# IMAGE ACQUISITION CONSTRAINTS FOR PANORAMIC FRAME CAMERA IMAGING

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**Commission III,WG III/5**

**KEY WORDS:** Close range photogrammetry, Perspective error, Camera geometry, Simulation, Concentric, Eccentric

**ABSTRACT:**

The paper describes an approach to quantify the amount of projective error produced by an offset of projection centres in a panoramic imaging workflow. We have limited this research to such panoramic workflows in which several sub-images using planar image sensor are taken and then stitched together as a large panoramic image mosaic. The aim is to simulate how large the offset can be before it introduces significant error to the dataset. The method uses geometrical analysis to calculate the error in various cases. Constraints for shooting distance, focal length and the depth of the area of interest are taken into account. Considering these constraints, it is possible to safely use even poorly calibrated panoramic camera rig with noticeable offset in projection centre locations. The aim is to create datasets suited for photogrammetric reconstruction. Similar constraints can be used also for finding recommended areas from the image planes for automatic feature matching and thus improve stitching of sub-images into full panoramic mosaics.

The results are mainly designed to be used with long focal length cameras where the offset of projection centre of sub-images can seem to be significant but on the other hand the shooting distance is also long. We show that in such situations the error introduced by the offset of the projection centres results only in negligible error when stitching a metric panorama. Even if the main use of the results is with cameras of long focal length, they are feasible for all focal lengths.

## 1. INTRODUCTION

Panoramic images are considered as images or image sequences with large field of view (FoV). Typically, the FoV of panoramic images is between 100 degrees to complete 360 degrees. Applications of panoramic images are various, such as virtual museums (Zara, 2004), virtual travel (Yan et al., 2009), architecture visualizations (Hotten and Diprose, 2000), 3D object reconstruction (Luhmann and Tecklenburg, 2004), and robot navigation (e.g., Yen and MacDonald, 2002; Briggs et al., 2006), just to name few.

Several methods for creating panoramic images do exist, such as using fish-eye or other large FoV lenses, stitching several sub-images (e.g., Deng and Zhang, 2003) collecting data with rotating line camera (Huang et al., 2003) or reflecting captured image through rotating, spherical, conical, hyperbolic or parabolic mirror (e.g., Svoboda et al., 1998; Gaspar and Victor, 1999; Nakao and Kashitani 2001; Fernandes et al., 2006; Fan and Qi-dan, 2009). In addition, similar methods can be used for the creation of extremely large images using low resolution cameras, even if the FoV does not exceed 100 degrees (Kopf et al., 2007). Such approach, typically, requires a long focal length (Kauhanen et al., 2009). In this article, however, we are only discussing about stitched panoramic images.

Usually, panoramic imaging in photogrammetric applications calls for a tedious calibration setup to eliminate any geometric errors. Metric panorama is considered to require a stable panoramic rig with precise adjustments to accurately place the projection centre into a correct place. Such concentric imaging setup ensures that perspectives of all sub-images are identical (Pöntinen, 2004). Only then it is possible to construct a panoramic image that meets the criteria of an ideal geometry. However in all cases, concentric imaging is not possible or even desired. For example, if camera clusters are preferred for simultaneous sub-image capture, it is physically difficult to make such a system that fulfils the requirements of concentric imaging. Examples of such camera clusters are Dodeca 2360 camera system, OPTAG and DVS Panoramic Viewing System.

Camera-based geometric distortions of sub-images can be calibrated and corrected (Brown, 1971). On the contrary, if sub-images are not acquired concentrically, perspective differences remain. Such perspective errors cannot be corrected without a complete 3D model of the scene. The amount of perspective differences defines how well sub-images can be stitched together into a seamless panoramic image. In some cases, however, even if perspective differences of sub-images are large, stitching can be done with acceptable accuracy.

In this paper, we describe a simulation method to accurately quantify the error introduced by offsets of projection centres in a panoramic imaging process. The paper is motivated by our previous work with long focal length panoramic images where the shooting distance was longer than in usual close range photogrammetric applications. That work yielded good results and we came into conclusion that we need to be able to calculate beforehand perspective errors caused by an eccentric rotation of projection centres.

