Design of thermal imaging continuous-zoom optical system

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Abstract. The report tells about the design of a middle wave infrared continuous-zoom imaging optical system. To capture the image in an «eye-type» infrared optical system a multi-element sensor is used. To increase the contrast of the thermal image the sensor is equipped with a cold aperture. The use of an optical system based on the continuous-zoom lens makes it possible to solve the problems of object detection and identification more effectively but requires taking into account some features of varifocal lenses. The optical system being analyzed in the report includes front zoom objective system and secondary imaging system. The front zoom optical system is composed of four groups and provides the focal length that is continuously changed with a large zoom ratio (15–20X) under the condition of a constant total length of the system. The secondary imaging system is designed for system exit stop and sensor cold stop conjugation. The design technique represents analytical expressions and equations to obtain optical parameters of the front and secondary system components and the motion curves for movable groups.

1. Introduction

Infrared (IR) zoom lenses are used in an eye-type thermal imaging systems to solve the problems of object detection and identification more efficient. When "searching the target" mode is active IR zoom system provides a wide field of view (FOV) in the short effective focal length (EFL). After the target has been detected the EFL is adjusted to long and the system changes to "distinguish the target" mode.

Therefore, infrared zoom systems can be widely used in military and civilian areas, such as target detection, infrared forward-looking, life rescue, vehicle tracking etc. Thus, increasing the zoom ratio is always relevant because it may search targets in a wider field-of-view and distinguish them at farther distances.

The IR imaging optical system is usually composed of two parts: the front and the secondary. The front zoom optical system provides the EFL that is continuously changed from short to long under the condition of a constant total system length. The secondary imaging system is designed for zoom system exit stop and sensor cold stop conjugation [1].

The front middle-wave or long-wave infrared (MWIR/LWIR) optical system is frequently composed as a four group zoom objective lens with fixed, zoom and compensation groups. The first group is usually fixed. Changing the position of the zoom group makes it possible to vary the EFL while moving the compensation group restores the image plane position relatively stable that provides the constant overall length of the optical system [2–6].

The variants of the front objective lens may be classified as 423 and 424 types [7], where the first digit is the total number of groups, the second and third digits are the numbers of movable (zoom and
compensation) groups. Both 423 and 424 types provide high magnification $M = f'_{\Sigma,max}/f'_{\Sigma,min}$, where $f'_{\Sigma,min}$ and $f'_{\Sigma,max}$ correspond to the short and long EFL, respectively.

Various design examples of 423 type zoom lenses are given in references [2–5] and the methods and techniques to design this type of lens can be found in references [7–11]. The examples of 424 type design are found to be not so numerous and are demonstrated in patents [6, 12]. Unfortunately the patent data contain no information about movable groups motion curves, that is why the design technique for this type of zoom lenses may be of high interest. It should be noticed that the method described in [7] may help solving the problem just partially because it doesn't take into account the constancy of the total length of the system. The design technique described below has been specially developed for 424 type constant length zoom optical systems. Thus, section 2 gives the description of the 424 type layout. Section 3 gives analytical expressions and equations to obtain optical parameters of the 424 type zoom optical system groups and to define the motion curves for its movable groups. Section 4 summarizes the expressions to acquire secondary imaging system lens data. Note, that it is possible to use the secondary optical system with both 423 and 424 type front zoom lenses.

2. Optical layout of 424 type constant length zoom system

Zoom objective lens composed according to the 424 type layout and shown in figure 1 consists of groups (1)–(4), where the first and the third groups are fixed, and positions of the second and fourth groups change. Note, that each group may be embodied as a single lens or a number of lenses in future practical design examples.

![Figure 1. Layout of 424 type constant length zoom optical system.](image)

The overall front zoom system length $L$ between the first group and the image plane (5) is to be constant. The objective lens forms an intermediate image (5) that is optically conjugate to a sensitive part of a detector (not shown in figure 1). This conjugation is provided with the secondary optical system so called as relay-type system [1] or erecting system [2] and is described in section 4. The fixed third group splits the layout into two parts which lengths $L_{1-3}$ and $L_{3-5}$ are also constant. The overall length is $L = L_{1-3} + L_{3-5}$. For preliminary design the aperture stop AS is combined with the third group.

