

Automated Real-Time Dimension Measurement of Moving Vehicles Using Infrared Laser Rangefinders

by

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We accept this thesis as conforming
to the required standard



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Abstract

In the last few years, much research and development has been carried out on Intelligent Vehicle-Highway Systems (IVHS) due to increased demand on the current transportation infrastructure. One aspect of IVHS is the development of automatic vehicle classification systems.

The Automatic Vehicle Dimension Measurement System (AVDMS) has been developed by a team of Engineers at the University of Victoria and the British Columbia Ministry of Transportation and Highways. The research and development included in this thesis forms the main part of the AVDMS project. The developed system allows vehicles to be classified based on height, width, length, or overall volume. The AVDMS consists of two high-speed infrared laser range-finding scanners, an infrared laser vehicle speed sensor, a high-speed data acquisition board, and an 80486 computer to process the data.

In this thesis, vehicle dimension measurement methods are discussed, as well as, the processes which led to the selection of the range sensing solution for the AVDMS. Background on range sensing techniques and range data processing are provided. A brief overview of geometric model generation and multiple-view fusion is included to help the reader understand range sensing applications and the possibilities for other related applications of this technology. The reader is also provided with a detailed look at vehicle dimension measurement, including description and specifications of the AVDMS range-finding scanners, and technical details on the AVDMS method of range data acquisition and vehicle dimension measurement. The vehicle speed measurement problem is reviewed including an overview of the investigations, a description and comparison of the different measurement methods, and a detailed look

at the speed measurement solution. The layout of the AVDMS hardware configuration is presented, as well as, descriptions and flowcharts of the AVDMS software. Results of the AVDMS prototype testing in the laboratory and on the highway with a number of highway travelling vehicles are provided to demonstrate the capability and usefulness of the system. A number of potential applications for the technology used in the AVDMS are discussed as a possibility for future work.

The AVDMS is to be installed on the approach causeway to the Tsawwassen ferry terminal at Tsawwassen, British Columbia, where it will measure the maximum length, width, and height of commercial and oversize vehicles travelling at speeds up to 120 *km/hr*. Vehicle height and width will be measured to within 15 *cm* and vehicle length to within 30 *cm*. This information will be used for determining the fare for each vehicle based on its volume. Volume is calculated as the product of a vehicle's dimension maximums, that is, the maximum height, width, and length measured by the AVDMS system. The measurements and calculations are made in real-time as each vehicle passes through the system helping reduce queue sizes at the toll booths and improving efficiency.

The automatic real-time vehicle dimension measuring system (AVDMS) developed in this work is the first system capable of automatically measuring the dimensions of vehicles travelling at highway speeds. The AVDMS system demonstrates new capabilities of laser range-finding devices. The development of this technology may lead to many other applications.

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To My Family and Friends

Chapter 1

Introduction

1.1 Intelligent Highways and Traffic Management Systems

In the last few years there has been much research and development in the area of Intelligent Vehicle-Highway Systems (IVHS) due to increased demand on the current transportation infrastructure. IVHS represents a group of technologies which are emerging in response to the congestion and safety problems on the world's highway systems. These technologies provide improved usage and safety of the highway systems without costly and often environmentally damaging infrastructure expansion. Safety and congestion problems directly impact the efficiency of our road transportation system resulting in longer travel time and increased costs of both goods and people. Improved efficiency and accessibility of the road transportation system also have a significant social benefit. In Canada, it is estimated that by the year 2011, congestion will be reduced by 15 to 20 percent, the number of accidents reduced between 8 and 10 percent, and fuel savings around 1.3 Billion litres per year.[19]

Although IVHS developments are currently moving most rapidly in Europe, Japan, and the United States there are many IVHS developments underway in Canada. Most Canadian activity is clustered in Ontario, Quebec, and British Columbia. Canadian Industry has much to benefit by taking advantage of the great potential in the IVHS market.

Due to the recent emphasis on IVHS developments and the large market potential within IVHS, there are many more players from various sectors becoming involved in road transportation development. The key players include:

- The Federal Government through various departments.
- The Provincial and Territorial governments.
- Municipal Governments.
- The transportation and technology industries.
- Universities and other research centres.
- Various transportation industry associations.

IVHS is now divided into six functional areas, with each area having its application group of IVHS technology. The areas are designated by the following acronyms and their meanings:

1. **ATMS:** Advanced Traffic Management Systems;
2. **ATIS:** Advanced Traveller Information Systems;
3. **AVCS:** Advanced Vehicle Control Systems;

4. **CVO/AFMS:** Commercial Vehicle Operations/Advanced Fleet Management Systems;
5. **APTS:** Advanced Public Transit Systems;
6. **ARTS:** Advanced Rural Transportation Systems.

The Automatic Vehicle Dimension Measuring System (AVDMS) discussed in this thesis has been developed specifically for more efficient management of commercial vehicles and is therefore considered within both the Advanced Traffic Management Systems (ATMS) and Commercial Vehicle Operations (CVO) functional areas. ATMS is generally considered the cornerstone or foundation of IVHS on which many other IVHS applications are built. Currently, most development in this functional area has involved the monitoring of traffic flow within a specific road section or network area. Traffic flow monitoring is usually done by sensors mounted in the roadway or by remote imaging sensors, and is able to detect vehicle presence, speed, delay times, traffic accidents, and other parameters that can be used to help manage the traffic more efficiently. Real-time data acquisition and vehicle surveillance are the primary characteristics of ATMS.

The AVDMS provides real-time dimension measurement of commercial vehicles at highway speeds, and also reduces their delay time at the toll booth. Real-time in this context means that the measurements are completed on each vehicle before the next vehicle passes through the system without delaying or slowing down vehicles. This will improve efficiency for commercial vehicles at B.C. Ferries terminals where fares will be charged based on the volume of commercial vehicles. The AVDMS can also be used for vehicle counting, classification, speed measurement, and determining the optimal placement of commercial vehicles on the ferries.

1.2 Range Sensing and Geometric Model Generation

With many processes in industry becoming automated, it is often important to make spatial observations of various objects, machinery and the working environment, and to make remote measurements in applications with rugged environments or where manual measurements are not efficient or permissible. These observations are normally made using range sensing devices. These devices commonly use light waves as the measurement medium since light waves can easily be focussed, and they travel quickly to and from the objects and environment. A laser is usually used as the light source. With recent development in the ability to focus sound waves, they too are being used, depending on the application.

Most commonly-used range sensing devices can be classified into two categories. These are the triangulation based devices and time-of-flight (TOF) based devices. Triangulation devices are used at shorter ranges where high accuracy is required. For example, many mechanical part profile scanning devices use triangulation based laser range sensors for quality control and reverse engineering applications where high precision is required. TOF laser range-finding technology has been developed more recently and is typically used at ranges not less than a few meters. These TOF systems have range measurement accuracies from a few millimeters to a few inches depending mainly on the rate of measurement. It is common for both triangulation and TOF sensors to use rotating mirrors to facilitate high speed scanning of an object and its environment. Both of these optical sensing techniques can be used to acquire 3D range data.

After obtaining 3D information from a particular scene, it is often necessary for a computer to create a geometric model of the object(s) and the environment. Geometric

modelling is generating a set of information that geometrically defines an object as required for a given application. Geometric model generation usually requires viewing an object from multiple locations to obtain the complete geometric model of the object. This leads the need to perform multiple-view fusion from separately acquired range images. Range-finding and geometric model generation will be further discussed in Chapter 3.

1.3 Related Research in Range Sensing Applications

Research and development of range sensors and range sensing technology have gained considerable attention in recent years. Due to its superior capability to provide an accurate and informative 3D range profile of the scanned objects (and environment), range sensing becomes an emerging technology for many design and manufacturing applications.

Some examples of applications where range sensors are being used include:

- **Geometric Model Generation;**[26]
- **Reverse Engineering;**
- **Manufacturing Accuracy Control;**[2]
- **Finishing, Inspection and Quality Control;**[8]
- **Military applications for scanning enemy territories;**
- **Robotic applications;**[18, 20]

- **Tree scanning** in orchards for efficient pesticide spraying;
- **Log scanning** in saw mills for maximum lumber output;
- **Surface Topography Measurements**;^[17]
- **Navigation** in spaces where normal vision is insufficient;

Other potential applications may include:

- **Basic Measuring Systems** in 1-D, 2-D, or 3-D;^[12]
- **Vehicle dimension measurement and classification systems**;
- **Autonomous vehicles**;^[2]
- **Various assembly applications**;

The real-time automatic vehicle dimension measuring system (AVDMS) developed in this work is the first system capable of automatically measuring the dimensions of vehicles travelling at highway speeds. The AVDMS system demonstrates new capabilities of laser range-finding devices. The development of this technology may lead to many other applications.

1.4 Vehicle Dimension Measurement Required by B.C. Ferry Corporation

The B.C. Ferry Corporation has a number of ferry routes that connect the mainland to Vancouver Island. Between Tsawwassen and Schwartz Bay alone, more than 10,000 commercial and oversize vehicles use the B.C. Ferries each month. This large number

of vehicles requires organized and efficient management to maintain ferry schedules while transporting the maximum number of vehicles per trip. In order to increase the efficiency of the ferry system, an Electronic Vehicle Monitoring Station (EVMS) is being developed that will include an Automatic Vehicle Identification (AVI) system, a Weigh-In-Motion (WIM) system, a static weigh scale, and the AVDMS system which will automatically measure the three major dimensions of vehicles; length, width and height.

Currently, fares for commercial and oversize vehicles are determined based on vehicle length. The existing system requires toll booth staff to manually measure the length of each vehicle. This is an inefficient and labor-intensive method that does not account for the variation in height and width of different vehicles. In order to improve the efficiency, accuracy, and comprehensiveness of determining and collecting fares for commercial and oversize vehicles, it was decided that toll collection should be based on the volume of oversize vehicles and that a system was required to automatically measure vehicle dimensions.

1.5 Automatic Vehicle Dimension Measurement System

The real-time Automatic Vehicle Dimension Measuring System (AVDMS) was developed to automatically measure the maximum length, width, and height of commercial and oversize vehicles. It is to be used as one component of the Electronic Vehicle Monitoring Station (EVMS) on the highway close to one of the B.C. Ferries terminals where it will measure the dimensions of commercial vehicles travelling at speeds up to 120 *km/h*. Vehicle height and width will be measured to within 15 *cm* and vehicle length to within 30 *cm*. This information will be used to calculate the volume of each

vehicle for determining the fare for the vehicle. The measurements and calculations will be made in real-time as each vehicle passes through the system helping reduce queue sizes at the toll booths and improving efficiency.

The AVDMS was developed by a team of Engineers at the University of Victoria and the British Columbia Ministry of Transportation and Highways. The system consists of two high-speed infrared laser range-finding scanners and an infrared laser vehicle speed sensor, connected to a 66 MHz/80486 personal computer. A drawing of the prototype system layout is shown in Figure 1.1. The AVDMS system operation flowchart, indicating the method in which vehicles are processed, is shown in Figure 1.2. Specifications for the laser scanners and speed sensor were developed based upon the targeted function of the AVDMS. These specifications were provided to Schwartz Electro-Optics (SEO), the manufacturer of the range-finding scanners and speed sensor. SEO is located in Orlando, Florida, and has been developing leading edge laser range-finding scanners and sensors for many years including a number of developments for the US Department of Defense.

