Modeling and analysis of pixel quantization error of binocular vision system with unequal focal length

Danlan Lin1, Zhenwei Wang1*, Hongsheng Shi1, Hong Chen1

1School of Aeronautics and Astronautics, University of Electronic Science and Technology of China, Chengdu, Sichuan, 611731, People’s Republic of China

*Corresponding author’s e-mail: wangjanvey@163.com

Abstract. Current Analysis of pixel quantization error has following problems in the binocular vision system. Most literatures are based on the ideal binocular vision system with equal focal length. Moreover, the precision of pixel quantization is relatively low. In order to solve above problems, an analysis method of pixel quantization error for binocular vision system with unequal focal length is proposed. Firstly, a pixel quantization error model is established and a mathematical expression is presented to characterize the pixel quantization error model. Secondly, in the case of equal and unequal focal lengths, measurement error of object point is discussed respectively. Finally, simulation experiments were conducted and the effect of some parameters on measurement error was analyzed. Reasonability and efficiency of proposed methods are verified.

1. Introduction

With the rapid development of stereo vision technology, the in-depth application and development of measurement field are limited by measurement precision. Therefore, measurement precision is required to be higher and higher. There are many factors affecting measurement accuracy, such as precision of camera calibration, lens parameters and structural parameters of system. Aguilar evaluated the precision of camera calibration and measurement methods[1]. Li analyzed the average pixel quantization error, total error and photonic noise of multiple images under fixed and different exposure time[2]. Sankowski proposed a simulation model and mathematical formula to determine measurement error[3]. Yu analyzed the correlation of structural parameters of parallel binocular vision system and discussed the effects of structural parameters on measurement accuracy, such as baseline distance, focal length and visual angle[4].

The research of analyzing pixel quantization error is as follows. Frane projected 3D error area to 2D diamond area and analyzed the relationship between pixel quantization error and object depth, baseline distance, focal length[5]. Blostein projected 3D pixel quantization error model into a 2D diamond region and deduced the closed probability distribution function of measurement error[6]. Wu modeled the 3D error region as a polyhedral region and fitted the vertices of polyhedron into an ellipsoid, volume of ellipsoid was used to estimate measurement error[7]. Fooladgar modeled the field of view of a pixel as a cone and proposed three simplification methods, including line-circle projection, line-cone intersection and Lagrange method[8-9]. Behzad proposed a mathematical model to estimate quantization error of hexagonal structure[10]. Some literatures analyzed probability density function of depth error caused by pixel quantization and calculated expectation of depth error amplitude[11-13].

In this paper, in the case of equal and unequal focal lengths, pixel quantization error is investigated respectively. Firstly, geometric analysis and mathematical expression of pixel quantization error model
are presented. Then, characterizations of measurement error are discussed, including line-line intersection and the midpoint of common perpendicular in different planes methods. In addition, the measurement error caused by pixel quantization is estimated by 3D uncertain region volume. At last, simulation experiments were carried out. Meanwhile, the discussed method was compared with 3D convex hull algorithm under the condition of unequal focal length.

2. Pixel quantization error modeling

2.1 Geometric analysis of pixel quantization error model

In this paper, pinhole camera model is adopted. Firstly, object point $P$ in world coordinate system is marked as $P_w(x_w, y_w, z_w)$. Then, as shown in equation (1), object point $P$ is converted to camera coordinate system and corresponding point is marked as $P_c(x_c, y_c, z_c)$. When object point is projected onto image plane, physical coordinate $(u, v)$ is expressed as equation (2).

\[
\begin{align*}
\begin{pmatrix} x_c \\ y_c \\ z_c \end{pmatrix} &= R_w \begin{pmatrix} x_w - x_0 \\ y_w - y_0 \\ z_w - z_0 \end{pmatrix} \\
&= \begin{pmatrix} x_c \\ y_c \\ z_c \end{pmatrix} \\
u &= f \frac{x_c}{z_c}, \quad v = f \frac{y_c}{z_c}
\end{align*}
\]

Where, $R_w$ is the rotation matrix converted from world coordinate system to camera coordinate system, $T = (x_0, y_0, z_0)$ is the translation matrix converted from world coordinate system to camera coordinate system and $f$ is focal length.

