Low-Cost Triangulation 3D Laser Scanner for Lambertian Surfaces

A Thesis Presented to
The Academic Faculty

by

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Declaration

This is to certify that the project entitled "Triangulation 3D laser scanner" is supervised by Dr. Khondkar Siddique-e-Rabbani. This project is the result of the efforts of the members and has not been submitted anywhere for a degree.

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ABSTRACT

The design of a low-cost triangulation 3D laser scanner using off-the-shelf electronics is described. This system has a wide range of applications in 3D modeling, and is particularly useful because of its portability and inexpensiveness. The hardware setup was implemented and the 3D reconstruction was performed for a sample object. The result is compared to the actual object, and possible sources of error are identified and investigated. A discussion of the results attempts to show that advanced image processing algorithms can be used to minimize inaccuracies and create a workable prototype.

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TABLE OF CONTENTS

Page

ACKNOWLEDGEMENTS i

LIST OF FIGURES iv

LIST OF SYMBOLS AND ABBREVIATIONS v

CHAPTER

1. INTRODUCTION 1
2. BACKGROUND 3
    2.1 NECESSITY AND REQUIREMENTS 3
    2.2 TYPES OF 3D SCANNERS 3
    2.3 OUR METHOD 4
3. METHODOLOGY 6
    3.1 TRIANGULATION 6
    3.2 PEAK DETECTION 6
    3.3 PLOTTING 7
4. RESULTS 10
5. DISCUSSION 14

5.1 THEORETICAL ASSUMPTIONS AND LIMITATIONS 14

5.2 IMPROVEMENT TO PROCEDURE 16

6. CONCLUSION 17

APPENDIX A: MATLAB CODE FOR IMAGE ACQUISITION 18

APPENDIX B: MATLAB CODE FOR IMAGE PROCESSING
AND PLOTTING 19

APPENDIX C: LIST OF COMPONENTS USED 22

REFERENCES 23

LIST OF FIGURES

2.1 Principle of triangulation using two cameras, where P is the laser peak ……. 5

3.1 The principle of triangulation for the setup used ……………………………. 8

3.2 The cylindrical coordinate system used to obtain the surface plot .....……… 8

3.3 The proposed setup with a line laser source. ……………………...……… 9

4.1 The 3D reconstruction obtained by plotting the points in MATLAB ……… 11

4.2 The number of peaks obtained when the number of adjacent pixels

(a) n = 2(b) n = 3 (c) n = 4 and (d) n = 5…………………………………….. 12

5.1 A typical laser stripe in a captured image. The width is about 2 mm ……….. 15

LIST OF SYMBOLS AND ABBREVIATIONS

SNR	Signal-to-Noise Ratio
RGB	Red, Green, Blue
FIR	Fixed Impulse Response

CHAPTER 1

INTRODUCTION

With the vastly increased importance of computer-aided design in modern times, three dimensional models of objects are becoming desirable or even indispensable in many areas of science and technology. Hence 3D scanners have become the focus of much attention recently. Many different types of 3D scanners are available, including triangulation, contact and time-of-flight scanners. Each is suited to its particular application and has certain advantages and disadvantages. But by far the most common type uses laser triangulation. Triangulation 3D laser scanners offer reasonable accuracy and generalization at relatively low cost. They also provide the scope to improve reconstruction accuracy by improving the laser peak detection algorithm without any major modification to the hardware. Therefore, this technology is ideal for low-cost implementation. The particular design proposed in this paper uses components that are cheap and widely available, and still delivers an accurate 3D reconstruction.

The method developed in this paper relies on detecting the peak of a laser stripe in order to create a 3D reconstruction of the surface the laser is incident on. Since it uses images of the surface, it is susceptible to the kinds of noise that are inherent in such imaging systems [1]. The three noise sources in this case are (1) speckle, (2) electrical noise and (3) quantization noise. Speckle is due to the nature of the laser, while electrical and quantization noise, which are prominent in low SNR conditions, are inherent to the image sensor. The type of surface also plays a major role since it can result in additional noise. Here only the most common type of surface, the Lambertian surface, has been considered.

