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- (73) Patenthaver: **Thales, Tour Carpe Diem Esplanade Nord , Place des Corolles, 92400 Courbevoie, Frankrig**
- (72) Opfinder: **HORAK, Raphaël, 2 Avenue Gay Lussac, CD90502, 78995 ELANCOURT, Frankrig**
- (74) Fuldmægtig i Danmark: **Marks & Clerk (Luxembourg) LLP, 44 rue de la Vallée, B.P. 1775, L-1017 Luxembourg, Luxembourg**
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**HANSON A R ET AL: "Generalized parallel-perspective stereo mosaics from airborne video", PATTERN ANALYSIS AND MACHINE INTELLIGENCE, IEEE TRANSACTIONS ON, IEEE SERVICE CENTER, LOS ALAMITOS, CA, US, vol. 26, no. 2, 1 février 2004 (2004-02-01), pages 226-237, XP011105998, ISSN: 0162-8828, DOI: 10.1109/TPAMI.2004.1262190**  
**POLLEFEYS M ET AL: "Detailed Real-Time Urban 3D Reconstruction from Video", INTERNATIONAL JOURNAL OF COMPUTER VISION, KLUWER ACADEMIC PUBLISHERS, BO, vol. 78, no. 2-3, 20 octobre 2007 (2007-10-20), pages 143-167, XP019581883, ISSN: 1573-1405**  
**AKIHIKO TORII ET AL: "From Google Street View to 3D city models", 2009 IEEE 12TH INTERNATIONAL CONFERENCE ON COMPUTER VISION WORKSHOPS, ICCV WORKSHOPS : KYOTO, JAPAN, 27 SEPTEMBER - 4 OCTOBER 2009, INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, PISCATAWAY, NJ, 27 septembre 2009 (2009-09-27), pages 2188-2195, XP031664581, ISBN: 978-1-4244-4442-7**



The field of the invention is that of 3D reconstruction of a scene on the basis of successive panoramic images of this scene, followed by 3D mosaicking of this scene.

The 3D reconstruction of a scene consists in obtaining, on the basis of successive 2D images of this scene taken from various viewpoints, a reconstructed image, called 3D image, such that each pixel of the reconstructed image, i.e. at any point where the reconstruction declares that there is a scene element, is associated with the coordinates of the point of the corresponding scene, defined in an X, Y, Z reference frame associated with this scene.

Conventional mosaicking, called 2D mosaicking, consists in, on the basis of successive images of a scene, successively projecting said images onto a main plane of the scene and assembling them in order to produce a mosaic therefrom.

Passive techniques for 3D reconstruction of a scene on the basis of cameras are described in various reference works:

- R. Horaud & O. Monga, "Computer Vision: Fundamental Tools", Editions Hermès, 1995, <http://www.inrialpes.fr/movi/people/Horaud/livre-hermes.html>;
- Olivier Faugeras, "Three-Dimensional Computer Vision", MIT Press, 1993;
- Frédéric Devernay, INRIA Grenoble, "3D Computer Vision" course, <http://devernay.free.fr/cours/vision/>;
- Tébourbi Riadh, "SUP'COM 2005 3D IMAGING", 08/10/2007;
- "Learning OpenCV: Computer Vision with the OpenCV Library", Gary Bradsky, 2008.

These works cite all of the techniques for 3D reconstruction of a scene on the basis of pairs of stereoscopic images originating from cameras positioned at various viewpoints, which can be either fixed cameras positioned at various points in space or a camera whose position varies temporally, always with the same basic principle of matching the images from cameras taken 2-by-2 in order to form a stereoscopic 3D reconstruction of the portion of space viewed by the cameras.

They also explain the principle of epipolar rectification where the focal plane image of each camera is rectified according to the attitude of the camera on a plane, called rectification plane, in order to facilitate the matching between the images of the stereoscopic pair and to enable the 3D reconstruction. The method is relatively optimised by various authors but is still based on the principle that the optical distortions of the camera firstly need to be corrected and then the relative attitudes of the 2 cameras need to be used in order to determine the rectification plane from which the matching and the 3D reconstruction are performed.

Further passive 3D reconstruction techniques exist in the literature, for example, the techniques called silhouetting, which are not considered herein as they apply to particular cases and require prior knowledge of the scene.

Among the techniques of active reconstruction of a scene it is possible to cite those that are Lidar-based, which allow the 3D mesh of the scene to be directly reconstructed through a distance computation.

The following can be cited from the reference works:

- MATIS work for IGN: "Using Full Waveform Lidar Data for Mapping of urban Areas", Doctoral Thesis, Clément Mallet, 2010;

- "Pairing Airborne and Photogrammetric Laser Data for Analysing Three-dimensional Scenes", Doctoral Thesis, Frédéric Bretar, 2006.

5 One interesting article shows that these techniques have limits with respect to the reconstruction of 3D objects with complex shapes (for example, concave): flat structuring of a cluster of non-structured 3D points and detection of areas of obstacles, Vision interface conference, 1999, Nicolas Loémie, Laurent Gallo, Nicole Cambou, Georges Stamon.

With respect to mosaicking, the following reference works can be cited:

10 • L.G. Brown, "A Survey of Image Registration Techniques", in ACM Computing Surveys, vol. 24, No. 4, 1992;

- "Mosaic of multi-resolution images and applications", Doctoral Thesis, University of Lyon, Lionel Robinault, 2009,

15 • HANSON A.R. ET AL.: "Generalized parallel-perspective stereo mosaics from airborne video", PATTERN ANALYSIS AND MACHINE INTELLIGENCE, IEEE TRANSACTIONS ON, IEEE SERVICE CENTER, LOS ALAMITOS, CA, US, vol. 26, no. 2, 1<sup>st</sup> February 2004 (2004-02-01), pages 226-237, ISSN: 0162-8828, DOI: 10.1, 109/TPA-MI.2004.1262190,

20 • POLLEFEYS M. ET AL.: "Detailed Real-Time Urban 3D Reconstruction from Video", INTERNATIONAL JOURNAL OF COMPUTER VISION, KLUWER ACADEMIC PUBLISHERS, BO, vol. 78, no. 2-3, 20<sup>th</sup> October 2007 (2007-10-20), pages 143-167, ISSN: 1573-1405.

To summarise the prior art relating to 3D reconstruction, it can be said that 3D reconstruction can be partially obtained by using:

25 • pairs of cameras producing a spatially stereoscopic image of the scene and merging these images in order to produce a 3D reconstruction and optionally a mosaic of the scene. This solution has several disadvantages:

- o the cameras are difficult to calibrate (vibration problems),

- o imprecision in the restoration of the 3D reconstruction as a result of a stereo base that is limited by the spacing between the cameras,

- o a low-field and low-extent restoration as a result of the limited optical field of the cameras.

30 Furthermore, the finalised 3D reconstruction is not clear as it is formed by assembling local 3D reconstructions (resulting from the method for stereoscopic restoration of 2 images that are often small-field), which can be very noisy as a result of the limited number of images that allowed it to be formed, the limited field of the cameras and the fact that the reconstruction planes depending on the respective attitudes of the cameras have a geometry that is difficult to measure precisely (the relative position and geometry of  
35 the cameras used to complete the 3D reconstruction is often imprecise in practice due to the fact that it involves cameras that are spaced apart from each other by 1 or 2 metres and are likely to vibrate relative to each other: it is even more obvious when these cameras are motorised). The precise way of assembling the

intermediate 3D reconstructions is never described in detail and in practice many errors are observed in the finalised 3D reconstruction, which nevertheless remains low in terms of spatial and angular extent (typically less than 200 m x 200 m for spatial extent, with an angular extent that is typically less than 30°).

5 Finally, the method for rectification and matching, depending on the attitudes of the cameras and including a preliminary step of de-rotation of the focal plane in the rectification process, itself is such that there are examples where the 3D reconstruction exhibits holes, especially if the system exhibits temporal rotation movements.

10 Ultimately, the stereoscopic system poorly restores planes that are practically perpendicular to one of the 2 cameras (this is the problem of the restoration of pitched roofs in airborne or satellite stereoscopic imaging).

