

# Stereoscopic flatbed scanner

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**Abstract.** 3-D scanning has become increasingly popular in a wide range of applications. We present a prototype 3-D/stereoscopic scanning system based on a cheap, readily available flatbed scanner. Stereoscopic imaging is achieved by modifying the optical path of the ordinary flatbed scanner. The results of 3-D imaging using our prototype system are demonstrated, and a number of design alternatives are discussed. © 2009 SPIE and IS&T.  
[DOI: 10.1117/1.3059582]

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## 1 Introduction

Flatbed scanners are cheap consumer electronic devices that are typically used for producing high-resolution digital images of documentation or photographs. Many flatbed scanners are also capable of capturing 2-D images of 3-D objects with small depth of field. Such scanners are ideal for scanning botanical or geological samples or archeological specimens and are therefore important tools for artists and art and architecture historians. They have also been used as part of a light field capture system<sup>1</sup> and in an inexpensive very high resolution scan camera system.<sup>2</sup> All these applications use ordinary flatbed scanners.

A scanner capable of capturing two or more images of an object from different angles can be used in a variety of applications requiring stereoscopic perception or 3-D processing. Examples include 3-D object inspection and quality control (of printed circuit boards, currency/numismatics, art, and orthotics), cataloging of botanical and archeological samples for museums, and cataloging of articles for Internet/commercial use.

Stereoscopic images are usually obtained by taking pho-

tos of an object from two slightly different perspectives using cameras. There are many types of cameras available for this purpose. However, camera-based stereo is usually expensive, especially for high-resolution images. Stereoscopic images can be obtained using a flatbed scanner, as demonstrated in Ref. 3, by physically moving the object or scanner sideways relative to the scanning direction to obtain images from different orientations. It is worth noting that the imaging geometry of flatbed scanners is different from that of traditional area cameras. In flatbed scanning, the perspective projection is in the lateral direction, i.e., perpendicular to the scanning direction. Cameras in flatbed scanners use parallel projection in the scanning direction. This geometry is similar to the pushbroom imaging used in the airborne or remote sensing applications.<sup>4–6</sup>

In this paper, we describe several new designs for a flatbed scanner head assembly capable of obtaining stereoscopic images of 3-D objects. Some of these designs are very easy to implement, and none of them requires relative movement of the object or scanner.

The paper is organized as follows: Sec. 2 describes the designs of our stereoscopic flatbed scanner. Section 3 describes our 3-D viewing, processing, and modeling processes. We show examples of 3-D results on 3-D model construction using images acquired from our prototype stereo flatbed scanner in Sec. 4. Section 5 gives concluding remarks.

## 2 Scanner Head Designs

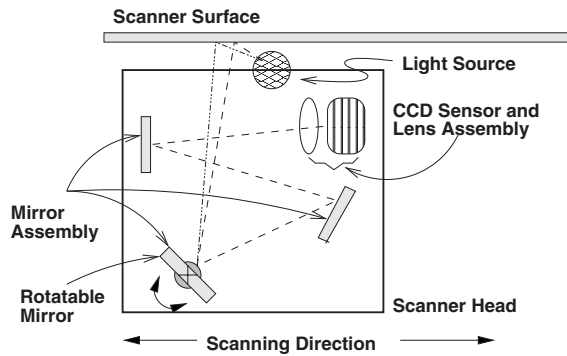
A flatbed scanner head typically consists of a few mirrors, a lens, a light source and a charge-coupled device (CCD) sensor. Some scanners have contact image sensors (CISs), which have a very limited depth of field and are therefore unsuitable for stereo applications. Our stereoscopic scanner head involves modifications to the standard design of a flatbed scanner that allow a 3-D object to be imaged from different angles (as shown in Fig. 1) so that stereoscopic perception or processing can be carried out. These modifications allow stereoscopic imaging without moving the object or the scanner body, compared to Ref. 3.

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Paper 08085R received Jun. 4, 2008; revised manuscript received Oct. 17, 2008; accepted for publication Nov. 16, 2008; published online Jan. 9, 2009.



