ABSTRACT

We investigated the opportunities and risks of (stereo) zoom camera systems for space applications for different mission types by analyzing typical mission requirements. Based on this analysis, we derived general requirements for the camera design. Two main design approaches have been investigated in more detail: a continuous zoom and a field-of-view changer with fixed zoom settings. A comparison between the two concepts highlights the advantages and disadvantages. A CAD design draft for the field-of-view changer is presented. The paper closes with an outlook on further developments.

1. INTRODUCTION

Up to now, zoom camera systems have only rarely been used for robotic space applications [1]. For several mission types, the use of a zoom camera system might be beneficial due to the large number of single cameras that would otherwise be required, e.g. for

- rendezvous and docking,
- planetary lander,
- planetary rover.

For e.g. a rendezvous and docking application, the range between 2 km and 1 m shall be monitored. This requires at least a far range, a mid range and a close range camera as well as a docking camera for the extreme close range below 1 m. If 3D reconstruction is required, the number of cameras doubles in order to arrange them as stereo camera systems. A further increase in the number of cameras is possible depending on redundancy requirements. This not only drives up weight and power budgets, but also requires to process data of a large number of cameras simultaneously.

A stereo zoom camera system can replace several cameras for different operating ranges and also allows for 3D reconstruction, e.g. for range measurement of non-cooperative targets or space debris. Depending on the mission, the requirements on the camera with respect to mechanical loads, thermal environment, radiation as well as accuracy of the optical system are different. In general, a high accuracy of each zoom setting (e.g. focal length, distortion, line-of-sight) and high image quality are required. In addition, the components used for building the camera need to be selected according to space environments.

This paper describes the general evaluation of these requirements with respect to a zoom camera system for space application and shows a possible realization of such a system.

2. ACCURACY ANALYSIS

In general, the optical requirements for a stereo camera system for robotic space applications are relatively strict, especially concerning the measurement resolution of the imager [2, 3, 4]. The error in range calculation dominates over the error in line-of-sight determination [4, 5]. Due to the practical relevance of the range calculation for 3D reconstruction, the accuracy requirements can be analyzed on the basis of the range error.

This analysis was done using a pinhole camera model with virtual image plane:

![Figure 1. A stereo camera system according to the pinhole camera model [6]](image)

The base length $b$ for the two stereo cameras is $2d$, the camera constant $f$ (equivalent to the focal length for large object distances). The distance $z$ (positive towards the right) is calculated via the disparity $x''-x'$ in the image plane.

The range error can be calculated via the standard deviation:

$$
\sigma_z^2 = \left( \frac{\partial z}{\partial b} \sigma_b \right)^2 + \left( \frac{\partial z}{\partial f} \sigma_f \right)^2 + \left( \frac{\partial z}{\partial x} \sigma_x \right)^2 + \left( \frac{\partial z}{\partial \gamma} \sigma_\gamma \right)^2
$$

(1)

The range error can be attributed to an error in focal length, angle of the optical axis and image recording quantization, leading to Eq. 2:
\[ \sigma^2 = \left( z + \frac{f}{f} - 1 \right)^2 \sigma_z^2 + \frac{\left( z + \frac{f}{b^2} \right)^2}{2 \sigma^2} \sigma_f^2 + 2 \left( \frac{z + \frac{f}{b}}{b} \right)^2 \sigma_b^2 + 2 \left( \frac{z + \frac{f}{f}}{b} \right)^2 \sigma_{\alpha,\text{MAX}}^2 \]  
\[ \text{(2)} \]

The result of the formula is visualized in Fig. 2 using data for the Mars Exploration Rover (MER) Panoramic Camera (Pancam):

![MER Pancam @ 10m](image)

Figure 2. Dependence of the range error on error in angular and focal length using MER Pancam data

The remaining range error for small angular and focal length errors is determined by the measurement resolution (quantization error), in agreement with [3]. This error can be reduced by increasing the resolution of the imaging medium (e.g. CCD chip) or sub-pixel interpolation [5].

3. REQUIREMENTS OF RENDEZVOUS AND DOCKING MISSIONS

As a general requirement for rendezvous and docking missions, a range error below 1% has to be achieved by the camera system, meaning that at a distance of 100 m the accuracy of the range measurement has to be better than 1 m.

For a calculation of the range error, the following camera parameters are used:

- base length of stereo system: 1.5 m
- error in base length: \(1.0 \times 10^{-3} \) m
- quantization error: \(3.75 \times 10^{-6} \) m (equivalent to \(1/2\) pixel of disparity)

The results are shown in Tab. 1. For a distance of 1000 m, the 1%-requirement cannot be fulfilled at the given base length of the stereo camera system. At the other distances, the range error is at or below 1%. The table also shows that the allowable focal length error and angular error of the optical axis are quite small so that a respective design for a zoom camera system with metrology applications has to keep these two errors to a minimum.

