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1. Introduction

For the autonomous movement of a robotic system, in real time, it has to perceive its environment, to calculate the position of a target or of a block and to move properly. For this reason, many types of sensors and apparatus have been proposed. The target state is required to be accurately calculated and a desired task or procedure to be safely and successfully integrated. In cases of limited intelligence of the system, mainly in industrial environments, the adaptation of the system to new data is necessary. The advantages of the proper use of sensors mounted on the end effector of a manipulator or on a mobile robot are multiple.

Using cameras as sensors it is possible to have mainly vision systems with one or more cameras. A stereovision system is composed of two cameras. For the recovery of a 3-D scene from a pair of stereo images of the scene, it is required to establish correspondences. Correspondence between points in images is a major step in stereo depth perception. This step is known as the correspondence process, and many algorithms for it have been developed. Another major step is the computation of depth values from the point correspondences.

The stereo process can be summarized by the following steps: 1) detection of features in each image 2) matching of features between images under certain geometric and other constraints and 3) calculation of depth using the disparity values and the geometric parameters of the imaging configuration. While each of these steps is important in the stereo process, the matching of features (correspondence between points) is generally thought to be the most difficult step and can easily become the most time consuming.

Depth perception via stereo disparity is a passive method that does not require any special lighting or scanner to acquire the images. This method may be used to determine depths of points in indoor as well as outdoor scenes, and depths of points that are centimeters or kilometers away from the viewer.

A correspondence algorithm can produce more reliable matches if the underlying images have smaller intensity and geometric difference. If the scene has Lambertian surfaces, there would be no difference in the intensities of corresponding points in images. For stereo images acquired by the two cameras, the focal lengths and zoom levels of the cameras are often slightly different. Differences in the optical properties of the two cameras cause intensity differences between corresponding points in stereo images. The optical axes of the

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cameras may not lie in the same plane also. These unwanted geometric and intensity differences should be reduced as much as possible to increase the ability to find correspondences reliably.

In cases of monocular (single camera) stereovision systems the above problems are reduced. In these systems, a single camera and some mirrors or a biprism, properly placed, are used, so that the reception of a stereo pair of images to be possible. The correspondence points are usually found on a single line (epipolar line), the intensity differences of these points are reduced and the two virtual cameras, which constitute the stereovision system, have the same geometric properties and parameters.

In this chapter, the design and the construction of a new apparatus for stereovision with a single CCD camera, is presented. It is called Pseudo Stereo Vision System (PSVS) and it is composed of a camera, three mirrors and a beam-splitter. PSVS, compared with other monocular or binocular stereovision systems (Section 2), has the following advantages:

- 1. It is a relatively low cost and robust apparatus, it has no moving parts and it can be used in place of any vision system.
- 2. It uses only one common CCD camera and thus the two created virtual cameras of the stereo system have the same geometric properties and parameters.
- 3. It receives a complex image (the superposition of a stereo pair of images), which is directly processed (pseudo stereo), in a single shot.
- 4. It has the double resolution of other monocular systems and the same resolution with an ordinary stereo system.
- 5. It can be constructed to any dimensions covering every type of camera, length of baseline, accurate measurement of depth.
- 6. Using the correspondence algorithm (Pachidis & Lygouras, 2002a), (Pachidis et al., 2002) and (Pachidis & Lygouras, 2006), it is easy to find points disparities.

Drawbacks of PSVS could be the following:

- 1. Known correspondence algorithms cannot be implemented to complex images. For this reason, a new correspondence algorithm capable to find correspondences in edges has been developed.
- 2. Correspondences cannot be found when the two different views of an object are overlapped. In these cases the proposed correspondence algorithm can find correspondences in edges of overlapped objects or parts of them. Moreover, in this chapter, two methods to separate complex images into pairs of stereo images (where any correspondence algorithm can be implemented) are described.

The chapter is organized as follows. In Section 2, single camera stereovision systems, described by other researchers, are examined. In Section 3, construction details of PSVS and refraction phenomena due to the beam-splitter are presented. In Section 4, recalculation of the final equations, taking into consideration refraction phenomena and camera calibration parameters, of the coordinates of a point by using PSVS, are introduced. In Section 5, basic concepts of the correspondence algorithm used are presented. In Section 6, two methods for the separation of a complex image into a pair of stereo images and the reconstruction of them are given. In Section 7, some experimental results are depicted. Finally, in Section 8, conclusions of this work and future plans are presented.

2. Existing Single Camera Stereovision Systems

Many single camera stereovision systems have been proposed in the literature. Teoh and Zhang (Teoh & Zhang, 1984) described a single-lens stereo camera system. Two mirrors, fixed to the body of the camera, make a 45° angle with the optical axis of the camera. A third mirror that can rotate is placed directly in front of the lens. The rotating mirror is made parallel to one of the fixed mirrors and an image is obtained. Then, it is made parallel to the other fixed mirror and another image is obtained. Here, although a single camera is used, the result is the same as using two cameras with parallel optical axes.

Nishimoto and Shirai (Nishimoto & Shirai, 1987) proposed a single-lens camera system that can obtain stereo images. In this system, a glass plate is placed in front of the camera, and images are obtained with the plate at two different rotational positions. When the glass plate is rotated, the optical axes of the camera shifts slightly, simulating two cameras with parallel optical axes. The obtained stereo images have very small disparities making the point correspondence easy. However, only coarse depth values can be obtained from the disparities. This camera system requires two shots from a scene and therefore should be used only in static environments. Otherwise, the scene will change during the time the images are obtained, and the positions of the corresponding points will no longer relate to the depths of points in 3D.

Both of these cameras considerably reduce unwanted geometric and intensity difference between stereo images. But the cameras have parts that should be rotated when obtaining a pair of images. Exact rotation of the parts is a major design issue in these systems, and two shots of a scene are required.

Several researchers demonstrated the use of both curved and planar mirrors to acquire stereo data with a single camera. Curved mirrors have been primarily used to capture a wide field of view. Nayar (Nayar, 1988) suggested a wide field of view stereo system consisting of a conventional camera pointed at two specular spheres. Later, Southwell et al. (Southwell et al., 1996) proposed a similar system using two convex mirrors, one placed on top of the other.