There were many steps involved in the development of the real-time vehicle dimension measurement system which are discussed in Chapter 4. A detailed description of the AVDMS and its components is also provided in Chapter 4.

1.6 Thesis Outline

- **Chapter 2:** An overview of the vehicle dimension measurement methods investigated and the processes which lead to the selection of the range sensing system.
- **Chapter 3:** Background on range sensing techniques and range data processing

is provided. Information on geometric model generation is also provided to help the reader understand range sensing applications.

- **Chapter 4:** A detailed look at vehicle dimension measurement, including description and specifications of SEO's sensors and scanners, and technical details on the AVDMS method of dimension measurement.
- **Chapter 5:** The vehicle speed measurement problem is reviewed including an overview of the investigations, a description and comparison of the different measurement methods, and a detailed look at the speed measurement solution.
- **Chapter 6:** The AVDMS hardware configuration is presented.
- **Chapter 7:** Descriptions and flowcharts of the AVDMS software is provided.
- **Chapter 8:** Results of the AVDMS prototype testing in the laboratory and on the highway with a number of highway travelling vehicles are provided to demonstrate the capability and usefulness of the system.
- **Chapter 9:** A number of potential applications for the technology used in the AVDMS are discussed, as well as, future development possibilities for the AVDMS.

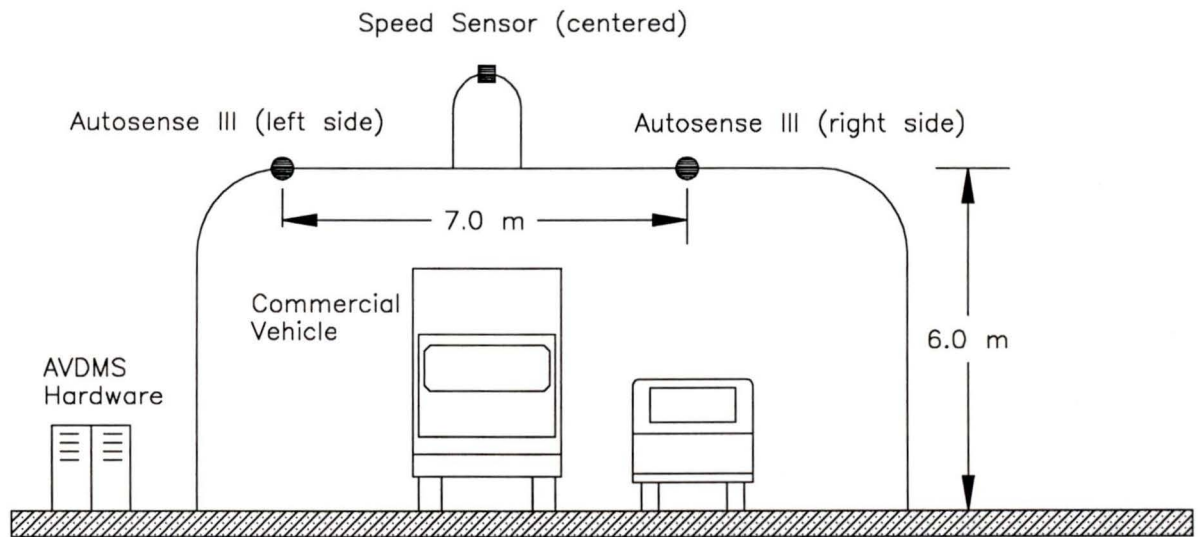


Figure 1.1: AVDMS Prototype System Layout

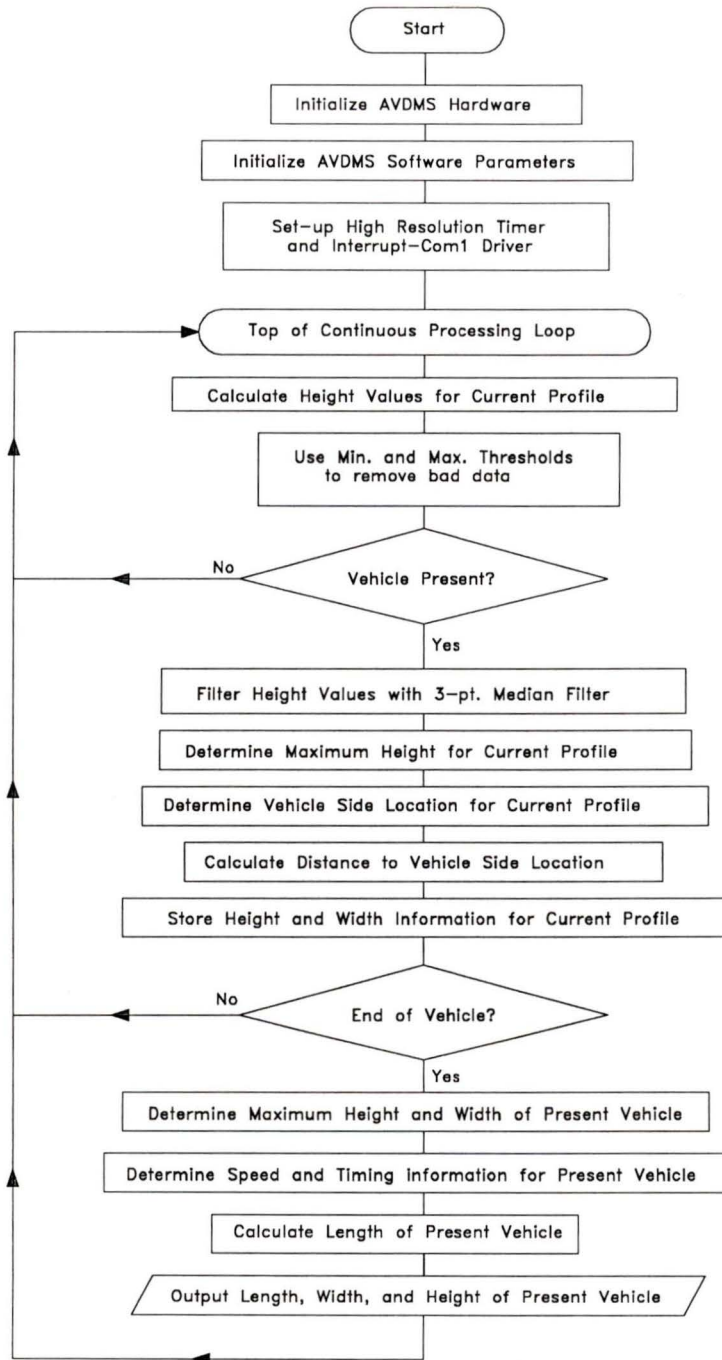


Figure 1.2: AVDMS System Operation Flowchart

Chapter 2

System Design and Embedded Technology

2.1 Specification for the Vehicle Dimension Measurement System

When the research to develop the AVDMS began, the technique and sensor systems to be used were unknown and therefore the specification was limited to brief operational requirements. The system had to be able to automatically measure length, width, and height dimensions of vehicles. Measurement accuracies were expected to be within 15 *cm* for vehicle width and height, and within 30 *cm* for vehicle length. The AVDMS will operate 24 hours per day, exposed to outdoor weather conditions, and therefore must be robust and reliable. It is necessary that the system operate in real-time so that vehicle dimension information for a given vehicle is available to the toll booth before that vehicle arrives at the toll booth. Real-time in this sense means that the measurements are completed on each vehicle before the next vehicle passes through

the system without delaying or slowing down all vehicles.

2.2 Evaluation of System Design Alternatives

Considering the problem of measuring the dimensions of vehicles travelling along the highway, a system is required that can make size measurements in quick succession from a distance. The technologies considered most promising for the real-time vehicle dimensioning task were image processing with both 1D and 2D gray image cameras, light curtain techniques with photo-electric sensors, and 2D range imaging with laser range-finding scanners. The next sections discuss these range sensing techniques related to the automatic vehicle dimension measuring application. In this work, many different 1D range sensors were also investigated but most of the 1D range sensors were made for shorter ranges with high accuracy or longer ranges with poor accuracy and slower measurement rates. They cannot serve our need.

2.2.1 Dimension Interpretation from Two Dimensional Gray Image

Two-dimensional (2D) gray images can be acquired using a CCD camera and an image grabbing board. Image acquisition and processing methods were investigated in cooperation with a local company specializing in image acquisition equipment. Attempts were made to process recorded video images of vehicles travelling on the highway to determine the feasibility of vehicle dimension measurement from the acquired images. This investigation showed difficulties with the image processing methods for a number of reasons. The main difficulty is that gray images do not directly contain geometric information and require complex processing algorithms to determine 3D geometric

information. Currently, there are no known applications of image processing which accurately process the geometric information of fast-moving, complex-shaped objects in real-time. Investigating image processing thoroughly would be costly and require much development time. The most difficult task would be developing the algorithms required to process the acquired gray images and determine vehicle dimensions in real-time. This would require much expertise in image processing.

A combination of both image processing and laser range-finding devices was also considered. However, such a system would contain the same difficulties of a pure image processing system and would require complex software and significant development time to integrate the systems. It would also be more costly and more difficult to install and maintain than a system involving purely laser range-finding scanners as will be discussed in section 2.2.4.

2.2.2 Dimension Interpretation from One Dimensional Gray Image

A linescan camera uses an array of photoelements for linear imaging. The number of photoelements varies from 256 to 6000 depending on the application and the resolution required. Line scan cameras are commonly used in document scanning systems, for measurement and inspection of industrial components and products, and for many other non-contact measurement applications. A number of configurations of linescan cameras were considered for the measurement of vehicle dimensions. Arrangements were made with EG&G Reticon to try their LC1912 linescan camera. The LC1912 was tested in the laboratory to determine how well it could detect color variation and object features. The camera performed quite well and appeared to be quite sensitive in detecting slight color variation. Due to the extraordinary high speed at which the

linescan cameras would be operating for measuring vehicle dimensions, it would be necessary to have quite bright illuminate lighting. The two configurations of linescan cameras that were considered most feasible are the linescan camera curtain and stereo pair linescan cameras.

Linescan Camera Curtain

For vehicle width measurement, an array of linescan cameras could be mounted on an overhead bridge and look directly down at the vehicles as they pass, detecting the widest points. This same concept with the cameras aligned down the side of the bridge could be used for height measurement. However, linescan cameras acquire gray images which do not contain depth information. Therefore, a large number of closely spaced linescan cameras, as shown in Figure 2.1, would be required to meet the accuracy specification, and to avoid the dead angle of observation. Each camera would have a narrow field of view and would be used to determine whether the vehicle extends into their view. Image processing would involve determining, for each camera, which parts of the image are road and which are the vehicle. One would not have to do any complex geometrical calculations or coordinate the information from the adjacent cameras. However, the costs associated with purchasing, interfacing and maintaining the linescan camera curtain were considered too high.