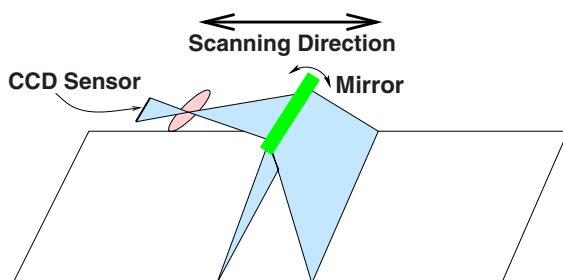
**Fig. 1** Illustration of our scanner head with a rotatable mirror and a scanner surface.

### 2.1 Use of a Rotatable Mirror

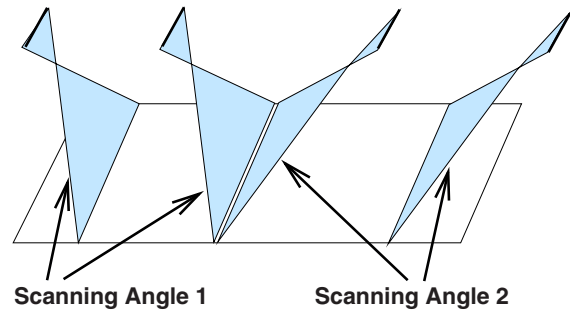
The first design, illustrated in Fig. 1, employs a rotatable mirror to scan the object from different angles for stereoscopic imaging. The axis of rotation of the mirror relative to the motion of the scanner head is illustrated in Fig. 2. Figure 3 shows the pushbroom imaging geometry at two different angles. Figure 4 illustrates in detail the design of the rotatable mirror mounting. This design requires only one lens and one sensor array.

A number of strategies can be employed to rotate the mirror, depending on the degree of integration with the scanner hardware and software. The simplest strategy is to manually adjust the mirror prior to each image capture pass. For example, a pivoted handle may be attached to one end of the rotatable mirror. The handle moves along with the scanner head during scans. The position or angle of the rotatable mirror and the handle is fixed for one particular scan (a forward or a return pass). After this first scan, when the scanner head returns to the initial position, the handle is manually turned together with the mirror so that the second scan can be performed to collect a second image at a different angle. In this mode of operation, two complete return passes are needed for collecting the two images at two different angles. The rotation of the mirror can also be carried out at the end of the forward pass before it returns to the initial position. After collecting the first image at the end of the first pass, the scanner head is kept stationary while the mirror is being rotated. Then the scanner head collects the second image from a different angle during the return pass.

The rotation of the mirror can also be carried out automatically by the use of a computer-controlled motor that is connected to the axis of the rotatable mirror. The rotatable



**Fig. 2** Illustration of the scanning paths.



**Fig. 3** Illustration of pushbroom imaging geometry at two angles.

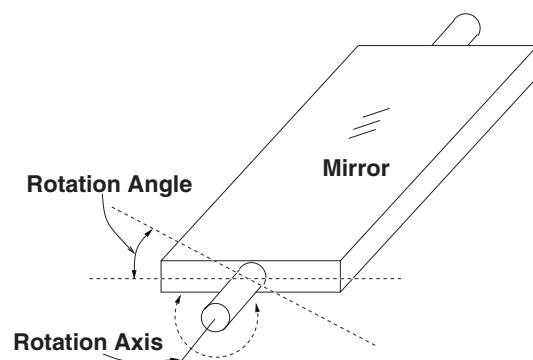
mirror is fixed at one angle when the scanner head moves forward from the initial position to collect the first image. At the end point of the forward scanning, the rotatable mirror is rotated automatically by the motor. After the rotation of the rotatable mirror, a second image is collected when the scanner head returns to the initial position. Therefore, two images are obtained during one forward and one return pass.

