Passive and Active Stereo Vision for Smooth Surface Detection of Deformed Plates

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***Abstract*— Passive stereo vision is proposed to work in a complimentary manner with active stereo vision for detection of smooth surfaces of deformed plates. Passive stereo vision is used to obtain the boundary of the smooth surfaces, whereas active stereo vision with the projection of structured light is applied to detect the details of the surfaces. An inherent problem in passive stereo vision, called false boundary problem, is identified. The problem is solved by calibrating the structured light in active stereo vision and dynamically placing the cameras in passive stereo vision. The matching criteria in active stereo vision and the sensing process of the proposed approach are presented. An experiment was conducted to test the effectiveness of the proposed approach.**

I. INTRODUCTION

MAKING a machine see objects is one of the most important tasks in artificial intelligence, manufacturing automation, and robotics. To enable a machine to see involves at least two works: sensor detection to obtain data points of the object, and shape representation of the object for object recognition, inspection, and manipulation. A special case in 3-D shape detection using stereo vision is considered in this paper. We are concerned about how to detect the smooth surfaces of metal plates. This study is stimulated by the observation that metal plates are often used in many applications. For example, in shipbuilding, aerospace, and automobile industries, vehicle bodies are essential parts of their products. These bodies are usually constructed by assembling together numerous pieces of metal plates. A vision sensor is chosen for shape detection of these parts because of its harmlessness and lower cost compared to other sensors such as laser range scanners.

Stereo vision is an attractive technique for depth perception, which is suitable in many application domains [1]. However, the operation of stereo vision relies on the changes of the light reflection or radiation from the object surfaces. For objects made of metal plates, it is difficult to use stereo vision to detect their smooth surfaces since the smooth surfaces do not generate matching features in the image pair. This inherent problem prevents stereo vision from being widely used in industrial automation applications where the objects to be detected are smooth.

Active ranging methods by projection of structured light provide solutions to the inherent problem of stereo vision in detecting smooth surfaces. In essence, ranging methods using structured light are still stereo methods. If only one camera is used, the depth of the object can be derived by matching the created features on the surface to the features extracted from the acquired image through triangulation. A typical work using this method can be seen in [2]. Alternatively, a pair of cameras can be used. In such cases, depth of the object is derived by using exactly the same method in stereo vision except that the matching features in the image pair are created by the projection of structured light. By using structured light, it is easier to extract image features from the image pair. Usually, binary images can be generated when illumination of the working environment is well controlled. Most importantly, the correspondence problem in stereo vision becomes simpler since the pattern of the matching features in the stereo images are more regular following the pattern of the light source [2]. The ranging method using structured light is named *active stereo vision*. Conversely, conventional stereo vision without the usage of structured light is referred to as *passive stereo vision* in this paper.

The correspondence problem does not exist in active stereo vision if a single light beam or a single light plane is used as the light source. Only the brightest spot or curve in the images generated by the light beam or the light plane respectively needs to be detected and matched. As successive scanning is required to detect the whole surface, the sensing process will become slow. If a grid of light is used as the light source, there will be more data points in a single detection, and the matching of the created features in the image pair will become complicated. The matching problem can be solved by imposing unique properties on the stripes of the light. Approaches using colors [3], space encoding [4] have been suggested and implemented. These approaches require special devices (color detection) and require multi-frames (space encoding), and are thus not convenient for implementation. It is easier to generate and detect a uniform grid of light. However, matching the features created by the uniform grid is a difficult task. Such a task has been studied by Hu and Stockman. They used constraint propagation to solve such a matching problem in active stereo vision [2]. In order to find the correct surface solution, the surfaces derived from their algorithm have to be back projected to the projection plane. Their algorithms are therefore complicated and time consuming.

In this paper, it is proposed to use dynamic passive and active stereo vision to detect the surface of the deformed plates.

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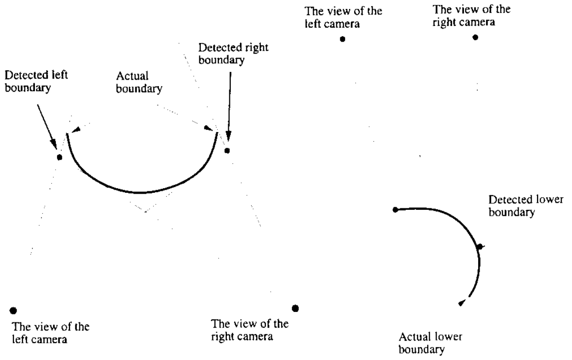


Fig. 1. Two examples of the false-boundary problem in stereo vision.

