Design of a high-resolution stereo zoom microscope

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Abstract. A stepped magnification stereo microscope and a stereo zoom microscope are designed and fabricated using a modular concept. A resolution of 4 μm is achieved with both instruments. The design details are discussed.

Subject terms: microscopes; resolution; zoom design.

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1 Introduction

With the help of a microscope, we can view objects that are too small to see with an unaided eye. A simple positive lens constitutes a simple microscope, which has limitations in achieving high magnifications with the required field of view. The compound microscope, which greatly exceeds the power of the simple microscope, consists of an objective lens and an eye lens. With a stereoscopic microscope we can observe the three-dimensionality of the object. In stereo microscopes (Fig. 1), to achieve stereoscopic vision the left and right eyes of the observer must see the object from slightly different angles.

In watch factories and electronic industries, variable magnification stereo microscopes are required in the assembly and testing of the minute components. The resolution requirement is 4 μm. The instrument must be comfortable to use and there should not be any aberrations introduced by the system. In this system, we need both a large field of view and high magnification. First we view the total object in low-magnification and high-field-of-view mode. Then we select a small part of the object and see it in high-magnification and low-field-of-view mode with high resolution.

We have designed two systems to vary magnification. The first is a stepped magnification stereo microscope and second is a stereo zoom microscope, where the magnification can be continuously varied.

2 Stepped Magnification Stereo Microscope

It is well known that when a telephoto lens having one positive element and one negative element with air space between the two components equal to the difference in the values of their focal lengths is attached to a photographic lens, the overall focal length of the optical system will increase without shifting the original image plane of the photographic lens. Using this principle we designed a stepped magnification stereo microscope (Fig. 2). This microscope consists of the main objective, the magnichanger, the binocular objective, and the eye piece.

2.1 *Main Objective*

To interpret the spatial variations in the object, the objective must be capable of accepting a wider angular beam. It transmits this beam to the two parallel primary image-forming systems. The focal plane of this main objective is the object plane for observation. The focal length of the objective is 100 mm and the working distance is also 100 mm. Since the object size is 40 mm, the objective must be corrected for this linear field of view. In this stereo microscope, the two eyes of the observer see through the objective. Hence the diameter of the objective is taken as 60 mm. Thus, to correct this system we designed a four-lens objective. We used GENII optical design software (Genesee Computer Centre, Inc., Rochester, New York) to design the system. It uses a damped least-squares optimization program to correct the aberrations. The radii, thicknesses, and glasses are given as variables. We have reduced spherical aberration, coma, color, curvature, and distortion in the system.

2.2 *Magnichanger*

The magnichanger is an assembly of different Galilean afocal telescopes with different magnifications in a rotatable barrel. The barrel is introduced in the microscope between the main objective and binocular objective. By rotating the drum vertically one of the Galilean telescopes comes into the optical path of the system. The presence of the Galilean telescope in the system optical path changes the system magnification. By rotating the drum we can invert the Galilean system before the binocular objective, thereby changing the system magnification to another value. We used two Galilean systems. The first Galilean system consists of two doublets with focal lengths of 110 and -68 mm. In the second Galilean system, the positive doublet focal length is

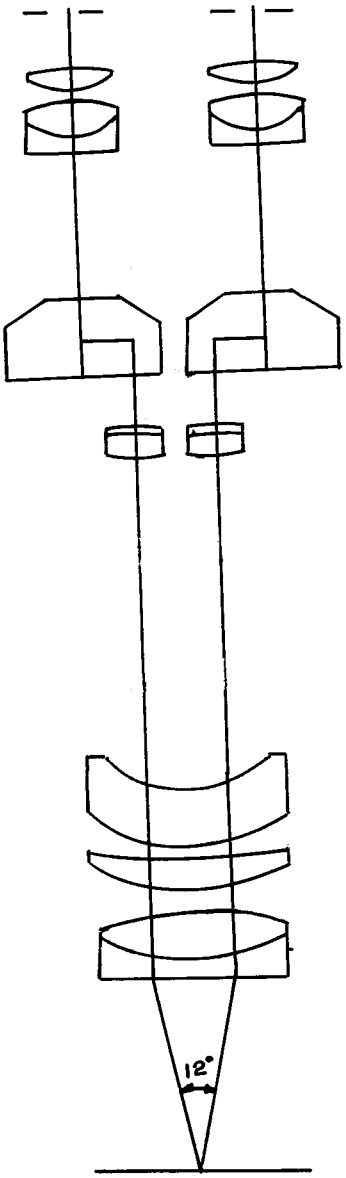

Fig. 1 Stereo microscope.

