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High precision focus correction system for multispectral filter-wheel cameras

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Abstract. Spectral Imaging is one of the current topics in science and industry. To capture spectral images many investigations were made in the past and will be done in the future. For reasonable and robust results in spectral imaging, a high image quality should be provided. One part of all spectral imaging systems is the optical system beside illumination and sensor characteristics. Lenses with a low chromatic aberration or systems, which can correct these aberrations, will lead to good image quality as mentioned. This article will show an approach to correct the chromatic aberrations, which is natural generated in refractive lens systems. This is realized by moving the image sensor with a very high precision. Therefore, investigations considering the accurate bearing of the sensor as well as an evaluation of the system characteristics were done and explained in th.is paper. Finally, the image sensor can be placed in less than microseconds with a micron accuracy of less than a pixel of the sensor. The tilt along the moving axis stays below one micron.

1. Introduction

Multispectral imaging systems based on filter wheels suffer from strong chromatic aberration, i.e. for each wavelength present on the illumination source, a slightly different focal position is achieved. This comes from the dependence on the refraction index with the wavelength. The introduction of a parallel late on the optical axis (in this case, the introduction of a wavelength selecting filter) also contributes to the change of focal position. Both chromatic aberration and this etalon effect contribute to blurred images and to different magnifications on the different image planes [1]. Figure 1 shows the dependence of the focal position of a filter wheel multispectral camera with different wavelength. To account for this effect, one possible solution is to move the image plane (in this case, the image sensor) along the optical axis to the best focal position (to be chosen with the appropriate focusing algorithm). This can be done by using a calibration target and saving the position of the best focus for filter on the smart camera's EEPROM [2].

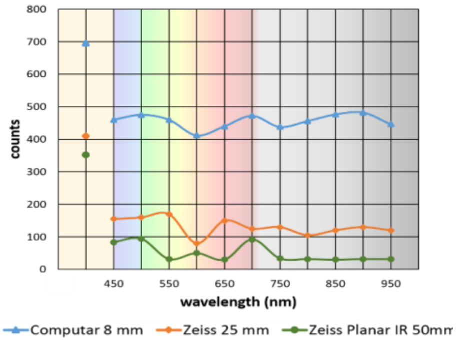

Figure 1: Influence of inclination on outgoing wavelength on different objective lenses [2] (a single count equals 4µm)

2. Approach for Focus correction using Spring bearings

2.1. System approach for optical path correction

One method to compensate the optical deviation along the optical axis is to adjust the image sensor in this direction. The alignment of the image sensor is done by actuating the sensor along the optical axis as depicted in Figure 2. In a precision system, all other directions should not be varied. The challenge is to create an actuating system, which is accurate enough to produce no parasitic movements in other orientations with a high dynamic range and high resolution in direction of the optical axis.

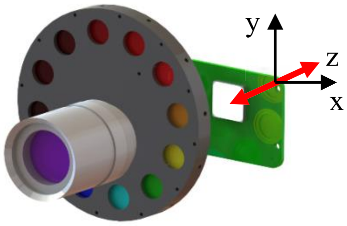

Figure 2: Optical path in principle – objective lens with filter-wheel and image sensor, red arrow indicates the moving direction of the image sensor

Furthermore, the system has to be compatible with existing camera system housing (10x10x11cm³) [2]. Based on an existing camera system the desired technical constraints were identified. These major parameters are an adjustment moving range of 2.0 mm, a dynamic positioning frequency of 15 Hz and a linear position resolution of 1 µm. The deviation in non-positioning directions should be less than a half pixel width. In this special case the position requirement is 2.65 µm.

2.2. Approach for high precision spring bearing for the image sensor guideway

Several mechanical linear stages were compared, e.g. linear cylindrical ball travels und linear slides. In comparison to linear bearings which have a statistical displacement characteristic depending on the accuracy of the bearing parts, flexure bearing can offer a backlash-free guideway. A technical realization of that is a flexure bearing based on leaf springs as illustrated in Figure 3.

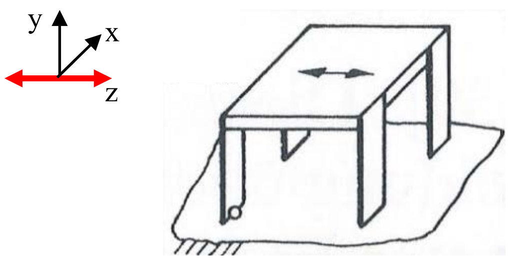

Figure 3: Parallelized leaf spring [3]

If the movement is actuated in the z-direction the x-direction is blocked against parasitic movement. With the spring deflection along the z-axis a shift downwards in the negative y-direction leads to a displacement. For the image sensor movement all displacements changing the spatial information in x and y have to be avoided. To overcome this displacement error, two couples of parallelized leaf springs have to be combined together like depicted in