Gosthasby and Gruver (Gosthasby & Gruver, 1993) proposed a single camera system that can obtain images in a single shot using a single lens. The obtained images are reflected about the image of the mirrors axis. This camera system can obtain images in a single shot and through a single camera. But, the reversed image should be transformed to appear as if obtained by cameras with parallel optical axes, before carrying out the correspondence and measuring the depth values from the correspondence. The inter-reflection between the mirrors causes intensity difference between corresponding points in stereo images.

Stereo systems using four planar mirrors were proposed by both Inaba et al (Inaba et al., 1993) and Mathieu and Devernay (Mathieu & Devernay, 1995). In their recent work, Nene and Nayar (Nene & Nayar, 1998) proposed four stereo systems that use a single camera pointed toward planar, hyperboloidal, ellipsoidal, and paraboloidal mirrors. By using of non-planar reflecting surfaces such as hyperboloids and paraboloids, a wide field of view (FOV) images are easily obtained. However, their stereo system needs a complex mirror mechanism. Gluckman and Nayar (Gluckman & Nayar, 1998a) and Gluckman and Nayar (Gluckman & Nayar, 1999) demonstrated how two mirrors in an arbitrary configuration could be self-calibrated and used for single camera stereo. Gluckman and Nayar (Gluckman & Nayar, 1998b) presented the design of a compact panoramic stereo camera, which uses parabolic mirrors and is capable of producing 360° panoramic depth maps. Gluckman and

Nayar (Gluckman & Nayar, 2000) also presented a novel catadioptric sensor, which uses mirrors to produce rectified stereo images.

Lee, Kweon and Cipolla (Lee et al., 1999) and Lee and Kweon (Lee & Kweon, 2000) proposed a practical stereo camera system that uses only one camera and a biprism placed in front of the camera. The equivalent of a stereo pair of images is formed as the left and right halves of a single charge coupled device (CCD) image using a biprism. This system is more accurate for nearby objects than for far ones. Their system is simple but a biprism cannot be found easily. Peleg et al. (Peleg et al., 2001) presented two stereovision systems with one camera by using a spiral-like mirror or lens. These systems, right now, cannot be used in real time applications. By imaging an object and its mirror reflection, a stereo image can also be obtained using only a single mirror, Wuerz et al (Wuerz et al., 2001).

Song et al. (Song et al., 2002) presented an apparatus with a rotated mirror. For the measurement of depth, they observed that from the sequence of the captured images, the velocity of pixels is increased when the distance of objects in a scene is increased. Finally, Kawasue and Oya (Kawasue & Oya, 2002) presented an apparatus based on a single camera and a rotated mirror. The apparatus can be only used in a small number of applications.

3. System Description and Analysis

3.1 System Description

The main idea is based on using three mirrors with a 100% reflection of their incident light and a 50% beam-splitter. Refraction phenomena do not appear to first three mirrors because the first surface of them is used (first surface mirrors).

To determine the relative location of mirrors in PSVS, a right-hand orthogonal coordinate system is defined. *Z*-axis of this system coicides with the optical axis of the real camera and the origin of it is the optical center *O* of the camera. *X*-axis, vertical to *Z*-axis, is parallel with the direction of columns increment in the image plane and *Y*-axis is vertical to the plane *XZ*. Mirrors of PSVS are vertically located to *XZ* plane and form 45° angle with *Z*-axis (Fig. 1(a)). It is considered that initially no refraction phenomena exist due to mirror (1) (i.e. by using a Pellicle beam-splitter). Then two virtual cameras are created with their optical axes parallel to the optical axis of the real camera. These cameras are symmetrically located to *Z*-axis. They have the same geometric properties and parameters (the same of the real camera). Consequently, these virtual cameras constitute an ideal stereovision system with two cameras. This vision system, as it presented here, receives in a single shot one complex image. This image consists of two superimposed images captured from the left and right views of the apparatus.

If the intensity of each pixel of an image captured from the left and from the right view are $I_L(i,j)$ and $I_R(i,j)$ respectively, the intensity of each pixel of the complex image is given as:

$$I_{c}(i,j) = k \cdot I_{L}(i,j) + (1-k) \cdot I_{R}(i,j)$$

(1)

Where *i*, *j*, are indices of the current row and column of a pixel in the image. *k* is a parameter (*k*=0.5 with the beam-splitter used) declaring the reduction of the intensity of pixels of each view because of the beam-splitter. It is obvious that the intensity in a complex image never exceeds its maximum value, (for gray-scale images $I_C(i, j) \le 255$). The baseline of this stereo system is *b* and it is the distance between the two virtual parallel optical axes (Fig. 1(a)).



Figure 1. PSVS: (a) Mirrors position (b) PSV apparatus mounted on the end effector of a PUMA 761 robotic manipulator

Problems with correct luminosity are reduced from the system by using a regulated lighting system on the apparatus (Fig. 1(b)). A small laser module is incorporated to the apparatus. The red spot laser beam is used to periodically check the alignment of mirrors. The front view of the PSVS is properly formulated to accept "spatial" or color filters.

3.2 PSVS Geometry Equations

In PSVS, to avoid probable shades of parts of complex images because of the improper size or of the location of mirrors and the appearance of ghost images, the calculation of mirrors dimensions is required. The equation providing these dimensions is the following:

$AC = AB + BC \Rightarrow AC =$	$\frac{OB \cdot \tan a \cdot \cos \omega_1}{\tan (\omega_1 - a)} + OB \cdot \tan a \cdot \sin \omega_1$)+	$\left(\frac{OB \cdot \tan a}{\sin a + \cos a \cdot \tan a}\right)$	(2)
($\tan(\omega_1 - a)$		$\sin \omega_1 + \cos \omega_1 \cdot \tan a$	~ /

Angle 2*a* represents the angular field of view of the lens while ω_1 is the angle the optical axis forms with a mirror plane (Fig. 2). *OB* is the path a light beam follows along the optical axis from the optical center of the real camera to a mirror. From equation (2) partial cases for ω_1 =45° and ω_1 =90° are derived.





