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INVESTIGATION OF OBJECT SHADOWS UTILIZATION IN 3D SHAPE RE-CONSTRUCTION USING INEXPENSIVE EQUIPMENT

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Abstract
A technique is proposed in this paper to acquire and re-construct 3D objects utilizing shadow data. The proposed technique is capable to extract object height features that are not directly visible to the camera scene; however, the technique is only valid to acquire object height information for the directions associated with the incident light and the generated object shadows, hence, acquired height features represents the object features that have actually obstructed the incident light. The technique is tested using objects of different shapes. Close to real measurements are gained using the adopted imaging hardware and setup. The obtained results therefore assure the validity of the suggested approach, hence open the way for further implementation in wider applications.

Keyword: 3D, Object, utility, shadow, image, hardware

1. Introduction

It is often the case that users create 3D object models using Computer Aided Design (CAD), however CAD systems require highly trained professional users and usually takes much time to create complicated models, hence they present a bottleneck in real applications [1]. Alternatively, vision-based techniques to obtain 3D object model data automatically by observing real objects may establish a beneficial solution that is of great significant in reverse engineering applications.

Application of 3D object reconstruction has been set as common focus of many published articles e.g. [2-7]. Other methods for 3D surface reconstruction include "shape-from-shading" [8,9] and photometric stereo [10].

The main goal of this paper is to investigate the feasibility of 3D object re-construction by using object's shadows, generated by controlled incident light. A technique is proposed and applied to evaluate its potential in the 3D reconstruction of objects using inexpensive equipment and simple calculations. It is worth noting that the technique is meant to acquire objects height attributes which are not directly visible to the camera; however, the technique is valid only to acquire object height features in the directions associated with the generated shadows. Hence, acquired height features represent the object features that have actually obstructed the incident light. This makes the technique quiet different from "Shape from Shading" technique that relay on acquiring the shape of the object using reflected intensities from the object and reaching the camera [9]. Future application areas of the technique may include the eye-in-hand Robot field to beneficially increase the perception level available for the imaging system, the dimensional measurement of manufactured parts, and the area of reverse engineering utilizing CAD/CAM systems. The technique will work efficiently if the lighting system is well controlled, hence more precise selection of threshold values could be achieved.

2. Concept of Shadows and Illumination

Shadows are closely related to illumination. They are the result of an occluding object that obstructs involved light path. For a scene point to appear illuminated, several distinct events must occur [2]:

(1) Light must be emitted from the light source in the direction of the point in question.
(2) The path followed by the resulting light rays must be unobstructed.
(3) The object must reflect some or the entire incident light into the direction of the camera.
(4) The path of the camera's projection ray to the point must be unobstructed.

If any of these conditions is not fulfilled, then the point will not appear to be illuminated in the image.

3. Hardware Setup

An Epson PC-500 type camera is used to acquire the images of this work. A single light source is used and set in an oblique direction relative to the horizon and only parallel light rays are assumed to intercept the object. Reflected light is then reaching the camera due to the diffused reflection phenomena. Figure (1) shows the system set-up used in this work, whereas Figure (2) represents the symbols employed in the proposed technique. The perpendicular distance between the light source and the base line is denoted by (l), while the distance between the object edge and the light source along the base line is denoted by (d). The symbols (h), (w), and (s) represent the object height, width, and shadow length, respectively.

4. Proposed 3D Shape Re-Construction Technique

The proposed technique acquires 3D features of the object using a single image. Two versions of the single input image are created by processing of the acquired image data. The first is the ***Shadow Image*** that is achieved by converting the image data into a binary image presentation by using an appropriate threshold value, whereas the second version of the image is the ***Object Image*** that is created by eliminating shadow information using a suitable threshold value to enable the detection of the object features. Both Length and width data attributes of the object are then extracted easily from this version of the image; the methodology presented in [11] was adopted to achieve this task using the calibration model gained in this work.

The suggested technique of object height recovery is based on the trigonometric relationships of a right triangle. The technique determines the height of an object from a number of known parameters, Figure (2).