The aim of this thesis is to demonstrate a fast, inexpensive solution to the 3D scanning problem can be developed, the accuracy of which would depend primarily on the image processing algorithm rather than the hardware, which can be implemented using readymade components.

CHAPTER 2
BACKGROUND

2.1 NECESSITY AND REQUIREMENTS

Three-dimensional models of real-world objects have had a range of important applications throughout history in science, art and engineering. Statues, molds and small-scale models of actual objects, often constructed right to scale, have been crucial ingredients in processes such as the construction of buildings. However, modern applications require a high degree of precision and accuracy, which are achievable with current technology but may not be so with typical handcrafted models.Also, since digitization has made the design process much more convenient, digital 3D models are preferable in numerous applications.

The process of 3D modeling must satisfy certain criteria. The precision and accuracy required varies from one application to another. An error of 0.1 cm is negligible when scanning a building, but may be unacceptable for a small object. The speed and portability of the 3D scanner may also be an issue, since laboratory conditions may not always be available for optimum performance. In cases where the subject is small and fragile, not inflicting any damage during the scanning process is also a requirement.

2.2 TYPES OF 3D SCANNERS

Since the study of the problem of 3D scanning commenced, a number of distinct approaches have been developed. Each method has its own advantages and disadvantages, and its usefulness is often limited to a certain range of applications.

Contact scanners rely on measurements taken during physical contact with the subject. This results in a highly accurate 3D model, but the process is slow and may cause damage to the subject. Modern non-contact 3D scanners are based on light (especially laser).

Time-of-flight laser scanners rely on the same principles as sonar. Instead of sound waves, short pulses of laser are directed towards the object. Using sophisticated equipment, the time taken for the reflected pulse to arrive back can be measured. Repeating this process many times from different angles gives information about the dimensions of the subject, which can be used to create a 3D model.

Triangulation can be used to create an easily implementable solution to the 3D scanning problem. This method basically finds out the location of a laser dot using one or more cameras, by locating the point of intersection of two straight lines which pass through the dot. If the locations of the two cameras (or alternatively, one camera and the laser source) are known precisely, the repetition of the triangulation process all over the object surface can be used to create a 3D plot.

Structured-light scanners obey the same general principle but have a more complex implementation. The light incident on the subject is structured so that the light intensity varies with the location. After scanning, the intensity values can be used to compute the locations and create a 3D plot.

2.3 OUR METHOD

Time-of-flight laser scanners are suitable for very large objects, but for small ones they are inefficient both in terms of cost (the equipment needed is expensive and

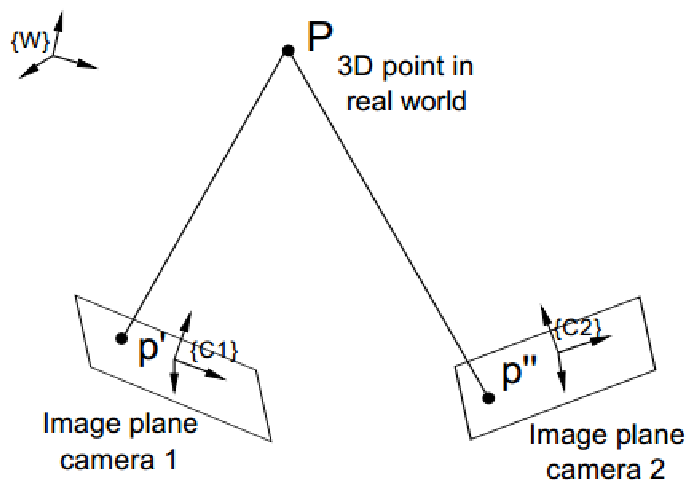


Fig. 2.1 Principle of triangulation using two cameras, where P is the laser peak

difficult to obtain) and effort. Structured-light scanners are fast and accurate, but have a complex implementation process since good results depend on very accurate calibration of light intensity values and the corresponding extraction of information from them.

For our purposes, which is to create a simple and low-cost 3D scanner, we have chosen to develop a generic triangulation laser scanner which can be implemented with comparatively low cost and complexity, and whose accuracy depends mainly on the software processing rather than on the hardware used. Therefore, this solution fulfills our aims and leaves scope for significant improvement in the future.