The rotation of the mirror can also be performed mechanically by a switch that is controlled by the direction of the movement of the scanner head. Control can be by way of friction with the driving belt within the scanner or with the scanner body. For instance, a brush can be attached to the mirror for controlling the rotation of the mirror. When the scanner head moves in a different direction, the brush points in a different direction. Therefore, by having different directions of the brush that is attached to the rotatable mirror, stereo images can be obtained, one image at each direction.

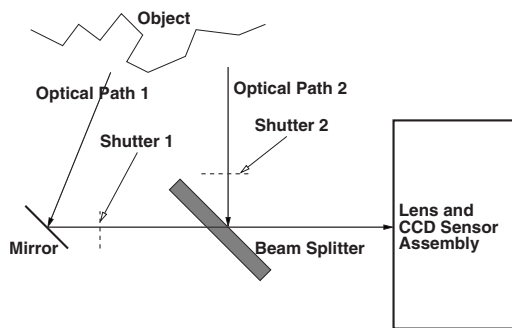
Our approach of using a rotatable mirror for stereoscopic flatbed scanning is very cheap to implement, with the manual version requiring only minor modifications to existing scanner heads. In the automatic mode, only a motor and motor control are required. With the use of a motor, a sequence of images at different angles can be obtained easily. There is no need to change the lens or the CCD arrays.

### 2.2 Use of Shutters

An alternative approach to achieving two viewing angles is to provide two light paths and selectively block one using shutters, which select the desired optical path and hence the



**Fig. 4** Illustration of the rotatable mirror.



**Fig. 5** Illustration of the use of a mirror, shutters, and a beamsplitter to achieve multiple light paths.

desired viewing angle. The shutters could be mechanical or electronic, such as liquid crystal. For some forms of liquid crystal, one might need to consider polarizing light. Thus, the optical path may not be simple, and therefore, the cost might be high. Other types of shutters, such as active domain liquid crystal display (LCD) shutters and liquid crystal pi-cell shutters, can also be considered. Figure 5 illustrates an example of this configuration in which shutters may be located at positions labeled Shutter 1 and Shutter 2.

A pair of images can be captured in a single pass over the object if the shutters are alternated rapidly. Alternatively, one of the shutters can be selected for an entire or a forward pass and then changed to the second shutter for the next pass or for a return pass.

The configuration in Fig. 5 uses a beamsplitter that allows the last stages of the two optical paths to be identical, hence avoiding sensor alignment issues.

The version of this configuration using electronic shutters and a beamsplitter requires no moving parts. The additional costs compared to a conventional scanner head will be minimal, and many of the components will be unchanged. This design also requires only one lens and one CCD array. The mirror can also be rotated to adjust the relative angle between the two optical paths.

### 2.3 Other Scanner Head Designs

A scanner head assembly can have two parallel scanner heads. Each scanner head contains a mirror assembly and lens for directing the light path onto a CCD sensor. Each scanner head is arranged to view the scanner surface and the object at a different viewing angle. In this design, the scanner requires only a single pass of the scanner head assembly to acquire a pair of images of the object.

The whole scanner head can also be rotated such that the angle of light received from the object and incident on the detector array is changed. The rotation allows images of the same object to be captured from a number of different viewing angles, and the images can be used in stereo processing. To rotate the whole scanner head, the normal scanner head needs to be modified such that part of the head is rotatable while there are fixtures that can move along the sliding rail.

Another design is to have a single mirror assembly used to direct light onto both CCD sensors with a lens. This design requires only a single pass to acquire the two images. The mirror assembly enables two different light paths to be focused onto each sensor array, respectively. Each

sensor receives a different view of the object through the same optical assembly by using a different viewing angle.

The relative movement between the scanner head assembly and the object may also be provided by moving the object with respect to the scanner head assembly at a constant velocity—for instance, by means of a conveyor belt. In this case, the scanner head needs to have mechanisms to collect two images at one time. The scanning process of the scanner is replaced with the movement of the conveyor belt.

