

# Natural optical design concepts for highly miniaturized camera systems

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## ABSTRACT

Microcameras for computers, mobile phones, watches, security systems and credit cards is a very promising future market. Semiconductor industry is now able to integrate light reception, signal amplification and processing in a low-power-consuming microchip of a few  $\text{mm}^2$  size. Active pixel sensors (APS) supply each pixel in an image sensor with an individually programmable functionality.[1] Beside the electronic receptor chip, a highly miniaturized lens system is required. Compared to the progress in microelectronics, optics has not yet made a significant step forward.[2] Today's microcamera lenses are usually a downscaled version of a classical lens system and rarely smaller than  $3 \text{ mm} \times 3 \text{ mm} \times 3 \text{ mm}$ . This lagging of optics is quite surprising. Biologists have systematically studied all types of natural eye sensors since the eighteenth century.[3] Mother Nature provides a variety of highly effective examples for miniaturized imaging systems. Single-aperture systems are the appropriate solution if the size is a free design parameter. If the budget is tight and optics limited in size, nature prefers multiple-aperture systems, the so-called compound eyes. As compound eyes are limited in resolution and night view, a cluster of single-aperture eyes, as jumping spiders use, is probably a better solution. The recent development in micro-optics offers the chance to imitate such natural design concepts. We have investigated miniaturized imaging systems based on microlens arrays and natural optical design concepts. Practical limitations for system design, packaging and assembling are given. Examples for micro-optical components and imaging systems are presented.

## 1. OPTICAL DESIGN IN NATURE

Since the Cambrian period about 500 million years ago nature has been exploring and optimizing image-forming lens systems.[3, 4, 5] For all types of creatures evolution has found appropriate image capturing systems to give them all necessary visual information about their environment. For relatively large vertebrates, like humans, eyes were optimized to provide a high resolution, large field of view, focusing ability, color detection and a very large dynamic range to see both in the bright sunshine and in the dark night. Here, the size or volume of the eye is a free parameter for the design. The optical performance is the key issue. A large single-pupil eye seemed to be the best solution. For small invertebrates having an external skeleton, the volume, weight and functionality is the figure of merit. The smaller an animal is, the higher is usually the percentage of the animal's body reserved for the eye. For small animals the eyes are very expensive in weight and metabolic energy consume. If the budget is tight, nature prefers to distribute the image capturing to a matrix of some small eye sensors instead of using a single eye. The resolution of such so-called compound or fly's eyes is usually poor compared to the single-aperture eyes.[4] However, this lack of resolution is often counterbalanced by additional functionality like a large view angle, polarization or fast movement detection. Natural eyes are a perfect compromise suited to the requirements of the life-style of the animal. In the following, we will briefly explain the optical properties of natural eye sensors.

### Single-aperture eyes

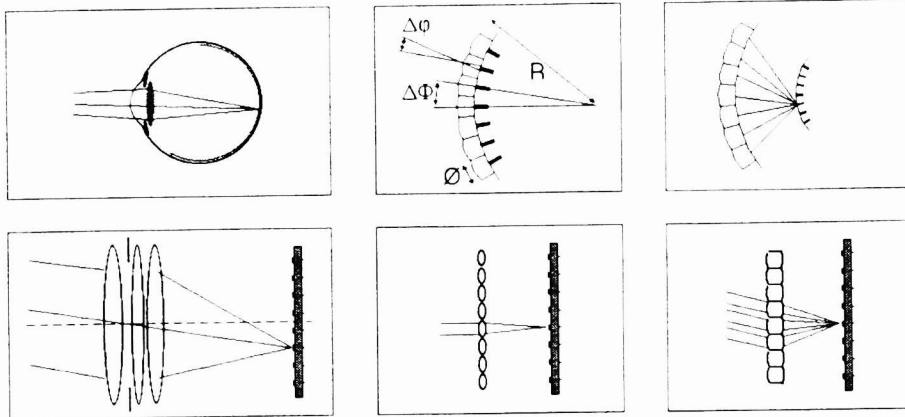
The human eye is a single-aperture image capturing system similar to photographic or electronic camera systems (see Table 1). The eye consists of a flexible lens for focussing, a variable pupil (iris) for fast sensitivity adaptation and the retina, the image detector. A nice definition of the human eye is given by Hofmann.[6] "The human eye is a special version of a pinhole camera, where Fresnel diffraction is compensated by the introduction of a focussing system". The diameter of the pinhole or iris is variable from 1.8 mm to 8 mm for bright light and dark viewing. The lens of the human eye is spherically overcorrected by graded index effects and aspherical surface profiles. The refractive index of the lens is higher in the central part of the lens, the curvature becomes weaker towards the margin. This correction offsets the undercorrected spherical aberration of the outer surface of the cornea. Contraction or relaxation of muscles changes the focal length. The retina contains nerve fibers, light-sensitive rod and cone cells and a pigment layer. There are about 6 million cones, about 120 million rods, and only about 1 million nerve fibers. The cones of the fovea (center of sharp vision) are 1 to 1.5  $\mu\text{m}$  in diameter and about 2 to 2.5  $\mu\text{m}$  apart. The rods are about 2  $\mu\text{m}$  in diameter. In the outer portions of the retina, the sensitive cells are more widely spaced and are multiply connected to nerve fibers (several hundred to a fiber). The field of vision of