- A low-field or average-field camera can be moving, but the 3D reconstruction is limited by the path and the orientation of the camera and therefore is not omnidirectional; furthermore, the reconstruction can exhibit holes as a result of uncontrolled movements of the camera or the non-overlapping thereof as it moves. The algorithms that are used for 3D reconstruction require a reconstruction in a reference frame that is associated with or is close to the focal plane of the camera, which limits the possibilities of reconstruction (a single main reconstruction plane and very limited reconstruction when the camera changes orientation). The result of the reconstruction is also very noisy and can exhibit numerous errors as a result of the poor overlapping between images, a constant reconstruction plane of the reconstructed scene (and of a camera that can deviate from this plane) and the use of algorithms that only use two images which are separated by a relatively short distance for the 3D reconstruction. The mosaicking that is obtained by the ground overlaying of the successive images does not work and is not conformal when the scene is not flat and/or comprises 3D elements.

- There can be active sensors, i.e. with range finding, but again the 3D reconstruction is not omnidirectional and is not necessarily segmented, with the measurements being obtained in the form of clusters of points that are difficult to use automatically. Furthermore, the mesh that is obtained by these active sensors has the disadvantage of being non-angularly dense (typically less than 4 points per m<sup>2</sup> for 1 km high airborne applications). The technique is not currently adapted to be able to produce a textured image of the scene and nearly always has to be corrected manually.

30 All of the aforementioned solutions are unsuitable for obtaining a 3D mosaic or a 3D reconstruction for a large 3D scene, i.e. larger than 500 m x 500 m. The instantaneous 3D mosaics that are obtained exhibit deformations and are limited in their angular (typically < 30°) or spatial extent. Assembling the mosaics is complex when the terrain is 3D and the final result does not conform to the geometry of the scene.

35 The disadvantages of the methods of the prior art are by no means limiting, further disadvantages are disclosed in the patent.

The object of the invention is to overcome these disadvantages.

The proposed solution is based on the use of a panoramic system which covers a very large angular sector of the scene and which can cover the entire sphere if required, and on the use of the displacement thereof in the scene with processing of the 2D images that are obtained, in order to reconstruct the 3D

information of the scene based on all that has been viewed by the panoramic system and in various reconstruction planes.

The panoramic system comprises one or more sensors, the images of which do not necessarily exhibit any mutual overlap, and allows the entire scene that is to be reconstructed to be covered  
5 instantaneously (with holes if the sensors are not overlapping) or during the movement.

This solution also allows a mosaic to be produced at the same time with a very large spatial and angular extent representing this scene at all of the viewpoints of the panoramic system during its displacement.

The invention relates to a method for mosaicking a scene, as claimed.

10 A 3D mosaic is thus produced that is a generalisation of the 2D mosaic in so far as the projection can be carried out on any 3D surface, which itself can be made up of a plurality of flat surfaces or of surfaces without discontinuities. This 3D mosaicking consists in, on the basis of successive 2D images of a scene (taken from different viewpoints) and of the 3D reconstruction of the scene in the aforementioned sense, projecting and assembling the various 2D images onto the geometric model of the 3D reconstruction,  
15 thus allowing the entire scene to be restored in the form of a textured mosaic overlaid on the various 3D elements of this scene. It allows a set of images to be conformally restored on any scene exhibiting relief or 3D elements. The reconstructed 3D mosaic is thus a textured 3D reconstruction of the scene.

These methods allow a 3D mosaic to be produced over the largest possible spatial and angular extent.

20 The invention further relates to equipment for 3D mosaicking of a scene comprising:

- a panoramic system capable of forming 2D images of the scene, called 2D panoramic images, provided with location means and

- a processor connected to this panoramic system comprising:

- o means for implementing the method for mosaicking as previously defined;

25 o means for automatically processing complementary images optionally associated with a human-machine interface or replaced by said interface.

In this way, a simple, precise method is obtained that allows textured maps to be produced, for example, on which measurements can be carried out, the scene can be reconstructed over a large spatial (ranging up to  $180^\circ \times 360^\circ$ ) and angular extent and in real time, without constraints with respect to the  
30 trajectory, on any scene (without assuming a flat scene and without using a prior model of the scene, for example).

The proposed solution:

- allows a compact solution to be provided for the problem of 3D reconstruction and/or mosaicking of the scene, whilst requiring only one panoramic system, whereas those of the prior art require  
35 a plurality of independent sensors and are more complex to implement;

- produces a mosaic of the scene

- o that is conformal, i.e. without geometric deformations and that thus can be superposed on a map,

- 5 -

- o over a very large spatial and angular extent and without holes,
- o that is complete, i.e. can be made along planes of various directions, which is very different from the conventional methods that only produce a single reconstruction plane as output and which do not allow restoration, or poorly restore, objects of the scene having faces that are different from the selected restoration plane,
- o that is robust by virtue of the temporal redundancies that are implemented,
- o that is precise by virtue of the temporal stereovision, which on its own produces a large, virtual stereoscopic base, which explains the precision,
- o that is instantaneous, in the sense that the 3D panoramic restoration and the associated mosaic are re-computed and updated at each instant,
- o that is compatible, for example, with low-end MEMS attitude units when they are used to find the trajectory or with simple means for measuring relative displacements, such as an odometer or a basic GPS,
- o that is compatible with extensive or uncoordinated movements of the sensor, which a low-field sensor does not allow,
- o and that is applicable to any type of trajectory, including a curvilinear trajectory, and in any direction.

Further advantages can be cited, such as:

- allowing the operator to select any reconstruction planes (for example, to reproduce both what is on the ground and on the facades or following a cylindrical projection). The solution is also adapted to the reproduction of concave objects, which is very difficult to achieve with other methods,
- producing textured reconstructions, on which precise measurements are possible (the reproduced images are conformal),
- allowing any movements of the panoramic system in the scene, including an approach,
- not requiring any external measurement other than those measuring the relative displacement by position and attitude between 2 image captures, with measurement precision that is compatible with low-end COTS instruments (MEMS unit, basic GPS or odometer),
- not requiring any other a priori information relating to the scene to be reconstructed,
- allowing real-time operation on a PC.

Further features and advantages of the invention will become apparent upon reading the following detailed description, which is provided by way of non-limiting example, and with reference to the appended drawings, wherein:

figure 1 schematically shows an example of equipment for implementing the method for 3D reconstruction and for mosaicking according to the invention,

figure 2 schematically shows various steps of the method for 3D reconstruction,

figure 3 schematically shows various steps of the method for mosaicking according to the invention,

figure 4 shows the measurement ambiguities produced by a concave object when there is only one reconstruction plane,

5 figure 5 shows an example of the sectoral decomposition of a panoramic image resulting from a panoramic system,

figure 6 shows examples of rectified images of sectors of the panoramic image of figure 5 projected onto various rectification planes,

figure 7 schematically shows, for one example of a trajectory, examples of rectification planes, 10 with lines of sight LoS1 and LoS2 of the panoramic system being independent of these planes,

figure 8 schematically shows an example of the temporal evolution of rectification planes and of 3D reconstruction planes for a given trajectory.

The general idea of the invention consists in maximising the use of the frontal (for which the direction of the line of sight extends through a plane in the direction of the movement of the panoramic system) and transverse (for which the direction of the line of sight extends through a plane in the direction 15 perpendicular to the movement of the panoramic system) angular field of a panoramic system moving in a scene along a known trajectory, in order to restore the relief and optionally the texture of this scene from various viewpoints.

The transverse field is used by reconstructing the relief and optionally the texture from all of the 20 lateral viewpoints viewed by the panoramic system that can be presented to the operator in accordance with various reconstruction planes.

The frontal field is used by using the temporal merging of the preceding reconstructions observing the objects of the scene from various viewpoints. These various reconstructions of an object viewed from various viewpoints allow an extended overall view to be produced that is precise and conforms to the scene, 25 which scene can be presented to an operator from various viewpoints.

Using the temporal stereoscopy in various angular directions that the displacement of the panoramic, optical (or optronic) system moving in a scene can produce allows a 3D reconstruction of the scene to be simultaneously produced that can be projected in various directions and optionally allows a conformal and multi-face mosaic to be produced of said scene.