## 3 3-D Viewing, Processing, and Modeling

### 3.1 Scanning and 3-D Viewing of Stereo Images

An object is placed on top of the scanner surface for scanning. The stereo scanner scans this object using the methods described in Sec. 2.1, and two (or more) stereo images of the same object are acquired. The two images can be viewed through cross or parallel viewing or by the use of shutter glasses to achieve 3-D perception. The two images can be displayed and viewed using standard off-the-shelf commercial stereo goggles with an associated video graphics adaptor capable of displaying good-quality stereo images.

### 3.2 3-D Processing and Modeling

Disparity is the positional difference for matching points in the stereo images. Disparity estimation is the main step in estimating 3-D structure from stereo images. All the disparity measurements for all the points in the stereo images build a disparity map that can be obtained through a stereo matching process.<sup>7-14</sup> The algorithm that we used involves a pyramid structure, fast correlation, rectangular subregioning, and dynamic programming techniques.<sup>14</sup> Because of the simple imaging geometry with flatbed scanners, the disparity mainly appears in the scanning direction. Subpixel accuracy of disparity is obtained by fitting a second-degree curve to the correlation coefficients in the neighborhood of the disparity, and the position of the extrema of the curve is obtained analytically as the estimated disparity. The 3-D measurements can be obtained from the disparity map using knowledge of the imaging geometry and lens parameters.

If the 3-D measurements or shapes from multiple views about the 3-D object are available, the 3-D shapes or models from these multiple views can be combined to build a single complete or coherent 3-D model of the object surface.

### 3.3 Processing Steps

Figure 6 shows a block diagram of the stereo scanning, viewing, and processing of the scanned images of our stereo scanner system. Stereo images from two or multiple views of a 3-D object can be obtained. These stereo images can be viewed directly or processed to generate the 3-D measurements.

## 4 Experimental Results

Here, we describe some experimental results that have been obtained using our stereo flatbed scanner. The results are mainly on the reconstruction of 3-D objects.

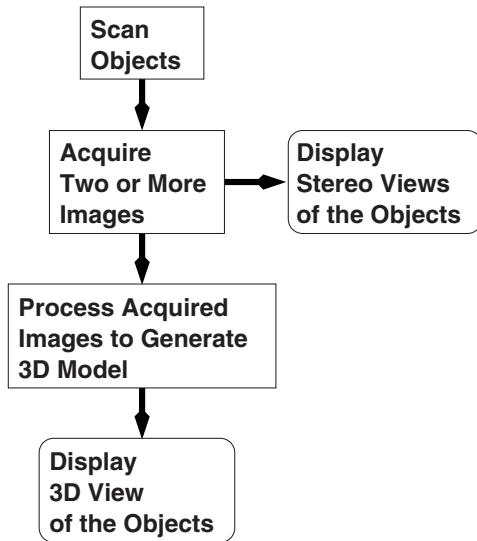


Fig. 6 Flow chart for 3-D object scanning, viewing, and processing of the obtained stereo images.

Figure 7 shows a photo of the modified scan head, with arrows indicating some parts of the scan head. The rotatable mirror rotates around the rotation axis. The handle that is attached to the rotation axis is used to rotate the rotatable mirror. The range of the rotation angle can be controlled by the position of the tip of the two screws close to the handle. The glass plate on top of the scan head has been removed when taking this photo.

Figures 8(a) and 8(b) show a pair of stereo images of a shell scanned from our prototype stereo scanner. The shell was placed on the glass plate. The physical size of the shell is about 3.0 cm in diameter and about 1.3 cm in depth or height. The pair of stereo images was scanned at two different orientations at 600 dpi. The angle between the two views is about 9 deg. Figure 8(c) shows the disparity map obtained from Figs. 8(a) and 8(b) using our fast stereo matching algorithm.

