

A method for calibrating a multi-camera system

FIELD OF THE INVENTION

The invention relates to an apparatus and method for calibrating a multi-camera
5 system.

BACKGROUND

A synchronized multiple perspective imaging system may be used to obtain a
number of different views around a subject, such as a 360 degree view. This
10 image data may then be utilised by processing systems where 3D or volumetric
information is desired. In such systems often there will be a large number of
cameras mounted onto a jig, cage or track. The cameras may be repositioned on
the jig, cage or track but such a repositioning of a camera may require
re-calibration of the camera or image data. The need for re-calibration with every
15 new position results in a system which is inflexible and unsuitable for camera
arrangements which change over time.

Further, the calibration of the cameras of the multiple imaging device system
becomes increasingly tedious as the number of cameras increases. This is
20 because the calibration process has to be performed for every permutation of
camera pairs. Taking for example the case where N cameras are present in the
system, a relocation of just one camera requires the recalibration of (N-1) camera
pairs.



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SUMMARY OF THE INVENTION

In general terms the invention relates to measuring master calibration data for each individual camera at the factory and using the master calibration data to
5 derive new calibration data each time the camera is relocated.

In a first specific expression of the invention there is provided a method according to claim 1. This may have the advantage of eliminating/minimizing the need for recalibration of a camera.

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Embodiments may be implemented according to any of claims 2 to 17.

An apparatus and method for calibrating a camera according to one or more of the embodiments may have one or more advantages including:

- 15 - adapting new calibration data from master calibration data in an easier manner;
- eliminating/minimizing the need for recalibration of the camera upon relocation of the camera(s) or reassembly of the shooting setup;
- having a camera system which is easy to use and highly flexible;
- 20 - being highly adaptable to different shooting requirements and setups;
- being highly adaptable to a variety of camera subjects;
- being highly customizable; and/or
- being scalable.

BRIEF DESCRIPTION OF THE DRAWINGS

One or more example embodiments of the invention will now be described, with reference to the following figures, in which:

5 Figure 1 is a schematic drawing showing an apparatus for multiple imaging according to an example embodiment;

 Figure 2 is a flow diagram showing a method of calibrating a plurality of cameras of the apparatus of Figure 1;

 Figure 3a is a photograph showing one of the plurality of cameras of Figure
10 1 being mounted onto a camera seat;

 Figure 3b is a photograph showing the one of the plurality of cameras of Figure 3a being held in the camera seat;

 Figure 4 is a schematic drawing showing a left camera and a right camera of a pair of the plurality of cameras of Figure 1 undergoing calibration;

15 Figure 5a is a photograph showing the plurality of cameras of Figure 1 being mounted on a platform and undergoing calibration;

 Figure 5b is a photograph showing a left image captured by the left camera of Figure 4;

 Figure 5c is a photograph showing a right image captured by the right
20 camera of Figure 4;

 Figure 6 is a screenshot showing a projection matrix and a conversion matrix for one of the pair of cameras of Figure 4;

 Figure 7a is a photograph showing the left image of Figure 5b after compensation;

Figure 7b is a photograph showing the right image of Figure 5c after compensation;

Figure 8 is a schematic drawing showing the right camera of Figure 4 relocated from a first position to a second position;

5 Figure 9 is a schematic drawing showing an interpolation of the respective left and right images of Figures 7a and 7b;

Figure 10 is an image acquired by a camera of Figure 2 showing an angular tilt off a vertical; and

10 Figure 11 is a photograph showing a marker located in the centre of a stand of the apparatus of Figure 1.

DETAILED DESCRIPTION

Figure 1 shows an apparatus 1000 for multiple perspective imaging according to an example embodiment. The apparatus 1000 comprises a stand 1100 having
15 thirty two cameras 1110 for capturing images from all around a subject, an acquisition and processing device 1400 for acquiring images from the cameras 1110 and processing the images, and an image display / storage device 1500 for displaying or storing the processed images.

