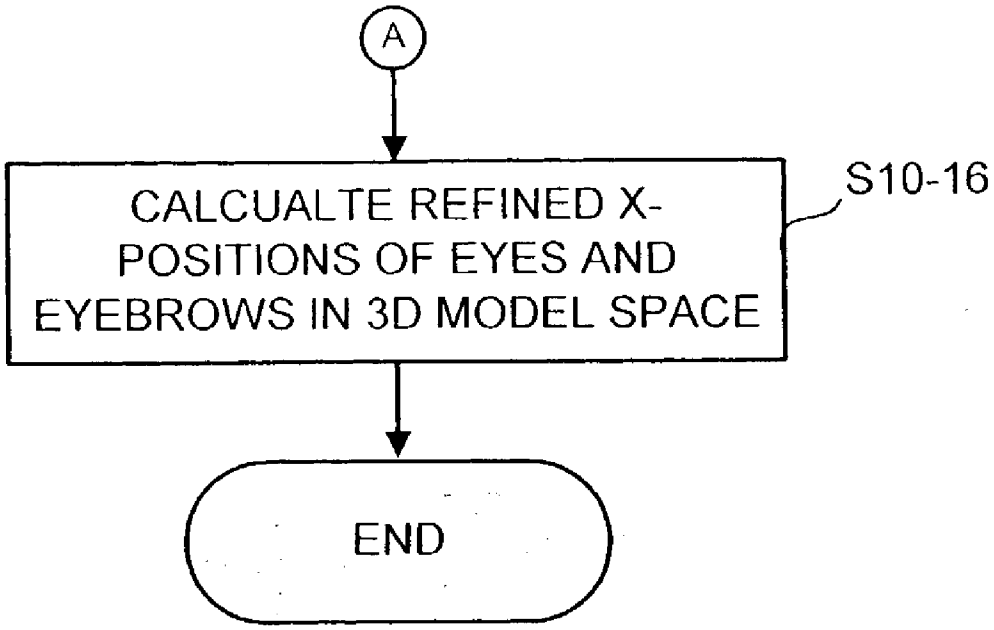
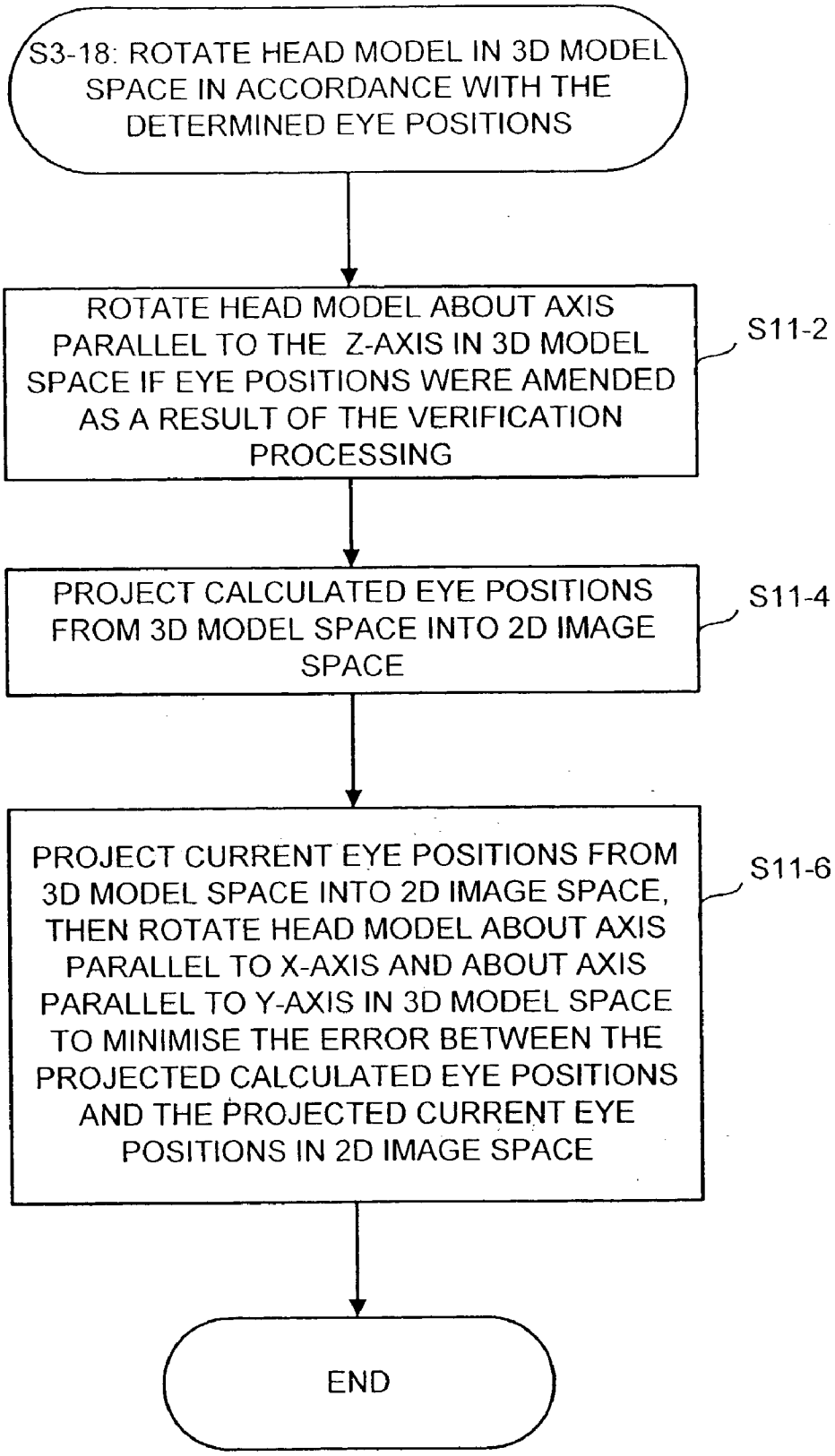

A
CALCUALTE REFINED X-POSITIONS OF EYES AND EYEBROWS IN 3D MODEL SPACE
S10-16
END

Fig.11.


S3-18: ROTATE HEAD MODEL IN 3D MODEL SPACE IN ACCORDANCE WITH THE DETERMINED EYE POSITIONS
ROTATE HEAD MODEL ABOUT AXIS PARALLEL TO THE Z-AXIS IN 3D MODEL SPACE IF EYE POSITIONS WERE AMENDED AS A RESULT OF THE VERIFICATION PROCESSING
S11-2
PROJECT CALCULATED EYE POSITIONS FROM 3D MODEL SPACE INTO 2D IMAGE SPACE
S11-4
PROJECT CURRENT EYE POSITIONS FROM 3D MODEL SPACE INTO 2D IMAGE SPACE, THEN ROTATE HEAD MODEL ABOUT AXIS PARALLEL TO X-AXIS AND ABOUT AXIS PARALLEL TO Y-AXIS IN 3D MODEL SPACE TO MINIMISE THE ERROR BETWEEN THE PROJECTED CALCULATED EYE POSITIONS AND THE PROJECTED CURRENT EYE POSITIONS IN 2D IMAGE SPACE
S11-6
END

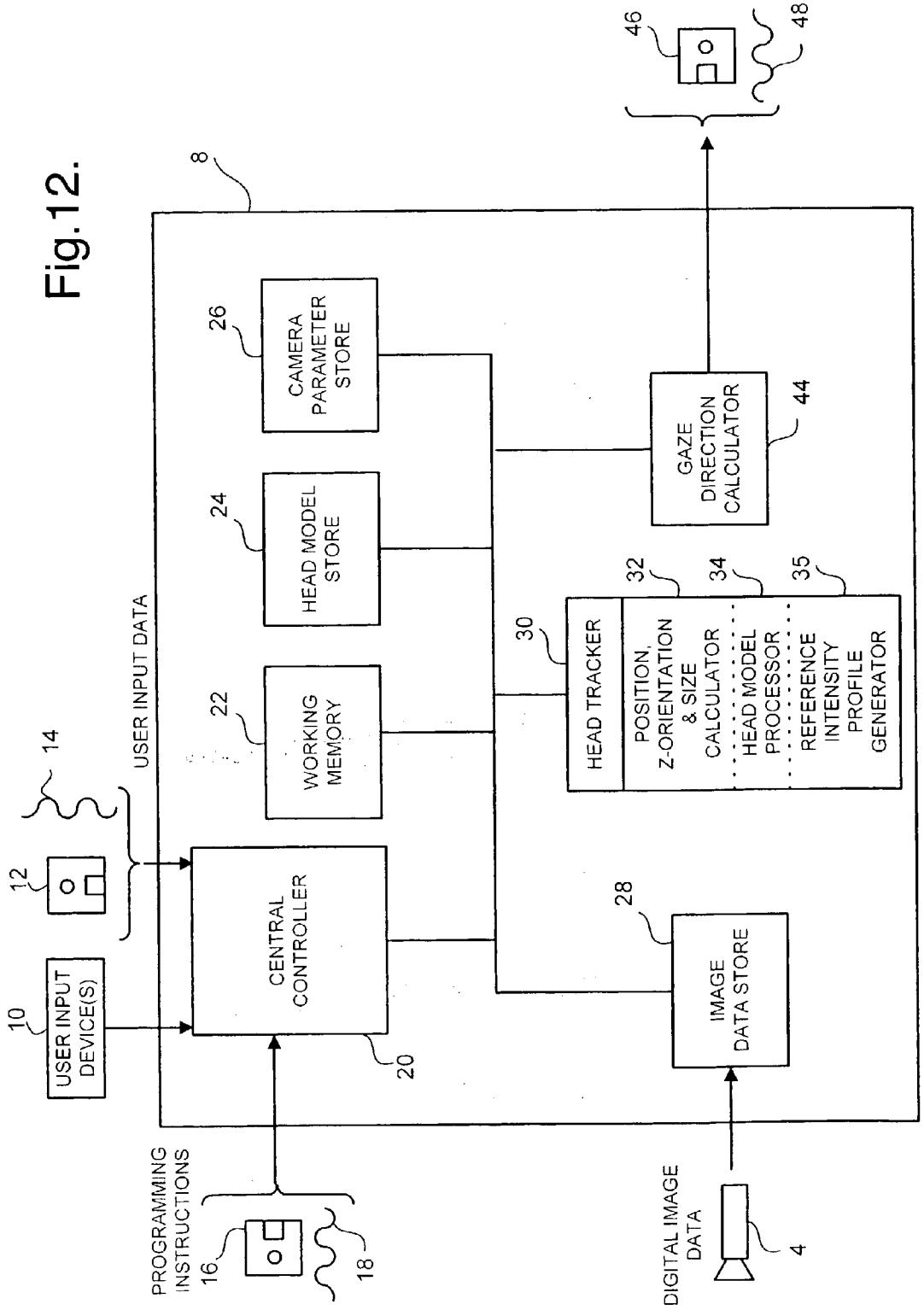

8
USER INPUT DATA
14
12
10
USER INPUT DEVICE(S)
CENTRAL CONTROLLER
20
PROGRAMMING INSTRUCTIONS
16
18
22
WORKING MEMORY
24
HEAD MODEL STORE
26
CAMERA PARAMETER STORE
30
HEAD TRACKER
32
POSITION, Z-ORIENTATION & SIZE CALCULATOR
34
HEAD MODEL PROCESSOR
35
REFERENCE INTENSITY PROFILE GENERATOR
28
IMAGE DATA STORE
DIGITAL IMAGE DATA
4
44
GAZE DIRECTION CALCULATOR
46
48

Fig.12.

Fig.13a.

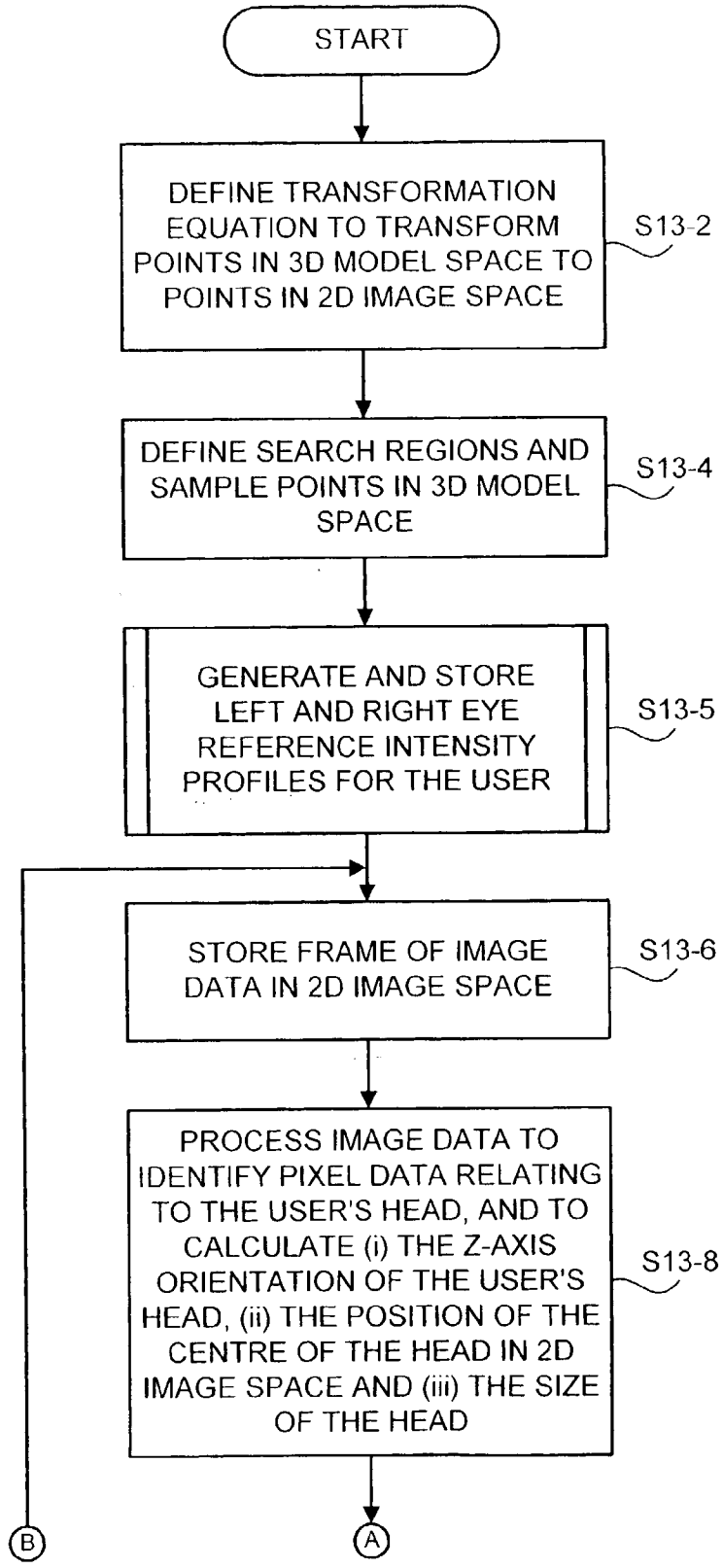

START
DEFINE TRANSFORMATION EQUATION TO TRANSFORM POINTS IN 3D MODEL SPACE TO POINTS IN 2D IMAGE SPACE
S13-2
DEFINE SEARCH REGIONS AND SAMPLE POINTS IN 3D MODEL SPACE
S13-4
GENERATE AND STORE LEFT AND RIGHT EYE REFERENCE INTENSITY PROFILES FOR THE USER
S13-5
STORE FRAME OF IMAGE DATA IN 2D IMAGE SPACE
S13-6
PROCESS IMAGE DATA TO IDENTIFY PIXEL DATA RELATING TO THE USER'S HEAD, AND TO CALCULATE (i) THE Z-AXIS ORIENTATION OF THE USER'S HEAD, (ii) THE POSITION OF THE CENTRE OF THE HEAD IN 2D IMAGE SPACE AND (iii) THE SIZE OF THE HEAD
S13-8
B
A

Fig.13b.

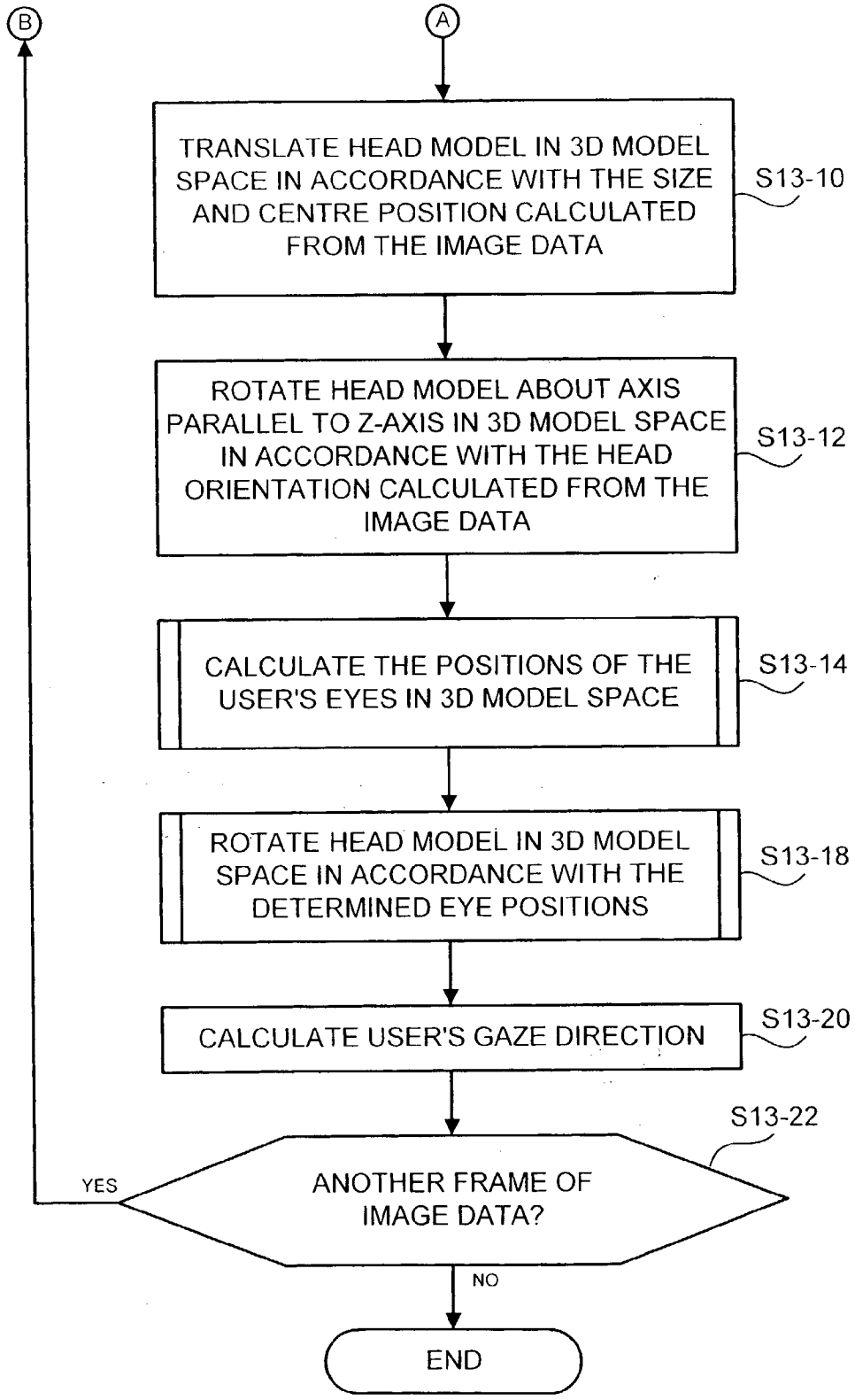

B
A
TRANSLATE HEAD MODEL IN 3D MODEL SPACE IN ACCORDANCE WITH THE SIZE AND CENTRE POSITION CALCULATED FROM THE IMAGE DATA
S13-10
ROTATE HEAD MODEL ABOUT AXIS PARALLEL TO Z-AXIS IN 3D MODEL SPACE IN ACCORDANCE WITH THE HEAD ORIENTATION CALCULATED FROM THE IMAGE DATA
S13-12
CALCULATE THE POSITIONS OF THE USER'S EYES IN 3D MODEL SPACE
S13-14
ROTATE HEAD MODEL IN 3D MODEL SPACE IN ACCORDANCE WITH THE DETERMINED EYE POSITIONS
S13-18
CALCULATE USER'S GAZE DIRECTION
S13-20
S13-22
ANOTHER FRAME OF IMAGE DATA?
YES
NO
END

Fig.14a.

