Proc. of SPIE Vol. 0590, Infrared Technology and Applications, ed. L.R. Baker, A. Masson (Jan 1985) Copyright SPIE

THE DEVELOPMENT OF A COMPACT I.R. ZOOM TELESCOPE

Philip Parr-Burman
Allan Gardam

Pilkington P.E. Ltd, Glascoed Road, St. Asaph, Clwyd, LL17 OLL, U.K.

Abstract

Zoom telescopes offer the system designer great flexibility and give the user an uninterrupted change from wide angle to narrow angle fields of view. This has been recognised by the selection of a zoom telescope for the U.K. MoD's Phoenix RPV programme. The mechanical design of such a telescope is described. Those aspects relating to volume production are considered in more depth.

Introduction

Until relatively recently thermal imaging system designers have had two classes of I.R. telescope available to them. These are single field of view lenses and dual field of view systems incorporating a field change mechanism. Dual field systems give the ability to fulfil two separate requirements with a single telescope. Commonly this is a low magnification for surveillance and a high magnification for target acquisition. This flexibility does have an increase in cost in what is already an expensive telescope namely, the expense due primarily to the high cost of the optical materials used. System demands for such flexibility are now so great, however, that this cost is usually felt acceptable. The major drawback with dual field of view systems is the loss of picture that occurs during switching. This can cause the following problems:-

a) Momentary confusion of orientation to the viewer, possibly resulting in loss of the target, particularly with an automatic tracking system.

b) If boresight is not held during switching from wide to narrow the risk of losing the target is increased.

Continuous zoom telescopes solve these problems by allowing smooth transition from surveillance to target acquisition. Moreover, development work at PPE has established that such telescopes can be mechanically simpler than dual FOV systems. These advantages have led to the selection of a PPE zoom telescope for the thermal sensor in the UK MoD's remotely piloted vehicle programme.

The initial development of a zoom telescope, codenamed "ZULU" was dealt with in a paper presented at a previous SPIE conference[1] This paper today describes developments of the telescope that have made it suitable for volume production. It describes the basis of the PPE proprietary design and goes on to discuss the particular problems of zoom telescopes that have been addressed. The solutions to these problems are described. In addition, the influence of the important parameter, athermalisation, is also discussed. Its effect on the design is highlighted.

The arrangement of the PPE proprietary zoom lens Design

In the optical design of I.R. zoom lenses, PPE have opted for the mechanically compensated type. This involves moving the two or more zoom groups independently of each other (figure 1). The alternative arrangement is the optically compensated type in which a fixed distance is maintained between the zoom groups as they move through the zoom range (figure 2).

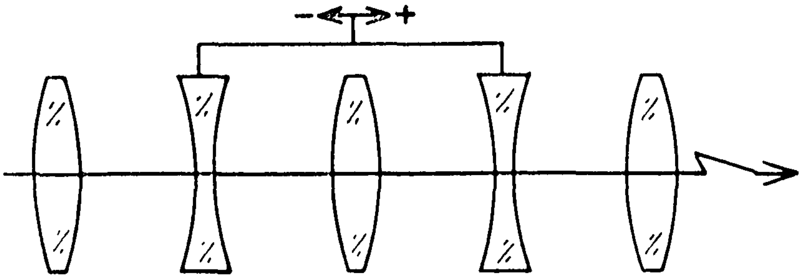

Figure 1. Optically Compensated Zoom

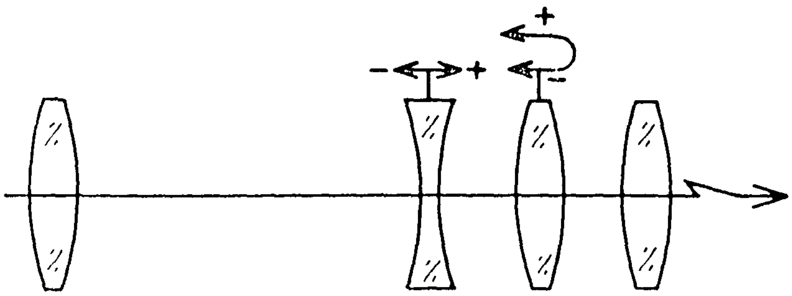

Figure 2. Mechanically Compensated Zoom

On the basis of these simple definitions it would appear that the mechanically compensated configuration presents a less satisfactory solution from the point of view of mechanical design. This would be true for a conventional lens design but in the case of ultra compact I.R. zoom lens designs, the optically compensated option leads to very significant tolerancing problems[2].