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## 2. METHODS

Non-ideal panoramic camera rigs cause offset to projection centres causing perspective errors. The amount of perspective error due to such offset is proportional to the distance between camera system and targets but also to the depth of a target.
In this work, we use developed Matlab simulation program to calculate the perspective error introduced by a projection centre offset. We use one camera as a reference with an arbitrary projection centre location, which we can give as an input into our simulation program. We can also specify two target planes. One is closer to the camera and the second is further away. The closer plane is also smaller so it does not occlude the second plane. The amount of perspective error is calculated by placing another camera beside the reference camera with slightly shifted projection centre location (Figure 1). Furthermore, we are able to specify any shooting distance, object size and projection centre offset in all three dimensions of the object coordinate system.

Once we have established the geometry of the system, we can rotate the camera in order to illustrate the panoramic rotation. The ideal panoramic image is achieved when there is no offset in projection centre locations. In such case, the perspective is constant because the coordinates of projection centres are fixed during the rotation. If some projection centre offset does exist, the rotation in relation to the reference projection centre causes the projection centre locations of sub-images to form a circular path around the reference projection centre. This creates a set of unique perspectives which leads to varying perspective errors.

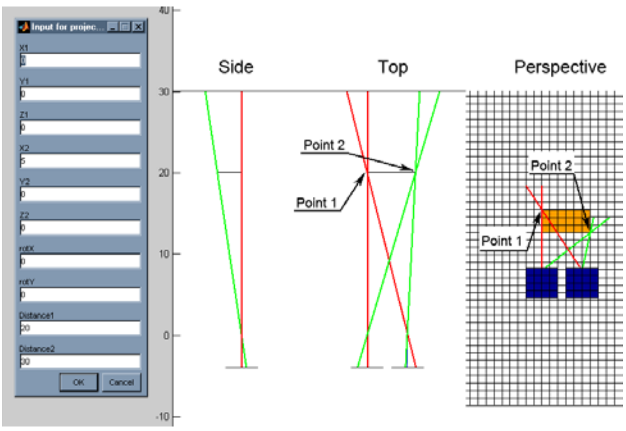


Figure 1. Matlab simulation program showing a geometry with 5 unit offset in X-direction, 20 unit distance to first target plane and 30 unit distance to second target plane. The first target plane is illustrated with orange and the second target plane with non-color grid in the perspective view. Image planes are shown in blue color.

The simulation program calculates rays starting from the projection centres of camera locations, going through the corners of our first target plane and reaching onto our second target plane. Corner points of the first target plane are named "Point 1" and "Point 2" in all cases of this article. However, the offset of the projection centre causes the rays to not reach the same coordinates on the second plane. This gives us an estimate of the perspective error at the object space, simulating a real world situation where we know the offset of the projection centre, shooting distance and the target depth. By target depth we mean the distance between two target planes. In Figure 1, we distinguish the rays that pass through the same point at the first target plane with different colours (Point 1, red lines; Point 2, green lines). The distance between two corresponding rays in the second target plane indicates the amount of shadowing due the perspective error. This error also causes physical shifts of image features at the image plane that are detected as misalignment when sub-images are stitched into a panoramic image.

## 3. RESULTS

In our simulation, we specify the coordinates as project units without any prefix but they can be considered as metric units. In this particular simulation example, our first target plane is 20 units away from the panoramic rotation axis and the distance to the second target plane is 30 units. A camera constant is four units and the image plane size is 4x4 units. This translates to 53.13° horizontal and vertical FoV for each sub-image. The Z-axis is set parallel to the initial attitude of the imaging axis of the reference camera and the X-axis is perpendicular to the Z-axis and parallel to the width of the image plane. In addition, the Y-axis is perpendicular to the X-axis and points up.

A concentric camera rotation forms geometry where there is only a single projection centre offering common perspective to all sub-images. Figure 2 illustrates an ideal concentric panoramic rotation with sub-images taken with 20° increments. In such a case, there is no perspective error in the object space. The program plots red and green observation lines for every image rotation. Concentric image acquisition leads to single lines (Figure 2) and eccentric image acquisition to a bundle of lines (Figures 3-6). Orange plane in Figures 1-5 is the first target plane and the white grid on the background is the second target plane where we calculate the perspective error. In addition, simulation always shows the reference camera image plane. This can be best seen in Figures 5 and 6 and should not be confused to the image planes belonging to a group formed by an eccentric rotation.