30 The proposed solution uses the following new concepts:

- temporal stereoscopy with a panoramic system, which differs from the conventional stereoscopy that uses two low-field cameras,
- simultaneous rectification along various planes, the directions of which are freely selected, which differs from the conventional rectification, which occurs on only a single plane, the 35 direction of which is imposed by the direction of the line of sight of the two sensors that are used. A further innovation is direct rectification, which occurs directly between any part of the 2D image of the panoramic system and the selected rectification plane, contrary to the conventional rectification that is used in stereovision, which requires an intermediate straightening plane, which generates information losses,

- merging of intermediate reconstructions using very different directions of line of sight, allowing greater precision and robustness;

- a confidence map associated with the hierarchisation of the quality of the information extracted from the 2D images targeting an object of the scene on very different viewpoints and which is directly associated with the temporal use of the 2D images of a moving panoramic system.

More specifically, the method is implemented by means of equipment, an example of which is shown in figure 1, which comprises:

- a panoramic system 1 capable of forming 2D panoramic images of the scene, comprising a sensor 14 connected to an optic 11 and provided with location means such as a GPS 12 and an inertial unit 13; and

- a processor 2 connected to this panoramic system comprising:
  - o means 21 for implementing the method for 3D mosaicking as described and
  - o means for automatically processing additional images optionally associated with or replaced by a human-machine interface 22.

According to the invention, the 2D images come from the panoramic system 1 by moving along a known trajectory, which can be measured on an image-by-image basis as the movement progresses, by virtue of the location means and the processor 2.

The system is panoramic in the sense that it allows a 2D panoramic image to be obtained. To this end, it can comprise a large-field optic 11 of the fisheye type or any conventional optical or large-field catadioptric means capable of providing a 2D panoramic image, or even can be based on an optic with a smaller field but one that moves in relatively large movements in order to detect the various portions of scenes for which full reconstruction is desired. A 2D image covering a large field of more than  $60^\circ$  is obtained, for example, on the basis of a system 1 with a  $45^\circ$  field that moves in a movement that allows it to cover this total field of  $60^\circ$ . The selection of the technology for the panoramic system 1 is not limited: it can be passive, but it can be generalised to an active system since it allows the multi-plane merging step described above to be implemented; this also includes ultra-large-field optics that exceed  $360^\circ \times 180^\circ$  or complete sphere optics (for example, two sensors with head-to-tail fisheye optics exploring the entire sphere of observability). This panoramic system can further comprise a set of optical sensors that are not mutually independent, together covering a predetermined, for example that is identical from one image to the next, or maximum angular panoramic coverage. All of these optical sensors may not be overlapping, i.e. the global image that is obtained at an instant by this set is not continuous (can comprise holes), the "holes" being filled when this set is moved. An example of a 2D panoramic image obtained with an optic of the fisheye type and of sectors (5 in this example) is shown in figure 5.

The trajectory can be computed as the movement of the panoramic system progresses by location means that measure the relative position and attitude displacements of the panoramic system in the scene, such as a GPS 12, inertial unit 13 or other means. This displacement can be controlled by an operator via a human-machine interface 22 or can be autonomous. The images that are thus obtained are such that the

image of at least one point of the scene is in at least 3 panoramic images that are respectively obtained in different panoramic system/point of the scene directions.

The step of processing these 2D panoramic images, which are respectively obtained at successive instants, by the processing unit 21 comprises the following sub-steps, which are described with reference to figure 2; they are sub-steps of an example of a 3D reconstruction method of a scene using 2D panoramic images of the scene, preceding the mosaicking method.

The 2D panoramic images are from a panoramic system moving in accordance with a predetermined trajectory, such that the image of at least one point of the scene is in at least 3 successive 2D panoramic images which are obtained in accordance with different panoramic system/point of the scene directions; the processing step of these successive 2D panoramic images which are obtained at successive instants, respectively, comprises the following sub-steps:

a) determining reconstruction planes in the scene to be reconstructed,

b) on the basis of pairs of panoramic images which are formed by a 2D panoramic image which is obtained at an instant  $t$  and another 2D panoramic image which is obtained at an instant  $t+\Delta t$ , respectively, determining, for each pair of images selected, rectification planes which correspond to the different reconstruction planes selected and projecting on each of them a sector of a 2D panoramic image of the pair in a direct manner, that is to say, without passing via one or more intermediate planes dependent on the viewing line of the panoramic system, in order to obtain a 2D rectified image, and projecting on these same rectification planes in a direct manner a sector of the other 2D panoramic image of the pair in order to obtain another 2D rectified image,

c) matching, for each rectification plane selected, the two 2D rectified images in order to obtain an intermediate 3D reconstruction in a 3D reference frame which is connected to the rectification plane, which is called the intermediate 3D reference frame,

d) transforming each intermediate 3D reconstruction to a 3D reference frame including the reconstruction planes selected in a), referred to as the 3D reconstruction reference frame, in order to obtain a transformed intermediate 3D reconstruction,

e) reiterating at least once the steps b) to d) on the basis of a new pair of 2D panoramic images and at least one other rectification plane in order to obtain at least one other intermediate 3D reconstruction which is transformed into this 3D reconstruction reference,

f) merging in terms of time for each construction plane selected at least two intermediate 3D reconstructions which are transformed in order to obtain a 3D reconstruction of the scene,

g) the steps b) to f) are carried out for each reconstruction plane selected in step a), with the same panoramic images but with different sectors in order thus to obtain as many 3D reconstructions as reconstruction planes selected.

These steps a) to g) will now be described in detail.

Step a) Determining reconstruction planes in the scene.

Various reconstruction planes  $C_j$  can be selected in order to establish the 3D reconstructions by highlighting various aspects of the scene, for example in order to cover the scene over a large spatial and

angular extent, or that will allow a better representation thereof to be obtained. They are freely selected by the operator or can be determined automatically as a function of the trajectory of the panoramic system, which is typically around the average of this trajectory that is computed between two image captures, and as a function of the complexity of the scene.

5           In the complete absence of an initial 3D reconstruction and in the initialisation phase (= 1<sup>st</sup> iteration), by default, the selected reconstruction planes can be, for example, the 3 or 4 planes tangent to a cylinder that could surround the average trajectory of the system, so as to provide a reconstruction in the various directions that can be seen by the panoramic system. For example, for a horizontal trajectory that is located 100 m from the ground, it would be possible to select the following reconstruction planes: the  
10 ground plane, a plane perpendicular to the ground and tangent at one side to the cylinder surrounding the trajectory, a plane perpendicular to the ground and tangent at the other side of the cylinder, a plane parallel to the ground located higher than 100 m. Once an initial 3D reconstruction starts to be constructed, these previously defined reconstruction planes can be updated in order to approach or coincide with the flat surfaces of the ongoing reconstruction, which can be automatically or experimentally extracted by an  
15 operator. When a single reconstruction plane is not sufficient for providing a sufficient 3D representation of the scene, a plurality of parallel or perpendicular planes are used to restore the uniqueness and the completeness of the 3D representation. This is the case, for example, when the scene comprises a concave object or in the case that a single reconstruction plane provides various measurements of 3D sizes that depend on the angle at which the measurement is taken, and is consequently incapable of providing a single  
20 measurement, as shown in figure 4. This figure shows the reconstruction ambiguity at Z of the point (X, Y): the acquisitions at positions 1 and 2 of the trajectory reconstruct z1 on the reconstruction plane P1, but the acquisitions at positions 2 and 3 of the trajectory reconstruct z2 on the same projection plane P1. A new reconstruction plane P2 is then selected to remove the ambiguity, as there will be z1 for P1 and z2 for P2. A plane P3 is also selected to find the lateral limits of the concave object.

25           As the displacement of the panoramic system progresses, when new planes appear or disappear in the scene it may also be found to be necessary for the selected reconstruction planes to be renewed.

Step b): A concept of generalised rectification is introduced in order to be able to rectify two successive panoramic 2D images in any direction. These two panoramic images are respectively acquired at an instant  $t$  and an instant  $t + \Delta t$  and form a pair of panoramic images.

30           This rectification consists in computing at least one projection plane that is most suitable for the rectification and in applying the transformation that transforms any sector of each of the two 2D panoramic images on each plane.

Each projection plane that is used for the rectification, called rectification plane, can be freely selected by the operator from an infinite selection of positions and orientations that are all parallel to the  
35 trajectory of the panoramic system; the plane, or each plane, is independent of the evolution of the line of sight of the panoramic system (which can pivot on itself during its displacement along its trajectory), contrary to conventional stereoscopy, where the selected rectification plane depends on the evolution of the line of sight and where the selections of rectification planes are very limited.