CHAPTER 3

METHODOLOGY

3.1 TRIANGULATION

The method of triangulation involves a laser source and two image sensors, which are usually cameras. Given that the positions of the cameras relative to each other is known, the images they take can be used to work out the position of the laser dot. This is because each camera ‘sees’ the same point from two different perspectives, meaning that there must be two straight lines, each passing through the laser dot on the object surface as well as being perpendicular to the image plane of one camera. The intersection point of the two lines gives the location of the dot. However, if the position of the laser source relative to one camera is known, it eliminates the need for the second camera as there is sufficient information to apply triangulation. This setup is shown in fig. 1.

Locating each individual laser dot on the surface of the scanned object and plotting the corresponding point in the 3D model is a cumbersome process that increases time required for both data acquisition and image processing. A much more computationally efficient way to apply triangulation is to work with laser stripes, treating each stripe as a vertical series of dots [2].

3.2 PEAK DETECTION

The intensity (i.e. energy) pattern of the laser stripe is assumed to have a Gaussian distribution, although instead of the ideal single peak it is found to have multiple peaks. This can be attributed to the speckle of the laser light as well as the quantization error that arises when the images are transferred to MATLAB, which is used to both acquire and process them.

Due to the Gaussian profile, it is expected the first derivative of the intensity pattern will be zero at the peak location. However, due to the apparent presence of multiple peaks in the image, it is necessary to modify this simplified theoretical model. Instead of just one pixel, this criteria can be applied to a number of adjacent pixels. Based on the sum of the intensities and first derivative values, the location of a single peak can be estimated.

Fig. 2 shows the principle of triangulation for the proposed setup. Once the peak is detected, we can find the horizontal distance x between the laser stripe segment on the object surface and the laser source L. The laser beam LO is always perpendicular to the line CL is fixed, and the distance CL is fixed. Hence, after the peak detector provides the value of the angle between CO and CL, the value of x can be calculated using simple trigonometry. Since peak detection is a row-parallel process, the process is repeated for every laser stripe segment until the entire stripe is covered.

3.3 PLOTTING

Peak detection provides values of x for each point on the vertical laser stripe, which can be used to plot the shape of a segment of the object surface. If the objectis rotated slightly, the same information can be obtained for another segment.

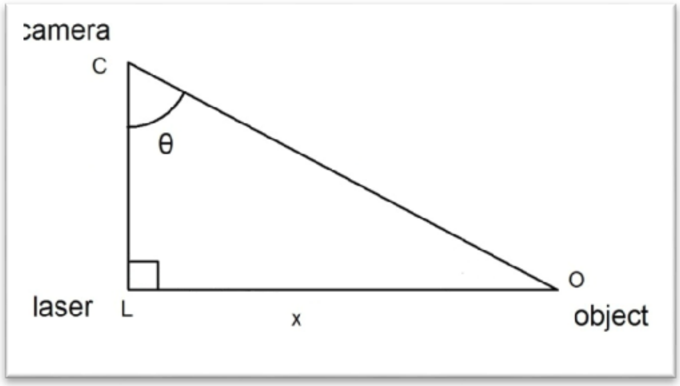


Fig. 3.1. The principle of triangulation for the setup used.

When the object is rotated through a full circle, 2D information about the surface of the entire object can be obtained. Using this 2D information to construct a 3D model can be done by finding the corresponding three-dimensional cylindrical coordinates. The cylindrical coordinate system is shown in fig.3, and the information obtained from image processing can be plotted in it using the appropriate transformations, by factoring in the angle through which the object is rotated as well as the distance of its axis of rotation from the laser source.

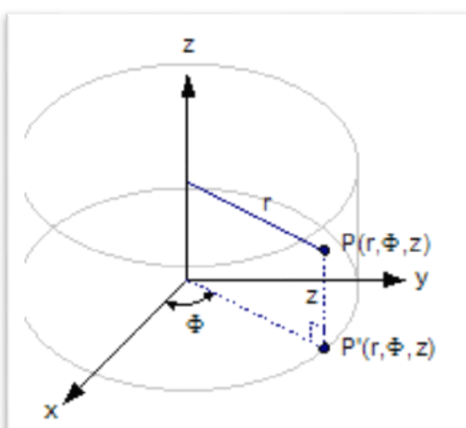


Fig. 3.2. The cylindrical coordinate system used to obtain the surface plot.