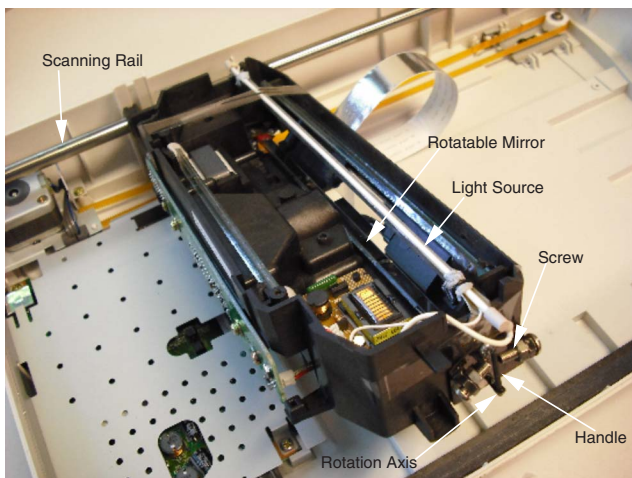


Fig. 7 Photo of the modified scan head with indications of various parts.

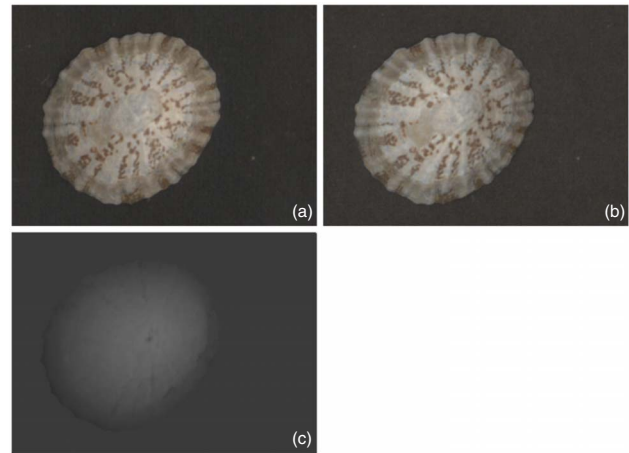


Fig. 8 (a) and (b) A pair of stereo images of a shell. (c) Disparity map obtained from the stereo images.

Another example of 3-D reconstruction is a 3-D toy with the use of multiple views. The orientations of the different views are illustrated in Fig. 9 for this experiment. The object was placed on the scanner glass plate, and for some scans, the object was held by a clamp on a stand. The stereo viewing angle is about 9 deg. Figure 10 shows the left images of the 18 input stereo image pairs scanned at different orientations around the object. The disparity map is obtained for each pair of the stereo images, and the obtained disparity map is converted to a 3-D depth map for each particular view with the calibrated scanning geometry. The geometry calibration of the scanner head was carried out using objects of known depth (see Ref. 4 for details). Each of the depth maps contains the  $x$ ,  $y$ , and  $z$  values of a 3-D point for this viewing direction. Figure 11 shows the depth maps of the 18 views with background (shown in black) removed.

Figure 12 shows four different views of a single, complete 3-D model of the object obtained from the 18 depth maps from different orientations. The integration of the multiple depth maps involves the registration of different

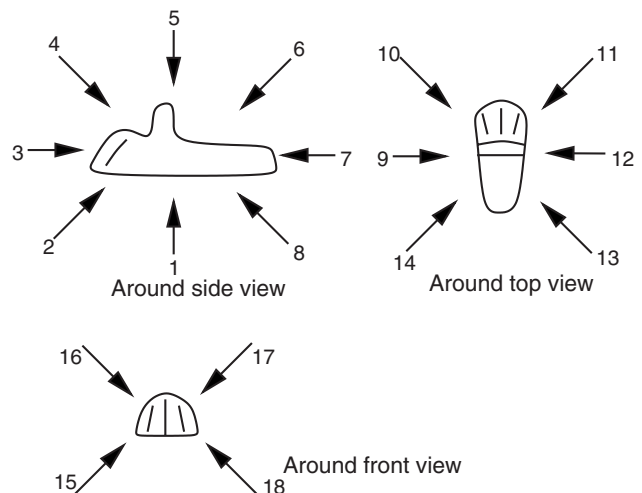


Fig. 9 Eighteen orientations to scan the toy object.

