3D Scanner using Line Laser

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1. Introduction

The goal of 3D reconstruction is to recover the 3D properties of a geometric entity from its 2D images. We have implemented the passive stereo method in one of the previous projects. Passive stereo method needs the images from two cameras. But active stereo vision, which is different from passive stereo vision, is a technique for the reconstruction of the 3D description of a scene from images observed from one camera and one light projector.

In this project, I used the line laser as the light projector to implement the active stereo method to recover 3D objects. Reconstruction results of four different objects and reconstruction accuracy are showed.

2. Theory

1). Active Stereo Vision

Active stereo vision is a technique that actively uses a light such as a laser or a structured light to simplify the stereo matching problem.

The equation between the pixel (c, r) on an image and its corresponding 3D coordinates (x, y, z) is:

$$\lambda \begin{pmatrix} c \\ r \\ 1 \end{pmatrix} = W[R\ T] \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}$$

Let (x, y, z) be in the camera frame, then R=I, and T=0. Thus the equation is simplified to

$$\lambda \begin{pmatrix} c \\ r \\ 1 \end{pmatrix} = W[I\ 0] \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} = W \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

W is the intrinsic matrix of the camera

$$W^{-1} \begin{pmatrix} c \\ r \\ 1 \end{pmatrix} = \frac{1}{\lambda} \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x/\lambda \\ y/\lambda \\ z/\lambda \end{pmatrix} = \begin{pmatrix} x/z \\ y/z \\ 1 \end{pmatrix}$$

So with one camera, we can just compute $\begin{pmatrix} x/z \\ y/z \\ 1 \end{pmatrix}$. It is impossible to get the depth from one image without additional information.

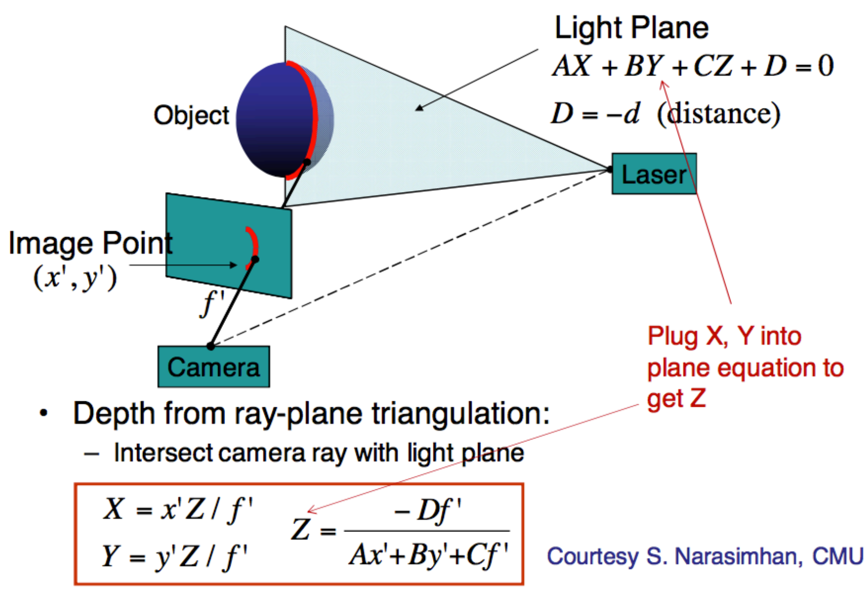


Fig 1: Triangulation

However, when we project a laser line onto an object and it will result in a curve in the picture. Then we can compute the 3D coordinates of the surface of the object that is illuminated by the laser line, if we know the equation of the light plane.

Assume the laser line projected onto the surface of the object is on the light plane:

$$Ax + By + Cz + D = 0$$

Let one image point on the line projected by the laser is (x', y'), and its $pixel\ is\ (c, r)$(Fig 1). We can have:

$$W^{-1}\begin{pmatrix} c \\ r \\ 1 \end{pmatrix} = \begin{pmatrix} x/z \\ y/z \\ 1 \end{pmatrix} = P$$

Let $W^{-1}\begin{pmatrix} c \\ r \\ 1 \end{pmatrix} = P$, which is a vector. And $P(i)$ is the ith component of P. Then

$$x = zP(1), y = zP(2)$$

Substitute them into the equation of the light plane

$$AzP(1) + BzP(2) + Cz + D = 0$$

We can get the depth z from this equation, thus obtain the 3D coordinates

$$(x, y, z) = (zP(1), zP(2), zP(3))$$

To obtain the 3D properties of the whole object, we just need to scan the laser line over the object and shoot a video at the same time. Then use the method above to analyze every frame of the video to reconstruct the 3D coordinates of the surface of the object.

In order to implement the method above, we need to know:

1. The intrinsic parameters of the camera. I used a calibration toolbox to obtain the intrinsic parameters of my camera. I will talk about the details later in the part of approach.
2. The location of the curve produced by the laser in every image. I implemented the edge detection method to extract them out in every image. More details are talked in the later part.
3. The equation of the light plane in every frame of the video. I set up a system with two boards to help to compute the light plane.