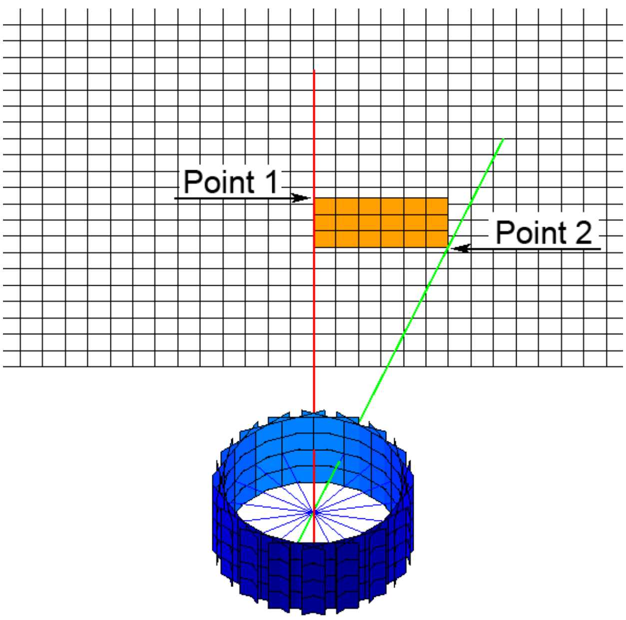


Figure 2. Concentric panoramic sub-image acquisition with the frame camera geometry using 20° rotation increments. Because this camera setup do not cause perspective errors, all rotation positions lead to the same simulation rays (red and green lines).

In Figure 3, we introduce an error for the projection centre coordinates in relation to the rotation axis. The amount of error is one project unit in X-direction. The offset causes the rotation to form a geometry where each camera location has a different projection centre. This means that each sub-image has its own perspective view of the scene. The result is the diverging bundle of observation rays. Our program calculates the error as the divergence of the observation ray in relation to the case where the projection centre lies in the rotation axis. Thus, the width of the spread of an observation ray bundle at the second target plane is half of the error our simulation program outputs.

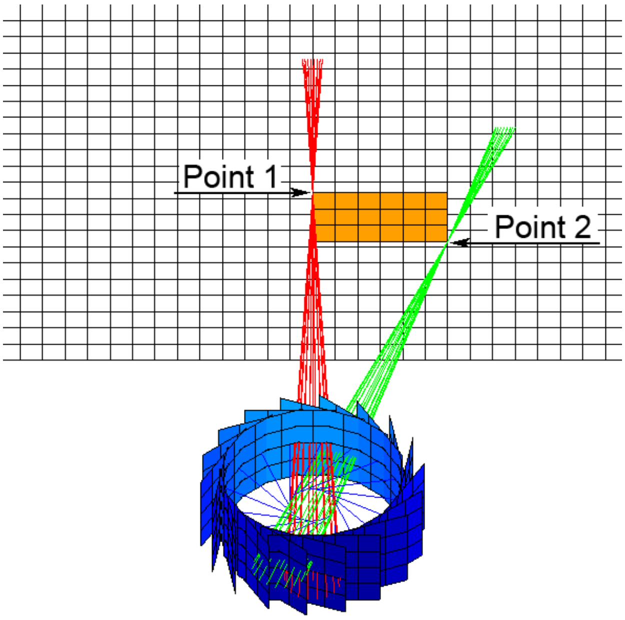


Figure 3. Eccentric sub-image panoramic frame camera geometry with one project unit offset in X-direction and 20° increments.

Figure 4 illustrates the case in which the offset of the projection centre is one project unit in the Z-direction. We can see that the width of the spread of an observation ray bundle is similar than in Figure 3, but the deformation of the image changes. However, in practice the FoV limits the usefulness of such an analysis. That is because when we have rotated the camera more than half of our FoV of 53.13°, we run into a situation where we cannot see our target anymore assuming the target was in the centre of the image when the rotation started. Our simulation draws the observation lines from each projection centre coordinates, whether the camera actually sees the target or not. The program can be modified to take this into account and draw only the lines which resects with the image plane.

