A Pseudo Stereo Vision System as a Sensor for Real Time Path Control of a Robot

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Abstract-In this paper, the design and the construction of a new system for stereo vision using planar mirrors and a single camera is presented. Two superimposed stereo images are received simultaneously as a complex image and using a proper algorithm, disparities and depth of objects of the scene can be obtained. Two virtual cameras are created from this pseudo stereo vision system (PSVS) with exactly the same geometric properties, parameters and angular FOV of the real camera. This vision system has no moving parts, its construction is quite simple and it is mechanically robust. Thus, it is easy for this system to be mounted to the end effector of a robotic manipulator or to a mobile robot.

I. 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.

Using cameras as sensors it is possible to have mainly vision systems with one or two cameras. A stereo vision system is composed of two cameras. For the recovery of a 3-D scene from a pair of stereo image of the scene, it is required to establish correspondences.

The stereo process can be summarized by the following steps: 1) detection of features in each image, 2) matching of features between the 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.

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 cameras may not lie in the same plane also.

In cases of monocular (single camera) stereo vision systems the above problems are reduced. In these systems, a single camera and some mirrors [1-3], or a biprism, [4], [5], properly placed, are used, so that the reception of a stereo pair of images to be possible [6-11]. The correspondence points are usually found on a single line (epipolar line), the intensity differences to these points are reduced and the two virtual cameras which constitute the stereo vision system have the same geometric properties and parameters.

In this paper, the design and the construction of a new apparatus for stereo vision with a single CCD camera, is presented, which is called Pseudo Stereo Vision System (PSVS) and it is composed of a camera and four mirrors. The PSVS has the following properties:

1. The reception of a complex image is permitted from the apparatus and using proper algorithms, disparities and depth of objects of the scene can be obtained.
2. The images have all the advantages of single camera stereo vision systems.
3. The angular Field of View (FOV) of the apparatus is the same with the angular FOV of used camera.
4. The calibration of PSVS is quite easy and it has no moving parts.

In the sections below, the initial idea as well as the construction details and examples of the received images are presented.

This paper is organized as follows. In Section II, the construction details of the new system are presented. In Section III, theoretical analysis of the construction of the apparatus and calculation details of the coordinates of a point using the PSVS are introduced. A correspondence algorithm is presented. In Section IV, experimental results are given. Finally, in Section V, the conclusions of this work are presented.

II. SYSTEM DESCRIPTION

For real time depth calculation, a vision system with the following properties sould be used:

1. It must be able to receive simultaneously two images. (One shot of the camera)
2. It must process these images in a small interval of time. (to find the correspondence points and then to find the depth of each point).
3. It must be a robust, compact apparatus, so that to be reliably used, mounted on the end effector of a robotic manipulator.

The target of this work was the construction of a system with a single camera for reception of stereo images and with no moving parts. Moreover the construction of this system sould be relatively simple so that it can be used in robotic systems and to be relatively cheap. It must be easily calibrated also.

The main idea is based on using three mirrors with a 100% of reflection of their incident light and one mirror which reflects 50% and passes the other 50% of the incident light. Refraction phenomena disappear to first three mirrors using front cover surface of them.

Here, we are considering an orthogonal coordinate system XYZ with origin to the optical center of the real camera, Z axis to be identified with the optical axis, X axis to be on the plane of sheet and Y axis vertical to X and Z axes.
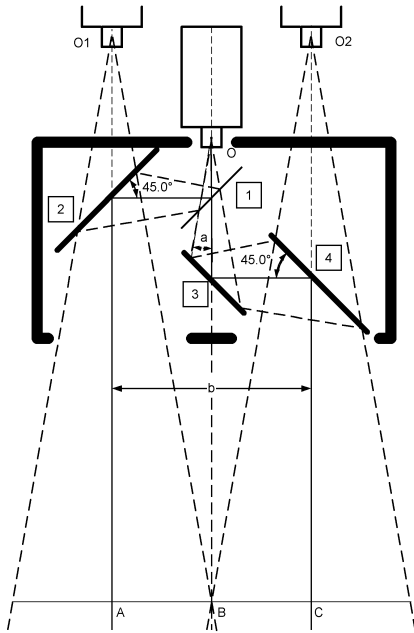

Fig. 1. The PSV system and the two virtual cameras.

