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16. Abstract:
Based on the research results in Projects 0-4282, lightweight in compact size pushcart and vehicle-mount laser thickness-measurement devices have been successfully developed. The Length, Width, and Height which are 42.5 inches, 29 inches, and 47 inches in the old pushcart version have been reduced to 28 inches, 15 inches and 37 inches in the new pushcart version. The weight of the new pushcart is only the half of the old version. The new pushcart is easy to be handled by one person to conduct routine project monitoring practice. To increase the TPPM thickness measurement speed, a prototype of vehicle-mount laser thickness measurement system is developed. Two independent laser devices are installed onto a golf cart. One laser device shots a laser beam on the pavement with tape, and the other one shots a beam on the pavement without tape. The tape thickness is obtained by processing the output signals from two laser devices. Both lab and field results of the pushcart and vehicle-mount devices are very close to real thickness of thermoplastic. The measurement accuracy can reach 5 mils in both lab and field conditions.

An auto-synchronized laser scanning for the 3D measurement of the TPPM thickness is also studied. The optical simulation and some initial tests show that this new method with high speed laser scanning makes a highway speed vehicle-mount TPPM thickness measurement feasible.

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Develop Pushcart and Vehicle-mount Laser Thickness-Measuring Devices for Thermoplastic Pavement Marking Material

by

Yuanhang Chen, Wei Sun, Aditya Ekbote
Xuemin Chen, Jing Li, and Richard Liu

Research Report 0-4882-1

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Performed in Cooperation with the
Texas Department of Transportation
and the
Federal Highway Administration

by the

Subsurface Sensing Laboratory
Department of Electrical and Computer Engineering
University of Houston

October 2004

DISCLAIMERS

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CHAPTER 1: INTRODUCTION

1.1 PROJECT BACKGROUNDS AND OVERVIEW

In Project 0-4282, the researchers developed a laser device that can accurately measure the thickness of thermoplastic pavement marking material (TPMM) on both flat and rough surfaces [1]. The device was installed on a pushcart designed for manual operation. In addition, the hardware and software that were developed for the device was lab and field-tested. The results of the research show that this device is able to reach an accuracy of 2 mils on flat pavement and 5 mils on rough surfaces. The success of the initial research demonstrates that it is quite feasible to use a non-contact method for thermoplastic thickness measurement with high accuracy.

Based on the research results in Projects 0-4282, lightweight in compact size pushcart and vehicle-mount laser thickness-measurement devices have been successfully developed in this project. The two TPMM thickness measurement devices are shown in Figure 1.1 and Figure 1.2. The Length, Width, and Height which are 42.5 inches, 29 inches, and 47 inches in the old pushcart version have been reduced to 28 inches, 15 inches and 37 inches in the new pushcart version. The weight of the new pushcart version is only a half of the old version. The new pushcart is easy to be handled by one person to do the routine project monitoring practice. To increase the TPMM thickness measurement speed, a prototype of vehicle-mount laser thickness measurement system is also developed. Two synchronized laser devices are installed in a golf cart. One device shots a laser beam on TPMM tape, and the other one shots a beam on the pavement without tape. The tape thickness is obtained by processing the two laser devices' output signals. The experiment results of the pushcart and vehicle-mount devices are very close to real thickness of thermoplastic tape.

An auto-synchronized laser scanning system for measurement of the TPMM thickness is also pursued. The purpose of this development is to increase the tolerance of vehicle zigzagging. The optical simulation and initial tests show that this new method with high speed laser scanning makes a highway speed vehicle-mount TPMM thickness measurement faster and more accurate.

Figure 1.1 New version of pushcart TPMM thickness measurement system

Figure 1.2 Vehicle-mount TPMM thickness measurement system

CHAPTER 2: THE PUSHCART LASER THERMOPLASTIC TAPE THICKNESS MEASUREMENT SYSTEM

2.1 SYSTEM GENERAL DESCRIPTION

The manual version of thermoplastic marking material thickness detector is a pushcart device, which measures the thickness of marking materials on pavement surface by using laser technology. The device consists of two parts: a hardware system to measure the pavement-marking by using laser triangulation technique and a software package to analyze and process the measured data. Figure 2.1 is the designed pushcart. The Length, Width, and Height of the pushcart are 28 inches, 15 inches, and 37 inches respectively. The standoff distance defined as the distance between laser transmitter and pavement surface is 12 inches.

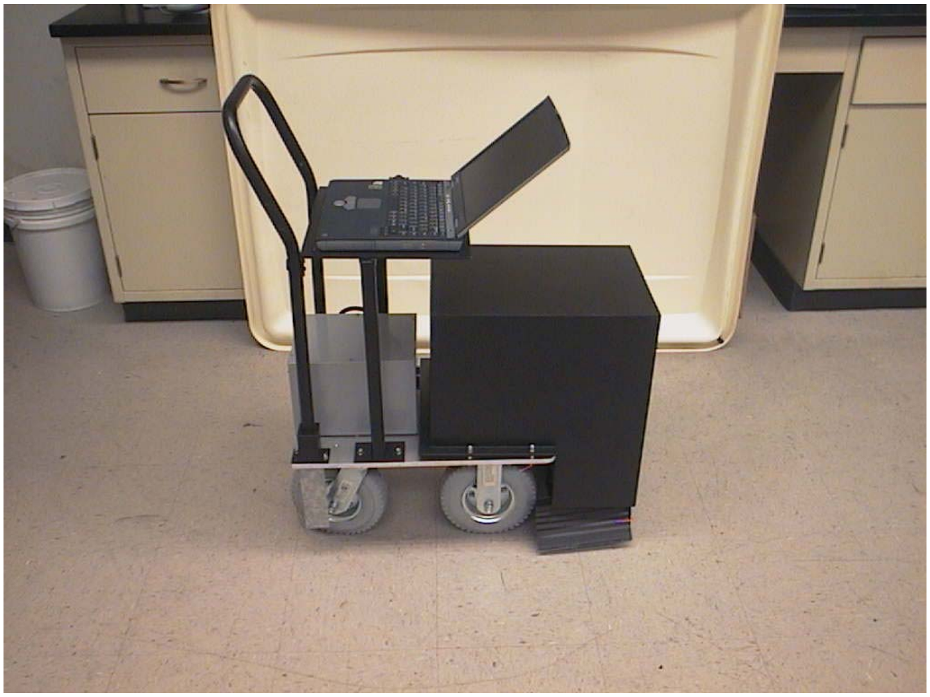

Figure 2.1 New pushcart TPMM measurement device

2.2 SYSTEM BLOCK DIAGRAM

The software of the system will be illustrated in Chapter 5. To descript the architecture of the device, a simple hardware block diagram is depicted in Figure 2.2.

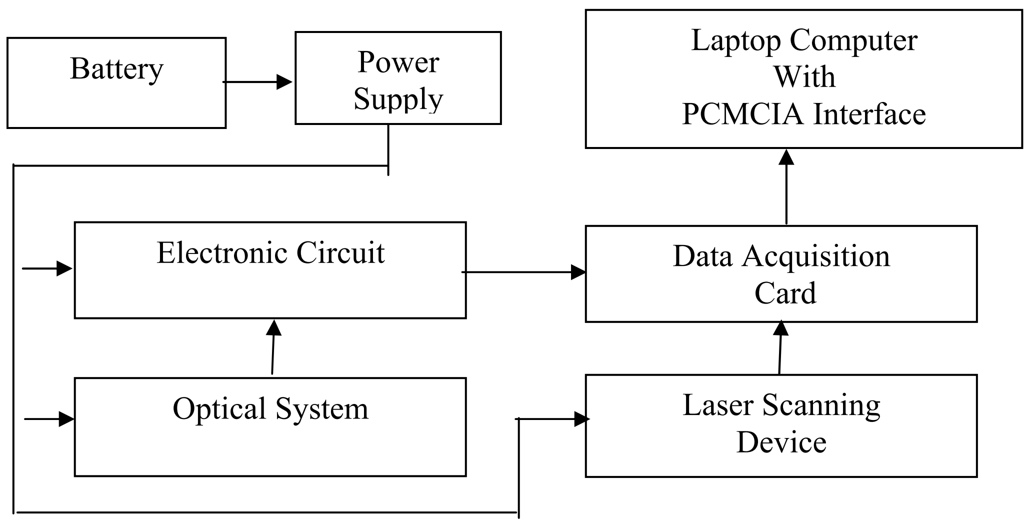

Figure 2.2   Block diagram of hardware system

The prototype hardware of pavement-marking thickness measurement system is divided into three subsystems: the laser scanning subsystem, laser range finder subsystem, and power supply subsystem. The inside of the pushcart device is shown in Figure 2.3.

The laser scanning subsystem ueses a motion controller to precisely control the motion of step motor, which is connected to laser range finder device. The laser range finder subsystem is divided into optical block and signal processing block. Figure 2.4 is laser-based triangulation optical system, and Figure 2.5 is the block diagram of signal processing circuit.