If we increase the offset further, we can see how the projection centre coordinates deviate further from the rotation axis. In Figures 5 and 6, the offset is five units and a camera constant is four. Especially in Figure 6 this makes it hard to comprehend how the image plane geometry is formed. The blue lines are the image axes and at the end of each blue line is the projection centre. Starting from each projection centre there are two observation rays, red and green, going to the first target plane and continuing to the second plane. At the other end of the blue line, is the image plane.

In the case of five unit offset in Z-direction, the deformation is so large that the cylinder we can see near the rotation axis are actually the backsides of the image planes facing the rotation axis and image axes are pointing outwards.

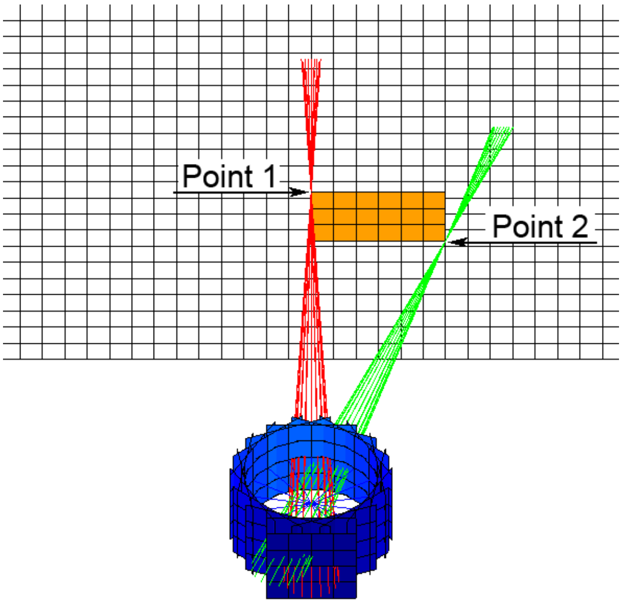


Figure 4. Eccentric sub-image panoramic frame camera geometry with one project unit offset in Z-direction and 20° increments.

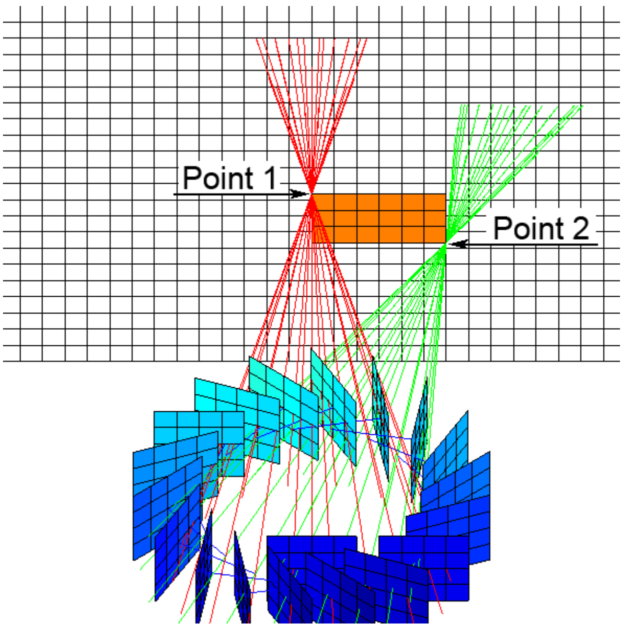


Figure 5. Eccentric sub-image panoramic frame camera geometry with five project unit offset in X-direction and 20° increments.