3. Design technique for 424 type constant length zoom system

The goal of the design technique presented below is to determine the optical power of the fourth compensation group and its zoom motion curve (cam curve). Optical powers of groups 1–3 are considered to be given and the motion of the second zoom group is to be linear.

Analytical expressions given below are illustrated with figures formed for the following set of initial parameters: zoom ratio (magnification) $M = 22'$. short EFL $f'_{\Sigma,min} = 3.9$ mm and long EFL $f'_{\Sigma,max} = 85.8$ mm, F number F3.5, intermediate image size: $2y' = 2.25$ mm.
3.1. Design of the 424 type zoom optical system front part

The layout of a zoom objective lens front part is shown in figure 2. This part may be considered as a double-element optical system composed of a fixed first group and a movable second group. The optical power is positive for the first group and negative for the second group.

It is first assumed that the motion of the second zoom group and the change of \( d_1 \) distance is linear. It’s evident that the change of \( d_2 \) distance is also linear (see figures 1, 2)

\[
d_2 = L_{1-3} - d_1.
\]  

The image distance \( a_2' \) of the second group has a negative sign in figure 2 according to the sign rule used in Russian school of optical design.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.png}
\caption{Layout of 424 type zoom lens front part.}
\end{figure}

Changing the moving distance \( d_1 \) of the zoom group makes it possible to change its lateral magnification \( \beta_2 = a_2'/a_2 \). Since the object plane \( A_2 \) of the second group is located in the back focal plane \( F_1 \) of the first group, the object distance \( a_2 \) for the second group can be expressed as follows

\[
a_2 = f_1' - d_1,
\]  

where \( f_1' \) is the focal length of the first group. The minimum value \( a_{2,\text{min}} = -f_2 = f_2' \) corresponds to the case when the front part turns into a Galileo-type afocal system and \( f_2, f_2' \) are the object and image space focal lengths of the second group. In this case the second group image distance \( a_2' \) is infinite (\( a_2' = \infty \)) and its lateral magnification \( \beta_2 \) is also infinite (\( \beta_2 = \infty \)). The maximum value \( a_{2,\text{max}} = f_1' \) corresponds to the case when \( d_1 = 0 \). It should be noticed that these boundary values are not practically implemented, so the real \( \Delta a_2 \) range is less.

To extend \( \Delta a_2 \) and \( \Delta \beta_2 \) ranges it is necessary to increase \( f_1' \) values and to reduce \( |f_2'| \). The back focus of the first group may be placed at the stop (AS) center. Therefore, the first group focal length is \( f_1' = L_{1-3} = kL \), where \( k \) coefficient sets some asymmetry in the third group location with a shift to the intermediate image plane (5).

The lateral magnification \( \beta_2 \) of the second group and its image distance \( a_2' \) can be obtained as follows

\[
\beta_2 = \frac{f_2'}{f_2 + a_2} = \frac{f_2}{f_2 + f_1' - a_1},
\]  

\[
a_2' = a_2 \beta_2 = \frac{f_2 a_2}{f_2 + a_2} = \frac{f_2(f_1' - d_1)}{f_2 + f_1' - d_1}.
\]  

The graphs of \( \beta_2 \) and \( a_2' \) as functions of \( d_1 \) distance (zoom group (2) motion) are shown in figure 3.
3.2. Design of the 424 type zoom optical system third group

Groups (3) and (4) may be considered as a secondary part of the 424 type zoom objective lens (see figure 4). The third group is fixed and the motion of the fourth (compensation) group is non-linear. Both groups have positive optical powers.

The graph $a'_2 = f(d_1)$ presented in figure 3 shows that the image distance formed by the front part of the objective lens is not constant and its shift is $\Delta a'_2$. The motion of the compensation group (4) will reduce the objective lens image shift and keep the image plane position relatively stable. Therefore the overall length of the optical system will become constant.

In spite of a fixed position of the third group its object plane distance is not constant changing from $a_{3,\text{max}}$ to $a_{3,\text{min}}$ with a shift $\Delta a_3$ (see figure 5).

The parameters of the third group such as its object distance $a_3$, lateral magnification $\beta_3$ and image distance $a'_3$ can be expressed as follows

$$a_3 = a'_2 - d_2,$$

$$\beta_3 = \frac{f_3}{f_3 + a_3} = \frac{f_3}{f_3 + a'_2 - d_2} = \frac{f_3}{f_3 + f_2(f_3' - d_3) - L_{4-3} + d_4}.$$
\[ a_3' = a_3 \beta_3 = \frac{f_3 a_3}{f_3 + a_3}. \]  

(7)

Figure 5. Layout of 424 type zoom lens third group.