An example of rectification planes referenced R1, R2, R3 is shown in figure 7; they are parallel to the trajectory. The direction of the Line of Sight (LoS1, LoS2) of the panoramic sensor is also shown at two points of the trajectory, which illustrates the fact that the selection of these planes is independent of the LoS.

5           Examples of rectification and reconstruction planes are shown in figure 8, which is a top view of a scene comprising 3D objects. Position pairs (1, 2, 3) of the panoramic sensor are shown on the trajectory that correspond to 3 pairs of panoramic images acquired during this step b); each position pair is associated with two rectification planes (R11, R21 for pair 1, R12, R22 for pair 2 and R13, R23 for pair 3). Three reconstruction planes P1, P2, P3 have been selected in the example of this figure.

10           In order to optimise the 3D reconstruction, each selected rectification plane corresponds to the various reconstruction planes. The rectification plane is, for example, selected so as to be as close as possible (in the geometric sense) to the reconstruction plane determined in step a).

The transformation that switches from the image to the rectification plane is direct, i.e. does not have to include an intermediate straightening step in a focal plane, as is the case in conventional stereovision. This allows a rectified image to be obtained that:

- is independent of the rotation movement of the sensor and
- is without holes, contrary to what can be found in conventional rectification,
- is more precise as it is obtained by a direct floating computation without a quantified intermediate image.

20           The mathematical steps of this rectification for a panoramic image obtained at the instant t are, in the case of a sensor of the fisheye type, as follows:

Selection of a rectification plane  $P_i$ , from a reference frame  $(\vec{X}_r, \vec{Y}_r, \vec{Z}_r)$  associated with this plane  $P_i$ , and of a sector of the panoramic image (that may be up to the complete panoramic image if the field thereof is included in the zone that is selected on the rectification plane) to be projected onto this rectification plane, this sector advantageously allowing the coverage of the rectification plane to be maximised. If the sector of the projected image does not cover the entire panoramic image, the sectors remaining in the image are projected in other rectification planes, as in the example of figure 6, where the sector 1 is projected onto a horizontal rectification plane and does not cover the entire image so as to maintain a given resolution; other vertical rectification planes are needed to project the other sectors of the panoramic image.

30           Computation of the transformation that transforms a point (x, y) of the panoramic image into a point  $(X_i, Y_i)$  of the plane  $P_i$ ; to this end, the match is used that exists between the angular direction  $(\theta, \varphi)$  of a point of the scene and the coordinate (x, y) of the corresponding point in the image that depends on the selected panoramic system. In the case of a rectilinear panoramic system, this relationship can be simply written as:

35           If R is the radius of the position of the point (x, y) relative to the optical centre, then:

$$\operatorname{tg}\theta = (y - y_c)/(x - x_c),$$

where  $(x_c, y_c)$  are the coordinates of the optical centre;

$$\varphi = k.R,$$

with k = rectilinear factor of the sensor.

The equation of the plane  $P_i$  then simply needs to be written as a function of the  $(\theta, \varphi)$  that is found.

- 5 For a plane  $P_i$  with a normal that is oriented per  $(\theta, \varphi)$ , having the focal plane for  $\theta_i=\varphi_i=0$  as a particular case, it can be seen that the following relationship exists for the particular case of the centred projection, with f being the focal length of the panoramic system:

$$\begin{matrix} X_i = f \frac{s \sin \varphi \cos \theta - s \theta_i \sin \varphi_i \cos \theta_i - c \varphi s \sin \varphi_i \sin \theta_i}{s \sin \varphi \sin \theta + s \theta_i \sin \varphi \cos \theta_i + c \varphi c s \varphi_i} \\ Y_i = f \frac{s \sin \varphi \sin \theta - s \theta_i \sin \varphi \sin \theta_i}{s \sin \varphi \sin \theta + s \theta_i \sin \varphi \cos \theta_i + c \varphi c s \varphi_i} \end{matrix}$$

10 This transformation is an example of transformation in the case of a rectilinear panoramic optic (fisheye type); it does not comprise the distortion parameters of the panoramic system, which can be computed and compensated for elsewhere. The transformation can easily be generalised and adapted to any panoramic system with its own optical formula.

15 It follows that for any point  $(x, y)$  of the sector of the panoramic image, its corresponding rectified point can be found in the selected rectification plane and the rectified image can thus be constructed in this plane.

The various rectification planes that are selected during the iterations, and the preceding relationship, allow a sectoral rectification to be defined on the various rectification planes. A sector of the panoramic image corresponds to an equivalent portion projected onto a rectification plane. The sectoral decomposition of the panoramic image depends on the selected rectification planes and on the coverage of the projection onto these planes.

25 Examples of rectified images are shown in figure 6. The first results from the projection of the sector 1 of the image of figure 5 onto a vertical rectification plane, the second results from the projection of the sector 2 of the image of figure 5 onto another vertical rectification plane, the third results from the projection of the sector 3 onto a vertical rectification plane that is different from the first two planes, the fourth results from the projection of the sector 5 onto a horizontal rectification plane.

30 This projection is repeated in the same rectification plane  $P_i$  for a sector of another 2D panoramic image obtained at the instant  $t+\Delta t$  in order to obtain another rectified image, with  $\Delta t$  being experimentally predetermined or determined so that the displacement  $D_c$  of the system between  $t$  and  $t+\Delta t$  produces a stereo base that is large enough to be compatible with the precision desired for the 3D reconstruction. For example, in the case of an overflight at an average distance  $H$  from the scene, and assuming, for example, that minimum disparities of 1/8 pixel (current value) can be measured by the sensor 14, the displacement  $D_c$  for obtaining the desired reconstruction precision  $d_H$  is:  $D_c=(\text{resol}/8)*H^2/d_H$ , where  $\text{resol}$  is the resolution of the sensor 14 (for example, 3 mrd for a 1 Mpixel sensor provided with a fisheye).

In the cited example, and assuming that the desired reconstruction precision  $d_H$  is 20 cm for  $H=50$  m,  $D_c$  must at least be equal to 5 m, which corresponds to a minimum angular difference of  $6^\circ$  between 2 acquisitions by the panoramic system.

For the same precision  $d_H$  and for  $H=100$  m,  $D_c$  must at least be equal to 19 m, which corresponds to a minimum angular difference of  $11^\circ$  between 2 acquisitions by the panoramic system.

The use of a panoramic system allows the reconstruction precision to be enhanced by increasing the distance  $D_c$  and the angular separation between two acquisitions, beyond that which can be performed by a low-field or average-field sensor for the same spatial coverage for 3D reconstruction. The stereoscopic base  $D_c$  used for the 3D reconstruction can be larger than that of a conventional stereoscopic method by using a panoramic field (and the longer presence of the objects in this field), and this provides the method with greater ultimate reconstruction precision, which precision is also enhanced by merging the measurements provided by the method.

Taking the previous example of an overflight at an average distance of 100 m from the scene (ground reconstruction on a field of at least  $120^\circ$  corresponding to a restored band that is at least 350 m wide without counting the reconstruction on the sides), the theoretical reconstruction precision  $d_H$  becomes 10 cm for  $D_c=38$  m and an angular difference of  $21^\circ$ , and 2 cm for  $D_c=200$  m and an angular separation of  $60^\circ$ ; preferably, the measurement uncertainties need to be taken into account with respect to the relative location between the viewpoints in order to obtain real  $d_H$ .

Using the context of a visual inspection performed by a panoramic system with a 1 Mpixel fisheye camera, at a distance from the scene of  $H=20$  cm, and assuming a displacement  $D_c$  of 10 cm between two acquisitions,  $15 \mu\text{m}$  high or deep details can be restored ( $d_H = 15 \mu\text{m}$ ).

In order to average the various 3D reconstructions obtained during the repetitions, and to thus benefit from a significant reduction in errors and in restoration noise, the real acquisition of the panoramic system can be faster, whilst preserving the displacement between the pairs of 2D rectified images used to reconstruct the 3D of the scene. The method then comprises taking a first pair of 2D panoramic images on the basis of a displacement  $D_c$ , performing an intermediate 3D reconstruction with this pair, then taking another pair of 2D images, still on the basis of a displacement  $D_c$  at the next acquisition in order to complete another intermediate 3D reconstruction, whilst the points of the scene affected by these various image pairs remain in the field of the panoramic system.