Physical coordinates of left and right image points are denoted as $(u_l, v_l)$ and $(u_r, v_r)$ respectively. Meanwhile, baseline distance and the focal lengths of left and right cameras are marked as $d$, $f_1$ and $f_2$ respectively. In this paper, the world coordinate system is established in left camera coordinate system. Therefore, the translation matrices for left and right cameras are $T_l = (0, 0, 0)$ and $T_r = (0, 0, d)$ respectively, the rotation matrices of left and right cameras both are unit matrices. Thus, the physical coordinates of left and right image points are obtained from equations (3) and (4).

\[
\begin{align*}
(u_l, v_l) &= \left( f_1 \frac{x_w}{z_w}, f_1 \frac{y_w}{z_w} \right) \\
(u_r, v_r) &= \left( f_2 \frac{x_w - d}{z_w}, f_2 \frac{y_w}{z_w} \right)
\end{align*}
\]

Due to the pixels quantization in image plane, the image points will not be located in the coordinates $(u_l, v_l)$ and $(u_r, v_r)$ precisely. In reality, they will be located in the region of $\pm 1/2$ pixel size, as shown in figure 1, where $du$ and $dv$ are equal to half of length and width of pixel size respectively. According to perspective projection model, the perspective center of camera and four vertices of pixel quantization unit form a projection cone. The intersection area of left and right cones is uncertain area of object point, as shown in figure 2. In figure 2, eight vertices of left and right pixel units are marked as a, b, c, d and e, f, g, h respectively. Physical coordinates of these vertices are shown in equations (5) and (6).

\[
\begin{align*}
\begin{array}{c}
(u_l, v_l) - du \\
\hline
\hline
(u_l + du, v_l) \\
\hline
\hline
\end{array}
\end{align*}
\]

Figure 1. Pixel quantization unit
Figure 2. Pixel quantization error model with unequal focal length

\[ a = (u_l + d_u, v_l + d_v) \]
\[ b = (u_l + d_u, v_l - d_v) \]
\[ c = (u_l - d_u, v_l - d_v) \]
\[ d = (u_l - d_u, v_l + d_v) \] (5)
\[ e = (u_r + d_u, v_r + d_v) \]
\[ f = (u_r + d_u, v_r - d_v) \]
\[ g = (u_r - d_u, v_r - d_v) \]
\[ h = (u_r - d_u, v_r + d_v) \] (6)

Then, the world coordinates of eight vertices are calculated. Vertices \( a = (u_l + d_u, v_l + d_v) \) and \( e = (u_r + d_u, v_r + d_v) \) are converted to camera coordinate system with coordinates \( a_c = (u_l + d_u, v_l + d_v, f_1) \) and \( e_c = (u_r + d_u, v_r + d_v, f_2) \). The world coordinates of vertices \( a \) and \( e \) can be obtained from equations (7) and (8).

\[ a_w = R_{cl-w} \begin{pmatrix} u_l + d_u \\ v_l + d_v \\ f_1 \end{pmatrix} + T_l \] (7)
\[ e_w = R_{cr-w} \begin{pmatrix} u_r + d_u \\ v_r + d_v \\ f_2 \end{pmatrix} + T_r \] (8)

Where, \( R_{cl-w} \) and \( R_{cr-w} \) represent the rotation matrix converted from left and right camera coordinate system to world coordinate system respectively. From discussed above, rotation matrices are unit matrices, \( T_l \) and \( T_r \) are known. Therefore, equations (9) and (10) can be obtained. Similarly, the world coordinates of other six vertices are shown in equations (11) and (12).

\[ a_w = (u_l + d_u, v_l + d_v, f_1) \] (9)
\[ e_w = (u_r + d_u + d, v_r + d_v, f_2) \] (10)
\[ b_w = (u_l + d_u, v_l - d_v, f_1) \]
\[ c_w = (u_l - d_u, v_l - d_v, f_1) \]
\[ d_w = (u_l - d_u, v_l + d_v, f_1) \] (11)
\[ f_w = (u_r + d_u + d, v_r - d_v, f_2) \]
\[ g_w = (u_r - d_u + d, v_r - d_v, f_2) \]
\[ h_w = (u_r - d_u + d, v_r + d_v, f_2) \] (12)