Mirrors to this vision system (Fig. 1) form 45° angle with the optical axis (Z axis) of the camera and all of them are vertically mounted to the plane of camera (plane XZ).

The paths which a thin light beam, follows, in two different directions are adjusted so that to be exactly of the same length for the images which are created of the system. Thus, two virtual optical axes are created which correspond to two virtual parallel cameras. These cameras are symmetrically positioned to the Z axis. They have the same geometric properties and parameters (the same of the real camera). Consequently, these cameras constitute an ideal stereo vision 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 which are created from the left and right side of the apparatus. The base line of this stereo system is b and it is the distance between the two virtual parallel optical axes. These images have the same mean luminosity which is the half of the luminosity of the initial images because of the use of mirror (1). (See Fig. 1).
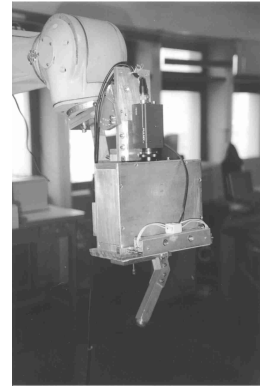

Fig. 2. PSVS mounted on the end–effector of a robotic manipulator.

Problems with correct luminosity are reduced from the system because of the use of a regulated lighting system on the apparatus (Fig. 2). Problems of images shifting because of refraction on mirror (1) are eliminating during the calibration of the system [10].

III. THEORETICAL ANALYSIS OF PSVS

III.1. MIRRORS DIMENSIONS

For the calculation of the mirror dimensions will be first analyzed the general case, where the optical axis forms a random angle ω_1 with a mirror plane. Fig. 3 will help to the analysis which follows. It is desirable here to calculate the length of the side AC of the triangle (AOC).

Lengths AB and BC of the triangle will be separately calculated. After some simple trigonometric calculations we can find that:

$$AB = \frac{OB \cdot \tan a \cdot \cos \omega_1}{\tan(\omega_1 - a)} + OB \cdot \tan a \cdot \sin \omega_1 \qquad (1)$$

Calculation of length BC

The sections BC, OD and DB are given by the relations:

$$BC = \frac{CD}{\sin \omega_1} \qquad (2)$$

$$OD = \frac{CD}{\tan a} \qquad (3)$$

$$DB = BC \cdot \cos \omega_1 \qquad (4)$$

Making again some trigonometric calculations we have that:

$$BC = \frac{OB \cdot \tan a}{\sin \omega_1 + \cos \omega_1 \cdot \tan a} \qquad (5)$$

The side AC results from adding (1) and (5):

$$AC = AB + BC \Rightarrow$$

$$\Rightarrow AC = \frac{OB \cdot \tan a \cdot \cos \omega_1}{\tan(\omega_1 - a)} +$$

$$+ OB \cdot \tan a \cdot \sin \omega_1 + \frac{OB \cdot \tan a}{\sin \omega_1 + \cos \omega_1 \cdot \tan a} \qquad (6)$$
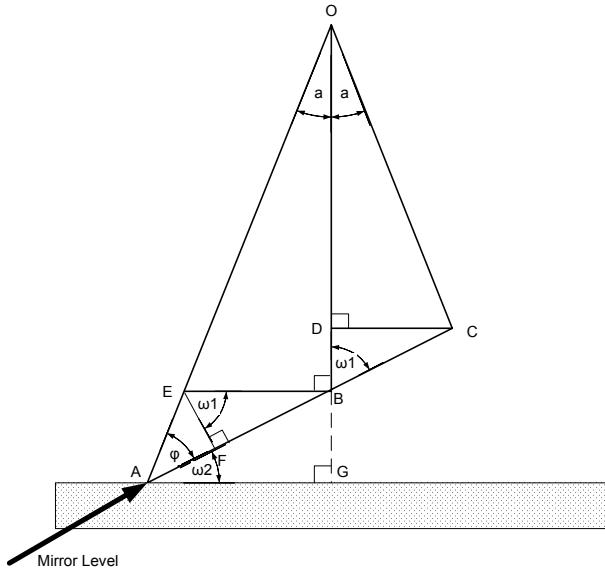

Fig. 3. Mirror dimensions calculation.

