A NEW GROUND-BASED STEREO PANORAMIC SCANNING SYSTEM

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ABSTRACT:

This paper introduces a linescan-based stereo panoramic scanning system that employs an off-axis camera configuration mode. In this mode, the two stereo linescan cameras are mounted off-axis on the horizontal bar of a camera mast, approximately equidistant from the rotation axis. Compared to the on-axis mode used in many other linescan-based panoramic scanning systems, the off-axis mode enables the system to acquire multi-perspective stereo panoramas that can provide uniform accuracy in all 360º directions at each depth. A prototype using a color linear array camera with RGB channels has been developed at the Mapping and GIS Laboratory of The Ohio State University. The future version of this system will be a Mobile Panoramic Multi-spectral Scanner (MPMS) in which each camera will include multi-spectral channels such as VNIR (Visible and Near Infrared) and SWIR (Short Wavelength Infrared). This new system has the potential to be used in future Mars landed missions for the detection and mapping of minerals, water and other habitability signatures as well as for support of Earth-based applications.

1. INTRODUCTION

Linescan-based panoramic scanning systems are based on rotating linear array sensors and recording image lines within a cylindrical geometry. One of their major capabilities is quick image acquisition of any panoramic scene. Another is the acquisition of high-quality images having high resolution and homogeneous brightness and contrast throughout the entire image. These features make linescan-based panoramic scanning systems suitable for applications such as recording landscapes and city squares, cultural heritage documentation, and data capture for virtual reality applications. Examples of two commercially available scanning systems used for these purposes are the EYESCAN M3 terrestrial digital panoramic camera, which was jointly developed by the German Aerospace Center (DLR) and KST Dresden GmbH, and the Sasta Digital DRS 5000 camera developed by Spheron PanoCam.

There are two camera configuration modes applied in panoramic scanning systems: the on-axis mode and the off-axis mode, designating whether or not the camera's perspective center is designed to be on the rotation axis. The panoramas acquired with these two modes are referred to as either single-center panoramas (on-axis) or multi-perspective panoramas (off-axis). Many systems use the on-axis mode such as the EYESCAN M3 and the Sasta Digital DRS 5000, and single-center panoramas have been well researched concerning calibration, geometric modelling, and bundle adjustment of the data (Schneider and Mass, 2003; 2004; 2005; 2006). Other examples of the research and application of these systems include visualization and texture mapping (Haala and Kada, 2005), and data fusion with laser scanners (Scheibe et al., 2004).

Although they have a simpler geometric model, single-center stereo panoramas have a disadvantage in stereo vision, which is formed by two cameras rotating around two separate axes; the 3-D information derived from such two stereo panoramas by spatial intersection does not have uniform accuracy in all 360º directions, particularly in the baseline direction. As a result, more panoramas normally have to be taken in order to avoid weak intersection geometries. Otherwise, we can form a vertical baseline, but this would cause difficulties in stereoscopic viewing. This may limit the potential of on-axis panoramic scanning systems in situations where constraints (e.g., vertical height) would not allow a vertical stereo configuration, for example, for a space exploration vehicle.

On the other hand, while multi-perspective (off axis) panoramas have a more complicated geometric model, they are able to overcome the problem of nonuniform accuracy in different directions. Furthermore, the off-axis mode offers more flexibility in system configuration.

The panoramic camera system presented is a Mobile Panoramic Multi-spectral Scanner (MPMS) that employs the off-axis camera configuration mode. The system can be mounted on either a manned or unmanned vehicle. The designed system will include two stereo multi-spectral cameras, each having 10 vertical linear array CCDs representing visible (RGB), infrared (IR) and other multi-spectral channels. With only one sweep, MPMS can acquire all the channels of stereo panoramic images to fully characterize the surrounding environment. This system can be used for environmental monitoring, homeland security, transportation, and landed planetary missions.

The system introduced in this paper is a prototype of MPMS that uses a color linear array camera with RGB channels. A future version will include multi-spectral channels. In the following section, the stereo camera configuration and hardware integration of the prototype are described. Section 3 addresses the geometric model and stereo geometry of multi-perspective panoramas. In Section 4, sample panoramas

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acquired using the prototype and some preliminary 3-D mapping results are shown. An overall summary is given in the final section.

2. THE MPMS PROTOTYPE - AN OFF-AXIS PANORAMIC SCANNING SYSTEM

2.1 Configuration of the Stereo Cameras

In a linescan-based panoramic scanning system using an off-axis camera configuration mode, there are many ways to configure the stereo cameras regarding their heights, rotation axes, rotation radius, etc. A geometric model that considered these factors was described in Huang et al. (2001).