Figure 4. For this solution an additional support frame is needed which acts as a bearing for the coupled spring pairs. With the approach that the spring length is long compared to the adjustment range, the parasitic deviation is very marginal and can be neglected. For the aforementioned constraints, a solution for a short spring length and low deviations is needed. A combination of two parallel-springs with the stiffness c_1 and c_2 in series to a third parallel spring c_3 offer the best possibility to compensate the appearance of an offset in a parasitic displacement direction. Another advantage of the series connection is the reduction of the bending stress. The resulting stiffness could be calculated by the following equation (1):

$$\frac{1}{c} = \frac{1}{c_1 + c_2} + \frac{1}{c_3} \tag{1}$$

The required throw force is limited by two thresholds: in minimal deflection under bending load, the remaining initial spring force has to be greater than the weight of the image sensor including support. The maximum force is limited by the actuator and should be as low as possible to save energy; reduce friction; and allow a high dynamic. Calculations based on those constraints show that two different springs with thickness of 3mm, length of 35mm and respective widths of 4.5mm and 9mm are needed. The spring system was simulated in ANSYS Workbench with finite elements method. The result was used to optimize the coupling geometry between the springs. The results of the FEM confirm the results from the manual calculation with a deviation of 1.4 percent in case of the maximum force. The maximum force calculated by FEM in case of maximum linear movement and an initial tension is 3.162 Newton.

2.3. Actuating stage for the image sensor movement

The actuator was selected by a comparison of several types of linear actuators. Possible were linear DC-Servomotors, piezo-electric actors, voice-coil motors and stepper motors. Based on departed experiences the voice-coil was discarded. Under consideration of available space and cost aspects and needed throw force the stepper-motor is the best solution. The combination of a stepper motor with an integrated shaft provides the needed throw force and a small construction size. Nanotec offers a linear stepper motor with shaft and a resolution of 5 µm per full step. By using the micro-step-technology a resolution smaller than 1 µm could be achieved. This fits the requirement of 1 µm precision in direction of the optical path. The backlash of the shaft could be eliminated by the initial tension of the spring system and a well dimensioned mounting of the shaft. Adding a precise reference switch allowing an absolute traceable actor position by counting the steps and execute a reference movement. The construction of the complete actuating system is shown in the following image.

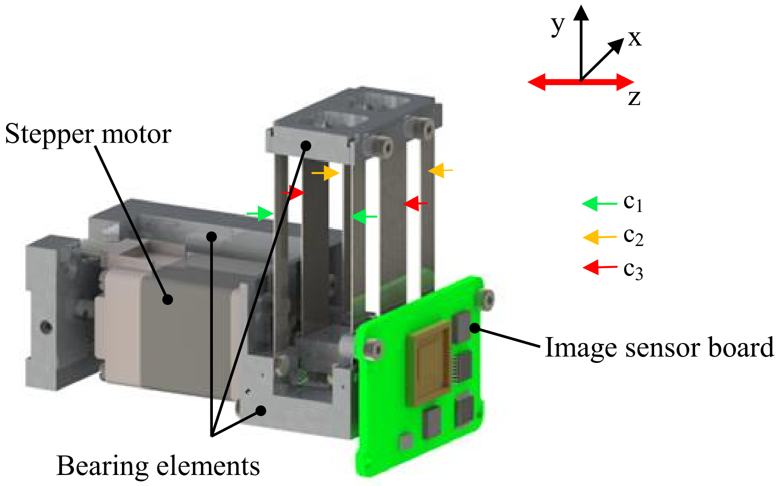

Figure 4: Three dimensional computer sketch of the realized image sensor guideway concept (small arrows indicating the paralleled spring bearings according to eq. 1)

3. System Evaluation

The system parameters were confirmed by several measurements. The system dynamic was determined and optimized with an oscilloscope und the adjustment of the stepper motor timing parameters in the stepper motor controller. For the maximum moving range a repositioning frequency of 15.7 Hz was achieved.
The accuracy of placement was measured with a "Carl Zeiss Industrielle Messtechnik" coordinate measuring machine Type "F25". The following parameters were evaluated:

- Linear positioning accuracy in optical path direction
- Parasitic displacement error in several position steps
- Tilt of the image sensor while positioning
- Repeatability of reference position movement

4. Results and conclusion

The results are a maximum deviation in the blocked direction x/y of 4.5µm and 1.2µm in a working range of 2 mm. The deviation in the sensor moving direction z alternates approx. 3.5 µm inside a working range of 2 mm. The tilt of the image sensor alternates over the working range with a maximum of 0.27 angular minutes and 0.05 angle minutes. The reference position could be initiated with a precision of 0.85 µm. The mean deviation and standard deviation achieve the required parameters inside the considered typical working range of 800 µm. The investigated objective lenses shown in **Fehler! Verweisquelle konnte nicht gefunden werden.** can be corrected with this high precision movement stage.

5. Acknowledgements

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