Case studies:
1. $\omega_1 = 45°$. Then:

$$AC = AB + BC \Rightarrow AC = \sqrt{2} \cdot OB \cdot \tan 2a \qquad (7)$$

2. $\omega_1 = 90°$. Then

$$AC = AB + BC \Rightarrow AC = 2 \cdot OB \cdot \tan a \qquad (8)$$

III.2. COORDINATES OF A RANDOM POINT TO SPACE BY MEANS OF PSVS

Here, we consider that the refraction phenomena due to mirror (1) are insignificant.

A world coordinate system is established (Fig. 4). The origin of the world co-ordinate system coincides with the optical center O of the lens of the real camera. The Z axis coincides with the optical axis, X axis is parallel with the horizontal axis which passes from two images and Y axis is vertical to the plane XZ. Consequently, the plane XY is parallel with the image plane. The points P′(xl,yl) and P″(xr,yr) are the projections of the random point P(x,y,z) to the left and to the right image respectively.

The optical centers of these cameras, O1 and O2 are displaced by b/2 to the optical center O and their optical axes are parallel to the optical axis (Z axis) of the real camera. The coordinates of the optical centers O1 and O2 are:
$O_1 \rightarrow (xo1,yo1,zo1) \rightarrow (-b/2,0,-b/2)$ and
$O_2 \rightarrow (xo2,yo2,zo2) \rightarrow (b/2,0,-b/2)$

The pinhole camera model will be considered during the calculations.

With the above consideration, the equations which give the coordinates of a random point in space to the world coordinate system are calculated when the length of baseline, the distances xl and xr from the center of image frame on x axis and the active focal length of the camera are known. In reference to Fig. 4 we have:
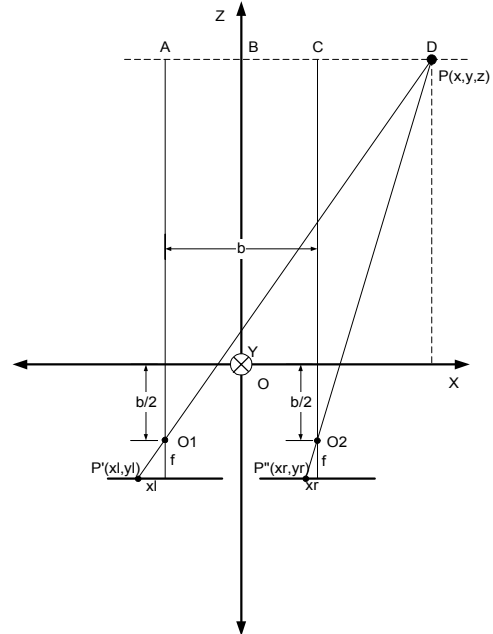

Fig. 4. The projection of a point to the image planes of the two virtual cameras.

$$\frac{xr}{CD} = \frac{f}{z + \frac{b}{2}} \Rightarrow \frac{xr}{x - \frac{b}{2}} = \frac{f}{z + \frac{b}{2}} \qquad (9)$$

$$\frac{xl}{AD} = \frac{f}{z+\frac{b}{2}} \Rightarrow \frac{xl}{x+\frac{b}{2}} = \frac{f}{z+\frac{b}{2}} \qquad (10)$$

$$(9)(10) \Rightarrow \frac{xr}{x-\frac{b}{2}} = \frac{xl}{x+\frac{b}{2}} \Rightarrow$$

$$\Rightarrow xr \cdot (x+\frac{b}{2}) = xl \cdot (x-\frac{b}{2}) \Rightarrow$$

$$\Rightarrow xr \cdot x + xr \cdot \frac{b}{2} = xl \cdot x - xl \cdot \frac{b}{2} \Rightarrow$$

$$\Rightarrow x \cdot (xl - xr) = \frac{b}{2} \cdot (xl + xr) \Rightarrow$$

$$\Rightarrow x = \frac{b}{2} \cdot \frac{xl + xr}{xl - xr} \qquad (11)$$

From the relations (9) and (11) the equation for z is calculated:

$$(9)(11) \Rightarrow \frac{xr}{x-\frac{b}{2}} = \frac{f}{z+\frac{b}{2}} \Rightarrow$$

$$\Rightarrow z = \frac{b \cdot f}{xl - xr} - \frac{b}{2} \qquad (12)$$

Using relation (9), the equation for x is:

$$(9) \Rightarrow \frac{xr}{x-\frac{b}{2}} = \frac{f}{z+\frac{b}{2}} \Rightarrow$$

$$\Rightarrow x = \frac{xr}{f} \cdot (z+\frac{b}{2}) + \frac{b}{2} \qquad (13)$$

The equation for the coordinate y of point P(x,y,z) is given from a similar relation as for x, where the projection to the image plane (image sensor plane) for the right image is yr:

$$y = \frac{yr}{f} \cdot (z+\frac{b}{2}) \qquad (14)$$

If the two sub-images are vertically aligned, as it is the case in PSVS, the corresponding points on image plane for a random point in space will have the same coordinate, namely yr=yl and points will be found to the same scan line.
The above equations, considering refraction phenomena due to mirror (1), are modified as follows:

$$z = \frac{b \cdot f}{xl - xr} - \frac{b}{2} + \frac{xl \cdot l}{xl - xr} + \frac{f \cdot m}{xl - xr} \qquad (15)$$

$$x = \frac{xr}{f} \cdot (z+\frac{b}{2}) + \frac{b}{2} \qquad (16)$$

$$y = \frac{yr}{f} \cdot (z+\frac{b}{2}) \qquad (17)$$

Parameters l and m depend on the mirror (1) thickness d, the refraction coefficient n of mirror (1) and angle ω_1 (Fig. 3).

III.3. CORRESPONDENCE ALGORITHM

Points correspondences, for an object as it is presented in the complex image, are found using a new algorithm. This algorithm permits manually or automatically the matching of edge points of the same object. The basic steps of the algorithm are the following:

1. Find edge points of objects with image processing. (Filtering, edge detection, binary conversion) There is the possibility of using any combination of different filters and edge detection algoritms.
2. Select desired edges from the left side of the complex binary image. To select an edge first a desired color is selected. Then using mouse, with a simple double click on a pixel of the desired edge the whole edge is colored with the predefined color.
3. Find for every selected pixel all edge pixels to the same line and store them.
4. Select from these pixels the set of pixels with the following properties: a) in each horizontal line, these pixels have the same distance from the pixels of the initial selected edge, and b) this set has the maximum number of pixels (shape match). These pixels are called seeds. The number of the desired correspon-ding pixels are predefined. The range of this number is 2-100.
5. Consider these pixels as selected (pixels of the corresponding edge). Selected mean that they have the same color as the color of the initial edge of the left view of the complex image.
6. Select all pixels that are 4-neighbour with seeds or selected pixels of the corresponding edge.
7. Repeat step 6 so that the whole corresponding edge to be selected.
8. Store the coordinates of the corresponding pixels to a matrix as well as the disparity of each pair of corresponding pixels.

IV. EXPERIMENTAL RESULTS

IV.1. IMAGES RECEPTION

Fig. 5 and 6 show images received from the PSVS. The camera used was a PULNIX TM-520. Most of them (Fig. 5a)

contain simple objects in a proper minimum distance so that the separation of these objects to be possible. Some images show cases where the left and right views of an object are partially overlapped (Fig. 5b). In complex images (Fig. 6) where many objects are appeared must be applied a special technique for the separation of objects of the left and right view.

IV.2. DISPARITIES OF SELECTED POINTS

In this stage an image is processed. The outlines of the left and right view of an object in an image of a simple scene can be found. Then the corresponding points will be found using the correspondence algorithm and finally the object will be presented as the left and right outline views of the object in the image (Fig. 7).