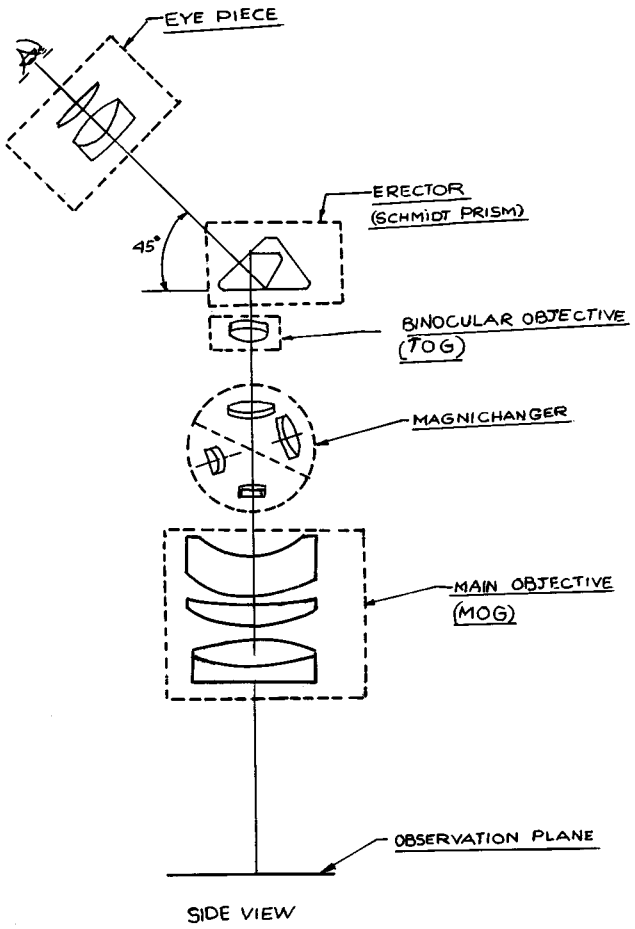

Fig. 2 Stepped magnification stereo microscope.

57 mm and negative doublet focal length is −18 mm. These two doublets are separated by some distance so that the back focus of the positive doublet coincides with the negative doublet back focus. With these two Galilean systems we get four magnifications, and the fifth magnification is obtained when there is no Galilean system between the main objective and the binocular objective. The Galilean systems are separately optimized with GENII using the afocal option. In this afocal option, we use a 50-mm imaginary ideal lens (which will not introduce any aberrations) after the Galilean system to focus the image beam to a distance of 50 mm. Thus, with this option, the Galilean system becomes a focusing system. In these systems, spherical aberration, coma, color, and field curvature are corrected.

2.3 *Binocular Objective*

An $f/10$, 160-mm-focal-length doublet with a 7-deg field of view (FOV) is designed with a Schmidt prism. The Schmidt prism is used to invert and revert the image and also to deviate line of sight by 45 deg. Spherical aberration, coma, color, and curvature are reduced in this system.

2.4 *Eyepiece*

A 10× eyepiece is designed with an FOV of 44 deg and with the exit pupil located at a distance of 25 mm from the first surface of the eyepiece. With 250 mm of least distance of distinct vision, the focal length of eyepiece becomes 25 mm (i.e., 250/10). The exit pupil diameter is taken as 3 mm. This is a three-lens system with a doublet and a singlet. Distortion, spherical aberration, coma, astigmatism, and color are corrected in the eyepiece.

2.5 *Total System Calculations*

The stereo microscope has one main objective, two Galilean systems in parallel, and a binocular telescope. The two arms of the binoculars will have a symmetrical set of components. The two binocular objectives have diameters of 15 mm each. The center-to-center distance between the binocular objectives is 22 mm. The arms are rotated for interocular adjustment. There is a parallel beam between the main objective and the Galilean system. Also, a parallel beam exists between the Galilean system and the binocular objective. The erected image is formed at the eyepiece image plane. We reduced the aberrations of the total system

by tracing rays from the eyepoint to the object plane. Starting from the eyepoint, the rays pass through the eyepiece, Schmidt prism, binocular objective, Galilean system, and the main objective to the object plane. We fixed the focal lengths of the eyepiece, binocular objective, and the Galilean doublets and the main objective using the ''ZOOM COMPONENT'' option. With this option in the GENII program, we can fix the focal lengths of the components while optimizing the total system. Different magnifications will have different FOVs and exit pupil diameters. Let the binocular objective focal length be TOG, and the main objective focal length is MOG. When there is no magnichanger between the binocular objective and the main objective the instrument magnification is given by

$$\frac{\mathrm{TOG}}{\mathrm{MOG}}\times \mathrm{EPM}=\frac{160}{100}\times 10=16\times, \tag{1}$$

where EPM is the eyepiece magnification. Now let us take the Galilean system with doublets of focal lengths of +57 and −18 mm. With the positive doublet of the Galilean system near the binocular objective, the combined focal length of the Galilean and the binocular objectives becomes

$$\frac{18}{57}\times 160=50.52=\mathrm{GOG},$$

and the total instrument magnification becomes

$$\frac{\mathrm{GOG}}{\mathrm{MOG}}\times \mathrm{EPM}=\frac{50.52}{100}\times 10=5\times. \tag{2}$$

Now if we reverse the afocal Galilean system so that the negative doublet is near the binocular objective, the GOG becomes

$$\frac{57}{18}\times 160=506.7,$$

and the total instrument magnification becomes

$$\frac{\mathrm{GOG}}{\mathrm{MOG}}\times \mathrm{EPM}=\frac{506.7}{100}\times 10=50\times. \tag{3}$$

With the second Galilean system with doublet focal lengths of 110 and −68 mm, we get instrument magnifications of 10× and 25×. The field stop diameter at the eyepiece image plane is 20 mm. The objective size seen by the microscope is

$$\frac{\mathrm{MOG}}{\mathrm{TOG}}\times 20, \tag{4}$$

when there is no Galilean system in the optical path. With the Galilean system, the object size is

$$\frac{\mathrm{MOG}}{\mathrm{GOG}}\times 20. \tag{5}$$

The instrument resolution and depth of focus for each magnification are calculated by the following equations:

Table 1 Characteristics of the stepped magnification stereo microscope.