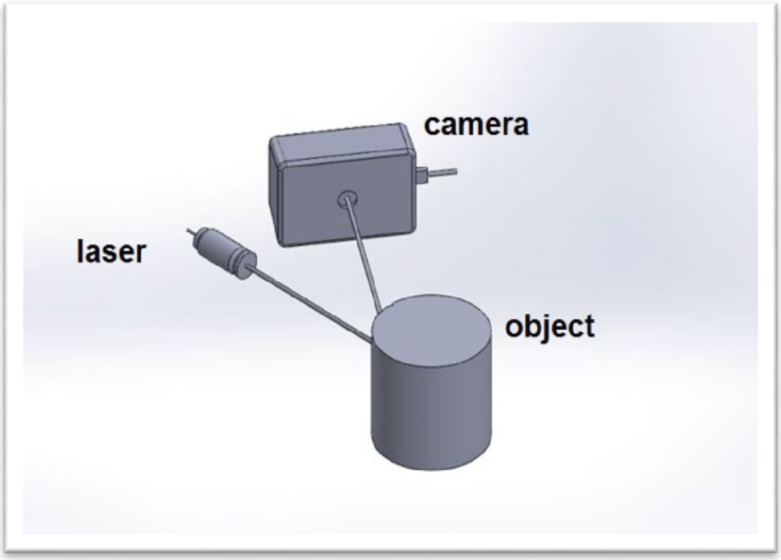


Fig. 3.3. The proposed setup with a line laser source.

CHAPTER 4

RESULTS

The object selected to be the target of the developed 3D scanner was a smooth cylinder with one open end. It was chosen due to its structural simplicity which would facilitate comparison of the 3D reconstruction with the original object. The cylinder was mounted on a servo motor which was turned at a certain step angle at regular intervals, controlled by a laptop computer through an Arduino Uno board. A webcam plugged into the laptop was used to acquire images of the laser stripe on the cylinder surface. Both the acquisition and processing of the images was done in MATLAB. The acquired images were first fed to a simple peak detector, and the locations of the obtained peaks were transformed into three-dimensional cylindrical coordinates and plotted. The resulting model is shown in fig. 4.

As expected from the lack of a filtering stage or any other form of mathematical processing, an accurate reconstruction could not be produced. The radius of the reconstructed cylinder ranged from as low as 2.43 cm to as high as 3.34 cm, with an overall average of 2.83 cm. Compared to this, the actual radius of the cylinder was measured as 2.8 cm. Even though the average was found to be close, the variations in the calculated values of radius were too large to render an effective 3D reconstruction. This can be attributed to the noise inherent in the images, which the simple peak detector failed to filter out. However, as will be described later, a suitable peak detection algorithm can rectify this shortcoming.

In terms of computing time, the results were more encouraging. The total time required for image acquisition was found to be 217.36 seconds. The image processing time was found to be 18.5 seconds for a typical case, although it was observed to be as high as 27.3 seconds in some cases since it is dependent on computational power. The entire process was completed in about 4 minutes.