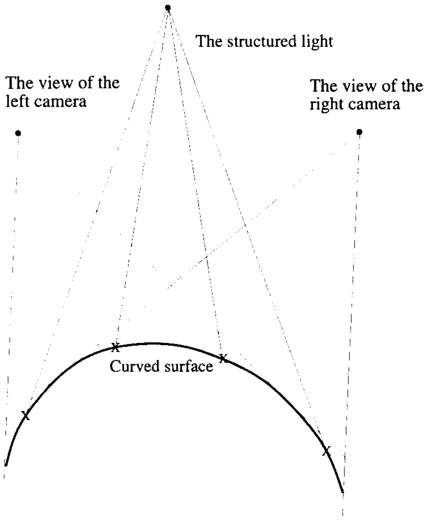
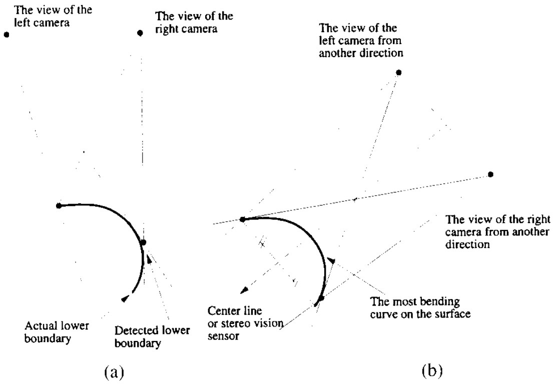


Fig. 2. A mismatch of the created features on the surface. The "x" symbol stands for the created features.

Passive stereo vision is used to detect the surface boundary, while active stereo vision with a projection of the structured light is used to detect the shape of the surface. In active stereo vision, the two cameras and the light projector are mounted on movable platforms such as robot manipulators. As a result, the cameras and the projector can be moved to appropriate positions and orientations for easy detection and matching of the features created by the structured light.

A particular problem of stereo vision in the detection of curved and smooth surfaces is considered. This problem, named the *false boundary* problem, deteriorates boundary detection in passive stereo vision and complicates feature matching in active stereo vision. With the adoption of the dynamic sensing approach, two methods have been developed to move the sensor and projector to adequate positions to prevent the false boundary problem.

In the following section, we will first explain the false boundary problem and how dynamic sensing is used to solve this problem. Then matching criteria in active stereo vision are described in Section 3. The process of dynamic sensing which integrates passive and active stereo vision for detecting smooth surfaces is presented in Section 4. In order to test the effectiveness of the proposed approaches, an experiment was conducted and is described in Section 5. The paper is concluded by Section 6.



(a) (b)

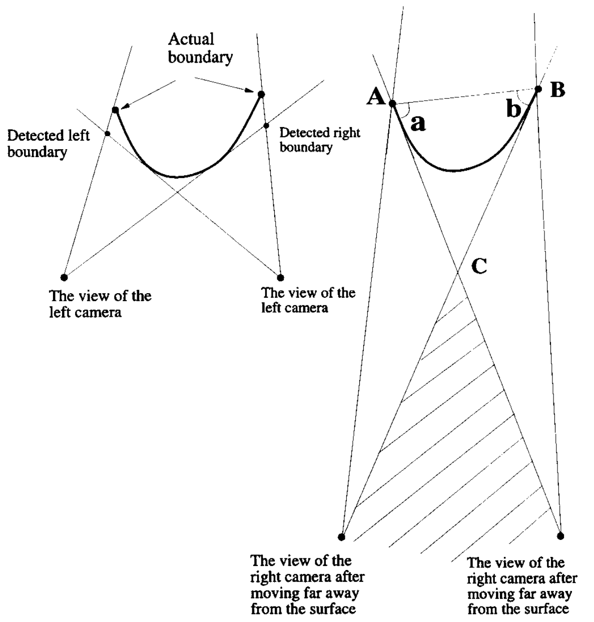
Fig. 3. (a) The false boundary problem occurs. (b) The false boundary problem is nonexistent.