Magnification	FOV (mm)	Exit Pupil Diameter (mm)	Resolution (μm)	Depth of Focus (μm)
5×	40	2.4	14	±11
10×	20	2.4	7	±6.3
16×	12	2.4	4	±3.6
25×	8	1.8	3.6	±3.0
50×	4	1.0	3.5	±3.0

$$\text{Airy radius}=0.61\times\frac{\text{nominal wavelength}}{n'\sin U'}, \tag{6}$$

$$\text{depth of focus}=\pm\frac{\text{nominal wavelength}}{2n'\sin U'}, \tag{7}$$

where n' is the refractive index in image space (assumed to be 1) and U' is the exit angle of the exact marginal ray.

In this stepped magnification stereo microscope, we achieved magnifications of 5, 10, 16, 25, and 50× with object plane diameters of 40, 20, 12, 8, and 4 mm, respectively, as shown in Table 1. The modulation transfer function (MTF) graphs at different magnifications are shown in Fig. 3.

2.6 *Mechanical Design*

The design of the binocular instrument is challenging since comfortable viewing with two eyes presents difficulties that do not occur with monocular instruments. The coordinated motion of the two eyes must not be disturbed. The interpupillary distance adjustment from 50 to 80 mm must be provided. Magnification difference to the two eyes should not exceed 0.5%. The amount of light to the two eyes should be balanced. The optical axes of the telescope should be set such that the eyes do not become strained while attempting to fuse the images.

The magnichanger is a drum containing the lenses as per the optical layout maintaining the air gaps given in the optical design. As it is very difficult to maintain the air gaps exactly between each set of telescope lenses; one lens position of each telescope is fixed and the other lens is given the facility to move in either direction to maintain the air gaps. To retain the drum at any magnification position, a normal leaf spring lock with a positioning stainless steel lock screw is designed so that the drum is retained in the position at which the locating end of lock screw is seated in the slot of the leaf spring (Fig. 4). The position of the magnichanger can be changed from the locked position by exerting more torque than that exerted by the leaf spring on the lock screw. Six such screws are used for five magnification positions. To facilitate convenient rotation of the drum, two slotted knobs are fixed on each side of the drum. An engraved sleeve indicating the magnification value is also fixed to the drum (Fig. 5).

The two Schmidt prisms are housed in two prism housings, which are linked through a gearing system to have a relative rotation of the prisms with respect to each other.