2). Compute the light plane

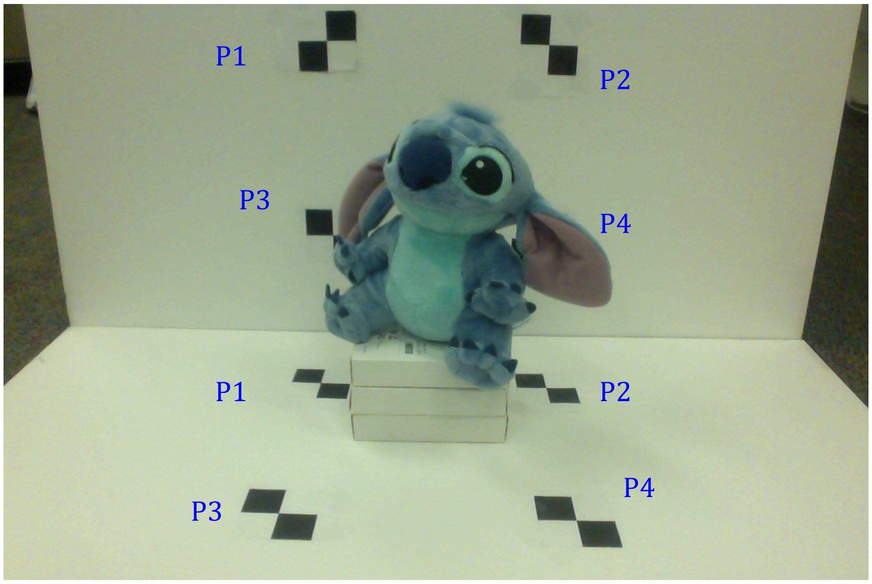


Fig 2: Two white boards with 8 fiducials

I set up a system for 3D scanning with two white boards (Fig 2). There will be two intersection lines when the laser is scanning over the two boards. If we know the 3D coordinates of any three points from that two intersection lines, we can decide the equation for the light plane.

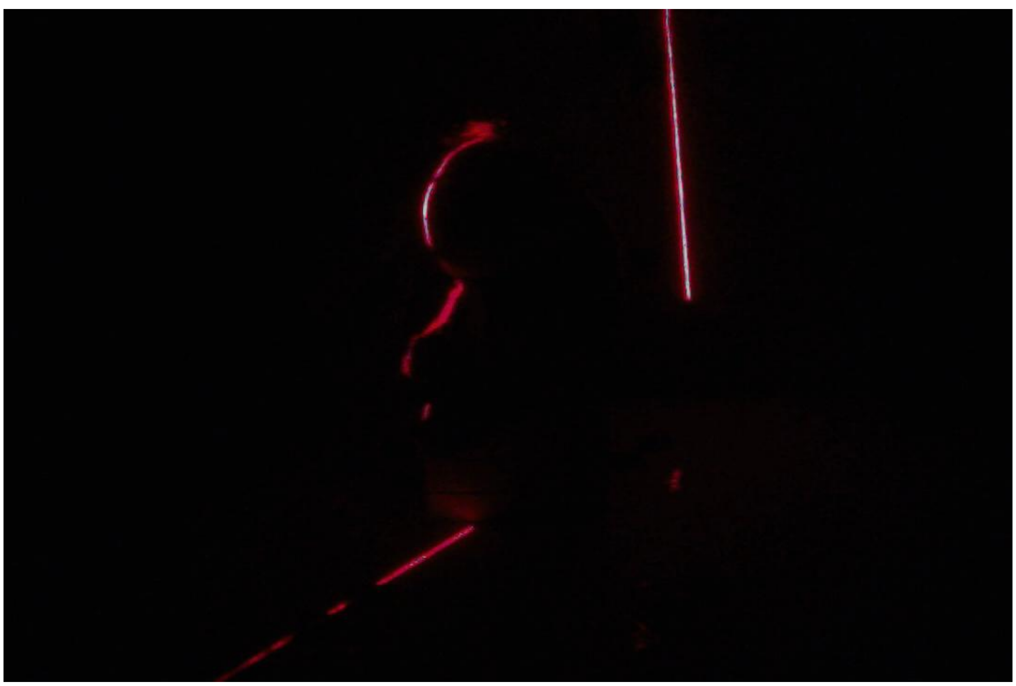


Fig 3: The image with laser line scanning over the object

To compute the 3D coordinates of the points in the two intersection lines, we need to know the equations for the two boards first. So I attached four fiducials (P1, P2, P3, P4)(Fig 2) on each board, which compose a rectangle. The length (P1---P2) and width (P1---P3) are known, which are l and w respectively.

With known intrinsic matrix, the equation between an image pixel (c, r) and its corresponding 3D point (x, y, z) is:

$$\begin{pmatrix} c \\ r \\ 1 \end{pmatrix} = W \begin{pmatrix} x/z \\ y/z \\ 1 \end{pmatrix} = \begin{pmatrix} fs & 0 & c_0 \\ 0 & fs & r_0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x/z \\ y/z \\ 1 \end{pmatrix}$$

$$\begin{cases} \dfrac{fsx}{z} + c_0 = c \\ \dfrac{fsy}{z} + r_0 = r \end{cases}$$

$$\begin{cases} x = \dfrac{z}{fs}(c - c_0) \\ y = \dfrac{z}{fs}(r - r_0) \end{cases}$$

So the 3D coordinates of the four fiducials are:

$$P1 = \begin{pmatrix} \dfrac{z_1}{fs}(c_1 - c_0) \\ \dfrac{z_1}{fs}(r_1 - r_0) \\ z_1 \end{pmatrix}$$

$$P2 = \begin{pmatrix} \dfrac{z_2}{fs}(c_2 - c_0) \\ \dfrac{z_2}{fs}(r_2 - r_0) \\ z_2 \end{pmatrix}$$

$$P3 = \begin{pmatrix} \dfrac{z_3}{fs}(c_3 - c_0) \\ \dfrac{z_3}{fs}(r_3 - r_0) \\ z_3 \end{pmatrix}$$

$$P4 = \begin{pmatrix} \frac{z_4}{fs}(c_4 - c_0) \\ \frac{z_4}{fs}(r_4 - r_0) \\ z_4 \end{pmatrix}$$