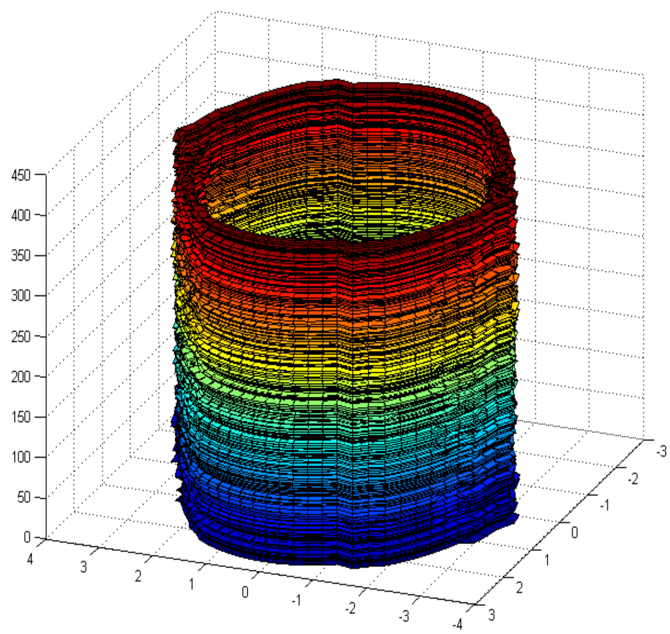
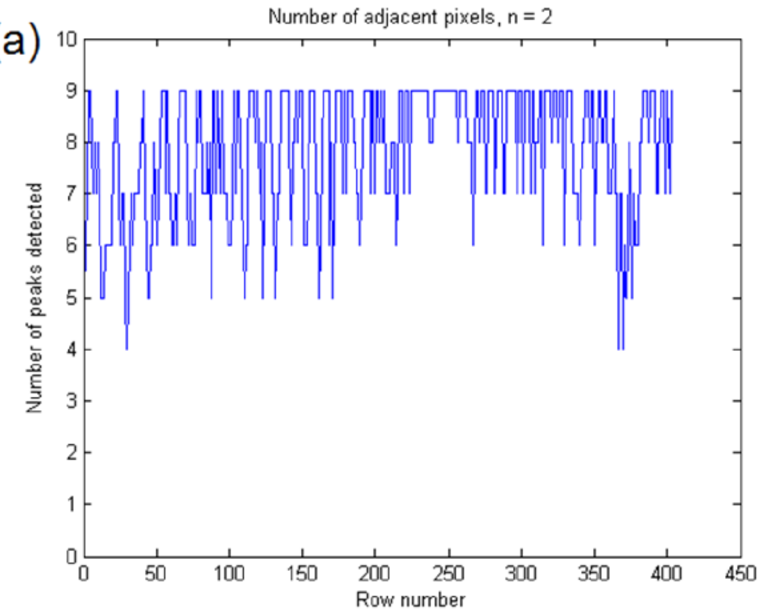


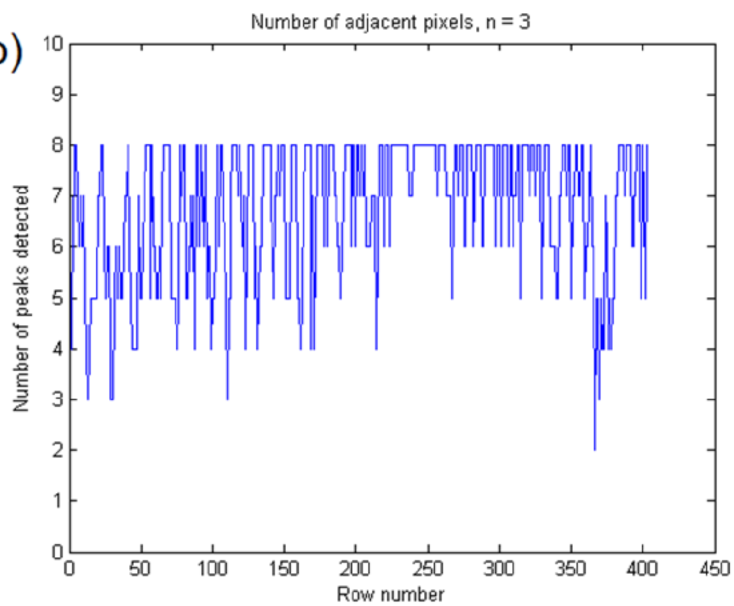
Fig. 4.1. The 3D reconstruction obtained by plotting the points in MATLAB

Originally, 3 adjacent pixels were used at a time for the computation of the peak. The procedure was then repeated for 2, 4 and 5 adjacent pixels. Increasing the number further caused loss of rows that did not fit the criteria. Counting the number of peaks in each row, it was seen that increasing the number of adjacent pixels caused a significant reduction in the number of peaks, as show in fig. 4.2.

