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Design of a retinal tracking system for jumping spiders

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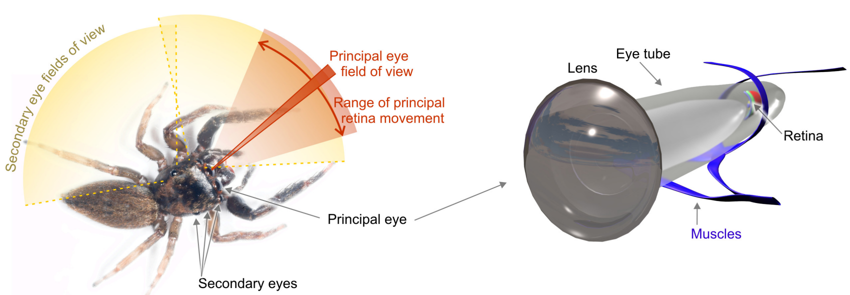
ABSTRACT

We designed an optical system for tracking the retinal movement of a jumping spider as a stimulus is presented to it. The system, using all off-the-shelf optical components except for one custom aspheric plate, consists of three sub-systems that share a common path: a visible stimuli presentation sub-system, a NIR illumination sub-system, and a NIR retinal imaging sub-system. A 25 mm clearance between the last element and the spider ensures a stable positioning of the spider. The stimuli presentation system relays an image from a display to the spider eye, matching the 15 arcmin resolution of the two principal eyes and producing a virtual image at a distance of 255 mm from the spider, with a visual full field of view of 52^o. When viewing a stimulus, the spider moves its retinas, which cover a full field of view of only 0.6^o, and directs them to view different places in the visual field. The retinal imaging system uses a NIR camera to track changes of 0.5^o in the field of view seen by the spider. By tracking retinal movement across images presented to spiders, we will learn how they search for visual cues to identify prey, rivals, and potential mates.

Keywords: jumping spider, retinal imaging

1. INTRODUCTION

The visual system of salticids, spiders in the family *Salticidae* commonly known as jumping spiders, supports some astonishing feats of mammal-like behavior that is unexpected in a tiny spider[1-3]. A salticid's eight eyes can simultaneously view a wide visual field; a modular division of labor between the two large frontal narrow-field principal eyes and the remaining wide-field secondary eyes results in a combined field coverage close to 360°.



(a) (b)

Figure 1. (a) Photograph of a salticid spider indicating principal and secondary eyes and their fields of view. (b) The eye tube of each principal eye is moved by muscles to sample the field of view.

Salticid eye arrangement and one of its principal eyes are shown in Fig 1. The fields of view covered by the corneas of the two principal eyes overlap and combine to approximately 50°. Behind the cornea, a long eye tube extends posteriorly

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into the head of the animal. At the posterior end of each eye tube, a pit acts as a diverging lens and extends the focal length of the eye[2]. The retina is small, with fewer than 1500 receptors (in contrast to 200 million in the human eye) arranged in four layers. The rearmost layer has a region of especially tight receptor spacing, the fovea, with maximum spatial resolution. The fovea is minute, with only about 200 receptors. Thus, if a principal eye were immovable, it would be able to view only a very small field of view with maximum precision (0.8°-5°, depending on species)[2], and the key to understanding how the principal eyes work is in the context of active vision. Three pairs of muscles rotate and move the eye tubes horizontally and vertically by as much as 50° as the spider explores its surroundings[1]. As the tube moves, it samples the much larger image projected by the corneal lens as if aiming a spotlight at different parts of the image. By presenting a stimulus to the spider and imaging its retina, it will be possible to study how salticids respond to different visual cues and gain a better understanding of the sensory processes underpinning their mating and predatory behavior.

2. OPTICAL DESIGN

An optical system was designed with the lens design software CODE V (Synopsys) to present a stimulus to the spider and image its retina. The design consists of three sub-systems that share a common path, as shown in Fig. 2. All elements are off-the-shelf components, with the exception of one custom aspheric element.