The image that will be processed is of Fig. 7(a). First the image is filtered with a median filter, is converted to binary (threshold=92) (Fig. 7(b)) and then Roberts algorithm for edge detection is applied. Using correspondence algorithm left and right views are obtained. In Fig. 7(c), (d), these colored views are illustrated after their inversion and their conversion to gray scale. A 3D graph of disparities versus pixel position is presented in Figure 8.
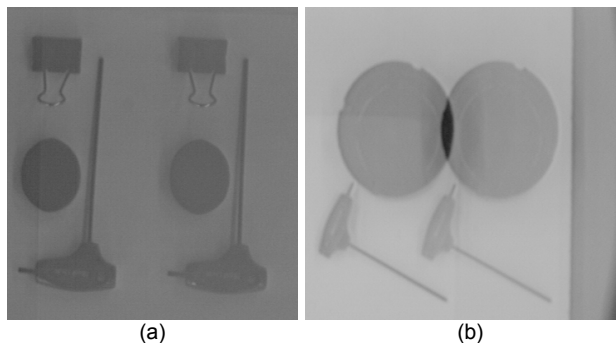

(a)　　　　　　　　　(b)

Fig. 5. (a) Simple superimposed images by means of PSVS, (b) One image where the overlapping of the ashtrays is shown.
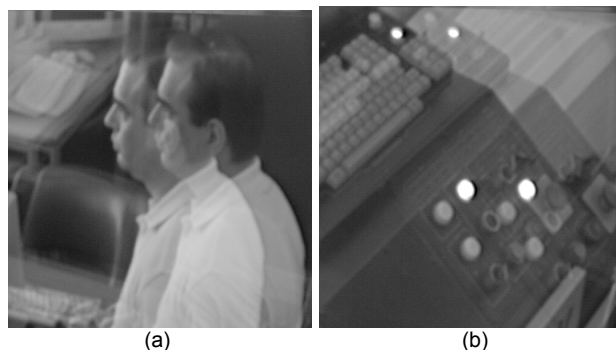

(a)　　　　　　　　　(b)

Fig. 6. Images of complex scenes.

To verify the accuracy of PSVS the pattern of Figure 9(a) was used. The camera was un-calibrated, the length of base line of the system is b=100mm and the estimated active focal

length is f=11.3mm. Figure 9(b) shows the complex image received from the PSVS. The diameter of each circle is d=10mm and the distance between them is a=20mm. Using the robotic manipulator PUMA 761 and a proper program in Val II, the distance from the pattern was increased each 50 mm. A part of the software application, written in visual C++, was used to find the corresponding points and to calculate the values of the depth Z, the values of the diameter of a circle and the values of the distance between centers of the first and last circle. The results for the calculated depth, the circle diameter and the distance between the centers of the first and the last circle are shown in Table I. Fig 10 shows the related graphs.

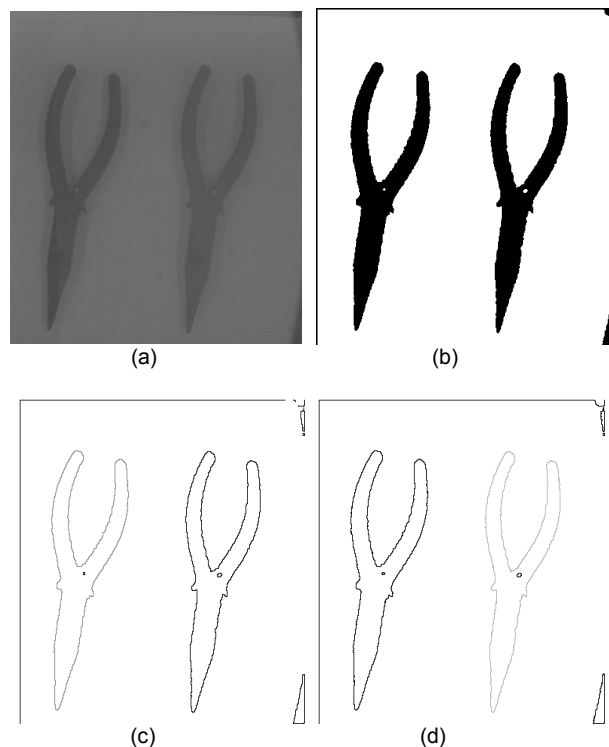(a)　　　　　　　　　(b)

(c)　　　　　　　　　(d)