(a)


Number of adjacent pixels, n = 2
Number of peaks detected
Row number
0
1
2
3
4
5
6
7
8
9
10
0
50
100
150
200
250
300
350
400
450

(b)


Number of adjacent pixels, n = 3
Number of peaks detected
Row number
0
1
2
3
4
5
6
7
8
9
10
0
50
100
150
200
250
300
350
400
450

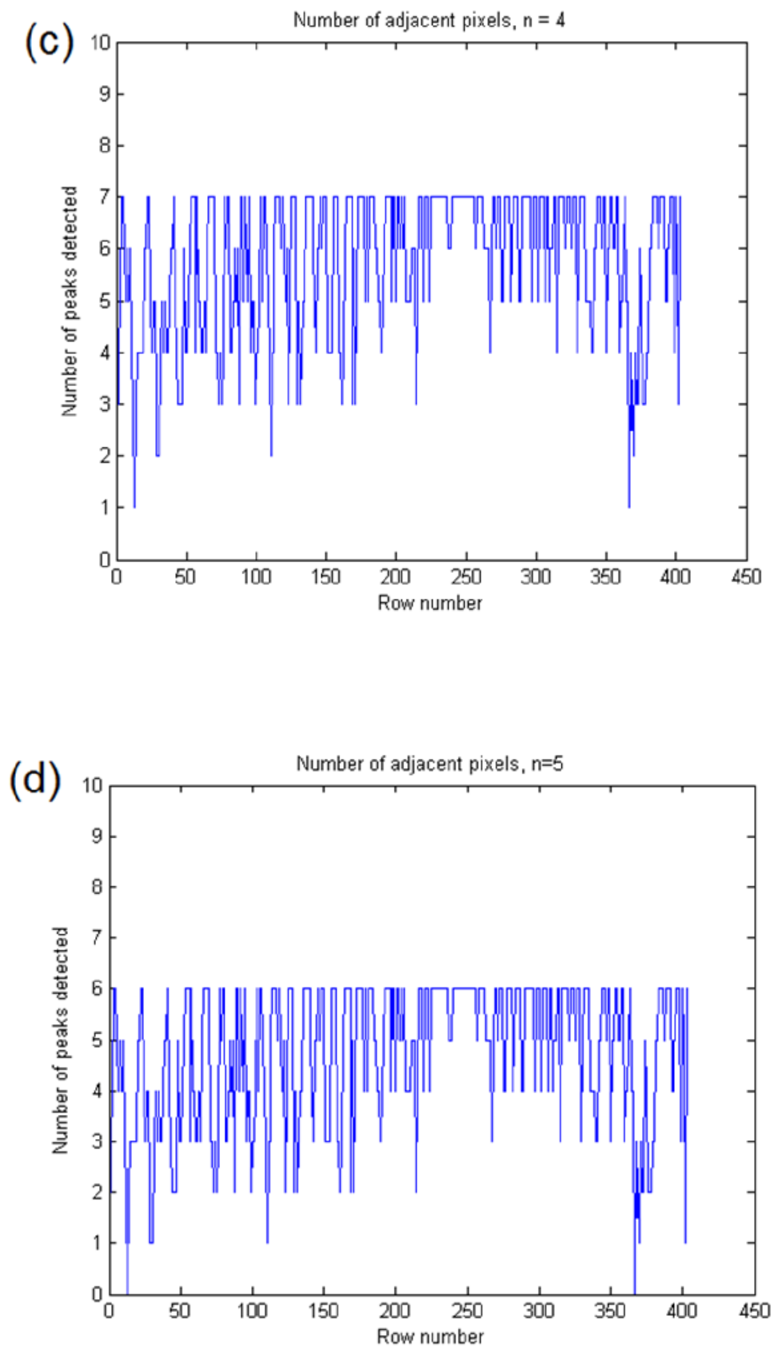


Fig. 4.2. The number of peaks obtained when the number of adjacent pixels (a) n= 2 (b) n = 3 (c) n = 4 and (d) n = 5

CHAPTER 5

DISCUSSION

The absence of a filtering stage appears to be the primary reason for the inaccuracy of the 3D reconstruction. However, a number of other sources of error were identified which would have to be dealt with in the experimental method along with implementing a proper peak detection algorithm in order to produce an accurate 3D model.