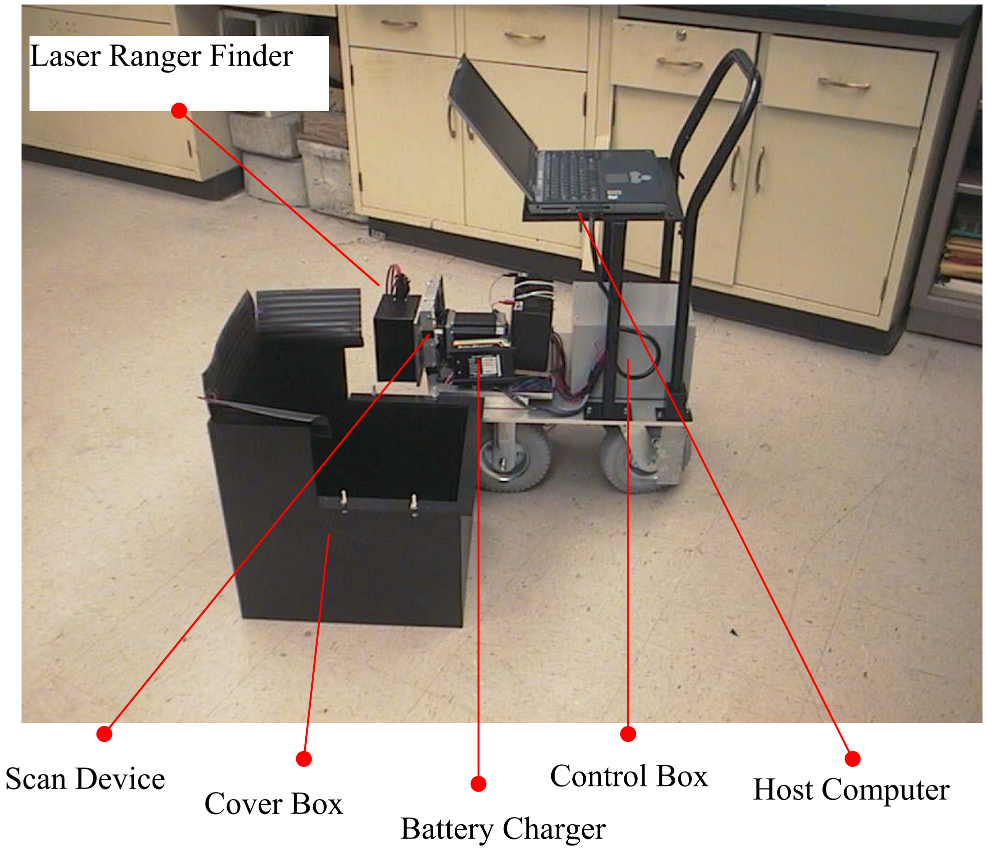

Figure 2.3 TPMM measurement system components

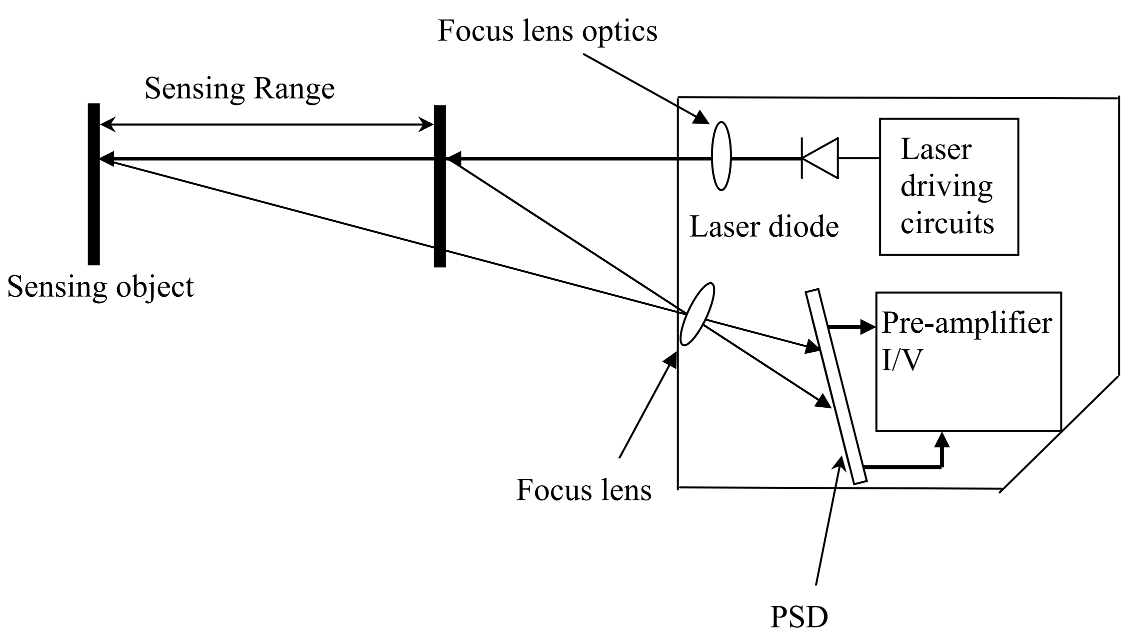

Figure 2.4 Laser-based triangulation optical system

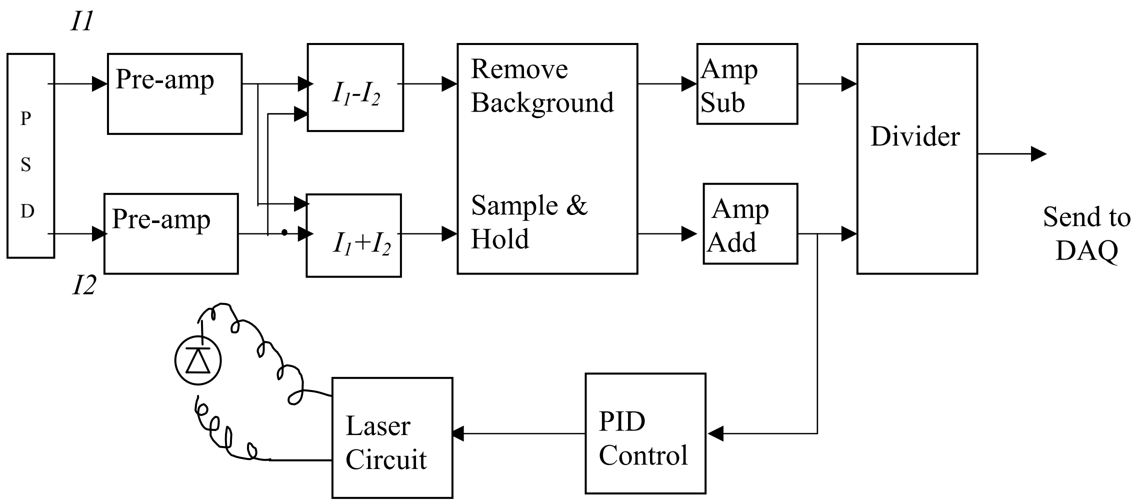

Figure 2.5 Block diagram of signal processing circuit

The optical block includes a laser source, position sensitive detector (PSD), laser beam focusing lens, and optical filtering components. Laser signal processing block removes influence from background color, reflectivity changes, and other noises.

The power supply subsystem is to provide power for device in the field without using AC power input. Only one 12V battery is needed in the device. By using DC-DC voltage converters and voltage regulators, 12V is converted to 24V, ± 15V, and ± 5V. The converted power supplies provide necessary voltages used in scanning system and electronic circuits. Figure 2.6 shows the block diagram of power supply system.

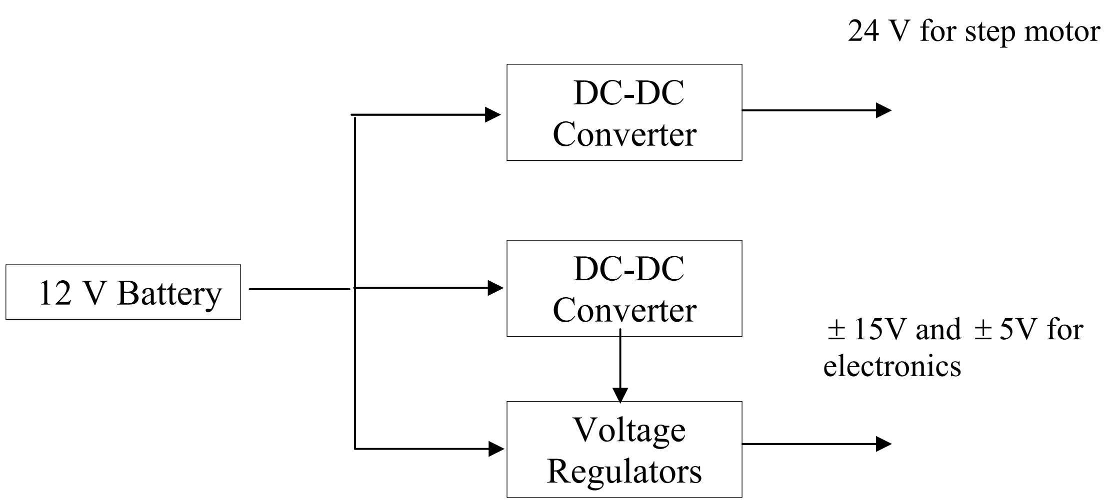

Figure 2.6 Block diagram of power supply system

2.3 SYSTEM PERFORMANCE DESCRIPTION

The detector scans laser over marking material, and sensor system receives the reflected laser beam. The signal processing circuit sends distance information to host computer, and host computer processes and displays the thickness of TPMM in real time (Figure 2.7).

Figure 2.7 TPMM thickness pushcart in field test

The system specifications are as follows:

(1) Standoff Distance: 12 inches

The Standoff distance means the distance between the laser source and object.

(2) Sample Rate: 150 KHz

The laser source is operated in the frequency range of 150 KHz.

(3) Maximum Range of Measured Thickness: 6 inches

This detector has been verified to detect thickness change of 6 inches.