3D Head Coordinate System, H

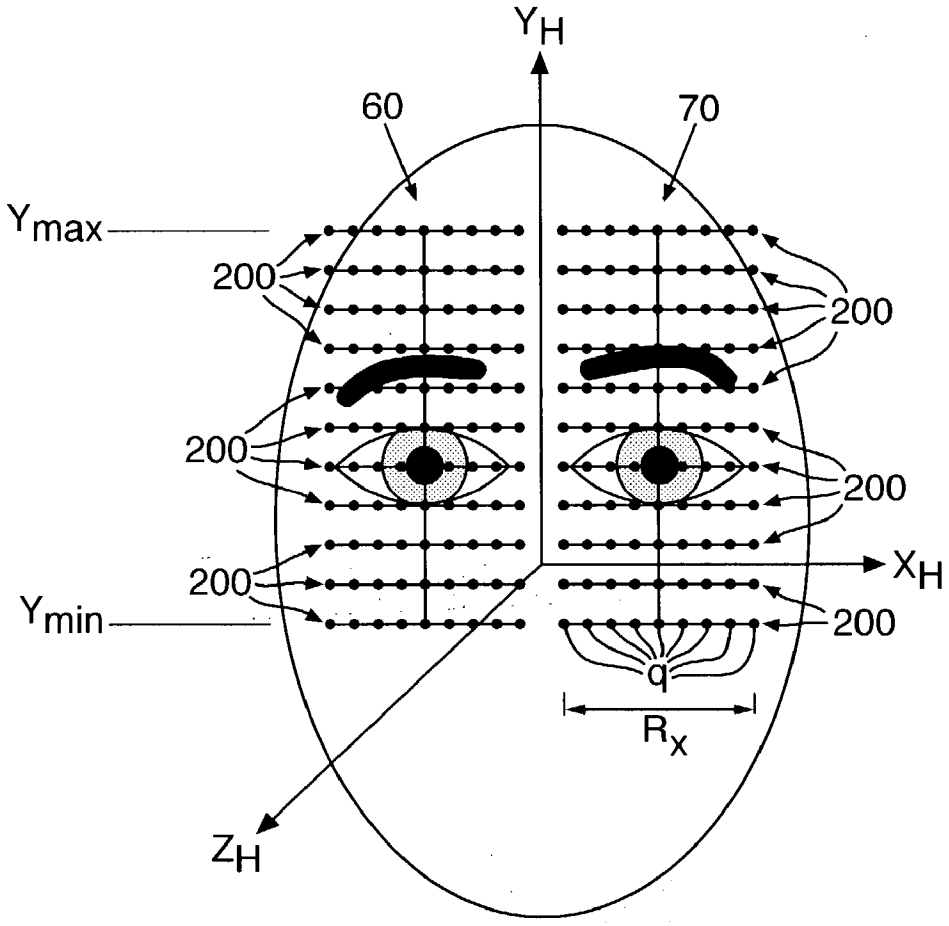


Fig.14b.

3D Head Coordinate System, H

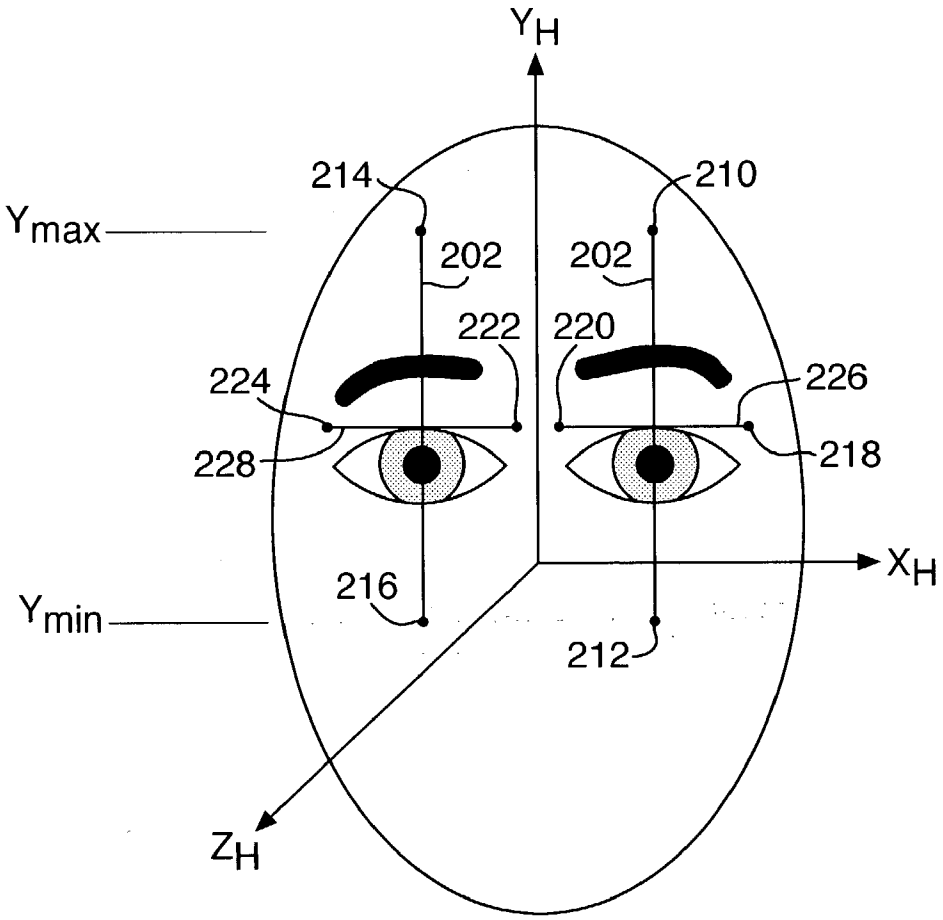


Fig.15a.

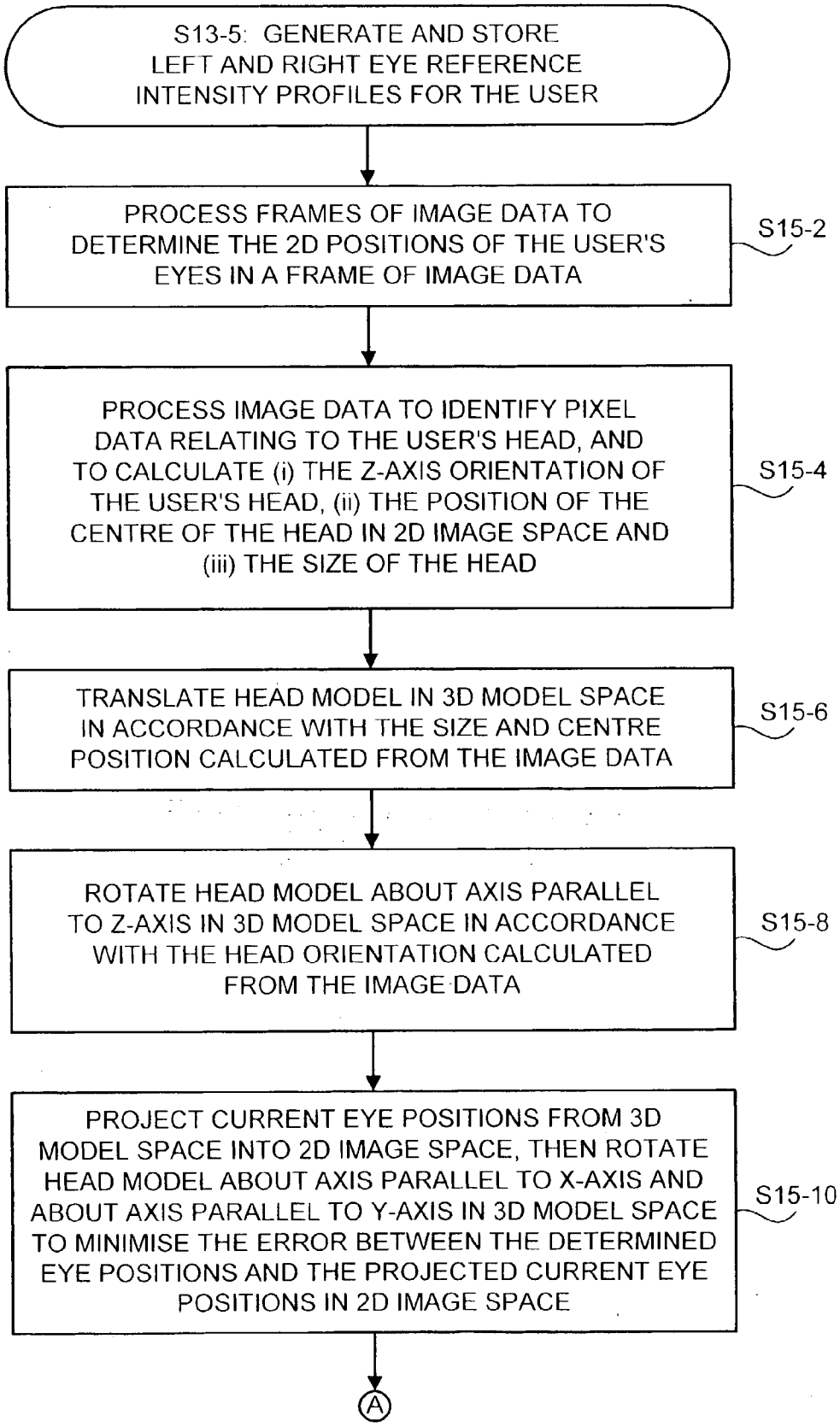

S13-5: GENERATE AND STORE LEFT AND RIGHT EYE REFERENCE INTENSITY PROFILES FOR THE USER
PROCESS FRAMES OF IMAGE DATA TO DETERMINE THE 2D POSITIONS OF THE USER'S EYES IN A FRAME OF IMAGE DATA
S15-2
PROCESS IMAGE DATA TO IDENTIFY PIXEL DATA RELATING TO THE USER'S HEAD, AND TO CALCULATE (i) THE Z-AXIS ORIENTATION OF THE USER'S HEAD, (ii) THE POSITION OF THE CENTRE OF THE HEAD IN 2D IMAGE SPACE AND (iii) THE SIZE OF THE HEAD
S15-4
TRANSLATE HEAD MODEL IN 3D MODEL SPACE IN ACCORDANCE WITH THE SIZE AND CENTRE POSITION CALCULATED FROM THE IMAGE DATA
S15-6
ROTATE HEAD MODEL ABOUT AXIS PARALLEL TO Z-AXIS IN 3D MODEL SPACE IN ACCORDANCE WITH THE HEAD ORIENTATION CALCULATED FROM THE IMAGE DATA
S15-8
PROJECT CURRENT EYE POSITIONS FROM 3D MODEL SPACE INTO 2D IMAGE SPACE, THEN ROTATE HEAD MODEL ABOUT AXIS PARALLEL TO X-AXIS AND ABOUT AXIS PARALLEL TO Y-AXIS IN 3D MODEL SPACE TO MINIMISE THE ERROR BETWEEN THE DETERMINED EYE POSITIONS AND THE PROJECTED CURRENT EYE POSITIONS IN 2D IMAGE SPACE
S15-10
A

Fig.15b.

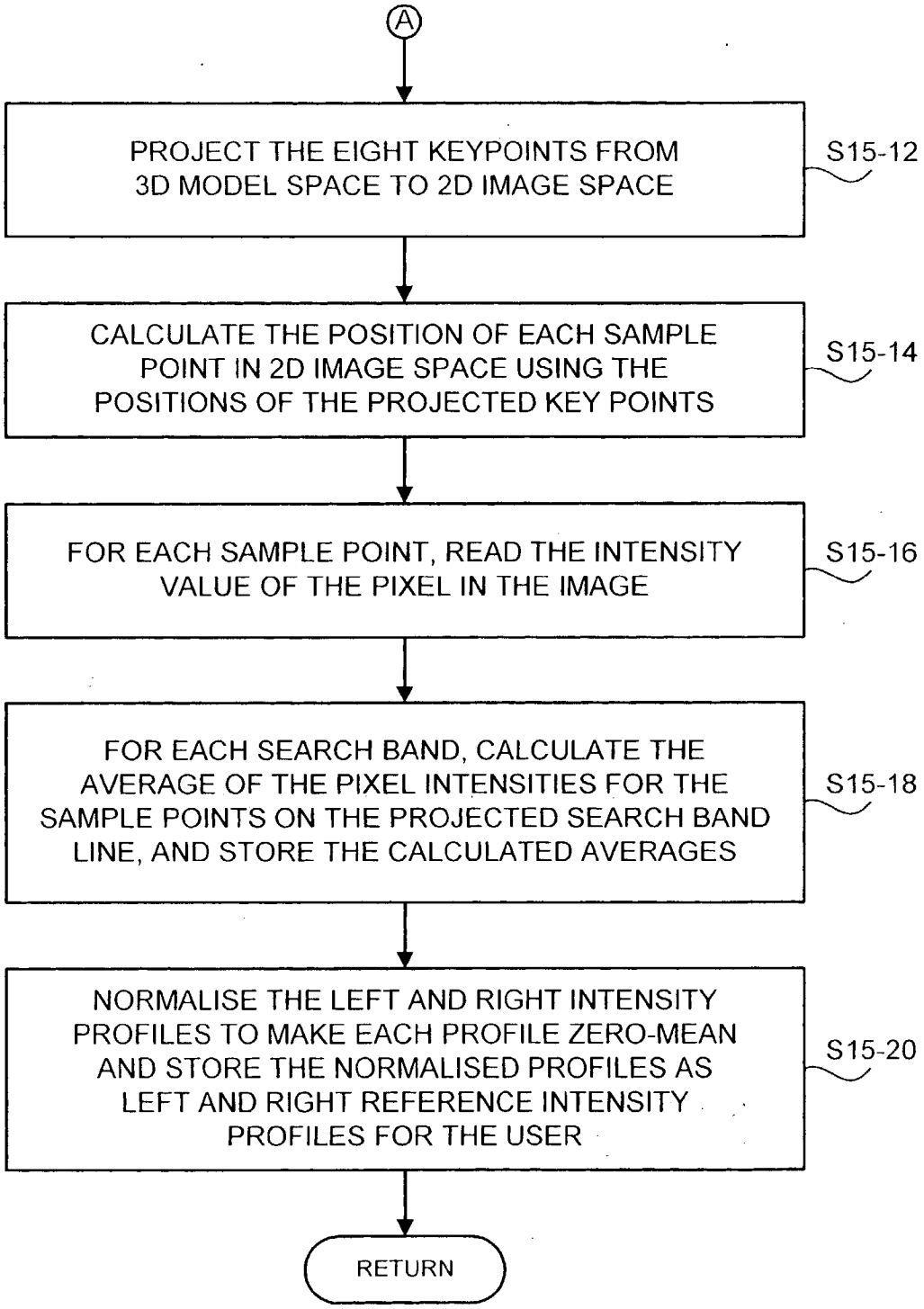

A
PROJECT THE EIGHT KEYPOINTS FROM 3D MODEL SPACE TO 2D IMAGE SPACE
S15-12
CALCULATE THE POSITION OF EACH SAMPLE POINT IN 2D IMAGE SPACE USING THE POSITIONS OF THE PROJECTED KEY POINTS
S15-14
FOR EACH SAMPLE POINT, READ THE INTENSITY VALUE OF THE PIXEL IN THE IMAGE
S15-16
FOR EACH SEARCH BAND, CALCULATE THE AVERAGE OF THE PIXEL INTENSITIES FOR THE SAMPLE POINTS ON THE PROJECTED SEARCH BAND LINE, AND STORE THE CALCULATED AVERAGES
S15-18
NORMALISE THE LEFT AND RIGHT INTENSITY PROFILES TO MAKE EACH PROFILE ZERO-MEAN AND STORE THE NORMALISED PROFILES AS LEFT AND RIGHT REFERENCE INTENSITY PROFILES FOR THE USER
S15-20
RETURN

Fig.16a.

3D Head Coordinate System, H

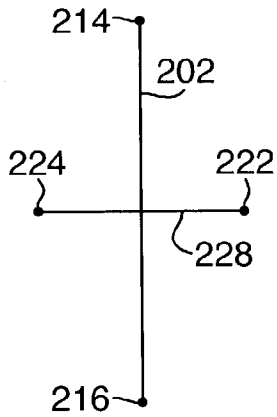


Fig.16b.

2D Image Coordinate System, I

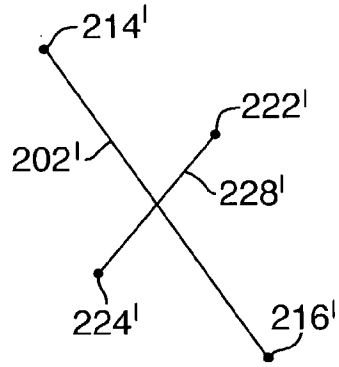


Fig.16c.

2D Image Coordinate System, I

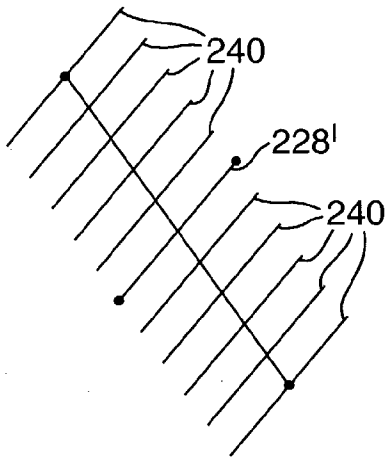


Fig.16d.

2D Image Coordinate System, I

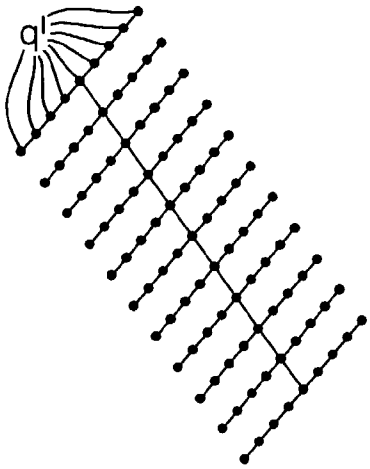


Fig.17.

3D Head Coordinate System, H

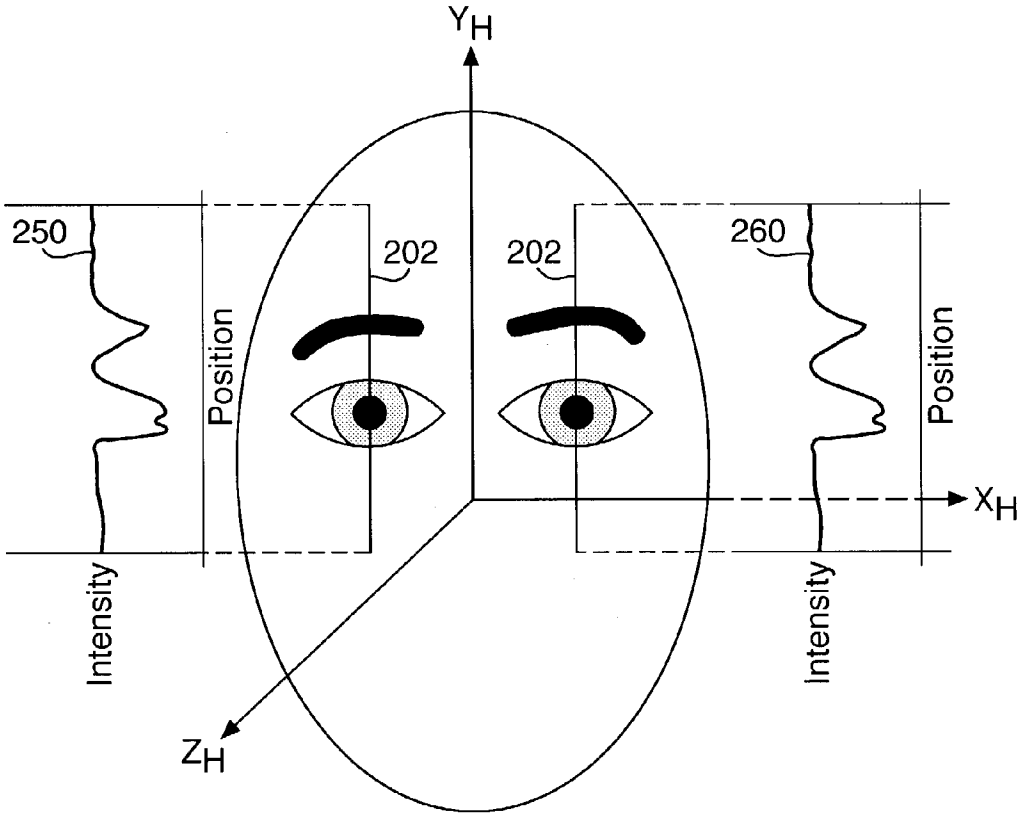


Fig.18.