20 The stand 1100 comprises a level annular platform 1130 suitable for a 360 degree all-around capture system. The platform 1130 is supported by ten legs 1120. The cameras 1110 are mounted on top of the platform 1130. The platform 1130 is precision machined so as to allow for easy but highly precise positioning of the plurality of cameras 1110. The subject (not shown) is typically located at

the center of the stand 1100. The platform 1130 may not be a perfect full circle; for example, it may be semi-circular or oval.

The acquisition and processing device 1400 is capable of issuing a capture
5 command 1402 simultaneously to all the cameras 1110. The acquisition and
processing device 1400 is a workstation with a plurality of capture cards
interfacing with the some or all of the cameras 1110 using the IEEE1394b
protocol. The reception of the command 1402 at the cameras 1110 causes them
to capture respective images of the subject. These captured images are then
10 transferred 1404 from each camera 1110 to the acquisition and processing
device 1400. The cameras 1110 are synchronized by means of an internal
triggering or external triggering signal.

In the case where internal triggering is used, the internal trigger is generated at
15 the acquisition and processing device 1400 and transmitted to each camera
1110. The internal trigger is generated by programmatically calling the
appropriate software commands specified in the software development kit (SDK)
of the camera 1110. The SDK may be manufacturer dependent.

20 In the case where external triggering is used, external connective hardware e.g.
wiring is present between each camera 1110 and the acquisition and processing
device 1400. A trigger signal taking the form of an external square wave is
generated at the acquisition and processing device 1400 and transmitted across
the connective hardware. The trigger signal is input into each camera 1110 via a

connector as specified by the manufacturer. One way of generating square waves would be to use TTL outputs, or to use commonly available timing chips e.g. the IC555 chip. Optionally, it is envisaged that the acquisition and processing device 1400 may trigger each camera 1110 wirelessly. It is also envisaged that a device different from the acquisition and processing device 1400 may be used to trigger the cameras 1110.

The plurality of captured images are then processed at the acquisition and processing device 1400 by compensating with calibration data as will be described later. Additional processing may be performed before and after compensation. The resultant processed image 1502 is then transmitted to an image display / storage device 1500 for display to a user, or for storage. The image display / storage device 1500 may be a hard disk unit, or a solid-state drive, and may be further equipped with a monitor. In some applications the processing device 1400 may interpolate between each image to give a larger number of intermediate and novel views of the subject.

It is envisaged that the acquisition and processing device 1400 may be a personal computer, or a server computer, or an embedded device, which may either be separate from the cameras 1110, or be embedded on-board in each camera 1110. Also, it is envisaged that the image display / storage device 1500 may be a computer monitor, a projector, a storage array or hard disk.

A method 200 of calibrating the plurality of cameras 1110 according to an example embodiment is shown in Figure 2. Master calibration data is obtained for each specific camera 1110 at the factory. The master calibration data can then be used by the processing device 1400 to determine the new calibration data
5 after any subsequent relocation of that specific camera.

In 100, the cameras 1110 are initially set up at the factory. This involves mounting each of the cameras 1110 onto a camera seat 1190 as is shown in Figure 3a. Each camera 1110 is fastened on the camera seat 1190 using three screws. The
10 screws are inserted into screw holes present on the under surface of the camera seat 1190 and then tightened.

A check is then performed of the placement of the camera 1110 within the camera seat 1190. This check verifies that the camera is not tilted excessively
15 along the optical axis.

Figure 10 shows an image which is used for checking if an angular tilt 1354 is present in the placement of a camera 1110. An angular tilt 1354 in excess of 1-2deg is considered excessive. The tilt of the camera results when the camera
20 does not sit level on the track surface. By capturing an image with the camera 1110, a tilt is detected by observing if the image is rotated either clockwise or counter-clockwise.