The basic mechanical design is shown in figure 3. It has two main functions, namely zooming, as discussed above, and focussing. These are carried out separately as follows.

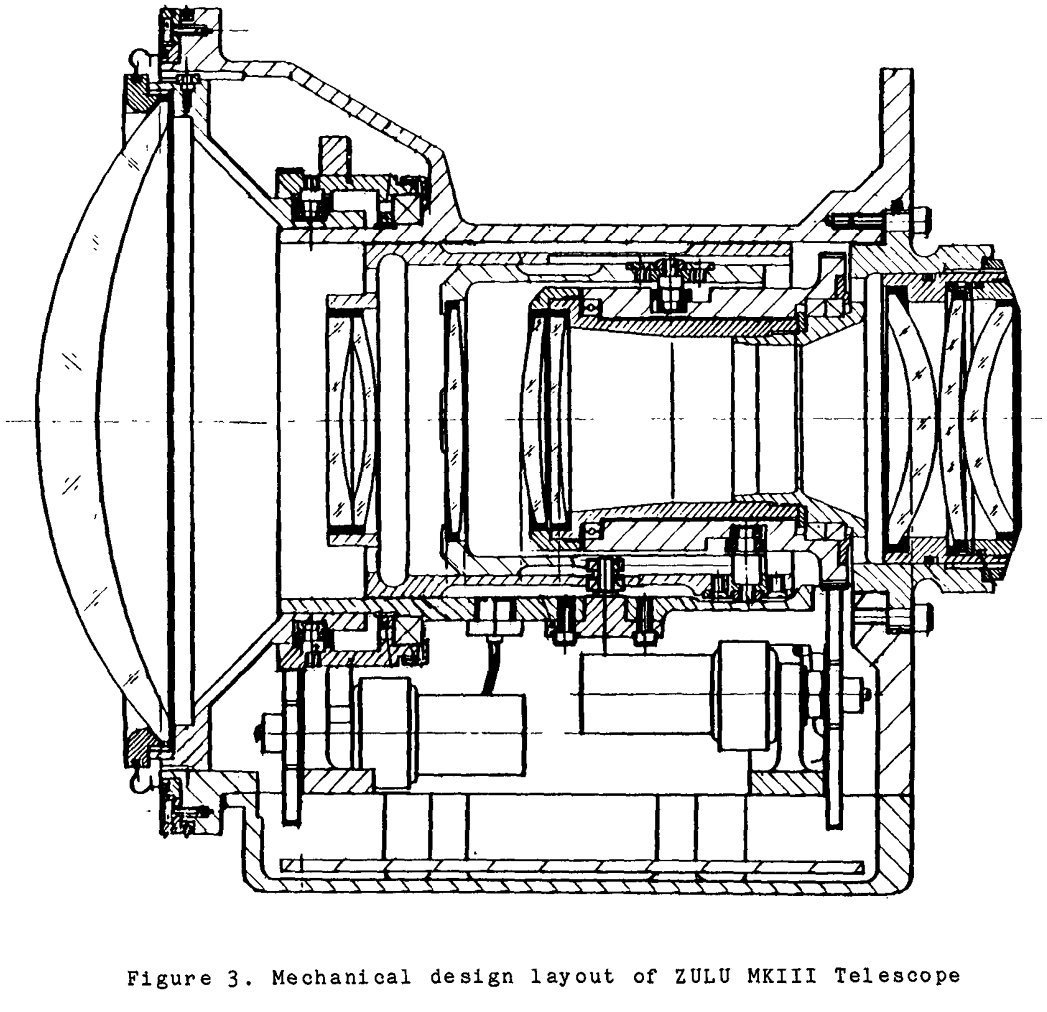

Figure 3. Mechanical design layout of ZULU MKIII Telescope

The two zoom groups are contained in concentric cylinders which slide inside the main housing and are keyed together to prevent relative rotation. Control of the zoom motion is achieved by means of cam followers located in a double scroll cam. The concentric cylinder arrangement is inherently self centring. This means that no optical alignment is necessary and that tracking and boresight errors are minimised.