(4) System Clock: 1.544 MHz

(5) Digitization Resolution: 12 bits

(6) Average Power Consumption: 1.75 A at 12 V

A motorcycle battery is used to provide power for the system to work for a few hours.

(7) Maximum Measurement Resolution: 5 mils

(8) By using the software, you can either start a new measurement, save the results, or open saved files. You can also obtain the thickness profiles from the save results.

(9) Maxim traces number in one page for multi-trace display: 5, totally maxim is 300 pages.

CHAPTER 3: VEHICLE-MOUNT LASER THERMOPLASTIC THICKNESS MEASUREMENT SYSTEM

3.1 GENERAL DESCRIPTION

To increase the TPMM thickness measurement speed, a prototype of vehicle-mount laser thickness measurement system is developed. Two synchronized laser devices are installed in a golf cart. One laser device shots a laser beam on the pavement with tape, and the other one shots a beam on the pavement without tape. The tape thickness is obtained by processing the two laser devices' output signals. The system block is shown in Figure 3.1. The developed system is shown in Figure 3.2.

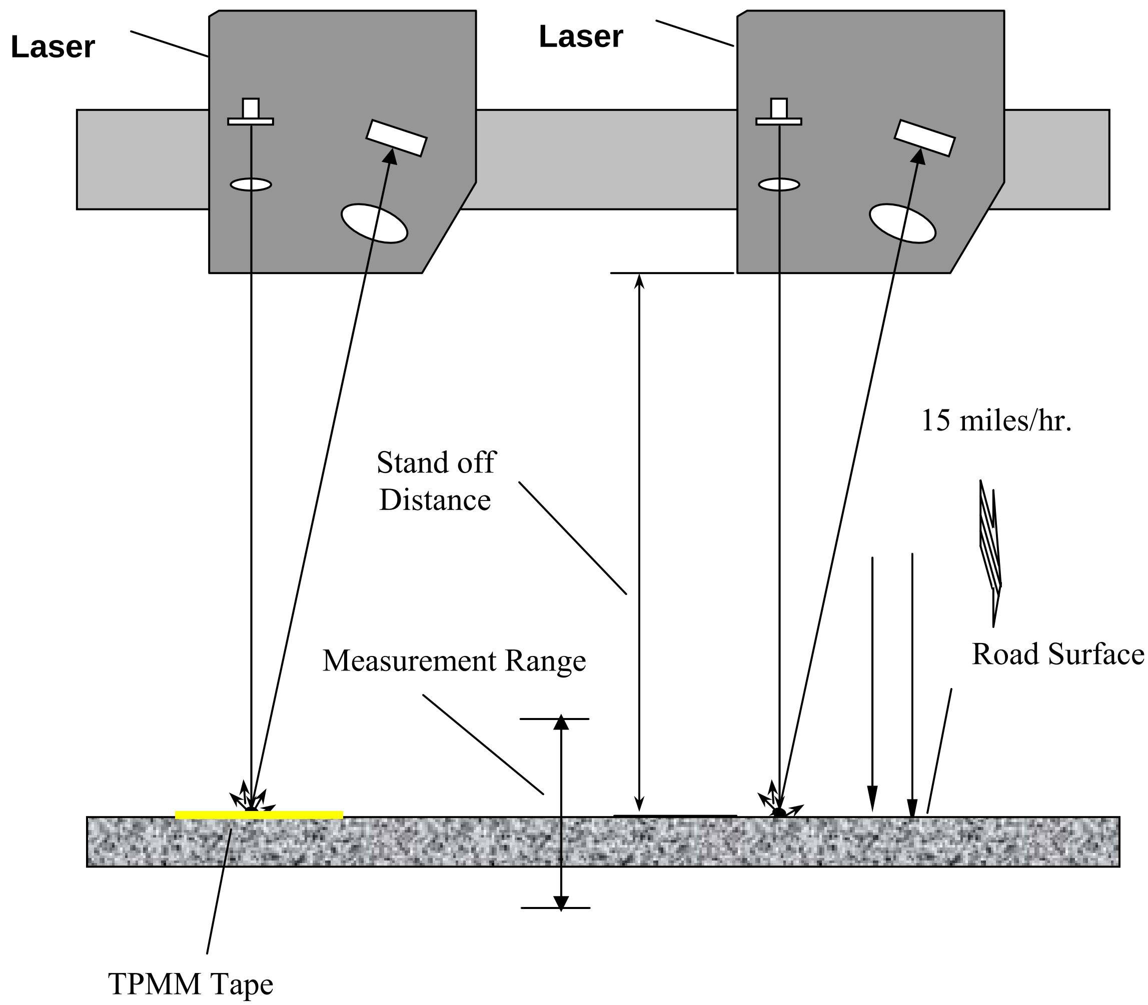

Figure 3.1 Two synchronized laser devices used to the TPMM thickness

Figure 3.2 Measurement on pavement surface by using golf cart version

Note that the mobile version shown in Figure 3.2 assumes that one of the synchronized laser devices measures the distance between the golf cart and the other on the pavement without tape. This requires prices driving of the vehicle. However, it is difficult to do so when the speed of the vehicle is high. The software and hardware designed in the golf cart version will identify the areas when both lasers are not on tape, the data will be discarded.

CHAPTER 4: AUTO-SYNCHRONIZED LASER SCANNING FOR TPMM THICKNESS MEASUREMENT

4.1 INTRODUCTION

The vehicle mount version showing in Figure 3.2 has strict limit to vehicle zigzagging. It is difficult for a driver to keep straight line driving with the tolerance of the width of a TPMM tape; in some cases it is as narrow as about 4”. Therefore, a new optical configuration based on auto-synchronized laser scanning for the 3D measurement of the TPMM thickness is pursued in this research project. The purpose of this study is to scan the laser beam wide enough in cross sectional direction to the tape to relieve the limit of vehicle zigzagging.

The measurement of the TPMM thickness requires the laser scanning covers at least 8 inches to double the vehicle direction tolerance. The classical approach of laser triangulation uses a video camera and a separate laser line projector at a fixed angle. The vertical measurement resolution of this typical laser triangulation method is reduced linearly as the field of view increases. Since the collection optics of the camera must have a short focal length to cover the inspection area, the classical laser triangulation method suffers from a limited vertical resolution. To overcome this problem, an approach based on auto-synchronized laser scanner was developed.

4.2 BASIC PRINCIPLE OF CLASSICAL OPTICAL TRIANGULATION MEASUREMENT

Figure 4.1 shows the basic geometrical principle of optical triangulation. The light beam generated by the laser is deflected by a mirror and scanned on the object. A camera, constituted of a lens and a position sensitive photodetector, measures the location of the image of the illuminated point on the object. By simple trigonometry the three-dimensional coordinates of that point are calculated [3].

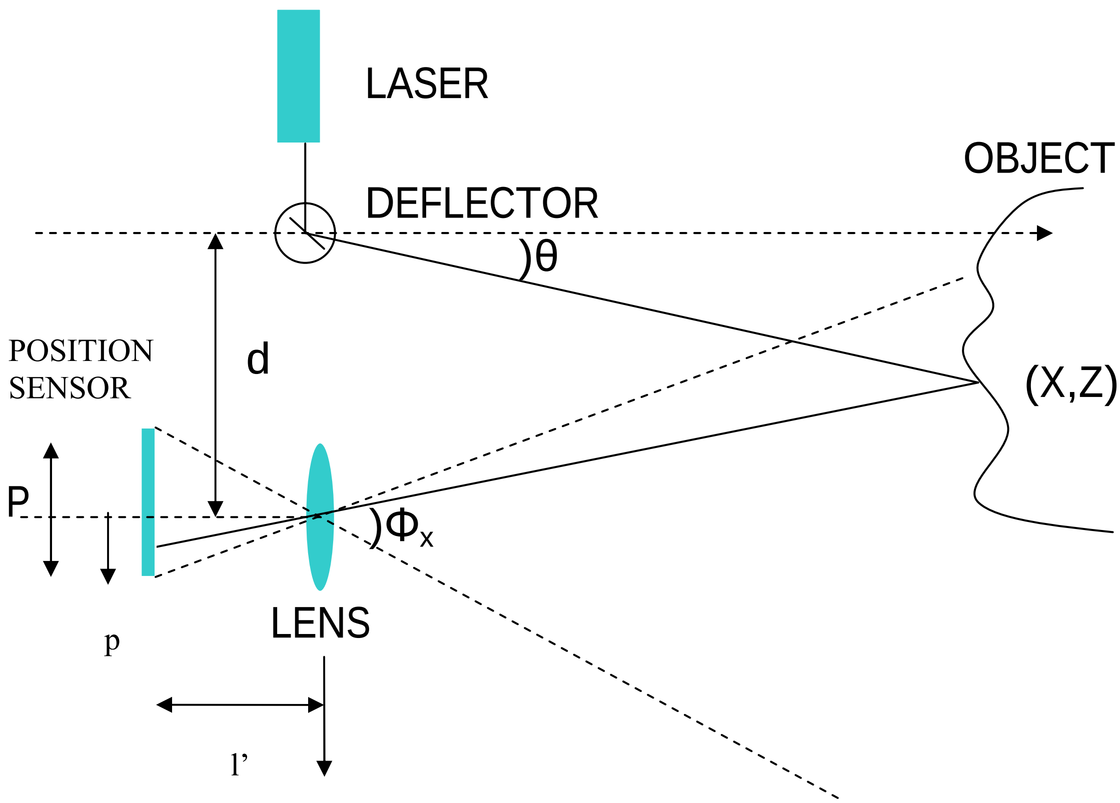

Figure 4.1 Classical laser triangulation methods

From Figure 4.1 we have

$$z = \frac{dl'}{p + l' \tan\theta} \tag{4.1}$$

and

$$x = z \tan\theta \tag{4.2}$$

where p is the position of the imaged spot on the photodetector, x and z are 3-D locations of the illuminated point on the object, θ is the deflection angle of the laser beam, d is the separation between the lens and the laser source, and

$$l' = \frac{lf}{l - f} \tag{4.3}$$

where f is the focal length of the lens and l the distance to the object plane.