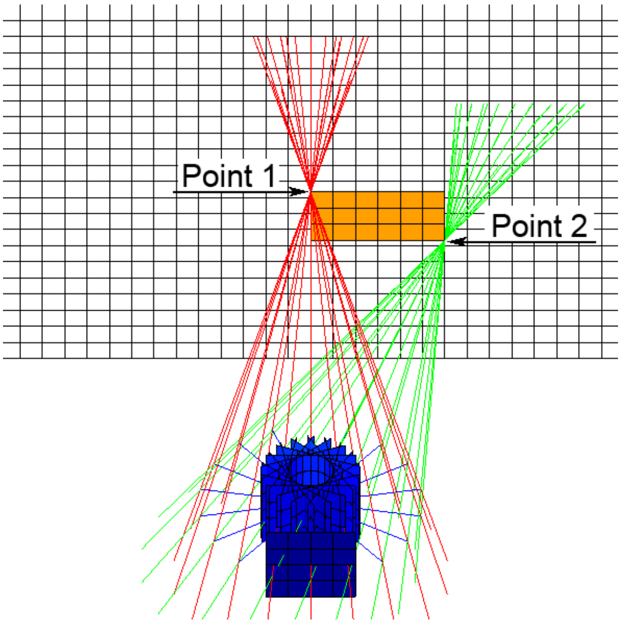


Figure 6. Eccentric sub-image panoramic frame camera geometry with five project unit offset in Z-direction and 20° increments.

Eccentricity can also be visualized with graphs. The graph in Figure 7 shows the error caused by various offsets in X-direction, as specified by the legend, as the function of the rotation angle in degrees. The distance to the first target plane is 70 units and 100 units to the second plane. The offset varies from 5 to 15 units. The graph in Figure 8 illustrates the effect of the Z-direction offset, respectively. Vertical axis shows the error at the object space.

In Figure 1, we showed the image geometry using distance of 20 units to the first target plane, five units offset in the X-direction and 30 units distance to the second target plane. Figure 9 present an addition of two cases with longer distances to the target planes. In the second case, the distance to the first target plane is 40 units and 50 units to the second target plane. The third case shows 40 units distance to the first target plane but the distance to the second target plane is extended to 60 units.

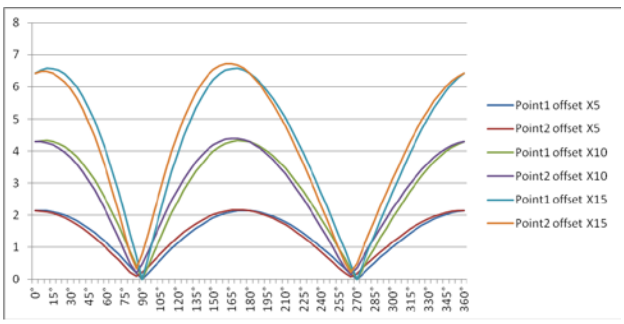


Figure 7. Errors at the object space with various offsets in the X-direction as a function of rotations in degrees. The distance to the first target plane is 70 units and 100 units to the second plane. The vertical axis shows the error in project units.

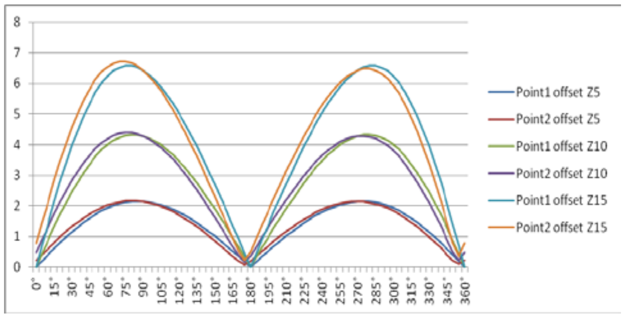


Figure 8. Errors at the object space with various offsets in the X-direction as a function of rotation in degrees. Distance to the first target plane is 70 units and 100 units to the second plane. The vertical axis shows the error in project units.

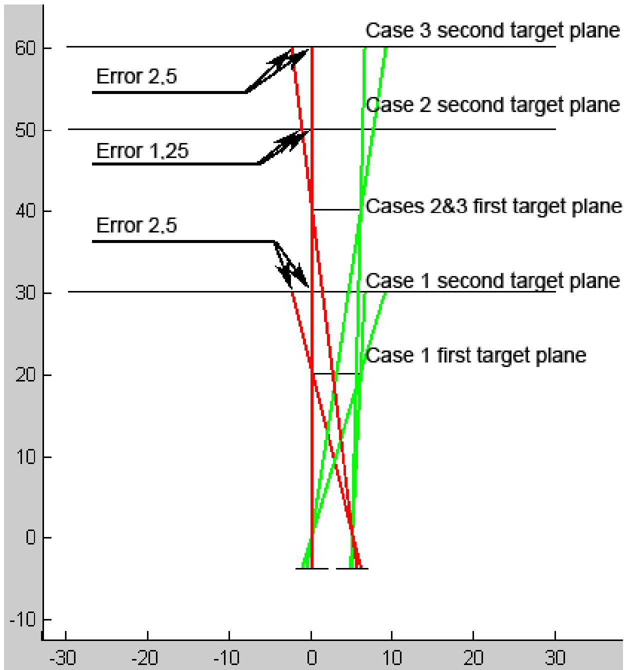


Figure 9. Five unit offset of the projection centre in the X-direction causes different amounts of perspective error in various shooting distance to depth ratios.