Focusing is achieved by moving the front element. Since it is in front of the zoom groups this method has the advantage of ensuring that focusing is independent of zoom position. This more than offsets the disadvantages associated with sealing of the telescope and of moving a relatively large mass. (This movement provides no great disadvantage since its extent is limited compared to the zoom). The front lens is also controlled to compensate for the focus shift produced by temperature changes i.e. athermalisation. The element is potted into a lens cell using a setting polyurethane compound. This cell slides inside the housing and has three helical slots machined onto it. Cam followers mounted in a rotating ring are located in these slots such that rotation of the ring causes the lens to move along the axis of the telescope.

Motive power for the focus and zoom mechanisms is provided by D.C. servo motors and gearheads. These are controlled by remote position servo control circuits contained within the body of the telescope.

This design embodies several developments that have made the telescope suitable for volume production. These developments are now discussed in more detail.

Aspects of design relating to production

With respect to the PPE zoom lens design, there are two particular areas of technical difficulty. These are:-

1. Control of centring errors
2. Control of air gaps between the zoom elements

1. Centring errors

The zoom lens configuration chosen by PPE has a number of important advantages in that it is self centring, requires no alignment and is easy to assemble.There is however, a difficulty concerning the build up of tolerances between cylinders, lens cells and lenses in this area of the design. The task must be to minimise the build up of tolerances without sacrificing the inherent advantages of a cylindrical design.

Analysis shows that the performance parameter that is affected most by decentration of lens elements is the boresight error. This is important for target acquisition roles where a graticule is involved and where interchangeability of telescopes is important.

Tolerances are thus analysed with a view to achieving two main results.

1. Meeting the system requirement with regard to boresight error.

2. To minimise unit cost, the productionised zoom telescope design must be such as to require no special optical alignment of individual lens elements and no selection of components on assembly.

To analyse the build up of centring errors the telescope is considered to consist of five separate lens groups each of which can be decentred from the reference plane (taken to be the telescope housing). The amount of decentration is dependent on both the number and type of interfaces between the group and the housing. Taking the No. 4 lens (figure 3) as an example the decentration is the sum of the errors due to:-

1. Potting of the lens.

2. The necessary clearance between the inner and outer cylinders.

3. The concentricity of the bore in the outer cylinder with respect to the outside diameter of the outer cylinder.

4. The clearance between the outer cylinder and the telescope housing.

The total boresight error of the telescope is then the sum of the contributions due to each group.

It is obviously unrealistic to add the maximum errors arithmetically to arrive at a total. The true situation is that the size of the error produced by each interface is a random variable. Over a production run of telescopes the boresight errors will vary according to a probability density function which can be computed. This will indicate the proportion of telescopes that will have less than any chosen boresight error.