Stereo Pair Linescan Cameras

As mentioned in the above section, linescan cameras do not have depth perception which makes it difficult to profile the object that it is imaging. However, the possibility of using two linescan cameras as stereo pairs and combining the information from both of them to calculate depth at each feature point was investigated as shown in Figure 2.2. This method would require the widest or highest point of the vehicle to have

Line Scan Camera Curtain

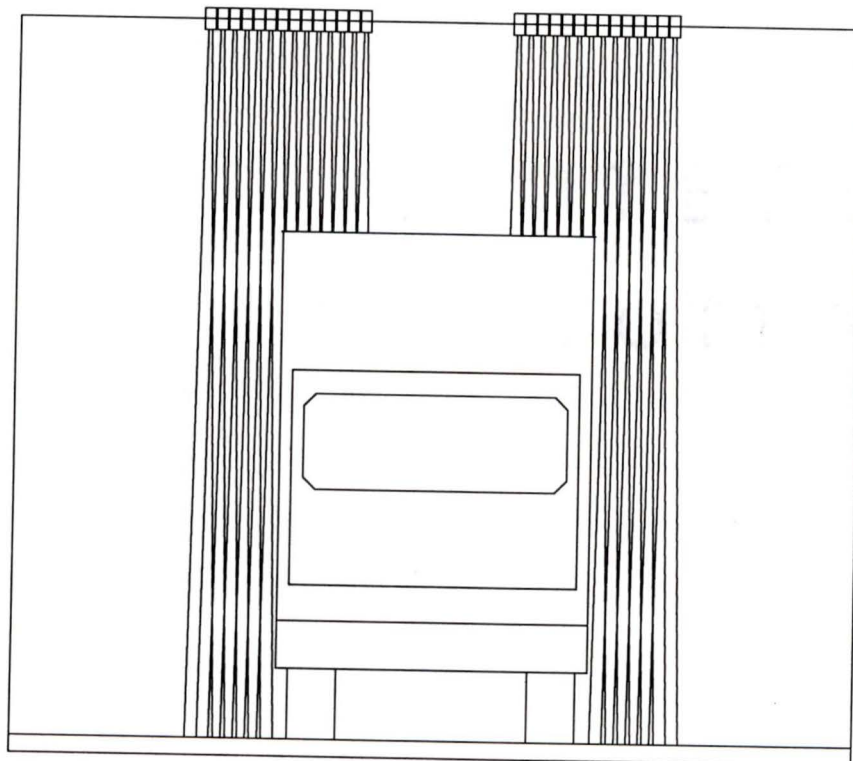


Figure 2.1: Array of Linescan Cameras for Width Measurement

a strongly identifiable feature such as a change in color or a sharp corner. Edge detection methods may be used, assuming that both cameras will be seeing the same set of edges. A point-to-point correspondence for a number of feature points can thus be created with moderate confidence. For each pair of points a “stereo” calculation can be done as shown below to determine the horizontal and vertical position of the point. The relations between x_1 and y_1 can be obtained as

$$x_1 = y_1 \tan \theta_{1a} + a_0 \quad (2.1)$$

$$x_1 = y_1 \tan \theta_{1b} + b_0 \quad (2.2)$$

where, θ_{1a} and θ_{1b} are determined directly by the locations of pixel a_1 and b_1 in the image. Solving for y_1 ,

$$y_1 = \frac{b_0 - a_0}{\tan \theta_{1a} - \tan \theta_{1b}} \quad (2.3)$$

and to determine x_1 , substitute the value for y_1 back into Eq. (2.1). Now, with Eqns. (2.1) and (2.3), we can solve for the two unknowns, x_1 and y_1 , which define the location of the first feature point. Similarly, the method can be applied to other feature points, such as x_2 and y_2 ,

The stereo pair linescan camera technique could provide a good profile of the sides or top of a vehicle assuming there are a number of identifiable feature points on the surfaces. It would be necessary that the feature points define the highest and widest points on a vehicle. It would also be necessary to maintain quite bright illuminate lighting in order for the linescan cameras to capture the feature points at the high measurement rates. In order to thoroughly determine the feasibility of this method, a large amount of development time would have been required, and instead the laser range-finding method discussed in Section 2.2.4 and Chapter 4 appeared to be a more promising solution for vehicle dimension measurement.

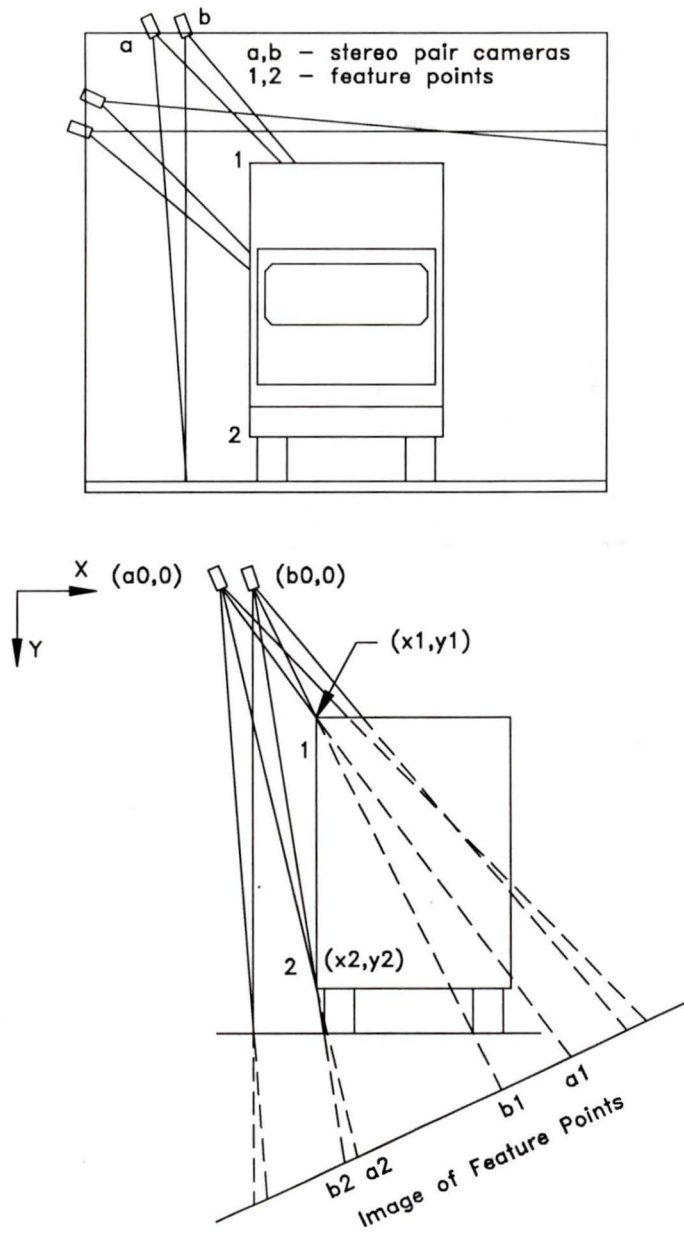


Figure 2.2: Stereo Pair Linescan Cameras

2.2.3 Dimension Measuring Using a Photo-Electric Light Curtain

A well developed technique for rough dimension measurement is the light-curtain approach. The technique has been used quite extensively in the logging and steel industries in harsh environments. A light curtain is an array of infrared photo-electric sensors (or sensor pairs) which detect the presence and position of an object.

For vehicle dimension measurement, the photo-electric sensors can be mounted on an overhead bridge above the vehicles and possibly on the road surface or in a specially designed trench flush with the road surface. They cannot however, be mounted on both sides of the vehicles due to the impracticality of a mounting structure between lanes of traffic. Photo-electric sensors were thus considered for vehicle width measurement only, and also for helping make length measurements. The width of vehicles would be measured by determining which of the sensors have their signals interrupted as the vehicle travels through the light curtain as shown in Figure 2.3. The exact position of each of the sensors is known which allows the program to determine where each side of the vehicle is. The sensors are cycled at high frequencies so that the widest point along the vehicle is measured. The use of photo-electric sensors for helping make vehicle length measurements is discussed in section 5.2.2.

Three different types of photo-electric sensors were investigated:

1. **Transmitted Beam (or Thru Beam) Sensors** consist of two separate units; an infrared transmitter and a receiver. When the object to be sensed passes between the transmitter and receiver, it interrupts the transmission of the infrared beam which is detected by the receiver. Transmitted beam sensors have the longest operating range among all photo-electric sensors that we have tested. The transmitter and receiver can be separated by up to 100 metres. These sen-

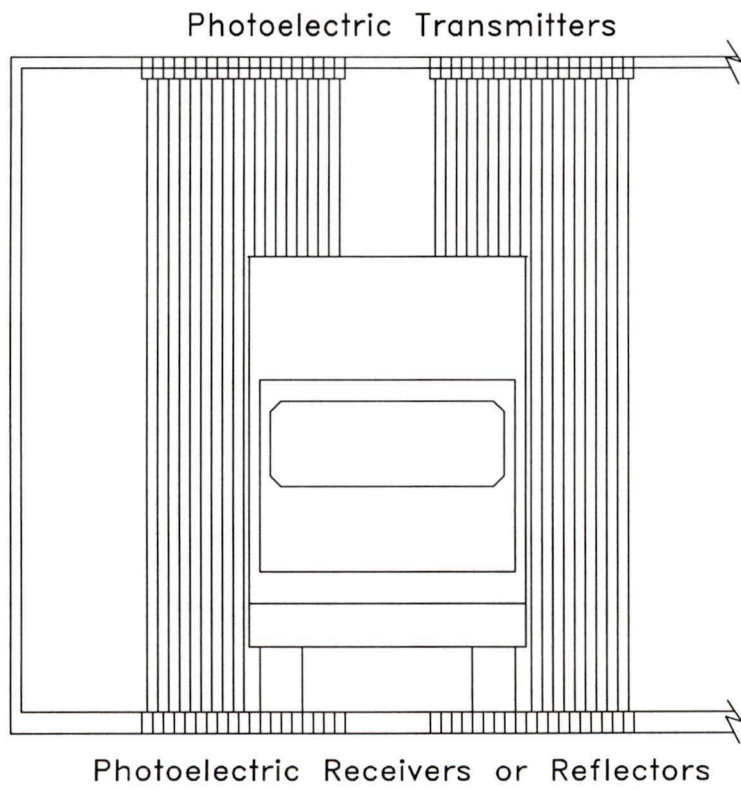


Figure 2.3: Photoelectric Light Curtain Technique for Vehicle Width Measurement

sors are commonly used in industry for protecting workers from dangerous areas and equipment.