Figure 2. Calculation of mirror dimensions Case studies: 1. $\omega_1 = 45^\circ$. Then:

$$AC = AB + BC = \frac{\sqrt{2} \cdot OB \cdot \tan a}{1 - \tan a} + \frac{\sqrt{2} \cdot OB \cdot \tan a}{1 + \tan a} = \sqrt{2} \cdot OB \cdot \tan 2a$$
(3)

Equation (3), permits the calculation of the dimension of each mirror which forms an angle of $\omega_1 = 45^{\circ}$ with the optical axis. More details can be found in (Pachidis & Lygouras, 2005). The other dimension of each mirror is vertical to the optical axis, namely $\omega_1 = 90^{\circ}$. 2. $\omega_1 = 90^{\circ}$. Then:

$$AC = AB + BC = OB \cdot \tan a + OB \cdot \tan a = 2 \cdot OB \cdot \tan a$$
(4)

Sections *AB* and *BC* are equal, when $\omega_1 = 90^\circ$. From the previous relations and taking into consideration that the optical axes are vertical to the sub-frames (left and right views), it results that each virtual optical axis will pass from the geometric center of the corresponding sub-frame (view) captured by PSVS.

In PSVS, the four mirrors are grouped in two pairs. The first pair consists of mirrors (1) and (2) and it is responsible for the creation of the virtual camera 1, while the second pair consists of the mirrors (3) and (4) and it is responsible for the creation of the virtual camera 2.

By definition the distance of the two pairs of mirrors is the distance *AB* (Fig. 3). The estimation of distance *OB* used in the previous equations (Fig. 2), giving the dimensions of mirrors, presuppose the knowledge of the length of baseline *b* or and the distance *AB* of the two mirror pairs. The minimum length of the baseline b_{min} depends on the angular field of view 2*a* of the lens, the distance of the beam-splitter from the optical center *O* and the distance *AB* of the mirror pairs.



Figure 3. Calculation of b_{\min} and AB_{\min}

The design of PSVS permits to freely select the distance *OA* of the real camera optical center from the beam-splitter. Only a maximum value of it, OA_{max} , is necessary to be determined. Equation (5) provides the minimum length of the baseline, b_{min} in its general form and equation (6) b_{min} when the angle of mirrors with the optical axis is 45° :

$$b_{\min} = \frac{4 \cdot \tan a \cdot (\tan \omega_1 - \tan a)}{\tan \omega_1 \cdot (1 + \tan^2 a) \cdot (1 - \tan \omega_1 \cdot \tan a_1) - 2 \cdot \tan a \cdot (\tan \omega_1 - \tan a)} \cdot (OA + AB_{\min})$$
(5)
$$4 \cdot \tan a = (A - A) \cdot (A - A)$$

$$b_{\min} = \frac{4 \cdot \tan a}{(1 - \tan a)^2} \cdot \left(OA + AB_{\min}\right) \tag{6}$$

It is considered that the distance *OA* has its maximum value.



The minimum distance of the two pairs of mirrors, AB_{\min} , in its general form, is given by the relation (7):



For angle $\omega_1 = 45^\circ$, (7) is simplified to:

$$AB_{\min} = OA \cdot \frac{2 \cdot \tan a}{(1 - \tan a)} + \sqrt{2} \cdot d \cdot \cos a \cdot (1 + \tan a)$$
(8)

To calculate the *Minimum Distance of Common View*, Fig. 1(a) is used. The distance of interest is *OB*. The point *B* represents the first common point, which is created from the two virtual cameras, where no refraction phenomena are taken into consideration. From the right triangle (O_1AB), it results:

$$\tan a = \frac{AB}{O_1 A} \Longrightarrow O_1 A = \frac{AB}{\tan a} \Longrightarrow OB + \frac{b}{2} = \frac{\frac{b}{2}}{\tan a} \Longrightarrow OB = \frac{b}{2\tan a} - \frac{b}{2} \tag{9}$$

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3.3 Refraction Phenomena

In this part, the influence of refraction phenomena due to mirror (1) of PSVS is examined. It is desirable, the left and right view of a scene captured by means of PSVS to coincide and to have exactly the same magnification. The second virtual camera, due to refraction phenomena to beam-splitter, undergoes a parallel displacement to the optical axis of the real camera. Simultaneously the optical center O_2 shifts on the virtual optical axis (Fig. 4).

To accurately calculate paths of a light beam in two different directions, created by these two virtual cameras, the displacement of the virtual axis and the shifting of the virtual optical center O_2 must be calculated. Using Snell law, (Pedrotti & Pedrotti, 1998), the refraction angle of a light ray from the optical center O, along the optical axis, is the following:

$$=\sin^{-1}\left(\frac{n_{air}}{n_{glass}}\cdot\sin\theta_{i}\right)$$

(10)

Where θ_i is the incidence angle. If ω_1 is the angle formed by the optical axis with mirror (Fig. 4), then $\theta_i=90^{\circ}-\omega_1$. If *d* is the mirror (1) thickness the displacement *m* of the second virtual camera, after some simple trigonometric calculations, can be calculated as:

 θ_r

$$m = \frac{d \cdot \cos(\omega_1 + \theta_r)}{\cos \theta_r} = \frac{d \cdot \sin(\theta_i - \sin^{-1}(\frac{n_{air}}{n_{glass}} \cdot \sin \theta_i))}{\sqrt{1 - \frac{n_{air}^2}{n_{glass}^2} \cdot \sin^2 \theta_i}}$$
(11)



$$l = \frac{d}{\cos\theta_r} \left(1 - \sin(\omega_1 + \theta_r) + \cos(\omega_1 + \theta_r) \cdot \tan\omega_1 \right) = \frac{d}{\sqrt{1 - \frac{n^2_{air}}{n^2_{glass}} \cdot \sin^2\theta_i}} \left(1 - \frac{n_{air}}{n_{glass}} \right)$$
(12)

We can see that parameters *m* and *l* are depending on the refraction indices and the beamsplitter thickness. For incidence angle $\theta_i = 45^\circ$, *m* and *l* have the values of Table 1.