The gain of a triangulation system is a useful parameter define as

$$M_{SD} = \frac{\Delta p}{\Delta z} = \frac{fd}{z^2} \tag{4.4}$$

which indicates that for a given distance z and position sensor resolution Δp, the accuracy of the sensor is directly related to the focal length of the lens of the position sensor f and the separation between the laser source and the position sensor d. Unfortunately f and d cannot be made as large as desired. d is mainly limited by the mechanical structure of the optical setup and by the shadow effect [4]. Note that d must be kept small to minimize these effects of shadow effect which can be seen from Figure 4.2.

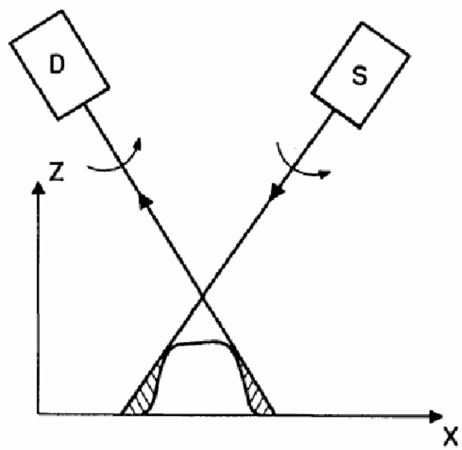

Figure 4.2 Shadow effect

In the conventional triangulation geometry, the field of view of the sensor is approximately given by

$$\Phi_z = 2\tan^{-1}(\frac{P}{2l'}) \approx 2\tan^{-1}(\frac{P}{2f}) \tag{4.5}$$

where P is the linear dimension of the position detector. Therefore, in the conventional setup, a compromise between the field of view and the accuracy of the 3-D measurement must always be considered [4]. A large angular separation has to be used with usual triangulation technique to get a good compromise between resolution and field of view. The limitations imposed by a large angular separation are twofold; first, continuous profile measurement is prevented by severe shadow effect, second the optical head consisting of a scanner plus a camera is bulky [3].

4.3 AUTO-SYNCHRONIZED LASER SCANNING PRINCIPLES FOR 3D MEASUREMENT

Because of the problems associated with classical triangulation sensors, a different approach based on auto-synchronized laser triangulation was developed with the contribution of the IIT lab of the CNRC. The large fields of view can be obtained using synchronized scanner techniques without sacrificing the gain M_{SD} of the triangulation system. The basic idea is to synchronize the projection of a light spot with its detection. This optical configuration, which was first proposed by Rioux[3], uses a double sided scanning mirror where one face of the mirror is used to scan a laser spot on the surface to be measured and the second face is used to orient the collection optics. The method we selected is based on *a longitudinal synchronization scheme,* the instantaneous field of view being parallel to the scan. The basic principle of the longitudinal auto-synchronization technique using a double-sided coated mirror is shown in Figure 4.3.

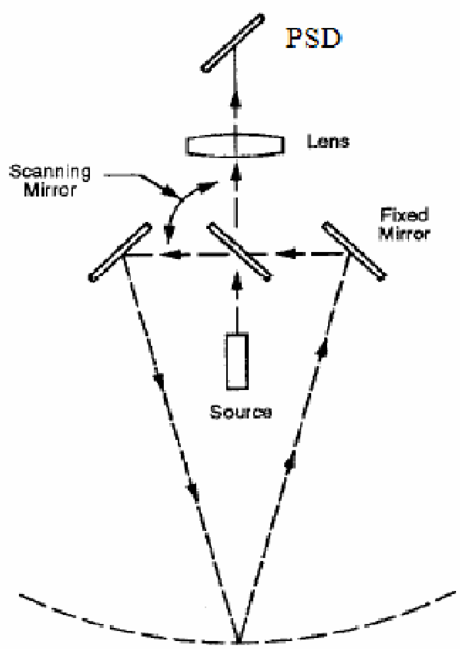

Figure 4.3 Basic principle of the longitudinal auto-synchronization technique using a double-sided coated mirror [5]

In contrast to the usual triangulation geometry, a single point on the position sensor defines a surface in the object space as shown in Figure 4.4.

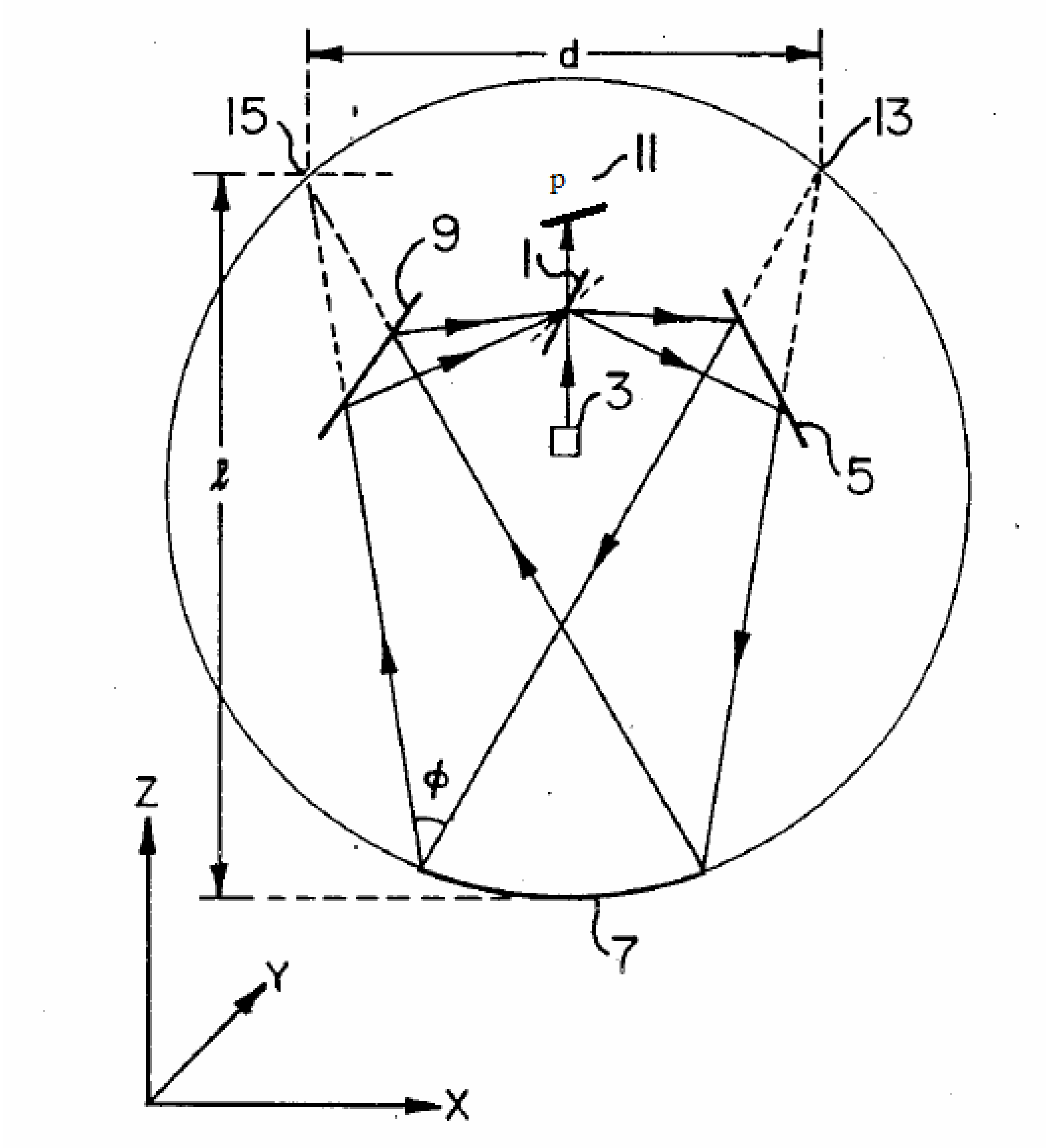

Figure 4.4 A single point on the position sensor defines a surface in the object space [6]

The Trajectory of the intersection of axis in Figure 4.4 is shown in the Figure 4.5.