an eye approximates an ellipse about  $150^\circ$  high by about  $210^\circ$  wide. The angular resolution or acuity  $\Delta\Phi$  is around 0.6 to 1 min of arc for the fovea.

### Compound eyes

Compound eyes are multi-aperture optical sensors of insects and crustaceans and generally divided into two main classes: *apposition* compound eyes and *superposition* compound eyes (see Table 1). An apposition eye consists of an array of lenses and photoreceptors each of the lenses focusing light from a small solid angle of object space onto a single photoreceptor.

Each lens-photoreceptor system is referred to as ommatidia or 'little eye'. Apposition eyes have some hundreds up to tens of thousands of these ommatidia packed in non-uniform hexagonal arrays.[7]



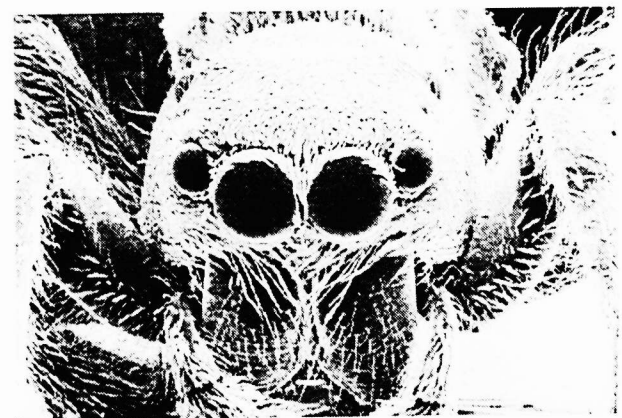
**Table 1. Different types of natural eye sensors and its artificial counterpart. Artificial eye sensors are based on planar components due to manufacturing restrictions.**

The superposition compound eye has primarily evolved on nocturnal insects and deep-water crustaceans. The light from multiple facets combines on the surface of the photoreceptor layer to form a single erect image of the object. Compared to apposition eyes, the superposition eye is much more light sensitive. Nature has evolved two principal optical methods to

create superposition images: gradient refractive index and reflective ommatidia.[4] Some insects use a combination of both types of compound eyes. Variable pigments switch between apposition (daylight) and superposition (night) or change the number of recruited facets making up the superposition image.[8] A very interesting modification is the neural superposition eye of a housefly, where each ommatidia has seven detector pixels or rhabdomeres. Signals of different adjacent ommatidia interact within the neurons of the fly's brain system. This allows fast directionally selective motion detection, which enables the housefly to maneuver perfectly in three-dimensional space.[9]

### Jumping spiders

In contrast to insects, jumping spiders have opted for single-lens eyes, but eight of them (see Figure 1). Jumping spiders have two high-resolution eyes, two wide-angle eyes and four additional side eyes. The two antero-median eyes provide a magnified image at a high resolution for a rather small visual field.[10] Jumping spiders use these eyes for detailed inspection of objects of interest. It is worth to note that these eyes have a moveable retina. The retina can be moved vertically, laterally and rotationally. The spider can track a prey without moving itself. The two antero-lateral eyes provide a large visual field at a reduced resolution.[11] The small side eyes cover the large field left and right of the spider. The spider uses different single-lens eyes tailored for different functions. This trick seems to be the best compromise to combine high resolution and large observation field within the limited budget of a small animal or microsystem.