Tilt detection at each camera 1110 comprises:

- 1) placing a calibration (checkered) board at the centre of the stand 1100 such that it is visible at the camera 1110;
 - 2) capturing an image with the camera 1110;
 - 3) Identifying in the image a vertical line of the checkered board which is closest to the centre of the board;
 - 4) deriving a vertical imaginary line 1352 down the image centre. The vertical imaginary line 1352 is a reference line to be used for determining if the image is vertical. As an example, if the image is 480x480 pixels, a vertical imaginary line is drawn right down the 240 pixel column;
 - 5) comparing the identified vertical line 1350 with the vertical imaginary line 1352 to estimate the amount of angular tilt 1354 between both lines; and
 - 6) If angular tilt 1354 is present, the camera 1110 is adjusted to eliminate/reduce the angular tilt 1354.
- 15 In 101, the plurality of cameras 1110 are mounted on the platform 1130 of the stand 1110. This may for example be performed after the cameras 1110 are delivered to the user and the user reassembles the apparatus 1000.

20 In 102, the master calibration data 120 is retrieved from a storage device. If the master calibration data 120 is absent for a camera 1110 e.g. in the case where the camera 1110 is set up for the first time at the factory, or where the master calibration data 1110 is lost, the master calibration data 120 is obtained by the process of a full calibration 140. If the master calibration data 120 however is present for a camera 1110 e.g. in the case where the camera 1110 is being

relocated on the platform 1130, there would not be a need to calibrate the camera 1110 anew and the master calibration data 120 is adjusted in Step 121.

The process of full calibration 140 comprises the steps of fine-tuning 103 each camera 1110 on its corresponding camera seat 1190, calibrating 104 the camera 1110, checking 105 if the calibration is correct, then enclosing 106 the camera 1110 in a housing, and finally saving 107 the master calibration data 120. The steps of fine-tuning 103, calibrating 104 and checking 105 are iterative and are repeated until when the master calibration data is correctly derived.

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In 103, the position of each camera 1110 on its corresponding camera seat 1190 is fine-tuned. Images are taken using each camera 1110. If the images reveal that the camera 1110 is tilted about the Z-axis i.e. there is an angular roll, the roll is compensated by adding spacers between the camera 1110 and the camera seat 1190. It is noted that the Z-axis is co-aligned with the optical axis and angular rolls about the Z-axis result in the acquired image being "rotated" i.e. seen to be "not level". Spacers when added correct for this.

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The cameras 1110 may also experience tilt about the Y-axis i.e. there is an angular yaw or tilt about the X-axis i.e. there is an angular pitch. The presence of an angular yaw results in the acquired image appearing displaced to the left or right. The presence of an angular pitch results in the acquired image appearing displaced upwardly or downwardly. The left/right and/or up/down displacement is corrected by shifting the acquired image using image processing techniques.

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Alternatively, the displacement may be compensated by the addition of spacers as is done for an angular roll. The use of image processing techniques to compensate for the displacement however may have the advantage of being easier and more easily automated.

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Step 103 is done in two sub-steps for each camera 1110. In the first sub-step, angular roll is first compensated using spacers. Thereafter, in the second sub-step, angular yaw and/or angular pitch are then compensated using image processing techniques. The latter sub-step is performed using a marker 1310 as
10 a reference point. Figure 11 shows the marker 1310 in the middle of the platform 1130. The marker 1310 is mounted on a stand 1320 and has a white coloured apex which stands out against the surroundings. The stand 1320 is placed in the centre of the platform 1130 and the angular yaw and/or pitch are compensated by processing the acquired image so that the marker 1310 is in the centre of each
15 processed image.

In 104, each camera 1110 is calibrated. Calibration of the cameras 1110 involves obtaining the following matrices:

1. Projection Matrices – these matrices project captured images from the 3D
20 coordinate system onto a 2D image plane.
2. Conversion Matrices – also known as Rectification Matrices, these matrices are used to rectify the captured images by bringing the left and right captured images of respective left and right cameras onto a same plane. Once rectified, there is correspondence between the image pair.

When calibrating a pair of cameras, the projection matrices belonging to both cameras of the camera pair are used to generate a corresponding pair of rectification matrices.