Fig. 7. (a) Initial image (b) Binary image (c) Left view (inverted) where the selected edge is the left shape. (d) Right view (inverted) where the selected edge, after the implementation of the correspondence algorithm, is the right shape.
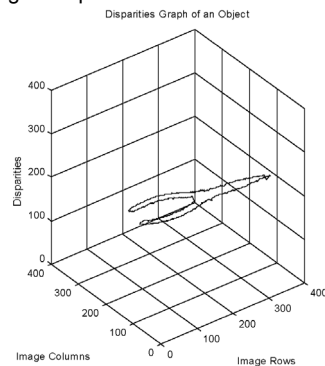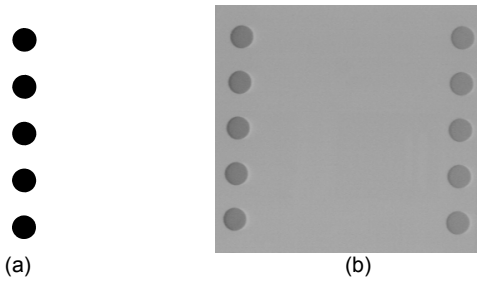

Fig. 8. Disparity Map.

Fig. 9. (a) The original pattern (b) A sample of the complex image.

TABLE I

| Z meas. (mm)	Z calcul. (mm)	d meas. (mm)	d calcul. (mm)	a meas. (mm)	a calc. (mm)
440.0	439.082	10	10.043	80	78.541
489.0	490.747	10	10.174	80	78.399
537.5	539.249	10	10.136	80	78.030
590.0	587.431	10	10.187	80	79.198
636.0	634.599	10	10.288	80	78.956
685.5	684.006	10	9.933	80	79.423
736.0	728.767	10	9.984	80	79.824
786.0	777.394	10	9.942	80	79.362
833.0	830.534	10	9.888	80	79.194
883.5	880.250	10	9.725	80	80.110
928.5	929.444	10	10. 230	80	79.872
977.5	975.734	10	9.950	80	80.117
1027	1025.416	10	9.821	80	80.120
1073	1071.799	10	10.078	80	80.127
1123	1122.425	10	9.721	80	81.178
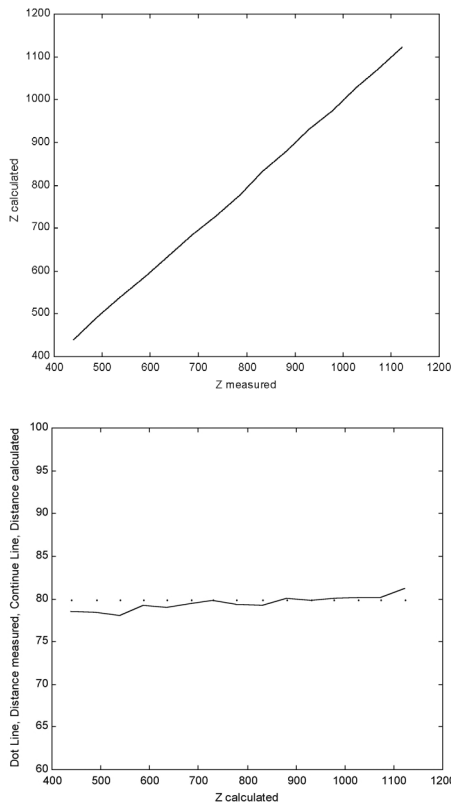
Fig. 10. Z calculated versus Z measured and measured and calculated distance versus Z calculated.

VI. CONCLUSIONS

In this paper, the design and the construction of a new apparatus for stereo vision with a single camera is presented.

The presented PSVS, as it is called, has many remarkable features which permit its use in real time applications:

1. It has no moving parts.
2. It uses only one common CCD camera and in this way the two virtual cameras of the stereo system have exactly the same geometric properties and parameters.
3. It receives a complex image, which is composed of a stereo pair of images, in a single shot.
4. It directly processes a complex image.
5. It can be constructed to any dimensions covering every type of camera, length of baseline, accurate measurement of depth.
6. It is a relatively low cost apparatus and robust mechanically construction so it can be used to every vision system.
7. Using our correspondence algorithm, it is easy to find points disparities.

The experimental results with an uncalibrated camera are better compared to those of some older systems.

With the development of a fast intelligent algorithm for separation of the pair of images it could be used to any complex scene. This vision system combined with a PUMA 761 robotic manipulator could be used to a vision based arc welding system.

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