2. **Retro-reflective Sensors** contain an infrared transmitter and receiver in a single unit. They operate by sending an infrared beam to a specially designed reflector or reflective surface and then sensing the returned signal. When an object passes between the sensor and the reflector, the signal is interrupted indicating presence of the object. Retro-reflective sensors can be separated from the reflector by up to 30 metres depending on the quality of the reflector. An example of the retro-reflective sensors is the common customer entrance detectors used at many retail stores.
3. **Proximity (or Diffuse Reflection) Sensors** also contain an infrared transmitter and receiver in a single unit. However, they use the target object rather than a reflector to reflect the sensors infrared beam back to the receiver. When an object passes by the sensor, some of the transmitted signal will be reflected to the receiver and the object is detected. The reflection from the object to be sensed is usually much more diffuse than reflection from a specially designed reflector and thus proximity sensors can detect an object's presence at ranges up to about 6 m. These sensors are commonly used in industry to control the level of liquids in containers.

Initially, the retro-reflective type sensor was investigated. This sensor was considered most suitable for the application as less-costly reflectors rather than sensors would be mounted at the road surface with the sensor being installed on an overhead bridge. However, after some testing of these sensors it was discovered that slight degradation in the quality of the reflective surface disabled the sensor. With the reflectors placed on the road surface, it is quite likely that the reflectors would be

degraded due to dirt, oil, and breakage on a regular basis. The maintenance of such a system would be too costly.

Transmitted beam sensors which do not depend on signal reflection were then considered. An easy-maintenance trench cabinet to house the receivers would have to be constructed and placed in the road, flush with the road surface. The same problem of eliminating signal obstruction due to dirt and oil still exists. The costs and complexity involved in the construction and maintenance of such a system were considered too high by the Ministry of Transportation and Highways.

At first, the idea of using proximity sensors seemed quite good since the sensors are placed on only one side of the vehicle. However, these sensors cannot be focussed well enough (measurement envelope is too large) and do not have the required operating range for vehicle dimension measurement.

Another major problem with using any of the photo-electric sensors is their response time. These sensors are not able to make measurements quickly enough on fast-moving vehicles to obtain the measurement resolution required.

After investigating and testing the various photo-electric sensors, it was evident that the light curtain technique was not feasible for vehicle dimension measurement.

2.2.4 Dimension Interpretation Using Two Dimensional Range Images

Laser range sensors determine the range from the sensor to an object by sending out continuous pulses of infrared light and measuring the time for the light to travel to the object and back. This is known as time-of-flight laser range-finding which is based on the constant travel speed of light. The location of the scanner and the direction of measurement are known, and the distance to the object is measured. The

coordinates of the projected point on the object can be calculated. It is also possible to incorporate a fast rotating mirror which directs the laser light to cover a given angle and to form a scanning plane. A 2D range image of objects is formed as the object moves through the scanning plane in an orthogonal direction. The pulses of infrared light are reflected off of the mirror as it rotates and measurements are made at regular angular intervals in the scanning plane. Most often an object must be scanned from more than one view point to obtain the complete profile as shown in Figure 2.4. The profile of the vehicle is now defined by each point at which the laser reflected off of the vehicle and back to the scanner.

There has been much development in the area of laser range-finding in the last few years, but the technology is still relatively new. Currently, range measurement accuracies for a high speed time-of-flight based range-finding scanner are approximately 8 *cm* at best. This is considered acceptable for the AVDMS. The advantages of the scanning laser rangefinder are that the scanners are completely overhead, special lighting is not required, little maintenance is involved, and the complete vehicle is imaged, providing more information than the other systems considered. Three different laser range sensors were tested and the results indicated that this technique would be a good solution for the AVDMS. More details on the testing of the range-finding devices and their application in the AVDMS solution is discussed in Chapter 4.

2.3 Selection of Dimension Measurement Technique

After investigating the most promising range sensing techniques for the dimension measurement of vehicles, the most suitable method and the only proven technology considered suitable for the AVDMS was laser range-finding scanners. Table 2.1 out-

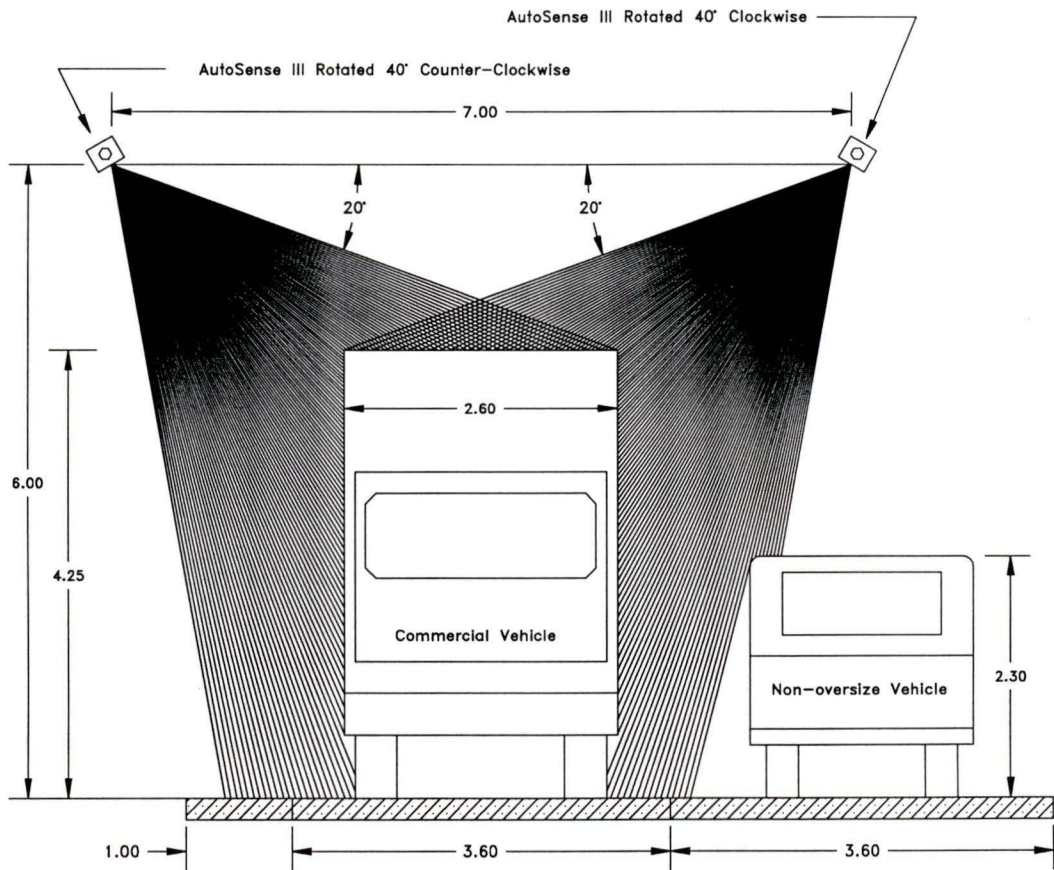


Figure 2.4: Multiple Viewpoint Laser Scanning for Complete Profile

Table 2.1: Summary of Dimension Measurement Techniques

Technique	Problems	Features
2D Gray Image	High cost and development time Real-Time Processing not feasible Requires bright lighting	Only 2 cameras req'd Low maintenance
1D Gray Image	High cost and development time Too much processing time req'd At least 4 cameras req'd Requires bright lighting	Low maintenance
Light Curtain	Response time not quick enough High maintenance costs Many sensors req'd	Well proven technology
2D Range Image	High initial cost Speed measurement system req'd	Meets design accuracy req'mts Well proven technology Only 3 sensors required Not affected by light variation

lines the various problems and features of each of the measurement techniques.

2.4 Methods for Sensor Evaluation

The stated measurement techniques were evaluated by testing the various sensing devices in the laboratory at the University and in some cases on the road. The road testing took place at the University of Victoria and on the Royal Oak-Highway 17 overpass.

2.4.1 Laboratory Testing and Development Highlights

The laboratory testing setup used for testing the Autosense III scanners is shown in Figure 2.5. The laboratory was also used for testing many other sensing systems as

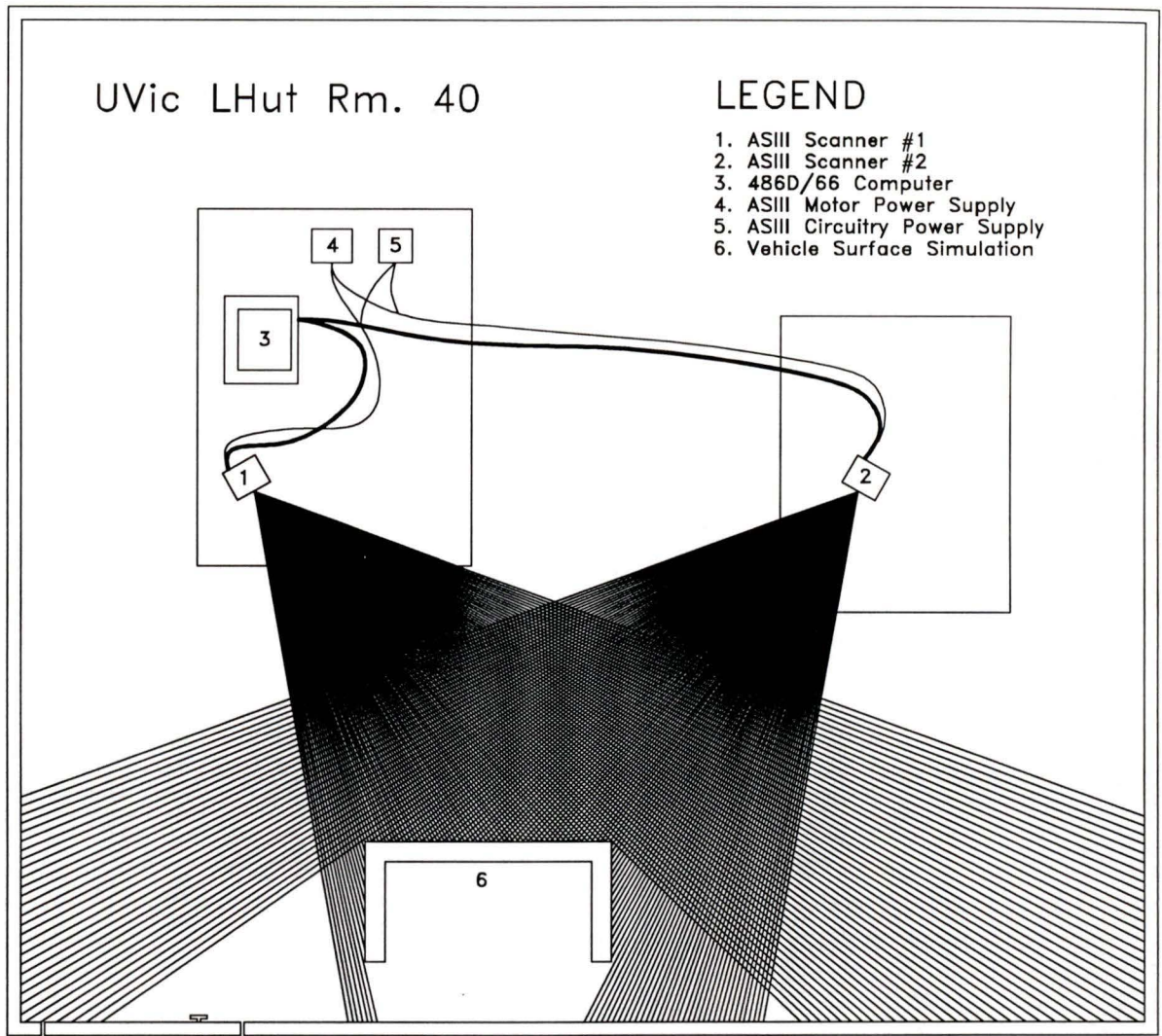


Figure 2.5: UVic Laboratory Setup for Testing the ASIII Scanners

Table 2.2: In-Lab Sensor Evaluation Summary

Supplier	Equipment Tests/Development Description	Date
EG&G	Linescan camera presentation	Feb. 10/ 93
Argo Ind.	STI Retro-reflective sensors demo	Feb. 18/93
Infrascan	Image Processing Equipment demo	March / 93
Electrol Dist.	GL45-P250 Retro-reflective sensor	Feb 93.
SEO	ASI unit arrived / lab tested	Feb. 24/ 93
Argo Ind.	Retro-reflective sensor STI-205 demo	Mar. 11/ 93
Argo Ind.	STI-705 sensor pairs tested	Mar./ 93
Chartwell Elec.	WS12/WE12 sensor pairs tested	Mar. /93
SEO	HOPSS Scanner arrived and tested in lab	April 28 / 93
EG&G	Linescan cameras tested in lab	August / 93
SEO	ASIII scanners testing and development	April/94 - June/95

outlined in Table 2.2.