- 5 The master calibration data 120 for each camera 1110 comprises the matrices mentioned above. Calibration is done pair-wise between pairs of the plurality of cameras 1110. In order to reduce any discontinuities between the resultant images of the camera pairs, each camera pair is formed using cameras which are located immediately next to each other. Camera pairs however may also be
- 10 formed using any of the plurality of cameras. Figure 4 shows a pair of cameras 1110 undergoing calibration. The left camera 1112 is the n th camera while the right camera 1114 is taken to be $n+1$ th camera. Both cameras are distributed circumferentially about a reference point such that the Z-axis (which is co-aligned with the optical axis) of each camera projects to intersect at the reference point.
- 15 The process of calibration is performed in the acquisition and processing device 1400. It is however envisaged that calibration may be performed on-board in each of the cameras 1110.

- Images of a calibration board 1008 (which is shown in Figure 5a) are captured at
- 20 each of the cameras 1110 of the camera pair undergoing calibration. Figure 5a shows a plurality of cameras 1110 mounted on the platform 1130 undergoing calibration. The calibration board 1008 consists of a checkered plurality of black and white squares. For each pair of cameras 1110, images of the calibration board 1008 are captured by the respective cameras. Figures 5b and 5c show left

and right images 1002, 1004 captured respectively by a right camera and a left camera of a camera pair. The captured images 1002, 1004 are then acquired by the acquisition and processing device 1400 for processing. It is noted that the calibration board 1008 does not have to be located precisely at the centre of the stand 1100, so long that for each pair of cameras 1110 under going calibration, the calibration board 1008 is visible by both cameras 1110.

A projection matrix and a conversion matrix are obtained for each camera 1110 of the camera pair. Figure 6 shows the projection matrix 1202 (also denoted as Matrix A) and the conversion matrix 1204 (also denoted as Matrix B) for a camera of a camera pair.

The projection matrix 1202 is a 3×4 matrix which transforms the 3D x, y, z coordinate system of the real world into a 2D image using a x, y coordinate system.

The conversion matrix 1204 is a 3×3 matrix which transforms the left and right images 1004 (which respectively have different epipolar planes and image planes) onto a common epipolar image plane. This is derived from the projection matrix. As an example, the technique disclosed in "*A compact algorithm for rectification of stereo pairs*", A. Fusiello, et. al. in *Machine Vision and Applications* (2000) - the contents of which are incorporated herein by reference - may be used to obtain the conversion matrix 1204.

While techniques are described above in which the projection and conversion matrices may be obtained, it however is envisaged that matrices may be obtained using any other technique that is known in the art. Also, images of any other calibration object other than the calibration board 1008 may be used when
5 performing calibration.

In 105, the master calibration data 120 is checked for correctness. This is done by applying the master calibration data 120 to images acquired and checking for its rectification quality. This may be done by checking if the squares of a
10 calibration board 1008 are aligned to be along the same epipolar lines.

Should the master calibration data 120 be deemed correct, step 106 is performed. However, should the data 120 be deemed incorrect, steps of 103, 104 and 105 are repeated.

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In 106, each camera 1110 and camera seat 1190 is enclosed in a housing in order to shield it from external knocks and forces. This keeps the camera 1110 in alignment within the camera seat 1190 and may help to preserve the correctness of the master calibration data 120. The housing is made out of metal.

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In 107, the master calibration data 120 is stored. Where there are N number of cameras 1110 in the apparatus 1000, each of the N cameras 1110 thus may be paired with (N-1) other cameras. The master calibration data 120 for each

camera 1110 thus comprises (N-1) number of projection matrices and conversion matrices i.e. one of each matrix for each pair of cameras 1110.

The master calibration data 120 for each camera 1110 may be stored on the cameras 1110, or may be stored on the acquisition and processing device 1400. Optionally, this data 120 may also be stored in a removable storage device e.g. a flash drive. This data 120 when stored is rewritable. The master calibration data 120 may be modified and updated whenever the cameras 1110 are rearranged and this may thus give the apparatus 1000 flexibility.