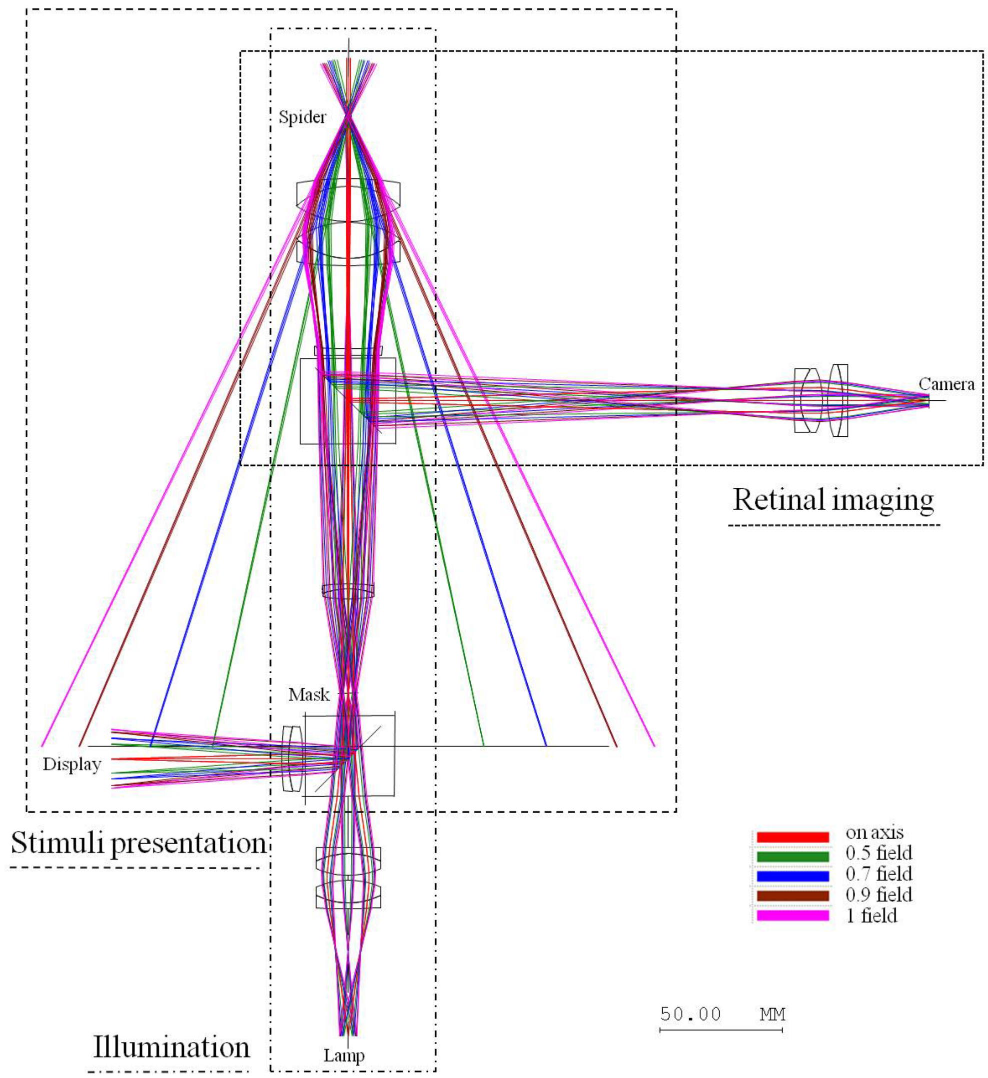

Figure 2. Optical system for retinal tracking of jumping spiders, consisting of a visible stimuli presentation sub-system, a NIR illumination sub-system and a NIR retinal imaging sub-system.