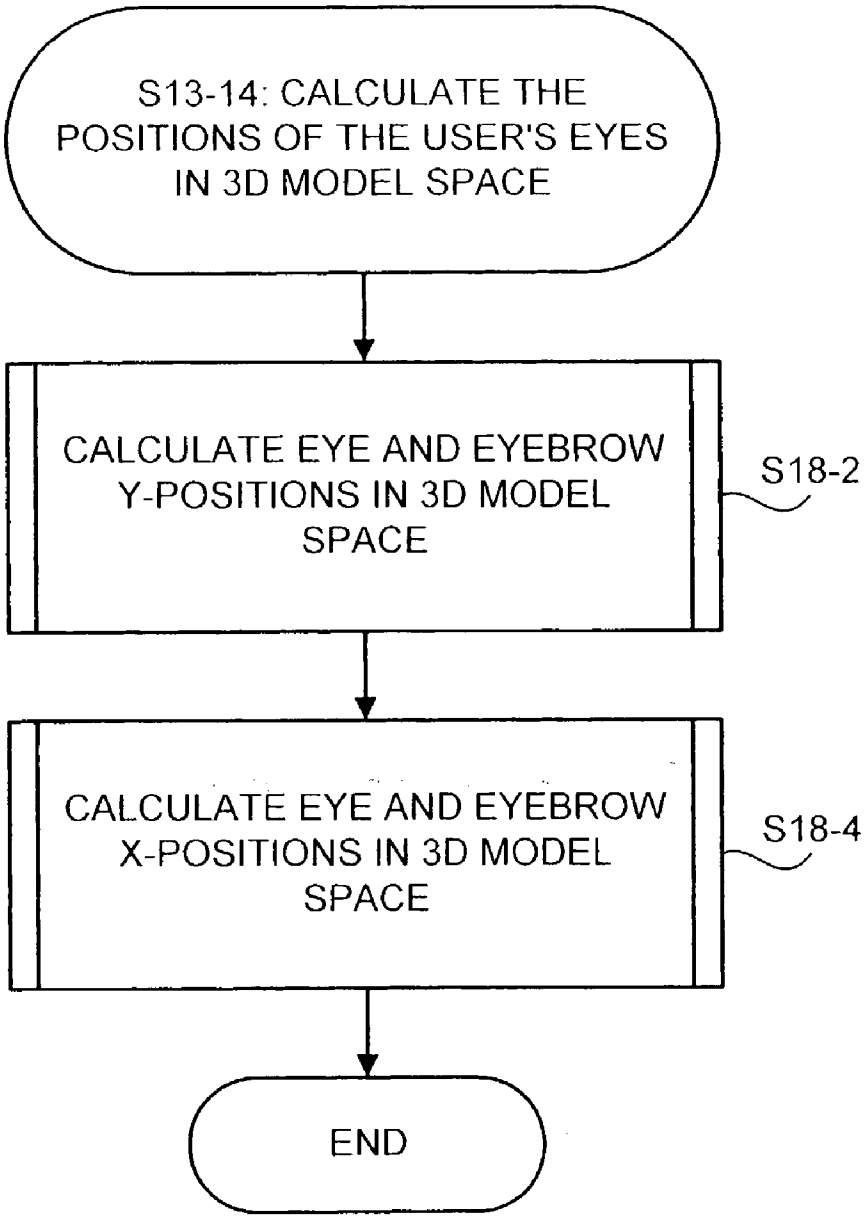

S13-14: CALCULATE THE POSITIONS OF THE USER'S EYES IN 3D MODEL SPACE
CALCULATE EYE AND EYEBROW Y-POSITIONS IN 3D MODEL SPACE
S18-2
CALCULATE EYE AND EYEBROW X-POSITIONS IN 3D MODEL SPACE
S18-4
END

Fig.19a.

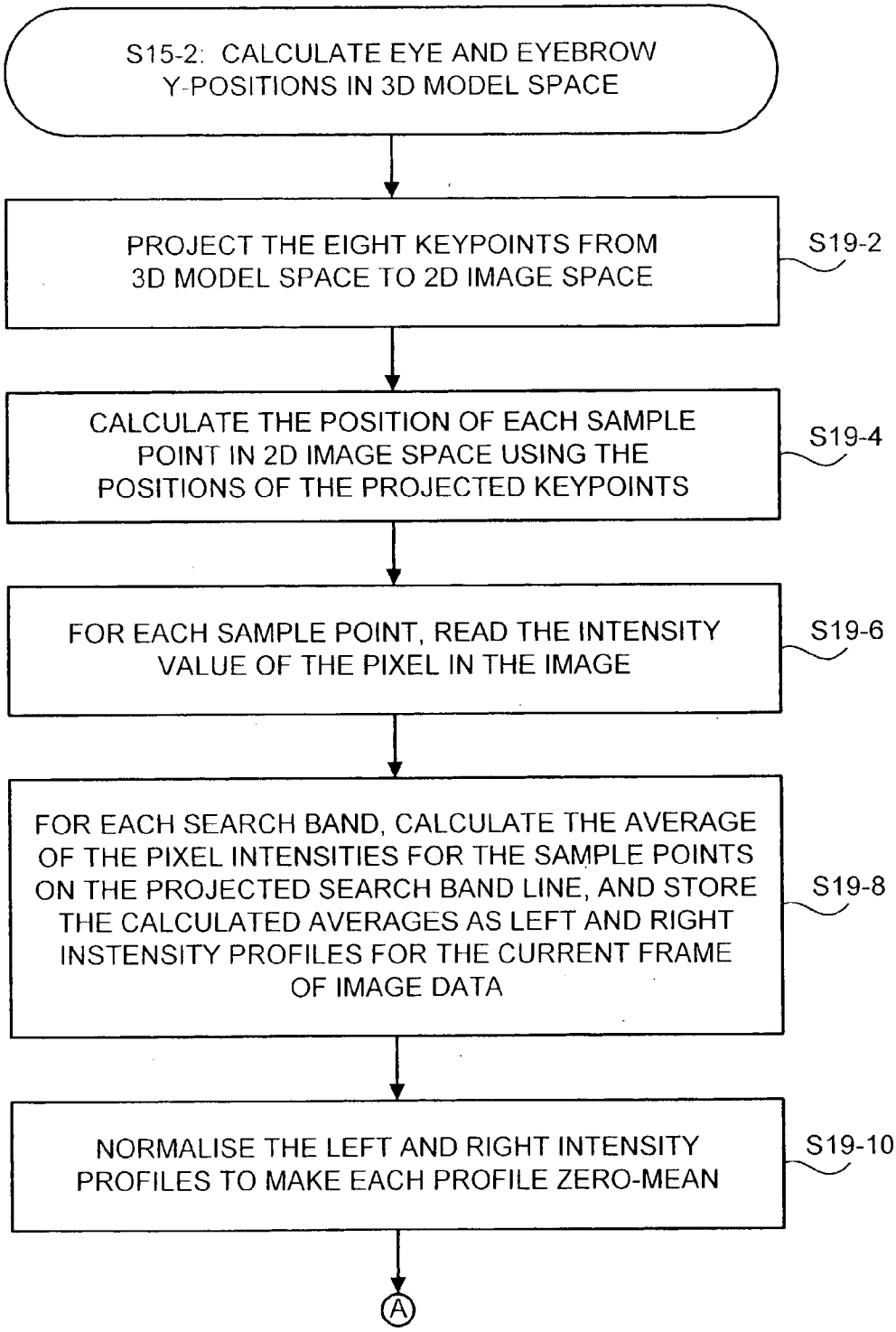

S15-2: CALCULATE EYE AND EYEBROW Y-POSITIONS IN 3D MODEL SPACE
PROJECT THE EIGHT KEYPOINTS FROM 3D MODEL SPACE TO 2D IMAGE SPACE
S19-2
CALCULATE THE POSITION OF EACH SAMPLE POINT IN 2D IMAGE SPACE USING THE POSITIONS OF THE PROJECTED KEYPOINTS
S19-4
FOR EACH SAMPLE POINT, READ THE INTENSITY VALUE OF THE PIXEL IN THE IMAGE
S19-6
FOR EACH SEARCH BAND, CALCULATE THE AVERAGE OF THE PIXEL INTENSITIES FOR THE SAMPLE POINTS ON THE PROJECTED SEARCH BAND LINE, AND STORE THE CALCULATED AVERAGES AS LEFT AND RIGHT INSTENSITY PROFILES FOR THE CURRENT FRAME OF IMAGE DATA
S19-8
NORMALISE THE LEFT AND RIGHT INTENSITY PROFILES TO MAKE EACH PROFILE ZERO-MEAN
S19-10
A

Fig.19b.

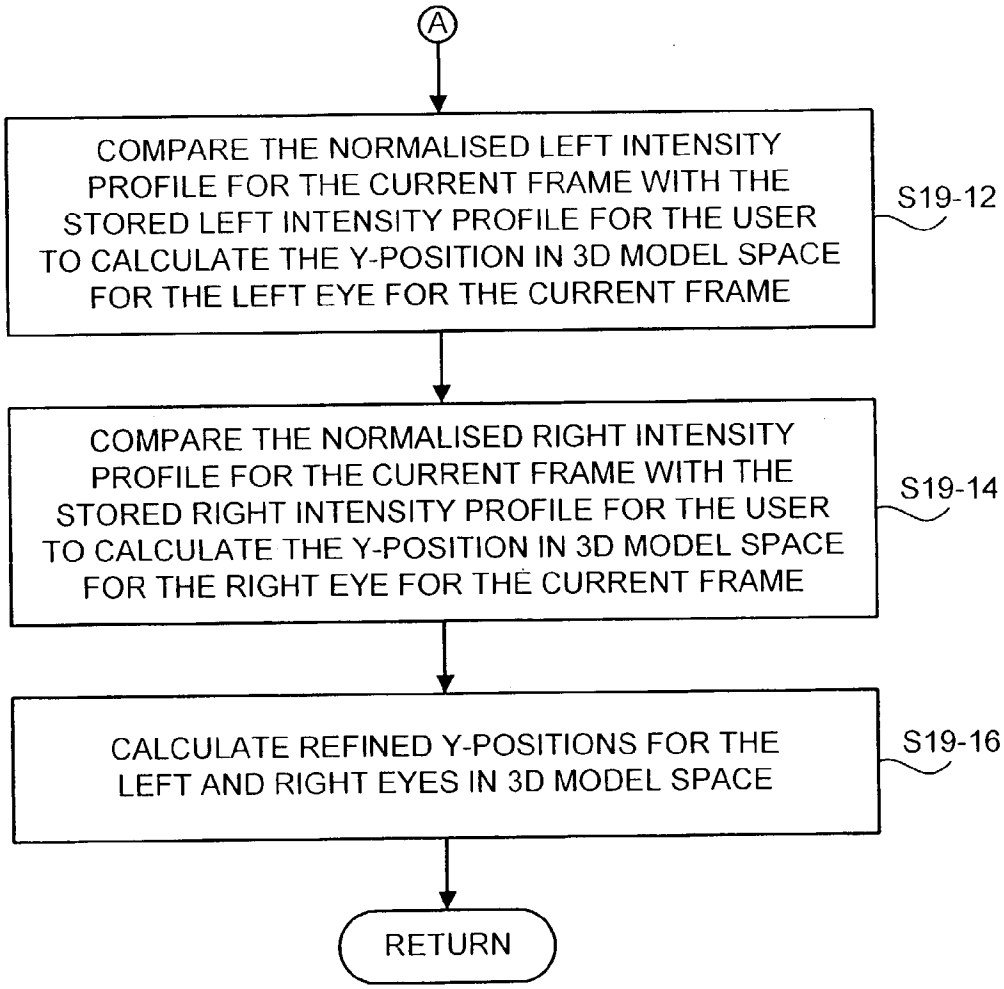

A
COMPARE THE NORMALISED LEFT INTENSITY PROFILE FOR THE CURRENT FRAME WITH THE STORED LEFT INTENSITY PROFILE FOR THE USER TO CALCULATE THE Y-POSITION IN 3D MODEL SPACE FOR THE LEFT EYE FOR THE CURRENT FRAME
S19-12
COMPARE THE NORMALISED RIGHT INTENSITY PROFILE FOR THE CURRENT FRAME WITH THE STORED RIGHT INTENSITY PROFILE FOR THE USER TO CALCULATE THE Y-POSITION IN 3D MODEL SPACE FOR THE RIGHT EYE FOR THE CURRENT FRAME
S19-14
CALCULATE REFINED Y-POSITIONS FOR THE LEFT AND RIGHT EYES IN 3D MODEL SPACE
S19-16
RETURN

Fig.20a.

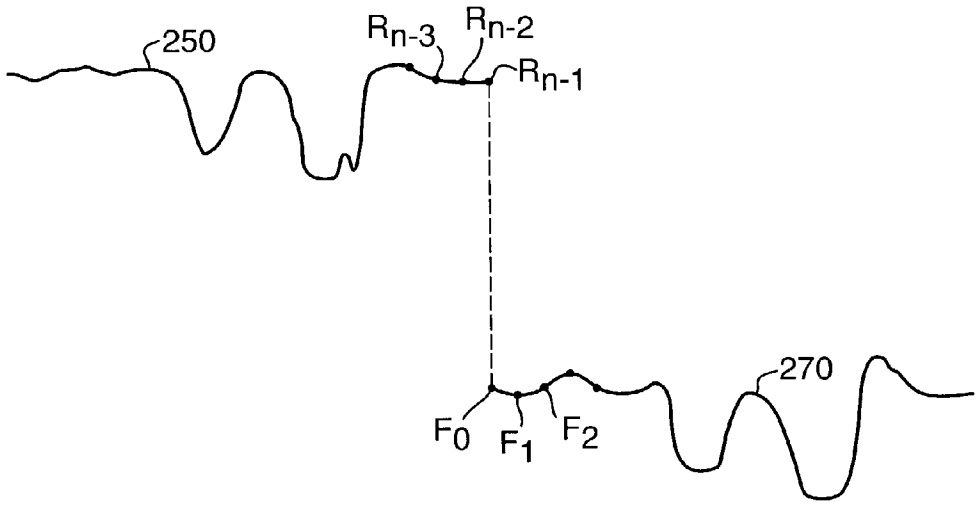


Fig.20b.

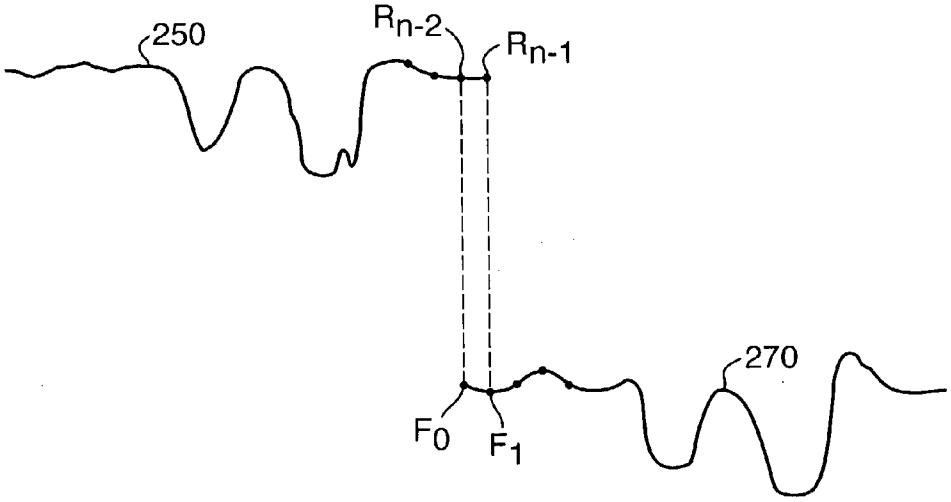


Fig.20c.

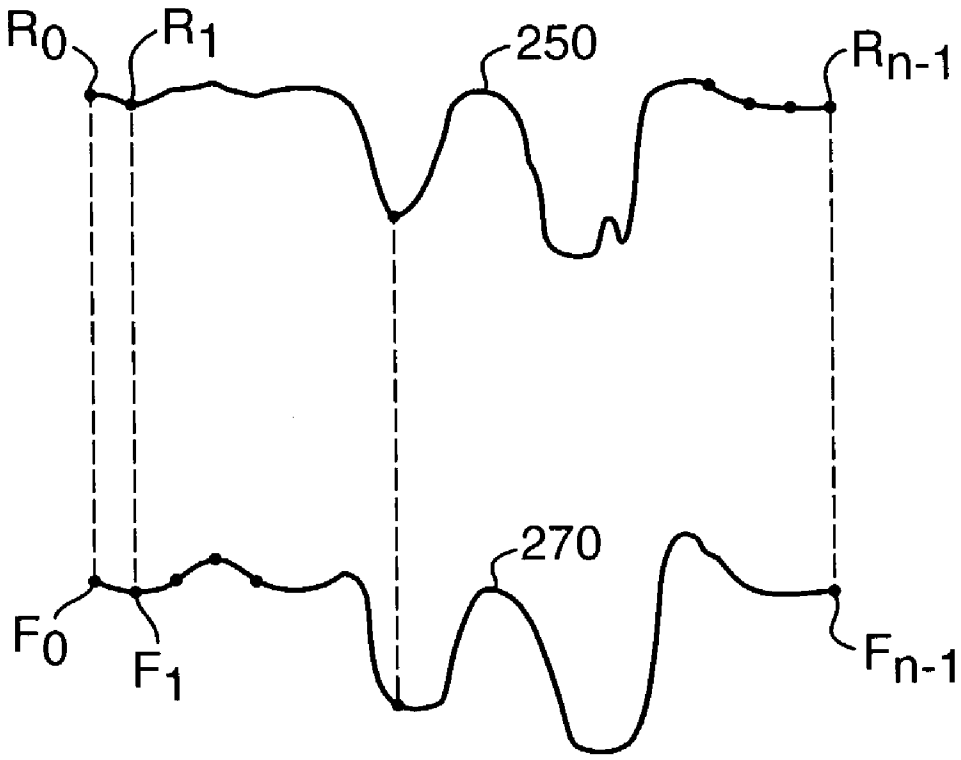


Fig.20d.

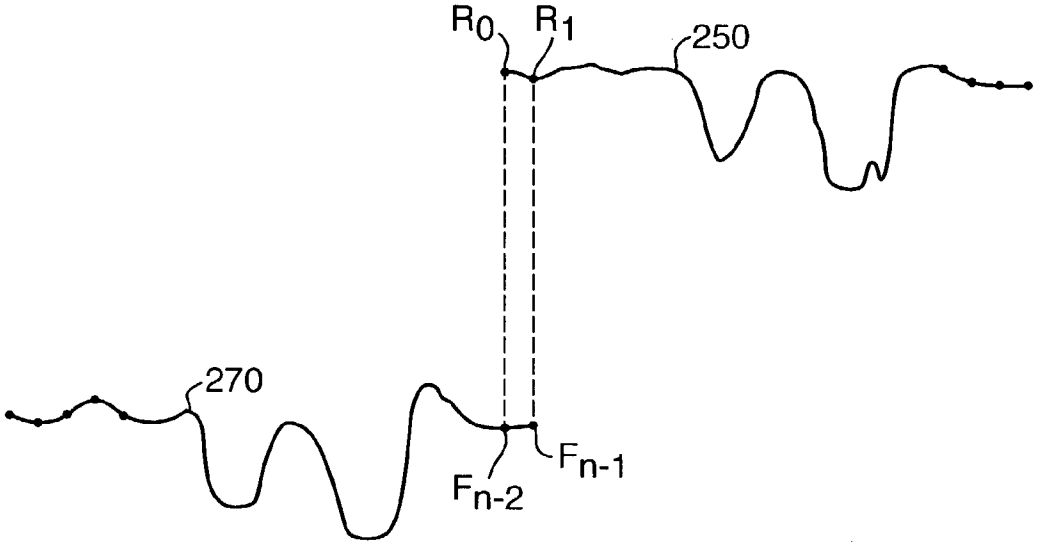
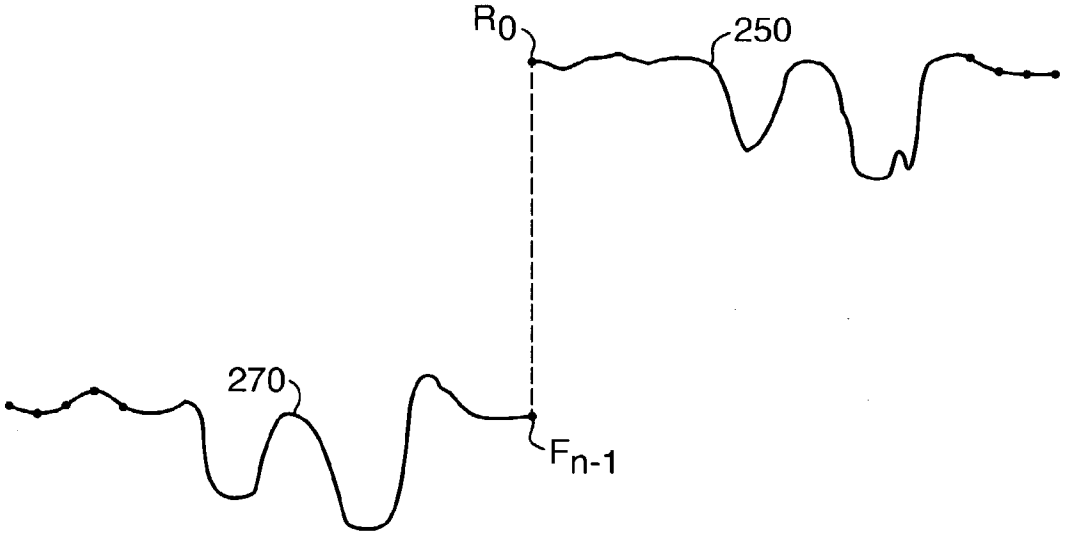


Fig.20e.