5.1 THEORETICAL ASSUMPTIONS AND LIMITATIONS

The primary reason for the failure of an accurate 3D reconstruction appears to be the noise [1] which was not filtered out. The peak detector used in this experiment located peaks based on the maximum intensity values and zero-crossing of the first derivative. It did not account for noise which could cause false peaks to be located. This assumption of a simplistic, noiseless environment was partly the result of prioritizing efficacy over accuracy.

Efforts were made to minimize the width of the laser stripe and it was limited to 2 mm, to the nearest millimeter. However, the width of the laser stripe was not factored into the process of peak detection. As the stripe widens, the possibility of multiple peaks being detected also increases. Also, increasing width is likely to increase the quantity of noise and enable it to have a greater effect on the final output. One way to reduce the sources of error and improve the experiment would be to use a thinner laser stripe.

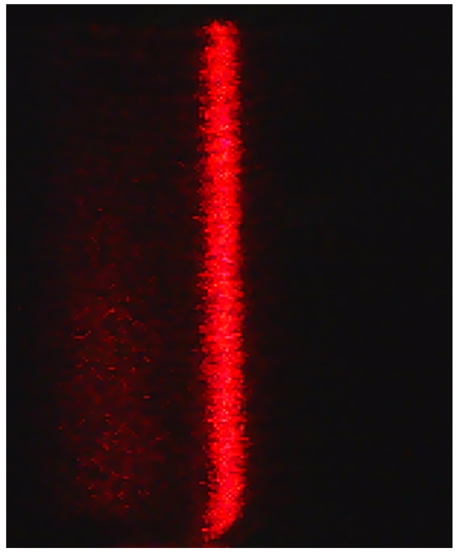


Fig. 5.1. A typical laser stripe in a captured image. The width is about 2 mm.

The images used were of 1920x1080 resolution, taken with a webcam with full 1080p resolution, as claimed by the manufacturer. However, such commercial cameras actually have one-third of their advertised resolution. Each pixel in an image has an R, G and B value, and detecting those values require three separate sensors. The camera uses a single monochrome sensor with a mosaic pattern filter [3], followed by an interpolation algorithm which creates a full array of RGB image data. Also, when the image is scaled up to enhance quality, the intensity values for new uncaptured pixels is interpolated from the values of adjacent pixels. The interpolated resolution is higher than the native resolution of the camera. This loss of information and the use of technically 'false' information was not accounted for, and is a possible source of error.

5.2 IMPROVEMENT TO PROCEDURE

It has already been mentioned that the peak detector used in this experiment is incapable of filtering out noise, since its output depends solely on the intensity values and the unfiltered first derivative. More sophisticated peak detectors have already been developed. Early methods of peak detection relied on the center of mass technique [4] and curve-fitting [5], but more recent techniques have taken a filter-based approach. Notable among them is the method proposed by Blais and Rioux which uses an FIR filter followed by linear interpolation [5], and a similar method that adjusts the filter parameters based on a frequency analysis and the surface optical properties [1][6].

In peak detection, the number of adjacent pixels considered at a time was found to be a factor. Due to the simplicity of the peak detector, multiple peaks were detected in each row. A greater number of extra peaks would indicate quantity of noise which, as mentioned before, would have a greater effect on the output. One way of improving the procedure would be to find the number of adjacent pixels that minimizes the number of additional peaks.

CHAPTER 6

CONCLUSION

Based on the results of this project which were obtained without the use of advanced peak detection techniques, it can be stated that laser triangulation can provide a viable low-cost solution to the 3D scanner problem. The problem of accurate 3D reconstruction still remains, although it can be conceivably solved using the guidelines laid out in this thesis, as well as additional error-correction and optimization that can be achieved using other methods. Smart image processing algorithms can be designed to achieve this, and a further step would be to automate the adjustment of filter parameters based on optical properties of the object. With such efforts, a low-cost triangulation 3D laser scanner can be realized for a diverse array of applications.