II. False Boundary Problem in Stereo Vision

When a smooth and curved surface is seen by the two cameras of a stereo vision sensor, the boundary of the surface detected in each camera may not reflect the actual boundary of the surface. As a result, the boundary of the surface recovered from matching these two false boundaries in the two cameras will be incorrect. Shown in Fig. 1 are two examples of the false boundary problem in stereo vision. The false boundary problem also affects the correctness of feature matching in active stereo vision. Fig. 2 shows an example of feature mismatching in active stereo vision. In Fig. 2, four features are created by the structured light on the surface. However, each camera can only see three of the four created features.

To solve the false boundary problem, one effective approach is to use dynamic and exploratory sensing. Two methods have been developed using this approach. The first method eliminates the false boundary problem by orienting the center line of the stereo vision in the direction that bisects and is perpendicular to the line segment connecting the two end points of the most bending curve of the surface. Note that a bending curve is the intersection of the plate surface and a normal plane, whereas the normal plane is a plane that includes the center line of the two cameras. The most bending curve is the one which has the largest bending angle between the two end points of the curve. Such an arrangement of the center line will reduce the likelihood of the boundary being hidden from the views of the cameras. This method is illustrated in Fig. 3.

The second method is to move the cameras farther away from the surface. In this way, the view angle of the cameras formed by the curved surface will be decreased and may include the entire surface boundary. This method is illustrated in Fig. 4. The amount of movement of the camera can be



(a) (b)

Fig. 4. (a) The false boundary problem occurs. (b) The stereo vision sensor is moved farther away from the surface to prevent the false boundary problem.

determined from the following analysis. As shown in (b) of Fig. 4, the ending points of the bending curve are denoted as A and B respectively. The two tangent lines intersect at point C and form a shadowed area as shown in (b) of Fig. 4. Clearly, the two cameras used in the passive stereo vision must be in this shadowed area to avoid the false boundary problem. If the angles between AB and AC and between AB and BC are given as a and b, respectively, the distance between point C and line AB can be given by the following equation:

$$L = AB\frac{tga tgb}{tga + tgb}.$$

It can be seen that as the angles a and b become larger, the camera should be moved farther from the surface. The amount of the camera movement can also be determined empirically from the result of active stereo vision. The more the features are mismatched, the farther the cameras should be moved away from the plate surface. It should be noted that the above two methods can be used only when the false boundary problem is detected. The detection of the false boundary problem will be described in Section 4.

III. MATCHING CRITERIA IN ACTIVE STEREO VISION

In this section, we discuss the criteria for matching the features in the image pair. The features created by the structured light are arbitrarily chosen to be an array of squares. The corners or the center of the squares can be used as matching points for deriving the data points in a 3-D space. Other kinds of regular shape features can also be used as matching features, such as circles, triangles, pentagons, and hexagons. Simpler features like circles and triangles provide fewer matching points than those less simple features like pentagons and hexagons. However, the corners of simple features like triangles can be extracted more easily than those less simple features like hexagons. To ease the feature matching problem, we chose a conventional imaging geometry to be used in stereo vision. Such geometry involves a pair of cameras, with their optical axes and image planes mutually parallel and separated by a horizontal distance denoted as the stereo baseline.

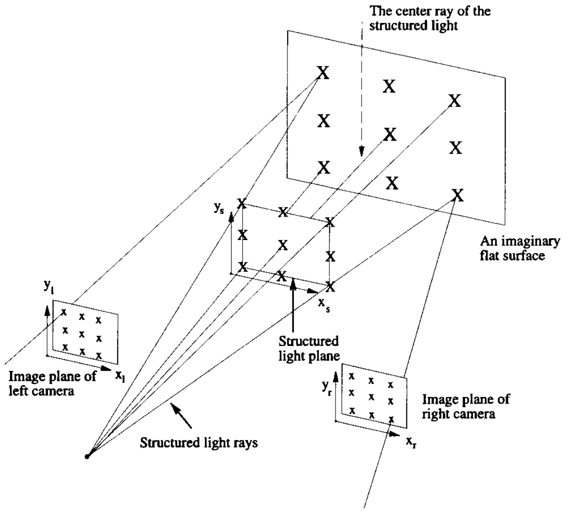
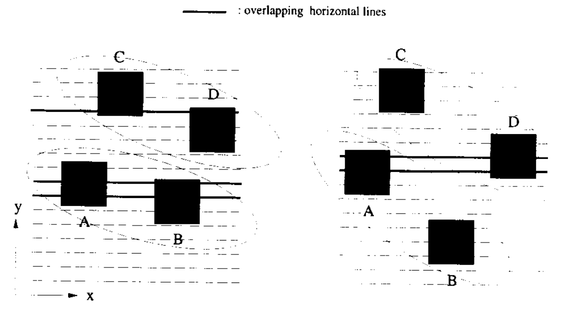