**Figure 1. SEM picture of the head of a jumping spider.** Photograph by Aaron Bell, <http://www.hofstra.edu/web/docs/SEM>

### Natural optical materials

The way in which animal eyes form images are either based on refracting lenses, reflecting mirrors or in the simplest case just on pinholes. Nature has experimented with all types of refractive index-variant materials and aspherical surfaces. Natural lens systems are e.g. constructed from an optically inhomogeneous gradient of protein and water mixtures. Natural

mirrors are made of multiple quarter-wavelength thick layers of materials with alternating high and low refractive indices, e.g. guanine ( $n = 1.83$ ) and cytoplasm ( $n = 1.34$ ).[4]

In image forming systems based on spherical shaped lenses, the most serious potential problem is spherical aberration. Peripheral rays tend to be over-focussed, and uncorrected the image quality is often poor. Most other defects matter less. For example, off-axis aberrations and field curvature do not matter much in a human eye, where critical resolution is only needed in the center and the receptors are located on a concave surface.[4] A correction of the spherical aberration in natural eyes is achieved by using aspherical surfaces profiles and graded refractive index (GRIN). For example, the refractive index of the human eye lens varies from 1.386 in the center to 1.406 at the periphery.[12]

Natural imaging systems are based on refraction and reflection. The optical imaging system is often not perfect, but the complete eye sensor including the retina and the computing neural network is optimized and well adapted to needs of the animal. Nature handles carefully the tightest budgets and never wastes space and metabolic energy. This is the real benefit of studying natural eye sensors for micro-optical system designers. In the following we discuss the influence of scale and physical dimensions on the optical properties of image forming systems.

## 2. OPTICAL PROPERTIES OF SMALL-SCALE LENS SYSTEMS

### Aberrations and diffraction limit

The stop number of a lens is given by  $F = f/\varnothing$ , where  $f$  is the focal length and  $\varnothing$  is the lens diameter. The diffraction limited resolution of a lens is given by  $\delta x \propto \lambda F$ , the depth of focus by  $\delta z \propto 4\lambda F^2$ . Both values are independent of the lens scale. A downscaling of both, the diameter  $\varnothing$  and the focal length  $f$  does not affect the diffraction-limited resolution, if the stop number is not changed. Furthermore, scaling will not change the type of aberrations created by a certain lens profile. However, it will change the magnitude of the wavefront aberrations, as aberrations are expressed in fractions of the wavelength. Small lenses have fewer aberrations than large lenses (for the same F-number and wavelength).[13] It's relatively simple to achieve diffraction-limited performance for miniaturized lens systems. Aberrations do not have the same weight in micro-optics as they have for macro-optics. For small-scale lens systems, the diffraction limit itself is the important criteria describing and limiting the resolution and image fineness.

### Space-bandwidth product

It was mentioned that a downscaling of the physical dimensions of a lens system does not change the size of the diffraction-limited spot or image pixel the system generates. On the other hand, a downscaling reduces the number of transported image pixels drastically. We assume a diffraction limited lens system that provides a quadratic image field of  $I \times I = \varnothing^2/2$  size. The diagonal  $d_1 = \sqrt{2} \cdot I$  is set equal to the lens diameter  $\varnothing$ . For such an optical system, the number of transported image pixels  $M$  is given by

$$M \approx \frac{I^2}{(\lambda F)^2} = \frac{1}{2} \frac{\varnothing^2}{(\lambda F)^2} = \frac{1}{2} \frac{\varnothing^4}{(\lambda f)^2} \quad (1)$$

The number of image pixels  $M$ , also referred as space-bandwidth product, scales with the square of the lens diameter  $\varnothing$  for a

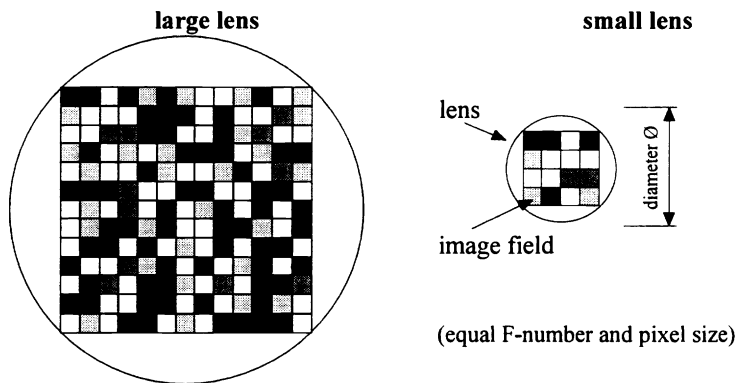


Figure 2. The number of image pixels  $M$  scales with the square of the lens diameter.

constant F-number and with the fourth power in  $\varnothing$  for a constant focal length  $f$ . A miniaturized imaging system is able to image fine details of a scene, but not many.