Because P1, P2, P3 and P4 compose a rectangle, $\overrightarrow{P2 - P1} = \overrightarrow{P4 - P3}$

$$\begin{pmatrix} \frac{z_2}{fs}(c_2 - c_0) \\ \frac{z_2}{fs}(r_2 - r_0) \\ z_2 \end{pmatrix} - \begin{pmatrix} \frac{z_1}{fs}(c_1 - c_0) \\ \frac{z_1}{fs}(r_1 - r_0) \\ z_1 \end{pmatrix} = \begin{pmatrix} \frac{z_4}{fs}(c_4 - c_0) \\ \frac{z_4}{fs}(r_4 - r_0) \\ z_4 \end{pmatrix} - \begin{pmatrix} \frac{z_3}{fs}(c_3 - c_0) \\ \frac{z_3}{fs}(r_3 - r_0) \\ z_3 \end{pmatrix}$$

$$\begin{pmatrix} \frac{z_2}{fs}(c_2 - c_0) - \frac{z_1}{fs}(c_1 - c_0) \\ \frac{z_2}{fs}(r_2 - r_0) - \frac{z_1}{fs}(r_1 - r_0) \\ z_2 - z_1 \end{pmatrix} = \begin{pmatrix} \frac{z_4}{fs}(c_4 - c_0) - \frac{z_3}{fs}(c_3 - c_0) \\ \frac{z_4}{fs}(r_4 - r_0) - \frac{z_3}{fs}(r_3 - r_0) \\ z_4 - z_3 \end{pmatrix}$$

Rearrange the three equations

$$\begin{pmatrix} \frac{(c_0 - c_1)}{fs} & \frac{-(c_0 - c_2)}{fs} & \frac{-(c_0 - c_3)}{fs} \\ \frac{(r_0 - r_1)}{fs} & \frac{-(r_0 - r_2)}{fs} & \frac{-(r_0 - r_3)}{fs} \\ 1 & -1 & -1 \end{pmatrix} \begin{pmatrix} \frac{z_1}{z_4} \\ \frac{z_2}{z_4} \\ \frac{z_3}{z_4} \end{pmatrix} = \begin{pmatrix} \frac{-(c_0 - c_4)}{fs} \\ \frac{-(r_0 - r_4)}{fs} \\ -1 \end{pmatrix}$$

That is

$$AX = B$$

$$A = \begin{pmatrix} \frac{(c_0 - c_1)}{fs} & \frac{-(c_0 - c_2)}{fs} & \frac{-(c_0 - c_3)}{fs} \\ \frac{(r_0 - r_1)}{fs} & \frac{-(r_0 - r_2)}{fs} & \frac{-(r_0 - r_3)}{fs} \\ 1 & -1 & -1 \end{pmatrix}$$

$$X = \begin{pmatrix} \frac{z_1}{z_4} \\ \frac{z_2}{z_4} \\ \frac{z_3}{z_4} \end{pmatrix}$$

$$B = \begin{pmatrix} \frac{-(c_0 - c_4)}{fs} \\ \frac{-(r_0 - r_4)}{fs} \\ -1 \end{pmatrix}$$

So we can obtain the value of vector X

$$X = (A^t A)^{-1} A^t B$$

Thus, $z_1 = X(1)z_4;\ z_2 = X(2)z_4;\ z_3 = X\ (3)z_4$

$$P1 = \begin{pmatrix} \frac{z_1}{fs}(c_1 - c_0) \\ \frac{z_1}{fs}(r_1 - r_0) \\ z_1 \end{pmatrix} = \begin{pmatrix} \frac{X(1)z_4}{fs}(c_1 - c_0) \\ \frac{X(1)z_4}{fs}(r_1 - r_0) \\ X(1)z_4 \end{pmatrix}$$

$$P2 = \begin{pmatrix} \frac{z_2}{fs}(c_2 - c_0) \\ \frac{z_2}{fs}(r_2 - r_0) \\ z_2 \end{pmatrix} = \begin{pmatrix} \frac{X(2)z_4}{fs}(c_2 - c_0) \\ \frac{X(2)z_4}{fs}(r_2 - r_0) \\ X(2)z_4 \end{pmatrix}$$

Because the distance between P1 and P2 are known, and z_4 is the only unknown, so we can obtain z_4 through simple computation. Then we can have the 3D coordinates of the all four fiducials. With three points on a plane, we can get the equation for that plane. Apply the same method to the other board. Then we can obtain the equations for the two white boards.

When we have the equations of the two boards, we can choose two points from the intersection line on each board and easily compute their 3D coordinates. With these four points, we can compute the equation for the light plane.

To easily choose the points from the intersection lines, I just left the top and button parts of the image blank, without blocked by the scanned object. When the laser line scans over the object, it must project the lines to the areas close to the top and button of the picture (Fig 3). So we can always find such four points easily in every frame to obtain the equation for the light plane.

Assume the equation for the vertical board is

$$A_1 x + B_1 y + C_1 z + D_1 = 0$$

The equation for the horizontal board is

$$A_2 x + B_2 y + C_2 z + D_2 = 0$$

Choose two points (p1, p2), which are in the intersection line of the light plane and the vertical board. And choose two points (p3, p4), which are in the intersection line of the light plane and the horizontal board. The corresponding 3D coordinates of the image point (c, r) is:

$$P = \begin{pmatrix} \frac{z}{fs}(c - c_0) \\ \frac{z}{fs}(r - r_0) \\ z \end{pmatrix}$$

Substitute it into the equation of the vertical board:

$$A_1 \frac{z}{fs}(c - c_0) + B_1 \frac{z}{fs}(r - r_0) + C_1 z + D_1 = 0$$

We can easily compute the only unknown z, then to obtain the 3D coordinate of P. Repeat the computation for all the four points, and we get the 3D coordinates of them. Then we can find the plane that match them best, which is the light plane we need. Just repeat the same process for every frame.

3). Edge detection

To simplify the procedure, I scan the object in dark and there is no ambient light.

I used a simple first order filer to enhance the edge.