Fig. 5. A well defined case for explaining the matching criteria in active stereo vision. The "x" symbol stands for the matching squares.

Fig. 5 shows an illustration which explains the matching criteria in active stereo vision. A surface is assumed to be flat and parallel to the image planes of the cameras. An imaginary plane, named *structured light plane*, is defined as the intersection of the structured light and an arbitrary plane perpendicular to the center ray of the structured light. The center ray of the structured light is oriented parallel to the optical axes of the cameras, while the structured light plane is oriented parallel to the image planes of the cameras. The created matching squares on the structured light plane will then lie parallel to the x and y axes of the structured light plane. The orientation of the matching squares is chosen the same as that of the structured light plane. For the convenience of the following discussion, we denote each row of squares positioned in the structured light plane or the image plane as a *horizontal square array* in the structured light plane or the image plane, respectively.

The uniqueness constraint and continuity constraint identified by Marr and Poggio [5] can be utilized for matching the squares in such a well defined case. According to the uniqueness constraint, there will be only one square in the images of the cameras corresponding to one square on the flat surface. Adjacent squares in the image will be projected from adjacent squares on the flat surface if continuity constraint is imposed. Here the term "adjacent" means that two squares are next to each other in the x or y direction and no other square is between them. Furthermore, because the conventional imaging



(a) (b)

Fig. 6. (a) A required projection of two horizontal square arrays in the structured light plane to the image plane. (b) A projection that should be avoided. In (a) and (b), squares A and B are projected from the same horizontal square array, and squares C and D are projected from another horizontal square array.

geometry is adopted, the positions of corresponding points in the two images can differ only in the x coordinate [6]. Thus, the horizontal square arrays in the image planes can be matched according to their y coordinates in the image planes. With the use of the uniqueness and continuity constraints, each square in the horizontal square array in the image pair can be matched according to their relative positions in the x direction. The matching criteria described above is not restricted to the case of rectangular surfaces shown in Fig. 5 and can be applied to the nonrectangular cases.

In reality, a deformed plate may have a curved surface. As a result, the positions of the squares in the image pair may be shifted in both the x and y directions from their positions projected in the well defined case. To ensure successful sorting of the squares in the square matching algorithm described in the next paragraph, two conditions need to be satisfied. First, two squares adjacent in the x direction in the structured light plane should be projected to the image plane as two squares adjacent in the x direction with their y coordinates overlapped. Second, a square in the image plane projected from a particular horizontal square array should not be adjacent to the squares projected from the other horizontal square arrays in the structured light plane. Fig. 6 explains these two conditions. The first condition can be satisfied by designing the spacing between two squares adjacent in the x direction in the projection plane to be sufficiently small. The second condition can be satisfied by designing the spacing between two horizontal square arrays adjacent to each other in the structured light plane to be sufficiently large.

The algorithm for matching the squares in the image pair is stated as follows: The squares in each of the two images are sorted into groups, corresponding to the horizontal square arrays in the structured light plane. Since any two squares adjacent in the x direction in the image plane must be projected from the same horizontal square array in the structured light plane, sorting of the squares is an easy task. After the squares are sorted, groups in the image pair can be matched according to the y coordinate of their leftmost squares. The squares of the groups in the image pair can then be matched according to their relative positions in the x direction.