Electronic light receptor chips have typically a pixel pitch of 3 to 5  $\mu\text{m}$  corresponding to a spatial resolution  $v_s$  of 100 to 166 lines per mm. According to the sampling theorem, it does not make sense that the resolution of an optical system  $v_{co}$  is better than that of the

receptor mosaic. An F-number of 6 to 10 is sufficient for most artificial eye sensors. Table 2 gives the number of image pixels  $M$  for  $f/6$  and  $f/10$  diffraction limited systems of different diameters  $\emptyset$ . The image fineness is rapidly decreasing below 5 mm lens diameter.

We now better understand why the single-lens eye concept does not work for tiny insects. The number of pixels respectively the space bandwidth product supplied by a small-scale single-lens eye sensor is not sufficient to recognize the insect's mates and enemies. The nature's design strategy was to further reduce the lens diameter and to distribute the imaging task to some hundreds or thousands of individual eye facets.

### Resolution of compound eyes

For a round-shaped apposite compound eye, the observed scene is divided in angular sectors  $\Delta\phi$  as shown in Table 1. The angle between the optical axes of two adjacent eyes or ommatidia is referred as the inter-ommatidial angle  $\Delta\Phi$ . Each ommatidium usually detects only one pixel. The image detection is performed massively parallel. This is a very effective concept for movement detection and large object field observation. A fly almost achieves observation range of  $4\pi$  by using two compound eyes on each side of the head.

lens diameter $\emptyset$	5 mm	2 mm	1 mm	500 $\mu\text{m}$	100 $\mu\text{m}$	50 $\mu\text{m}$
image pixels $M$ ( $f/6$ )	1389000 <i>1180 × 1180</i>	222000 <i>283 × 283</i>	56000 <i>236 × 236</i>	14000 <i>118 × 118</i>	560 <i>23 × 23</i>	140 <i>12 × 12</i>
image pixels $M$ ( $f/10$ )	500000 <i>707 × 707</i>	80000 <i>283 × 283</i>	20000 <i>141 × 141</i>	5000 <i>71 × 71</i>	200 <i>14 × 14</i>	50 <i>7 × 7</i>

**Table 2. Number of image pixels  $M$  for a diffraction limited  $f/6$  and  $f/10$ -systems providing an image field of  $I \times I = \emptyset^2/2$ .**

In general the resolution of a compound eye depends on two factors: a) the fineness of the mosaic of receptive elements that sample the image and b) the optical quality of the image, that those elements receive.[14] A sinusoidal pattern structure is resolved if the spatial frequency of the detector mosaic  $\nu_s$  is equal, or

higher than the pattern frequency  $\nu_{co}$  of the image. The spatial resolution ( $\nu_s = 1/(2 \cdot \Delta\Phi)$ ) of the receptor mosaic and the optical cut-off limit of  $\nu_{co} = \emptyset/\lambda$  leads to the definition of the eye parameter  $p$  given by

$$p = \emptyset \cdot \Delta\Phi \geq \frac{\lambda}{2}. \quad (2)$$

The eye parameter  $p$  is a measure how close an eye sensor comes to the diffraction limit and reaches  $\lambda/2$  for diffraction limited eyes. For a diffraction-limited round-shaped compound eye the eye parameter  $p_{dl}$  corresponds to

$$p_{dl} = (R_{eye} \Delta\Phi) \Delta\Phi = \frac{\emptyset^2}{R_{eye}}, \quad (3)$$

where  $\emptyset$  is the lens diameter,  $\Delta\Phi$  the inter-ommatidial angle and  $R_{eye}$  the radius of the compound eye as shown in Table 1. From equation (1) and (3), we now understand the key problem of compound eyes. It is very difficult to increase the resolution of a compound eye as a whole, because the eye becomes too big.[14] The diffraction-limited resolution is inversely related to the lens diameter  $\emptyset$ . To achieve a higher resolution we have to increase the diameter of the eye facets. By doubling the lens diameter  $\emptyset$ , the radius of the eye must increase by factor 4 to keep the eye parameter constant.

In conclusion, compound eyes are inherently low-resolution image sensors. For small animals, a limited number of image pixels is the only way to avoid a flooding of the animal's neural system with too much information. The low resolution is often counterbalanced by additional functionality like wide-angle observation, polarization or fast movement detection.

### 3. MICRO-OPTICS

Since the invention of the first integrated circuit (IC) in 1958, optical lithography is a key technology for the rapidly growing semiconductor industry. Optical designers and lens manufacturers have used all possible tricks to further improve the resolution of photolithography. Despite of the enormous success in these large-scale imaging systems, optical designers

are quite inexperienced in working with small volume budgets of 100 mm<sup>3</sup> and below. Miniaturization requires different design strategies than perfection does. The severest problems are the availability of miniaturized optical elements. The micro-optical toolbox is still quite incomplete. In addition, packaging and alignment of optical microsystems is an ambitious task. Standard mounting using a close-fitting sleeve, lock- or distance rings and grooves are not very practical. Micro-optics designers have to learn how to overcome these restrictions.