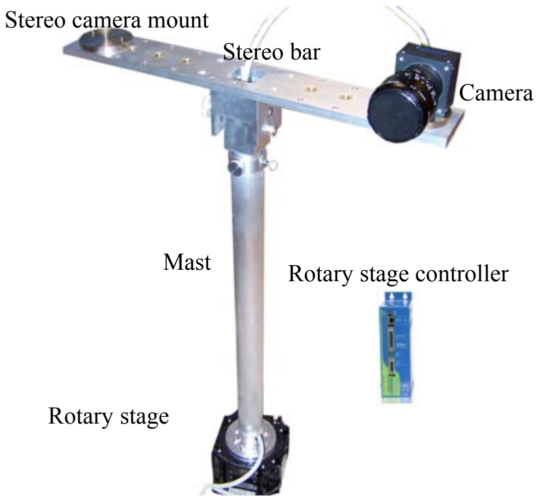


Figure 1. Hardware components of the MPMS prototype

In the design of this prototype, both stereo cameras have the same height, share the rotation axis and are equidistant from the rotation axis. With this configuration, shown in Figure 1, the acquired stereo multi-perspective panoramas will have not only uniform accuracy in all 360º directions in each depth, but also, in theory, horizontal epipolar lines. This will allow the use of simplified algorithms to quickly find corresponding points, and provides the potential for onboard applications.

2.2 Hardware Integration

The major hardware components of the MPMS prototype include stereo cameras (optical system, linear array CCDs and housing), a frame grabber, and a support system that includes a rotary stage with controller, remote sensing mast, and stereo camera bar (see Figure 1). In the prototype we have used only one camera. To obtain stereo panoramas, the camera is alternately mounted on the opposite ends of the stereo bar. The height of the mast is adjustable from 70 cm to 130 cm, and different mounting positions on the stereo bar for the cameras allow for baseline lengths from 20 cm to 50 cm. Table 1 shows the main technical parameters of this prototype.

Software was developed to integrate the hardware components for image acquisition, where the exposure time (also scan time of an image line) of the camera and the rotation speed are configured to create different resolutions in the horizontal direction. The horizontal Field of View (FOV) of acquired panoramas (the rotation angle) can be pre-defined in this software, and does not have to be 360º.

Focal Length	35 mm
Vertical dimension of CCD	4,080 pixels
Channels	RGB
Vertical FOV	64.5º
Image Columns (360º, varying)	22,000 (e.g.)
Data Volume (360º)	220 MB
Recording time (10 ms/column, 360º)	3.3 min

Table 1 Major parameters of the MPMP prototype

2.3 Geometric Model of Multi-perspective Panoramas

The geometric model of multi-perspective panoramas is similar to that of single-center panoramas as described in Schneider and Mass (2003). It differs, however, in that it has two additional parameters: R, the rotation radius, measuring from the rotation axis to the camera's perspective center, and Ω, the swing angle between the baseline and the camera's line of sight. The stereo computation is based on the off-axis stereo model.

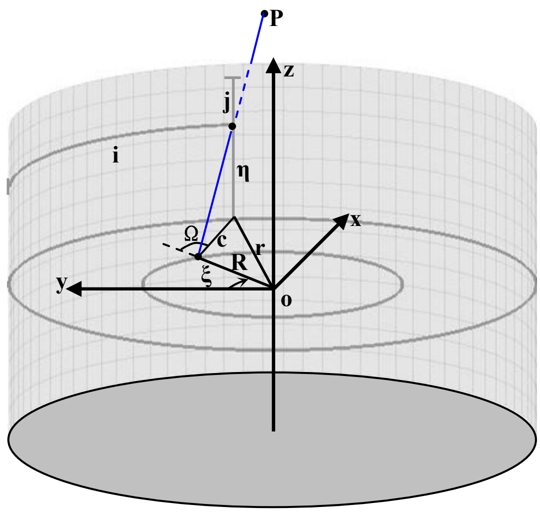


Figure 2. Geometrical modeling of multi-perspective panoramas

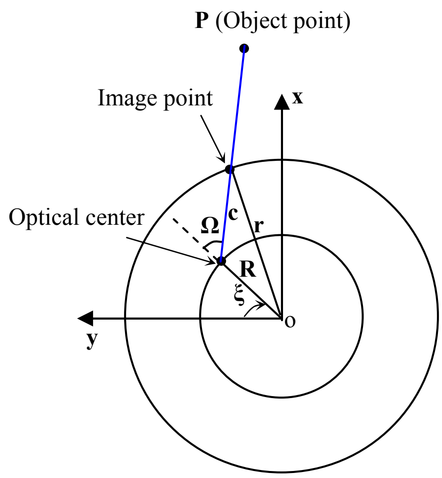


Figure 3. Top view: internal circle represents the trajectory of the camera's perspective center; external circle represents the cylindrical panorama