Table 1. Values of parameters *m* and *l* in mm

By means of the above results for the displacement m and the shifting l the construction of the apparatus could be separated in two partial cases. In first case the simplicity in construction and in mirrors alignment is desirable. The distance between mirrors (1) and (2) or (3) and (4) is selected to be exactly the same and equal to b/2. Then, the second virtual camera optical axis, due to refraction phenomena to mirror (1), is displaced along *X*-axis by m and the optical center O_2 is shifted along *Z*-axis by l. Shifting by l means that the left view of the apparatus, in relation with the right view, is a bit magnified. This means that not all the corresponding points are found in exactly the same scan line (epipolar line) and a correspondence algorithm should be able to manipulate this kind of points.

In second case, during construction and calibration the distance between mirrors (3) and (4) is regulated to be b/2+l. Then the result is a ray radiated from the optical center O to follow slightly different in length paths in two different directions. The magnification of the two virtual cameras is exactly the same and the displacement of the second virtual axis with respect to the optical axis of the real camera is b/2+m+l. In this case the construction and the calibration procedure requires the careful placement of mirrors (3) and (4). The corresponding points are always found in the same scan line (epipolar line).

4. Coordinates of a Random Point in 3D Space - Recalculation

To calculate the modified equations, giving the coordinates of a random point in 3D space, we solve the stereo problem using as cameras the two virtual cameras created by PSVS. Each of the above virtual cameras can be separately calibrated and the matrix A with the intrinsic parameters can be found. A right hand ortho-normal coordinate system with origin the optical center O of the real camera and Z-axis to coincide with the optical axis of the real camera is established (Fig. 5). The coordinates of a point P in space, with respect to this coordinate system, are expressed by the vector $X = [x, y, z, 1]^T$ while the coordinates of optical centers O_1 and O_2 are provided from vectors $\mathbf{X}_{oL} = [x_{oL}, y_{oL}, z_{oL}]^T$ and $\mathbf{X}_{oR} = [x_{oR}, y_{oR}, z_{oR}]^T$ respectively. Then, using matrix relations, the calculation of vectors $m_L = [u_L, v_L, 1]^T$, $m_R = [u_R, v_R, 1]^T$ in the image plane for each virtual camera of a point P is possible. Here, the assumption made, is that the two virtual cameras are parallel to the real camera as a result of PSVS mirrors alignment and checking procedure (Pachidis & Lygouras, 2002b). Thus, rotation matrices R_{oL} , R_{oR} describing the orientation of the virtual cameras with respect to the real camera are equal to the identified matrix I_{3x3} . The calculation methodology provides equations giving the coordinates of a point in space, in a more general form. Then, special case studies concerning PSVS are examined.

$$m_{L} = \lambda \cdot A_{L} \cdot \begin{bmatrix} R_{oL} & -X_{oL} \end{bmatrix} \cdot X$$
(13)

$$\boldsymbol{m}_{R} = \boldsymbol{\lambda} \cdot \boldsymbol{A}_{R} \cdot \begin{bmatrix} \boldsymbol{R}_{oR} & -\boldsymbol{X}_{oR} \end{bmatrix} \cdot \boldsymbol{X}$$
(14)





Figure 5. In this figure the established ortho-normal coordinate system is illustrated Matrices A_L , A_R , (providing intrinsic parameters of cameras) as they are calculated, using the calibration method proposed by Z. Zhang (Zhang, 2000), are of the form:

$$\boldsymbol{A}_{L} = \begin{bmatrix} a_{u_{L}} & c_{L} & u_{Lo} \\ 0 & a_{v_{L}} & v_{Lo} \\ 0 & 0 & 1 \end{bmatrix}, \quad \boldsymbol{A}_{R} = \begin{bmatrix} a_{u_{R}} & c_{R} & u_{Ro} \\ 0 & a_{v_{R}} & v_{Ro} \\ 0 & 0 & 1 \end{bmatrix}$$
(15)

In the previous matrices, (u_{Lo}, v_{Lo}) and (u_{Ro}, v_{Ro}) are the coordinates of the principal points in each image view, a_{u_L} , a_{u_R} are the horizontal scale factors and a_{v_L} , a_{v_R} are the vertical scale factors. The parameters c_L and c_R describe the skew of the corresponding image axes. The mean value of parameters c_L , c_R is near zero, thus $c_L=c_R=0$. Making some multiplications from relations (13) and (14) the following systems of equations are derived:

$$\begin{bmatrix} u_{L} \\ v_{L} \\ 1 \end{bmatrix} = \lambda \cdot \begin{bmatrix} a_{u_{L}} \cdot (x - x_{oL}) + u_{Lo} \cdot (z - z_{oL}) \\ a_{v_{L}} \cdot (y - y_{oL}) + v_{Lo} \cdot (z - z_{oL}) \\ (z - z_{oL}) \end{bmatrix}$$
(16)

and

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$$\begin{bmatrix} u_{R} \\ v_{R} \\ 1 \end{bmatrix} = \lambda \cdot \begin{bmatrix} a_{u_{R}} \cdot (x - x_{oR}) + u_{Ro} \cdot (z - z_{oR}) \\ a_{v_{R}} \cdot (y - y_{oR}) + v_{Ro} \cdot (z - z_{oR}) \\ (z - z_{oR}) \end{bmatrix}$$
(17)