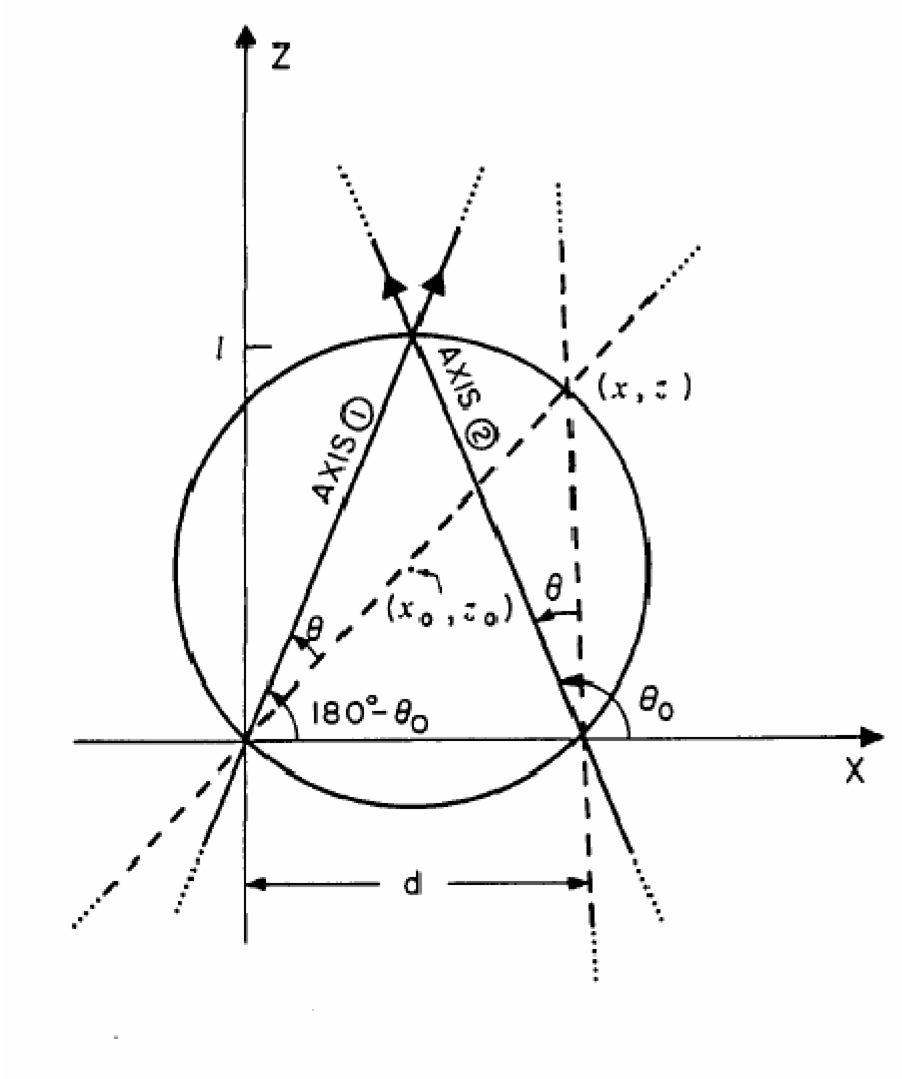

Figure 4.5 Trajectory of the intersection of axis [3]

For all angular rotation θ, the point p on the position sensor defines the circle in the XZ plane. The radius of circle expressed as

$$\frac{l^2 + \frac{d^2}{4}}{2l} \tag{4.6}$$

which is centered at the coordinates

$$x_0 = \frac{d}{2}$$
$$z_0 = \frac{l^2 - \frac{d^2}{4}}{2l} \tag{4.7}$$

The following are the simulation result using Optica Ray Tracing Software from Wolfram Research.

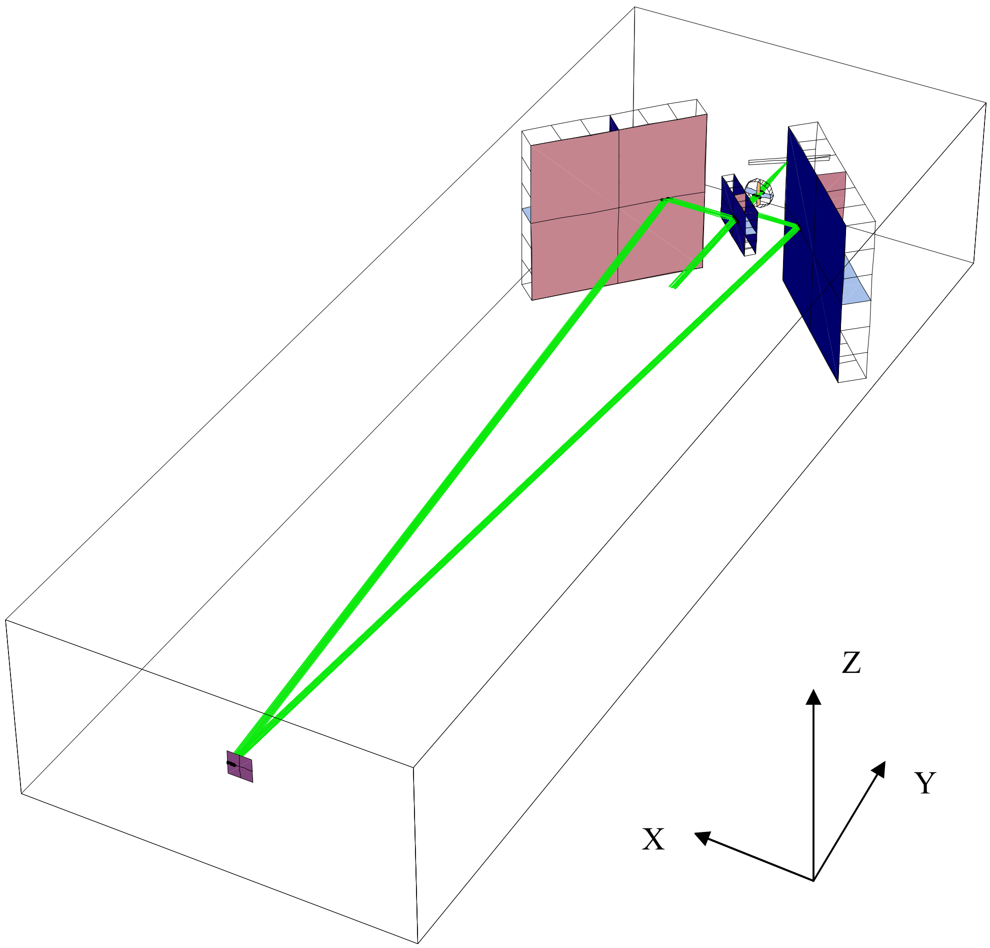

Figure 4.6 Simulating Configuration

The Optical simulating parameters is as following:

The Fixed Mirror on both side is 75mmx75x12mm(length x width x thickness) and the acute angle between the mirror and X axiis is 47.082^{o}.

The Scan Mirror is 30mm x 20mm x 5mm, when it's not rotating the acute angle between the Scan Mirror and the X axis is 45^{o}

The lens of 30mm focal length tiled angle 35^{o} for expanded range of depth.[7]

The Position detecting screen is 34mm x 2.5mm (the actual size of the PSD).

The filed view is 40^{o}

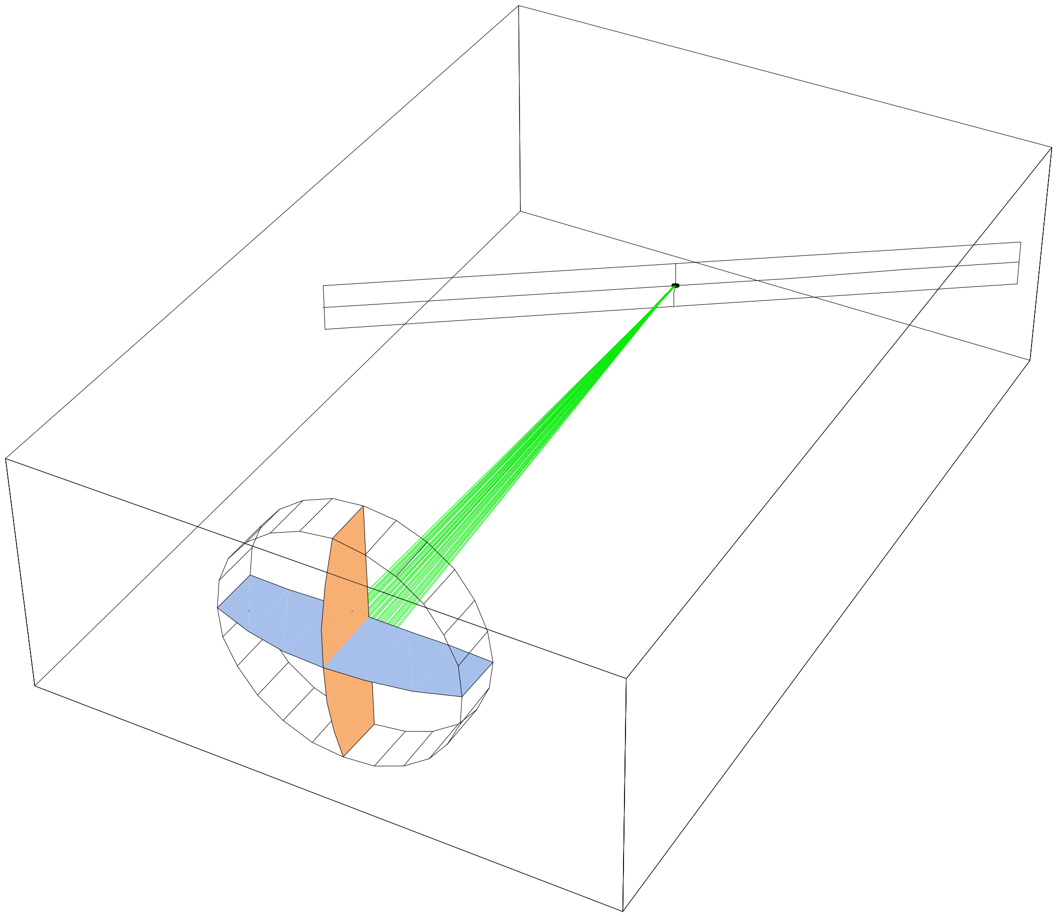

Figure 4.7 Detail view between Lens and the Screen

From Figure 4.7, we can see the light is focused on the center of the detecting screen.