EYE TRACKING USING IMAGE DATA

[0001] The present invention relates to the field of eye tracking.

[0002] Tracking the eyes of a real-life person is important for many applications. In particular, it allows the person's gaze direction (and therefore what the person is looking at) to be determined.

[0003] The present invention is concerned with the processing of images showing the face of a user as the user moves his head, to track the movement of the user's eyes in an accurate and reliable manner.

[0004] According to the present invention, eye tracking is carried out using a stored three-dimensional (3D) computer model of at least the eyes and eyebrows of a head in a three-dimensional space. Search regions are defined in the three-dimensional space corresponding to the eyes and eyebrows. For each image in a sequence of images of a user's head, pixels within the projection of the predefined search regions from the three-dimensional space to the two-dimensional image are sampled to determine pixel image values (intensity, or one or more colour component values, or hue, etc) for each search region. Positions for the eyes in the three-dimensional space are then calculated in dependence upon the determined pixel image values. The 3D computer model and search bands are then moved within the three-dimensional space to align the eyes with the calculated eye positions. In this way, when the next image in the sequence is processed, the search bands project into the image from a head configuration in three-dimensional space determined from the previous image. This facilitates reliable and accurate eye tracking for all of the images in the sequence.

[0005] In one embodiment, each search region is a two-dimensional area in the three-dimensional space, and positions for the eyes in the three-dimensional space are calculated on the basis that eyes and eyebrows are recorded as dark bands in the images relative to the other parts of the face, and the dark band caused by an eye will be below the dark band caused by an eyebrow.

[0006] In another embodiment, each search region is a line in the three-dimensional space, and positions for the eyes in the three-dimensional space are calculated by comparing the pixel image values for the search regions with prestored reference image values.

[0007] The present invention provides apparatus and methods for use in performing the processing, and computer program products for enabling a programmable apparatus to become operable to perform the processing.

[0008] Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which like reference numbers are used to designate like parts, and in which:

[0009] **FIG. 1** illustrates the recording of images of a user as the user changes the position and orientation of his head, the image data subsequently being processed to track the user's eyes;

[0010] **FIGS. 2***a* and **2***b* schematically show the components of a first embodiment of the invention, together with the notional functional processing units into which the processing apparatus component may be thought of as being configured when programmed by programming instructions;

[0011] **FIGS. 3***a* and **3***b* show the processing operations performed by the processing apparatus in **FIG. 2** to process input data;

[0012] **FIG. 4** schematically illustrates the transformation defined at step **S3-2** in **FIG. 3**;

[0013] **FIG. 5** illustrates the search regions and sample points defined at step **S3-4** in **FIG. 3** for use in determining the y-axis positions of the user's eyes and eyebrows;

[0014] **FIGS. 6***a* to **6***f* illustrate the search regions and sample points defined at step **S3-4** in **FIG. 3** for use in determining the x-axis positions of the user's eyes and eyebrows;

[0015] **FIG. 7** shows the processing operations performed at step **S3-14** in **FIG. 3**;

[0016] **FIGS. 8***a* and **8***b* show the processing operations performed at step **S7-2** in **FIG. 7**;

[0017] **FIG. 9** illustrates the processing to calculate a refined y-position at step **S8-22** in **FIG. 8**;

[0018] **FIGS. 10***a* and **10***b* show the processing operations performed at step **S7-4** in **FIG. 7**;

[0019] **FIG. 11** shows the processing operations performed at step **S3-18** in **FIG. 3**;

[0020] **FIG. 12** schematically shows the components of a second embodiment of the invention, together with the notional functional processing units into which the processing apparatus component may be thought of as being configured when programmed by programming instructions;

[0021] **FIGS. 13***a* and **13***b* show the processing operations performed by the processing apparatus in **FIG. 12**;

[0022] **FIGS. 14***a* and **14***b* illustrate the search bands and sample points defined at step **S13-4** in **FIG. 4** for use in determining the Y-axis positions of the user's eyes;

[0023] **FIGS. 15***a* and **15***b* show the processing operations performed at step **S13-5** in **FIG. 13**;

[0024] **FIGS. 16***a* to **16***d* illustrate the projection of keypoints and the calculation of sample points at steps **S15-12** and **S15-14** of **FIG. 15**;

[0025] **FIG. 17** illustrates the reference intensity profiles generated by the processing at step **S15-18** of **FIG. 15**;

[0026] **FIG. 18** shows the processing operations performed at step **S13-14** in **FIG. 13**;

[0027] **FIGS. 19***a* and **19***b* show the processing operations performed at step **S15-2** in **FIG. 15**; and

[0028] **FIGS. 20***a* to **20***e* show examples to illustrate the processing performed in step **S19-12** in **FIG. 19**.

[0029] First Embodiment

[0030] Referring to **FIG. 1**, in an embodiment of the invention, images of a user **2** are recorded by a single video camera **4**, of conventional design, as the user **2** changes the position and orientation of his head, which, in this embodiment, occurs as the user operates a personal computer **6**.

[0031] The digital image data recorded by camera **4** is input to the processing apparatus component **8** of the personal computer **6**, which processes the data to track the eyes of the user **2** in a way which will be described below.

[0032] The processing apparatus component **8** of the personal computer **6** contains, in a conventional manner, one or more processors, memories, graphics cards, etc.

[0033] Referring to **FIGS. 2***a* and **2***b,* the processing apparatus component **8** is programmed to operate in accordance with programming instructions input, for example, as instructions stored on a storage medium, such as disc **16**, and/or as a signal **18** input to the processing apparatus **8**, for example from a remote database, by transmission over a communication network (not shown) such as the Internet or by transmission through the atmosphere, and/or entered by the user via a user input device **10** such as a keyboard.

[0034] As will be described in more detail below, the programming instructions comprise instructions to cause the processing apparatus **8** to become configured to process input data defining a three-dimensional (3D) computer model of the head of the user **2**, input data defining parameters of the camera **4**, and image data recorded by camera **4** of the user **2**, to track the eyes of the user **2** through each frame of image data received from camera **4**. More particularly, search regions are defined in the three-dimensional co-ordinate space of the 3D head model to cover the eyes and eyebrows therein, and sample points are defined within each search region. For each frame of image data received from camera **4**, each sample point defined in the three-dimensional space of the 3D head model is projected from its current position (resulting from the processing of the previous frame of image data received from camera **4**) into the 2D image space, and the value of the corresponding pixel is determined. An average is then calculated for all of the sample pixel values corresponding to the sample points in each search region. This defines a respective average intensity for each search band. Based on the positions of the intensity minima within the search regions, the positions of the user's eyes and eyebrows in the three-dimensional coordinate space of the head model are determined using the principle that the user's eyes and eyebrows will both generate dark bands (minima) in the image and the eye dark bands will always be below the eyebrow dark bands. Based on these positions, the 3D head model and associated search regions are moved in 3D space so that the positions of the eyes in the 3D model correspond to the positions determined from the 2D image recorded by camera **4**. This processing is repeated for each frame of image data received from camera **4** to track the user's eyes in an accurate and reliable way.

[0035] When programmed by the programming instructions, processing apparatus **8** can be thought of as being configured as a number of functional units for performing processing operations. Examples of such functional units and their interconnections are shown in **FIGS. 2***a* and **2***b*. The units and interconnections illustrated in **FIGS. 2***a* and **2***b* are, however, notional, and are shown for illustration purposes only to assist understanding; they do not necessarily represent units and connections into which the processor, memory etc of the processing apparatus **8** actually become configured.

[0036] Referring to the functional units shown in **FIGS. 2***a* and **2***b,* a central controller **20** is arranged to process inputs from the user input devices **10** and to control the storage of data input by the user on a data storage medium, such as disc **12**, or as a signal **14**. Central controller **20** is also arranged to provide control and processing for the other functional units.

[0037] Working memory **22** is provided for use by central controller **20** and the other functional units.

[0038] Head model store **24** is configured to store data input to the processing apparatus **8**, for example as data stored on storage medium **12** or as a signal **14**, defining a 3D computer model of the head of the user **2**. The input data defining the 3D computer model of the user's head may be generated, for example, in a conventional manner by a laser scanner, 3D touch sensing probe, etc.

[0039] Camera parameter store **26** is configured to store data input to the processing apparatus **8**, for example as data stored on a storage medium **12**, as a signal **14**, or using a user input device **10**, defining parameters of the camera **4** which records the image data for processing. More particularly, in this embodiment, camera parameter store **26** is configured to store data defining a scale factor of the camera **4**. In this embodiment, the image data for each image recorded by camera **4** is defined in a two-dimensional coordinate system having x and y axes parallel to the x and y axes of the three-dimensional imaging coordinate system of camera **4**. The z-axis of the camera coordinate system is defined to lie along the optical axis of the camera **4**, so that the origin of the camera coordinate system is at the optical centre of the camera **4**. The scale factor stored in camera parameter store **36** is a scalar constant defining how the size of a unit-size object changes in the recorded image as the object moves in the z-axis direction of the camera coordinate system. Consequently, as will be understood by the skilled person, the scale factor will depend upon a number of internal camera parameters and is determined by calibration in a conventional manner.

[0040] Image data store **28** is configured to store frames of image data received from camera **4**. In this embodiment, image data store **28** has a capacity to store one frame of image data, which is then processed in real-time and discarded before the next frame of image data is received from camera **4**.

[0041] Head tracker **30** is arranged to process the pixel data defining each image frame stored in image data store **28**, to calculate a position for the centre of the 3D computer head model in three-dimensional space and positions for the eyes of the 3D computer head model in three-dimensional space. In addition, head tracker **30** is arranged to translate and rotate the 3D computer head model in three-dimensional space in accordance with the calculated positions. In this way, the position and orientation of the 3D computer head model is updated after the processing of each frame of image data.

[0042] In this embodiment, head tracker **30** comprises a position, z-orientation and size calculator **32**, and a head model processor **34**.

[0043] Position, z-orientation and a size calculator **32** is arranged to process each frame of image data to identify pixels therein relating to the face of the user **2** and, in dependence upon the identified pixels, to determine the position and size of the user's head in the image, and the

orientation of the user's head about an axis perpendicular to the 2D image data plane (which corresponds to an axis parallel to the z-axis of the three-dimensional coordinate space of the 3D computer head model in this embodiment).

[0044] Referring to **FIG. 2***b,* the head model processor **34** comprises a transformation calculator **36**, a search parameter definer **38**, an eye position calculator **40** and a rotator and translator **42**.

[0045] Transformation calculator **36** is arranged to define a transformation equation to map points from the three-dimensional coordinate space in which the 3D head model of the user is defined into the two-dimensional image space in which a frame of image data received from camera **4** is defined.

[0046] Search parameter definer **38** is arranged to define search regions in the three-dimensional space of the 3D head model so as to cover specific parts of the 3D head model, which, as will be described in detail below, comprise the eyes and eyebrows of the 3D head model. In addition, search parameter definer **38** is arranged to define sample points within each search region for subsequent projection into the 2D coordinate space of a frame of image data received from camera **4**.

[0047] Eye position calculator **40** is arranged to determine positions for the eyes of the 3D computer head model using each frame of image data received from camera **4**. This is done by projecting the sample points defined by search parameter definer **38** from the three-dimensional space of the head model into the two-dimensional space of the image data, and processing the intensity values of the image pixels corresponding to the projected points. This processing will be described in detail below.

[0048] Rotator and translator **42** is arranged to rotate and translate the 3D computer head model within its three-dimensional coordinate system in dependence upon the results of the processing by position, z-orientation and size calculator **32** and eye position calculator **40**. In practice, this is done by changing the values of the rotation and translation components of the transformation equation defined by transformation calculator **36**. Again, this processing will be described in detail below.

[0049] Referring again to **FIG. 2***a,* gaze direction calculator **44** is arranged to determine the user's eye orientation and to calculate the direction in which the user **2** is looking for each frame of image data based on the determined eye orientation and the position and orientation of the 3D computer head model after it has been rotated and translated by rotator and translator **42**.

[0050] Data defining the calculated gaze direction may be processed further within processing apparatus **8** by an additional application (not shown) or may be output from the apparatus, for example as data on a data storage medium, such as disc **46**, and/or as a signal **48**. A recording of the output data may be made by recording the output signal **48** either directly or indirectly using recording apparatus (not shown). More particularly, the data may be output from processing apparatus **8** and stored directly on storage medium **46**. Alternatively, the data output from processing apparatus **8** may be stored on a "master" storage medium and then further storage media storing the code may be generated therefrom. In this way, an indirect recording is made of the data. Similarly, the signal **48** carrying output data may be the direct output of processing apparatus **8** or a signal generated indirectly therefrom.

[0051] Referring now to **FIG. 3**, the processing operations performed by the functional components within processing apparatus **8** in this embodiment will now be described.

[0052] At step **S3-2**, transformation calculator **36** defines a transformation equation to map points in the three-dimensional coordinate system in which the 3D computer head model of the user **2** is defined into points in the two-dimensional coordinate system in which each frame of image data received from camera **4** is defined. More particularly, in this embodiment, transformation calculator **36** defines a projective transformation equation in accordance with the camera parameters stored in camera parameter store **26**. As explained previously, in this embodiment, the image data for each image recorded by camera **4** is defined in a two-dimensional coordinate system having x and y axes parallel to the x and y axes of the three-dimensional imaging coordinate system of camera **4**. The z-axis of the camera coordinate system is defined to lie along the optical axis of the camera **4**, so that the origin of the camera coordinate system is at the optical centre of the camera **4**. Thus, referring to **FIG. 4, a** transformation equation is defined which maps points in the 3D head coordinate system "H" to points in the 2D image coordinate system "I" in accordance with the following equation:

$$P_{image}=TSR_zR_yR_xP_{head} \quad (1)$$

[0053] where

[0054] P_{image} is a point in 2D image space

[0055] P_{head} is a point in 3D head model space

[0056] T is a translation matrix defining translation in the 3D coordinate system of the 3D computer head model

[0057] R_x, R_y and R_z are rotations about the x, y and z axes respectively in the 3D coordinate system of the 3D computer head model

[0058] S is a scale matrix defined by $S=(^s/P_z)I$, where s is the scale factor previously stored in camera parameter store **26**, P_z is the z-coordinate of P_{head} and I is the identity matrix.

[0059] At step **S3-2**, transformation calculator **36** defines initial values for T, R_z and R_y and R_x which map the 3D computer head model into 2D image space such that the head is at the centre of the image, is front-facing, and has a predetermined size. As will be explained below, T, R_z, R_y and R_x are updated to define movement of the 3D computer head model representing real world movement of the head of user **2** determined from image data received from camera **4**.

[0060] Referring again to **FIG. 3**, at step **S3-4**, search parameter definer **38** defines search regions within the three-dimensional coordinate system of the 3D computer head model together with a plurality of sample points within each search region. In this embodiment, search parameter definer **38** defines a set of search regions for use in calculating y-coordinates of the eyes and eyebrows in the three-dimensional coordinate system and a set of search regions for use in calculating x-coordinates of the eyes and eyebrows in the three-dimensional coordinate system.

[0061] **FIGS. 5 and 6** show the search regions defined at step S3-4 by search parameter definer **38** in this embodiment. Referring to **FIG. 5**, the set of search regions defined by search parameter definer **38** within the three-dimensional coordinate system of the 3D computer head model for use in determining the y-axis positions of the head model's eyes and eyebrows in the 3D space are shown.

[0062] More particularly, search parameter definer **38** defines a left group **60** of search bands **80** and a right group **70** of search bands **80** arranged on either side of the head symmetry line (which, in this embodiment, is defined by the y-axis of the three-dimensional coordinate space).

[0063] In this embodiment, the search bands **80** within each group **60,70** are adjacent and non-overlapping. Each search band **80** is defined relative to the 3D computer head model so that the search bands move with the head model when it is translated and rotated within the three-dimensional coordinate system.

[0064] Search parameter definer **38** defines the bands **80** within each group **60,70** to lie between y-axis limits of Y_{min} and Y_{max}. These limits are defined to ensure that the search bands **80** within each group cover fully the left eye and left eyebrow and the right eye and right eyebrow, respectively of the 3D computer head model.

[0065] The centre, S_l, of the left group **60** of search bands and the centre, S_r, of the right group **70** of search bands are defined as follows:

$$S_l = \frac{E_l + B_l}{2} \tag{2}$$

$$S_r = \frac{E_r + B_r}{2} \tag{3}$$

[0066] where E_l and B_l are the x,y-positions of the centres of the left eye and left eyebrow, respectively, in the 3D coordinate system of the head model, and E_r and B_r are the x,y-positions of the centres of the right eye and right eyebrow, respectively, in the 3D coordinate space.

[0067] Thus, the centre of each group **60,70** is the mid-point in the y-axis direction between the centre of an eye and the corresponding eyebrow.

[0068] Each search band **80** is defined, in this embodiment, to be a rectangular region centred on a point lying on a perpendicular line between Y_{max} and Y_{min} which passes through the point S_l or S_r. Accordingly, each search band lies in a plane perpendicular to the z-axis of the 3D coordinate system. In this embodiment, the z-coordinate value of the plane containing the search bands is set such that it is equal to the z-coordinate value of the eyes of the 3D computer head model (with the result that the plane passes through the 3D computer head model).

[0069] The width of each search band **80** in the x-axis direction is R_x. Search parameter definer **38** defines R_x to ensure that each search band **80** is sufficiently wide in the x-axis direction to enclose fully an eye or eyebrow.

[0070] The width of each search band **80** in the y-axis direction is R_y. Search parameter definer **38** defines R_y to ensure that each band is sufficiently wide to enclose an eye pupil or eyebrow, but is sufficiently narrow to ensure that each search band **80** cannot enclose both a part of an eye pupil as well as a part of an eyebrow. In this embodiment, Y_{max}, Y_{min} and R_y are such that there are **10** search bands **80** in each group **60,70** as shown in **FIG. 5** (although a different number of search bands **80** could, of course, be set).

[0071] Within each respective search band **80**, search parameter definer **38** defines a plurality of sample points, "q" (shown for only some of the search bands **80** in **FIG. 5** but, in practice, defined for each search band **80**). In this embodiment, the number of samples points "q" is defined to be the same for each search band **80**, and the number for each search band is selected to be in the range 20 to 50 points, which are evenly spaced throughout the search band.

[0072] **FIGS. 6***a* to **6***f* show the set of search regions defined at step S3-4 by search parameter definer **38** within the three-dimensional coordinate system of the 3D computer head model for subsequent use in determining the x-axis positions of the head model's eyes and eyebrows in the three-dimensional space.

[0073] Referring to **FIGS. 6***a* to **6***f*, search parameter definer **38** defines a plurality of groups **100,110,120,130,140** of search bands **90**. Each group **100-140** comprises four search bands **90**, which, in this embodiment, have the same dimensions R_x and R_y as the search bands **80** described above.

[0074] Each search band **90** lines in the same plane perpendicular to the z-axis as the search bands **80**, and is defined relative to the 3D computer head model so that the search bands move with the head model when it is translated and rotated within the three-dimensional coordinate system.

[0075] Within each group **100-140**, the relative positions of the four search bands **90** is the same. More particularly, the centres of the top two search bands **90** are constrained to lie on a line Y_B parallel to the x-axis which passes through the centre of the eyebrows in the 3D computer head model. Similarly, the centres of the lower search bands **90** are constrained to lie on line Y_E parallel to the x-axis which passes through the centre of the eye pupils in the 3D computer head model. Thus, the distance between the centres of the upper and lower search bands is Y_B-Y_E, as shown in **FIG. 6***a*. The distance between the centres of the search bands **90** in the x-axis direction is defined, in this embodiment, to be equal to the distance in the x-axis direction between the points S_l and S_r, where S_l and S_r are defined by equations (2) and (3) above.