APPENDIX A

MATLAB CODE FOR IMAGE ACQUISITION

```
clear all;
close all;
clc;
tic                    %start the clock
a=arduino('COM9');     %initialising arduino board which is
connected to com9
a.servoAttach(9);      %initialising servo connected to arduino
for w=0:1:18;
    pos=w*10;
    a.servoWrite(9,pos);
    vidobj = videoinput('winvideo',1,'MJPG_1920x1080');
%initialising camera
    set(vidobj,'ReturnedColorSpace','rgb');
    triggerconfig(vidobj, 'manual')
fn='E:\8th semester\thesis\pics\im000.png'; %saving locaton of
images
k=1;
x=floor(w/10);
y=w-x*10;
fn(31)=num2str(x);
fn(32)=num2str(y);
start(vidobj)

for i = 1:2
    snapshot = getsnapshot(vidobj);  %capturing images
    fn(33)=num2str(k);
    k=k+1;
    imwrite(snapshot,fn);
end
stop(vidobj)
delete(vidobj)
end
delete(a);
asd=toc
```

APPENDIX B

MATLAB CODE FOR IMAGE PROCESSING AND PLOTTING

```
clear all;
close all;
clc;

tic
fname='D:\Study\Final year project\3D
scanner\Matlab\pic3\im000.png';
t=uint8(fname);
m=length(t);
roih=403;
rowcut=657;

for im=1:73

imfn=num2str(im);
l=length(imfn);
for j=l:-1:1
fname(m-l+j-4)=imfn(j);
end

I=imread(fname);
I2=I(:,:,1);
[r c]=size(I2);
k=1;
for i=1:c
col=I2(:,i);
avg=sum(col)/length(col);
if(avg>=100) roi1(:,k)=col;
if(k==1) colcut=i;
end
        k=k+1;
end
end
k=1;
rowcut=657;
for i=rowcut:roih-1+rowcut
roi(i-rowcut+1,:)=roi1(i,:);
end
```

```
fd=diff(roi,1,2);
[r1 c1]=size(fd);
k=1;
for i=1:r1
fd_row=fd(i,:);
roi_row=roi(i,:);
roi_row=double(roi_row);
    l=1;
for j=2:c1-1
        if(fd_row(1,j-1)+fd_row(1,j)+fd_row(1,j+1)==0)
            roi_row_intensity(i,l)=roi_row(1,j-
1)+roi_row(1,j)+roi_row(1,j+1);
maxpts(i,l)=j;
            k=k+1;
            l=l+1;
end
end
end

for i=1:r1
    w=roi_row_intensity(i,:);
tmp=find(w==max(w));
    tmp2=ceil(length(tmp)/2);
    tmp3=maxpts(i,tmp2);
max_int(i,1)=tmp3;
end
peak=roi;


I2_peak=I2;

for i=1:r1
    k=rowcut-1+i;
    j=max_int(i,1);
    l=colcut-1+j;
p(i)=k;
q(i)=l;
    I2_peak(k,l)=0;
end

d=19;

for i=1:r1
    x=(q(i)-1039)*0.02636;
maxint_deg(i,1)=41.94-2*asind(x/(2*d));
```

```
end

s=13.8;
rad=15;

for i=1:r1
x(i)=s*tan(pi*maxint_deg(i,1)/180);
end
t=rad-x;
t=t';
if(im==1) ra=t;
elsera=[ra t];
end

end

ra=flipud(ra);
t=1:roih;
z=t';
u=0:(5*pi/180):2*pi;
th=u;
for i=1:im-1
    z=[z t'];
end
fori=1:roih-1
th=[th;u];
end

[x,y,z]=pol2cart(th,ra,z);
surf(x,y,z)
Runtime=toc
```

APPENDIX C

LIST OF COMPONENTS USED

1. Dot laser
2. Glass rod (cylindrical lens)
3. Servo motors (2)
4. LiPo batter (11.1 V, 2200 mAh)
5. LM7806 voltage regulator
6. A4tech PK-900H webcam
7. Arduino Uno board
8. Computer (laptop) running MATLAB

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