In summary, the conditions that will ensure successful square matching can be stated as follows: First, the projector should be oriented in such a way that the center ray of the structured light is parallel to the optical axes of the cameras and the structured light plane is parallel to the image planes of the cameras (see Fig. 5). Second, according to the matching criteria, it is required that the regions where the squares are to be matched be defined after the application of passive stereo vision. Finally, the condition shown in Fig. 6 regarding the relation of the squares in the image planes should be satisfied. To further ensure this condition, the structured light plane and the image planes should be oriented perpendicularly to the normal vector of the *boundary plane* as much as possible. The boundary plane is defined as the best-fit plane that the overall distance from the detected boundary to the boundary plane is minimum. That is, the overall distance from the detected boundary to the boundary plane is minimum. Mathematically, the boundary plane should minimize the following integral:

$$\oint D(s)ds$$

where $D(s)$ is the distance from a point s on the boundary to the plane. This arrangement will decrease the disparity in the y direction of adjacent squares in the image plane and thus the chance of feature mismatching.

IV. SENSING PROCESS

Two kinds of calibration are necessary for the dynamic operation of vision sensing. The robotic hand/eye calibration of the stereo vision sensors is designed to obtain the relative pose between the robot hand and the cameras. The other kind of calibration is structured light calibration, designed to obtain the equations that describe the structured light in the coordinate system of the robot hand holding the projector. In the following, a simple robotic hand/eye calibration method and how it is used to calibrate the structured light are first described. Then the process of dynamic sensing for detecting curved/smooth surfaces is presented.

A. Robotic Hand/Eye and Structured Light Calibration

There are three major steps in the proposed hand/eye calibration method. The rotation angle of the target block and the orientation of the optical axis of the camera are first obtained by using active movement of the camera. Then, the positions of the target block and the optical axis are derived by using the coordinates of two intersection points of the optical axis with the target block. Finally, the last step is to perform two-plane camera calibration [7] by moving the camera to two different positions where the image is parallel to the target block. The target block seen by the camera at these two positions can be used as the two calibration planes required in two-plane camera calibration.

A simple trigonometric relation between the optical axis and the target block is utilized in the first step. In deriving the rotation angle of the target block, the robot hand holding the camera is moved in the robot x direction without changing its orientation. The rotation angle is exactly the angle between the x axis of the target block and the intersection segment of the optical axis on the target block. Similarly, to derive the orientation of the optical axis, the camera is moved in the z direction of the robot coordinate system. The two intersection segments that result from these two movements and the amount of these movements of the camera can be utilized to derive the orientation of the optical axis. In order to identify the position of the intersection of the optical axis with the target block, the target block is placed parallel to the x-y plane of the robot coordinate system and is designed to be a checkerboard with three distinct grey levels. A detailed description of the proposed hand/eye calibration method can be found in [8].

The structured light calibration can be performed by using the same method for calibrating the optical axis described above. In structured light calibration, the intersection points of the structured light rays at the target block are detected by the calibrated robot "eye." For easy detection of these intersection points, the target block should be white colored and certain criterion should be designed to match these intersection points to their corresponding structured light rays.

B. Three Stages of Sensing Process

In the first stage, passive stereo vision is applied to obtain a rough boundary of the surface. In the literature, there are many approaches proposed to solve the matching problem in passive stereo vision [6]. However, passive stereo vision is not the emphasis of this research. We consider a specific working environment that will simplify the implementation of passive stereo vision, instead of a general environment considered in [6]. The working environment is assumed to be dark with light illuminated from the top to the black ground. As a result, it will be easy to detect a rough surface boundary that will provide guidance for the movement of the cameras in the second stage of sensing.

In the second stage of the sensing process, the vision sensor is moved to a closer position to the surface so that the distance between the cameras and the surface will be within the effective focal length of the cameras. In addition, the image planes are oriented as perpendicular to the boundary plane as described in Section 3. The surface boundary is detected more accurately by applying passive stereo vision again. The boundary detected by passive stereo vision in this stage will define the area where active stereo vision should be applied.

In the third stage of the sensing process, the projector is moved to a proper position and orientation to project a structured light on the surface. This structured light must satisfy the conditions stated in the previous section. The false boundary problem can be detected by comparing the number of squares extracted in the image pair to the actual number of squares within the surface boundary. If the actual number of the squares is larger than that in either of the two images, the false boundary problem exists. The actual number of squares can be known by checking how many structured light rays are projected within the surface boundary since the position and orientation of the structured light are available from structured light calibration.