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The stimuli presentation sub-system uses visible wavelengths, while the illumination and retinal imaging sub-systems use a NIR wavelength range (700-800 nm). The common path between the three sub-systems includes a custom aspheric plate, while a mask is placed in the stimuli presentation and illumination sub-systems to block reflections from the spider's face.

2.1 Stimuli presentation sub-system

The stimuli presentation sub-system is designed to relay the stimulus from a display to the spider and produce a virtual image that appears to be at a distance of 250 mm, or greater, from the spider. The requirements and design specifications of this sub-system are summarized in Table 1.

Table 1. Design specifications for the stimuli presentation system.

Parameter	Specification	Design
Spider Eye Space		
Wavelength range	Photopic	Photopic
Spider pupils eyebox diameter (mm)	1.60	1.57
Full field of view (degree)	>44 up to 60	52
Presented image distance (mm)	>250	255
Clearance between spider and closest lens (mm)	>25	25.5
MTF at 0.92 lp/mm at spider by design	>0.3	>0.3
Focal length (mm)	TBD	-29.3
Display Space		
Display pixel size (μm)	To accommodate full FOV and focal length	< 65
Stimulus display size (mm, full diagonal)	TBD	23.8
Display dimensions (mm, full diagonal)	To accommodate full image diagonal	> 24
Mechanical		
Mask outer diameter (mm)	~4.9	4.22
Mask thickness (mm)	0.13-0.17	0.15
Space before mask (mm)	>6.9	8.4
Space after mask (mm)	>28.4	38.5

The spider's maximum spatial resolution of 15 arcmin results in a resolution element of size 1.09 mm (i.e. equivalent to two pixel spacing) at a distance of 250 mm, corresponding to a spatial frequency of 0.92 lp/mm at the spider (line pairs per mm). This specification corresponds to 8.2 lp/mm at the display. The required modulation transfer function (MTF) at 0.92 lp/mm is 0.3 or greater in spider eye space. The principal eyes of the salticid have a combined width of 1.6 mm. A custom mask holder is required to be included in the design, with a space of at least 6.9 mm before and 28.4 mm after the mask. The width of the mask by design is 4.22 mm, resulting in an effective 2.6 magnification between the conjugate pupil planes of the spider eyes and the mask.

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A main constraint of the design was to use to the extent possible off-the-shelf components to minimize cost. The resulting system has five elements (four of which are off-the-shelf doublets and one is a custom aspheric plate) and the two beamsplitters needed to combine the stimuli presentation sub-system with the retinal imaging and illumination sub-systems. The aspheric element is instrumental in minimizing pupil aberrations between the plane of the mask and the plane of the spider's eye. The stimulus is presented to the spider as a virtual image at a distance of 255 mm from the spider and it has a field of view of 52°. The MTF of this sub-system is shown in Fig. 4.