[0076] Search parameter definer **38** defines each group **100-140** of search bands so that each respective group **100-140** is displaced in the x-axis direction relative to all of the other groups **100-140**, as shown in **FIGS. 6***b* to **6***f* (although, as noted above, the y-axis positions of each group **100-140** are the same). Accordingly, referring to **FIGS. 6***b* to **6***f*, this can be thought of as sliding the group **100** parallel to the x-axis while keeping the relative positions of the search band **90** within the group fixed to define new groups **110**, **120**, **130** and **140** at different positions in the x-axis direction.

[0077] Although only five groups **100-140** are shown in **FIGS. 6***b* to **6***f*, in this embodiment, search parameter definer **38** defines eight groups of search bands evenly spaced between a minimum x-coordinate limit X_{min} and a maxi-

mum x-coordinate limit X_{max} (although a different number of groups could, of course, be set). Consequently, although not shown in **FIGS. 6***b* to **6***f*, the search bands **90** from the different groups overlap each other.

[**0078**] The x-coordinate limits X_{min} and X_{max} are defined so that the eyes and eyebrows in the 3D computer head model lie fully between these limits. As shown in **FIG. 6***b* and **FIG. 6***f*, the outermost groups **100** and **140** are defined so that the centres of the outermost search bands **90** have x-axis coordinates corresponding to X_{min} and X_{max}, respectively.

[**0079**] Within each search band **90**, search parameter definer **38** defines a plurality of sample points, "q", (shown for one search band **90** only in **FIGS. 6***b* to **6***f* but, in practice, defined for each search band **90**). In this embodiment, the number of sample points "q" is defined to be the same for each search band **90**, and the number for each search band is selected to be in the range of 20 to 50 points, which are evenly spaced throughout the search band.

[**0080**] Referring again to **FIG. 3**, at steps **S3-6** to **S3-22**, processing apparatus **8** processes each frame of image data received from camera **4** to calculate the position, size and z-axis orientation of the head of the user **2** in each frame, to calculate eye positions in three-dimensional space for the 3D computer head model, and to translate and rotate the 3D computer head model of the user in accordance with the results of the calculations. In addition, in this embodiment, processing apparatus **8** calculates the user's gaze direction for each image frame in dependence upon the user's eyeball orientation and the translated and rotated 3D computer head model. This processing will now be described in detail. It should be noted, however, that steps **S3-2** and **S3-4** described above are performed only once and are not repeated as part of the processing for each frame of image data described below.

[**0081**] At step **S3-6**, the next frame of image data received from camera **4** is stored in image data store **28** as digital pixel data under the control of central controller **20**.

[**0082**] At step **S3-8**, position, z-orientation and size calculator **32** processes the image data stored at step **S3-6** to identify pixels therein relating to the head of the user **2**, and to process the identified pixel data to determine:

[**0083**] (i) the orientation of the user's head about an axis through the centre of the head perpendicular to the 2D image plane (which corresponds to an axis parallel to the z-axis of the 3D coordinate system in which the 3D computer head model is defined in this embodiment);

[**0084**] (ii) the position of the centre of the user's head in the 2D image space; and

[**0085**] (iii)the size of the user's head.

[**0086**] In this embodiment, the processing at step **S3-8** is performed in a conventional manner, for example as described in "Computer Vision Face Tracking for Use in a Perceptual User Interface" by Bradski, Intel Technology Journal Q2 1998 available at http://developer.intel.com/technology/ITJ/Q21998/articles/art-2.htm.

[**0087**] At step **S3-10**, rotator and translator **42** changes the position of the 3D computer head model within its 3D coordinate system in accordance with the size and centre positions calculated at step **S3-8**. More particularly, rotator and translator **42** moves the 3D computer head model in the z-axis direction in accordance with the determined size, and moves the 3D computer head model in the xy plane in accordance with the determined centre position. This is achieved by changing the translation matrix T in equation (1) above.

[**0088**] At step **S3-12**, rotator and translator **42** rotates the 3D computer head model about an axis through the centre of the head parallel to the z-axis in the 3D model space coordinate system in accordance with the head orientation calculated at step **S3-8**. This is achieved by changing the rotation R_z in equation (1) above.

[**0089**] At steps **S3-14** to **S3-18**, head model processor **34** performs processing to determine the positions for the eyes of the 3D computer head model in three-dimensional space using the image data stored in image data store **28**, and to rotate the 3D computer head model about respective axes through the centre of the head parallel to the x-axis and y-axis in dependence upon the determined eye positions.

[**0090**] More particularly, at step **S3-14**, eye position calculator **40** performs processing to process the stored frame of image data to determine the positions of the eyes of the user **2** within the three-dimensional coordinate system of the 3D computer head model.

[**0091**] **FIG. 7** shows the processing operations performed by eye position calculator **40** at step **S3-14**.

[**0092**] Referring to **FIG. 7**, at step **S7-2**, eye position calculator **40** performs processing to calculate the y-coordinate positions of the eyes and eyebrows of the user **2** within the three-dimensional coordinate system of the 3D computer head model.

[**0093**] **FIG. 8** shows the processing operations performed by eye position calculator **40** at step **S7-2**.

[**0094**] Referring to **FIG. 8**, at step **S8-2**, eye position calculator **40** considers the next search band **80** (FIG. **5**) previously defined at step **S3-4** for the y-coordinate eye and eyebrow calculations (this being the first such search band **80** the first time step **S8-2** is performed).

[**0095**] At step **S8-4**, eye position calculator **40** projects the next sample point "q" defined at step **S3-4** for the search band currently being considered from the three-dimensional coordinate system of the 3D computer head model to the two-dimensional coordinate system of the image data. More particularly, eye position calculator **40** projects the sample point "q" using the transformation equation previously defined at step **S3-2** and updated at steps **S3-10** and **S3-12** (as well as step **S3-18** if step **S3-18** has previously been performed), which maps points from 3D model space to 2D image space.

[**0096**] It should be noted that the search band **80** selected at step **S8-2** and the sample point "q" selected at step **S8-4** have a position and orientation within the three-dimensional coordinate space of the 3D computer head model determined by the translation and rotation of the 3D computer head model at step **S3-10** and **S3-12**, as well as steps **S3-18** (described below) if step **S3-18** has already been performed for a previous frame of image data. Accordingly, each search band **80** will map with representative distortion onto an area

in the image corresponding to approximately the same position on the face in the image as the position of the search band relative to the 3D computer head model. This facilitates reliable tracking of the eyes of the user **2** through the sequence of the frames of image data received from camera **4**.

[**0097**] At step S**8-6**, eye position calculator **40** reads an image value of the image pixel onto which the sample point "q" was projected at step S**8-4**. In this embodiment, eye position calculator **40** reads the grey-scale intensity value of the pixel.

[**0098**] At step S**8-8**, eye position calculator **40** determines whether there is another sample point "q" in the search band **80** currently being considered. Steps S**8-4** to S**8-8** are repeated until each sample point q in the search band has been processed in the way described above.

[**0099**] At step S**8-10**, eye position calculator **40** calculates the average of the pixel intensity values read at step S**8-6** for the search band currently being considered, to give a single average value for the search band.

[**0100**] At step S**8-12**, eye position calculator **40** determines whether there is another search band **80** to be processed. Steps S**8-2** to S**8-12** are repeated until each search band **80** within the left group of bands **60** and within the right group of bands **70** (**FIG. 5**) has been processed in the way described above. Consequently, as a result of this processing, eye position calculator **40** calculates a respective average pixel intensity value for each search band **80**.

[**0101**] At step S**8-14**, eye position calculator **80** performs processing to spatially smooth the average intensities for the search bands **80** in the left group **60** and performs processing to spatially smooth the average intensities for the search bands **80** in the right group **70**.

[**0102**] More particularly, in this embodiment, eye position calculator **40** performs the smoothing processing by convolving the average intensity values for the search bands in the left group with a rectangle function (of size 3 in this embodiment) and convolving the average pixel intensity values for the search bands in the right group with a rectangle function (again of size 3 in this embodiment). This spatial smoothing removes artefacts in the average intensities caused by the search bands **80** within the respective left and right groups **60**,**70** being defined without an overlap.

[**0103**] As a result of the processing at steps S**8-2** to S**8-14**, eye position calculator **40** has calculated values representative of the intensity of the pixels in the stored image data for search bands arranged in left and right groups in the y-axis direction of the three-dimensional coordinate space of the 3D computer head model and covering the eyes and eyebrows of the head.

[**0104**] At steps S**8-16** to S**8-22**, eye position calculator **40** processes the calculated intensity values to determine the y-coordinate positions of the user's eyes in the three-dimensional coordinate space of the 3D computer head model based on the positions of the minima in the intensity values which represent dark regions on the user's face corresponding to his eyebrows and eyes.

[**0105**] More particularly, at step S**8-16**, eye position calculator **40** identifies minima within the smoothed intensity values of the left group **60** and minima within the smoothed intensity values of the right group **70**, where a minima is defined to be a search band **80** being a smoothed average intensity value for which the smoothed average intensity values of the second bands on both sides of it are larger.

[**0106**] At step S**8-18**, eye position calculator **40** identifies the least two minima from those identified at step S**8-16** for the left group **60** and also identifies the least two minima for the right group **70** (the least two minima in each case being the minima of lowest intensity value). The two identified least minima in each group correspond to the y-positions of the user's eyebrow and eye.

[**0107**] At step S**8-20**, using the principle that an eye of the user will always be below an eyebrow, eye position calculator **40** selects the left eye y-position in the three-dimensional coordinate system of the 3D computer head model as the y-coordinate of the centre of the search band **80** having the minima in the left group **60** identified at step S**8-18** which has the lowest y-position. In addition, eye position calculator **40** selects the left eyebrow y-position in the three-dimensional coordinate system of the 3D head model as the y-coordinate of the centre of the search band **80** having the minima in the left group **60** identified at step S**8-18** having the highest y-position. Eye position calculator **40** selects the right eye y-position and right eyebrow y-position in the three-dimensional coordinate system of the 3D head model in the same way using the relative y-positions of the minima identified at step S**8-18** in the right band **70**.

[**0108**] At this stage in the processing, the y-positions of the left eyebrow, right eyebrow, left eye and right eye are those of the centre of the search bands **80** containing the minima identified at step S**8-18** and selected at step S**8-20**.

[**0109**] To calculate more accurate y-position values, eye position calculator **40** performs additional processing in this embodiment at step S**8-22**.

[**0110**] More particularly, at step S**8-22**, eye position calculator **40** calculates a respective refined y-position for each of the user's left eyebrow, left eye, right eyebrow and right eye using a parabolic curve technique.

[**0111**] The processing performed at step S**8-22** is illustrated in **FIG. 9**.

[**0112**] Referring to **FIG. 9**, eye position calculator **40** considers the smoothed averaged intensity values **150**,**152** calculated at step S**8-14** for the search bands **80** on each side of the search band **80** containing the minima **154** selected at step S**8-20** having the y-coordinate value **156** which is to be refined. Eye position calculator **40** then defines a parabola **160** passing through the points **162** and **164** defined by coordinate pairs comprising an x-coordinate of the respective smoothed average intensity value and a y-coordinate of the centre of the search band **80** for which the smoothed average intensity value was calculated. Eye position calculator **40** then identifies the minima **170** of the parabola **160** and defines the y-coordinate value **180** of the parabola minima to be the refined y-coordinate for the eye or eyebrow for which the calculation has been performed. This processing is repeated for each of the left eyebrow, left eye, right eyebrow and right eye to calculate respective refined y-coordinates therefor.

[**0113**] Referring again to **FIG. 7**, at step S**7-4**, eye position calculator **40** performs processing to calculate respec-

tive x-positions in the three-dimensional coordinate space of the 3D computer head model for the left eye, left eyebrow, right eye and right eyebrow.

[0114] **FIG. 10** shows the processing operations performed by eye position calculator **40** at step **S7-4**.

[0115] Referring to **FIG. 10**, at step **S10-2**, eye position calculator **40** considers the next group **100-140** of search bands **90** (**FIG. 6**) previously defined at step **S3-4** for the calculation of x-coordinates (this being the first such group the first time step **S10-2** is performed).

[0116] At step **S10-4**, eye position calculator **40** projects the next sample point "q" for the group **100-140** of search bands currently being considered from the three-dimensional coordinate space of the 3D computer head model to the two-dimensional coordinate space of the image data (this being the first such sample point "q" the first time step **S10-4** is performed). This projection is carried out using the transformation equation previously defined at step **S3-2** and updated at steps **S3-10** and **S3-12** (as well as step **S3-18** if step **S3-18** has previously been performed).

[0117] At step **S10-6**, eye position calculator **40** reads an image value of the pixel in the image data onto which the sample point "q" was projected at step **S10-4**. In this embodiment, eye position calculator **40** reads the grey-scale intensity value of the pixel.

[0118] At step **S10-8**, eye position calculator **40** determines whether there is another sample point "q" within the group of four search bands currently being considered, and steps **S10-4** to **S10-8** are repeated until each such sample point has been processed in the way described above.

[0119] At step **S10-10**, eye position calculator **40** calculates the average of the sampled pixel intensity values read at step **S10-6** to give a single average intensity value for the group of four search bands **90** currently being considered.

[0120] At step **S10-12**, eye position calculator **40** determines whether there is another group **100-140** of four search bands **90** to be processed. Steps **S10-2** to **S10-12** are repeated until each group of four search bands has been processed in the way described above.

[0121] At step **S10-14**, eye position calculator **40** identifies minima within the average intensity values calculated at step **S10-10** (a minima being defined to be a value where the average intensity values for the group of four search bands on both sides are larger).

[0122] Eye position calculator **40** then selects the smallest minima (that is, the average intensity minima having the lowest value). The four centres of the search bands **90** for the group having the selected smallest minima define the x-coordinates in the three-dimensional coordinate system of the user's eyes and eyebrows. This is because the eyes and eyebrows produce dark regions in the image data received from camera **4** and these regions and identified by selecting the smallest minima at step **S10-14**.

[0123] At step **S10-16**, eye position calculator **40** calculates a refined x-coordinate value of the user's eyes and eyebrows in the three-dimensional coordinate space of the head model. This processing is performed using the parabola technique described previously with reference to step **S8-22**. However, the processing is carried out once to calculate a refinement applicable to the x-coordinates of both eyes and both eyebrows, rather than carrying out separate processing to calculate a respective refinement for each of the eyes and eyebrows. This is because the x-coordinate values of the eyes and eyebrows determined at step **S10-14** are all derived from a single group **100-140** of four search bands.

[0124] As a result of the processing described above with reference to FIGS. **8** to **10**, eye position calculator **40** has calculated a respective x,y coordinate pair defining the centre of each of the user's eye and eyebrows in the three-dimensional coordinate space of the 3D computer head model.

[0125] Referring again to **FIG. 3**, at step **S3-16**, eye position calculator **40** performs processing to verify the x,y positions calculated at step **S3-14** and to amend the positions should it be determined that this is necessary.

[0126] More particularly, eye position calculator **40** determines whether an eye and eyebrow have been identified for the left-hand and right-hand side of the user's face (because it may be the case that the processing at step **S8-16** identifies only one minima, or no minima at all, in each of the left and right groups **60**,**70** of search bands **80**), compares the relative calculated positions of the eyes and eyebrows in the three-dimensional space of the 3D computer head model, and performs the verification and amendment processing in accordance with the following rules:

[0127] 1. If both the eye and eyebrow have been identified for both the left and right sides of the face, then:

[0128] (a) If the identified eye positions lie on a line perpendicular to the y-axis in the 3D coordinate system of the 3D computer head model, then the eye positions are considered to be accurate and no amendment is necessary; else

[0129] (b) If any of the identified feature positions lie on a line perpendicular to the y-axis in the 3D coordinate system of the 3D computer head model (for example, left eye and right eyebrow), then these are determined to be the eye positions, and the eye position coordinates are amended accordingly.

[0130] (2) If only one feature (eye or eyebrow) has been identified on each of the left and right sides of the face, then:

[0131] (a) If the positions of the features lie on a line perpendicular to the y-axis in the 3D coordinate system of the 3D computer head model, then these are set to be the positions of the user's eyes; else

[0132] (b) The position of the feature having the lowest y-coordinate value is set to be the position of the first eye, and the second eye is defined to be at a position having the same y-coordinate value as the first eye and having an x-coordinate value the same as that originally calculated for the feature identified on the same side of the face as the second eye.

[0133] 3. If only one feature (eye or eyebrow) has been identified on one side of the face and two features have been identified on the other side of the face, then the positions of the eyes are set to be the positions of the features on opposite sides of the face for which the straight line therebetween is closest to parallel to the x-axis.

[0134] 4. If only one feature (eye or eyebrow) has been identified on one side of the face and no feature has been identified on the other side of the face, then the position of the identified feature is defined to be the position of the first eye, and the position of the second eye is defined to have the same y-coordinate value and an equal and opposite x-coordinate value.

[0135] At step **S3-18**, head model processor **34** rotates the 3D computer head model within its three-dimensional coordinate system in accordance with the eye positions calculated at steps **S3-14** and **S3-16**. The eyebrow positions calculated at steps **S3-14** and **S3-16** are not used in this embodiment to rotate the 3D computer head model at step **S3-18** because the user can move his eyebrows on his head, and it has been found that this can lead to the 3D computer head model being rotated inaccurately if the eyebrow positions are used at step **S3-18** as well as, or instead of, the eye portions.

[0136] **FIG. 11** shows the processing operations performed at step **S3-18**.

[0137] Referring to **FIG. 11**, at step **S11-2**, if the calculated eye positions were changed during the verification processing at step **S3-16**, then rotator and translator **42** rotates the 3D computer head model about an axis parallel to the Z-axis of the three-dimensional coordinate system in accordance with the change in the calculated eye positions. More particularly, rotator and translator **42** rotates the 3D head model about an axis through the centre of the head and parallel to the z-axis so that the symmetry plane of the 3D computer head model (that is, the notional "vertical" plan through the centre of the head model which divides the head model into left-hand and right-hand sides) is perpendicular to the straight line connecting the amended eye positions. This is achieved by changing the rotation R_z in equation (1) above.

[0138] At step **S11-4**, head model processor **34** projects (using the transformation defined at step **S3-2** and subsequently updated as described above) the eye positions calculated as a result of the processing at step **S3-14** (and amended, if necessary, during the processing at step **S3-16**) from the three-dimensional coordinate system of the 3D computer head model into the 2D coordinate system of the frame of image data stored in image data store **28** and currently being processed. These projected positions define the calculated eye positions in 2D image space.

[0139] At step **S11-6**, head model processor **34** performs processing to determine the rotation of the 3D computer head model about an axis through the centre of the head model parallel to the x-axis (R_z in equation (1)) and an axis through the centre of the head model parallel to the y-axis (R_y in equation (1)) of the three-dimensional coordinate system which orientates the head so that the eyes thereof project to the same positions in the 2D image space as the calculated eye positions generated at step **S11-4**.

[0140] More particular, in this embodiment, head model processor **34** projects the current eye positions (that is, the positions of the eyes in the 3D computer head model in its current orientation R_xR_y) from the three-dimensional coordinate system of the 3D computer head model into the 2D coordinate system of the image data. Each point is projected using the transformation previously calculated at step **S3-2** and subsequently updated as described above.

[0141] Head model processor **34** then iteratively rotates the 3D computer head model in its three-dimensional space about axes through the centre of the head parallel to the x-axis and y-axis (by iteratively changing R_x and R_y in equation (1)) to minimise the error between the projected calculated eye positions and the projected current eye positions in 2D image space. In this embodiment, this processing is carried out using a spring-mass-damper type numerical technique.

[0142] More particularly, head model processor **34** performs the following operations a predetermined number of times (set to 8 times in this embodiment):

$$CALCULATE\ \underline{y}''_n = \frac{K}{m}(\underline{E}_l + \underline{E}_r)_n - \frac{B}{m}\underline{y}''_{n-1}$$

CALCULATE $\underline{y}'_n\underline{y}'_{n-1}+\underline{y}''_n\Delta t$

ROTATE $\Theta_x=\Theta_x+V_y$

ROTATE $\Theta_y=\Theta_y+V_x$

[0143] REPROJECT CURRENT EYE POSITIONS INTO 2D IMAGE SPACE

[0144] where:

[0145] "K" is a spring constant (set to 0.002 in this embodiment).

[0146] "B" is a damper constant (set to 2 in this embodiment).

[0147] "m" is a mass (set to 1 in this embodiment).

[0148] E_l is the error vector between the projected calculated position and projected current position of the left eye.

[0149] E_r is the error vector between the projected calculated position and projected current position of the right eye.

[0150] "n" indicates a value for the current iteration.

[0151] "n−1" indicates a value for the previous iteration ($\underline{y}'_{n-1}$ being set to 0 for n=1).