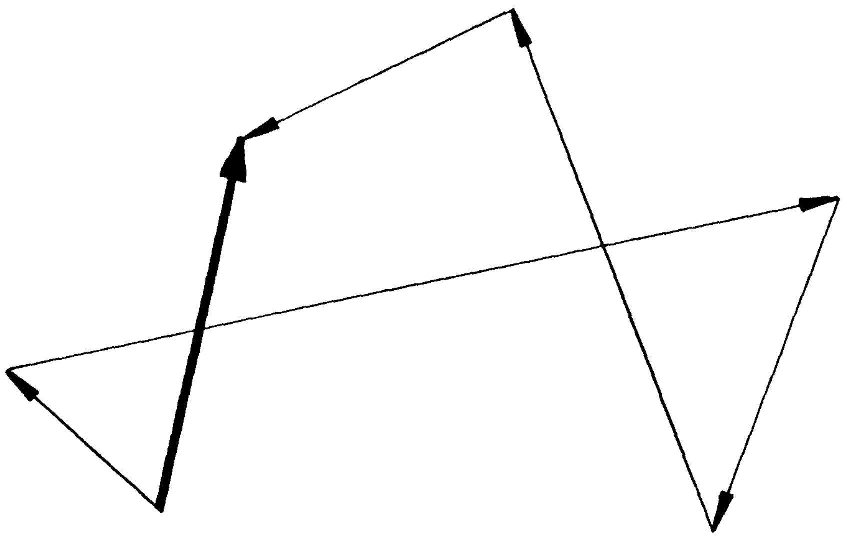

Figure 4. 2 Dimensional Random Walk

To compute the probability density function a realistic model is that of the two dimensional random walk (figure 4). The boresight error produced by each of the five lens groups is represented by a vector which varies randomly in both magnitude and direction. The total error for the telescope is the vector sum of this process. However, the random variation of the vector itself follows some probability density function. To arrive at this it is necessary to look at the manufacturing variation in the components. Taking the No. 4 lens as an example again, the error produced by each of the four interfaces is assumed to vary within its tolerance band in a normal or gaussian manner. By applying the "random walk" method on this basis a large number of times the probability density function for the No. 4 lens is arrived at. The result is a distribution skewed to the left (figure 5).

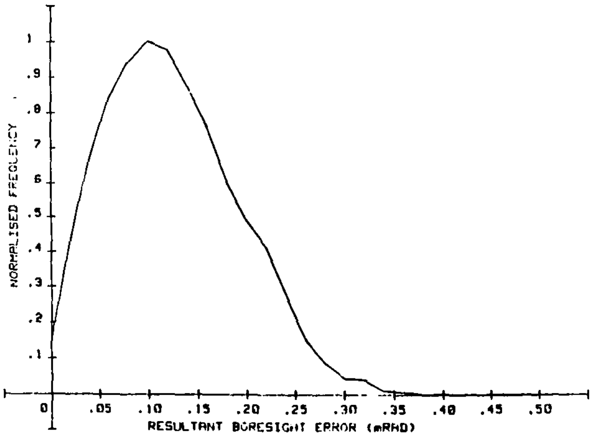

Figure 5. Probability density function
for No.4 lens boresight error

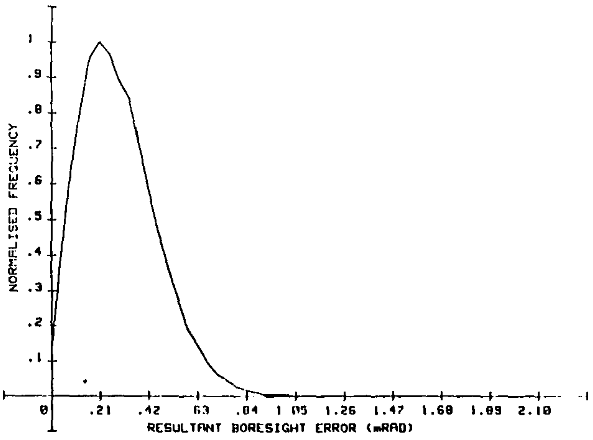

Figure 6. Probability density function
for telescope boresight error

This is repeated for all five lens groups to find the manner in which the errors produced by each group vary. The random walk is then performed again to add the errors of all five groups and find the total boresight error distribution for the telescope. This is found to be skewed even further to the left (figure 6). From this, it can be calculated that 99% of the telescopes manufactured will have a boresight error less than 40% of the theoretical maximum. Clearly 1% of the telescopes produced will require rework, but this is a small cost in relation to the savings made. Tolerances on components can be relaxed from that suggested by a simple analysis and this has obvious benefits in terms of production costs. In the case of the ZULU telescope it has meant that matching of cylinders is not required to achieve a telescope which has both low friction in the zoom mechanism and meets the specification.