Where λ is a parameter. By the solution of the previous systems the following equations, providing coordinates of a point in a 3D space are calculated:

$$x = \frac{(u_R - u_{Ro})}{a_{u_R}} \cdot (z - z_{oR}) + x_{oR} \text{ or } x = \frac{(u_L - u_{Lo})}{a_{u_L}} \cdot (z - z_{oL}) + x_{oL}$$
(18)

$$y = \frac{(v_{R} - v_{Ro})}{a_{v_{R}}} \cdot (z - z_{oR}) + y_{oR} \quad \text{or} \quad y = \frac{(v_{L} - v_{Lo})}{a_{v_{L}}} \cdot (z - z_{oL}) + y_{oL}$$
(19)

$$z = \frac{a_{u_{L}} \cdot (u_{R} - u_{Ro}) \cdot z_{oR} - a_{u_{R}} \cdot (u_{L} - u_{Lo}) \cdot z_{oL} + a_{u_{L}} \cdot a_{u_{R}} \cdot (x_{oL} - x_{oR})}{a_{u_{L}} \cdot (u_{R} - u_{Ro}) - a_{u_{0}} \cdot (u_{L} - u_{Lo})}$$
(20)

To find the form of final equations, adapted to PSVS, some simplifications were made. These simplifications are:

$$x_{oL} = -\frac{b}{2} - m, y_{oL} = 0, z_{oL} = -\frac{b}{2} + l, \qquad x_{oR} = \frac{b}{2}, y_{oR} = 0, z_{oR} = -\frac{b}{2}$$
(21)

Where the parallel displacement m and the shifting l (Fig. 4) due to refraction phenomena in mirror (1) are given from equations (11) and (12).

Substituting the equal values from (21), equations (18-20), are simplified to:

$$x = \frac{1}{a_{uR}} \cdot \left(z + \frac{b}{2}\right) \cdot \left(u_{R} - u_{Ro}\right) + \frac{b}{2} \text{ or } x = \frac{1}{a_{uL}} \cdot \left(z + \frac{b}{2} - l\right) \cdot \left(u_{L} - u_{Lo}\right) - \frac{b}{2} - m$$
(22)

$$y = \frac{1}{a_{vR}} \cdot \left(z + \frac{b}{2}\right) \cdot \left(v_R - v_{Ro}\right) \text{ or } y = \frac{1}{a_{vL}} \cdot \left(z + \frac{b}{2} - l\right) \cdot \left(v_L - v_{Lo}\right)$$
(23)

$$z = \frac{a_{uR} \cdot a_{uL} \cdot (b+m) + a_{uR} \cdot l \cdot (u_L - u_{Lo})}{a_{uR} \cdot (u_L - u_{Lo}) - a_{uL} \cdot (u_R - u_{Ro})} - \frac{b}{2}$$
(24)

Equations (22-24) are more simplified, if the origins of images from the two different views coincide and the scale factors horizontally and vertically are equal. Then the relations in (25), as result of mirrors alignment in PSVS and careful calibration of virtual cameras, are valid.

$$u_{Lo} = u_{Ro} = u_{o}, \quad v_{Lo} = v_{Ro} = v_{o}, \quad a_{uR} = a_{uL} = a_{u}, \quad a_{vR} = a_{vL} = a_{u}$$
(25)

The simplified equations are:

$$x = \frac{1}{a_{u}} \cdot \left(z + \frac{b}{2}\right) \cdot (u_{R} - u_{o}) + \frac{b}{2} \text{ or } x = \frac{1}{a_{u}} \cdot \left(z + \frac{b}{2} - l\right) \cdot (u_{L} - u_{o}) - \frac{b}{2} - m$$
(26)

$$y = \frac{1}{a_v} \cdot \left(z + \frac{b}{2}\right) \cdot \left(v_R - v_o\right) \quad \text{or} \quad y = \frac{1}{a_v} \cdot \left(z + \frac{b}{2} - l\right) \cdot \left(v_L - v_o\right) \tag{27}$$

Equations (26-28) correspond to the first case of mirrors location and alignment as it is described in a previous section. According to the second case of mirrors location and alignment, equations (30-32) are derived. Coordinates of the optical centers O_1 and O_2 are given from the relations in (29):

 $\frac{\cdot (b+m) + l \cdot (u_L - u_o)}{u_L - u_R}$

$$x_{oL} = -\frac{b}{2} - m - l, \ y_{oL} = 0, \ z_{oL} = -\frac{b}{2}, \ x_{oR} = \frac{b}{2}, \ y_{oR} = 0, \ z_{oR} = -\frac{b}{2}$$
(29)

$$x = \frac{1}{a_{u}} \cdot \left(z + \frac{b}{2}\right) \cdot \left(u_{R} - u_{o}\right) + \frac{b}{2} \text{ or } x = \frac{1}{a_{u}} \cdot \left(z + \frac{b}{2}\right) \cdot \left(u_{L} - u_{o}\right) - \frac{b}{2} - m - l$$
(30)

$$y = \frac{1}{a_v} \cdot \left(z + \frac{b}{2}\right) \cdot \left(v_R - v_o\right) \quad \text{or} \quad y = \frac{1}{a_v} \cdot \left(z + \frac{b}{2}\right) \cdot \left(v_L - v_o\right) \tag{31}$$

$$z = \frac{a_u \cdot (b + m + l)}{u_L - u_R} - \frac{b}{2}$$
(32)

According to the previous analysis, coordinates of the tracks of a point in 3D space, in a complex image, have different values along *X*-axis but the same values along *Y*-axis. Solving equations (27) or (31) in relation to v_R and v_L , the difference $v_L - v_R$ represents the difference in coordinates of the tracks of a point *P* along *Y*-axis (*Y* disparity) respectively:

$$v_{L} - v_{R} = y \cdot a_{v} \cdot \frac{1}{\left(z + \frac{b}{2} - l\right) \cdot \left(z + \frac{b}{2}\right)}$$
 (a) and $v_{L} - v_{R} = 0$ (b) (33)

It is concluded that when the first set of equations is used (26-28) the two tracks of point P in the complex image are not found in the same line (33(a)). However, this deviation creates a measurement error less than one pixel, which it is decreased as the depth z is increased. Consequently, it is considered that $v_L - v_R \cong 0$. When the second set of equations (30-32) is used (with the proper location and alignment of mirrors), the tracks of a point P are found in exactly the same scan line as the equation (33(b)) shows.