2.4.2 Field Tests

The field tests were performed on the roadways at the University of Victoria or at the Royal Oak overpass as outlined in Table 2.3.

Table 2.3: Field Testing Summary

Supplier	Equipment / Test Description	Date
SEO	ASI unit tested at UVic roadway	March / 93
SEO	ASI unit road tested at Royal Oak	March / 93
SEO	HOPSS Scanner road tested	April 30 / 93
Aromat	Retro-reflective sensors road tested	November 18 / 93
MD Charlton	K-55 Radar gun tested at UVic roadway	Jan. / 94
Kustom Signals	Falcon Radar system tested at Royal Oak	April / 94
SEO	ASIII scanners testing at Royal Oak	April 21/94 - June /95

Chapter 3

Range Sensing and Range Data Processing

3.1 Introduction

With many processes in industry becoming automated, it is often important to make real-time spatial observations of various objects, machinery, and the working environment. These observations can be made using CCD cameras and image processing, or various range-finding methods. Although CCD cameras are able to capture the image of a particular scene faster than range-finding devices, the gray image acquired does not directly contain geometric information and requires complex processing algorithms to determine 3D geometric information. Range-finding devices require more time for observing a given object or environment. However, in a range image, the geometric location of each point defining the image is known and complex processing is not required. Therefore, range images are often more suitable for automated and real-time operations in which geometric information is required. Range-finding de-

vices most commonly use light waves (laser) as their measurement medium. However, with recent development in the ability to focus sound waves, they too are being used, depending on the application. In this thesis, only optical range sensing techniques will be discussed as they were considered most suitable for the AVDMS.

After obtaining range data from a particular scene, it may be used for a number of purposes. For the AVDMS, the range data is used to determine the dimensions of vehicles without having to generate a complete 3D model of the vehicle. However, it is often necessary for a computer to create a 3D model of the object(s) and the environment from the range data. For example, the Autosense III scanners could be used for a vehicle recognition system in which 3D models of the vehicles would be created from the range data. Geometric model generation usually requires viewing an object from multiple locations to obtain the complete model of the object and its environment. This creates the need to perform multiple-view fusion which combines the data from each viewpoint to build the complete model. Geometric model generation and multiple-view fusion will be discussed in section 3.3.

3.2 Range Sensing Techniques

There are two optical methods which are most commonly used for range sensing. These are triangulation based devices and time-of-flight (TOF) based rangefinders. Triangulation is more commonly used at shorter ranges where high accuracy is required. Triangulation based devices consist of a laser light source, a scanning mechanism which projects the light spot onto the object, and a position sensor such as a CCD camera which detects the location of the light spot on the object. The range measurements are made using trigonometric algebra applied to the paths of projection and detection of the light spot. Different geometrical arrangements of the components

can be used for various applications to provide better range measurements. An example of a triangulation configuration which uses one-dimensional scanning is shown in Figure 3.1.

The TOF range-finding method also uses a laser source which transmits pulses of light that are reflected back from the target. The time delay between the transmission of the pulse and its return determines the distance to the target. TOF range-finding is only suitable for measuring distances of at least a few meters due to the high travel speed of light and the limitations of timing electronics. Triangulation methods have much better accuracies than TOF methods at short ranges. However, the method requires that the projected spot on the object be quite “visible.” This imposes a strict reflective property on the object surface and illumination lighting. The light intensity of the reflected spot also diminishes squarely with distance. Due to these limitations, no triangulation devices were found which operate at the ranges required for the AVDMS. One sensor supplier that was contacted has done some experimentation with a “proof of concept” triangulation system that operates at longer ranges, but did not consider it suitable for the AVDMS. Triangulation devices would most likely experience difficulty scanning complex shapes such as commercial vehicles due to shadow effects. The shadow effects occur since the path of incidence and reflection are not the same as shown in Figure 3.1. The advantage of the TOF rangefinder is that incident and reflected light travel the same path as indicated in Figure 3.2 and shadow effects are not a problem.

For TOF rangefinders, scanning about one axis or two axes can be accomplished yielding either 2D or 3D range data. It is also possible to scan about one axis to obtain three-dimensional range information if either the target or the scanning head are moving in a known or controlled manner.

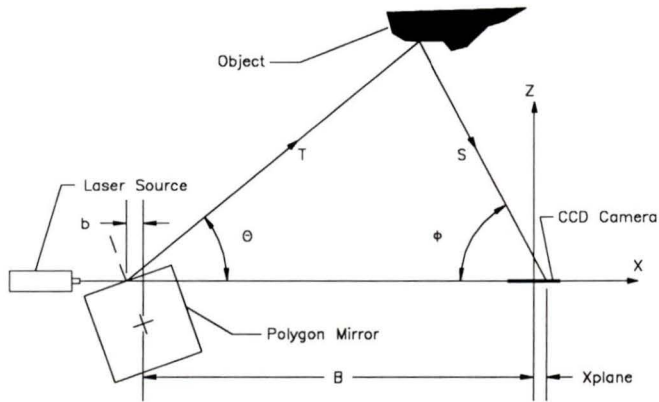


Figure 3.1: Geometry of Triangulation Range-Finder

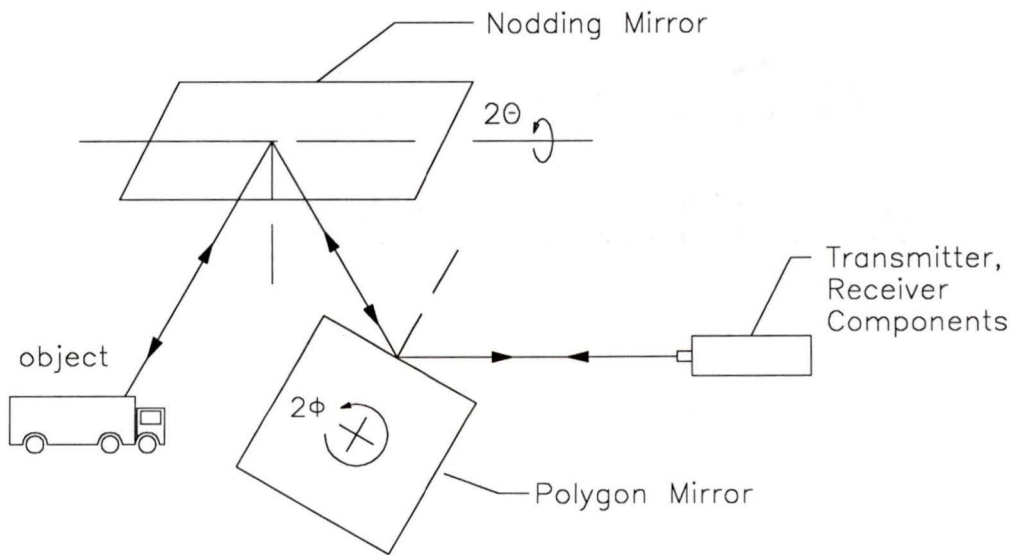


Figure 3.2: Internal Structure of Time-of-Flight Rangefinder

3.2.1 Time-of-Flight Range Sensing

When imaging stationary target objects, TOF Rangefinders can be rotated about two axes to obtain 3D range data in spherical coordinates. Most often the data is not usable in the device's spherical coordinate frame and must be transformed into the global Cartesian frame. Considering the range-finding device as a single point, spherical coordinates are transformed into the Cartesian coordinate system based on the model in Figure 3.3 by:

$$x(\theta, \phi, R) = R \cos \phi \cos \theta \quad (3.1)$$

$$y(\phi, R) = R \sin \phi \quad (3.2)$$

$$z(\theta, \phi, R) = R \cos \phi \sin \theta \quad (3.3)$$

In applications where the target object is moving perpendicular to the scan plane formed by one rotating mirror, the mirror is used to reflect the laser onto the object at regular angular intervals capturing profiles of the target object. In this case the measurements are made in the cylindrical coordinate system and must be transformed to the Cartesian coordinate system based on the model in Figure 3.3 as follows:

$$x(\theta, R) = R \cos \theta \quad (3.4)$$

$$y(\theta, R) = R \sin \theta \quad (3.5)$$

In this case, either the rangefinder or the object will have known or controlled motion to determine the third dimension. Both of these models assume that the rangefinder can be represented by a point in space, however, they are incomplete as they do not model the interior of the range-finding device. An alternative model

has been developed using homogeneous transformations, which is applied to model both the exterior and interior light paths of the rangefinder. The magnitude of the errors resulting from neglecting the interior light-paths are dependant on the internal geometry of the rangefinder. Essentially, if the total length of the internal light path, which changes with rotation of the internal mirrors, has significant magnitude when compared to the external light path, this length should be included using the alternative model. The details of the alternative model can be found in [23, 24]. Considering the Autosense III sensor, the interior light path is adjusted for with a constant offset adjustment to the range measurement. Although the internal light path is always changing slightly due to the rotation of the sensor's mirror, the variation is much less than the resolution of the sensor and can be ignored.

3.2.2 Triangulation Based Range-Finding

With triangulation based systems, the internal geometry of the rangefinder is essential information for determining the ranges to the points on an object. Referring to Figure 3.1, the laser source, point on the object, and the CCD camera form a triangle. By applying the law of sines, the distance between a point on the object and the camera is determined as follows:

$$\frac{\sin \theta}{S} = \frac{\sin \phi}{T} = \frac{\sin(180 - \theta - \phi)}{B + b + x_{plane}} \quad (3.6)$$

or

$$S = \frac{(B + b + x_{plane}) \sin \theta}{\sin(180 - \theta - \phi)} \quad (3.7)$$

Once S is determined the Cartesian coordinates are determined as

$$X = x_{plane} - S \cos \phi \quad (3.8)$$

$$Z = S \sin \theta \quad (3.9)$$

and the third dimension can be obtained by moving the range sensor or the object in the Y direction.