[0152] Δt is a constant (set to 0.1 in this embodiment).

[0153] V_x is the x component of $\underline{y}'$

[0154] V_y is the y component of $\underline{y}'$.

[0155] As a result of this processing, the 3D computer head model is rotated about axes through the centre of the head parallel to the x-axis and y-axis of the three-dimensional coordinate system to minimise the error vectors in a

stable manner. That is, values of R_x and R_y in equation (1) are calculated which give a minimum error.

[0156] Referring again to **FIG. 3**, as a result of the processing at step **S3-18**, head model processor **34** has changed the orientation of the 3D computer head model defined by the data stored in head model store **24** so that its orientation corresponds to the orientation of the head of user **2** determined from the image data received from camera **4**. In other words, the values of T, R_x, R_y and R_z in equation (1) define the position and orientation of the 3D computer head model calculated from the current frame of image data.

[0157] At step **S3-20**, gaze direction calculator **44** determines the direction in which the user **2** is looking. In this embodiment, gaze direction calculator **40** performs the calculation by processing the image data stored in image data store **28** to determine the positions of the irises and pupils of the eyes of the user **2** relative to the rest of the eyes, and then uses the calculated positions together with the determined position and orientation of the 3D computer head model (determined at steps **S3-10**, **S3-12** and **S3-18**) to calculate the direction in which the user **2** is looking.

[0158] The processing to calculate the positions of the irises and pupils within the eyes of the user **2** is carried out by gaze direction calculator **44** in a conventional manner, for example by extracting pixels from the image data relating to the eyes, scaling the pixel data to give an image of each eye of a predetermined size (so that an image is obtained at the same size regardless of the distance of the user **2** from the camera **4**), and processing the generated image of each eye to identify a dark circle surrounded by a white region, and the position of the dark circle relative to the white region.

[0159] As a result of performing the processing described above, processing apparatus **8** has calculated the gaze direction of the user **2** for the current frame of the image data received from camera **4**.

[0160] At step **S3-22**, central controller **20** determines whether another frame of image data has been received from camera **4**. Steps **S3-6** to **S3-22** are repeated for each frame of image data received from the camera **4**.

[0161] Second Embodiment

[0162] A second embodiment of the invention will now be described.

[0163] In the first embodiment, search bands **80** are defined in the three-dimensional coordinate space of the 3D head model covering regions corresponding to the left and right eyes and eyebrows. For each frame of image data received from camera **4**, sample points q for each search band **80** are projected from the three-dimensional space of the 3D computer head model into the two-dimensional space of the image, and the intensity value of each pixel onto which a sample point projects is read. An average intensity value for each search band **80** is then calculated from the intensity values read for the sample points within the search band. The positions of the user's eyes and eyebrows in the three-dimensional coordinate space of the head model are then determined in dependence upon the positions of intensity minima within the left group **60** of search bands **80** and right group **70** of search bands **80**.

[0164] In the second embodiment, on the other hand, the programming instructions input on storage medium **16** and/or signal **18** comprise instructions to cause the processing apparatus **2** to become configured to define search bands in the three-dimensional coordinate space of the 3D computer head model such that each band comprises a line (instead of an area having a width R_y as in the first embodiment) with sample point q defined on the line. For each frame of image data received from camera **4**, the intensity value of each pixel in the image data corresponding to a sample point q is read and an average intensity value is calculated for each search band in the three-dimensional coordinate space of the 3D computer head model. As a result, an intensity profile is generated as a function of position over the left and right eyes and eyebrows in the three-dimensional coordinate space of the 3D head model. Each generated profile is compared with a pre-generated intensity profile for the user **2** to calculate a respective Y-coordinate value in the three-dimensional coordinate space of the 3D computer head model for the left eye and the right eye of the 3D computer head model.

[0165] Referring to **FIG. 12**, when programmed by the programming instructions, the functional units in the second embodiment are the same as those in the first embodiment, with the exception that the functional units further comprise a reference intensity profile generator **35** operable to calculate and store a reference intensity profile for the left eye and left eyebrow and a reference intensity profile for the right eye and right eyebrow of each user of the apparatus (these being the reference profiles against which profiles determined for each frame of image data during eye tracking are compared). In addition, the processing operations performed by search parameter definer **38** and eye position calculator **40** are different to the processing operations in the first embodiment. These differences will be described below.

[0166] **FIG. 13** shows the processing operations performed by the functional components within processing apparatus **8** in the second embodiment.

[0167] Referring to **FIG. 13**, the processing operations performed at steps **S13-2**, **S13-6** to **S13-12**, and **S13-18** to **S13-22** are the same as the processing operations performed at steps **S3-2**, **S3-6** to **S3-12**, and **S3-18** to **S3-22** in the first embodiment. Accordingly, these processing operations will not be described again here.

[0168] On the other hand, the processing operations performed at steps **S13-4**, **S13-5** and **S13-14** are different to the processing operations performed in the first embodiment. Accordingly, these processing operations will now be described in detail.

[0169] The processing by search parameter definer **38** at step **S13-4** will be described first.

[0170] Search parameter definer **38** defines search bands for use in calculating Y-coordinates of the eyes of the 3D computer head model and search bands for use in calculating X-coordinates of the eyes of the 3D computer head model. The search bands defined by search parameter definer **38** at step **S13-4** for use in calculating the X-coordinates of the eyes of the 3D computer model are the same as those defined in the first embodiment and described above with reference to **FIGS. 6*a*** to **6*f***. However, the search bands defined for use in calculating the Y-coordinates of the eyes of the 3D computer head model are different to those in the first embodiment.

[0171] **FIG. 14***a* shows the search bands for use in calculating the Y-coordinates of the eyes of the 3D computer head model defined by search parameter **38** at step **S13-4** in the second embodiment.

[0172] Referring to **FIG. 14***a,* search parameter definer **38** defines a left group **60** of search bands **200** and a right group **70** of search bands **200** arranged on either side of the head symmetry line (which, in this embodiment, is defined by the Y-axis of the three-dimensional coordinate space, as in the first embodiment).

[0173] Each search band **200** is defined relative to the 3D computer head model so that the search bands move with the head model when it is translated and rotated within the three-dimensional coordinate system.

[0174] Search parameter definer **38** defines the search bands **200** within each group **60,70** to lie between Y-axis limits of Y_{min} and Y_{max}. These limits are the same as those in the first embodiment and are defined to ensure that the search bands **200** within each group **60,70** cover fully the left eye and left eyebrow and the right eye and right eyebrow respectively of the 3D computer head model.

[0175] Each search band **200** is defined by search parameter definer **38** in the second embodiment to be a straight line having a centre point lying on a perpendicular line **202** between Y_{max} and Y_{min} which passes through the centre of the left eye and left eyebrow or the centre of the right eye and right eyebrow. Each search band **200** is perpendicular to the lines **202** and lies in a plane perpendicular to the Z-axis of the 3D coordinate system. In this embodiment, the Z-coordinate value of the plane containing the search bands **200** is set such that it is equal to the Z-coordinate value of the eyes of the 3D computer head model (with the result that the plane passes through the 3D computer head model).

[0176] Within each group **60,70**, the search bands **200** are equally spaced along the line **202** between the limits Y_{max} and Y_{min}. In this embodiment, the spacing between adjacent search bands **200** is defined so that, when the search bands **200** are transformed from the three-dimensional coordinate system of the 3D computer head model to the two-dimensional coordinate system of an image, the transformed bands have a spacing in the image equal to the spacing of adjacent lines of pixels in the image. In this way, the search bands **200** correspond to adjacent lines of pixels in the image. Accordingly, although only eleven search bands **200** are shown in **FIG. 14***a* in each of the groups **60,70**, in practice **40** search bands **200** are typically defined in each group **60,70**.

[0177] The width of each search band **80** in the X-axis direction is R_x (this being the same width as the search bands **80** in the first embodiment). Search parameter definer **38** defines R_x to ensure that each search band **200** is sufficiently wide in the X-axis direction to enclose fully an eye or eyebrow.

[0178] Within each respective search band **200**, search parameter definer **38** defines a plurality of sample points "q". In this embodiment, the number of sample points q is defined to be the same for each search band **200**, and the sample points are evenly spaced throughout the width of the search band **200**. In this embodiment, the number of sample points q for each search band **200** is set such that, when the sample points q are projected from the three-dimensional coordinate system of the 3D computer head model to the two-dimensional coordinate system of an image, the spacing between the projected sample points is equal to the spacing between adjacent pixels on a row in the image. Accordingly, although only nine sample points q are shown in **FIG. 14***a* for each search band **200**, in practice, **30** sample points q are typically defined for each search band **200**.

[0179] Although each search band **200** and each sample point q is illustrated in **FIG. 14***a,* in this embodiment, search parameter definer **38** does not actually perform processing at step **S13-4** to calculate the position of each search band **200** and each sample point q in the three-dimensional space of the 3D computer head model. Instead, referring to **FIG. 14***b,* search parameter definer **38** defines the positions of eight sample points q **210-224**, referred to as "keypoints".

[0180] Keypoints **210,212,214** and **216** define the positions of the sample points q at the ends of the two lines **202**. Keypoints **218** and **220** define the positions of the sample point q at the ends of one of the search bands **200** in the right group **70** (labelled **226** in **FIG. 14***b*). In this embodiment, the keypoints **218,220** define positions of the sample points q at the ends of the search band **200** which passes through the centre of the line **202** defined by keypoints **210** and **212**. Similarly, keypoints **222** and **224** define the positions of sample points q at the ends of a search band **200** in the left group **60** (in this embodiment, the search band **200** which passes through the centre of the line **202** defined by keypoints **214** and **216** and labelled **228** in **FIG. 14***b*).

[0181] To define the positions of the other search bands **200** and sample points q, search parameter definer **38** stores data defining the number of search bands **200** in each of the left and right groups **60,70**, and data defining the number of sample point q in each respective search band **200**.

[0182] As will be explained below, instead of projecting every one of the sample points q shown in **FIG. 14***a* from the three-dimensional space of the 3D computer head model to the two-dimensional space of an image in order to calculated Y-coordinates for the eyes of the 3D computer model, in this embodiment only the eight keypoints **210-224** shown in **FIG. 14***b* are projected and the positions to which the other sample points q would be projected are calculated in the two-dimensional space of the image based upon the positions of the projected keypoints **210-224**. It has been found that performing processing in this way reduces the amount of computation required compared to processing which projects every individual sample point q from the three-dimensional space of the 3D computer head model to the two-dimensional space of an image.

[0183] Referring again to **FIG. 3**, the processing performed at step **S13-5** in the second embodiment to generate and store left and right eye reference intensity profiles for the user will now be described. This processing is performed by the reference intensity profile generator **35**. The purpose of the processing is to generate a respective reference intensity profile for the left and right eyes of the current user **2** of processing apparatus **8** for use in subsequent processing to calculate the Y-coordinates of the user's eyes when the user's eyes are being tracked. Each reference intensity profile defines the intensity (determined from an image of the user **2**) at each position corresponding to the position of a search band **200** along a respective one of the lines **202**. Accordingly, each reference profile defines how the intensity varies along a line **202** through positions corresponding to the pupil of the user's eye and the user's eyebrow.

[0184] **FIG. 15** shows the processing operations performed by reference intensity profile generator **35** at step **S13-5**.

[0185] Referring to **FIG. 15**, at step **S15-2**, reference intensity profile generator **35** processes frames of image data received from camera **4** to determine the 2D positions of the user's eyes within a frame of the image data. In this embodiment, the processing at step **S15-2** is performed in a conventional manner to process frames of image data from camera **4** to detect a frame in which the user blinks and to determine the positions of the user's eyes in this frame of image data, for example as described in "Coordination of Perceptual Processes for Computer-Mediated Communication" by Coutaz et al in 1996 Proceedings of 2nd International Conference on Automatic Face and Gesture Recognition, IEEE Computer Security Press, pages 106-111, and "Eigen Space Coding as a Means to Support Privacy in Computer-Mediated Communication" by Coutaz et al in 1977 Proceedings of INTERACT '97, published by Chapman and Hall. Of course, other processing techniques could be used at step **S15-2** to determine the positions of the user's eyes in one of the frames of image data.

[0186] At steps **S15-4** to **S15-10**, reference intensity profile generator **35** controls position, Z-orientation and size calculator **32** and head model processor **34** to perform processing to translate and rotate the 3D computer head model within its three-dimensional space to position the eyes of the 3D computer model at locations corresponding to the positions in the frame of image data determined at step **S15-2**. That is, reference intensity profile generator **35** rotates and translates the 3D computer head model to position the eyes such that, when the transformation previously generated at step **S13-2** is applied, the eyes project to the positions in the frame of image data calculated at step **S15-2**.

[0187] The processing performed at steps **S15-4** to **S15-10** is the same as the processing performed in the first embodiment at steps **S3-8**, **S3-10**, **S3-12** and **S11-6** (the only difference being that the processing at step **S15-10** is performed to minimise the error between the eye positions determined at step **S15-2** and the projected current eye positions rather than to minimise the error between the projected calculated eye positions and the projected current eye positions as in the processing at step **S11-6**). Since these processing operations have been described above, they will not be described again here.

[0188] When rotating and translating the 3D computer head model at steps **S15-4** to **S15-10**, the positions of the eight keypoints **210-224** shown in **FIG. 14***b* will move with the 3D computer head model since they are defined relative to the 3D computer head model.

[0189] At steps **S15-12** to **S15-18**, reference intensity profile generator **35** controls head model processor **34** to generate a respective reference intensity profile for each of the lines **202** by reading pixel data from the frame of image data in which the positions of the user's eyes were determined at step **S15-2**.

[0190] More particularly, at step **S15-12**, reference intensity profile generator **35** projects the eight keypoints **210-224** defined at step **S13-4** from the three-dimensional space of the 3D computer head model to the two-dimensional space of the frame of image data in which the positions of the user's eyes were determined at step **S15-2**. This projection is carried out using the transformation equation previously defined at step **S13-2** and updated at steps **S15-6**, **S15-8** and **S15-10**.

[0191] At step **S15-14**, reference intensity profile generator **35** calculates the position of each sample point q in the two-dimensional space of the frame of image data using the positions of the projected keypoints generated at step **S15-12**.

[0192] The transformation applied at step **S15-12** defines a linear projection from the three-dimensional space of the 3D computer head model to the two-dimensional space of the frame of image data. Therefore, referring to **FIGS. 16***a* and **16***b* (which show an example when the keypoints **214**,**216**,**222** and **224** for the left eye and left eyebrow are projected into a frame of image data), when the keypoints **214**,**216**,**222**,**224** are projected from the three-dimensional coordinate system of the 3D computer head model to the two-dimensional coordinate system of the frame of image data, the straight lines **202**,**228** defined by the keypoints remain as straight lines **202'**,**228'** in the two-dimensional space of the image data. Accordingly, the straight line **202'** connecting the points **214'** and **216'** (which are the projections of the points **214**,**216**) in the two-dimensional coordinate system of the image data defines the projection of the line **202**, and the straight line **228'** connecting the points **222'** and **224'** (which are the projections of the points **222**,**224**) defines the projection of the line **228** in the two-dimensional coordinate system of the image data.

[0193] It should be noted, however, that the lengths of the lines **202'** and **228'** are not necessarily the same as the lengths of the lines **202**,**228**, and that the angle between the lines **202'** and **228'** is not necessarily the same as the angle between the lines **202** and **228**.

[0194] Referring to **FIGS. 16***c* and **16***d*, at step **S15-14**, based on the data stored at step **S13-4** defining the number of search bands **200**, reference intensity profile generator **35** defines a plurality of straight lines **240** in the two-dimensional coordinate system of the frame of image data on each side of the line **228'**. A respective line **240** is defined for each search band **200** in the left group **60** of search bands in the three-dimensional coordinate system of the 3D computer head model (other than the search band corresponding to line **228**, for which line **228'** is already defined). Each line **240** is defined at a position such that the lines **240** and **228'** are evenly spaced along the line **202'**. Each line **240** has its mid-point on the line **202'**, and is defined to be parallel to the line **228'** with a length equal to the length of the line **228'**.

[0195] Having defined the lines **228'** and **240**, reference intensity profile generator **35** defines sample points q' along each line. For each respective line, the sample points q' are evenly spaced along the line and the number of sample points is set to be the same as the number of sample points for each search band **200** previously defined at step **S13-4**.

[0196] In this way, a respective sample point q' is defined for each sample point position q shown in **FIG. 14***a*.

[0197] Referring again to **FIG. 15**, at step **S15-16**, for each calculated sample point q', reference intensity profile generator **35** reads an image value of the image pixel within

which the sample point lies. In this embodiment, reference intensity profile generator **35** reads the grey-scale intensity value of the pixel.

[**0198**] At step **S15-18**, for each search band **200**, reference intensity profile generator **35** calculates and stores the average of the pixel intensity values read at step **S15-16** for the sample points q' on the line **228'** or **240** corresponding to the search band **200**. Consequently, as a result of this processing, reference intensity profile generator **35** calculates a respective average pixel intensity value for each search band **200** in the left and right groups **60,70** of search bands.

[**0199**] Referring to **FIG. 17**, the average intensity values calculated at step **S15-18** define an intensity profile **250** for the left eye and left eyebrow and an intensity profile **260** for the right eye and right eyebrow of the user. Each intensity profile **250,260** defines how the calculated average intensity value varies with position along the line **202**. Consequently, each intensity profile **250,260** includes a relative reduction in intensity at positions corresponding to the pupil of an eye and positions corresponding to an eyebrow.

[**0200**] Referring again to **FIG. 15**, at step **S15-20**, reference intensity profile generator **35** performs processing to normalise the left and right intensity profiles generated at step **S15-18** to make the respective mean value of each profile equal to zero. More particularly, in this embodiment, reference intensity profile generator **35** normalises each of the left and right intensity profiles to make it zero-mean by setting each value, x_i, in the profile to be:

$$x_i = \frac{x_i - \bar{x}}{x_m - \bar{x}} \tag{4}$$

[**0201**] where:

[**0202**] $\bar{x}$ is the mean value of the values in the intensity profile before normalisation;

[**0203**] x_m is the maximum value in the intensity profile before normalisation.

[**0204**] The normalised profiles are stored as left and right reference intensity profiles for the user.

[**0205**] Referring again to **FIG. 13**, the processing performed by eye position calculator **40** at step **S13-14** will now be described.

[**0206**] **FIG. 18** shows the processing operations performed at step **S13-14**.

[**0207**] Referring to **FIG. 18**, at step **S18-2**, eye position calculator **40** performs processing to calculate the Y-coordinate positions of the left and right eyes within the three-dimensional coordinate system of the 3D computer head model, and at step **S18-4** performs processing to calculate the X-coordinate positions of the eyes within the three-dimensional coordinate system of the 3D computer head model.

[**0208**] The processing performed at step **S18-4** is the same as the processing performed at step **S7-4** in the first embodiment. Accordingly, this processing will not be described again here, and only the processing performed at step **S18-2** (which is different to that in the first embodiment) will be described.

[**0209**] **FIG. 19** shows the processing operations performed by eye position calculator **40** for a frame of image data at step **S18-2** in the second embodiment.

[**0210**] Referring to **FIG. 19**, at steps **S19-2** to **S19-10**, eye position calculator **40** performs processing to project the eight keypoints **210-224** from their current positions in the three-dimensional space of the 3D computer head model (determined by the translation and rotation of the 3D computer head model at steps **S13-10**, **S13-12** and **S13-18**) into the two-dimensional coordinate system of the image data, to define sample point positions q' in the image data, to read the intensity values of the pixels in which the sample points q' lie, to generate a respective intensity profile for the left and right eyes of the user for the current frame of image data, and to normalise the left and right intensity profiles to make each profile zero-mean.

[**0211**] The processing performed at steps **S19-2** to **S19-10** is the same as the processing performed at steps **S15-12** to **S15-20**, described above. Accordingly, this processing will not be described again here.

[**0212**] At step **S19-12**, eye position calculator **40** compares the normalised left eye intensity profile for the current frame of image data (generated at step **S19-10**) with the stored reference intensity profile **250** for the user's left eye (generated at step **S15-20**) to calculate the Y-position in the three-dimensional space of the 3D computer model for the left eye for the current frame.

[**0213**] More particularly, in this embodiment, eye position calculator **40** compares the intensity profile for the current frame with the reference intensity profile **250** by performing a correlation-type operation on the two intensity profiles in accordance with the following equation:

$$c_i = \sum_{j=0}^{n-1} \frac{|R_j - F_{j+i}|}{\text{Number of valid intensity values}} \tag{5}$$

[**0214**] where:

[**0215**] n is the number of intensity values in a profile (that is the number of search bands **200** in the left or right group **60, 70**, which is **40** in this embodiment, with the intensity value number running from 0 to n−1, giving n values in total in the profile);

[**0216**] C_i is the "i"th correlation value;

[**0217**] i runs from −(n−1) to +(n−1) so that 2n−1 correlation values C_i are calculated;

[**0218**] R_j is the "j"th intensity value in the reference intensity profile **250**;

[**0219**] F_{j+i} is the (j+i)th intensity value in the current frame intensity profile;

[**0220**] valid intensity values are values for which $0 \leqq j+i \leqq n-1$.