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In 108, images of a subject are captured using some or all of the plurality of cameras 1110. This may be done in response to a capture command 1402 issued by the acquisition and processing device 1400. This capture may be done simultaneously on all the cameras 1110, or in a predetermined sequence as controlled by the acquisition and processing device 1400. The images captured at the cameras 1110 are transferred to the acquisition and processing device 1400 for compensation and processing in step 122.

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In 109, the user makes a decision on whether to reposition the cameras 1110 on the platform 1130. The repositioning is along the common horizontal plane i.e. the X-Z plane. The repositioning however may also be along any other plane, and may represent a 3D translation. If no repositioning is desired, the capturing of images may continue using the existing set up and master calibration data 120.

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Should the cameras 1110 however be repositioned, the master calibration data 120 is adjusted in step 121 in order to cope with any change in the placement of the cameras 1110. It is noted that the adjustment of new calibration data from the master calibration data may be simpler, and require less effort and time than
 5 performing calibration anew.

Figure 8 shows the right camera 1114 relocated from a first position (i.e. Pos 1) to a second position (i.e. Pos 2). The relocation is a rotation of θ_2 degrees about the Z-axis (i.e. a rotation about the vertical axis). The possible camera locations on
 10 the platform 1130 are discrete and pre-determined, and are machined to a degree of precision. This may allow the angle θ_2 to be easily obtained by observing the number of discrete camera locations between the first position and the second position. It is however envisaged that the platform 1130 may have sensors built in which are able to automatically feedback θ_2 to the acquisition and
 15 processing device 1400.

Referring back to Figure 1, in 121, the master calibration data 120 for the left and right cameras 1112, 1114 are adjusted. Taking the relocation of Figure 7 as example, since the relocation is a rotation, a 4 x 4 rotation matrix R is applied to
 20 the projection matrix P. The adjusting of the projection matrix P is shown in Equation 1.

$$P_{new} = P \bullet R \bullet T \quad (1)$$

A new projection matrix P_{new} is computed by multiplying the former projection matrix P with the rotation matrix R and with the translation matrix T . Equation 1 may be re-expressed as Equation 2.

$$\begin{bmatrix} a_{new} & b_{new} & c_{new} & T_{x,new} \\ d_{new} & e_{new} & f_{new} & T_{y,new} \\ h_{new} & i_{new} & j_{new} & 1 \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \end{bmatrix} \cdot \begin{bmatrix} \cos \theta_2 & 0 & -\sin \theta_2 & 0 \\ 0 & 1 & 0 & 0 \\ \sin \theta_2 & 0 & \cos \theta_2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & T_x \\ 0 & 1 & 0 & T_y \\ 0 & 0 & 1 & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

5

The rotation matrix R is derived from the angle θ_2 . It applies a rotation about the centre of the circular platform 1130 i.e. about the Y-axis. It is however envisaged that the rotation may not necessarily be made about the Y-axis; the rotation may be made about any other cardinal axis, or even about an axis co-aligned with any 3D vector. In these cases, the rotation matrix R respectively denotes a rotation about the other cardinal axis, or a rotation about the 3D vector. Specifically in the latter case, the rotation matrix R may comprise angular rotations about more than one cardinal axis; the rotation matrix R may thus be derived from a multiplication of more than one rotational matrices each representing rotation about respective cardinal axes.

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The translation matrix T is used to compensate for lateral translation of the camera 1114 along the X-axis and Z-axis i.e. T_x and T_z respectively when the camera 1114 is relocated from the original position (i.e. Pos 1) to the relocated position (i.e. Pos 2). Since the original position and relocated position of the relocation camera 1114 are on a common horizontal plane, T_y is 0. T_x and T_z are calculated using the radius of the platform 1140 which is known.

20

It is also envisaged that the cameras 1110 may be repositioned along planes other than the horizontal plane i.e. the plane containing the X and Z axes.