The arrangement of the internal components such as the angles of the focussing lens and the CCD camera are important in obtaining more accurate range measurements over a larger depth of view. The Scheimpflug geometry is one particular arrangement that improves the depth of view and is discussed in [18]. Synchronized scanning is another geometrical arrangement which improves the performance of the triangulation based rangefinder and is discussed in [17].

3.3 Geometric Model Generation from Acquired Range Data

Although, geometric models are not generated in the AVDMS, the range data acquired by the Autosense III scanners could be used to generate geometric models if required for a vehicle recognition system. A number of 3D images were created using the Autosense III at a single view point and scanning about one axis. These images are shown in Chapter 8. In order to generate a complete geometric model, range data must be acquired from at least one other view point. The type of geometric representation must also be determined and then the range data acquired from each view point must be fused to create one model.

Traditionally, 3D model generation has required the user to know the geometric information of an object and enter it into a solid modelling program. This is often not suitable for automated processes which require real-time decision-making or for modelling objects with ‘uncertain’ geometries. With range-finding systems, it is now possible to have continuous data-acquisition which can be used for real-time geometric

modelling of objects. In order to completely observe an object and its environment, views are required from multiple sensor locations and must be integrated to create the complete model. The integration process is known as multiple-view fusion and this process will be discussed in section 3.3.3. Before discussing fusion of the multiple views, the alternatives for representing the model must be compared to determine which is most appropriate for data acquired by range-finding devices at multiple view points. These representation alternatives will be discussed in section 3.3.1. The amount of data required to model an object and its environment is quite large and it is usually important to process the information in the most efficient manner. In section 3.3.2, modelling an object in the device frame of the range sensor is discussed as an option for improving the efficiency of the modelling process.

3.3.1 Selection of Representation

There are a number of ways in which objects can be geometrically represented. It is important that the representation chosen to model the object is compatible with the method of data-acquisition and that it meets the intended purpose. There are some important factors to consider when data is acquired by range-finding devices such as the Autosense III.

1. Objects are defined by discrete range-data,
2. Range-data is evenly spaced in the device frame, in the cylindrical or global coordinate form, but not in the local or global Cartesian frames,
3. Multiple-views require fusion to complete the model.

Keeping these factors in mind, the various methods of model representation can be compared to determine which is most suitable. Referring to [23, 25, 26], the represen-

tation alternatives are point, line, surface, volume, boundary, or object based. Among these representation types, surface based representations are most compatible with the range data obtained from the surfaces of vehicles using the Autosense III scanners. Of the surface based representations discussed in [23, 25, 26], the cross-section based representation is efficient for range data in general, and is especially effective for an application such as vehicle recognition where cross-sections are inherent with the method of scanning.

A cross-section based representation uses an array of 2D cross-section curves to represent objects. A cross-section curve can be thought of as the intersection of the 3D object's boundary surface with a cross-section plane, which cuts through the object. The cross-section planes are arranged perpendicular to a guide curve and if the guide curve is a line, the cross-section planes will be parallel to each other. In the case of a vehicle recognition system using the Autosense III scanners, the road could be considered the guide curve and the cross-section planes would be evenly spaced along the road. The distance between the cross-section planes can be chosen based on the scan rate of the Autosense III and the vehicle speed, to align the acquired data planes with the model cross-sections.

If the object to be modelled is bounded within the view of the range-finding device, the cross-section lines will be closed once the model is complete. In the case of the vehicle recognition application, two Autosense III scanners would be required to scan each side and top of the vehicles. Partial modelling and multiple-view fusion can now be handled in the two-dimensional space of each cross-section plane. A simple object is represented using the cross-section based representation in Figure 3.4. The number of planes used can be adjusted depending on the definition accuracy required.

Now that a suitable representation has been selected, the modelling process must be implemented. This is the process of using the range data from the range-finding

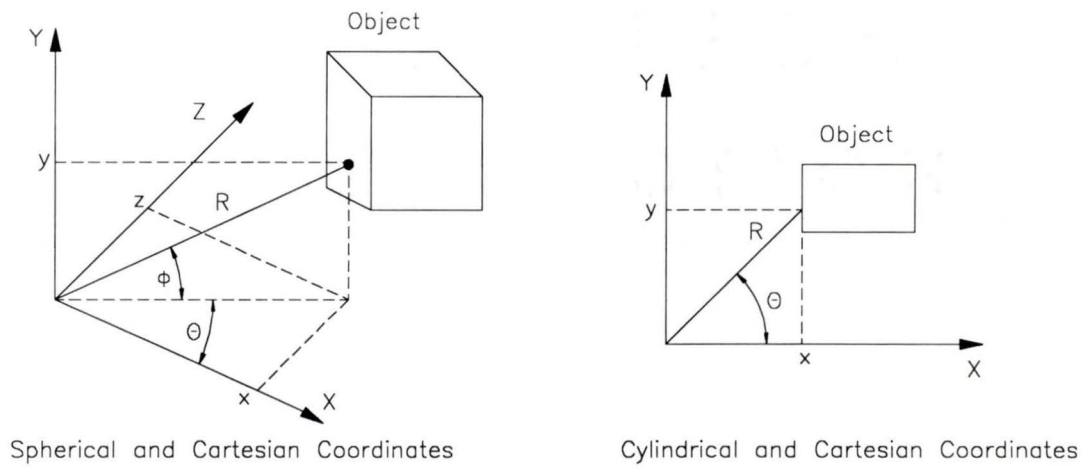


Figure 3.3: Spherical and Cylindrical Coordinate Transformations

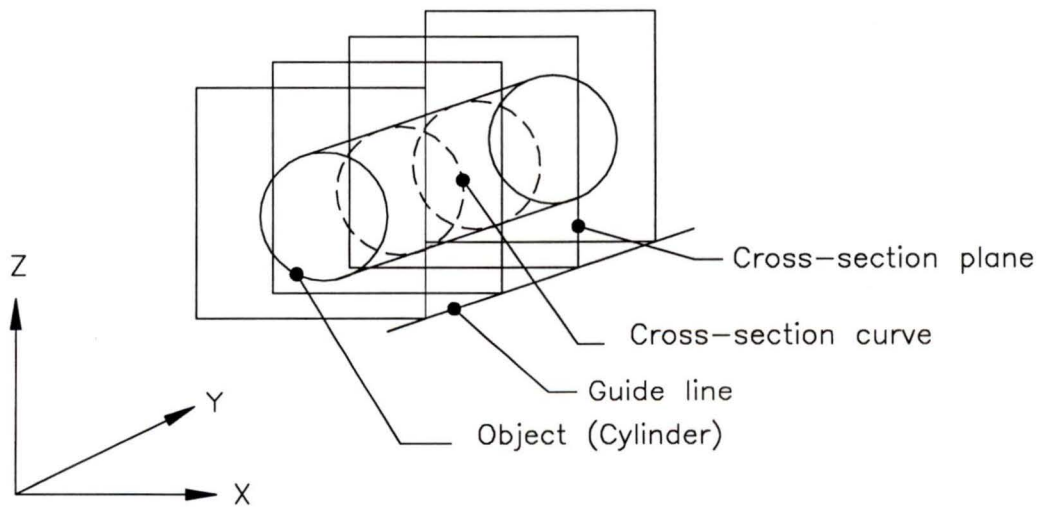


Figure 3.4: Cross-section Based Representation

device and the imaginary cross-section planes to create the cross-section curves.

3.3.2 Geometric Model Generation

There are three frames with different coordinate systems that have to be considered when modelling an object with a range-finding device. These are the device frame of the sensor, the local Cartesian frame, and the global Cartesian frame. When scanning about one axis, the device frame has a cylindrical coordinate system defined by the scanning angle of the sensor. The range data is acquired at regular angular intervals in the scanning directions and is therefore evenly spaced in the device frame. On the other hand, the data is not evenly spaced in the local or global Cartesian frames. It is computationally intensive to transfer all of the range data from the device frame to the Cartesian frame and then generate the cross-section curves using indirect addressing. A more efficient method is discussed in [23, 25, 26]. This method transfers the cross-section planes to the device frame and takes advantage of the evenly spaced range data. The same indices (scanning angles of sensor) used to measure the range data are used to calculate distances to the cross-section planes. The cross-section curves are generated by comparing the values of the range data with the distances to the cross-section planes at all of the indices. When the two values are within a threshold value of each other, interpolation is used to determine the location at which the plane intersects the object's surface.

For the vehicle recognition system, the task of generating the cross-section curves is greatly simplified by using the scanning plane of the Autosense III scanners as the cross-section plane. By doing this, the range data acquired by the scanners automatically creates the cross-section curves which are easily transformed to the local Cartesian frame.

After cross-section curves are generated for each cross-section plane, the partial model for a given sensor location is complete. These curves, as well as the curves from the other partial models, are then transformed to the global Cartesian frame where multiple-view fusion is required to form the complete model.

3.3.3 Multiple-View Fusion

After the partial models are generated from each viewpoint, the curves forming the partial models must be combined to form the complete model. This requires transforming all of the curves from the device frames to the global Cartesian frame. It is important that the same cross-section planes are used for constructing each partial model so that the cross-sections are completed during the fusion process.

In a vehicle recognition system, the cross-section planes for each Autosense III scanner would be the same assuming the scanners are alligned and scanning at the same rate. Therefore the cross-section curves from each scanner are inherently in the same cross-section plane and the fusion process is simply a matter of handling the redundant data.

Redundant data occurring when the cross-section curves overlap is used to estimate the best cross-section curve. Surface discontinuity may exist on the model due to object occlusions or an insufficient number of views. More details regarding estimation and integration of overlapped curve regions, and the multiple-view fusion process can be found in [23, 25, 26].

3.4 Conclusion

Range-finding devices have improved and added flexibility to the geometric modelling process. It is now possible to use continuous modelling in automated processes to monitor activities and make real-time decisions. Complex shapes which are not easily defined can now be modelled. Using the cross-section representation and generating partial models in the device frame has improved the efficiency of the modelling process. The multiple-view fusion problem is now reduced to two-dimensional curve integration which is much more efficient than three-dimensional surface integration.

Chapter 4

Development of the Range Sensing Solution

4.1 Introduction

The real-time Automatic Vehicle Dimension Measuring System (AVDMS) required a sensing system that could be used to automatically measure the maximum length, width, and height of commercial and oversize vehicles travelling at speeds up to 120 *km/h*. Vehicle height and width were to be measured to within 15 *cm* and vehicle length to within 30 *cm*. The task was not an easy one due to the high travel speeds and complex shapes of the vehicles.