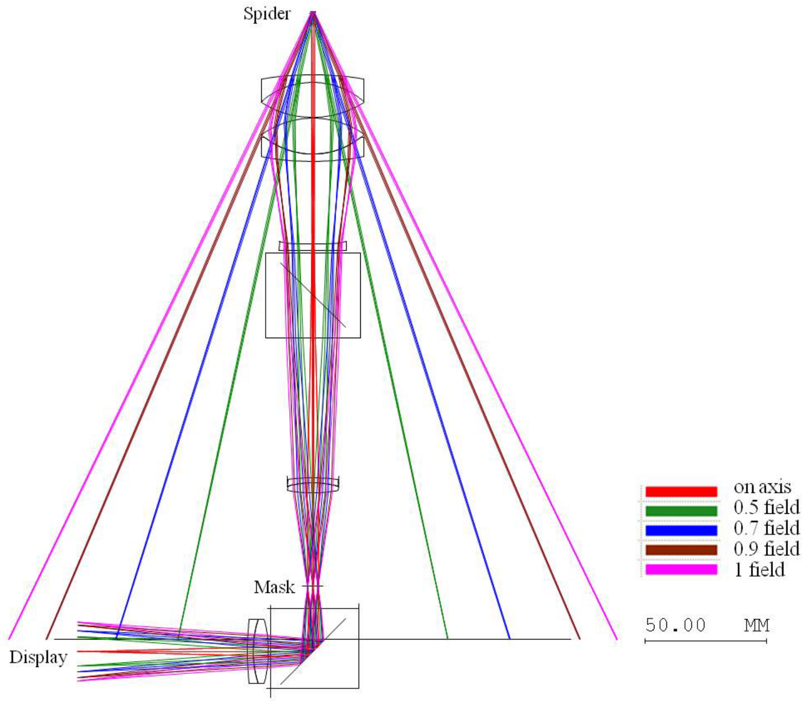

Figure 3. Stimuli presentation sub-system.

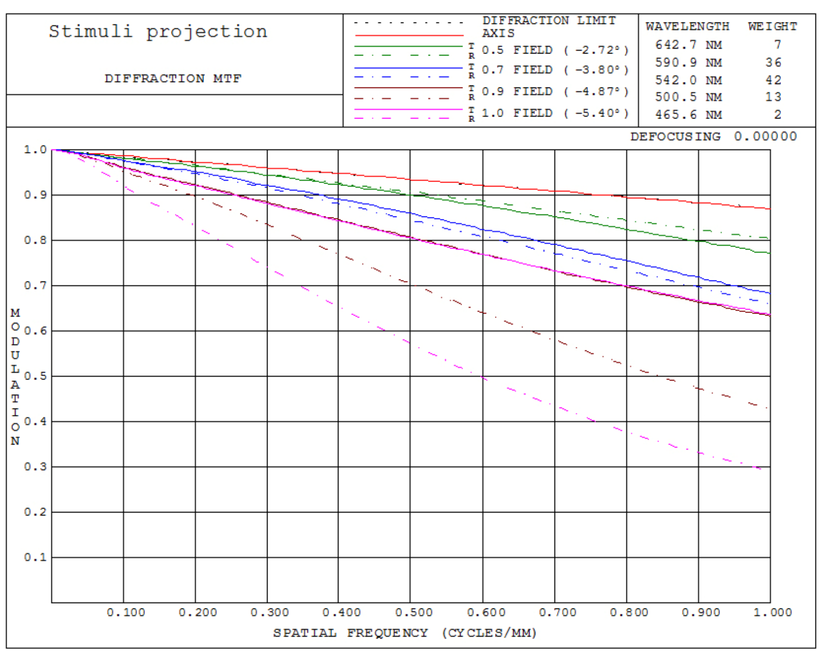

Figure 4. MTF of the stimuli presentation sub-system in spider-eye space.

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An image simulation of how a stimulus would appear to the spider is shown in Fig. 5.

Figure 5. Image simulation of how a stimulus (shown on left) projected with the stimuli presentation sub-system would appear to the spider. Some distortion (i.e 20% at the corner) is evident at the edge of the field, but the image quality is adequate for a successful stimulus presentation for this application.

2.2 Illumination sub-system

The illumination sub-system uses NIR light (700-800 nm) to illuminate the spider's retina. NIR light is used because the spiders are believed to see only wavelengths up to 700 nm. The illumination sub-system is shown in Fig. 6.