2.2 The mathematical expression of pixel quantization error model

The pixel quantization error model shown in figure 2 is analyzed by mathematical method. Firstly, the eight sides of left and right projection cones are represented by mathematical expressions. Then, the...
boundary of uncertain region of object point is obtained according to the expressions of sides of cones. According to the mathematical knowledge, the linear equation of points \( P_1(X_1, Y_1, Z_1) \) and \( P_2(X_2, Y_2, Z_2) \) can be defined as the formula (13). In the equation (14), \( L = (l_1, l_2, l_3) \) is the direction vector of the straight line. Therefore, the parametric equation is expressed as equation (15).

\[
\frac{X - X_1}{l_1} = \frac{Y - Y_1}{l_2} = \frac{Z - Z_1}{l_3} \tag{13}
\]

\[
L = P_1 - P_2 
\]

\[
\begin{align*}
X &= l_1 t + X_1 \\
Y &= l_2 t + Y_1 \\
Z &= l_3 t + Z_1 
\end{align*} \tag{15}
\]

If two straight lines have an intersection, the intersection can be obtained by solving simultaneous equation of two straight lines. Equations (16) and (17) are the parametric equations of two straight lines with an intersection, the simultaneous equation is shown in equation (18). In order to get the intersection, \( t_1 \) and \( t_2 \) of equation (18) should be solved firstly and then are substituted into the parametric equation. Firstly, the parametric equations of eight straight lines in figure 2 are analyzed, \( O_1a \), \( O_1b \), \( O_1c \), \( O_1d \) and \( O_1e \), \( O_1f \), \( O_1g \), \( O_1h \) represent the eight straight lines. Taking straight line \( O_1a \) as an example, the world coordinates of points \( O_1(0, 0, 0) \), \( a_w = (u_1 + du, v_1 + dv, f_1) \) and \( O_r(0, 0, d) \) are known. Hence the parameter equation of \( O_1a \) is shown in equation (19) and parametric equations of other seven lines are similar.

\[
\begin{align*}
L_1: & \quad \begin{cases} 
X = l_{11} t_1 + A \\
Y = l_{12} t_1 + B \\
Z = l_{13} t_1 + C 
\end{cases} \tag{16} \\
L_2: & \quad \begin{cases} 
X = l_{21} t_2 + D \\
Y = l_{22} t_2 + E \\
Z = l_{23} t_2 + F 
\end{cases} \tag{17} \\
\begin{align*}
l_{11} t_1 - l_{21} t_2 &= D - A \\
l_{12} t_1 - l_{22} t_2 &= E - B \\
l_{13} t_1 - l_{23} t_2 &= F - C 
\end{align*} \tag{18} \\
O_1a: & \quad \begin{cases} 
x = (u_1 + du) t_1 \\
y = (v_1 + dv) t_1 \\
z = f_1 t_1 
\end{cases} \tag{19} 
\]

3. Characterization of object point measurement error

3.1 Characterization of object point measurement error with equal focal length
In figure 2, when left and right focal lengths are the same, each of following pairs of lines has an intersection: \( O_1a \) and \( O_r e \), \( O_1a \) and \( O_r h \), \( O_1d \) and \( O_r e \), \( O_1d \) and \( O_r h \), \( O_1b \) and \( O_r f \), \( O_1b \) and \( O_r g \), \( O_1c \) and \( O_r f \), \( O_1c \) and \( O_r g \), and corresponding intersections are expressed as Intersection 1, Intersection 2, Intersection 3, Intersection 4, Intersection 5, Intersection 6, and Intersection 8 respectively. Taking the intersection of lines \( O_1a \) and \( O_r e \) as an example, the parametric equation of line \( O_1a \) has been given above and the parametric equation of line \( O_r e \) is given below, as shown in formula (20). Equations (3) and (4) are substituted into the formulas (19) and (20) respectively and the intersection coordinate is obtained through above method. The results of all intersection points are given in equations (21)-(28).

\[
O_r e: \quad \begin{cases} 
x = (u_r + du) t_2 + d \\
y = (v_r + dv) t_2 \\
z = f_2 t_2 
\end{cases} \tag{20} 
\]
The hexahedron formed by these vertices is uncertain region of object point. Therefore, Under the assumption that object points are uniformly distributed, the volume of uncertain region can represent measurement error of object point. But the volume of an hexahedron cannot be calculated directly. Therefore, the uncertain region is divided into five tetrahedrons in this paper, because volume of a tetrahedron is easy to be calculated. These five tetrahedrons include Intersection_ (1,3,4,7), Intersection_
(4,6,7,8), Intersection (1,4,6,7), Intersection (1,2,4,6) and Intersection (1,5,6,7). Vertices coordinates of a tetrahedron are \((x_1, y_1, z_1), (x_2, y_2, z_2), (x_3, y_3, z_3), (x_4, y_4, z_4)\) and the volume calculation formula of a tetrahedron is shown in equation (29).