Figures 2 and 3 illustrate the geometry of the left panorama, which is acquired with the camera being mounted on the left of the stereo bar, as shown in Figure 1. There are four coordinate systems considered in the geometric model, the object coordinate system (X-Y-Z), the local camera coordinate system (x-y-z), the cylindrical camera coordinate system (r-ξ-η), and the image coordinate system (i-j). The local camera coordinate system (x-y-z) is an auxiliary coordinate system. Its origin, o, is the intersection point of the rotation axis and the stereo bar, and its z-axis coincides with the rotation axis. The cylindrical camera coordinate system (r-ξ-η) is a coordinate system adapted to describe this special camera geometry. In this system, r is the radius of the cylindrical panorama, ξ is the angle between the positive y-axis and the rotation radius, measured clockwise, and η is the same as z. When the rotation radius R, the swing angle Ω, and the camera's focal length c are fixed, r is then fixed ($r = \sqrt{R^2 + c^2 + 2Rc\cos\Omega}$), and each point corresponds to unique (ξ, η) coordinates.

The relationship between a point's object coordinates (X, Y, Z) and its image coordinates (i, j) is defined by a sequence of coordinate transformations. The first transformation is a rigid body rotation and translation from the object coordinate system (X-Y-Z) to the local camera coordinate system (x-y-z):

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{22} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix} \cdot \begin{pmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{pmatrix} \tag{1}$$

where (X_0, Y_0, Z_0) are the object coordinates of the origin, o, of the local camera coordinate system; r_{11}, r_{12}, …, r_{33} are components of the rotation matrix

In the second transformation, the point (x, y, z) is projected onto the cylindrical panorama.

$$\xi = \arctan(\frac{x}{y}) - \left(\Omega - \arcsin(\frac{R\sin\Omega}{\sqrt{x^2 + y^2}})\right) \tag{2a}$$

$$\eta = \frac{cz}{\sqrt{x^2 + y^2 - R^2\sin^2\Omega} - R\cos\Omega} \tag{2b}$$

Equation 2b represents the pin-hole perspective projection of the linear array cameras in the off-axis panoramic scanning system.

The last transformation transforms (ξ, η) into the image coordinates (i, j):

$$i = \frac{\xi + \xi_0}{A_h} \tag{3a}$$

$$j = \frac{N}{2} - \frac{\eta + \eta_0}{A_v} \tag{3b}$$

where ξ_o = the bias of coordinate ξ
η_o = the bias of coordinate η
N = resolution of the linear array CCD
A_v = pixel size of the linear array CCD
A_h = horizontal angular resolution of a pixel

Thus the collinearity equations for the left panorama are:

$$i = \left[\arctan\left(\frac{x}{y}\right) - \left(\Omega - \arcsin\left(\frac{R\sin\Omega}{\sqrt{x^2 + y^2}}\right)\right) + \xi_0\right] / A_h \tag{4a}$$

$$j = \frac{N}{2} - \left(\frac{cz}{\sqrt{x^2 + y^2 - R^2\sin^2\Omega} - R\cos\Omega} + \eta_0\right) / A_v \tag{4b}$$

The observation equations that describe the transformation from the object point to the image point are given by incorporating Equation 1 and Equation 4.

In Equation 4, N and A_v are fixed values associated with the camera. A_h is dependent on the exposure time and rotation speed, while ξ_o, η_o, c and R are acquired through calibration.

For the right panorama, the collinearity equations are:

$$i' = \left[\arctan\left(\frac{x}{y}\right) - \left(\Omega' - \arcsin\left(\frac{R'\sin\Omega'}{\sqrt{x^2 + y^2}}\right)\right) + \xi_0'\right] / A_h' \tag{5a}$$

$$j' = \frac{N'}{2} - \left(\frac{c'z}{\sqrt{x^2 + y^2 - R'^2\sin^2\Omega'} - R'\cos\Omega'} + \eta_0'\right) / A_v' \tag{5b}$$

where η_o', ξ_o', A_h', A_v', c', N', R', Ω' are the corresponding parameters of the right panorama.

The parameters in collinearity Equations 4 and 5 have the following relationships, although some of them are difficult to realize:

1) if the same camera is used to take both left and right panoramas, then c = c', $A_v = A_v'$, and N = N';
2) if the two stereo camera positions are equidistant from the rotation axis, then R = R';
3) if the two swing angles are the same, then Ω = Ω'; and
4) if the two stereo camera positions have the same height, then $\eta_o = \eta_o'$.