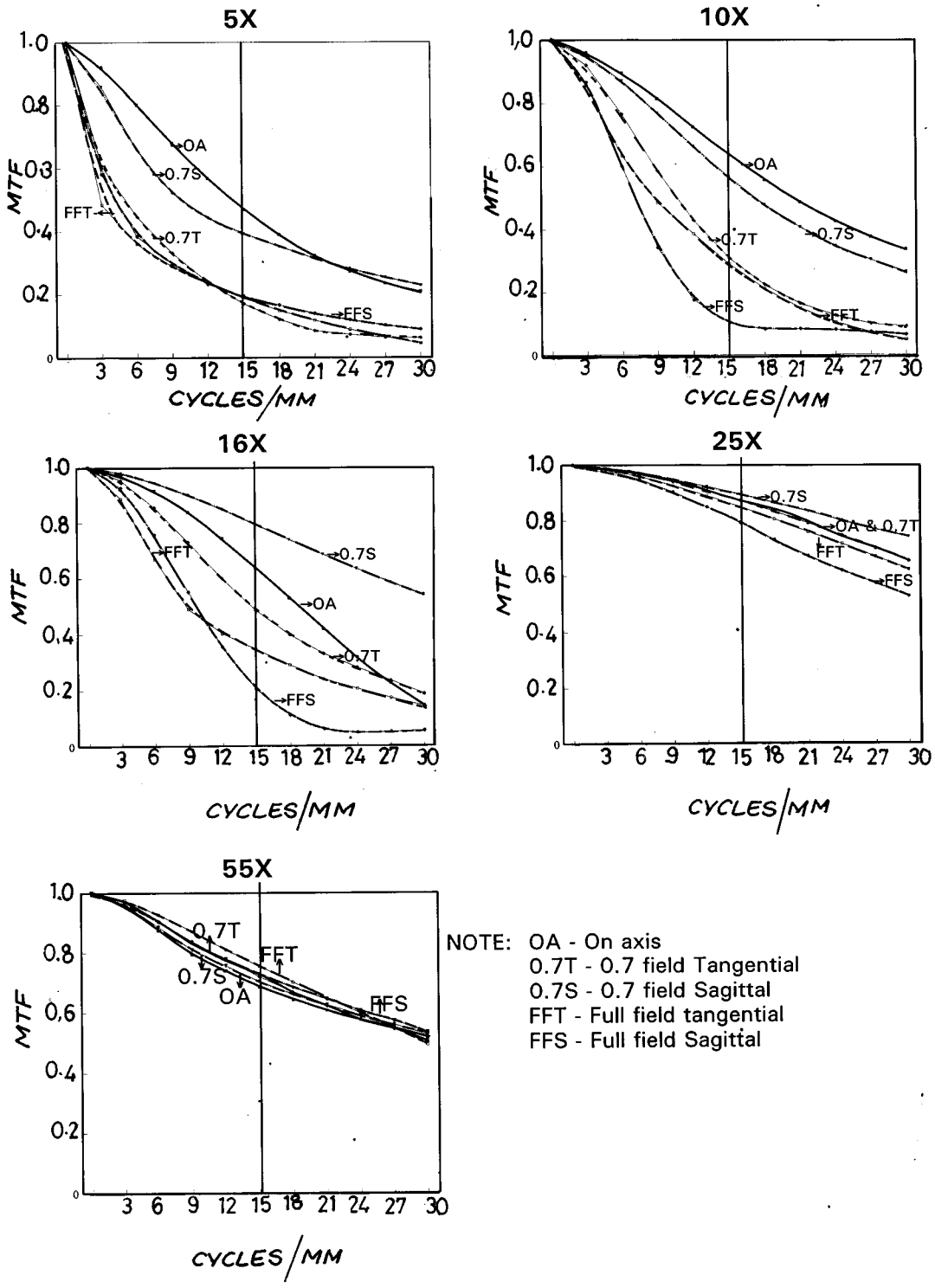

Fig. 3 MTF performance of the stepped magnification stereo microscope.

This arrangement is designed to have variable interpupillary distances as different users will have different interpupillary distances. The eyepieces are fixed to the prism housing, maintaining the air gaps as given in the optical layout (Fig. 6). For the purpose of field centering and collimation of the binocular head, a provision is made to move the eyepiece in any direction to an extent of 0.75 mm and lock it in the same position to the prism housing. The eyepiece is designed to provide a dioptric range of $+5$ to -5 D to cater to the eye powers of different users. This is achieved by moving the eyepiece from its diaphragm using four-start threading. The dioptric range is indicated on the sleeve attached to the eyepiece.

The main objective lenses are housed in the objective housing (Fig. 7), maintaining the air gaps, as given in the optical layout. The objective is fixed to the intermediate

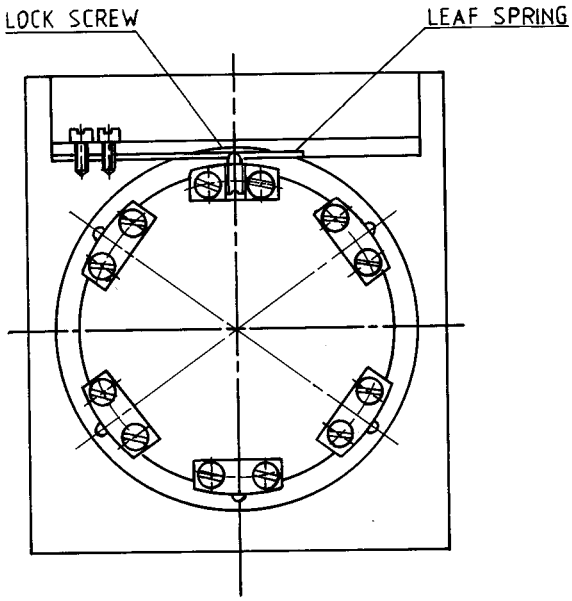

Fig. 4 Magnichanger drum locking mechanism.

ring, which is screwed to the magnichanger housing. Over the intermediate ring, special mountings are designed and mounted to clamp the external illuminators so that they can be conveniently positioned around the viewing axis.

The whole microscope head is connected to a focusing system through a bracket (Fig. 8). A rack and pinion system is designed to have a fine focusing facility. The rack is mounted on a fixed bracket and the pinion is mounted on the connecting bracket attached to the microscope so that when the pinion is rotated, it moves on the fixed rack along with which, the whole instrument head moves up and down. A clamping system using a leaf spring is designed to exert pressure by means of grub screws on the pinion so that intimate contact is always maintained between rack and pinion. The clamping system is designed to take care of wear and tear of the rack over the period of usage. The total system is designed to move the instrument up and down, guiding on the pillar to have coarse motion for initial coarse focusing of the instrument to the object. Once the instrument is roughly focused to the object being examined, it

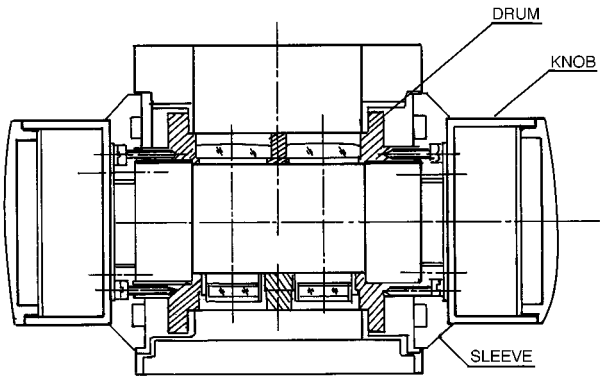

Fig. 5 Magnichanger assembly.