\[
V = \frac{1}{6} \cdot \text{abs} \left( \begin{array}{cccc}
x_1 & x_2 & x_3 & x_4 \\
y_1 & y_2 & y_3 & y_4 \\
z_1 & z_2 & z_3 & z_4 \\
\end{array} \right)
\]  

(29)

Where, abs (·) is the absolute value of the number in parentheses, and \(|A|\) is the determinant of matrix A. According to equation (29), the volume of five tetrahedrons are obtained respectively, as shown in equations (30)-(34). Obviously, these volume formula are independent of x and y. Finally, volume of uncertain region is sum of five tetrahedrons volumes.

\[
\text{Volume}_1 = \frac{4}{3} \frac{d}{f(2z_wdu - fd)(2z_wdu + fd)} \int dv du w^4
\]  

(30)

\[
\text{Volume}_2 = \frac{4}{3} \frac{d}{f(2z_wdu - fd)(2z_wdu + fd)} \int dv du w^4
\]  

(31)

\[
\text{Volume}_3 = \frac{8}{3} \frac{d}{f(2z_wdu - fd)(2z_wdu + fd)} \int dv du w^4
\]  

(32)

\[
\text{Volume}_4 = \frac{4}{3} \frac{d}{f(2z_wdu + fd)^2} \int dv du w^4
\]  

(33)

\[
\text{Volume}_5 = \frac{4}{3} \frac{d}{f(2z_wdu - fd)(2z_wdu + fd)} \int dv du w^4
\]  

(34)

3.2 Characterization of object point measurement error with unequal focal length

In the case of unequal focal length, each pair of straight line in figure 2 is in different planes, these pairs of straight line include \(O_l a\) and \(O_r e\), \(O_l a\) and \(O_r h\), \(O_l d\) and \(O_r e\), \(O_l d\) and \(O_r h\), \(O_l b\) and \(O_r f\), \(O_l b\) and \(O_r g\), \(O_l c\) and \(O_r f\), \(O_l c\) and \(O_r g\). Therefore, intersection cannot be obtained. The approximate method is used to characterize the measurement error in this paper. Firstly, the midpoint of common vertical line of each pair of different plane lines is calculated. Then, these midpoints are taken as vertexes of uncertain region and the uncertain region is also a convex hexahedron. Similarly, when object points follow uniform distribution pattern, the equation (29) is directly used in this section. Meanwhile, the convex hull algorithm is compared with the method discussed. Below we elaborate the method of solving midpoint of common vertical line of two straight lines in different planes.

Two points on line L1 are \(A(x_1, y_1, z_1)\) and \(B(x_2, y_2, z_2)\) and two points on line L2 are \(C(x_3, y_3, z_3)\) and \(D(x_4, y_4, z_4)\). Firstly, the direction vectors of L1 and L2 are calculated, which are denoted as \(l_1\) and \(l_2\) respectively, as shown in equation (35). Then the common perpendicular vectors of L1 and L2 is calculated, which is denoted as \(l_{12}\), as shown in equation (36).

\[
l_1 = AB = (x_2 - x_1, y_2 - y_1, z_2 - z_1)
\]  

(35)

\[
l_2 = CD = (x_4 - x_3, y_4 - y_3, z_4 - z_3)
\]  

(36)

\[
l_{12} = \text{cross}(l_1, l_2)
\]  

(36)

Where, cross\((l_1, l_2)\) denotes convolution of L1 and L2. The intersections of common vertical line L3 and lines L1 and L2 are \(M(x_m, y_m, z_m)\) and \(N(x_n, y_n, z_n)\) respectively. Therefore, equation (37) can be obtained.

\[
\begin{align*}
A M &= t_1 \cdot AB \\
C N &= t_2 \cdot CD
\end{align*}
\]  

(37)