2. CONTROL OF ZOOM AIR GAPS

With respect to the zoom air gap, there are two separate areas of concern. These are concerned firstly with the form of the cam and secondly with the cam width.

The form of the cam governs the air gaps at any intermediate magnification. It is an optical requirement that this form is held to within 25 microns. Because of the smooth cam profiles which result from the optical design and the relatively short axial movements of the zoom elements, this is in practice easily achievable.

The major problem is that of backlash in the cam track. The conventional arrangement is a roller in a parallel sided cam slot (figure 7). There must be some clearance between the roller and the sides of the cam slot or rolling would not be possible. This clearance, however, means that a certain amount of backlash is inevitable as the direction of zoom changes. If this is greater than 5 microns a noticeable defocus would be apparent. In practice, accuracies of this order can only be achieved by "running in" a roller that is slightly larger than the slot until a good fit is obtained. This is an expensive process and therefore not suitable for production quantities.

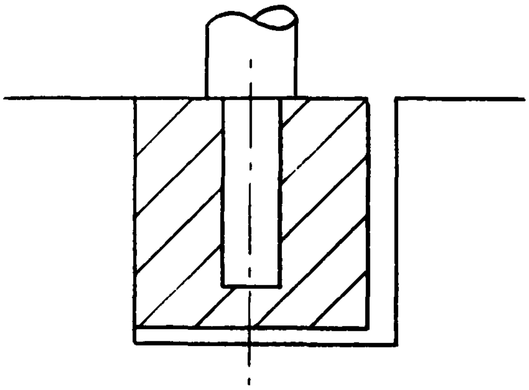

Figure 7. Roller in parallel sided cam track

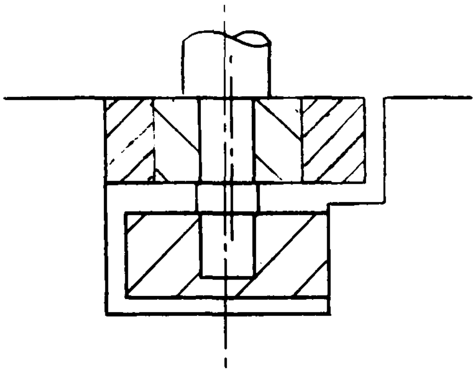

Figure 8. Anti-backlash cam follower

The ideal method is to spring a roller follower onto one side of the cam track. This was previously thought not practicable due to the tight space constraint, however, PPE have now developed a cam follower utilising a rubber roller to provide the spring force[3] (figure 8). With this arrangement it is now necessary to machine only one surface of the cam slot accurately. The rubber roller will absorb any variation in slot width. This leads to a great reduction in the cost of the cam which is one of the more expensive components in the telescope.

Athermalisation

There is one further aspect that has a major impact on the design of the telescope. This is the system requirement to be able to compensate for thermal effects on the telescope.

The refractive index of Germanium, the main optical material used, changes significantly with temperature. This means that, with no adjustment, the image from the telescope is defocussed at elevated or depressed temperatures. To correct for this effect the No. 1 element is moved by the focussing mechanism. To complicate matters, however, the amount of movement required changes as the magnification changes. This can be seen in figure 9 which shows a family of curves each relating to a different temperature. Each curve shows the position of the No. 1 lens against magnification to maintain focus. To avoid the operator having to operate both zoom and focus at the same time it is clearly advantageous to automate the athermalisation function. In ZULU this is provided for by incorporating closed loop servo control on both zoom and focus mechanisms. If magnification and temperature feedbacks are provided it is then only a matter of computing the correct focus position at the temperature/magnification combination.