The relationship formulation of similar triangles could yield the followings:

$$h = \frac{l \times s}{d + w + s} \qquad (1)$$

Both the ***object*** and ***shadow images*** are then subjected to further processing to obtain 3D shape re-construction by computing local heights at each object pixel location.

5. Image Calibration

The images in this work are calibrated to achieve required dimensional presentation. The calibration was achieved using the top view of a circular object of (25 mm) diameter. A set of images obtained using different camera heights. Each image is then processed to obtain the average diameter of the circular component in pixel units. Therefore, the actual object diameter is compared to the extracted diameters. The mathematical presentation of the equation that best fits the acquired results is given by:

$$c = 0.0083\, s^2 - 3.4\, s + 450 \qquad (2)$$

where s presents acquired entity length within the image in pixel units and c presents the physical camera height in mm units.

To evaluate the assumed case of that only parallel rays of light intercepts the object, a set of experimental tests was conducted. A block gauge of (10 mm) height is captured using a camera height (c) of 150 mm. Different light positions (p) along a line that is inclined from the horizon by 45^{o} are used in the range of 140 mm to 160 mm. The object shadow length (s) is extracted from each setting case. The mathematical presentation that best fits the acquired results is given by:

$$\Delta s = 0.025\, p - 0.35 \qquad (3)$$

where Δs presents the expected difference of the shadow length (s) in pixel units and p presents the employed light position in mm units. According to the obtained results, the diverted lighting angle α is less than (1.5)°, hence is small and could be neglected. In another evaluation test both camera height (c) and light source height (l) and distance (d) were fixed to (150 mm), however a number of objects having different object heights (h) were used. Linear relationship is obtained that could be expressed by the following equation:

$$h = 0.18\, s + 0.168 \qquad (4)$$

where h is the object height and s is the resulting shadow length using the camera height, light distance and light heights of 150 mm each.

6. Experimental Results and Evaluation

To assess the potential of the proposed algorithm further investigation was carried out using different object shapes, namely, block gauge, tapered wooden block, cam component, dome, and a rectangular-section rod component with two perpendicular grooves. The aim is to highlight any problem areas that encounter the execution of the proposed algorithm and to evaluate the accuracy level that could be achieved in real applications. All conducted tests were repeated 5 times and acquired results showed to be close; hence selected examples are given bellow to demonstrate the quality of gained results.

The cam component that has a curved shape is shown in Figure (3). Accordingly, the acquired images were processed and Figure (4) shows the extracted length, width and height attributes from the image using the proposed methodology. Results of this case have demonstrated that the proposed method is readily applicable to curved shape objects. The resulting shape has very close to real features. Only minor defects may be recognized that could be attributed to the limited adopted resolution of the imaging system.

To demonstrate one identified limitation of the proposed methodology, a rectangular-section rod with two perpendicular grooves cut in its top surface was used in the investigation, Figure (5). The light source was set in an inclined angle but with a parallel direction to the first groove. Obtained results, Figure (6) shows that the proposed methodology succeeded to provide the shape attributes of the object, however, only for the direction associated with the incident light and the generated object shadow. Figure (6.d) shows the acquired 3D reconstruction of the object, where it is obvious from this figure that only the first groove was recovered in the object shape, whereas the second groove was completely missed out due to the employed lighting direction. The second groove did not obstruct the incident light and therefore the formed shadow does not inherit any information regarding its shape. To overcome this limitation, additional images of the object with different lighting directions are required so that the formed shadows inherit all possible features of the object shape.

Table (1) lists the real physical dimensions of some of the objects used in the investigation. The computed dimensions based on the proposed methodology of these objects and related resulting errors of measurements are also included for comparison and clarity.