Let I(c, r) be the image intensity at pixel (c, r), then the first order image gradient can be approximated by

$$\nabla I(c,r) = \begin{pmatrix} \frac{\partial I(c,r)}{\partial c} \\ \frac{\partial I(c,r)}{\partial r} \end{pmatrix}$$

Where the partial derivatives are numerically approximately

$$\frac{\partial I}{\partial c} = I(c+1,r) - I(c,r)$$

$$\frac{\partial I}{\partial r} = I(c,r+1) - I(c,r)$$

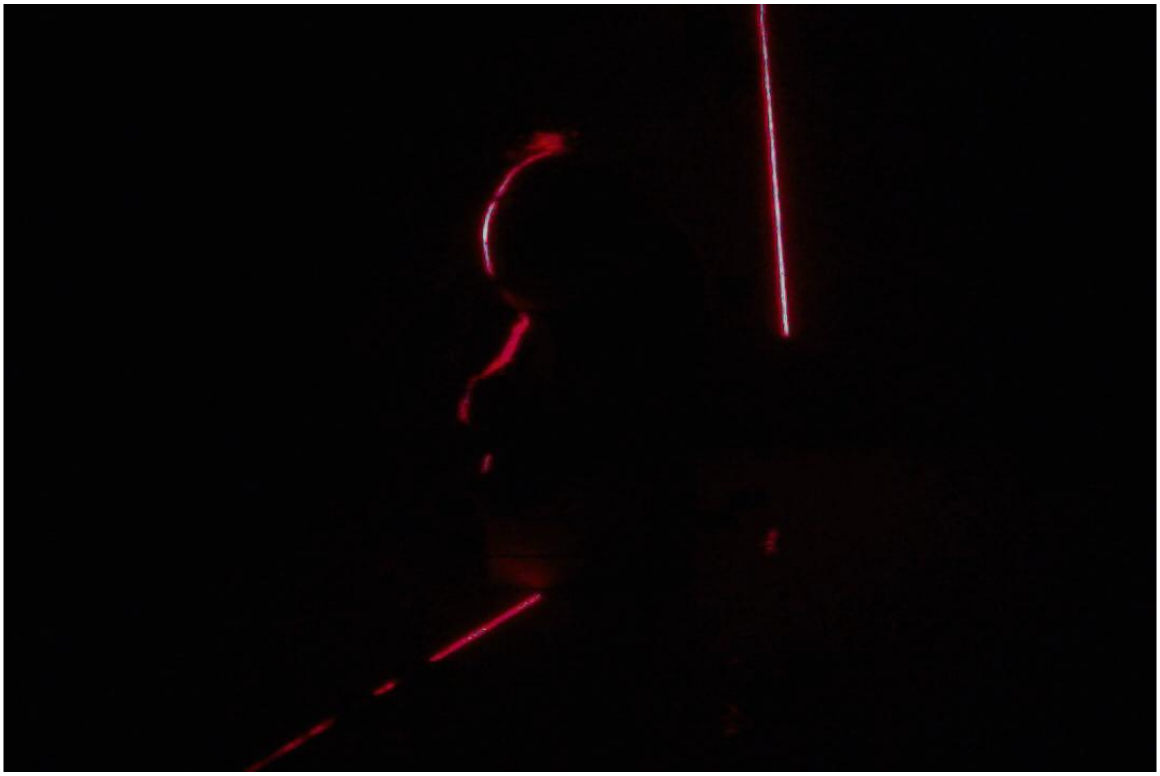
Gradient magnitude is defined as

$$g(c,r) = \sqrt{\left(\frac{\partial I(c,r)}{\partial c}\right)^2 + \left(\frac{\partial I(c,r)}{\partial r}\right)^2}$$

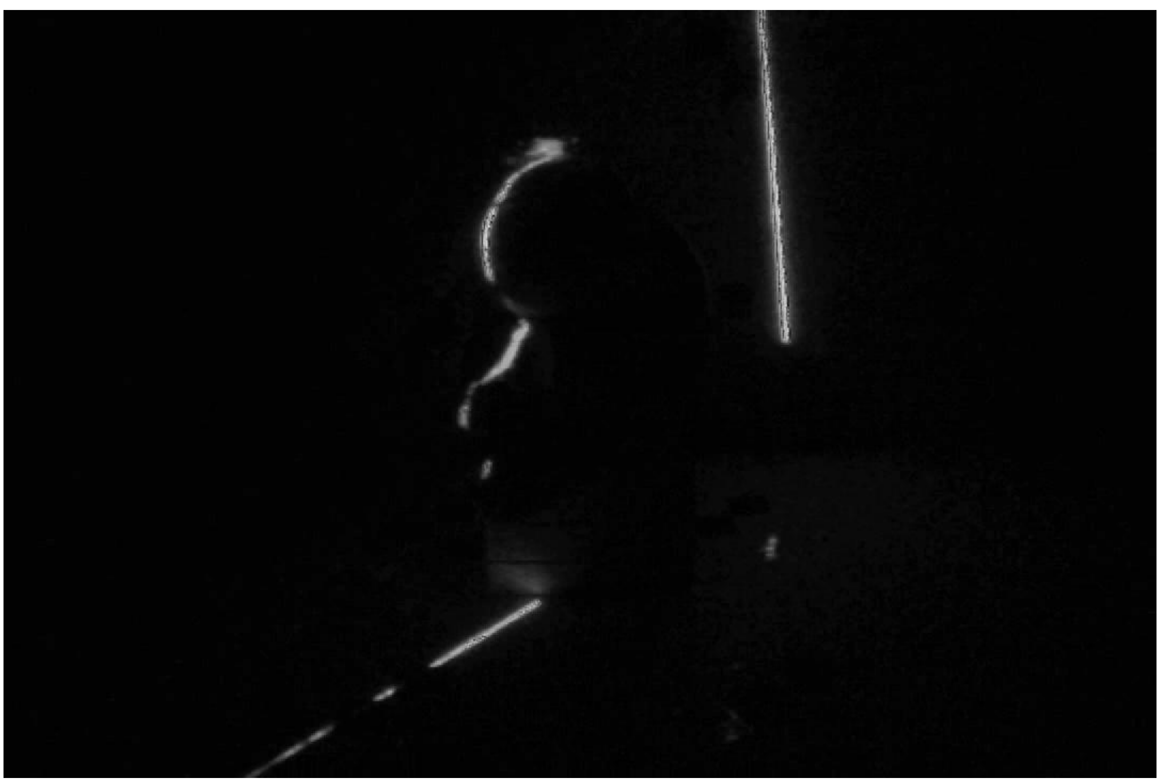
This leads to two first order image derivatives filters

$$h_x = [-1\ 1] \quad h_y = \begin{bmatrix} -1 \\ 1 \end{bmatrix}$$

The whole edge detection procedure includes edge enhancement, non maximal suppression and thresholding. In this project, the dark ambient light makes the edge easily be detected, so I just implemented the edge enhancement(Fig 4).