There were a number of steps involved in the research and development of the range sensing system:

1. **Determining Development Methodology:** Due to time constraints for development of the vehicle dimension measurement system, it was considered necessary to search for currently available sensor system rather than developing a

completely new sensor system. An extensive literature search on current and past IVHS developments was carried out. No publication was found to discuss systems directly useful for the vehicle dimension measurement system. Over fifty companies in North America and five in Europe specializing in measurement technology and traffic management systems were contacted. Although a response was not received from all of these companies, it became apparent that there was no system available for achieving the objectives of the project. A number of companies did express interest in the project and suggest ideas which were useful for directing the project's development.

2. **Technology Investigation:** Considering the problem of measuring the dimensions of vehicles travelling along the highway, a system is required that can make measurements at a distance. Initially, a study of optical, ultrasonic, and microwave mediums was completed to determine the features and drawbacks of each. After this study was completed, it was apparent that optical measuring techniques were most suitable for the vehicle dimension measurement application. The main reasons being that optical signals are easily focussed, are not affected by air turbulence, and can be used at the ranges of concern for the vehicle dimension measurement application.

The Library Resource Center at the Ministry of Transportation and Highways was used to search a number of transportation and science databases for research projects and papers that would provide direction for the vehicle sizing project. A number of research papers were discovered that discussed various Intelligent Vehicle-Highway Systems projects, range-finding techniques, and vehicle detection and classification systems, but none of the information was directly applicable to vehicle dimension measurement.

After the initial technology investigation, the following sensing systems were

considered most promising for the real-time vehicle dimensioning task:

- 2D Gray Image Cameras
- 1D Gray Image Cameras
- Photoelectric Sensors
- 2D Range Scanning Devices

3. **Testing and Optimizing:** Much time and effort was put into exploring image processing for vehicle dimension measurement. Vehicle images acquired using a video camera were analysed by professionals with much experience in the field. Due to the speed of the vehicles, the complexity of their shapes, and the processing time required, it was recommended that a different sensing system be used. Various companies supplied photoelectric sensors and systems which were tested by the research team. After many tests the vehicle dimension measurement task seemed to be near impossible due to the high travel speeds, complex vehicle shapes, and the adverse environment in which the system must operate. Finally, a company, Schwartz Electro-Optics (SEO) was discovered which develops infrared laser range-finding sensors that appeared promising for the AVDMS. SEO provided the UVic research team with a number of their sensors which were tested in the UVic lab and on the highway. Design specifications for the Autosense III (ASIII) scanners were generated based upon the targeted function of the system. SEO carried out the hardware and software design and the production of the ASIII scanners. After a number of tests, repairs, modifications and improvements were made to the ASIII scanners, they are ready to be used in implementing the AVDMS prototype.
4. **Software Development:** Software development was required for signal acquisition, range data processing, and integration of the Autosense III scanners with

the speed sensor to determine vehicle dimensions. This was not an easy task due to the large amounts of information that must be acquired and processed in real-time.

4.2 Schwartz Electro Optics' Sensors

Schwartz Electro-Optics (SEO) specializes in the design and development of lasers and electro-optical systems. The company was founded in 1984 and its main facility is located in Orlando, Florida. The primary focus of SEO's Sensor Systems Division is the design, development and manufacture of active infrared sensor technology. These systems range from hand held battery operated units with accuracies of one inch to multi-channel three-dimensional imaging systems complete with real time target recognition capability. SEO offers all the resources necessary to design, develop and manufacture any commercial or military electro-optic system. In the past the company has demonstrated the capability for high volume production of both military and commercial electro-optics systems. SEO's diverse capabilities and product line are reflected in a healthy proportion of government versus commercial sales. SEO has experienced steady growth and established itself as a leader in laser technology and its applications.

Schwartz Electro-Optics expressed high interest in the AVDMS project from when they were first informed of it and proceeded to work with the UVic research team, loaning a number of their laser range-finding sensors for test purposes. After testing the available sensors and finding them unsuitable, the UVic research team worked with SEO providing them with specifications for a new range-finding scanner, the Autosense III.

Information on the various sensors loaned from SEO, is provided below. The tests

performed with these sensors were an important part of the AVDMS development.

4.2.1 HOPSS Laser Scanner

The company first loaned their Helicopter Obstacle Proximity Sensor System (HOPSS) to the UVic research team as an example of their technology. The HOPSS provides continuous distance and azimuth measurements in the horizontal plane of a helicopter to alert pilots of the presence and location of obstacles.

The HOPSS laser scanner was evaluated at the Royal Oak overpass, over Highway #17 in Victoria, and also in the UVic laboratory. Although it was clear from the start that the HOPSS was not suitable for vehicle dimension measurement, the basic measurement technique of time-of-flight laser range-finding was to be evaluated to determine whether another scanner could be developed for vehicle dimension measurement.

The HOPSS laser scanner was mounted on the Royal Oak overpass and used to scan vehicles passing below on Highway #17. Although this sensor was not designed for scanning high speed vehicles, it was possible to capture some profiles of the vehicles and the road surface was clearly defined. A number of vehicles were scanned and their images saved on file for further processing at the university lab. After examining the vehicle and road surface profiles, it appeared that the laser range-finding scanner would be suitable for vehicle dimension measurement if it could operate at much higher scan rates.

Some initial testing of the prototype was done outdoors to determine its range. Bright sunlight and light rainfall that occurred during the outdoor testing did not appear to cause interference. The HOPSS unit was able to scan a small flat board at distances beyond 20 metres. Although the sensor could not be mounted directly

above the road at the university, it was used to scan the sides of passing vehicles at ranges similar to those at which the ASIII would operate.

4.2.2 Autosense I

SEO's Autosense I (ASI) employs a pulsed time-of-flight laser rangefinder to detect vehicle (moving or stationary) presence, determine type of vehicle and measure vehicle speed. Vehicle presence is indicated by a reduction in the range reading from the roadway. Vehicle speed is computed from the measured time interval between the interceptions of two laser beams. An on-board microprocessor is used for the determination of vehicle presence, speed count and classification. A real-time clock is used to time-tag the data to provide vehicle count and average speed for each hour of the day. Autosense I is completely eyesafe.

SEO's test results demonstrated that the sensor reliably (99.4 %) detects vehicles including cars, trucks, buses, and motorcycles and measures their speeds to within ± 1.6 km/h at speeds up to 80 km/h.

ASI System Features

- RS232 / RS422 serial interface for downloading vehicle data, uploading configuration data and initializing real-time clock.
- Relay and logic output for vehicle presence detection.
- LEDs to facilitate system installation.
- Anti-fog window.
- Automatic calibration and self test.

- Automatic compensation for changing environmental conditions

ASI Specifications

- **General**

- Range: 1.2 to 15.2 m (4 to 50 feet)
- Accuracy: 10.2 cm (4 inches)
- Laser: InGaAs diode-laser array, eyesafe
- Power: 115 Vac, 60 Hz, 4 W (20 W with heated window)
- Size: 13.37" x 7.95" x 4.37"
- Weight: 11 lb

- **Presence Detection**

- Relay Response Time: 10 ms
- Logic Output Response Time: 1 ms
- Presence Hold Time: As long as vehicle is in FOV
- Detection Range: 0 to 15.2 m (0 to 50 feet)
- Resolution: 10 inch separation between vehicles (for sensor mounting angle $\Theta = 0$ and vehicle speed less than 25 *mph*).

- **Speed Measurement**

- Range: 0 to >120 *km/h* (80 *mph*)
- Accuracy (1σ): ± 1.6 *km/h* (1 *mph*) up to 112 *km/h* (70 *mph*)

- **Vehicle Classification**

- Vehicle Classes: Car/Truck (other classes are programmable)

- **Time-Tagged Measurements**

- Vehicle Count, Average Speed of Vehicles

The Autosense I was tested in the laboratory and on the road at the University of Victoria and also tested on highway travelling vehicles at the Royal Oak overpass. The Autosense I measures the height profile of vehicles within the sensor's field of view quite well. However, it has a narrow field of view which covers only the middle top surface of vehicles and does not scan across the entire surface which is required for determining maximum vehicle height and width. Also, the speed measurements made by the Autosense I were not accurate enough for making accurate vehicle length measurements.

4.2.3 Autosense II

SEO has developed the Autosense II (ASII) for a number of different private and public organizations mainly within the United States. The ASII sensor provides overhead imaging of vehicles to allow classification and size measurements. Applications include toll collections, bridge or tunnel clearance verification, traffic flow, routing studies and traffic monitoring. A vehicle profile is developed using a dual line-scanned laser rangefinder that measures the profile of a vehicle. Using vehicle motion in the direction of travel allows a range image of the vehicle to be formed. The sensor can be used to provide absolute vehicle dimensions and vehicle speed. ASII has continuous self testing and is completely eyesafe.

ASII Specifications**• General**

- Range: 0.6 to 15.2 m (2 to 50 feet)
- Accuracy: 7.6 cm (3 inches)
- Laser: InGaAs diode-laser array, eyesafe
- Power Requirements: 115 Vac, 75 W
- Size: 17.6" x 9" x 5.75"
- Weight: 25 lb
- Interface: RS-422, RS-232

• Scanner

- Scan Rate: 720 scans per second per scan line
- Field of View: 30 degrees
- Range Measurements per scan: 30
- Separation Between Scanlines: 10 degrees

• Vehicle Classification

- Detection Accuracy: >99 %
- Classification Accuracy: >95 %
- Vehicle Classes: 13

4.3 The New Sensor for Real-Time Dimension Measurement

Based on the the evaluation of SEO's range-finding sensors and many conversations with SEO's representatives, it seemed that the TOF laser range-finding scanners were quite capable of making the range measurements required for vehicle dimension measurement. Although the Autosense II was not quite suitable, it was a good scanning system on which to base the specifications for the new sensor. The modifications of the Autosense II and the specifications of the new scanning system are discussed below.

4.3.1 From the Autosense II to the Autosense III

After thoroughly evaluating the Autosense II sensor system concept from Schwartz Electro-Optics, the research team concluded that these sensors, with a few modifications, were the best available solution to the Real-Time Automatic Vehicle Dimensioning task. The first modification required was improving the angular resolution from 1 pulse/degree to 2 pulses/degree to provide more accuracy for the height and width measurements and to capture more detail in each scan. Secondly, the field of view needed to be increased from 30 degrees to 60 degrees so that a complete vehicle can be scanned using two of the scanners. With these modifications, the new sensor, would theoretically perform adequately for the AVDMS. SEO confirmed the modifications would be completed and the new scanner would be called the Autosense III. The system specifications of the Autosense III are listed below.