[**0221**] Referring to **FIGS. 20***a* to **20***e*, an explanation will now be given of the correlation operation performed at step **S19-12**.

[0222] As explained above, a correlation value C_i is calculated in accordance with equation (5) for each value of i between −(n−1) and +(n−1), so that 2n−1 correlation values are calculated.

[0223] To generate each correlation value C_i, one or more intensity values in the intensity profile for the current frame are subtracted from corresponding intensity values in the reference intensity profile **250**, with the number and identity of the intensity values from the image frame profile and reference profile used in the subtraction being determined in accordance with the values of i and j in equation (5).

[0224] Referring to **FIGS. 20***a* to **20***e*, this can be thought of as sliding the intensity profile **270** for the current frame of image data to different positions relative to the reference intensity profile **250** (each position spaced apart from the previous position by a distance equal to the distance between adjacent search bands **200**) and performing the subtraction for each different relative position.

[0225] **FIG. 20***a* illustrates the calculation of the correlation value C_{-n+1}. In this case, the intensity value F_0 from the intensity profile **270** for the current frame of image data is subtracted from the intensity value R_{n-1} from the reference intensity profile **250**, but no other subtractions are performed because no other points in the reference intensity profile **250** and the intensity profile **270** for the current frame of image data align.

[0226] In **FIG. 20***b*, the intensity profile **270** for the current frame of image data has been moved to the next position relative to the reference intensity profile **250** (that is, the intensity profile **270** has been moved by a distance corresponding to the distance between adjacent points in the profile—which is equal to the distance between adjacent search bands **200**). The example shown in **FIG. 20***b*, corresponds to the calculation of the correlation value C_{-n+2}. In this case, the intensity value F_0 from the intensity profile **270** for the current frame of image data is subtracted from the intensity value R_{n-2} for the reference intensity profile **250**, and the intensity value F_1 from the intensity profile **270** for the current frame image data is subtracted from the intensity value R_{n-1} for the reference intensity profile **250**.

[0227] The intensity profile **270** for the current frame of image data is repeatedly moved by a distance equal to the distance between adjacent points therein to different positions relative to the reference intensity frame **250** to generate each new correlation value C_i.

[0228] **FIG. 20***c* shows the situation where the intensity profile **270** for the current frame of image data has been moved relative to the reference intensity profile **250** such that every point in the intensity profile **270** is aligned to correspond to a point in the reference intensity profile **250**. In this case, each intensity value F_0 to F_{n-1} in the intensity profile **270** for the current frame of image data is subtracted from the corresponding intensity value R_0 to R_{n-1} in the reference intensity profile **250** to generate the correlation value C_0.

[0229] The relative positions between the intensity profiles **250** and **270** for the two final correlation values C_{n-2} and C_{n-1} are shown in **FIGS. 20***d* and **20***e*, respectively, with the subtractions R_0-F_{n-2} and R_1-F_{n-1} being performed for C_{n-2} and the subtraction R_0-F_{n-1} being performed for C_{n-1}.

[0230] The correlation value C_i which has the highest value of all the correlation values calculated in accordance with equation (5) defines the alignment of the intensity profile **270** for the current frame of image data relative to the reference intensity profile **250** for which the two profiles **250**,**270** are maximally similar.

[0231] Accordingly, eye position calculator **40** selects the highest correlation value C_i generated in accordance with equation (5) and calculates the Y-coordinate of the position of the left eye of the 3D computer model in dependence upon the relative displacements of the intensity profiles **270** and **250** to which the maximum correlation value corresponds. More particularly, the relative displacement of the intensity profile **270** for the current frame of image data and the reference intensity profile **250** is defined by the value of i of the selected highest correlation value. That is, the relative displacement is zero for correlation value C_0, the relative displacement is equal to the distance between two adjacent search bands **200** in the positive Y-axis direction for correlation value C_1 (and increases in the positive Y-axis direction by a distance equal to the distance between two adjacent search bands **200** for each increase by one of the index i to the correlation value), and the relative displacement is equal to the distance between two adjacent search bands **200** in the negative Y-axis direction for correlation value C_{-1} (and increases in the negative Y-axis direction by a distance equal to the distance between two adjacent search bands **200** for each decrease by one of the index i to the correlation value).

[0232] Accordingly, eye position calculator **40** calculates the Y-coordinate of the left eye by adding or subtracting from the Y-coordinate value of the current eye position an amount defined by the index i to the highest correlation value calculated in accordance with equation (5).

[0233] Referring again to **FIG. 19**, at step **S19-14**, eye position calculator **40** repeats the processing performed at step **S19-12** to calculate the Y-coordinate of the right eye of the 3D computer model. This processing is the same as that performed at step **S19-12** and will therefore not be described again here.

[0234] At step **S19-16**, eye position calculator **40** performs processing to calculate refined Y-positions for the left and right eyes respectively of the 3D computer head model.

[0235] More particularly, the Y-positions calculated at steps **S19-12** and **S19-14** are "quantized" positions because each position corresponds to the position of a search band **200** along one of the left or right lines **202**. Accordingly, eye position calculator **40** performs processing corresponding to that performed at step **S8-22** in the first embodiment (described above with reference to **FIG. 9**) to calculate a respective refined Y-position for each of the left and right eyes, this processing allowing each refined Y-position to lie between the positions of search bands **200** along a line **202**.

[0236] By performing the processing in this way, eye position calculator **40** calculates accurate Y-coordinate values for the eyes of the 3D computer head model in three-dimensional space.

[0237] Modifications and Variations

[0238] Many modifications and variations can be made to the embodiments described above within the scope of the claims.

[0239] For example, the search regions can be defined at steps **S3-4** and **S13-4** to have different properties to those described above. For example, referring to **FIG. 5** and **FIG. 14***a,* the number of search bands **80,200** within the left group **60** and right group **70** does not need to be the same. In addition, the search bands **80,200** within the left group do not need to align with the search bands **80,200** in the right group.

[0240] In the first embodiment described above, the dimensions R_x and R_y of each search band **80** (**FIG. 5**) are the same as the dimensions of each search band **90** (**FIG. 6**). However, the search bands **90** can be defined to have different dimensions to the search bands **80**. Similarly, the width R_x of each search band **200** in the search embodiment may be different to the width of each search band **90**.

[0241] In the first embodiment described above, the search bands **80** within each of the left and right groups **60, 70** (**FIG. 5**) are defined so that they are adjacent but non-overlapping in the y-axis direction. However, instead, the search band **80** within a given group **60, 70** could be defined to overlap in the y-axis direction. By defining the search bands **80** with sufficient overlap, it becomes unnecessary to perform the spatial smoothing processing at step **S8-14** because such smoothing is inherently provided by the way in which the sample points "q" relate to overlapping search bands.

[0242] In the embodiments described above, refined Y-positions for the eyes are calculated at step **S8-22** and step **S19-16**. However, in the first embodiment each search band **80** (**FIG. 5**) could be defined with a very small dimension R_y, and in the second embodiment the search. bands **200** could be defined with sub-pixel spacing between adjacent bands **200**, so that it becomes unnecessary to calculate refined positions. Similarly, the dimensions R_x of each search band **90** (**FIG. 6**) could be defined such that the processing to calculate refined positions at step **S10-16** becomes unnecessary.

[0243] In the embodiments described above, the grey-scale intensity values of pixels are read at steps **S8-6**, **S10-6**, **S15-16** and **S19-16**, and are subsequently used to determine the y-position and x-position of the eyes in 3D model space. However, different image values of the pixels may be used instead of the intensity values. For example, in a colour system, image values comprising the red, green and blue component values or hue value may be read at steps **S8-6**, **S10-6**, **S15-16** and **S19-6**, and used to determine the y-position and x-position of the eyes and eyebrows in 3D model space. In particular, an image value comprising the green component value may be used.

[0244] In the embodiments described above, at steps **S8-10**, **S15-18** and **S19-8**, the average of the pixel image values (intensity values in the embodiments) in a given band is calculated. Similarly, at step **S10-10**, the average of the pixel image values in a group of search bands is calculated. However, rather than calculating an average value at steps **S8-10**, **S15-18** and **S19-8** and **S10-10**, a different statistical measure of the pixel image values may be calculated. For example, the median, mode, geometric mean or variance may be calculated.

[0245] As part of the processing in the first embodiment at step **S7-2** to calculate the eye and eyebrow y-positions in 3D model space, a test may be added, for example, between steps **S8-18** and **S8-20** to ensure that the least two minima in each search group **60, 70** are sufficiently spaced apart in the y-axis direction to ensure that minima have not been selected which represent features closer together than the minimum separation of the user's eye and eyebrow, thereby improving the reliability of the y-position calculations.

[0246] In the first and second embodiments above, processing may be performed, for example between steps **S10-14** and **S10-16**, to ensure that a region of skin-coloured pixels exist in the 2D image data between the identified eyebrow positions and between the identified eye positions, thereby improving the reliability of the x-position calculations.

[0247] In the embodiments above, a spring-mass-damper technique is used at steps **S3-18**, **S13-18** and **S15-10** to rotate the 3D computer head model about axes through the centre of the head parallel to the x-axis and y-axis (that is, to update R_x and R_y in equation (1)). Similarly, the same technique could be used to rotate the 3D computer head model about axes through the centre of the head parallel to the z-axis (that is, to update R_z), for example if the processing previously performed at step **S3-8**, **S13-8** or **S15-4** did not provide head orientation information (with the result that step **S3-12**, **S13-12** or **S15-8** could not be performed).

[0248] Instead of using a spring-mass-damper technique at step **S3-18**, **S13-18** and **S15-10** to rotate the 3D computer head model, other techniques could be used. For example, the 3D computer head model could be rotated about axes through the centre of the head parallel to the x and y axes (and also about an axis through the centre of the head parallel to the z-axis if required) to minimise the average pixel intensity in the group **100-140** of the search bands **90** previously determined at step **S10-14** to contain the eyes and eyebrows of the user. More particularly, the 3D computer head model may be rotated to a new orientation (new R_x and/or R_y), and the processing of steps **S10-4** to **S10-10** repeated for the group of search bands previously selected at step **S10-4**. The calculated average intensity would then be stored and the processing repeated a number of times, each time following a new rotation of the 3D computer head model. The orientation which generates the lowest average intensity would then be selected as the correct orientation of the 3D computer head model because this most correctly aligns the 3D computer head model with the darkest regions (representing the eyes and eyebrows of the user) in the image data received from camera **4**.

[0249] In the first embodiment described above, at step **S3-4**, sample points "q" are defined within each of the search bands **80, 90**, and at steps **S8-4** and **S10-4**, each sample point is projected from 3D model space into 2D image space to define a pixel in the 2D image whose intensity value is to be read. However, instead of defining sample points at step **S3-4**, the corner points of each search band **80, 90** may be projected from 3D model space into 2D image space at steps **S8-4** and **S10-4** to define a search region within the 2D image, and the intensity value of every pixel (or a sub-set, such as every other pixel) within the projected search band in the 2D image may be read. Similarly, the four corner points of the left group **60** of search bands **80** and the four corner points of the right group **70** of search bands **80** may be projected from 3D model space into 2D image space to

define a search region within the 2D image, the search region in the 2D image space may be divided into strips corresponding to the search bands **80**, and the intensity value of every pixel (or a sub-set thereof) within each strip defined in the 2D image may be read. Because the projection from 3D model space to 2D image space is a linear projection, instead of projecting the four corner points of a group **60**, **70** of search bands **80** from 3D model space into 2D image space, it is only necessary to project three such points to uniquely define a projection of a search band within a 2D image.

[**0250**] In the second embodiment described above, instead of projecting four keypoints **210**, **212**, **218**, **220** for the right group **70** of search bands **200** or four keypoints **214**, **216**, **222**, **224** for the left group **60** of search bands **200** from the three-dimensional space of the 3D computer head model into 2D image space, only three points need to be projected for each group (such as three of the four keypoints for each of the left and right groups **60**, **70**) in order to uniquely define the projected sample point positions q'. This is because the projection from the three-dimensional space of the 3D computer head model into 2D image space is a linear projection.

[**0251**] In the second embodiment described above, eight keypoints **210-224** are defined at step **S13-4** and are projected from the three-dimensional space of the 3D computer head model into 2D image space at steps **S15-12** and **S19-2**. Sample point positions q' are then calculated in the 2D image at steps **S15-14** and **S19-4** in dependence upon the positions of the projected keypoints. However, instead, the position of each sample point q in the three-dimensional space of 3D computer head model may be defined at step **S3-4** (as illustrated in **FIG. 14***a*), and instead of performing the steps at **S15-12**, **S15-14**, **S19-2** and **S19-4**, each sample point q may be projected from the three-dimensional space of the 3D computer head model into the 2D image space to define a sample point position q'.

[**0252**] In the second embodiment described above, the number of search bands **200** in each of groups **60**, **70** is fixed, and similarly, the number of sample points q for each search band **200** is fixed. However, the number of search bands **200** in each group **60**, **70** and/or the number of sample points q for each search band **200** may be varied during processing. For example, the number of search bands and/or number of sample points may be calculated for each frame of image data in dependence upon the size and z-axis orientation of the user's head within the image calculated at step **S13-8**. In this way, the number of search bands **200** and/or sample points q can be varied in dependence upon the head within the image to ensure that an unnecessarily large number of sample points q are not defined and processed, thereby saving processing resources.

[**0253**] In the second embodiment described above, the left and right eye reference intensity profiles **250**, **260** for the user are generated at step **S13-5** using one frame of image data (that is, the frame from which the positions of the user's eyes were determined at step **S15-2**). However, each reference intensity profile may be generated using image data from more than one frame, thereby producing left and right eye reference intensity profiles for the user which take account of lighting changes for example due to movements of the user. Thus, for example, the processing at steps **S15-2** to **S15-18** may be performed a number of times so that intensity profiles **250**, **260** are generated at step **S15-18** using different frames of image data. The generated intensity profiles for the left eye may then be averaged and normalised to give a reference profile for the left eye, and similarly the generated intensity profiles for the right eye may be averaged and normalised to give a reference profile for the right eye.

[**0254**] In the second embodiment described above, the correlation values C_i calculated in accordance with equation (5) may be thought of as a probability density function, with the Y-coordinate of the eye being defined by the peak (maximum likelihood) of the function. Accordingly, other processing operations conventionally applied when using probability density functions may be used. For example, the probability density function defined by the correlation values C_i may be multiplied by a Gaussian function representing the expected position of the eye (determined, for example, in dependence upon how far the user's eye may move given the likely speed of movement of a user's head and the time between the recording of consecutive frames of image data). Other operations, could, of course, be performed instead or as well.

[**0255**] In the second embodiment described above, the search bands **200** are defined in the three-dimensional space of the 3D computer head model such that, when the search bands are transformed into a two-dimensional image, the spacing between adjacent transformed search bands is equal to one pixel in the image. However, instead, the search bands **200** may be defined in the three-dimensional space with different spacings therebetween. For example, the search bands **200** may be define in three-dimensional space of the 3D computer head model such that, when the search bands are transformed into a 2D image, the spacing between adjacent transformed search bands is less than one pixel in the image.

[**0256**] In the second embodiment above, each search band **200** is a line. However, instead, the search bands **80** from the first embodiment may be used in the second embodiment instead of the lines **200**, and the processing from the first embodiment to calculate a respective average pixel intensity value for each search band **80** may be used in the second embodiment. In this way, left and right eye reference intensity profiles **250**, **260** would be generated using the search bands and associated processing from the first embodiment, but the number of values within each reference profile would be fewer in number than if the reference profiles were generated using lines **200** (because each search band **80** has a width R_y greater than the width of each line **200**).

[**0257**] In the embodiments described above, the 3D computer model stored in head model store **24** is a 3D computer model of the head of the user **2**, generated, for example, by laser scanning etc. However, instead, the three-dimensional computer model does not actually need to be a model of the head of the user **2**, but instead may be a 3D computer model of a representative head.

[**0258**] In the embodiments described above, the three-dimensional computer model defined by the data stored in head model store **24** comprises a 3D computer model of a complete head. However, instead, the 3D computer model may comprise a model of just the relevant parts of the head, that is the parts containing the eyes and eyebrows.

[0259] In the embodiments described above, the processing to calculate the eye y-positions in 3D model space (step **S7-2** and step **S18-2**) is performed before the processing to calculate the eye x-positions in 3D model space (step **S7-4** and step **S18-4**). However, instead, the processing to calculate the eye x-positions in 3D model space may be performed before the processing to calculate the eye y-positions in 3D model space.

[0260] In the embodiments described above, the search bands **80**, **200** for determining the eye and eyebrow y-coordinates are arranged (**FIG. 5** and **FIG. 14***a*) in groups **60**, **70** to divide the three-dimensional model space into bands extending from above the left eyebrow to below the left eye and bands extending from above the right eyebrow to below the right eye. On the other hand, the search bands **90** for determining eye and eyebrow x-coordinates are arranged (**FIG. 6**) in groups of four bands, and the x-coordinates are calculated in dependence upon the group having the smallest minima in the average pixel intensity values (step **S10-14**). However, instead, the search bands **90** for determining the eye and eyebrow x-coordinates may be treated as separate, independent search bands **90** arranged in two groups—the first group aligned on the y-coordinate line Y_B corresponding to the eyebrows in the 3D computer model and the second group aligned on the y-coordinate line Y_E corresponding to the eyes in the 3D computer model. The x-coordinates of the eyes and eyebrows may then be calculated by identifying the search bands **90** corresponding to the least two minima within each of the first and second groups. The least two minima in the first group identify the search bands corresponding to the left and right eyebrows, while the least two minima in the second group identify the search bands corresponding to the left and right eyes. Similarly, in the first embodiment, the search bands **80** for determining the eye and eyebrow y-coordinates may be arranged in groups of four bands having relative positions set in dependence upon the spacing between the eyes and eyebrows in the 3D computer model (in the same way that the relative spacing of the bands **90** in the embodiment described above is set) and the eye and eyebrow y-coordinates may be calculated by identifying the group of search bands having the smallest minima in the average pixel intensity values (in the same way that this was performed for the x-coordinate calculation in the embodiment described above).

[0261] In the embodiments described above, data is input by a user defining intrinsic parameters of the camera **4**. However, instead, default values may be assumed for some, or all, of the intrinsic camera parameters, or processing may be performed to calculate the intrinsic parameter values in a conventional manner, for example as described in "Euclidean Reconstruction From Uncalibrated Views" by Hartley in Applications of Invariance in Computer Vision, Mundy, Zisserman and Forsyth eds, pages 237-256, Azores 1993.

[0262] In the embodiments described above, processing is performed by a computer using processing routines defined by programming instructions. However, some, or all, of the processing could, of course, be performed using hardware.

[0263] Other modifications are, of course, possible.

1. A method of processing data in a processing apparatus to perform eye tracking across a sequence of images of a moving head, the method comprising processing each of at least some of the images in the sequence by:

identifying pixels in the image corresponding to search regions defined relative to a three-dimensional computer model representative of at least part of a head in a three-dimensional space, the search regions being defined with different positions in a portion of the three-dimensional space corresponding to the eyes and eyebrows of the model, and the identification of pixels being performed in dependence upon data defining a transformation between the three-dimensional space and the two-dimensional image;

determining image values of the identified pixels; and

determining eye positions in the three-dimensional space in dependence upon the determined image values.

2. A method according to claim 1, further comprising:

rotating the three-dimensional computer head model in dependence upon the determined positions for the eyes, so as to move the search regions within the three-dimensional space for subsequent processing of the next image in the sequence to be processed.

3. A method according to claim 1, wherein the processing to determine eye positions in the three-dimensional space comprises:

generating at least one respective representative image value for each search region using the read image values; and

determining eye positions in the three-dimensional space in dependence upon the generated representative image values for the search regions.

4. A method according to claim 1, wherein the identification of pixels is carried out by projecting sample points defined in the three-dimensional space within the search regions into the image, and identifying the pixels onto which the sample points project.

5. A method according to claim 1, wherein the identification of pixels is carried out by projecting points from the three-dimensional space into the image to generate projected points, defining projected search regions in the image in dependence upon the projected points, and identifying pixels in the projected search regions.