In the first case, the distance to the first target plane is 20 units and 30 units to the second target plane. Shooting distance to depth ratio is the distance to the first target plane divided by the difference between the distances of the two target planes. In the first case, the ratio is two and the resulting perspective error is 2.5 units. In the second case, the distance to the first target plane is 40 and 50 units to the second target plane. This translates to a shooting distance to depth ratio of four and the resulting error is 1.25 units. Therefore, by doubling the shooting distance and keeping the target depth the same, the perspective error is halved. In the third case, we extended the target depth in a way that the shooting distance to depth ratio is the same than in first case. This should lead to the same amount of perspective error than in the first case while extending the target depth by 200%. The distance to the first target plane is 40 and 60 units to the second target plane, so the shooting distance to depth ratio is two. The resulting error is 2.5 units.

The simulation can also be used for real world situations. Let us say that we have a target area we would like to measure. The distance to the closest relevant detail of the area is 350 meters away and the distance to the background of our target area is 400 meters. This kind of situation can occur for example in a case of a cityscape where we would like to measure some specific area within a city. Now, if we only have a normal photographic camera stand and would still like to capture a panoramic image with a long focal length lens to achieve high resolution from such a long distance, we need to consider the error caused by the offset projection centre. If we mount the camera on the stand from the camera base, the projection centre is, usually, located inside the lens. In the case of a long focal length this distance can be many centimeters.

For example in the case of a 600mm lens, it is safe to assume we could have approximately 200 to 300mm offset in the Z-direction. We can also assume 10 to 20mm offset in the X-direction if we do not calibrate our rig. Using a 35mm format camera the diagonal FoV is 4° 10' while the required FoV to cover our target is 8° 10'. If we use 50% overlap, we need to capture five photos. The resulting errors are presented in Table 1. The Z-direction offset is 250mm and 15mm in the X-direction. Offset in the Y-direction is set to zero and the camera is only rotated horizontally.

| Angle | -4.085° | -2.005° | 0.075° | 2.155° | 4.235° |
|---|---|---|---|---|---|
| Point1 | 0.4mm | 0.9 mm | 2.2 mm | 3.5 mm | 4.8 mm |
| Point2 | 4.8mm | 6.1 mm | 7.3mm | 8.6 mm | 9.8mm |

Table 1. Errors at the second target plane with different bearing angles. The distance to the first target plane is 350 meters and 400 meters to the second target plane. Z-direction offset causes Points 1 and 2 to produce different errors with different angles.

## 4. DISCUSSION

According to simulation, perspective errors due the eccentric panoramic frame-image acquisition are relatively small if the distance between camera system and objects is long enough. Even if we have examined only errors in the object space, this error is proportional to errors at the image space. Therefore, after a threshold distance, the maximum error at the image space can be tolerable, for example less than one pixel. For example, Wei et al. (1998) found similar conclusions in their research. For seamless stitching of sub-images, such small errors at the image space are advantageous. However, with some limitations we are able to have relative small error also for targets that are closer than previously mentioned threshold distance.

Overall, the perspective error caused by the projection centre offset obviously weakens the geometrical quality of the panoramic imaging system. However, if we only consider a shallow area of interest, the error caused by the perspective error is smaller than if we consider the whole image area as a whole as shown in Figure 10. This gives us various alternatives if we are only able to acquire images of sub-optimal quality regarding the panoramic geometry.

The first possibility is to use the images as they are, in a photogrammetric image block. Unfortunately, in the case of a long focal length this might cause problems due to correlation in the exterior orientation of the camera station. If we stitch the photos into a panoramic image, the geometrical exterior orientation of the image is more stable provided that the internal geometrical quality of the panorama is robust enough.