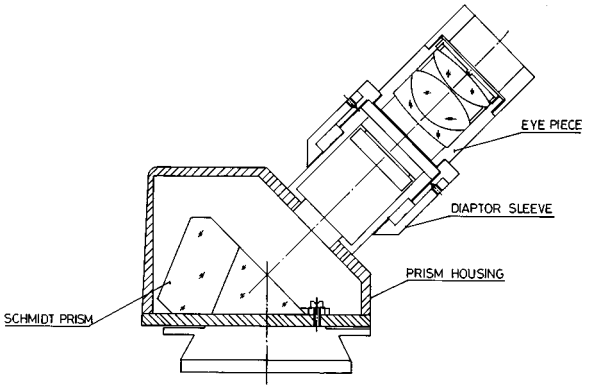

Fig. 6 Prism housing and eyepiece assembly.

can be finely focused using the rack and pinion system. The vertical guide pillar is rigidly fixed to the platform using a simple clamping principle (nut and bolt). On the platform, a dias is designed and fixed to hold the objects being examined.

3 Stereo Zoom Microscope

In the place of an afocal Galilean system between the main objective and the binocular objective, we introduce an afocal zoom system (Fig. 9) of zoom ratio 1:6 to continuously vary the magnification of the microscope from 7 to 42×. We designed a symmetrical Donders[1] type of afocal system in which the magnifying power is varied over a range of 6 to 1. The magnification of the negative component varies from $\sqrt{6}$ to $1/\sqrt{6}$ or from 2.449 to 0.408. The focal length of negative component is found by

$$\text{focal length} = \frac{\text{shift of lens}}{\text{change of magnification}}. \tag{8}$$

The focal lengths of three lenses are

$$fa = fc = 60 \text{ mm}, \quad fb = -15 \text{ mm}.$$

The shift of middle lens is 30 mm. The lens locations are calculated and are given in Table 2. The lens movements are calculated as follows. With $fa = 60$ mm, with a parallel beam input, the image will be formed at the focus of lens

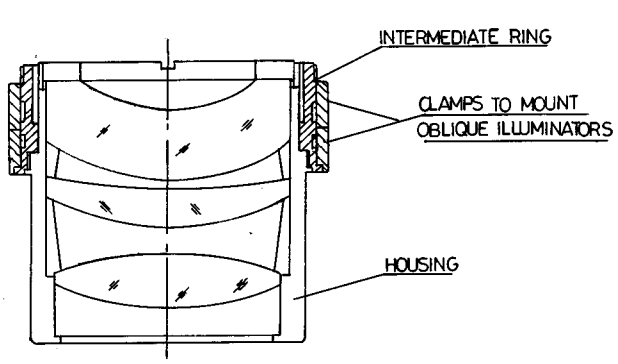

Fig. 7 Main objective assembly.

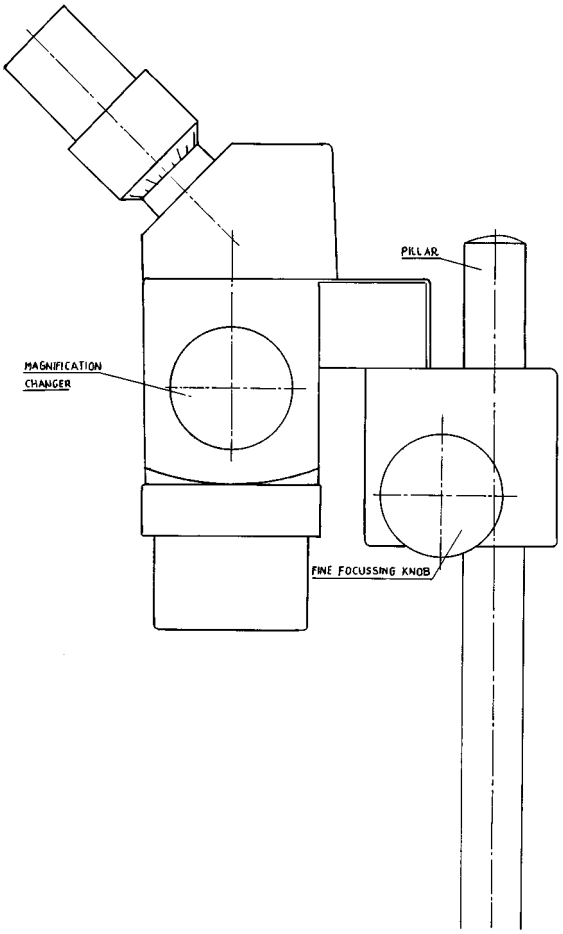

Fig. 8 Microscope focusing system.

A, i.e, at a distance of 60 mm. The image point of lens A will act as the object point for lens B. Now if the negative lens B is kept at a distance of 39 mm from lens A, the object distance for lens B will be 21 mm. With the formula

$$\frac{1}{v}-\frac{1}{u}=\frac{1}{f}, \tag{9}$$

and with $fb=-15$ mm, the image distance v will become -53 mm. The image point of the second lens will act as an object point for the third lens. Now the third lens focal length $fc=60$ mm. If the object is at the focus of this lens, its image will be formed at infinity. That is, we will again get a parallel beam from the lens system. Thus, to get the parallel beam output, the third lens C should be kept at a distance of 7 mm from lens B. Magnification of the system will be image distance/object distance of lens B. In this afocal $+$, $-$, $+$ zoom system, the middle negative lens moves linearly, and third lens moves in a cam.