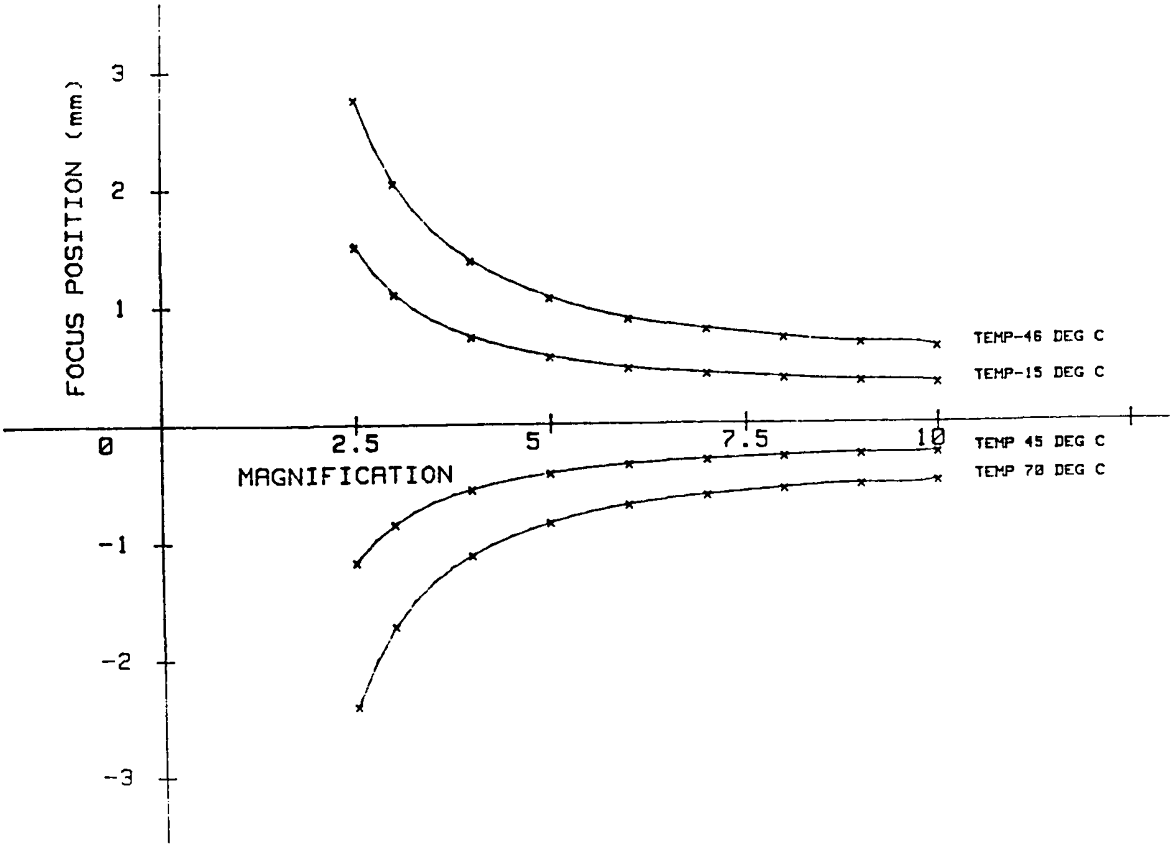

Figure 9. Athermalisation curves for ZULU MKIII

Conclusion

The inherent operational advantages of zoom telescopes has led to the selection of a PPE zoom for the thermal sensor in the UK MoD's RPV programme. Numerous other applications on currently being considered.

The cylindrical approach with zoom motions being achieved by a scroll cam provides a basically simple method of construction. The two major areas of technical difficulty are in the control of centration and the control of air gaps between the zoom elements. By solving these PPE now have a zoom telescope design suitable for volume production by relatively unskilled assembly workers and without the need for special matching of components.

The net result is that the telescope is less complex and is of lower cost than comparable DFOV telescopes.

Acknowledgements

The authors wish to thank the directors of Pilkington P.E. Ltd for their permission to present and publish this paper. They would also like to thank Miss P.D. Wright for typing this manuscript.

References

1. A. Gardam (1984) SPIE Volume 518, Optical Systems Engineering IV.

2. P.J. Rogers, Optics '84, Keele University, September 1984.

3. Patent applied for