Resulting errors of measurements of the block gauge component indicate that the maximum difference between the computed dimensions and the real physical dimensions is less than 0.65 mm which is occurred in the length attribute set. While for the tapered shape component the maximum error is found to be in the height attribute set of a value less than 0.74 mm. However, for the cam component the maximum error was found to be 0.68 mm in the object length attribute set. The dome shape component showed to have closer tolerances in the valid directions of measurements, a maximum error of less than 0.55 mm is recorded within the object length attribute set. Close to real measurements were also obtained using the rectangular-section rod. Maximum error of less than 0.45 mm was provided for the object attributes; however, no shape information regarding the second groove of the object was gained.

These minor object distortions and measurement inaccuracies especially at points close to the object boundary were obtained due to the employed imaging resolution, image threshold value used and the approximation used in the calibration process. It could be noted that points close to the object boundary are more prone to false feature extraction than the points inside the object surface area. However, the overall acquired results indicate that the proposed attribute extraction process is valid and could yield close to real dimensional measurements of the components under test within an accuracy of 0.75 mm using the adopted inexpensive system hardware. Though, to generalize this finding to other system hardware, care should be given to the calibration task and proper selection of image threshold value must be achieved to enable valid processing of image data and accepted extraction of object attributes.

7. Conclusions

Although the goal of re-constructing 3D objects from a single captured image is a challenging problem, the suggested methodology succeeded to achieve close to real measurements of different object shapes. However, the proposed methodology suffers from a defined limitation that it can recover object features only for the directions associated with the incident light and the generated object shadows. Object features that do not fulfill the obstruction of light are therefore un-recoverable using this methodology. Hence, additional images of the object with different light position would enhance the recovery of these features.

Results of the conducted experiments showed that the proposed algorithm is capable within the accuracy limit of the system to generate 3D re-construction of objects. The overall accuracy of the employed inexpensive system was found to be within 0.75 mm using the achieved setup. Results also showed that the system is applicable to handle different shape objects including those having various changes in materials, colors, heights, and sizes. These close to actual measurements were gained due to the well control of light, suitable selected image threshold value, and the careful setting of calibration. Hence to generalize this work findings fulfillment of the equipment setup, calibration and processing must be maintained.

Based on the conducted experiments, it can be observed that the points close to the object boundary are more prone to false feature extraction than the points inside the object surface area due to the image quality and the selected value of image threshold. These erroneous points may have a cumulative effect on the feature attribute assignment process and therefore may affect the process of 3D re-construction.

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Table (1) Attribute measurements of some of the investigated objects

(The maximum deviation value of each attribute set resulting from 5 times repetition of the test is recorded)

1.Block gauge component			
Object's attributes	**Real value**	**Computed value**	**Error**
Length (mm)	30	29.3501	0.6499
Width (mm)	9.8	9.3298	0.4702
Height (mm)	10	10.2358	0.2358
2. Tapered shape component			
Object's attributes	**Real value**	**Computed value**	**Error**
Length (mm)	21	20.7921	0.2079
Width (mm)	26	25.8514	0.1486
Height (mm)	30	29.2668	0.7332
3. Dome shape component			
Object's attributes	**Real value**	**Computed value**	**Error**
Length (mm)	56	55.4596	0.5404
Width (mm)	56	55.6994	0.3006
Height (mm)	29	29.3168	0.3168