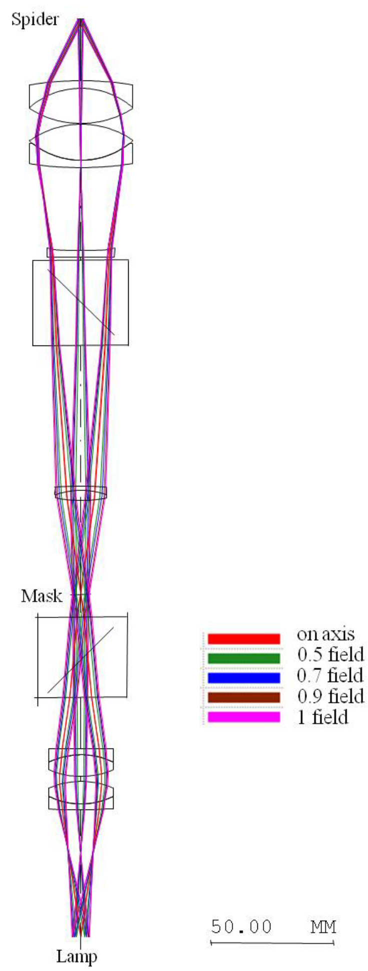

Figure 6. Illumination sub-system.

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A pair of doublets is used in the illumination sub-system to image a fiber illuminator source to the mask plane, which is conjugate to the spider eyes. The fiber source is sized to overfill the mask and spider planes with an appropriate iris, in order to fully illuminate the retina.

2.3 Retinal imaging sub-system

The retinal imaging sub-system images the spider's retina using NIR light (700-800 nm). The design specifications of this sub-system are summarized in Table 2.

Table 2. Design specifications for the retinal imaging system.

Parameter	Design
Wavelength range (nm)	700-800
Spider pupil diameter (mm)	1.6
Focal length (mm)	5.9
Full field of view (degree)	52
Clearance between spider and closest lens (mm)	>25
MTF at 20 lp/mm at display by design	>0.2
Paraxial image diameter (mm)	5.94
Image distortion at corner (barrel) (%)	16.5

To derive the MTF specification, we calculate the image size variation produced by a $d\theta = 0.5^o$ change in the field of view seen by the spider as $r = f \tan(d\theta/2)$, where $f = 5.9$ mm is the focal length of the retinal imaging sub-system. The element of resolution is $2r = 51.5$ μm, which corresponds to a spatial frequency of 20 lp/mm. The retinal imaging sub-system is shown in Fig. 7.

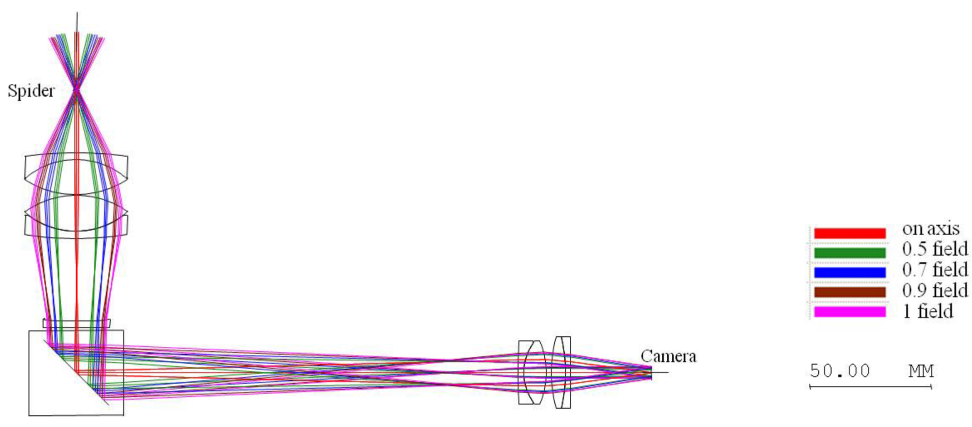

Figure 7. Retinal imaging sub-system.

The MTF of the retinal imaging sub-system is shown in Fig. 8.