5. Correspondence Algorithm - Basic Concepts

The proposed correspondence algorithm belongs in high-level feature-based algorithms and particularly in algorithms that can find correspondences in curves (Dhond & Aggarwal, 1989) (Goulermas & Liatsis, 2001). It is based on the concept of seeds and it is executed in two stages. To implement the proposed correspondence algorithm, a complex image or a stereo pair of images are initially processed. In the application developed in Visual C++ (Pachidis et al., 2002), (Pachidis & Lygouras, 2006), (Pachidis et al., 2006), a variety of filters

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(28)

and edge detection methods may be used. In the final edge images, the desired edges are selected as left view edges, in a semi-automatic procedure; i.e., by coloring a pixel manually and then by propagating the pixel to the whole edge. When all the desired edges are colored, with different color values, the corresponding edges are detected. In an automatic procedure, each left view edge is automatically selected first, the corresponding edge is detected and the whole procedure is repeated until all the pairs of corresponding edges are detected. Three criteria are used to select the corresponding edge:

- 1. The horizontal upper and lower limits of the initial edge plus a small permissible deviation measured in pixels.
- 2. The number of pixels in each initial edge extended by a predefined percentage of the initial number of pixels.
- 3. The criterion of the most probable edge. According to this criterion, the most probable candidate edge corresponds to the maximum population of pixels at the same distance from the initial image. At this distance, at least one pixel of the candidate edge is detected.

Using this algorithm the selection and processing of 11 independent edges or lines with different colors, of an image of the same scene, is possible. The results, namely, the color of points, their image plane coordinates and the disparities are stored in a matrix and at the same time in a file for future use.

An example is illustrated in Fig. 6(a). The color of the initial desired edge is on gray-scale. The other edges are excluded when the first two criteria are applied. Only one of them has the same upper and lower limits and a smaller number of pixels than the predefined one. For the application of the third criterion, seven points are automatically selected from the initial edge. After the criterion is applied, only one seed is found. This seed is propagated and the corresponding edge is created. Then, having implemented the second stage of the algorithm, the corresponding pairs of points are found. This mapping is illustrated with the parallel lines in Fig. 6(b).



Figure 6. The correspondence procedure is illustrated. a) In the first stage, seven points are selected for correspondence from the desired edge. Only one corresponding point was found. b) In the second stage, thirty corresponding pairs of points were found. Parallel lines show this mapping

6. Complex Image Separation and Stereo Images Reconstruction

PSVS, as it was presented right here, could be successfully used to calculate coordinates of random points in space, as well as to find edge or point correspondences of objects in any depth. This system, contrary to other monocular systems, captures two different stereo views in a single shot and with accuracy in measurements better of previous systems because of the angular field of view. The disparity values, detected by the system for an object, are the same with an ordinary stereo system with two cameras. But PSVS is faster and cheaper than an ordinary stereo system (one camera, one frame grabber card, one shot, one image processing). Using a high frame rate camera could be used to any application needs a fast vision system. In systems, where accurate measurements are required, in small distances, it can be used with success. Our system was initially developed for an arc welding system where the camera and the torch are mounted on the end-effector of a PUMA robotic manipulator. In this application, the PSVS is near the torch and consequently scene views are simple. A plethora of robotic tasks and procedures can be successfully manipulated by using PSVS (Pachidis et al., 2005).

When calculation of point locations in separated views of a scene is desirable, the separation of the complex image into a pair of stereo images is required. After their initial separation, the left and right images are reconstructed and can be processed as images of an ordinary stereo system. The complex image separation is examined in two cases. In the first case, a monochrome CCD camera is used. If $I_R(x,y)$, $I_L(x,y)$ and $I_C(x,y)$ are functions of the right, left, and complex images respectively, then the intensity of each pixel of the complex image is given by:

$$I_{c}(x,y) = k I_{R}(x,y) + (1-k) I_{L}(x,y)$$
(34)

where k (0<k<1) is the portion of the reflecting and the transmitting radiation from the beam-splitter. Here, k=0.5 (50% beam-splitter). In this case the intensities of the corresponding pixels of the right and left images are added and the separation of the complex image is not possible. Generally the intensities of the corresponding pixels of these sub-images, in each location, have different intensities.



Figure 7. Complementary spatial filters

For the separation of a complex image into a pair of stereo images, the concept of "spatial filters" is introduced. With the term "spatial filters" we consider filters made from plastic film with specific form of transparent and black areas, i.e. chessboard like with squares, or rectangles, or parallel lines. The filter of one view must act complementary to the filter of the other view (Fig. 7). The size of still elements is determined to be equal or multiple of the apparent size of a pixel in the distance where the filters are mounted on the PSVS. The filters are mounted on the front view of PSVS creating this way shading areas to left and right sub-images. As these images are superimposed, illuminated areas of the initial images create the complex image. For the separation of the complex image is required:

- 1. Alignment of the spatial filters by means of the regulators adapted on the PSVS and the related software developed for this reason.
- 2. Storage of the initial images (mask-images) captured by each view separately, in white background (white scene). In normal operation, these images are used for extraction of the pair of images from the complex image.

Then, separation of a complex image into a pair of stereo images is possible by selecting from the complex image only pixels that their corresponding pixels to each mask-image pixels have intensities greater than zero. The intensity of each pixel of mask-images is defined as $I_{RM}(x,y)$, $I_{LM}(x,y)$, for the right and left image respectively. Then, the intensities of pixels of the right and left images are of the form:

$$I_{R}(x,y) = \begin{cases} I_{C}(x,y) & \text{if } I_{RM}(x,y) > 0\\ 0 & \text{if } I_{RM}(x,y) = 0 \end{cases}$$
(35)

$$I_{L}(x,y) = \begin{cases} I_{C}(x,y) & \text{if } I_{LM}(x,y) > 0\\ 0 & \text{if } I_{LM}(x,y) = 0 \end{cases}$$
(36)

These images have black areas and areas with pixel intensities from only one view. For the reconstruction of these images, we borrow a concept and the related theory used in error recovery approaches for MPEG encoded video over Asynchronous transfer Mode (ATM) networks. From the proposed approaches, spatial error concealment has been adopted (Salama et al.,1995), (Salama, 1999), (Asbun & Delp, 1999). The method is used to reconstruct video images after their reception through the net. Because of the important percentage of black areas in the separated images, the above method, that is the estimation of missing blocks by using spatial interpolation, was modified and adapted to the requirements of this specific application.