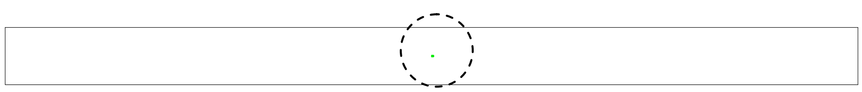

Figure 4.8 Simulation result on the screen

Figure 4.8 shows the simulating result, the central point in the dashed circle is the light spot hit on the detecting screen. The spot size is 0.00281833mm, and the position on the screen is (-0.0000257811mm, 0mm), where we choose the center of the screen as the origin (0,0). The following table shows the part of simulating results when the scan mirror is rotating.

Table 4.1 Simulation result

Rotating Angle	Spot Size on Screen(mm)	Spot Position On the Screen(mm,mm)
-5	0.00281907	(-0.0000258035, 0)
-4	0.00281911	(-0.0000258055, 0)
-3	0.00281913	(-0.0000258071, 0)
-2	0.00281915	(-0.0000258033, 0)
-1	0.00281916	(-0.000025809, 0)
0	0.00281833	(-0.0000257881, 0)
1	0.00281916	(-0.0000258091, 0)
2	0.00281915	(-0.0000258086, 0)
3	0.00281914	(-0.0000258076, 0)
4	0.00281912	(-0.0000258061, 0)
5	0.00281909	(-0.0000258043, 0)

From Table 4.1 we could see the light spot keep good focus on the fixed position on the screen when the scanner mirror is rotating.

The synchronized methods have the following advantages compared to the other methods.

a. The filed of view is independent of gain M_{SD}. The depth of field is improved.
b. For small separation between source and position sensor(d), shadow effect will be reduced.
c. The range error Δz is also less susceptible to angular errors($\Delta\theta$ or $\Delta\eta$) than in the classical triangulation approach.
d. Has a relative smaller compact optical head than the classical triangulation approach.
e. Ambient light and reflection immunities are also considerably improved with both synchronization methods due to the reduced instantaneous field of view.

CHAPTER 5: SOFTWARE DEVELOPMENT

5.1 SOFTWARE INTERFACE

The software package stores and processes the measured data. After signal processing steps, the processed data, and calculated average thickness can be displayed in real time. The Figure 5.1 and Figure 5.2 are the software interface for the pushcart and vehicle-mount TPMM thickness measurement.

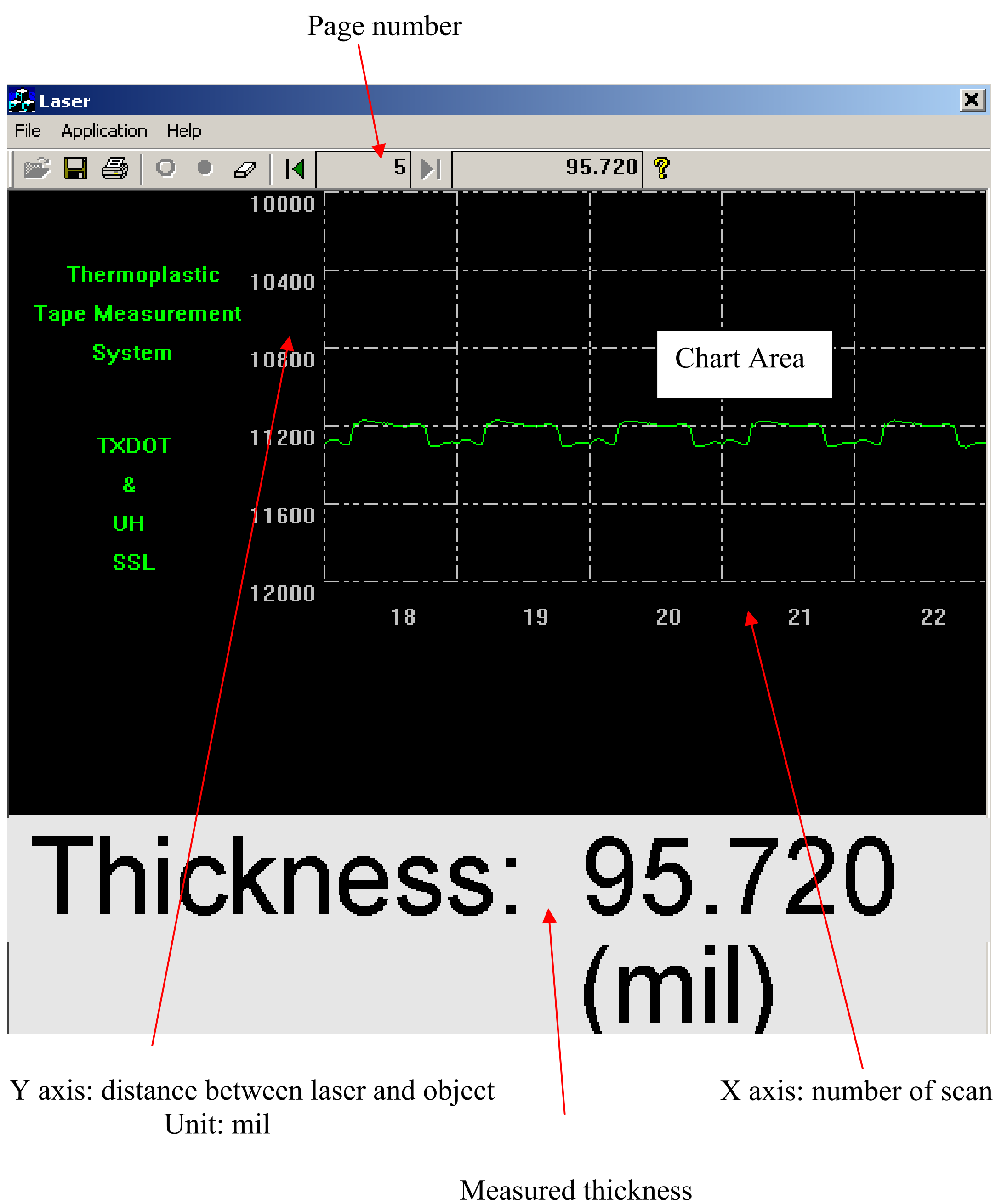

Figure 5.1 Software interface for pushcart device

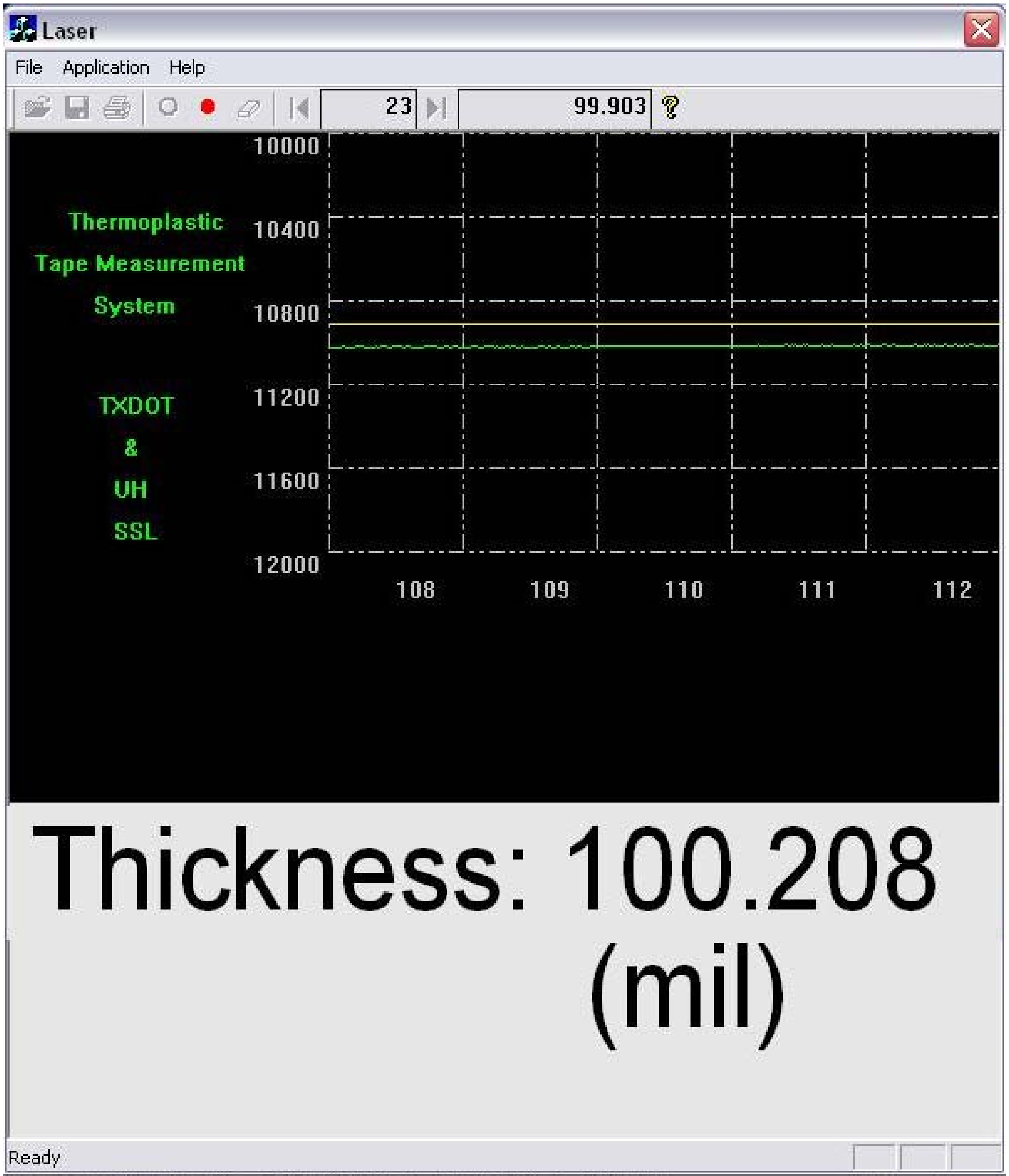

Figure 5.2 Software interface for vehicle-mount device

CHAPTER 6: FIELD TESTS

6.1 FIELD TEST OF PUSHCART TPMM THICKNESS MEASUREMENT DEVICE

The pushcart TPMM thickness measurement device was tested at FM2761 several times. The typical pavement surface is shown in Figure 6.1.