Where, t1 and t2 represent scale factors. Therefore, the coordinates of M and N are shown in formula (38). The direction vector of common vertical line L3 is denoted as \(l_3=MN\) and equation (39) can be obtained.

\[
\begin{align*}
M &= (t_1(x_2 - x_1) + x_1, t_1(y_2 - y_1) + y_1, t_1(z_2 - z_1) + z_1) \\
N &= (t_2(x_4 - x_3) + x_3, t_2(y_4 - y_3) + y_3, t_2(z_4 - z_3) + z_3)
\end{align*}
\]  

(38)
\[ \begin{align*}
\text{dot}(l_1, l_3) &= 0 \\
\text{dot}(l_2, l_3) &= 0
\end{align*} \]  
(39)

Where, \( \text{dot}(l_1, l_3) \) represents dot product of \( l_1 \) and \( l_3 \), \( \text{dot}(l_2, l_3) \) is similar. Then, the corresponding values are substituted into the calculation to work out expressions of \( t_1 \) and \( t_2 \). The results of \( t_1 \) and \( t_2 \) are shown in equation (40).

\[ \begin{align*}
t_1 &= \frac{\text{dot}(\text{cross}(AC, l_2), l_{12})}{\text{norm}(l_{12})} \cdot \text{norm}(l_{12}) \\
t_2 &= \frac{\text{dot}(\text{cross}(AC, l_1), l_{12})}{\text{norm}(l_{12})} \cdot \text{norm}(l_{12})
\end{align*} \]  
(40)

Where, \( \text{norm}(l) \) refers to the two norm of vectors \( l \) and \( AC \) refers to direction vector of a straight line \( AC \). Finally, \( t_1 \) and \( t_2 \) are substituted into coordinate expressions of \( M \) and \( N \) respectively. Finally, the midpoint \( O \) of common vertical line is shown in equation (41).

\[ O = \left( \frac{x_1 + x_2}{2}, \frac{y_1 + y_2}{2}, \frac{z_1 + z_2}{2} \right) \]  
(41)

4. Experiment

In this section, simulation experiments were carried out to verify the reasonability and efficiency of discussed methods. The effect of some parameters on pixel quantization error is analyzed and these parameters include baseline length, focal length, pixel size and depth. In the simulation experiments, simulation parameters are shown in Table 1.

Simulation results of vertices coordinates of uncertainty region with equal and unequal focal length are shown in table 2 and table 3 respectively. Furthermore, (a) and (b) in figure 3 are the simulation results of uncertain region, which are simulated by the method discussed in this paper. Figure (c) is simulation result of convex hull algorithm under the condition of unequal focal length. As we can see from the figures, uncertain regions are a hexahedron. Under the condition of unequal focal length, (b) and (c) also show that the result of method discussed and the convex hull algorithm are the same. Therefore, the reasonability and efficiency of methods mentioned above are verified.
Figure 3. Uncertainty region of object point

(a) The discussed method in the case of equal focal length (b) The discussed method in the case of unequal focal length (c) Convex hull algorithm in the case of unequal focal length

Figure 4 shows variation of error volume with baseline length. In the case of unequal focal length, the discussed method above and convex hull algorithm are simulated. As can be seen from the figure, error volume decreases with the increase of baseline length. Because the position of object point is fixed, when the baseline length increases, the left and right image points are far away from the center of image planes, so projection cone will become smaller and area where they intersect will become narrower, thus reducing the error volume.

Figure 5 depicts the change of error volume with the change of focal length. In the case of unequal focal length, the focal length of left camera is changed. As shown in the figure, the volume error decreases with the focal length increases. According to the error model, the projection cone of left and right pixel units will become narrower when the focal length of camera increases, resulting in smaller space intersection area. Therefore, in actual project, the camera with large focal length can be selected as much as possible to improve measurement precision.

Figure 6 shows the effect of pixel size on the error volume. The quantization error volume increases with the increase of pixel size as shown in the figure. Because the larger the pixel size is, the larger the projection cone of pixel unit will be, so the uncertainty area will be larger.

Figure 7 shows that farther the distance between object point and camera is, the greater the measurement error will be. While object point is (0, 0, z), z is variable. Obviously, when object point is far away from cameras, its pixel projection cone will intersect at a farther place. Therefore, when uncertain region increases, the measurement error will be greater.