According to our method two new concepts were used. The first one is the estimation of each block's start point (up and left pixel) as well as of the size of the block. Then the size of the block continuously changes as block pixels are reconstructed. The second concept is referred to the sequence each pixel in a block is examined. We propose a method, called "the Meander Method (MM)", where pixels in a block are scanned from the start point to a block center pixel, following a circular path, so that a meander to be created (Fig. 8).





Figure 8. A typical block (black pixels) and a meander are depicted. With A and B, the reconstruction of two pixels from the adjacent non-black pixels is presented.

MM is more efficient than simple spatial error concealment, permitting the reconstruction of variable size blocks with the block densities appeared to the separated images. If the block is restricted to one black pixel the new value of it is the mean value of the 4-neighbor pixels surrounding the pixel. If the coordinates of a start point in a block are (k, l) and the size of the block is *nxo*, the intensity of each black pixel is calculated by using the following equation:

$$I(k+i,l+j) = \frac{o - \left(j + \frac{1}{2}\right)}{\lambda \cdot o} \cdot I(k+i,l-1) + \frac{j + \frac{1}{2}}{\lambda \cdot o} I(k+i,l+o+1) + \frac{n - \left(i + \frac{1}{2}\right)}{\lambda \cdot n} \cdot I(k-1,l+j) + \frac{i + \frac{1}{2}}{\lambda \cdot n} \cdot I(k+n+1,l+j)$$
(37)

Where *i*, *j* are the variable indices in the block and λ is a parameter that determines the number of terms. Factors, multiplying pixel intensities, determine the contribution of each term to the final intensity.

When the whole image has been reconstructed, a proper smoothing filter is implemented to each image. The basic steps of the proposed algorithm are:

- 1. Scan each image from the upper left corner and find the start point and size of each black area in the image according to a pre-specified threshold.
- 2. Store the parameters in a matrix (start point location, *n*, *o*, dimension).
- 3. For each shape, beginning from the start point, move right and down and replace the intensity of a black pixel with a new value, calculated from adjacent non black pixels.
- 4. Repeat the procedure until all black pixels of the shape to be replaced by non-black pixels.
- 5. Repeat steps 3 and 4 for all black pixels of shapes until the whole image to be reconstructed.
- 6. Apply a smoothing filter to each image of the pair of the reconstructed images.

A number of problems are encountered by trying to use this method. If the shape's size is too small, diffusion of images and Moiré effects are observed and the complex image cannot be separated. From the other side if the shape's size is large the separation of the complex image is possible but the reconstruction has as result low quality images. An important portion of the information is lost.

In the second case for our study a simple color camera was used. For a color image, $I_{Color}(x,y)$, let be $I_{Red}(x,y)$, $I_{Green}(x,y)$ and $I_{Blue}(x,y)$ the gray scale images derived from the color image by using the RGB model. The idea here is to filter the initial views by using dichroic red and blue filters in each input view of PSVS. These filters are mounted again on the front view of PSVS but no alignment is necessary. Then the color image will be:

$$I_{C}(x,y) = I_{Color}(x,y) = k I_{Red}(x,y) + (1-k) I_{Blue}(x,y)$$
(38)

The red filter is placed in front of the left virtual camera and the blue filter in front of the right camera. The red filter operates as high pass filter with frequency f>600nm where the blue filter behaves as a low pass filter with frequency f<500nm. Then by splitting the color complex image captured by PSVS the left as red and the right as blue image of a stereo pair of images are created. Because of the frequencies cut of the previous filters a small portion of the green image might be appeared. Using this method, problems can be created if there are reflections on filters. Problems could also be created if the filters used have a common area in spectra. In such a case the complex image is not completely separated. The gray scale images, generated by the above method can be directly used for processing. However, if it is necessary to have gray scale images with normal distribution of pixel intensities, as it happens when a single camera captures a gray scale image, pixel intensities of the generated image could be replaced by new pixel intensities by means of an intensity map. This map might be created taking into consideration pixel intensity changes after their filtering through a color filter (here red and blue).

If a monochrome camera and the previous color filters are used then the separation is possible for simple scenes using histogram functions. The separation could be made because the effect of these filters to gray scale images is to emphasize some colors more than others.

7. Experimental Results

In experimental results presented in this section, PSVS is mounted on the end-effector of a PUMA 761 robotic manipulator or on an aluminum tube. Depending on the experiment, two Pulnix monochrome cameras, models TM-520 and TM-6705, two parallel IEEE-1394 (firewire) cameras composing a stereovision system, as well as a typical color camera for the reception of color images are used. The first case of mirrors alignment is examined. The whole procedure is supported by two personal computers, running Windows. In the first computer, at 350 MHz, the developed robotic software application, called *HumanPT*, is installed. An important number of operations and applications can be executed by means of *HumanPT* (i.e. high level robot control, visual servo control, image processing, communication, calibration, e.t.c.). In the second computer, at 700 MHz, a small part of *HumanPT* is installed (Pachidis et al., 2006). This part is responsible for the reliable and stable communication of the computer (server) with the robot controller through ALTER communication port at 38400 bps and with the first computer (client) through Ethernet.

7.1 Examples of Complex Images

Images of Fig. 9 are captured by means of PSVS from the environment of a PUMA 761 robotic manipulator. Images are referred to simple scenes, where the two views are separately appeared and to more complicated scenes where the different views of objects are superimposed.



Figure 9. (a) Simple complex image captured by means of PSVS (b) One image where the overlapping of the ashtrays is shown. (c) (d) Images of complex scenes are presented

(d)

(c)

7.2 Measurements Accuracy

To test the accuracy in measurement for different distances, a pattern with circular areas is used. Distances between the centers of the circular areas are 20 mm and their diameters are 10 mm. The manipulator is moving, along the world coordinate system Z-axis (axis of the world coordinate system, established on the robot), 50 mm each time.