Additionally, the axes contained in the plane of repositioning do not have to be cardinal axes i.e. the repositioning of the cameras 1110 may be a translation along all three cardinal axes. In this case, the relocation is a 3D translation and T_x , T_y and T_z are all non-zero.

Further, it is also envisaged that if more than one of the cameras 1110 are repositioned, each camera that is repositioned may be rotated about different planes and may represent different 3D translations.

The new projection matrix P_{new} is incorporated back into the master calibration data 120 as the matrix P. The master calibration data 120 after revision is then used for compensation in step 122.

Steps 101-107 may be performed at the factory before shipping to the user or they may be performed by a suitably qualified calibration technician during a first installation.

In 122, the images captured are compensated and processed at the acquisition and processing device 1400. Compensation may be performed using the matrices stored in the master calibration data 120. Alternatively, compensation may be performed using the adjusted calibration data resulting from step 121.

Figures 7a and 7b show left and right images 1012, 1014 corresponding to the images of Figures 5b and 5c after compensation. The left and right images 1012, 1014 are on a common epipolar plane and may now be matched line by line.

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Optionally, further processing may now be done between the left and right images 1012, 1014 to produce resultant images. Such processing may for example be an interpolation of the left and right images 1012, 1014 as is shown in Figure 9. The left and right images 1012, 1014 are interpolated to produce the
10 intermediate images 1016. The left and right images 1012, 1014, as well as any resultant images may be displayed and/or stored in the image display / storage device 1500

It is noted that the terms "conversion matrix" and "rectification matrix" are used
15 interchangeably throughout this specification to refer to a conversion matrix 1204.

Whilst exemplary embodiments of the invention have been described in detail, many variations are possible within the scope of the invention as will be clear to a
20 skilled reader. For example, the computation for the adjusting step 121 may be implemented as software, or it may be implemented as hardware in the form of a FPGA.

Claims

1. A method comprising
providing a master calibration matrix based a camera mounted in a first
5 location on a seat,
positioning the camera in a second location on the seat,
determining a rotation and/or translation to the master calibration matrix
to produce an adapted calibration matrix, the rotation and/or translation
dependent on the first location relative to the second,
10 capturing an image with the camera in the new relative location, and
rectifying the image based on the adapted calibration matrix.
2. The method of claim 1 wherein the rotation and/or translation includes a
rotation matrix and/or a translation matrix obtained from a parameter
15 representative of the first location relative to the second location.
3. The method of claim 2 wherein the parameter is derived from known
geometry.
- 20 4. The method of any preceding claim wherein the master calibration matrix
is provided by retrieval from a storage device.
5. The method of any preceding claim wherein providing the master
calibration matrix further comprises

determining a projection matrix for the camera at the first location relative to the seat, and

determining the master calibration matrix based on the projection matrix.

5 6. The method of claim 5 further comprising determining a rectification matrix to the master calibration matrix, the rectification matrix being dependant on the juxtaposition of the camera to another camera.

7. The method of claim 6 further comprising determining a conversion
10 matrix to convert the image to an epipolar image plane common to the camera and the another camera.

8. The method according to any of claims 5 to 7 wherein the projection
15 matrix is determined using least squares estimation with the camera at the first location.

9. The method according to claim 8 wherein the projection matrix is stored in the camera.

20 10. The method according to any preceding claim wherein the rotation is about a vertical axis.

11. The method according to claim 10 wherein an angular offset is estimated about the vertical axis.

12. The method according to any of claims 1 to 9 wherein the rotation is about a three-dimensional vector.
- 5 13. A camera stand for performing the method of any preceding claim comprising
a platform having a precision machined plurality of engagement portions each configured to engage the seat.
- 10 14. The seat of any of claims 1 to 12 comprising
one or more spacers positioned between the camera and the seat, the one or more spacers configured to compensate for an angular roll about an optical axis of the camera.
- 15 15. An integrated circuit or processor configured to perform the method of any of claims 1 to 12.
16. A camera configured to perform the method of any of claims 1 to 12.
- 20 17. An apparatus for capturing images configured to perform the method of any of claims 1 to 12.