Figure 6.1 A typical pavement surface on FM 2761 near I-10 at Sealy, Texas

Figure 6.2 Field test on rough pavement, FM 2761 near I-10 at Sealy, Texas

Figure 6.2 shows the measurement process during the filed tests. Since the tape surface is very rough, it is difficult to obtain thickness information directly form raw data. Figure 6.3 is an example of the raw data in one scan. Even it is difficult to identify the tape covered areas. However, using the reflectivity data obtained in PSD I1+I2 signal, the tape areas can be easily identified due to the fact that the reflection of tape area is much higher than that in pavement areas. By conducting data processing (filtering and averaging), the tape area can be clearly displayed and the thickness of the tape can be calculated. Figure 6.4 is the processed tape thickness data. It can be seen that the average thickness of the tape is 106 mils in this scan.

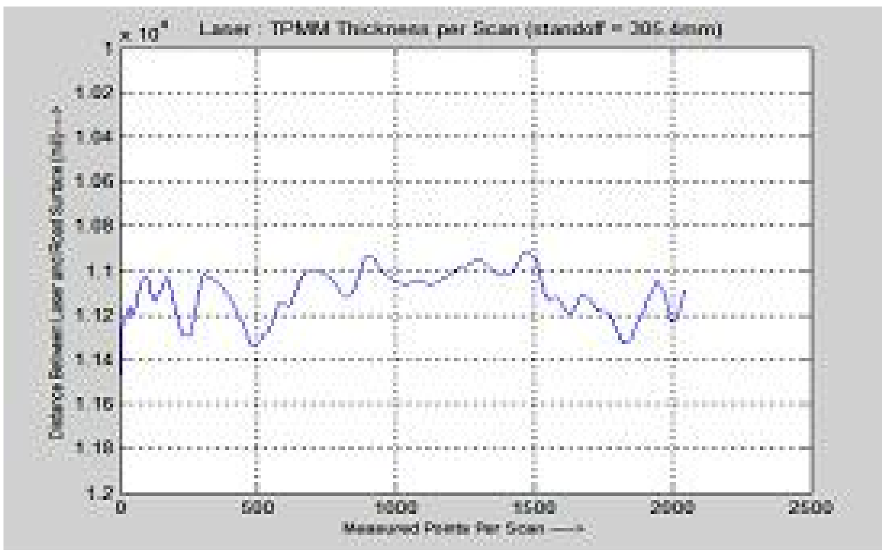

Figure 6.3. Measured thermoplastic thickness data on FM2761 before data processing

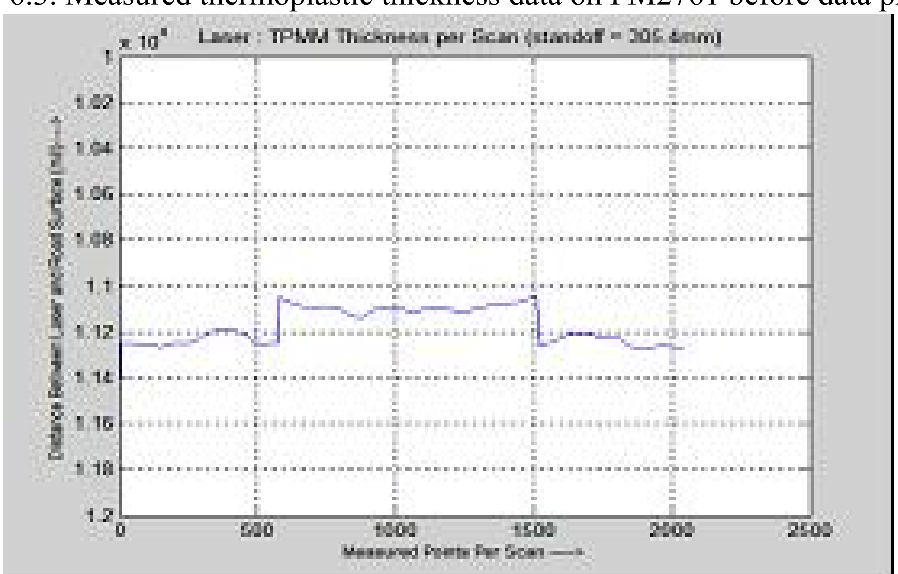

Figure 6.4. Measured thermoplastic thickness data on FM2761 after data processing

6.2 LAB TEST OF VEHICLE-MOUNT TPMM THICKNESS MEASUREMENT DEVICE

Numerous lab test of the vehicle-mount TPMM thickness measurement device had been conducted at the loading zone 19 at the University of Houston. The two synchronized laser devices were mounted on a golf car as shown in Figure 6.5.

Figure 6.5 Vehicle-mount device in lab test

After data processing of the two independent laser devices, the test results are shown in Figure 6.5. The Channel 1 represents the laser device output measured on tape; the Channel 2 represents the laser device output measured on pavement. The output of Channel 1 matches the output of Channel 2 very well. Figure 6.6 shows the tape thickness profile. The thickness measured by the vehicle-mount device is very close to actual tape thickness. The average error is 5 mils.