The error volume of object points on plane parallel to cameras is also analyzed, as shown in figure 8. It can be seen from the figure that error volume does not change under the condition of equal focal length, which can be seen from the third part. In the case of unequal focal length, the discussed algorithm is not changed, but the result does not prove that the actual situation is the same, because the approximation method is used in this paper. Nor can it demonstrate that error volume is independent of x and y.
5. Conclusion
This paper discussed an analysis method of pixel quantization error. Firstly, a pixel quantization error model is established. Then, the mathematical expression is presented to characterize pixel quantization error model. Meanwhile, in order to obtain the vertexes of uncertain region, the line-line intersection and the midpoint of common perpendicular are illustrated. Moreover, the volume of uncertain region is used to estimate measurement error. Finally, the reasonability and efficiency of discussed methods are verified by simulation experiments.

This paper draws an important conclusion, which is that the error volume of object points on the plane parallel to the camera does not change under the condition of equal focal length. This conclusion is different from following literatures. Sharma concluded that the dynamic range on the horizontal axis (x-axis) was larger than that on the vertical axis (y-axis) and error volumes was a valley[7]. Fooladgar concluded that object point far from the camera center had a low error volume[8-9]. The reason why the conclusion of this paper is different from these literatures is that Sharma and Fooladgar both used approximate volumes to estimate measurement error. While real volume were used to estimate measurement error in this paper, which has more practical reference value.

Acknowledgments
This research was funded by The National Natural Science Foundation of China (grant number 51675087).

References
[1] Aguilar, J.J., Torres, F., Lope, M. A. (1996) Stereo vision for 3D measurement: accuracy analysis, calibration and industrial applications. Measurement,18(4):193-200.
[2] Li, F., Barabas, J., Mohan, A., et al. (2020) Analysis on errors due to photon noise and quantization process with multiple images. In: The 44th Annual Conference on Information Sciences and Systems(CISS). New York. pp:1-6.
[3] Sankowski, W., Włodarczyk, M., Kacperski, D., et al. (2017) Estimation of measurement uncertainty in stereo vision system. Image and Vision Computing, 61:70-81.
[4] Yu, H., Xing, T.G., Jia, X. (2016) The analysis of measurement accuracy of the parallel binocular
stereo vision system. In: The 8th International Symposium on Advanced Optical Manufacturing and Testing Technologies: Optical Test, Measurement Technology, and Equipment. International Society for Optics and Photonics. Washington.

[5] Solina, F. (1985) Errors in stereo due to quantization. University of Pennsylvania, Department of Computer and Information Science, 1985.

[6] Blostein, S.D., Huang, T.S. (1987) Error analysis in stereo determination of 3-D point positions. Transactions on Pattern Analysis and Machine Intelligence, PAMI-9(6):752-765.

[7] Sharma, Rajeev. (1998) Analysis of uncertainty bounds due to quantization for three-dimensional Position estimation using multiple cameras. Optical Engineering, 37(1):280-292.

[8] Fooladgar, F., Samavi, S., Soroushmehr, S. M. R. (2012) Geometrical Analysis of Altitude Estimation Error Caused By Pixel Quantization in Stereo Vision. In: Iranian Conference on Electrical Engineering. New York. pp:701-705.

[9] Fooladgar, F., Samavi, S., Soroushmehr, S.M.R., et al. (2013) Geometrical Analysis of Localization Error in Stereo Vision Systems. Sensors Journal, 13(11):4236-4246.

[10] Kamgar, P. B., Sander, W. A. (1989) Quantization error in spatial sampling: comparison between square and hexagonal pixels. In: Computer Society Conference on Computer Vision and Pattern Recognition. New York. pp:604-611.

[11] Rodriguez, J.J., Aggarwal, J. K. (1990) Stochastic analysis of stereo quantization error. Transactions on Pattern Analysis and Machine Intelligence, 12(5):467-470.

[12] Rodriguez, J.J., Aggarwal, J. K. (1988) Quantization error in stereo imaging. In: Computer Vision and Pattern Recognition. New York. pp:153-158.

[13] Balasubramaniana, R., Dasband, S., Udayabaskaran, S. (2002) Quantization error in stereo imaging systems. Computer Math, 79(6): 671–691.

[14] Wang, Y.Z, Zhao, Z.Z. (2019) Space quantization between the object and image spaces of a microscopic stereovision system with a stereo light microscope. Micron, 116:46-53.