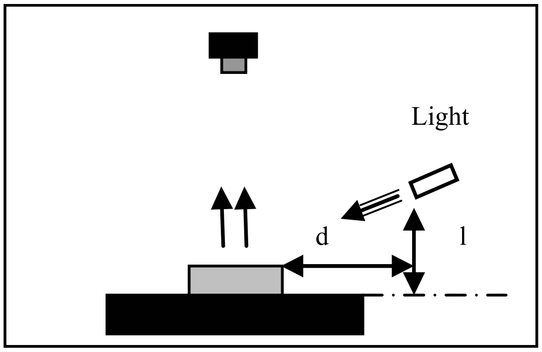


Figure (1) The implemented system set-up

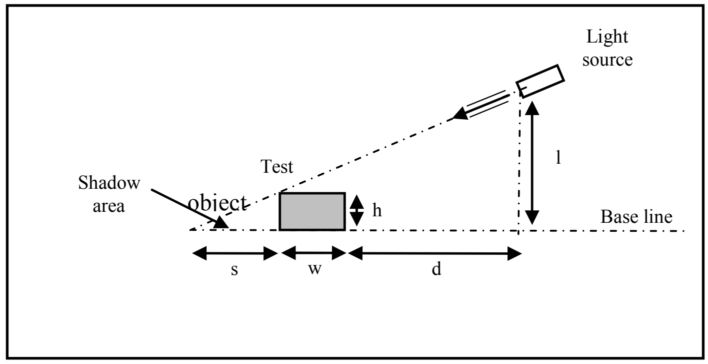


Figure (2) The employed symbols

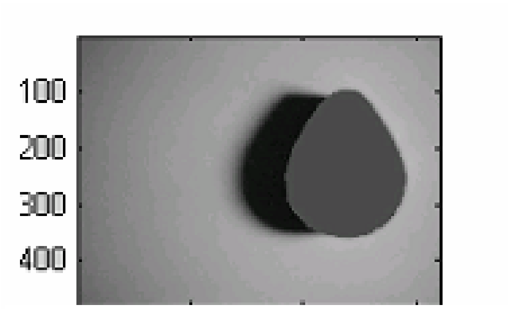
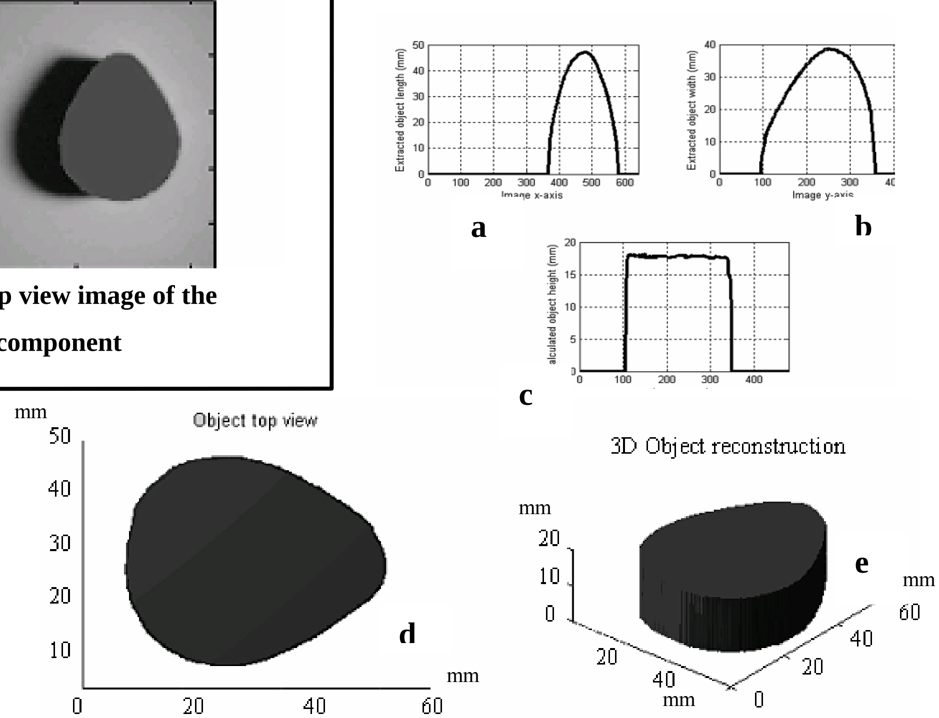


Figure (3) Top view image of the cam component



Cam component			
Object's attributes	**Real value**	**Computed value**	**Error**
Length (mm)	47.7	47.0153	0.6847
Width (mm)	38	38.7291	0.7291
Height (mm)	18.2	17.9426	0.2574

Figure (4) 3D shape re-construction of the cam component

a. Object Length, b. Object Width, c. Object Height, d. Top view reconstruction, and e. 3D reconstruction