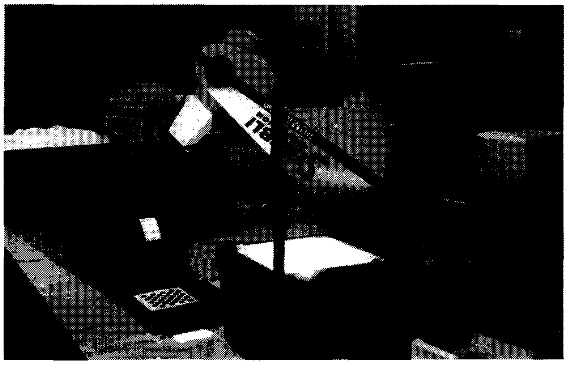


Fig. 7. The setup for the experiment in reconstructing the shape of a plate.

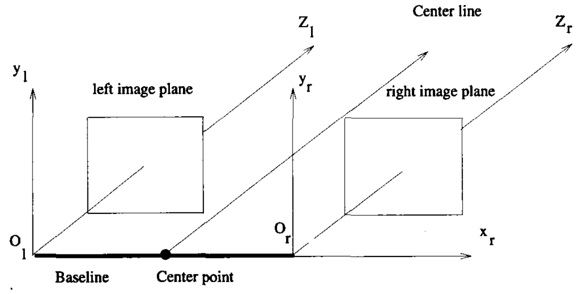


Fig. 8. The structure of a stereo vision sensor with conventional imaging geometry.

V. SHAPE DETECTION OF A DEFORMED PLATE

In order to illustrate the proposed approach, an experiment was conducted to detect the shape of a deformed plate. The procedure and the results of the experiment are described in this section.

A. The Setup of the Experiment

Shown in Fig. 7 is the picture of the setup of the experiment. The target for this experiment is a rectangular plate with 11.65 cm in length and 7.35 cm in width. The plate has a bright white color and is bent by 10° such that a curved surface is formed. A dark background is chosen. An overhead projector is used to project structured light on the plate. One PULNiX TM-540 camera is used and mounted on a PUMA 560 robot arm for the stereo vision. The left and the right images in the conventional imaging geometry of stereo vision are acquired by moving the camera to two different positions. In the following description, this single-camera stereo vision sensor will be treated as if there were two cameras mounted on the robot arm.

B. Exploring Strategy for the Experiment

The mission of the exploring strategy is to determine the pose of the vision sensor and the projector in the three stages of vision sensing. The determination of the pose of the stereo vision sensor is affected by many factors including the resolution, focus, field of view, visibility, view angle, and prohibited regions of the cameras [9]. In addition, the pose of

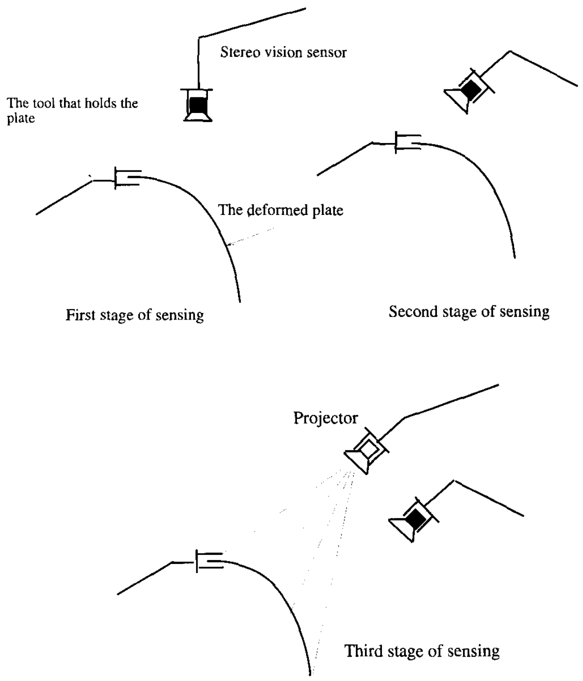


Fig. 9. The process of the vision sensing in detecting the deformed plate.

the center line, the orientation of the baseline, and the distance between the object and the center point of the stereo vision sensor should also be considered. In the following discussion, it is assumed that the length of the baseline is fixed and the focal lengths of the lenses of the cameras are on-line adjustable.

