Parallelized Chromatic Confocal Systems Enable Efficient Spectral Information Coding

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Parallelized imaging systems based on the chromatic confocal approach can be used for hyperspectral imaging and optical profilometry.

Chromatic confocal imaging systems\(^1\)–\(^3\) are based on the well-known principle of confocal microscopy.\(^4\) They use a polychromatic light source instead of a laser, and the focal length has strong wavelength dependence so that different wavelengths are focused at different axial distances. The wavelength dependence is achieved by replacing the standard objective lens with a hyperchromatic lens.\(^5\), \(^6\) Hyperchromatic systems are characterized by an optimized longitudinal chromatic aberration adapted to the specific application requirements.\(^7\), \(^8\)

The chromatic confocal approach can be used in various system concepts for chromatic information encoding and decoding. Currently, we are mainly working on parallelized systems for chromatic confocal distance sensing (profilometry) and hyperspectral imaging.\(^6\), \(^9\)–\(^11\) Hyperspectral imaging combines spatially and spectrally resolved imaging to detect the full spectral signature of the analyzed object. Typical applications include agriculture, geology, mineralogy, and surveillance.

To use a hyperchromatic lens for chromatic information coding, optically conjugate pinhole arrays are placed in the object and image space of the lens (see Figure 1). The object-space pinhole array transforms the polychromatic object information or the illumination beam into a number of spatially separated quasi-point sources.

When the hyperchromatic lens images these polychromatic point sources, their spectral components become separated along the direction of light propagation. The image-space pinhole array is placed within this focal range and attenuates all wavelengths except the one in focus at the pinhole plane. Thus, the spectral signals passing the pinhole plane show a significant peak for this specific wavelength.

The longitudinal chromatic aberration required by chromatic confocal systems may be created with refractive systems, diffractive systems, or hybrid combinations of diffractive and refractive elements. Because the longitudinal chromatic aberration caused by a diffractive optical element (DOE) is six to 25 times larger than that achieved with a refractive component of the same focal length, DOEs are very well suited for use in chromatic confocal systems.\(^12\) They enable an efficient correction of monochromatic aberrations through an aspherical phase function, but they are also linked to various challenges such as a limited diffraction efficiency. By balancing the powers of the diffractive and refractive components, the spectral sensor characteristics can be tailored to the specific measurement problem.\(^6\)

We use a two-stage design approach to develop application-specific chromatic confocal systems. During the first stage, we apply a collinear model to define the system layout. At this point, the main performance criteria (such as the spatial and spectral resolution) and the field and the system size are determined by the choice of the collinear system parameters. Among the most important parameters relevant to chromatic confocal systems are the numerical aperture, the longitudinal chromatic aberration, the pinhole diameter and spacing, and the lateral magnification. By an appropriate choice of these parameters, subnanometer spectral resolution can be reached.\(^6\) During the second stage, we use an optimization process based on ray tracing to cope...
with the on-axis and field-dependent monochromatic aberrations. For optimum performance, these aberrations must be corrected over the full spectral range of the optical system.

![Figure 2. Chromatic confocal single-pass system for hyperspectral imaging.](image)

We have used these techniques to design a single-pass chromatic confocal system for hyperspectral imaging (see Figure 2). To provide the quasi-point sources necessary for the chromatic confocal approach, the object scene is imaged onto the first pinhole array. A telecentric hyperchromatic lens system then separates the spectral information along the axis. We can select the spectral channels of interest by tuning the focal length of the hyperchromatic system or by moving the detector system axially. Thus, we combine a parallelized readout of the spatial channels with a sequential evaluation of the spectral channels, which may reach subnanometer bandwidths. Tuning concepts for the hyperchromatic group include classical zoom systems, adaptive mirrors, fluidic membrane lenses, and Alvarez-Lohmann lenses.11-13,14

![Figure 3. Chromatic confocal double-pass system for parallelized evaluation of an extended object.](image)

For chromatic confocal distance sensing, we use a double-pass system (see Figure 3). A polychromatic light source illuminates the pinhole array to create an array of quasi-point sources. The hyperchromatic lens focuses the spectral components of these point sources at different distances. If a reflecting or scattering surface is brought within the measurement range, for each pinhole only one specific wavelength will be in focus on the surface, according to the axial distance to the surface at that spot. The reflected or scattered light of this specific focus will also be in focus on the pinhole plane. It will pass the pinhole plane, whereas all other wavelengths will be defocused and strongly attenuated. By evaluating the wavelength of the spectral peaks, the shape and distance of the surface can be determined in parallel for all points of the pinhole array.

In summary, we have designed optimized parallelized chromatic confocal systems for conducting hyperspectral imaging and optical profilometry. Our current work on hyperspectral imaging is focused on the development of miniaturized, application-specific sensor systems. For this purpose, we are integrating actuators based on microelectromechanical systems (MEMS) to tune the focus of Alvarez-Lohmann lenses and to enhance the lateral resolution through a lateral movement of the pinhole arrays. The next step in our optical profilometry work will address the challenging task of performing the parallelized spectral evaluation of all the measurement points. To this end, we are working on a novel snapshot sensor that combines an array-based chromatic confocal setup with a hyperspectral detection system to enable measurement of the full surface topography with a single shot.

References