Totally, sixteen complex images are captured by means of PSVS (Fig. 10). After the initial processing of these images (filtering, conversion to binary, Roberts edge detection), geometric centers of two circular areas per image are found. The measured and the calculated distance in mm and the distance error in mm with respect to the calculated depth z are illustrated in Fig. 11(a) and (b) respectively.

As a second experiment the complex image of a pair of pliers is processed (Fig. 12(a)). After the initial processing (mean filtering, conversion to binary image, median filtering, Roberts edge detection) and the implementation of the correspondence algorithm, image coordinates of 500 points for this pair of pliers, are calculated. The disparity map is illustrated in Fig. 12(b).





Figure 11. a) Distance Measured and Calculated vs. Depth z. b) Distance Error vs. Depth z

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Figure 12. a) The complex image of pair of pliers. b) The disparity map

7.3 Comparison With Other Systems

To compare the performance of PSVS with respect to a standard stereovision system and to have the same measure, two parallel IEEE-1394 (firewire) cameras are used composing a stereovision system. The baseline length b of this vision system is again 10 cm (as PSVS). This stereovision system is calibrated (Zhang, 2000) and (Zhuang et al., 1994). The stereo system is mounted on a square profile 8x8 cm aluminum tube two meters long. Along this tube a target similar with this of Fig. 13(a), mounted on a specially constructed thick aluminum base, can be accurately moved. Stereo pair of images are acquired every 100 mm from 500 to 1900 mm. The experiment is repeated using one camera in the same location with respect to Z-axis and PSV apparatus instead of the stereovision system. Complex images are captured again every 100 mm. Images acquired by means of the two vision system are processed using the proposed correspondence algorithm. In each case, the depth z is calculated and the results of errors are illustrated in Fig. 14.



Figure 13. (a) The original pattern (b) A sample of complex images

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Figure 14. Errors measured with respect to the real distance of each vision system from the target

Comparing the results in Fig. 14 it is realized that a) the accuracy of PSVS is much better than the accuracy of the standard stereo vision system along *Z*- axis, b) PSVS can measure in smaller distances (smaller blind zone). Moreover cameras parallelism was a difficult procedure (that is why rectification in a stereo pair of images is usually implemented increasing the computational cost) and a computer is always necessary for the alignment of cameras while alignment of PSVS mirrors is possible (when it is necessary) by means of a simple laser beam. Comparing with the results presented in papers (Teoh & Zhang, 1984), (Lee et al., 1999) and (Lee & Kweon, 2000), results in Fig. 14 are more accurate also.

7.4 Complex Images Separation

7.4.1 Monochrome Camera and Spatial Filters

In this part of experimental results the procedure of the separation of a complex image by using a monochrome camera and spatial filters is presented. The filters used are of the form of Fig. 7. The dimension of each square in the spatial filters is 2X2 mm. These filters, first, are carefully aligned. The alignment is made by means of a part of the software application *HumanPT* (<u>http://users.otenet.gr/~pated</u>). During the alignment, the scene (the background) is white. Thus, images captured from PSVS, by means of spatial filters, contain only spatial information. When the alignment is completed the captured image must be an almost white image of the area of interest. Then, the right side of the apparatus is closed and an image is captured. This image contains information only for the left filter. The same procedure is repeated for the left side and an image containing information for the right filter is captured. These two initial images are stored. Following the above steps the system is ready to separate a complex image.

An example of this procedure in case of PSVS is illustrated in Fig. 15. In this example, mirrors are not completely regulated but for the separation, the two spatial filters are carefully aligned. The pair of images can be reconstructed by using the theory of section 6. The results are illustrated in Fig. 16. As smoothing filter a median filter is used.





Figure 15. Complex image separation a) The complex image b) The left view (right image) c) The right view (left image)



Figure 16. Complex image reconstruction and smoothing a), b) images reconstruction, c), d) Filtering with a median filter



Figure 17. Complex color images separation

7.4.2 Color Camera and Color Filters

To separate an image by using a color camera, as it mentioned previously, blue and red dichroic filters are mounted on the apparatus closing this way the front area of PSVS. No alignment is necessary and the apparatus is ready to capture images.

The complex image is the superposition of a "red" and a "blue" image. The separation of two complex images captured by means of PSVS and using a color camera is illustrated in Fig. 17. Some areas in the new images, as result of color filtering, are emphasized. However, these images can be used as they are for processing.

8. Conclusions and Future Plans

A system for stereovision based on mirrors and a beam-splitter, was presented. PSVS, as it is called, is a low cost system with well-located features (accuracy, stability, compact construction). Equations and relations, concerning its construction and calculation of points coordinates in 3D space, taking into consideration refraction phenomena due to beam-splitter, were derived. Keeping always in mind the low construction cost and the possibility to easy constructed and used by anyone, new methods were introduced. These methods concern the correspondence algorithm used complex images separation and stereoscopic images reconstruction. Some problems during separation and reconstruction of a spatial filter on a beam-splitter). The PSVS, as it is obvious from the experimental results can be successfully used for robotic applications. It was successfully used in different tasks, methods for robot path generation and stereo visual servo control. Moreover, it can be used to measure in space (to measure big distances) or in underwater applications.

Our future plans include implementation of PSVS in more robotic applications, the development of a new PSVS calibration method, the improvement of complex images separation method. They also include the construction of different in size PSVS devices that could accurately measure ultra small distances in the micro world or distances in space.

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Scene Reconstruction Pose Estimation and Tracking Edited by Rustam Stolkin

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This book reports recent advances in the use of pattern recognition techniques for computer and robot vision. The sciences of pattern recognition and computational vision have been inextricably intertwined since their early days, some four decades ago with the emergence of fast digital computing. All computer vision techniques could be regarded as a form of pattern recognition, in the broadest sense of the term. Conversely, if one looks through the contents of a typical international pattern recognition conference proceedings, it appears that the large majority (perhaps 70-80%) of all pattern recognition papers are concerned with the analysis of images. In particular, these sciences overlap in areas of low level vision such as segmentation, edge detection and other kinds of feature extraction and region identification, which are the focus of this book.

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