If we have a large projection centre offset between the sub-images, the perspective error of the resulting image can be too large to permit the use of such a photo in a metric photogrammetric application. In that case, one possible way to use such an image material is to stitch the photos, as shown in the Figure 10, using only features located within a limited depth of range. Stitching becomes seamless only within that depth of range, but we can create more stitched images for different depths. Examples of such stitched photos can be seen in the middle and rightmost photos of the Figure 10. The closer stitching distances result in poorer accuracy or smaller target depth. On the contrary, a usable depth of range increases if the offset of a perspective center becomes smaller. The leftmost image in Figure 10 illustrates how a small offset allows seamless stitching to a large depth of range.

Even if we have an eccentric sub-image acquisition, we can use images for photogrammetric scene reconstruction if we use only those parts of images that are within depth of range in focus (Figure 10, the middle and rightmost photos). On the other hand, similar constraints can be used also for finding recommended areas from the image planes for automatic feature matching and thus improve stitching of sub-images into full panoramic mosaics.

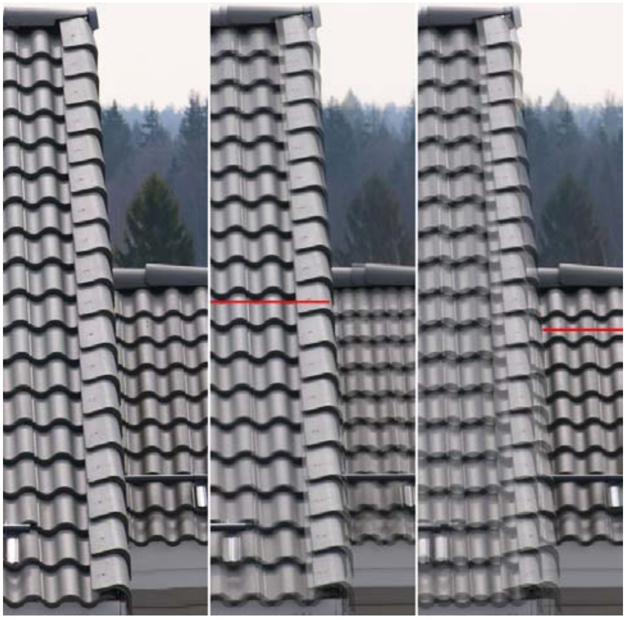

Figure 10. Left image shows two photos stitched with nearly concentric panoramic camera rig showing negligible perspective error. Middle and rightmost images show two photos with offset projection centre stitched together using only the points in close vicinity to the red line shown in the photo.

Our simulation program can be used to estimate the proper usage of the photos at hand to help to decide in which way to best use the image material. We use the simulation program in our own projects, mainly in cases where we have to measure a specific target located far away. Another application is oblique aerial imaging. Using the simulation, we can estimate the perspective error caused by the movement of the plane between the image capture when we know the speed of the plane and the time between the acquisitions of two images. In addition, simulation can also be used to illustrate the panoramic imaging geometry for educational purposes.

One drawback of our simulation is that it becomes inaccurate if we are not able to correctly estimate the eccentricity of rotating perspective centres. The future research includes how to accurately estimate the eccentricity of real panoramic image sequences.

## 5. CONCLUSIONS

The aim of this work was to quantify the perspective error introduced by an offset of projection centre in panoramic imaging process. This examination was limited to frame cameras. We developed simulation software for understanding and predicting the effect of such errors. Using our simulation software, we illustrated geometrical conditions in both concentric and eccentric image acquisition cases. Simulation allows us to calculate the largest allowable projection centre offset for any particular shooting distance to depth ratio.

This paper shows that if we increase the shooting distance or only consider some objects that are within relatively small depth of range, we can accept larger projection centre offsets and still maintain relatively high accuracy in the object space.

The results are applicable in real cases when planning panoramic image acquisition. Even if it is advisable to use properly calibrated camera rig to get uniform perspective to all images, in some cases this is not possible or desired. Therefore, it is advantageous to be able to estimate accuracies beforehand using simulation.

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## 7. ACKNOWLEDGEMENTS

The article is supported by the Finnish Society of Photogrammetry and Remote Sensing.