6. A method according to claim 1, wherein each search region is a two-dimensional area of the three-dimensional space.

7. A method according to claim 1, wherein each search region is a line in the three-dimensional space.

8. A method of processing data in a processing apparatus defining a sequence of images of a person as the person's head moves, to track the eyes of the person in the images, the method comprising processing each of at least some of the images in the sequence by:

determining image values of pixels located in the image at positions defined by the projection of search bands or points therein from a three-dimensional space into the two-dimensional image, wherein the search bands have different positions in the three-dimensional space, and wherein the projection is dependent upon the position and orientation of the search bands in the three-dimensional space resulting from the processing of the previous image in the sequence to be processed;

calculating positions for the eyes in the three-dimensional space in dependence upon the determined image values; and

moving the search bands within the three-dimensional space in dependence upon the calculated positions for the eyes, so as to move the search bands for subsequent processing of the next image in the sequence to be processed.

9. A method of processing data in a processing apparatus to perform eye tracking across a sequence of images of a moving head, the method comprising processing each of at least some of the images in the sequence by:

identifying pixels in the image corresponding to search regions defined relative to a three-dimensional computer model representative of at least part of a head in a three-dimensional space, the search regions being defined with different positions in a portion of the three-dimensional space corresponding to the eyes and eyebrows of the model, and the identification of pixels being performed in dependence upon data defining a transformation between the three-dimensional space and the two-dimensional image;

determining image values of the identified pixels;

generating an image value profile from the image values representative of the variation in image value with variation in search region position; and

comparing the generated image value profile with a reference profile to determine eye positions in the three-dimensional space.

10. A method according to claim 9, further comprising:

rotating the three-dimensional computer head model in dependence upon the determined positions for the eyes, so as to move the search regions within the three-dimensional space for subsequent processing of the next image in the sequence to be processed.

11. A method according to claim 9, wherein the identification of pixels is carried out by projecting sample points defined in the three-dimensional space within the search regions into the image, and identifying the pixels onto which the sample points project.

12. A method according to claim 9, wherein the identification of pixels is carried out by projecting points from the three-dimensional space into the image to generate projected points, defining projected search regions in the image in dependence upon the projected points, and identifying pixels in the projected search regions.

13. A method according to claim 9, wherein each search region comprises a line in the three-dimensional space of the computer model.

14. A method according to claim 13, wherein the spacing between adjacent search regions in the three-dimensional space is such that, when the search regions are transformed into a two-dimensional image in accordance with the transformation data, the spacing between adjacent transformed search regions is less than or equal to one pixel in the image.

15. A method according to claim 9, wherein the search regions extend in a transverse direction to a line through an eye and an eyebrow of the three-dimensional computer model.

16. A method according to claim 15, wherein the search regions extend in a perpendicular direction to the line through the eye and the eyebrow.

17. A method according to claim 15, wherein the search regions intersect the line through the eye and the eyebrow at different respective positions therealong.

18. A method according to claim 9, wherein:

the processing to identify pixels in the image comprises identifying a plurality of pixels in the image for each respective search region; and

the processing to generate an image value profile comprises processing the plurality of read image values for each respective search region to calculate a respective representative image value for each search region.

19. A method according to claim 18, wherein a respective average value of the plurality of image values is calculated as the representative value for each search region.

20. A method according to claim 9, wherein the processing to compare the generated image value profile with the reference profile comprises processing to compare the generated profile and reference profile for different relative positions thereof.

21. A method according to claim 20, wherein the processing to compare the generated image value profile with the reference profile comprises processing to compare the generated profile and reference profile for different relative positions thereof to determine the match therebetween for each relative position and to determine the relative position for which the match between the generated profile and reference profile is greatest.

22. A method of processing data in a processing apparatus defining a sequence of images of a person as the person's head moves, to track the eyes of the person in the images, the method comprising processing each of at least some of the images in the sequence by:

determining image values of pixels located in the image at positions defined by the projection of search bands or positions therein from a three-dimensional space into the two-dimensional image, wherein the search bands have different positions in the three-dimensional space, and wherein the projection is dependent upon the position and orientation of the search bands in the three-dimensional space resulting from the processing of the previous image in the sequence to be processed;

generating at least one representative image value for each search band using the determined pixel image values;

comparing the generated representative image values with reference image values representative of image values for an eye and an eyebrow to calculate positions for the eyes in the three-dimensional space; and

moving the search bands within the three-dimensional space in dependence upon the calculated positions for the eyes, so as to move the search bands for subsequent processing of the next image in the sequence to be processed.

23. A method of processing data in a processing apparatus to perform eye tracking across a sequence of images of a moving head, the method comprising processing each of at least some of the images in the sequence by:

identifying pixels in the image in dependence upon search regions defined relative to a three-dimensional computer model representative of at least part of a head in a three-dimensional space, the search regions dividing into parts a portion of the three-dimensional space corresponding to the eyes and eyebrows of the model,

and in dependence upon data defining a transformation between the three-dimensional space and the two-dimensional image;

determining image values of the identified pixels;

determining which of the search regions project onto dark regions in the image in dependence upon the image values; and

determining eye positions in the three-dimensional space in dependence upon the relative positions of search regions determined to project onto dark regions of the image.

24. A method according to claim 23, further comprising:

rotating the three-dimensional computer head model in dependence upon the determined positions for the eyes, so as to move the search regions within the three-dimensional space for subsequent processing of the next image in the sequence to be processed.

25. A method according to claim 23, wherein the identification of pixels is carried out by projecting sample points defined in the three-dimensional space within the search regions into the image, and identifying the pixels onto which the sample points project.

26. A method according to claim 23, wherein:

the search regions include first and second groups of search regions, the first group dividing into parts a portion of the three-dimensional space extending over a first two of the left eyebrow, left eye, right eyebrow and right eye of the three-dimensional computer model, and the second group dividing into parts a portion of the three-dimensional space extending over a second two of the left eyebrow, left eye, right eyebrow and right eye of the three-dimensional computer model;

first and second search regions which correspond to dark regions in the image are identified within each group; and

positions for the eyes are determined in dependence upon the relative positions of the identified search regions within each group.

27. A method according to claim 26, wherein:

the search regions include first and second groups of search regions, the first group dividing into parts a portion of the three-dimensional space extending from above the left eyebrow to below the left eye of the three-dimensional computer model, and the second group dividing into parts a portion of the three-dimensional space extending from above the right eyebrow to below the right eye of the three-dimensional computer model;

first and second search regions corresponding to dark regions in the image are identified within each group; and

positions for the eyes are determined in dependence upon the position of the identified search region within each group which corresponds to a lower position on the three-dimensional computer head model.

28. A method according to claim 26, wherein:

the search regions include first and second sets of search regions;

the first set of search regions contains first and second first and second groups of search regions, the first group dividing into parts a portion of the three-dimensional space extending over a first two of the left eyebrow, left eye, right eyebrow and right eye of the three-dimensional computer model and the second group dividing into parts a portion of the three-dimensional space extending over a second two of the left eyebrow, left eye, right eyebrow and right eye of the three-dimensional computer model;

within the second set of search regions, each search region comprises a plurality of spatially separated parts having relative positions dependent upon the spacing of the eyes and eyebrows in the three-dimensional computer model;

values of a first coordinate of the eye positions are determined by:

identifying first and second search regions within each group of the first set corresponding to dark regions in the image; and

determining values of the first coordinate for the eye positions in dependence upon the relative positions of the identified search regions within each group in the first set; and

values for a second coordinate of the eye positions are determined by:

identifying a search region in the second set corresponding to dark regions in the image; and

determining values of the second coordinate for the eye positions in dependence upon the positions of the spatially separated parts within the identified search region of the second set.

29. A method according to claim 28, wherein:

the plurality of search regions in the second set divide into parts a portion of the three-dimensional space extending from outside the left eye to outside the right eye of the three-dimensional computer model; and

the processing to determine the values of the second coordinate includes:

selecting from among the search regions in the second set the search region which corresponds to the darkest region in the image; and

determining values of the second coordinate for the eye positions in dependence upon the positions of the spatially separated areas within the identified search region of the second set.

30. A method according to claim 23, wherein the search regions are defined with overlaps in the three-dimensional space.

31. A method according to claim 23, wherein each search region is a two-dimensional area of the three-dimensional space.

32. A method according to claim 23, wherein the processing to determine which search regions project onto dark regions in the image includes:

using the read image values to calculate a respective representative image value for each search region;

spatially smoothing the representative image values; and

identifying search regions which project onto dark regions in the image using the smoothed representative image values.

33. A method according to claim 32, wherein an average value of the pixel image values is calculated as the representative value for each search region.

34. A method of processing data in a processing apparatus defining a sequence of images of a person as the person's head moves, to track the eyes of the person in the images, the method comprising processing each of least some of the images in the sequence by:

determining the image values of pixels located in the image at positions defined by the projection of search bands or points therein from a three-dimensional space into the two-dimensional image, wherein the search bands have different positions in the three-dimensional space so as to divide into parts a portion of the three-dimensional space, and wherein the projection is dependent upon the position and orientation of the search bands in the three-dimensional space resulting from the processing of the previous image in the sequence to be processed;

calculating a respective representative image value for each search band using the determined pixel image values;

calculating positions for the eyes in the three-dimensional space by using the representative values to identify search bands corresponding to dark regions in the image and in dependence upon the relative positions of the identified search bands; and

moving the search bands within the three-dimensional space in dependence upon the calculated positions for the eyes, so as to move the search bands for subsequent processing of the next image in the sequence to be processed.

35. A method according to any one of claims **1**, **8**, **9**, **22**, **23** and **34**, wherein the processing of each image further comprises:

processing the image data to determine a position of the head in the image; and

moving the three-dimensional computer model of the head and the associated search regions within the three-dimensional space in dependence upon the determined position.

36. A method according to any one of claims **1**, **8**, **9**, **22**, **23** and **34**, wherein the processing of each image further comprises:

processing the image data to determine a size of the head in the image; and

moving the three-dimensional computer model of the head and the associated search regions within the three-dimensional space in dependence upon the determined size.

37. A method according to any one of claims **1**, **8**, **9**, **22**, **23** and **34**, further comprising defining the search regions in the three-dimensional space.

38. A method according to any one of claims **1**, **8**, **9**, **22**, **23** and **34**, further comprising calculating a gaze direction for each of at least some of the images.

39. A method according to claim 38, further comprising transmitting a signal conveying the determined gaze direction.

40. A method according to claim 39, further comprising making a recording of the signal either directly or indirectly.

41. Image processing apparatus for processing image data of at least some images in a sequence of images of a moving head to perform eye tracking across the sequence, the apparatus comprising:

a data store configured to store data defining a three-dimensional computer model representative of at least part of a head in a three-dimensional space, and data defining search regions having different positions in a portion of the three-dimensional space corresponding to the eyes and eyebrows of the model;

a pixel identifier operable to identify pixels in an image corresponding to the search regions, the pixel identifier being operable to identify pixels in dependence upon a transformation between the three-dimensional space and the two-dimensional image;

an image value determinator operable to determine image values of the identified pixels; and

an eye position determinator operable to determine eye positions in the three-dimensional space in dependence upon the determined image values.

42. An apparatus according to claim 41, further comprising:

a computer model rotator operable to rotate the three-dimensional computer head model in dependence upon the determined positions for the eyes, so as to move the search regions within the three-dimensional space for subsequent processing of the next image in the sequence to be processed.

43. Apparatus for processing image data of each of at least some images in a sequence of images of a person as the person's head moves, to track the eyes of the person in the images, the apparatus comprising:

a pixel identifier operable to identify pixels located in the image at positions defined by the projection of search bands or points therein from a three-dimensional space into the two-dimensional image, wherein the search bands have different positions in the three-dimensional space, and wherein the projection is dependent upon the position and orientation of the search bands in the three-dimensional space resulting from the processing of the previous image in the sequence to be processed;

an image value determinator operable to determine image values of the identified pixels;

an eye position calculator operable to calculate positions for the eyes in the three-dimensional space in dependence upon the determined image values; and

a search band mover operable to move the search bands within the three-dimensional space in dependence upon the calculated positions for the eyes, so as to move the search bands for subsequent processing of the next image in the sequence to be processed.

44. Apparatus for processing image data of each of at least some images in a sequence of images of a moving head to perform eye tracking across the sequence, the apparatus comprising:

a data store configured to store data defining a three-dimensional computer model representative of at least part of a head in a three-dimensional space, and data defining search regions having different positions in a portion of the three-dimensional space corresponding to the eyes and eyebrows of the model;

a pixel identifier operable to identify pixels in the image corresponding to the search regions, the pixel identifier being operable to identify pixels in dependence upon a transformation between the three-dimensional space and the two-dimensional image;

an image value determinator operable to determine image values of the identified pixels;

a profile generator operable to generate an image value profile from the image values representative of the variation in image value with variation in search region position; and

a profile comparer operable to compare the generated image value profile with a reference profile to determine eye positions in the three-dimensional space.

45. Apparatus according to claim 44, further comprising:

a computer model rotator operable to rotate the three-dimensional computer head model in dependence upon the determined positions for the eyes, so as to move the search regions within the three-dimensional space for subsequent processing of the next image in the sequence to be processed.

46. Apparatus for processing image data of each of at least some images in a sequence of images of a person as the person's head moves, to track the eyes of the person in the images, the apparatus comprising:

a pixel identifier operable to identify pixels located in the image at positions defined by the projection of search bands or positions therein from a three-dimensional space into the two-dimensional image, wherein the search bands have different positions in the three-dimensional space, and wherein the projection is dependent upon the position and orientation of the search bands in the three-dimensional space resulting from the processing of the previous image in the sequence to be processed;

an image value determinator operable to determine image values of the identified pixels;

a value generator operable to generate at least one representative image value for each search band using the determined pixel image values;

a comparer operable to compare the generated representative image values with reference image values representative of image values for an eye and an eyebrow to calculate positions for the eyes in the three-dimensional space; and

a search band mover operable to move the search bands within the three-dimensional space in dependence upon the calculated positions for the eyes, so as to move the search bands for subsequent processing of the next image in the sequence to be processed.

47. Apparatus for processing image data of at least some images in a sequence of images of a moving head to perform eye tracking across the sequence, the apparatus comprising:

a data store configured to store data defining a three-dimensional computer model representative of at least part of a head in a three-dimensional space, and data defining search regions dividing into parts a portion of the three-dimensional space corresponding to the eyes and eyebrows of the model;

a pixel identifier operable to identify pixels in the image in dependence upon the search regions and in dependence upon data defining a transformation between the three-dimensional space and the two-dimensional image;

an image value determinator operable to determine image values of the identified pixels;

a search region selector operable to determine which of the search regions project onto dark regions in the image in dependence upon the image values; and

an eye position determinator operable to determine eye positions in the three-dimensional space in dependence upon the relative positions of search regions determined to project onto dark regions of the image.

48. An apparatus according to claim 47, further comprising:

a computer model rotator operable to rotate the three-dimensional computer head model in dependence upon the determined positions for the eyes, so as to move the search regions within the three-dimensional space for subsequent processing of the next image in the sequence to be processed.

49. Apparatus for processing image data of each of at least some images in a sequence of images of a person as the person's head moves, to track the eyes of the person in the images, the apparatus comprising:

a pixel identifier operable to identify pixels located in the image at positions defined by the projection of search bands or points therein from a three-dimensional space into the two-dimensional image, wherein the search bands have different positions in the three-dimensional space so as to divide into parts a portion of the three-dimensional space, and wherein the projection is dependent upon the position and orientation of the search bands in the three-dimensional space resulting from the processing of the previous image in the sequence to be processed;

an image value determinator operable to determine image values of the identified pixels;

a value calculator operable to calculate a respective representative image value for each search band using the determined pixel image values;

an eye position calculator operable to calculate positions for the eyes in the three-dimensional space by using the representative values to identify search bands corresponding to dark regions in the image and in dependence upon the relative positions of the identified search bands; and

a search band mover operable to move the search bands within the three-dimensional space in dependence upon the calculated positions for the eyes, so as to move the search bands for subsequent processing of the next image in the sequence to be processed.

50. A storage medium storing computer program instructions for programming a programmable processing apparatus to become operable to perform a method as set out in at any one of claims **1**, **8**, **9**, **22**, **23** and **34**.

51. A signal carrying computer program instructions for programming a programmable processing apparatus to become operable to perform a method as set out in any one of claims **1**, **8**, **9**, **22**, **23** and **34**.

52. Image processing apparatus for processing image data of at least some images in a sequence of images of a moving head to perform eye tracking across the sequence, the apparatus comprising:

means for storing data defining a three-dimensional computer model representative of at least part of a head in a three-dimensional space, and data defining search regions having different positions in a portion of the three-dimensional space corresponding to the eyes and eyebrows of the model;

pixel identifying means for identifying pixels in an image corresponding to the search regions, the pixel identifying means being operable to identify pixels in dependence upon a transformation between the three-dimensional space and the two-dimensional image;

means for determining image values of the identified pixels; and

means for determining eye positions in the three-dimensional space in dependence upon the determined image values.

53. Apparatus for processing image data of each of at least some images in a sequence of images of a person as the person's head moves, to track the eyes of the person in the images, the apparatus comprising:

means for identifying pixels located in the image at positions defined by the projection of search bands or points therein from a three-dimensional space into the two-dimensional image, wherein the search bands have different positions in the three-dimensional space, and wherein the projection is dependent upon the position and orientation of the search bands in the three-dimensional space resulting from the processing of the previous image in the sequence to be processed;

means for determining image values of the identified pixels;

means for calculating positions for the eyes in the three-dimensional space in dependence upon the determined image values; and

means for moving the search bands within the three-dimensional space in dependence upon the calculated positions for the eyes, so as to move the search bands for subsequent processing of the next image in the sequence to be processed.

54. Apparatus for processing image data of each of at least some images in a sequence of images of a moving head to perform eye tracking across the sequence, the apparatus comprising:

means for storing data defining a three-dimensional computer model representative of at least part of a head in a three-dimensional space, and data defining search regions having different positions in a portion of the three-dimensional space corresponding to the eyes and eyebrows of the model;

pixel identifying means for identifying pixels in the image corresponding to the search regions, the pixel identifying means being operable to identify pixels in dependence upon a transformation between the three-dimensional space and the two-dimensional image;

means for determining image values of the identified pixels;

means for generating an image value profile from the image values representative of the variation in image value with variation in search region position; and

means for comparing the generated image value profile with a reference profile to determine eye positions in the three-dimensional space.

55. Apparatus for processing image data of each of at least some images in a sequence of images of a person as the person's head moves, to track the eyes of the person in the images, the apparatus comprising:

means for identifying pixels located in the image at positions defined by the projection of search bands or positions therein from a three-dimensional space into the two-dimensional image, wherein the search bands have different positions in the three-dimensional space, and wherein the projection is dependent upon the position and orientation of the search bands in the three-dimensional space resulting from the processing of the previous image in the sequence to be processed;

means for determining image values of the identified pixels;

means for generating at least one representative image value for each search band using the determined pixel image values;

means for comparing the generated representative image values with reference image values representative of image values for an eye and an eyebrow to calculate positions for the eyes in the three-dimensional space; and

means for moving the search bands within the three-dimensional space in dependence upon the calculated positions for the eyes, so as to move the search bands for subsequent processing of the next image in the sequence to be processed.

56. Apparatus for processing image data of at least some images in a sequence of images of a moving head to perform eye tracking across the sequence, the apparatus comprising:

means for storing data defining a three-dimensional computer model representative of at least part of a head in a three-dimensional space, and data defining search regions dividing into parts a portion of the three-dimensional space corresponding to the eyes and eyebrows of the model;

pixel identifying means for identifying pixels in the image in dependence upon the search regions and in dependence upon data defining a transformation between the three-dimensional space and the two-dimensional image;

means for determining image values of the identified pixels;

search region selection means for determining which of the search regions project onto dark regions in the image in dependence upon the image values; and

eye position determining means for determining eye positions in the three-dimensional space in dependence upon the relative positions of search regions determined to project onto dark regions of the image.

57. Apparatus for processing image data of each of at least some images in a sequence of images of a person as the person's head moves, to track the eyes of the person in the images, the apparatus comprising:

means for identifying pixels located in the image at positions defined by the projection of search bands or points therein from a three-dimensional space into the two-dimensional image, wherein the search bands have different positions in the three-dimensional space so as to divide into parts a portion of the three-dimensional space, and wherein the projection is dependent upon the position and orientation of the search bands in the three-dimensional space resulting from the processing of the previous image in the sequence to be processed;

means for determining image values of the identified pixels;

means for calculating a respective representative image value for each search band using the determined pixel image values;

means for calculating positions for the eyes in the three-dimensional space by using the representative values to identify search bands corresponding to dark regions in the image and in dependence upon the relative positions of the identified search bands; and

means for moving the search bands within the three-dimensional space in dependence upon the calculated positions for the eyes, so as to move the search bands for subsequent processing of the next image in the sequence to be processed.

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