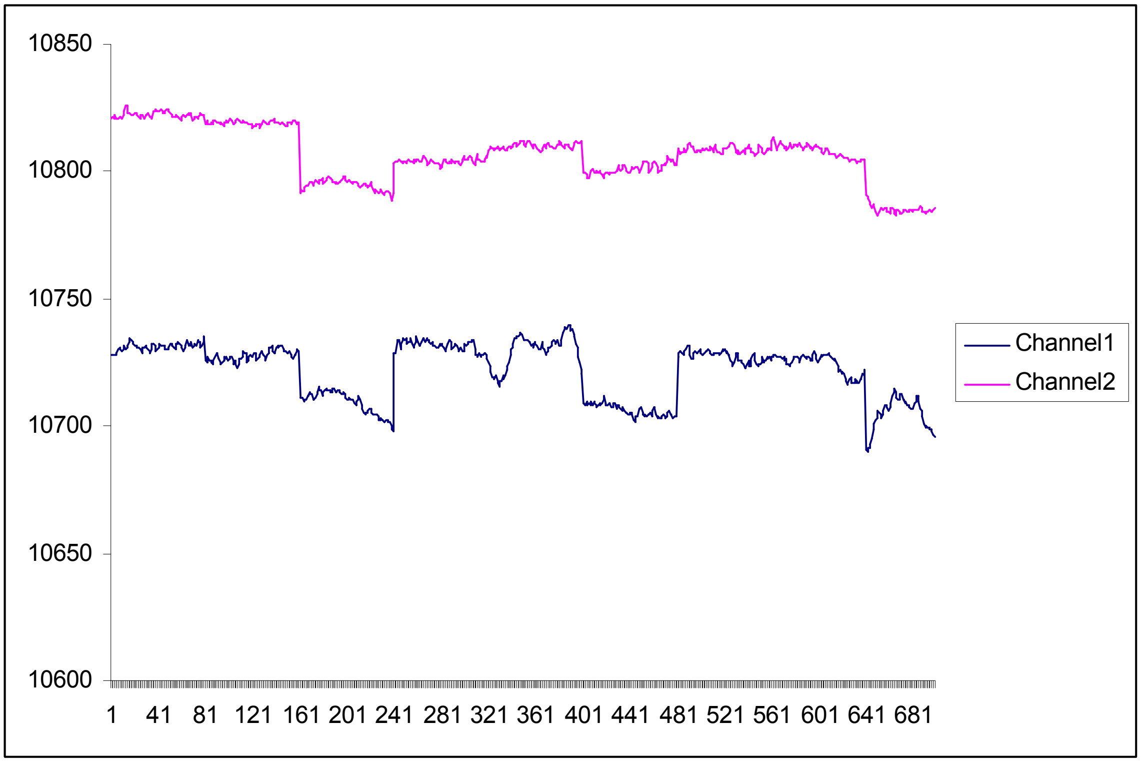

Figure 6.6. The output of two independent laser devices – raw data

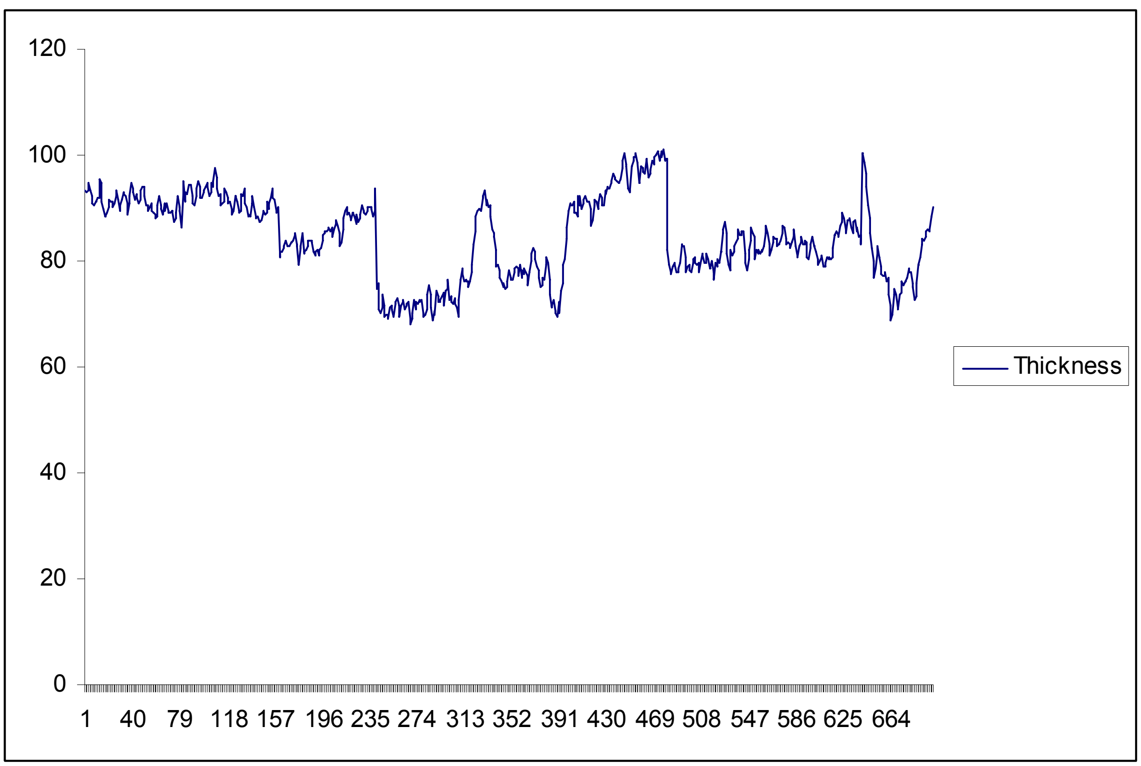

Figure 6.7. The thickness profile of tape – raw data

6.3 FIELD TEST OF VEHICLE-MOUNT TPMM THICKNESS MEASUREMENT DEVICE

The field-test of the vehicle-mount TPPM thickness measurement device were conducted on Spur 5, off I45 near Houston Downtown on October 17, 2004 as shown in Figure 6.7. Self-attachable TPMM tapes were used for the tests. Two types of TPMM tapes were used: 12 feet long, 100 mil thick regular tape and 30 feet long FLEX_O_LINE thin tape. After data processing, the thickness profile of the normal thermoplastic tape is plotted in Figure 6.8. Figure 6.9 is the thickness profile of FLEX_O_LINE. Note that the measured thickness a bit over the tape thickness due to the partial contact of the tape to the pavement surface.

Figure 6.8. Field tests of the vehicle mount TPMM tape thickness measurement device

was conducted on Spur 5 near I-45 at the University of Houston. The maximum measurement speed was 15 mile per hour. Both self-attachable yellow tape and thin Flex_O_Line tapes were used in the field tests.

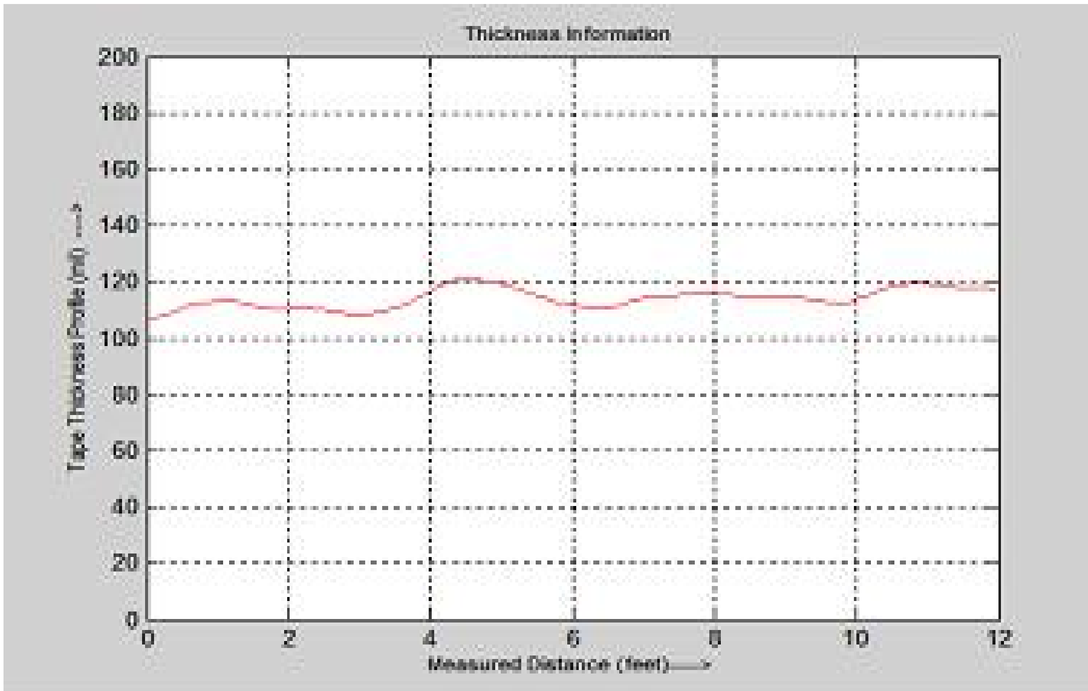

Figure 6.9. Measured TPMM thickness of 100 mils yellow tape by mobile device

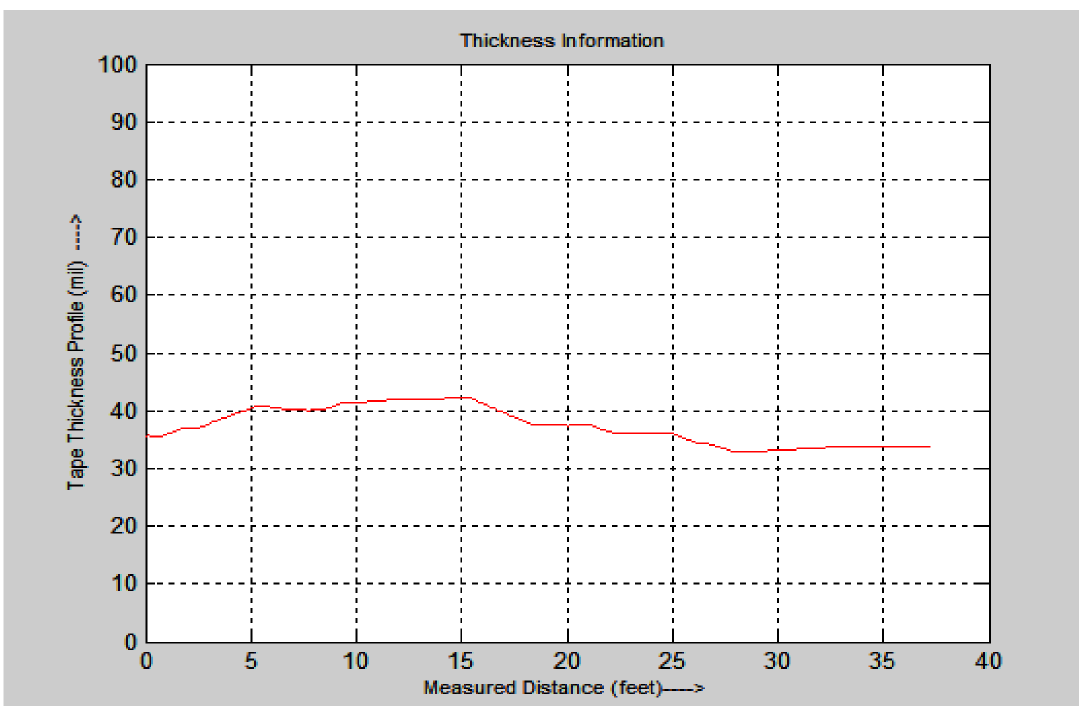

Figure 6.10. Measured FLEX_O_LINE thickness of 30 mils tape by mobile device

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

Based on the research results in Projects 0-4282, lightweight in compact size pushcart and vehicle-mount laser thickness-measurement devices have been successfully developed. The developed hardware and software can measure the thermoplastic thickness on concrete pavement and roughly rock pavement non-contact. The developed device was lab and field-tested. The test results show that the system can measure the thermoplastic thickness with high accuracy.

7.2 FUTURE WORK

Both developed TPMM thickness measurement devices have own limitation. The pushcart version has been reduced size and weight, but manual operation is not suitable for heavy duty TPMM thickness inspection. The vehicle-mount version increase the thickness measurement speed, but it still can't work on highway speed due to the manual tape following and computation ability of the notebook computer. So the researchers recommend to do further research on auto-synchronized laser scanning for 3D measurement of the TPMM thickness.

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