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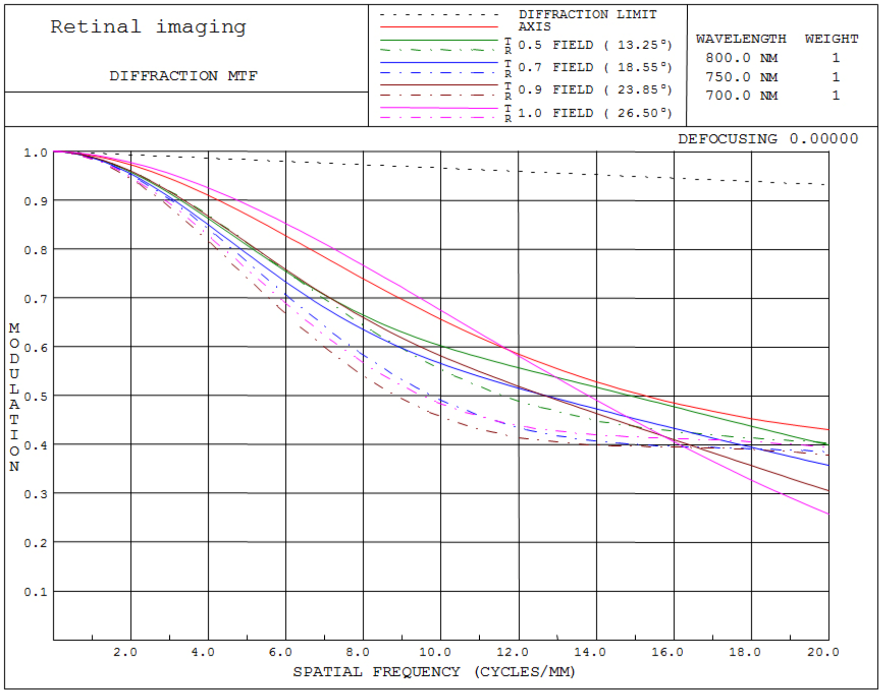

Figure 8. MTF of the retinal imaging sub-system.

A removable lens was included in the system to provide guidance on the correct positioning of the spider and mask within the system. When the additional lens is flipped into the system, instead of imaging the retina, the system images the eyes of the spider to verify that the mask and the spider eyes are aligned. The system with the additional lens is shown in Fig. 9.

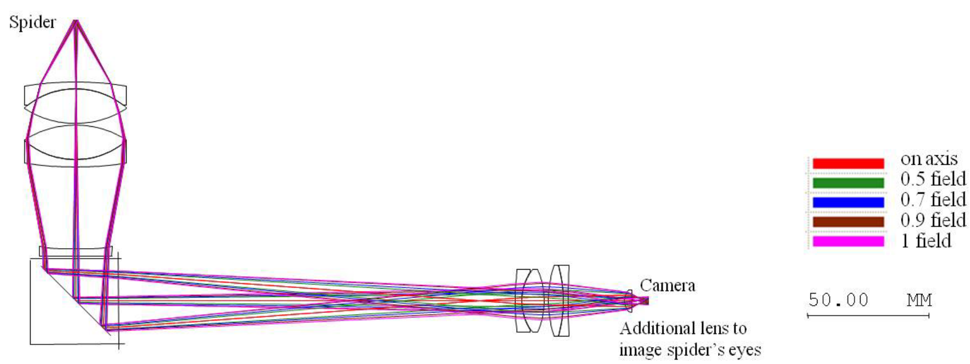

Figure 9. Retinal imaging sub-system with additional lens to image spider eye and verify alignment.

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3. CONCLUSION

An optical system was designed to present a stimulus to a jumping spider, and illuminate and image its retina, as it reacts to the stimulus. The design uses nine optical elements and two beamsplitters, all of which are off-the-shelf components with the exception of one aspheric plate. An additional off-the-shelf element can be toggled in the system to image the spider eyes and verify the correct alignment of the system. The stimuli presentation sub-system relays the stimulus from a display to the spider eye as a virtual image at a distance of 255 mm from the spider, matching the 15 arcmin resolution of the two principal eyes, with a visual full field of view of 52^o. The retinal imaging sub-system was designed to track changes of 0.5^o in the field of view seen by the spider.

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