<table>
<thead>
<tr>
<th>Range (m)</th>
<th>Focal Length (mm)</th>
<th>Range Error (m)</th>
<th>Max. allowable Focal Length Error (m)</th>
<th>Max. allowable angular error (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>145</td>
<td>24</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>50</td>
<td>1</td>
<td>(1.78 \times 10^{-4})</td>
<td>(5.62 \times 10^{-5}) rad</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>0.074</td>
<td>(5.62 \times 10^{-5}) m</td>
<td>(5.62 \times 10^{-4}) rad</td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>0.01</td>
<td>(5.62 \times 10^{-5}) m</td>
<td>(5.62 \times 10^{-4}) rad</td>
</tr>
</tbody>
</table>

Table 1. Range Error and corresponding focal length and angular errors.

4. GENERAL ZOOM CAMERA DESIGN ASPECTS

Following the accuracy analysis and the general requirements of space environments, the following design aspects should ideally be realized in a zoom camera design:

- small number of moving parts (ideally 1-2)
- moving parts with small influence on optical axis angular error
- compact design
- calibration of several focal length settings possible
- small F-number
- small image distortion
- telecentric optics design

Two approaches for a zoom camera design can then be followed: a classical continuous zoom and a field-of-view changer with defined zoom settings.

5. CONTINUOUS ZOOM DESIGN APPROACH

The commercial approach to designing a continuous zoom uses a curved groove to change a rotating movement into a linear movement of a lens group. This approach is not suitable for space applications due to the relatively low accuracy of the resulting movement. Therefore, a continuous zoom camera for space applications requires a different mechanism to move the lens groups, e.g. with a special linear motor or using a different mechanism to translate the rotation of the motor into the linear movement of the lens group. In addition, a variable overall length of the lens as known from commercial solutions is impractical for space applications.
A possible optical design for a continuous zoom camera with a fixed overall length is shown in Fig. 3. It is comparable in its functionality to the design of [1]:

![Image of continuous zoom design](image)

Figure 3. Optical design of a continuous zoom with fixed overall length.

Critical aspects of such a continuous zoom design is to guarantee the high accuracy of the lens positioning both along the optical axis (which translates to the accuracy of the focal length) and to avoid a tilting of the lens groups with respect to the optical axis. Therefore, highly accurate and robust space-qualified linear bearings would be necessary.

6. FIELD-OF-VIEW-CHANGER DESIGN APPROACH

Contrary to the continuous zoom design, it is also possible to switch between discrete focal lengths by moving lenses or lens groups in and out of the optical path, a so-called field-of-view-changer.

A possible realization of such an approach consists of a basis lens which is combined with several pre-lenses that either enlarge (acting as a near field lens) or reduce (acting as a tele lens) the optical angles (Fig. 4). One of the pre-lenses can be selected for the optical path and therefore different focal lengths can be obtained. If no pre-lens is used, the focal length of the basis lens alone is used. The optical path is switched using a prism.

There is one important aspect that makes the implementation of a field-of-view changer design highly attractive for space applications: the only moving part is the relatively light prism used to switch between the pre-lenses; the beam deflection via the prisma is also invariant with respect to tilting and rotational inaccuracies of the prisma. Therefore, the single lenses can be calibrated separately with respect to each other and no additional error is introduced by the prism. In addition, the necessary mechanics are relatively simple and easy to realize.

In Fig. 5 a CAD design draft for such an afocal field-of-view changer is shown.

![Image of field-of-view changer](image)

Figure 4. Optical design for an afocal field-of-view changer
7. DESIGN CONCEPT COMPARISON

Comparing the two design approaches with each other, both approaches possess certain advantages. While a continuous zoom is highly flexible with respect to the focal length, it has the disadvantage of a more complex construction, especially if aiming for a high accuracy under space conditions.

The afocal field-of-view changer is restricted in flexibility due to the limited number of focal length settings. On the other hand, the relatively simple design allows for a highly robust and accurate zoom camera. Comparing the size and weight of the two approaches, the continuous zoom is estimated to be larger and heavier than the afocal field-of-view changer as schematically depicted in Fig. 6.

8. OUTLOOK

Due to its high accuracy, compact size and robust design, the afocal field-of-view changer was selected for the ongoing design activities and manufacturing of a prototype. It is planned to build two cameras which can together be used as a stereo camera system. The cameras will be equipped with a Gigabit Ethernet interface for sending out image data and a serial port for controlling the prism via a small microcontroller and motor driver board within the camera.

9. ACKNOWLEDGMENTS

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10. LITERATURE