Step c): The stereoscopic pair of images rectified in the plane  $P_i$  is used to define an intermediate 3D reconstruction in a reference frame relating to this  $P_i$ .

The intermediate 3D reconstruction in a 3D reference frame, called intermediate 3D reference frame, associated with  $P_i$  is obtained by the point-to-point matching of the two images rectified in  $P_i$  and by using the knowledge of the movement of the panoramic system. This matching is a dense process, which matches, in so far as is possible, each of the points of a 2D image of the stereoscopic pair with a point of the other image. It can be carried out by a local correlation process that is relatively hierarchical and can use matching operations carried out at  $t-\Delta t$  or  $t-N\Delta t$ , with  $N$  being an integer  $>1$ ; the large-field nature of the panoramic system and the possibility of even seeing the same scene at a different angle, which a low-field

system conventionally used in stereoscopy does not allow, in this case allows some occultations or ambiguities to be removed.

Step d): Transforming this intermediate 3D reconstruction into a fixed (=absolute) 3D reference frame including the one or more reconstruction plane(s) determined in step a), called 3D reconstruction reference frame. A transformed intermediate 3D reconstruction is thus obtained.

Step e): Repeating steps b) to d) at least once on the basis of a new pair of panoramic images (this can involve a new pair of images formed on the basis of preceding images, or this new pair results from a new acquisition paired with one of the previously acquired images) and at least one other rectification plane  $P'_i$ , in order to obtain at least one other transformed intermediate 3D reconstruction; the same 3D reconstruction reference frame is kept as in step d). These iterations can be successive in the same way as steps b) to d) are successively sequenced in this order; these iterations can also be performed at the same time (several steps b) are carried out at the same time with a plurality of rectification planes  $P_i$  determined at the same time, etc.).

Preferably, these steps b) to d) are repeated as long as at least one point of the reconstructed scene remains in the field of vision of the panoramic system.

Step f): The transformed intermediate 3D reconstructions are temporally merged by a specific merging method that uses the spatial and temporal redundancies of the intermediate reconstructions. This is obtained by temporally merging at least two transformed intermediate 3D reconstructions obtained in the 3D reconstruction reference frame in order to obtain a corresponding 3D reconstruction.

This method allows the establishment of the dense 3D mesh which is most adequate for representing the scene so that there are associated with each point of this mesh the coordinates of the corresponding point in an X, Y, Z reference frame connected with the scene.

Step g): Repeat steps b) to f) for each reconstruction plane selected during a), with the same panoramic images but with different sectors, to thus obtain as many 3D reconstructions as there are selected reconstruction planes. These 3D reconstructions or the intermediate 3D reconstructions obtained during these iterations are advantageously spatially merged to update the one or more final 3D reconstruction(s) and thus to enhance the precision and robustness of these reconstructions. The spatial merging of the 3D reconstructions constructed along various planes takes into account the reconstruction precision of the various elements of each reconstruction, which is not the same along the various planes, and which can be mathematically predicted. This spatial merging is obtained by using a plurality of rectification planes that correspond to the various sectors of each image that is used.

All of steps a) to g) are also preferably repeated at least once with new pairs of panoramic images, for example with intermediate images that are temporally offset from the preceding images or with other sectors of panoramic images that are already considered. This allows a continuous process of updating the final 3D reconstructions to be obtained. These new pairs of panoramic images can originate from each acquisition of panoramic images, but this is not necessarily the case.

Here again, these iterations can be completed successively or at the same time.

The use of the redundancies and of the quality of the 2D rectified images (quality defined, for example, by the angular deviation that exists between the rectification plane and the reconstruction plane, or even by a confidence coefficient of the matching that led to each intermediate 3D reconstruction) allows the method to produce a confidence map that expresses the quality of the final reconstruction. This confidence  
5 map is constructed on a pixel-by-pixel basis for each 3D reconstruction, by considering the number of times that each pixel has been constructed and if the conditions of this construction were good, these being defined, for example, as a function of a matching quality threshold that is experimentally or mathematically determined. Cases are also considered in which a plurality of 3D sizes are obtained for the same pixel as a function of the angle of observation, in which case additional rectification and reconstruction planes are  
10 created to remove the ambiguity, for example for concave objects that require more than one reconstruction plane in order to be correctly reconstructed, as in the example of figure 4.

The mosaicking of the 2D images of the scene will now be considered, with the composition of these 2D images forming an overall image called a mosaic. This mosaic generally comprises a plurality of 2D textured planes present in the 3D scene or that approximate the scene, but can also be on a 3D surface.

15 The use of the 3D reconstruction of the progressively created scene allows each 2D image that originates from the sectoral decomposition of the 2D panoramic image to be projected onto various projection planes (or surfaces), also called mosaicking planes. These projection surfaces are the surfaces on which the mosaic is constructed; they can be freely selected by the operator or can be automatically determined on the basis of the 3D reconstruction. As previously indicated, some of these surfaces can be  
20 distorted (curved) or can even be a 3D surface, the modelling of which is known.

In the case of a panoramic system viewing a highly 3D scene exhibiting various faces, a plurality of mosaicking planes (or surfaces) can (or should) be selected. A highly 3D scene is understood to be a scene containing many 3D elements producing significant disparities between two successive acquisitions, as is the case of a drone flying over an urban environment at a low flying altitude, for example. The  
25 mosaicking method uses the fact that the projection surfaces or planes have different orientations for best projecting the textures of the images onto each of the projection surfaces or planes. It may be noted that the texture is a set of intensities of pixels on an image region.

The use of the 3D reconstruction also allows only the visible parts of the projected images to be retained. This avoids projecting onto a mosaicking plane image portions that would belong to other portions  
30 of the scene.

The process for multi-plane (or multi-surface) mosaicking for projection is preferably repeated for each new 2D image acquisition carried out by the panoramic system and the new mosaic is merged with the old one (obtained at t-1) in order to update said old mosaic.

35 The result of these various projections and of the continuous merging of the mosaics is an image that is conformal (i.e. without geometric deformations) and is highly extended on each projection plane. This is a direct result of the fact that the 3D mosaicking method explained in detail below, and described with reference to figure 3, simultaneously computes the 3D reconstruction of the scene and the projections of the textures thereon, that the method eliminates the hidden parts or the poorly resolved parts in the projection and that this method is repeated in all directions and over the whole trajectory.

The 3D reconstruction of the scene and the projections of the textures thereon are computed for each 2D image acquisition, called initial acquisition, with an acquisition being separated from the previous acquisition by a time interval  $\Delta t$  as previously defined.

According to one alternative, the 3D reconstruction of the scene and the projections of the textures thereon are computed for each image acquisition of the panoramic system and at a high frequency on the basis of previously stored preceding images. More specifically, the intermediate images included between two images separated by successive  $\Delta t$  used for the 3D reconstruction are stored so that they can also be used for the 3D reconstruction in the same way as a FIFO "First In First Out" (each new acquired image is compared to the first stored image in order to establish a new instance of 3D reconstruction, this first image is then deleted from the list and the last is added to the updated list). Furthermore, the intermediate images can also be used to facilitate the match between the first and last image or to fill "holes" in the 3D model.

A mosaic is then obtained at the end of the next steps A) to E), which are described with reference to figure 3, for each new 2D image acquired by the panoramic system. These steps are preferably reiterated for each new acquisition of a 2D panoramic image.

According to a first embodiment, the 3D reconstruction and the mosaicking are successively carried out after each acquisition; this assumes that a new reference 3D reconstruction has just been carried out following one or more previously completed 3D reconstructions.

According to a second embodiment, the 3D reconstruction and the mosaicking are carried out at the same time after each acquisition; this assumes that the mosaicking is carried out whilst a new 3D reconstruction is still in progress, in which case the reference 3D reconstruction is the one which is carried out during one of the preceding 2D image acquisitions, or even a previously completed 3D reconstruction.

These various steps will now be described in greater detail.

A) Selecting projection planes (or 3D surfaces).