In the first stage of the sensing process, the field of view of the cameras should cover all the possible extent of the plate. The pose of the center line and the orientation of the baseline can be chosen arbitrarily since only a rough boundary of the plate is needed in this stage. Based on the rough boundary, the boundary plane defined in Section 3 can be determined.

In the second stage of the sensing process, with the rough boundary of the curved plate available, the center line of the stereo vision sensor is oriented passing through the geometric center of the plate boundary and perpendicular to the boundary plane. Once the center line is determined, the baseline should be oriented perpendicularly to the direction where the plate is bent most. This arrangement of the center line and baseline of the stereo vision sensor increases the similarity of the shapes seen by the two cameras and thus decreases the possibility of the false boundary problem. The distance between the plate and the center point of the stereo vision sensor should be determined long enough for the field of view of the cameras to cover the extent of the plate. By the above arrangement, a more precise boundary is found from the passive stereo images.

In the third stage of the sensing process, the structured light projector should be oriented in a way that the center ray of the structured light passes through the center of and perpendicular to the boundary plane as defined in the second stage.

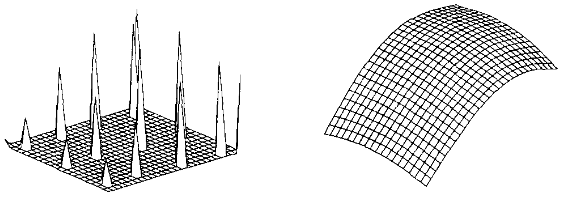

(a) (b)

Fig. 10. (a) The sensed data points of the curved rectangular plate. (b) The interpolated surface of the deformed rectangular plate.

The process of the experiment follows the three stages of the sensing process described in Section 4. The position and orientation of the stereo vision sensor and the projector were determined following the exploring strategy stated above. Fig. 9 shows the process of these three stages.

C. Image Processing Techniques

Four tasks are designed to accomplish the image processing required in passive and active stereo vision: thresholding the image, boundary extraction of the plate surface and matching squares, contour following of the plate boundary and squares, and corner detection of the squares. Bilevel moment preserving thresholding technique introduced by Tsai [10] was implemented for the image thresholding task. The implementation of the other three tasks is modified from the methods introduced by Cabrelli and Molter [11]. As a result, sixteen data points are detected from center points of the sixteen squares in the left and right images by using stereo triangulation method, which is shown in Fig. 10(a).

D. Results

The curved surface of the plate interpolated from the sixteen sensed data points (see Fig. 10(a)) is shown in Fig. 10(b). An interpolation method based on energy minimization is used [12]. In Fig. 10(b), the domain of the plate in the x-y plane is assumed to be a rectangular since the bending of the plate in the x and y direction is very small to be negligible.

A test was conducted to estimate the accuracy of the passive stereo vision. Passive stereo vision was applied to detect the positions of the corners of a square on the target block that was used in hand/eye calibration. The error in depth (z coordinate in the coordinate system of the target block) is within 2 mm and the error in the x and y coordinates is within 1 mm at a distance of about 40 cm.

VI. Conclusions and Discussions

Integration of passive and active stereo vision is introduced in this paper for shape detection. This approach is designed to detect the shape of curved/smooth surfaces of metal plates. The boundary and shape are first roughly identified by passive stereo vision. This identification helps ease the correspondence problem in active stereo vision, whereas active stereo vision detects the shape of the object. In particular, this dynamic passive and active integration approach is shown to be effective in detecting and solving the false-boundary problem embedded in the shape detection of the deformed metal plates. An exploring strategy is developed to assist such a sensing approach.

The three stages of sensing described in Section 4 should be sufficient for detecting surfaces that are not seriously deformed such as those targeted in Section 5. For surfaces that are bent in a large angle that the projection of its actual boundary in the image plane is within the projection of its apparent boundary, the three sensing stages should be applied in different directions and distances, and repeated whenever needed. The development of the exploring strategy for the movement of the vision sensor in such cases will be much more complicated than that in the case described in Section 5.

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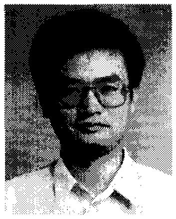

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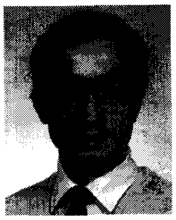

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