(a)



(b)

(c)

Fig 4: Edge Detection. (a) Original image. (b) Extract the red color out and convert it to gray scale. (c) After edge enhancement.

3. Approach

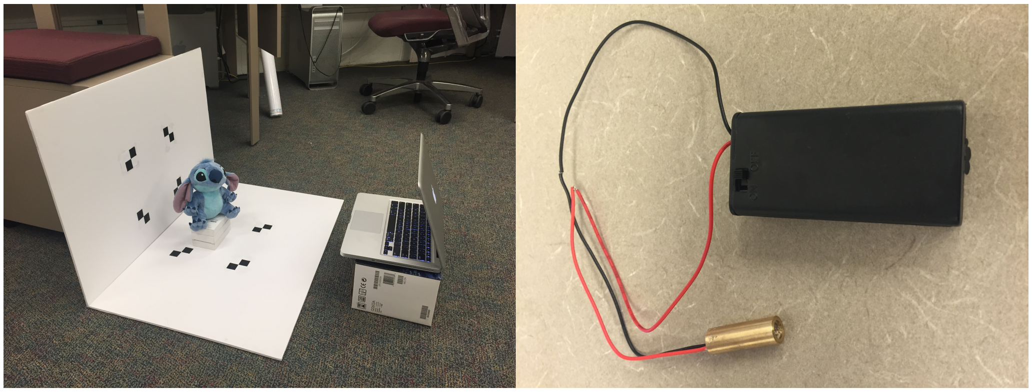
3D Scanning System

(a). Camera is the web camera on Macbook (Fig 5).

Because the photos and videos from that camera are flipped horizontal, I just flipped them back at the beginning of the process.

(b) Line laser with battery box (Fig 5).

I bought them online. Cost less than 30 dollars.



(a) System (b) Laser line with battery box

Fig 5. 3D scanning system

Calibration

I used the calibration toolbox from
http://www.vision.caltech.edu/bouguetj/calib_doc/

I printed out a checkerboard pattern and attached it to a hardcover book. Placed it in different positions and took twelve pictures (Fig 6). Then used the calibration toolbox to obtain the intrinsic matrix of the web camera. You can find the procedure of the calibration from the website above. The intrinsic matrix I obtained after calibration is:

$$W = \begin{bmatrix} 962 & 0 & 540 \\ 0 & 962 & 360 \\ 0 & 0 & 1 \end{bmatrix}$$

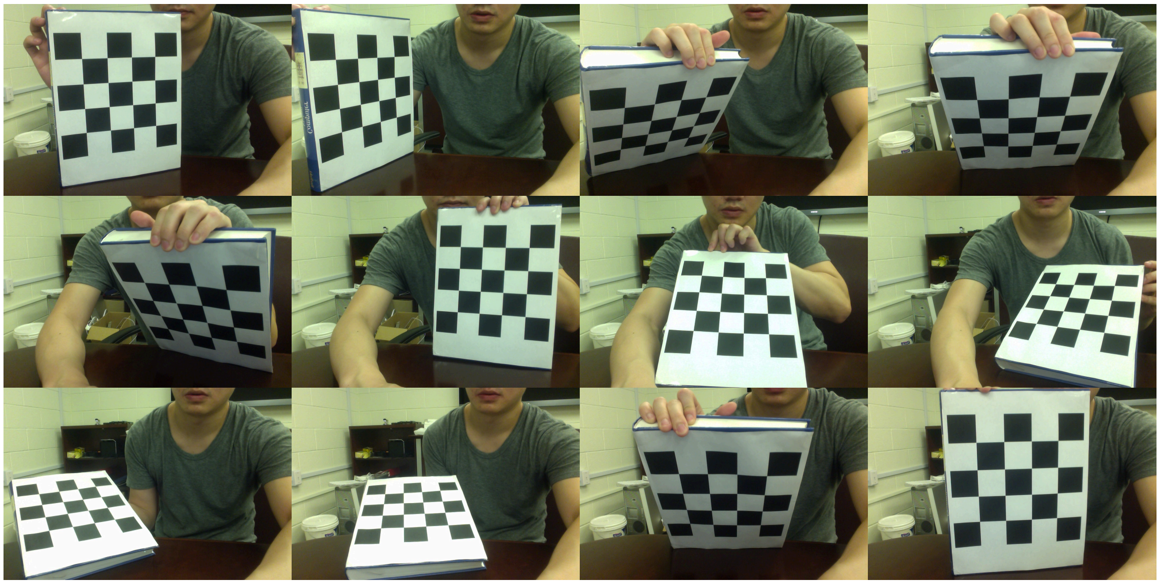


Fig 6: Twelve pictures for camera calibration

Scanning

During scanning, I scanned the object from different angles to cover the object as much as possible.

Image processing

- I extracted the red color from the images first because the laser line is red
- Implemented Edge Enhancement

3D reconstruction

- Determine the light plane and recover every point illuminated by the line laser
- Repeat the step above for every image

4. Experimental results

I scanned four objects to check the performance of my 3D scanner.