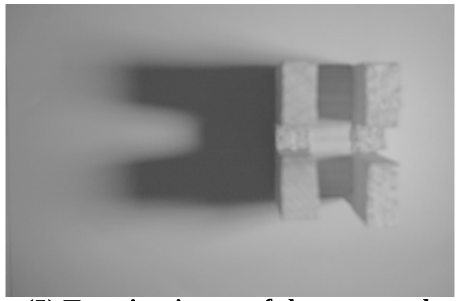
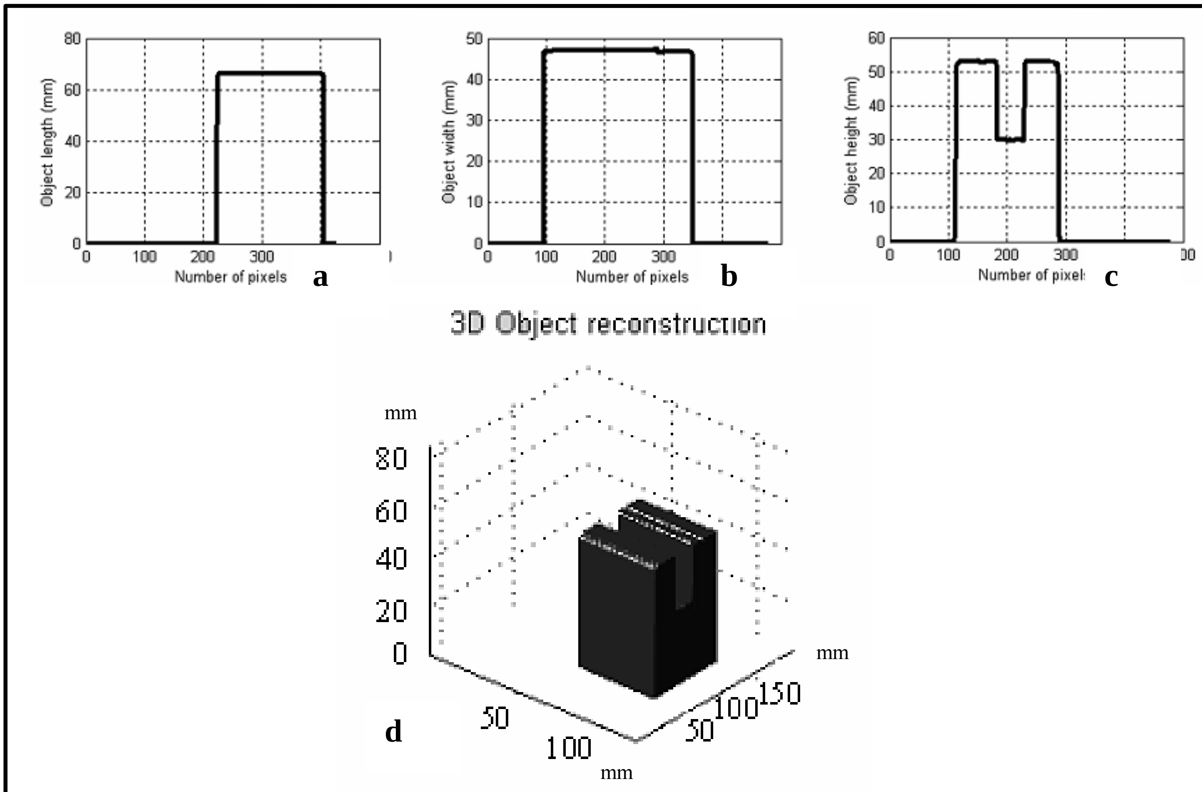


Figure (5) Top view image of the rectangular part



Rectangular-section rod component			
Object's attributes	**Real value**	**Computed value**	**Error**
Length (mm)	66	66.1104	0.1104
Width (mm)	47	48.4116	0.4116
Height (mm)	53	53.1888	0.1888

Figure (6) 3D reconstruction of a block of rectangular section part with perpendicularly crossed deep grooves in its top surface

a. Object Length, b. Object Width, c. Object Height, and d. 3D reconstruction