This first step comprises selecting the 3D projection planes or surfaces on which the mosaic is constructed. These 3D projection planes or surfaces can be freely selected by the operator at a given time of the mosaicking or can be automatically computed on the basis of the current (or reference) 3D reconstruction of the scene according to predetermined criteria (for example, planes parallel to the reconstructed surface of the ground or main planes extracted from the 3D reconstruction). 3D projection surfaces can also be used if the scene is ready for them and if the operator considers it advantageous; for example, this allows objects of the scene or a background to be shown that have specific geometric shapes, but this by no means removes the conformity that can be obtained by multiple projections which would be exclusively flat.

B) Determining rectified images or associated sectors in the panoramic image.

When rectified images have been computed during one or more previous 3D reconstruction steps, the closest (in the geometric sense) to the projection plane is selected and the parameters of the direct projection (without intermediate step) on the projection plane are computed.

If this rectified image is too far away, i.e. is not close to the projection plane compared to a threshold that is predetermined by the operator, for example, a 2D panoramic image is obtained, called

current 2D panoramic image, and the parameters of the direct projection of this current 2D panoramic image onto the projection plane and the sectors of this current image that will be used during the direct projection of step D are computed.

In both examples, the projection is not carried out straight away, but the projection parameters are stored in a memory in order to be used by step D).

C) Determining the usable parts (i.e. with sufficient resolution) for the projection of step D, using the 3D reconstruction to compute the hidden parts in the projection plane on the basis of:

- the 2D rectified image, if the first case of step B is applicable;
- or the sectors of the current panoramic image that will be used in the direct projection, if the second case of step B is applicable.

The 3D reconstruction that has just been computed allows automatic computation of the hidden or low resolution parts (and conversely the visible usable parts) in the projection plane that would result from occurrences of masking present in the scene. This involves selecting the textures to be preserved in the mosaic. This computation is precise due to the fact that the 3D reconstruction has firstly been constructed in the reference frame associated with the panoramic system.

One of the specific characteristics of the 3D mosaicking according to the invention is that it benefits from the computation of the hidden parts in order to eliminate on the various projection planes the masks that are generated by the scene and to consider only the visible parts on these planes. This allows temporal mosaicking of only parts of scenes that are always visible and thus prevents deformations that are due to the projection of parts of the scene that do not belong to the projection plane (which fault is present in conventional mosaicking, which from the outset projects all of the image onto the projection plane without being able to take into account occurrences of masking by the elements of the scene moving as the sensor moves).

D) Projecting the textures selected during the preceding step onto the planes or, more generally, onto the 3D projection surfaces and merging the textures in each 3D projection plane or surface to thus obtain a conformal mosaic on a plurality of planes.

The textures selected during the preceding step are projected onto the projection planes (or surfaces) and are temporally merged with the current mosaic in order to form a new mosaic.

It is important to note that projecting onto surfaces or planes coming from a 3D reconstruction produced on the basis of the same base images as those used to project the textures allows extremely high precision in the projection (and in the geometric transformations between the image reference frame and the reference frame of the reconstructed scene). It is also this that provides the conformity for the produced mosaicking. However, the main conformity element results from the fact that the mosaicking uses a 3D reconstruction that is produced in the same reference frame as the mosaic and only uses the portions of non-hidden images in its mosaic process. In the case where an external 3D reconstruction were to be used, which would not come from the base images used for the projection, there necessarily would be uncertainties with respect to the relative position of the sensor on the scene and in the overlapping of the projection.

E) Presenting the mosaic to the operator along different planes or more generally along various 3D presentation surfaces by projecting the one or more textured 3D reconstructions onto these presentation planes. These presentation planes are freely selected by the operator and are only used to present the results of the mosaic from various perspectives selected by the operator. The mosaic can be presented to the operator on a presentation plane-by-presentation plane basis or according to the planes that represent the folding of the curved surfaces onto which the textures have been projected (in the case of a projection onto a cylinder, for example). Clearly, the textured 3D result can also be presented directly in the form of a virtual 3D by using suitable software. The projection result provides an image that is always conformal, which is not necessarily the case, as has been explained, with a conventional mosaicking method.

10 This method for simultaneous, omnidirectional 3D reconstruction and mosaicking is not limited to an optical panoramic system. The measured textures equally can be used on a large directional field by a means other than the optical means, for example by an active means of the Lidar or sonar type; the method could then also use the distances given by the instruments.

From the industrial applications, the following can be contemplated:

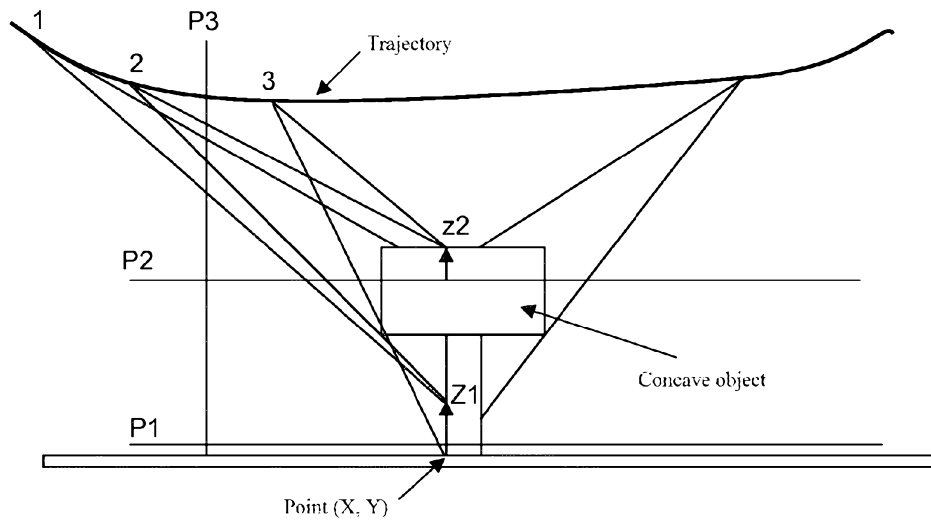
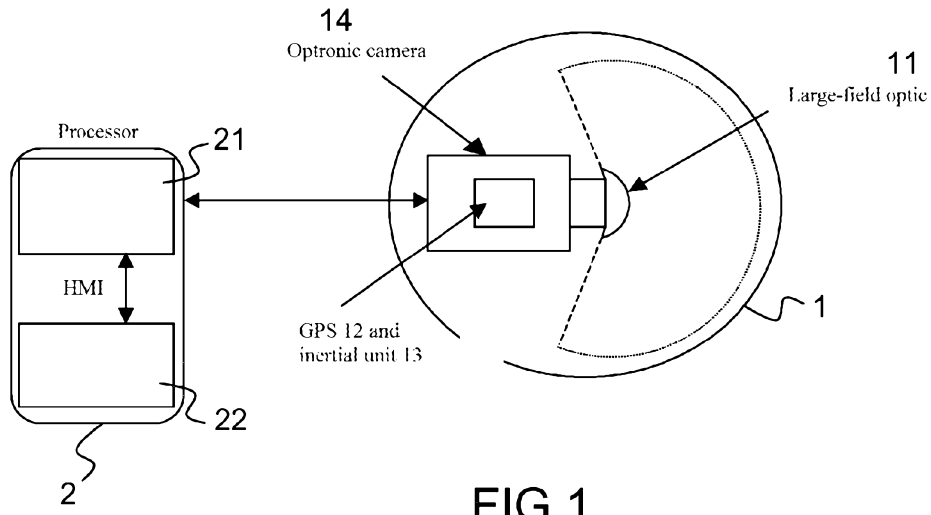
- 15
- the real-time 3D and textural restoration of a scene overflown by a drone or an aircraft (application to the production of 3D maps, orthophotographs, application to monitoring, etc.),
  - terrestrial or airborne navigation assistance,
  - industrial, medical or other visual inspection.