3.1 *Total System*

The zoom system is designed with the binocular objective keeping the parallel beam between the two.

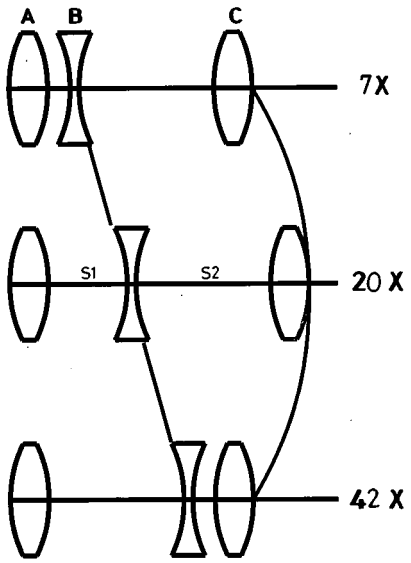

Fig. 9 Afocal zoom system.

if mag of zoom$\times$Bino OG EFL$=$GOG,

main OG EFL$=$MOG,

magnification of the microscope

$$=\frac{\text{GOG}}{\text{MOG}}\times\text{mag. of eyepiece.} \tag{10}$$

The value of the GOG changes with the zoom movement, thereby changing the magnification of the microscope. After the first-order layout is designed, we optimized the aberrations of the entire system (Fig. 10) from the eyepoint to the object plane at different zoom positions simultaneously, keeping the focal lengths of the different units constant. There is parallel beam between the main objective and zoom lens A. A parallel beam also exists between zoom lens C and the binocular objective. Keeping the modular concept in mind, we did not change the design of the eyepiece, the binocular objective, and the main objective in the zoom microscope. These are common modules for both microscopes. This by just replacing the magnichanger assembly with the zoom module, we can convert the stepped magnification stereo microscope into a stereo zoom microscope. This became possible due to the afocality of the Galilean system and the zoom system. To decrease the spherical aberration, coma, and color aberrations we increased the number of lenses in zoom components $A$and

Table 2 Zoom lens locations.

Data of Middle Component			Thin Lens Separation	
Magnification	Object Distance	Image Distance	Front	Rear
2.523	21	−53	39	7
1.869	23	−43	37	17
0.6	40	−24	20	36
0.405	52	−21	8	39

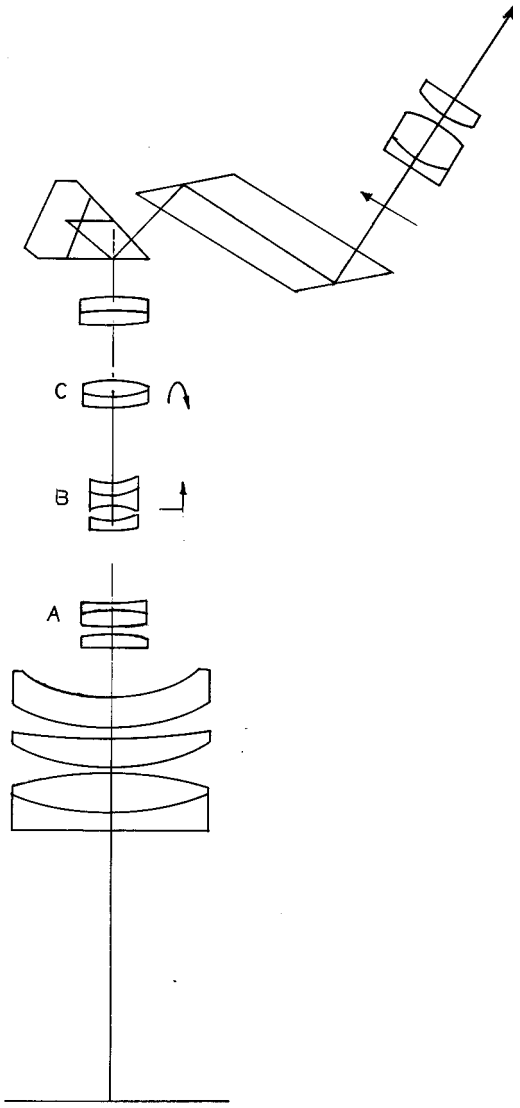

Fig. 10 Stereo zoom microscope.

B. The FOVs obtained for the stereo zoom microscope at different magnifications are shown in Table 3. At lower magnifications, the depth of focus is large compared to the higher magnifications, and at higher magnifications we get better resolution.