The graphs of the third group lateral magnification \( \beta_3 \) and image distance \( a_3' \) as functions of \( d_1 \) distance are shown in figure 6.

Figure 6. The third group parameters as functions of zoom group motion.

The current range of lateral magnifications \( \Delta \beta_3 = \beta_{3,\text{max}} - \beta_{3,\text{min}} \) for the third group is given by

\[ \Delta \beta_3 = \frac{\Delta a_3' - \beta_{3,\text{min}} \Delta a_3}{a_{3,\text{max}}}. \]  

(8)

3.3. Design of the 424 type zoom optical system fourth group

The fourth group is a compensation group and its motion will compensate the third group image shift \( \Delta a_3' \) and will keep the image plane \( P' \equiv A_{4,\text{max}}' \equiv A_{4,\text{min}}' \) position relatively stable (see figure 7).
The zoom objective lens EFL \( f'_{\Sigma} \) can be written as follows

\[
f'_{\Sigma} = f'_1 \beta_2 \beta_3 \beta_4.
\]

(9)

The lateral magnifications \( \beta_2, \beta_3, \beta_4 \) are the functions of \( d_1 \) distance, and the functions \( \beta_2(d_1), \beta_3(d_1) \) have already been expressed according to equations (3) and (6) respectively. The function \( \beta_4(d_1) \) is defined below.

First, it is important to adjust the values of \( f'_{\Sigma,\min} \) and \( f'_{\Sigma,\max} \) with the motion of the zoom group and \( d_1 \) distance range. In this case the short \( f'_{\Sigma,\min} \) and long \( f'_{\Sigma,\max} \) EFLs correspond to the boundary values \( d_{1,\min} \) and \( d_{1,\max} \) of the zoom group position, respectively.

Then the boundary values \( \beta_{4,\min} \) and \( \beta_{4,\max} \) of the fourth group lateral magnification are as follows

\[
\beta_{4,\min} = \frac{f'_{\Sigma,\min}}{f'_1 \beta_{2,\min} \beta_{3,\min}}
\]

(10)

\[
\beta_{4,\max} = \frac{f'_{\Sigma,\max}}{f'_1 \beta_{2,\max} \beta_{3,\max}}
\]

(11)

After that it is necessary to set the initial position \( d_{3,\min} \) of the correction group 4, that corresponds to the short EFL \( f'_{\Sigma,\min} \)

\[
d_{3,\min} = d_3 (f'_{\Sigma,\min}).
\]

(12)

The initial position may be corrected after the motion curve of the compensation group is obtained and the range \( \Delta d_3 \) of group (4) distances is defined.

Then we calculate the values of object \( a_{4,\min} \) and image \( a'_{4,\min} \) plane distances of the fourth group that correspond to the short \( f'_{\Sigma,\min} \) EFL of the zoom objective lens

\[
a_{4,\min} = a'_{5,\min} - d_{3,\min},
\]

(13)

\[
a'_{4,\min} = a_{4,\min} \beta_{4,\min},
\]

(14)

and define the focal length \( f'_4 \) of the fourth group

\[
f'_4 = \frac{a'_{4,\min}}{1 - \beta_{4,\min}}.
\]

(15)

The length of the secondary part of the zoom objective lens is

\[
L_{3-5} = (1 - k)L.
\]

(16)

The condition of \( L_{3-5} \) constancy can be written as follows.
\[ L_{3-5} = d_3 + a' \]  

(17)

Modifying equation (17) we obtain the following quadratic equation with \( \beta_4 \) variable

\[ \beta_4^2 + \left( \frac{L_{3-5} - a_3}{f_4'} - 2 \right) \beta_4 + 1 = 0. \]  

(18)

Hence, the roots \( \beta_4^{(1,2)} \) of equation (18) are the functions of the third group image plane distance \( a'_3 \). Since \( a'_3 \) distance depends on the zoom group motion (see figure 6) we can represent \( \beta_4^{(1,2)} \) graphs as the functions of \( d_4 \) distance (see figure 8).

\[ \Delta d_3 = \frac{\Delta \beta_4 (d_{3,\text{min}} - a'_3) - \beta_4,\text{min} \Delta a'_3}{1 - \Delta \beta_4 - \beta_4,\text{min}}, \]  

(19)
where $\Delta \beta_4 = \beta_4 - \beta_{4,\text{min}}$, and $\beta_4$ is a current value of the fourth group lateral magnification.