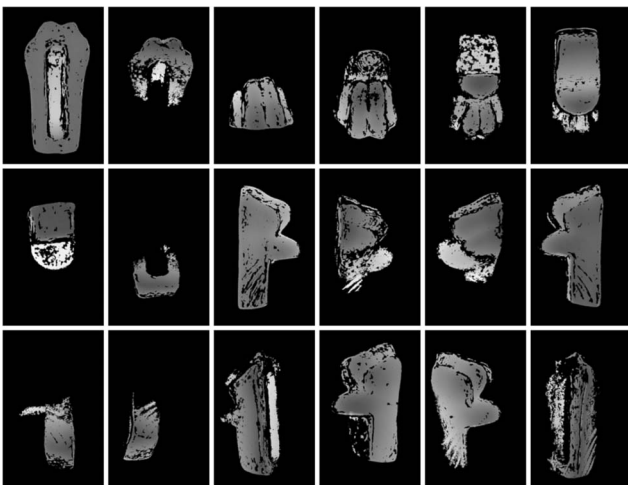


**Fig. 10** Eighteen images (the left images of the stereo pairs) from different views.

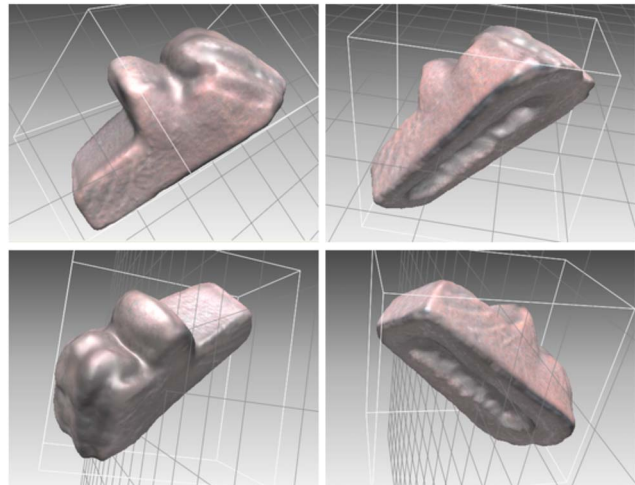
depth maps from different orientations. This step was carried out using the software package Rapidform.<sup>15</sup> This involves the following subtasks:

1. Import the 18 sets of 3-D data.
2. Triangulate.
3. Perform initial registration on each shell.
4. Remove the out-tracked part between two shells.
5. Remove the inside of the overlapping part.
6. Combine shells.
7. Complete the overall 3-D model form.
8. Remove all faces by selecting them; keep only vertex.
9. Perform 3-D triangulation.
10. Fill holes using bridges feature.

The single complete 3-D model can be saved into different formats and can be viewed in different software packages.



**Fig. 11** Eighteen depth maps from different views (obtained from images as shown in Fig. 10). White color indicates larger z values, i.e., points that are farther away from the camera.



**Fig. 12** Four different views of a single complete 3-D model obtained from 18 stereo image pairs scanned from our prototype stereoscopic flatbed scanner.

## 5 Conclusions

It is expected that the capability to acquire stereo images from our scanner can be an added feature for existing flatbed scanners. Users can exercise the option to use the scanner as a normal scanner or to use the added feature to scan stereo images of small objects or objects with a small depth of field. When used as a normal scanner, only one image is scanned; This can also be achieved by switching on one of the shutters or by using the image from only one detector array. The design of the scanner can also be used for photocopying machines, which can include software for processing the images and directly printing out or displaying red/blue-type stereo images for viewing. The scanned stereo images can also be saved to a storage media for other uses such as building 3-D models from single or multiple pairs of stereo images. The scanner head should be cheap for some designs, as the additional components are only handles, motors, or switches. None of the designs involves the relative movement between the scanner and the objects.

## Acknowledgments

We are grateful to the reviewers for valuable suggestions which improved the paper. We thank Anna McDonald, Carrie Bengston, Barry Parsons of CSIRO, and Dawn Perkins of Griffith Hack for their help during the course of this study. We thank Dr. Volker Hilsenstein of CSIRO for his comments on this paper.

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