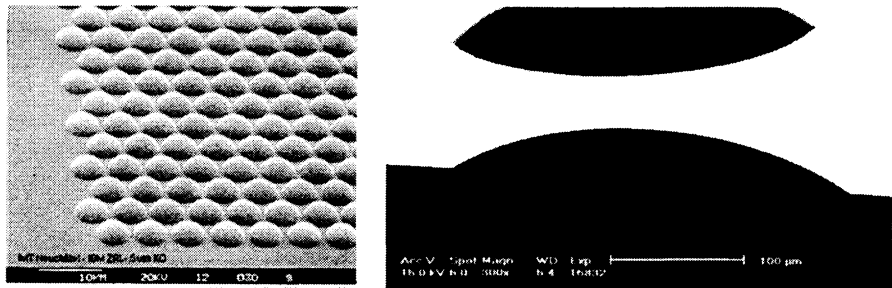
### Micro-optical design

Micro-optics is still closely tied to ideas, concepts and microfabrication technologies developed for semiconductor industry. [15, 16] This includes a general restriction to flat building parts (planar lens and receptor arrays), a matrix-oriented patterning (Cartesian coordinates) and pure bulk materials (very limited possibility of index modification). Micro-optics is still a component-oriented discipline aiming on the improvement of efficiency or functionality of single elements. In addition, micro-optics' research is often divided in diffractive, refractive and graded index communities. Nature never had these problems. Nature did not care if light is diffracted, refracted, reflected or absorbed. Nature always optimized the complete eye sensor, considering optics, detection and image processing.

Compared to nature, a micro-optics system designer has not much choice in building parts and optical materials. Commercially available micro-optical components are rare. Very often, a designer has to order individual components as 'special request' or even has to manufacture the components himself. Classifying units for micro-optics are missing, not standardized or misleading. For example, a diffraction efficiency of 99% must not mean that a grating diffracts 99% of the light. This lack of clarity leads to a more fundamental problem, the diversity of micro-optics. For example, a microlens for collimation might be diffractive, refractive or both (hybrid). All three types of microlenses will collimate the incoming light. Despite their equal optical functionality, their aberrations, tolerances and problems are completely different. It is not trivial to choose the right type of element for a specific optical design. Additionally, the decision is often influenced by the preferences of the individual optics designer. Most experts for micro-optics prefer either a diffractive or refractive solution, depending to what they know best or have available.

### Microlenses for imaging

As previously discussed, most animal eyes are based on a combination of curved lens surfaces and a radial symmetric variation of the refractive index within the bulk material (GRIN).[17] Different techniques to fabricate technical GRIN lenses have been developed: a) selective exchange of ions in a glass substrate by metal ions, b) diffusion polymerization in plastics and c) chemical vapor deposition.[16] GRIN lenses are well suited for imaging tasks and have been successfully implemented, e.g. for 1:1 imaging in photocopying machines.[18, 19] However, the difficult fabrication process severely limits the assortment of commercially available GRIN lenses.



**Figure 3. Refractive microlenses: a) Very small lenses of 5 μm diameter, b) lens profile<sup>1</sup> (310 μm diameter,  $f = 375 \mu\text{m}$ ).**

<sup>1</sup> Courtesy of J.C. Roulet, Institut de Microtechnique, Université de Neuchâtel, Switzerland

Diffractive microlenses are generally not well suited for imaging tasks. Focal length and efficiency depend strongly on the wavelength of the light and limit the lenses to monochromatic applications.[16] In addition, a finite angular field diameter, low numerical apertures, straylight and ghost images created by spurious diffraction orders will limit their ability for imaging. Nature has never used a diffractive lens for imaging (as far as the author knows).

A very simple fabrication technique for refractive microlens arrays is the reflow or melting resist technique.[20, 21, 22] Photoresist is micro-structured by photolithography and melted at a temperature of 150 to 200°C on a hot plate or in an oven. The melted resist lenses serve as a master element for subsequent transfer processes like reactive ion etching or replication in plastic. Figure 3 shows different types of plano-convex microlenses fabricated by reflow techniques.[23] A diffraction-limited optical performance ( $p$ - $v$  wave aberrations  $< \lambda/9$ , Strehl 0.98) was demonstrated for a refractive

microlens of 135  $\mu\text{m}$  diameter and a focal length of 370  $\mu\text{m}$ . Aspheric lens profiles are obtained by varying the etch parameters during the reactive ion etching transfer.