Eventually, we have the motion curve of the compensation group 4 as follows

$$d_3 = d_{3,\text{min}} + \frac{(\beta_4 - \beta_{4,\text{min}})(d_{3,\text{min}}-a'_3)-\beta_{4,\text{min}}(a'_3-a_{3,\text{min}})}{1-\beta_4},$$

(20)

where $a'_3 = f(d_4)$, $\beta_4 = f(d_1)$ are the functions of zoom group motion $d_4$ and the other values are the constants expressed above.

The motion curve of the compensation group is shown in figure 10.

![Figure 10. Compensation group motion curve.](image)

As a result, using 424 type zoom lens design technique we have obtained the optical powers of all the groups and the motion curves of the zoom and compensation groups. This set of parameters provides the demanded zoom magnification $M$ and the overall length constancy over all range of objective lens EFLs.

4. Design technique for secondary imaging optical system

The secondary imaging system (6) shown in figure 11 is used to couple the front zoom objective lens (1)–(5) (see figure 1) and an IR detector (7) with a cold stop diameter $D'$.

![Figure 11. Layout of secondary imaging optical system.](image)

This cold aperture of the IR detector is the aperture stop for the whole IR optical system (1)–(6). Its diameter $D'$ and position $p'$ relative to the sensor plane are given in the detector's manual. Thus, the exit pupil of the optical system (1)–(6) coincides with the aperture stop and its position relative to the imaging system (6) with the focal length $f'_6$ is $a'_p$. The exit pupil position of the front zoom objective lens (1)–(5) relative to the intermediate image plane (5) is $p$. If the pupils' positions and diameters are adjusted the exit pupil of system (1)–(5) coincides with the entrance pupil of system (6)
with diameter $D$. This condition allows meeting the design requirement of 100% efficiency of the cold stop.

Thus, the secondary imaging system will conjugate the exit pupil of the front zoom objective lens with the IR detector cold stop and the pupils lateral magnification $\beta_p$ can be expressed as follows

$$\beta_p = \frac{a_p'}{a_p}, \quad (21)$$

Moreover, the secondary imaging system (6) will conjugate the intermediate image plane (5) with the sensor plane (7) and the lateral magnification $\beta_6$ for these planes can be obtained as follows

$$\beta_6 = \frac{a_6}{a_6'}, \quad (22)$$

where $a_6$ and $a_6'$ are the object and image distances for imaging optical system (6).

To design the secondary imaging system (6) it is offered to use $a_6'$ distance as a variable to meet the requirements to the imaging system. Therefore, all the parameters of the secondary imaging optical system (6) shown in figure 11 are expressed as functions of $a_6'$ distance as follows

$$a_6' = a_6 - p', \quad (23)$$

$$a_p = \frac{a_6'}{\beta_p} = \frac{a_6 - p'}{\beta_p}, \quad (24)$$

$$f_6' = \frac{a_6'}{1 - \beta_p} = \frac{a_6 - p'}{1 - \beta_p}, \quad (25)$$

$$\beta_6 = \frac{a_6'}{f_6'} = \frac{f_6 - a_6'}{f_6} = \frac{a_6 - p'}{1 - \beta_p} = \frac{a_6\beta_p - p'}{a_6 - p'}, \quad (26)$$

$$a_6 = \frac{a_6'}{\beta_6} = \frac{a_6}{a_6\beta_p - p'} = \frac{a_6(a_6 - p')}{a_6\beta_p - p'}. \quad (27)$$

5. Conclusion

The analytical expressions presented in the report can be used to design thermal imaging continuous zoom optical system that consists of the front zoom constant length objective lens and imaging system to couple the objective lens with an IR detector with a cold stop. The analysis of the expressions presented in the report can help to define the optimal parameters of the groups for given initial conditions and to use it as a basis for future parametric synthesis. Future researches are connected with the problem of aberration correction for the front zoom lens and the secondary system to meet requirements for the resolution of thermal imaging continues zoom optical systems.

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