## FREMGANGSMÅDE TIL 3D-PANORAMAMOSAIKDANNELSE AF EN SCENE

## PATENTKRAV

1. Fremgangsmåde til 3D-mosaikdannelse af en scene i 3D-mosaik, kendetegnet ved, at mindst én 3D-rekonstruktion opnås uden forudgående informationer om scenen ved følgende trin:
  - 5 - opnåelse af successive billeder ved hjælp af en panoramasensor, ved bevægelse langs en ikke-tvungen 3D-rekonstruktionsbane, således at billedet af mindst ét punkt af scenen er i mindst 3 successive 2D-panoramabilleder og opnået ifølge forskellige retninger for panoramasystem-point af scenen,
    - samtidig berigtigelse af de opnåede billeder på forskellige berigtigelsesplaner og at bringe de berigtigede billeder i overensstemmelse,
  - 10 - 3D-rekonstruktion på flere rekonstruktionsplaner ud fra de berigtigede billeder, der er bragt i overensstemmelse,
    - hvor det sidste opnåede billede betegnes det aktuelle panoramabillede,
    - den endvidere omfatter følgende trin:
      - A) ud fra den opnåede 3D-rekonstruktion og det aktuelle panoramabillede, valg af flere  
15 projektionsoverflader, hvorpå mosaikken vil blive konstrueret,
      - B) valg af sektorer af det aktuelle panoramabillede og valg af teksturer i de valgte sektorer ved at vælge synlige dele, dvs. dele der ikke er skjult af en overfladen af scenen, ved hjælp af 3D-rekonstruktionen,
      - C) projektion af de valgte teksturer på hver projektionsoverflade og fusion af teksturerne i  
20 hver projektionsoverflade for således at opnå en overensstemmende mosaik på hver projektionsoverflade.
  2. Fremgangsmåde til 3D-mosaikdannelse af en scene ifølge det foregående krav, kendetegnet ved, at trinnet B omfatter et trin med valg af sektorer af det aktuelle panoramabillede, der svarer til de valgte projektionsoverfalder.
  3. Fremgangsmåde til 3D-mosaikdannelse af en scene ifølge et af de foregående krav, kendetegnet  
25 ved, at trinnene A til C gentages ved hver ny opnåelse af et panoramabillede.
  4. Fremgangsmåde til 3D-mosaikdannelse af en scene ifølge et af de foregående krav, kendetegnet ved, at valget af projektionsoverfalder sker i samtlige retninger, således at hver projektionsoverflade er den, der er tættest muligt på 3D-rekonstruktionsplanerne i geometrisk betydning.
  5. Fremgangsmåde til 3D-mosaikdannelse af en scene ifølge et af de foregående krav, kendetegnet  
30 ved, at hver tekstur opvisende en opløsning, fremgangsmåden omfatter et trin til bestemmelse af teksturerne opløsning, og ved, at fusionen af teksturerne fra trinnet C) sker som en funktion af disse opløsninger.
  6. Fremgangsmåde til 3D-mosaikdannelse af en scene ifølge et af de foregående krav, kendetegnet ved, at teksturerne projiceres direkte på projektionsoverfladen.
  - 35 7. Fremgangsmåde til 3D-mosaikdannelse af en scene ifølge et af de foregående krav, kendetegnet ved, at berigtigelsesplanerne vælges i retninger, således at berigtigelsesplanerne dækker det aktuelle panoramabillede.

8. Fremgangsmåde til 3D-mosaikdannelse af en scene ifølge et af de foregående krav, kendetegnet ved, at 3D-rekonstruktionen opnås ud fra de opnåede billeder på banen før opnåelse af det aktuelle panoramabillede.
9. Udstyr til 3D-mosaikdannelse af en scene, der omfatter et panoramasystem (1), der er egnet til at danne billeder af scenen og til at bevæge sig langs en bane, forsynet med relative billede-for-billede-lokaliseringsmidler (12, 13) og, forbundet med dette panoramasystem, en processor (2), der omfatter midler (21) til implementering af en 3D-mosaikdannelsesfremgangsmåde ifølge et af de foregående krav.