### Aperture arrays

Apertures, stops, pupils or baffles are essential parts of every optical system. They are used to improve the image contrast by blocking vignetting or aberrant rays, and reducing straylight. For lens array systems, aperture arrays are realized by thin film deposition, photolithography and consequent etch or lift-off steps.

### Packaging and assembling of micro-optics

Packaging and alignment of miniaturized optical systems or modules is a rather difficult task. Every micro-optical component has to be aligned according to 3 lateral and 3 rotational degrees of freedom. For micro-optics, standard "classical" mounting is not practical. One packaging approach is to reduce these 6 degrees of freedom by using a stack of planar optical layers as shown in Figure 4.[24] The optical elements are fabricated on one- or both sides of a planar wafer equipped with alignment marks. A stack of different optical layers is mechanically aligned in a mask- or bond-aligner. Glass plates, metal wires, optical fibers or plastic sheets are used as spacers. The different optical layers are bond by using UV-curing epoxy, fusion bonding or thick-film solder glass bonding. An accuracy of  $\pm 1 \mu\text{m}$  lateral and  $\pm 5 \mu\text{m}$  vertical was achieved using a MA6/BA6 from Suss KG Munich. Self-alignment techniques use lenses, balls or wires and grooves or rings as counterparts.

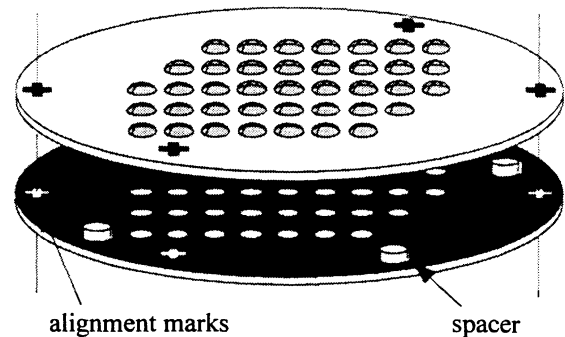


Figure 4. Alignment marks and spacers are used for the mounting of a micro-optical array imaging system.

## 4. DESIGN STRATEGY FOR IMAGE CAPTURING MICROCAMERAS

In most applications humans have to inspect the resulting microcamera images. Therefore, the image fineness must be sufficient for humans to identify the observed object or scene. In addition, microcameras should have (optional) wide-angle observation ability. Neither single-lens systems nor fly or bee eye systems are well suited to fulfill these demands. The restriction to planar lens- and receptor arrays makes it even more difficult to design artificial eye systems. Based on the prior considerations, we get the following design strategy for image capturing microcameras:

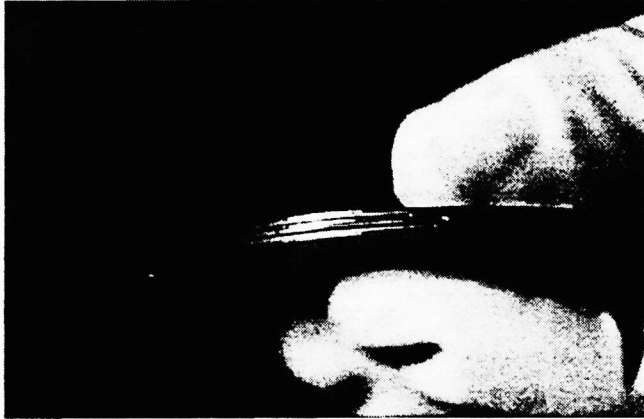
- 1) The resolution of the optical system should not be finer than the receptor mosaic. A detector resolution of 3 to 5  $\mu\text{m}$  requires a  $f/6$  to  $f/10$  optical system respectively.
- 2) For a  $f/6$  system, the image distance is about seven times the aperture diameter. The lens diameter is calculated from the desired overall thickness of the microcamera system.
- 3) If the number of image pixels (or angular field) of one single image channel is not sufficient for the envisaged application, multiple channels should be used in parallel. A superposition of the partial images is performed either within the signal-processing unit (neural superposition) or by spatial superposition in the image plane. For spatial superposition, erect imaging is required.[25, 26] Only next neighbor images should superimpose to limit off-axis aberrations.
- 4) The resolution of the imaging system should be higher in the center and lower at the rim to provide both, telephoto and wide-angle characteristics.