If all the above conditions are met, a point in the object space will be projected onto the same image row in the two stereo panoramas. Also, the image rows in the right panorama will be the epipolar lines of corresponding rows in the left panorama.

2.4 Stereo Geometry

Figures 4 and 5 illustrate the stereo geometry of multi-perspective panoramas acquired by this prototype system. The collinearity equations are used to model the optical rays from the left and right cameras to point P. From Figure 5(c) we can see that for any point at a constant distance from the mast (on a circle) in the object space, the stereo intersection angle is the same. That explains why the off-axis configuration of the cameras enables the system to have uniform 3-D measurement accuracy in all 360° directions. But the accuracy varies at difference distances in each radial direction.

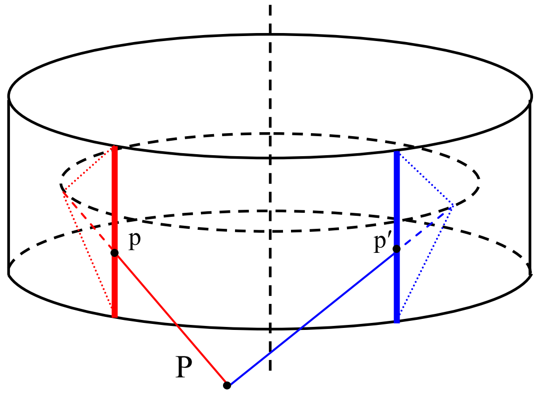
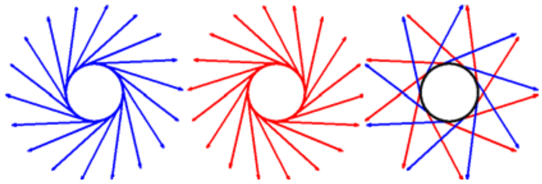


Figure 4. Spatial intersection of multi-perspective panoramas



(a) Left-eye view (b) Right-eye view (c) Spatial intersection
Figure 5. Top view of the stereo geometry

3. DATA ACQUISITION AND 3-D MAPPING TESTS

Experiments were performed under different situations to test the system as well as determine the optimal configuration of the camera as to exposure time, aperture and other parameters.

For example, when taking pictures outdoors, exposure time can range from 8,000 ms to 20,000 ms according to actual weather conditions. For indoor image acquisition, a 30,000 ms exposure time is usually selected. And under fluorescent lights, a fluorescent-cut filter is used on the camera lens. Sample panoramas taken with the prototype are shown in Figure 6.

Figures 7 and 8 show examples of a preliminary 3-D mapping test using a pair of 180º stereo panoramas that cover an area of relatively simple terrain (Figure 7). Image matching was performed using cross-correlation followed by a Least-Squares Matching. After corresponding points were found, ground positions were calculated using Equations 4 and 5. Consequently, a DTM was generated by Kriging interpolation. Then an orthophoto was produced by back-projection using Equation 4. The derived mapping results are shown in Figure 8. The calibration of the camera is pending at this time.

(a) Desert site near Reno, Nevada

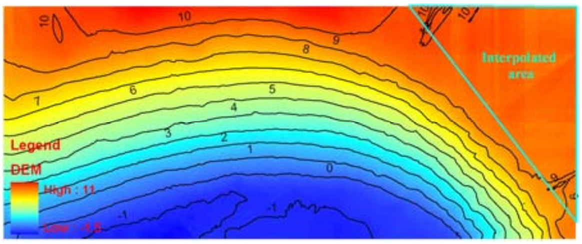
(b) Ohio State University Stadium

Figure 6. Sample panoramas taken with the prototype

(a) Left panorama (180º)

(b) Right panorama (180º)

Figure 7. Partial stereo panoramas used for 3-D mapping



(a) DTM and contour map

(b) 3-D view: orthophoto draped on the DTM

Figure 8. 3-D mapping results

4. CONCLUSIONS AND FUTURE WORK

In this paper, we presented a linescan-based panoramic scanning system developed as the prototype of a Mobile Panoramic Multi-spectral Scanner that employs an off-axis camera configuration mode. The system acquires 3-D information with uniform accuracy in all directions at each depth, and has the potential for rapid onboard processing. This system can be used to improve the performance of 3-D mapping, navigation and object-detection, all of which are very important for time- and energy-limited applications.

Preliminary 3-D mapping tests were performed to test the system and the proposed geometric model of the multi-perspective panoramas acquired with the prototype. Future work will concentrate on the calibration of this system with particular emphasis on the mechanical errors in the support system. We will continue our work on further assessment of the system and the automation of the data processing procedure.

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