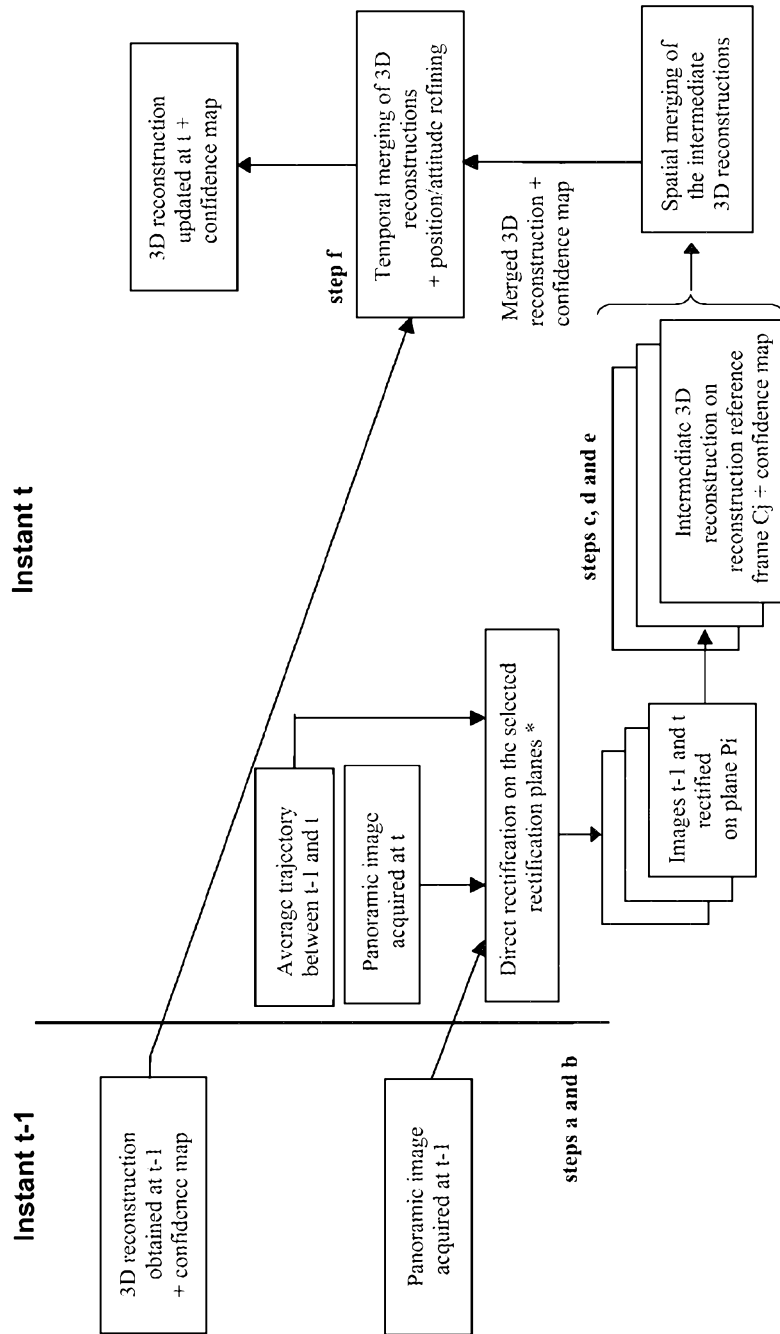


FIG.2

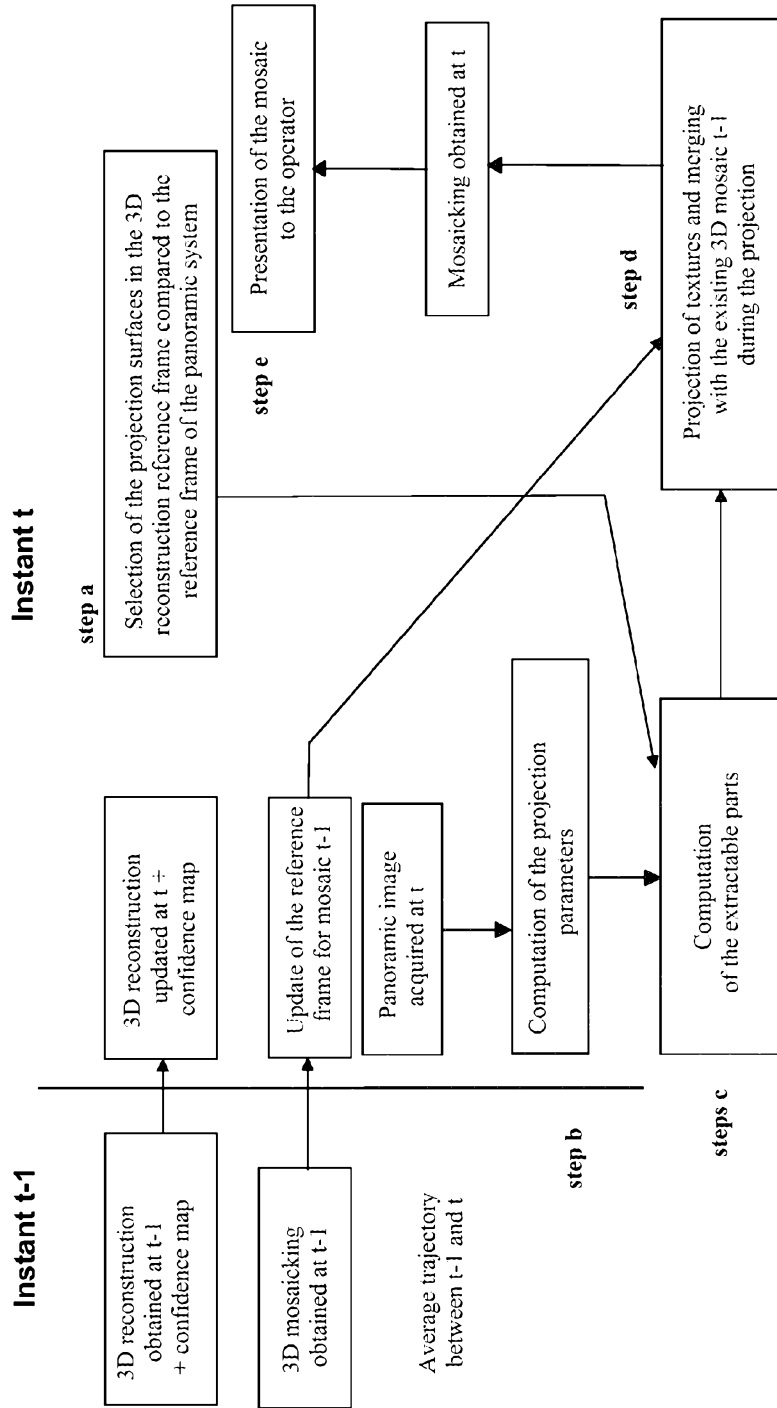


FIG.3

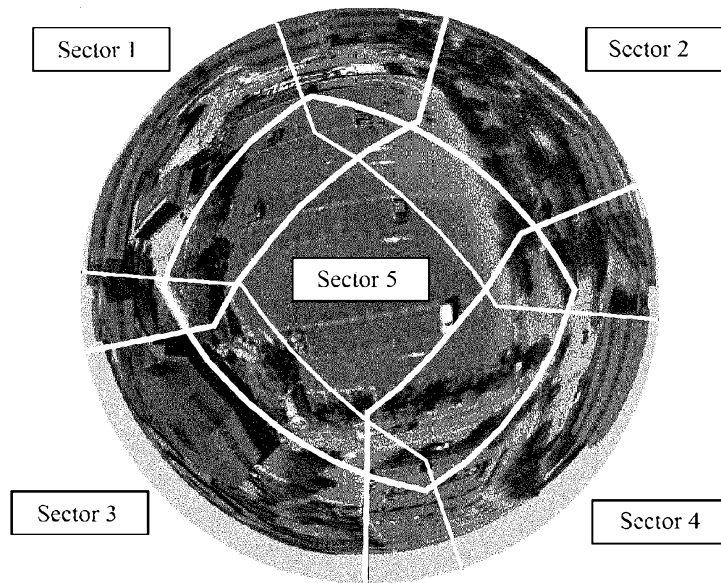


FIG.5

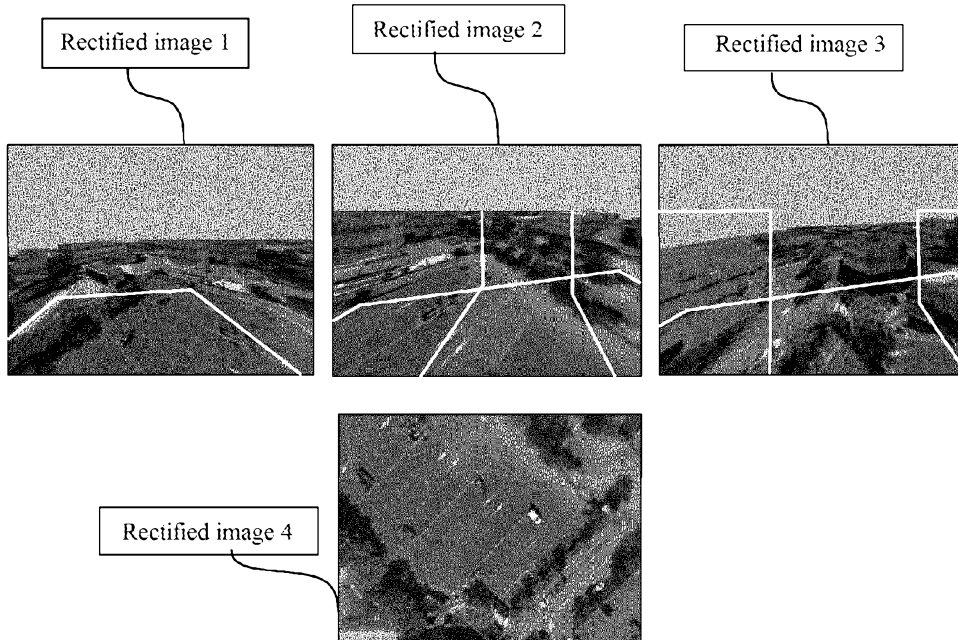


FIG.6

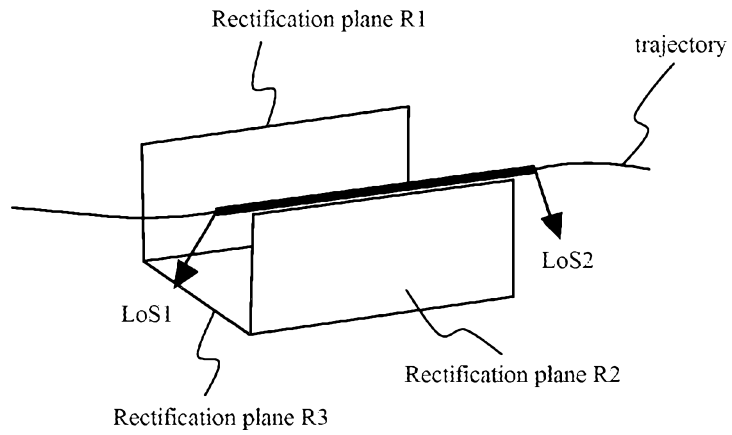


FIG.7

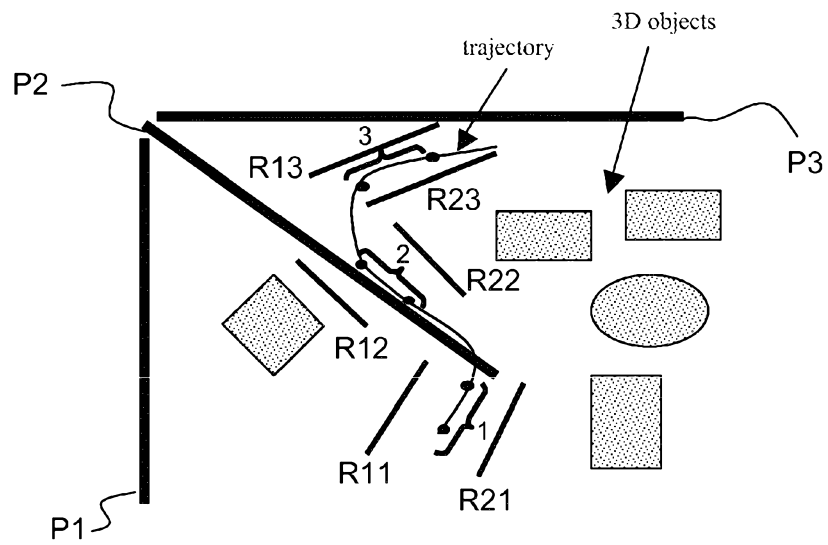


FIG.8