If we look for examples in nature, we find that the proposed camera design has very much in common with the eyes of jumping spiders. Jumping spiders do not have compound eyes. Their resolution would be too poor to identify targets worth to jump on. To have single-lens eyes as vertebrates, spiders are too small. The spider uses a cluster of single-lens eyes, each pair tailored for a different task. Spiders see almost as sharp as we do and have a good idea what is going on in its surroundings. The natural design concept to distribute the imaging task to a cluster of different single-lens eyes, is as well the most promising approach for very small microcamera systems. Examples for arrays of micro-camera systems are shown in the following.

## 5. MICRO-OPTICAL IMAGING SYSTEMS

### Array imaging systems for large object fields

Figure 5 shows a scheme of a multiple-lens imaging system for 1:1 imaging of extended planar objects ( $\beta = +1$ ). The micro-optical system consists of a stack of three microlens arrays forming an array of microcameras. Two lens arrays are used for imaging. The intermediate array serves as a field lens. A demagnification of the intermediate image is introduced to avoid crosstalk between adjacent camera channels. The imaging system takes advantage of the following optical design concepts:



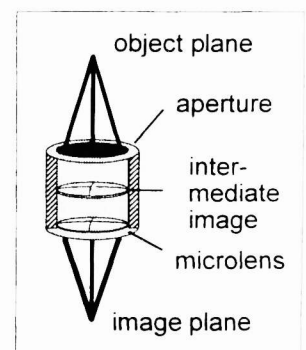
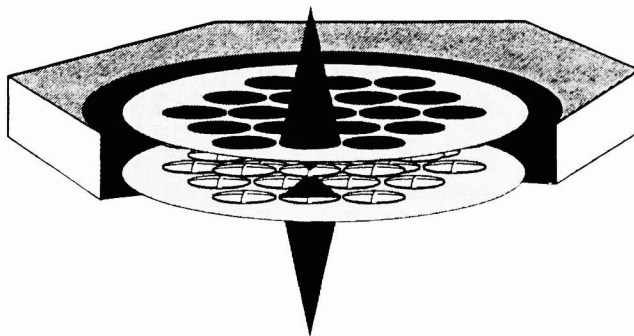
**Figure 5. Micro-optical array imaging system for 1:1 imaging of an extended planar object as used for microlens projection lithography (MPL).**

**Symmetry.** For symmetrical optical systems the antisymmetrical wavefront aberrations (coma, distortion, and lateral color) are minimized. However, symmetrical aberrations (spherical aberration) are doubled and have to be compensated in another way.

**Aspherical surfaces.** Spherical aberration is minimized by using aspherical lenses. A plano-convex hyperboloid has no spherical aberration for the paraxial region.

**Telecentry.** For telecentric systems a small defocusing by changing the distance of the object or the observing plane does not affect the image size.

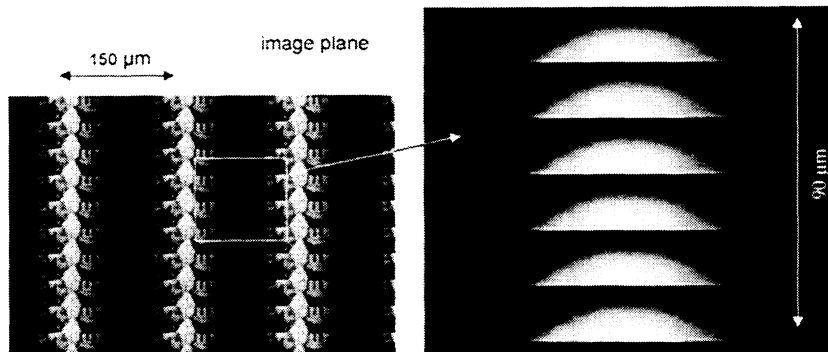
**Array optics.** Each point in the object plane is simultaneously transported by different microcameras. The partial images overlap coincidentally to provide a single, complete image of the object (superposition). The image quality is invariable for the whole image field. The image size is only limited by the size of the microlens array system. No matter how large the system is, it will provide uniform image quality (no field curvature, distortion, or contrast degradation at the edge of the image).