Object 1: Stitch

Fig 7: Image from camera

Fig 8: 3D images from different views

Object 2: Bobblehead Pedroia

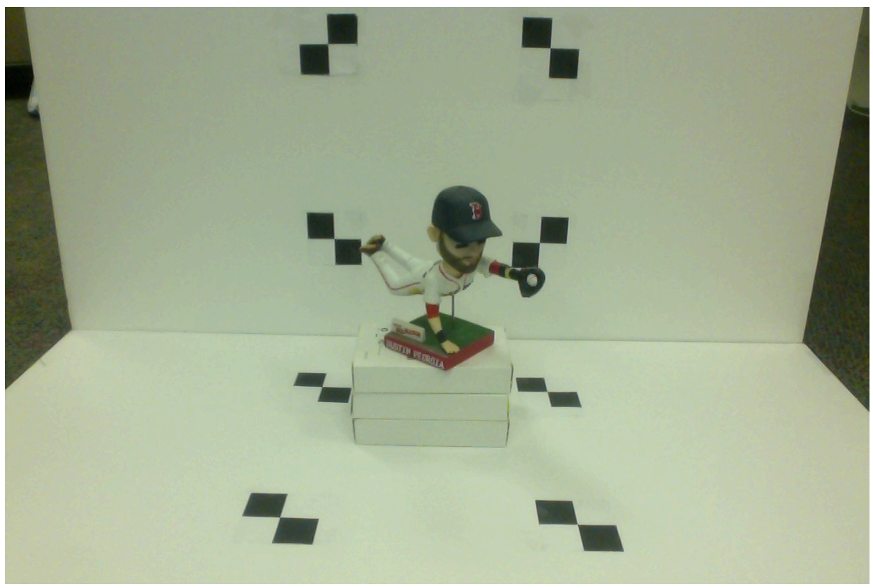
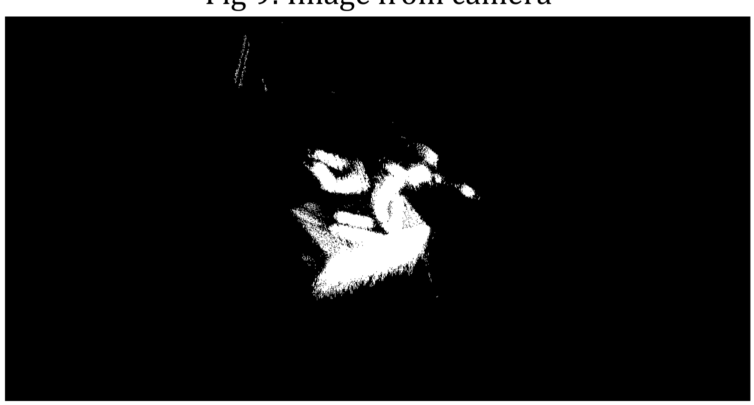


Fig 9: Image from camera



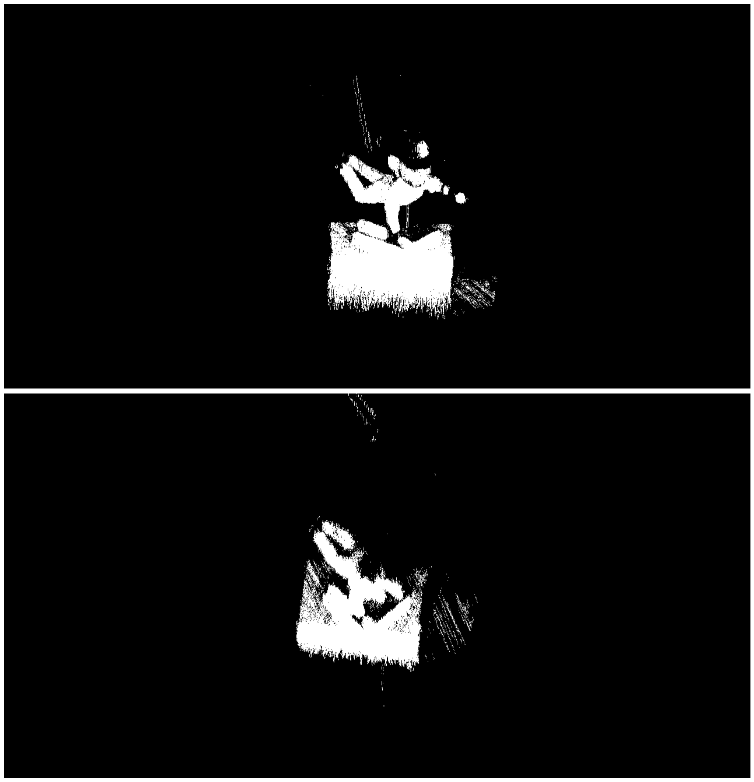


Fig 10: 3D images from different views

Object 3: Figure of Puerto Rico

Fig 11: Image from camera

Fig 12: 3D images from different views

Object 4: box

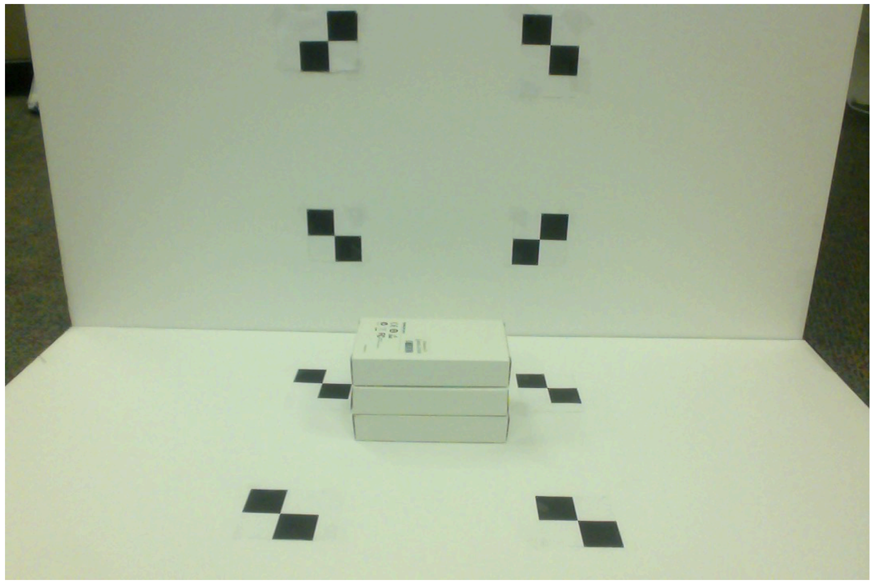
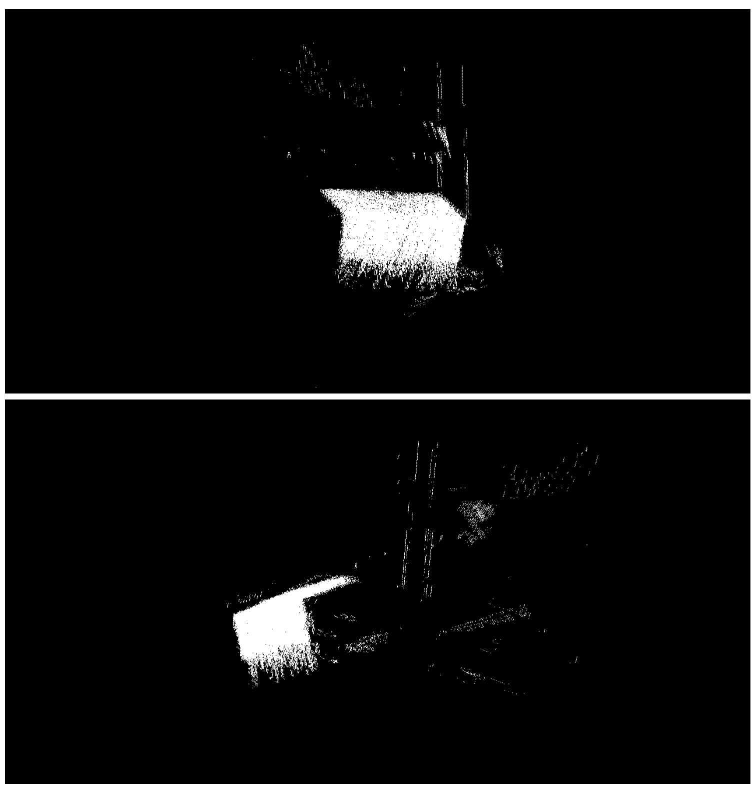