In this zoom system, the first component *A* from the main objective is fixed. The second component *B* moves linearly, and the top component *C* moves in a nonlinear fashion. The total system consists of a main objective, two parallel afocal zoom systems, and a binocular telescope. Both arms of the zoom systems have symmetrical components and both are kept in a single drum. The drum is rotated about the vertical axis to move the components. The zoom lenses must be positioned to maintain the air gaps at different magnifications. To achieve this, a cylindrical cam barrel is designed with nonlinear helical grooves on the periphery. The lens mounts and the cam barrel are connected through guide pins located in the helical grooves so that by rotating the drum, the required movement is achieved. In this microscope, the total rotation of the cylinder is 160 deg. Thus, with only a half rotation of the cylinder, the magnification is changed from minimum to maximum without any defocusing of the image. To locate the cam points, we developed a program that gives the equivalent focal length (EFL) and the back focal length (BFL) of the system at different zoom positions. We have given zoom plus binocular objective system as input to this program. If the distance between lenses *A* and *B* is $S1$and between lenses *B* and *C* is $S2$, the program calculates the value of $S2$ for different values of $S1$ to get the same BFL. To convert the axial movement of the lenses into the angular rotation of the cylinder, we give the initial and final $S1$ values and the total angle of rotation of the cylinder to the program. The program gives the values of the angle of rotation of the cam cylinder, $S1$, $S2$, EFL, BFL, and the first and second pin positions from the same edge of the cylinder in small steps of angular increment. With this program, we can determine the powers of the zoom components for the required cam by using the alter radius option. The powers of the zoom components are slightly adjusted to get a smooth cam curve. The total system is again optimized with these powers. The final stereo zoom microscope MTF graphs are shown in Fig. 11. If we compare the MTF graphs of both microscopes, we see that both provide excellent performance at 25×. At lower magnifications, both show equivalent performance. The zoom cam profile is shown in Fig. 12. In this cam, the first pin is connected to zoom component *B* and the second pin is connected to zoom component *C*. Zoom component *A* is fixed. At 7×, zoom component *B* is very close to zoom component *A*. Zoom component *B* moves up toward the binocular objective to increase the magnification. From 7×, the *C* component starts moving up toward the binocular objective, and after 16× it starts moving down toward the main objective. From the cam profile, we see that the second pin comes very close to the first pin after 42×, which means that after 42× zoom components *B* and *C* will touch.

Table 3 Characteristics of the zoom microscope.

Magnification	Field of View FOV	Exit Pupil Diameter (mm)	Resolution (μm)	Depth of Focus (μm)
7×	28.0	2.0	12	±10
25×	8.0	2.0	3.8	±3
42×	5.0	1.2	3.5	±3

3.2 *Accessories*

Since this is a modular design, by replacing the 100-mm-focal-length objective with a 150-mm-focal-length objective we get a 5 to 30× magnification variation with a 40 to 7 mm FOV. Again with the 100-mm-focal-length objective, if we replace the 10× eyepiece with a 15× eyepiece in the zoom microscope, we can change the magnification variation from 10 to 60×. Since we have a parallel beam between the zoom and the binocular objective, we can intro-