**Figure 6. Micro-optical array imaging system for 1:1 imaging of an extended planar object as used for microlens projection lithography (MPL) and microcamera arrays.**

Typical applications for such an optical system are microlens projection lithography (MPL), photocopy machines and scanners. Microlens projection lithography is a lithographic technique where a photomask is projected by using an array of microcameras.[26, 27] Figure 5 shows a photograph of a 6-layer imaging system for MPL consisting of a stack of 3 lens and 3 aperture arrays. The planar arrays were aligned in a SUSS-maskaligner<sup>1</sup> with a precision better than  $2 \mu\text{m}$ . A resolution of 3 to  $5 \mu\text{m}$  and a depth of focus of more than  $50 \mu\text{m}$  is achieved. Figure 6 shows the scheme of the micro-optical array imaging systems as used for microlens projection lithography. Figure 7 shows the image plane of the system shown in Figure 5 for a 25:1 demagnification of a photographic slide of the Neuchâtel castle. The image size is about  $90 \mu\text{m}$  diameter, the resolution on the order of  $3 \mu\text{m}$  (diffraction limited, Strehl 0.83).

i) MA6/BA6 maskaligner from Karl Suss KG FRG.

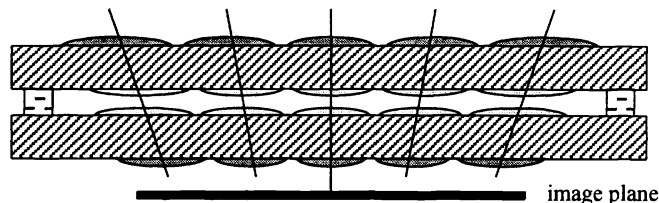


**Figure 7.** Image plane of the array imaging system shown in Figure 4 for a 25x demagnification. Each camera forms a separate image of the object. Diffraction limited resolution of 3 μm (Strehl ratio 0.83) is observed.

spatial superposition in the image plane or by neural superposition within the data processing system. A more sophisticated array imaging system is a so-called Gabor superlens. A Gabor superlens is an array of afocal telescopes, wherein both lens arrays differ slightly in the lens pitch or period.[29, 30] It is worth to note, that the change of the lens array period is also achieved by a rotation of the lens arrays with respect to each others.[31]

### Moiré effects

If an object consists of a periodic array of identical patterns, an observation by a compound eye or microcamera array might lead to moiré effects in the image pattern. For certain combinations of the object and lens period, the individual images generate a magnified or demagnified image of the object pattern. A periodic object pattern and a lens array imaging systems are referred as a 'moiré magnifier'. [32] This phenomenon frequently appears if microlens arrays are used in conjunction with arrays of light sources, photo-detectors, liquid crystals displays, CCD-chips, etc..



**Figure 8.** Cluster of microcameras consisting of two optical layers. Each microcamera observes a different angular field.

## 6. CONCLUSION

Nature has developed a diversity of optical lens designs that enable animals to recognize their mates, enemies and food. This immense pool of system designs is a very exciting resource for optical designers who search for new ideas how to miniaturize imaging systems. Unfortunately, the toolbox of a micro-optical designer is still quite incomplete. Today's micro-optics is closely tied to ideas, concepts and microfabrication technologies developed in semiconductor industry. This includes e.g. a general restriction to flat building parts (planar lens and receptor arrays), a matrix-oriented patterning (Cartesian coordinates) and pure bulk materials (very limited possibility of index modification).

Fundamental problems for small-scale lens systems are diffraction effects and the limited space-bandwidth product, which drastically limit resolution and image fineness for lens systems below 1 mm diameter. The natural optical design concept of compound or fly's eyes is very useful for wide-angle observation and fast movement detection, e.g. a camera system for path finding in a micro-robot. However, compound eyes are intrinsically low-resolution systems and not suited for capturing sharp images. Miniaturized single-lens cameras suffer from the low number of image pixels transmitted. A  $f/6$  system of 0.5 mm aperture provides an image fineness of less than 120 x 120 pixels. This makes it hard for humans to recognized objects or persons. The most promising compromise is a camera "cluster", where different single-lens microcameras are located side-by-side. Each camera observes only a small part of the object field. The partial images are combined by neural superposition in the signal-processing unit or by spatial superposition on the detector chip. The microcameras within the cluster should have a decreasing resolution and an increasing field of view from the center to the rim. The cluster concept is based on the eyes of jumping spiders, which use 4 pairs of different eyes to combine sharp view for a small visual field and wide-angle observation at a moderate resolution.

### Side-looking cameras and Gabor superlenses

A transversal misalignment of one of the lens arrays in a stacked array imaging system as shown in Figure 6 will result in a tilt of the optical axe(s) and will slant the field of view. This effect can be used to scan extended objects or scenes without moving the microcamera.[28] Figure 8 shows a modification of the system shown in Figure 6. A tilt of the optical axes is introduced by changing the lens diameter and pitch. Each camera of the cluster may now observe a different angular field. The image is obtained by

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