Fig 13: Image from camera



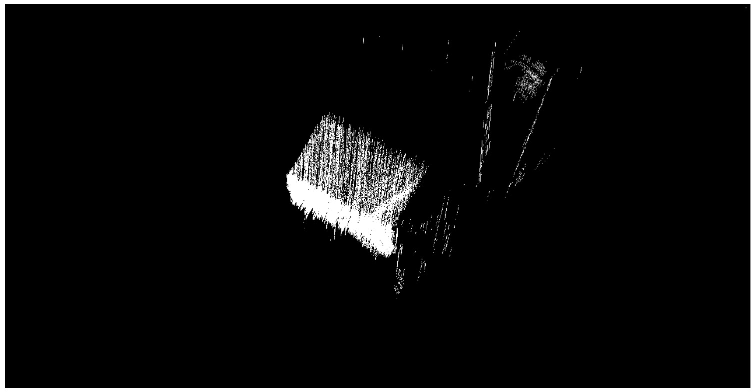


Fig 14: 3D images from different views

Accuracy

To check the accuracy I used two methods:

1. Geometry: Compare the real length and width of the box with the readings from the recovered 3D model

	Real value	Value read from image
Length	12.1cm	12.4cm
Width	7.6cm	7.1cm

Table 1: Comparison of the geometry parameters

The accuracy is acceptable if we don't require extreme precision.

2. Matching: Project the 3D coordinates back to the 2D image and see how well it matches with the image taken from the camera.