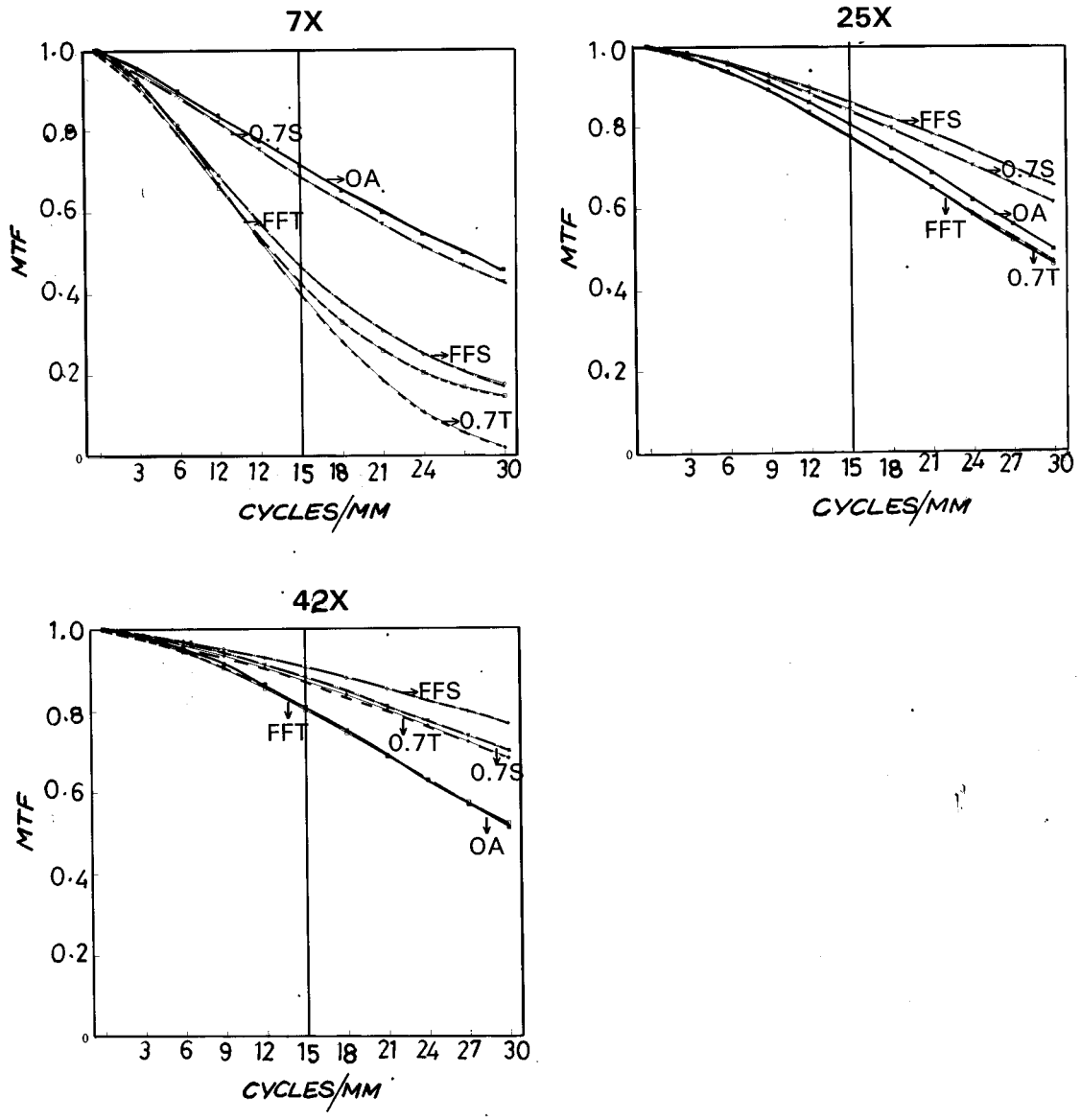

Fig. 11 Zoom microscope MTF performance.

duce a beamsplitter to incorporate a camera attachment or a closed–circuit television (CCTV) attachment and also on one side, an observation tube.

There is great demand for fiber optic coaxial illuminators in ophthalmic and surgical stereo zoom microscopes. From a halogen lamp with an ellipsoidal mirror the light rays are focused onto one end of the fiber bundle. The light passes through the flexible fiber cable and emerges from the second end. The second end is kept at the center of the two parallel zoom systems. The rays from the fibers form a 40-deg cone, and to focus the beam to the 40-mm object plane, we placed a condenser lens near the fiber edge. A 7-mm-diam aperture stop is between the fiber and the condenser lens. A triplet objective is placed so that the back focus of the triplet is at the aperture stop. Thus, the rays from the fiber pass through the aperture stop, condenser lens, triplet, and the main objective and focus at the object plane of the zoom microscope. The aperture stop is imaged by the triplet at infinity and that is imaged by the main objective at the object plane. To have bright illumination, vignetting of the rays was minimized.

4 Conclusion

The stepped magnification stereo microscope and stereo zoom microscope were manufactured and they both give

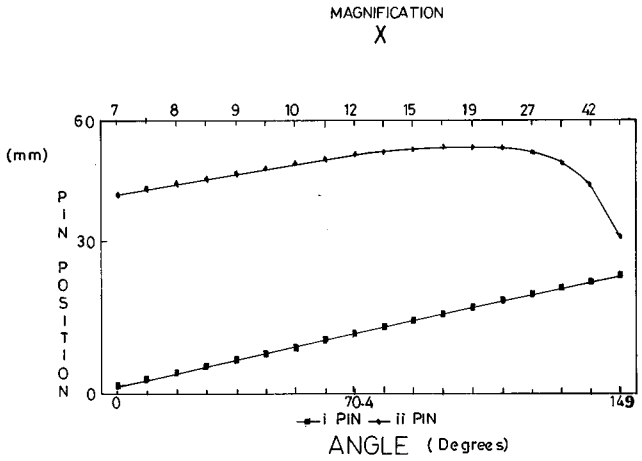

Fig. 12 Cam profile.

excellent performance. Although at lower magnifications, the MTF is not very good because of depth of focus, the image does not deteriorate in the actual system. At lower magnifications, the field curvature is not observed. There is no color and no distortion in the image. At 25×, a resolution of 4 μm is obtained. The image is also extremely sharp. Since the exit pupil distance is 25 mm and the exit pupil diameter is 2.5 mm, and since the systems do not introduce any aberrations, the observer will not become fatigued, even after long use of these microscopes.

Acknowledgment

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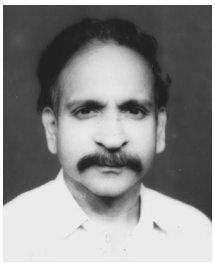

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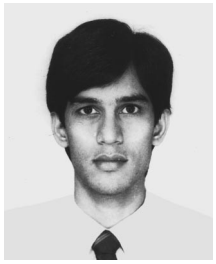

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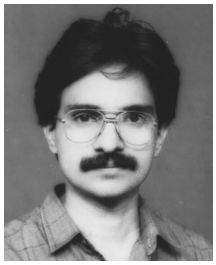

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G. R. C. Reddy received his PhD in applied optics in 1980 from the Regional Engineering College, Kakatiya University, Warangal, India, where he is currently a professor of physics. He is an investigator on a number of projects sanctioned by various industries in the areas of Fourier optics, holography, and lens design. His current research interests are optical imaging, laser speckle, and optical information processing. He is the author of 45 research journal papers.