Fig 15: Original image from camera

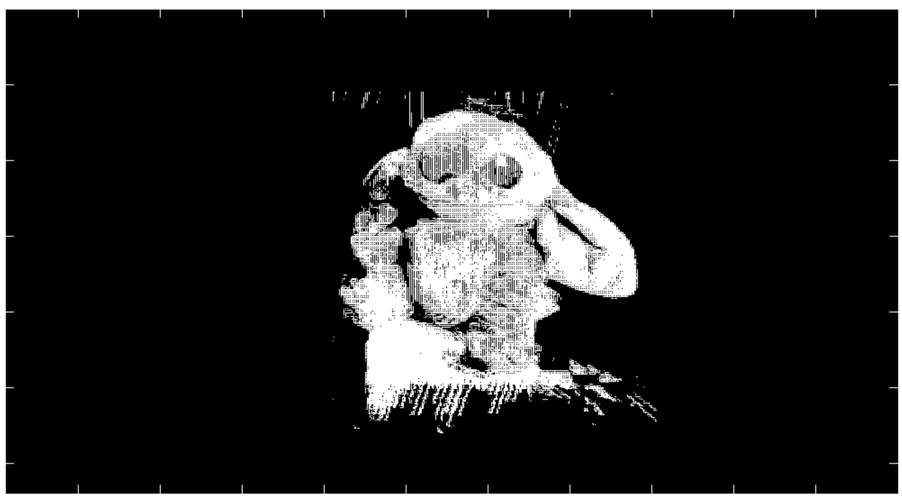


Fig 16: 2D image projected from 3D model

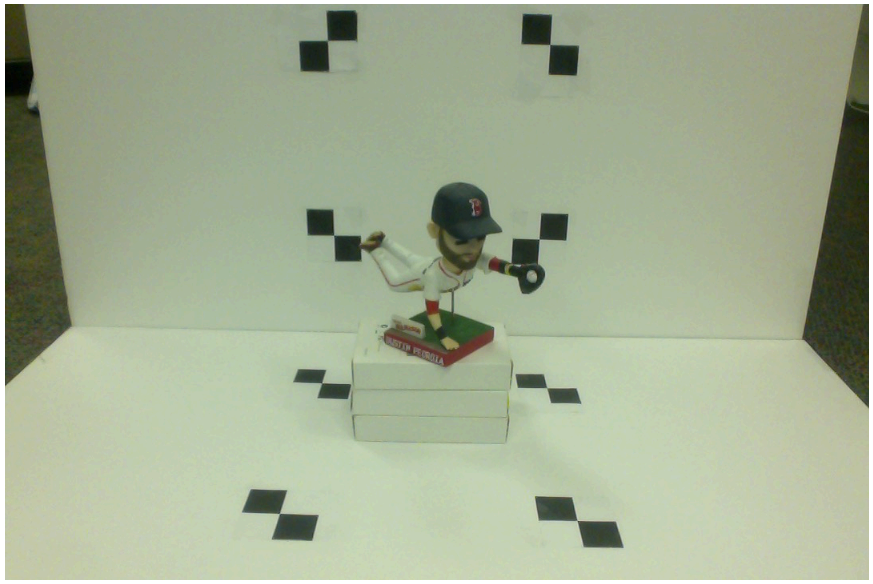


Fig 17: Original image from camera

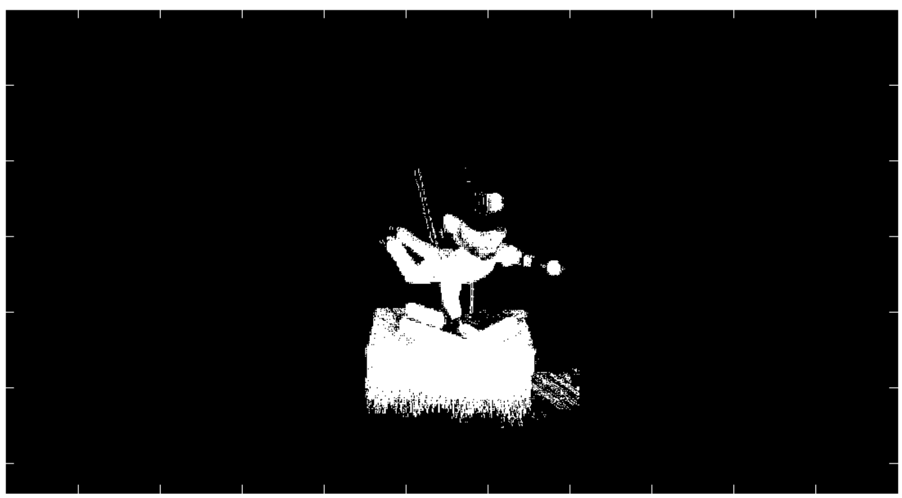


Fig 18: 2D image projected from 3D model

Fig 19: Original image from camera

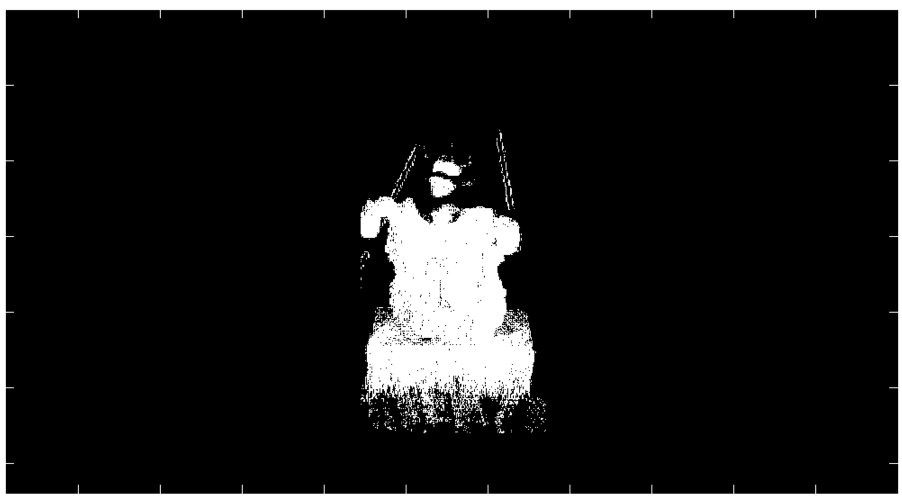


Fig 20: 2D image projected from 3D model

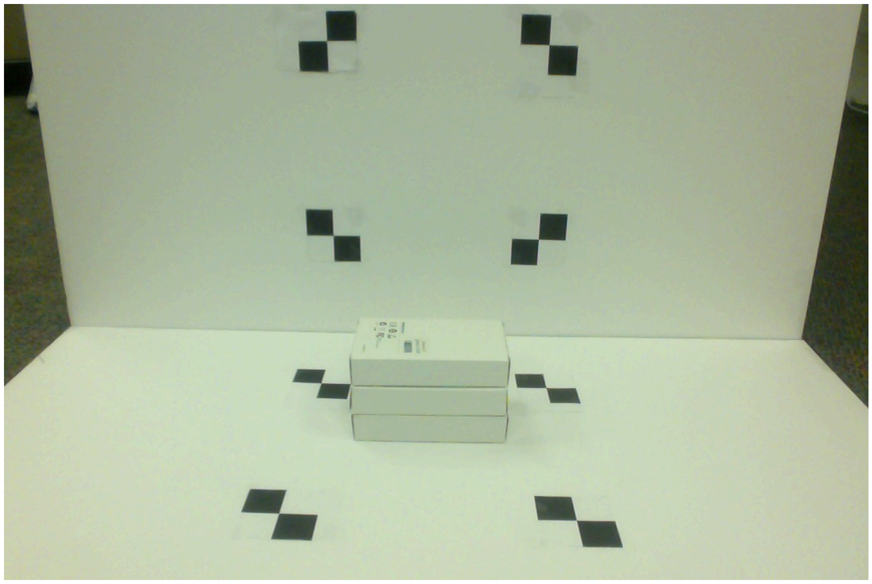


Fig 21: Original image from camera

Fig 22: 2D image projected from 3D model

5. Conclusion

With cheap equipment, which is fewer than 30 dollars, I successfully implement the 3D scanning using a line laser as the light source. There is some noise that affects the accuracy of the reconstruction. I think they are resulted from:

- The precision of the light plane.
- The precision of the coordinates of the fiducials on the two white boards
- The laser line is not thin enough

6. Future Work

The performance of the system can be improved with brighter and thinner laser line.

If the object is put on a rotating table with known rotating speed, then the 3D properties of the whole object can be recovered.

Reference

Course notes: http://mesh.brown.edu/byo3d/notes/byo3D.pdf

Calibration toolbox from:
http://www.vision.caltech.edu/bouguetj/calib_doc/