4.3.2 Autosense III System Specifications

- **General**

- Range: 2.4 to 15.2 m (8 to 50 feet)
- Accuracy: 7.6 *cm* (3 inches)
- Range System Power: 24 VDC at 0.4 Amps
- Scanner Motor Power: 24 VDC at 0.5 Amps
- Size: 11" x 9" x 4.6"
- Weight: 10 lb
- Interface: 1 MBit/s, RS-422 DMA

- **Scanner**

- Scan Rate: 240 (or 320 scans/s)
- Field of Regard: 59 degrees
- Range Measurements per scan: 118
- Angular Resolution: $1/2^\circ$

- **Rangefinder**

- Laser Type: GaAs Laser Diode, 904 *nm*
- Detector Type: Silicon Avalanche Photodiode
- Laser Power: 5 Watts
- Laser Pulsewidth: 6 *ns*
- Laser Burst Rate: 72 KHz
- Laser Beam Geometry: In-lane axis - 0.5 mrad Cross-lane axis - 5 mrad

For the AVDMS, the Autosense III scanners will operate in the first mode at 240 scans per second and 1/2 degree angular resolution.

4.3.3 Improvement of Autosense III

After the initial road test of the Autosense III scanners, there were a number of problems which required improvement:

1. Wiring error on EEPROM which corrupted the sensor's lookup table.
2. Reflection problem inside sensor limited the sensitivity of the receiver.
3. Erroneous maximum range measurements needed to be converted to minimum range values.
4. The time-walk look-up table required corrections to improve range measurement accuracy on low reflectivity targets.

After the above improvements were made, three incidents occurred while testing the ASIII scanners which required the scanners to be returned to SEO for repairs:

1. The capacitor in the laser transmitter failed due to an insufficient voltage rating which disabled the transmitter. The wrong capacitor was accidentally selected by SEO. SEO replaced the capacitor with the correct one which is currently used successfully in over 100 systems in the field.
2. The analog range counter failed due to a degraded transistor. The transistor lost about 50 percent of its current gain. The transistor was replaced and tested for a two week period before the ASIII scanners were returned to the UVic research team.

3. The analog range counter failed again due to degradation of the transistor again. SEO looked into the problem further and determined that the aging of the transistor was caused by the high level of reverse bias voltage on the base-emitter junction. The biasing circuit was modified which reduced the reverse bias voltage to less than half of its rated value. The scanners were then tested for one week and returned to the UVic research team.

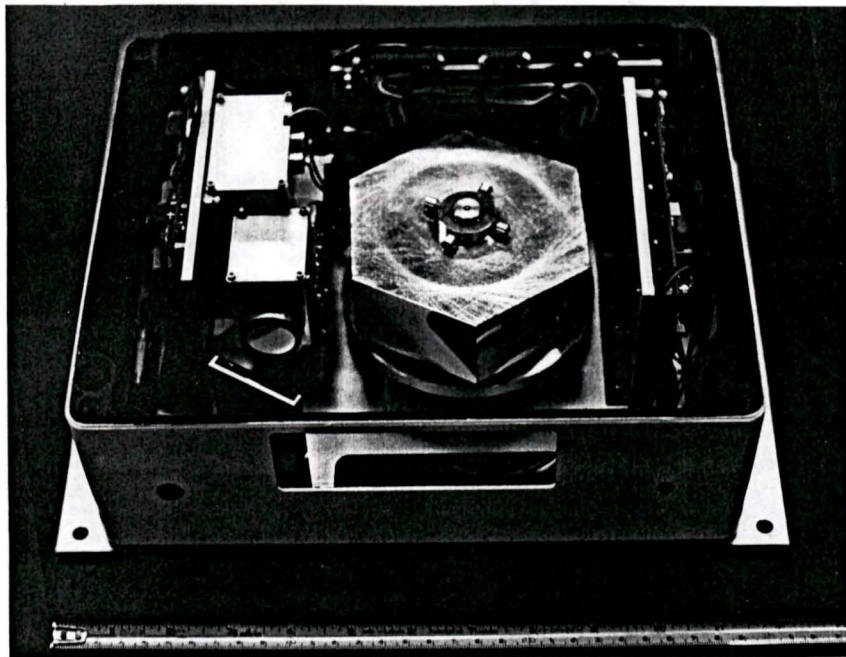
Table A.1 in Appendix A lists the testing and development history for the Autosense III scanners.

4.4 Autosense III and Real-Time Vehicle Dimensioning

The Autosense III infrared laser scanners will be mounted on each side of the vehicle lane and will generate many profiles of the vehicles as they pass through the scanning plane. The scanners utilize a six-faced polyhedron rotating at 4800 *rpm*. Each face of the polyhedron is polished metal which acts as a mirror for reflecting the laser to and from the vehicle. Photographs of the Autosense III are provided in Figure 4.1 for reference. Although there are six mirror faces, the scanners operate on a half-duty cycle providing three scans for every rotation. The half-duty cycle is used to create a time gap between scans to transfer and store the data from each scan separately. This translates to 240 scans per second and 118 range measurements per scan for a total of 28320 measurements every second. The scans cover a 59 degree field of view with an angular resolution of 0.5 degree. A scaled conceptual drawing is shown in Figure 4.2. In the next section, the method by which vehicle height and width dimensions are determined based on the scans is discussed.



(a) Enclosed ASIII



(b) Internal View of ASIII Scanner

Figure 4.1: Photographs of the Autosense III Range-finding Device

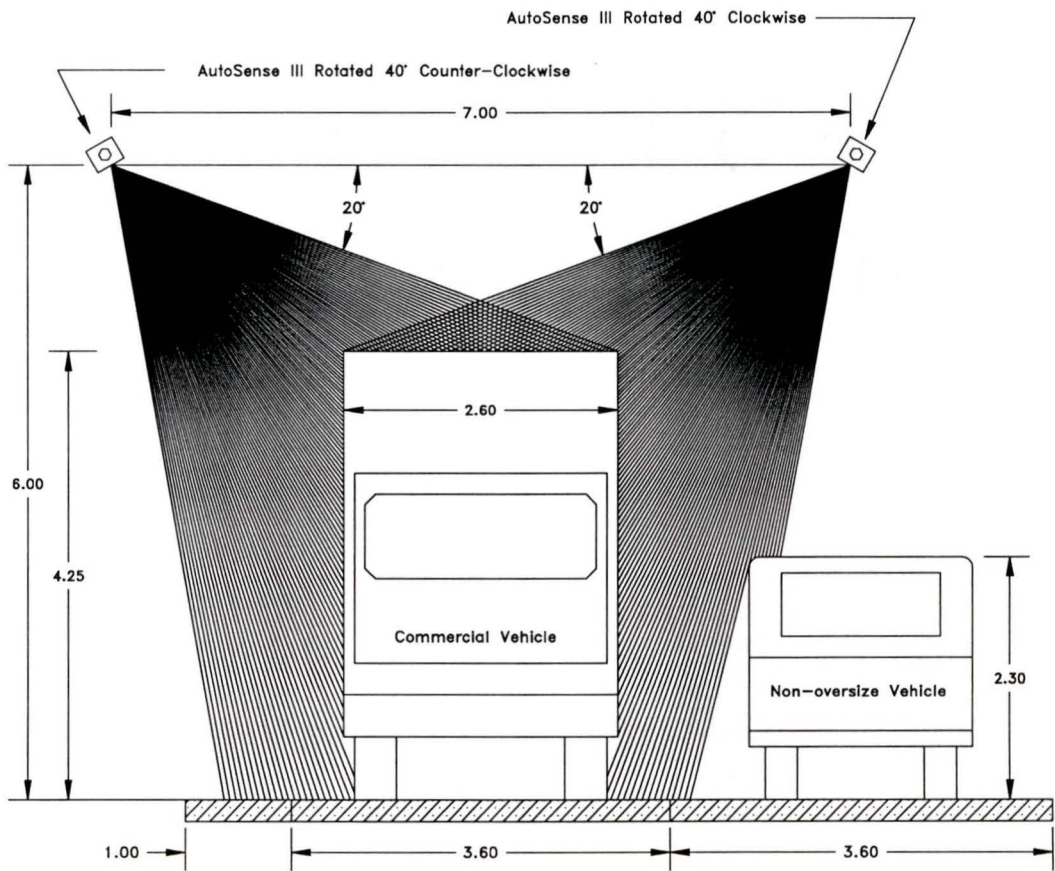


Figure 4.2: Automatic Vehicle Dimension Measuring System

Table 4.1: Arrays for Transforming to the Cartesian Coordinate System

Angle	Height Array	Width Array
α_1	$\cos(\alpha_1)$	$\sin(\alpha_1)$
$\alpha_1 + 0.5$	$\cos(\alpha_1 + 0.5)$	$\sin(\alpha_1 + 0.5)$
$\alpha_1 + 1$	$\cos(\alpha_1 + 1)$	$\sin(\alpha_1 + 1)$
...
...
$\alpha_1 + 58.5$	$\cos(\alpha_1 + 58.5)$	$\sin(\alpha_1 + 58.5)$
$\alpha_1 + 59$	$\cos(\alpha_1 + 59)$	$\sin(\alpha_1 + 59)$

4.4.1 Determining Vehicle Height and Width

Referring to Figure 4.2, the vehicles will be scanned from both sides. This is necessary since one scanner cannot scan the entire vehicle. The location of each scanner is known and the range measurements, relative to the scanners, define the perimeter of the vehicles as they pass through the scan gate. Each scan is processed immediately recording the highest and widest point on the vehicle for that scan. After the entire vehicle has passed through the scan gate, the maximum height and width of the vehicle are known.

Each scan produces an array of 118 range values which correspond to polar coordinate measurements made at equal angular intervals. These range values can be transformed to height and width values using a simple transformation of the values from the polar coordinate system to the cartesian coordinate system. Since the measurement angles are known and constant for each scan, an array of fixed constants can be used to translate the array of range values to height and width values. The array of constants are simply sine and cosine values calculated at 0.5 degree intervals over a 59 degree field of view as shown in Table 4.1.

Arrays of height and width values are quickly generated by multiplying the range

values array with the height and width constant arrays. The value of α_1 is measured when the scanners are installed and then entered as one of the system's software initialization parameters.

The Autosense scanners have an accuracy of 7.6 *cm* or better at the ranges of concern for the AVDMS. Therefore, the actual vertical and horizontal location of each point scanned will be determined to even better than 7.6 *cm* of accuracy as demonstrated in Figure 4.3. The range measurement error (E_r) is the hypotenuse of the error triangle. The horizontal (E_h) and vertical (E_v) error components will be less than the range error component according to the following relationships.

$$E_h = E_r \cos \theta \quad (4.1)$$

$$E_v = E_r \sin \theta \quad (4.2)$$

where θ is the angle between the laser beam and horizontal.

The spacing of the scans along the length of the vehicle will be directly proportional to the speed of the vehicle. A vehicle travelling at 100 *km/h* will be scanned every 11.6 *cm*, whereas, a vehicle travelling at 60 *km/h* will be scanned every 6.9 *cm* along the vehicle.

The spacing between range measurements across the vehicle will depend on the size and shape of the vehicle. The Autosense III scanners make range measurements at regular angular intervals as the scanner rotates and thus the distance between measurements is greater at surface locations furthest from the scanner. Across the top of a truck's flat trailer the distances between measurements will vary between 4 and 10 *cm* as shown in Figure 4.4. Down the side of this same trailer, the maximum spread between the laser measurements will vary between 3 and 13 *cm*. Only small bumps or thin objects such as mirrors and antennas may not be seen by the scanner.

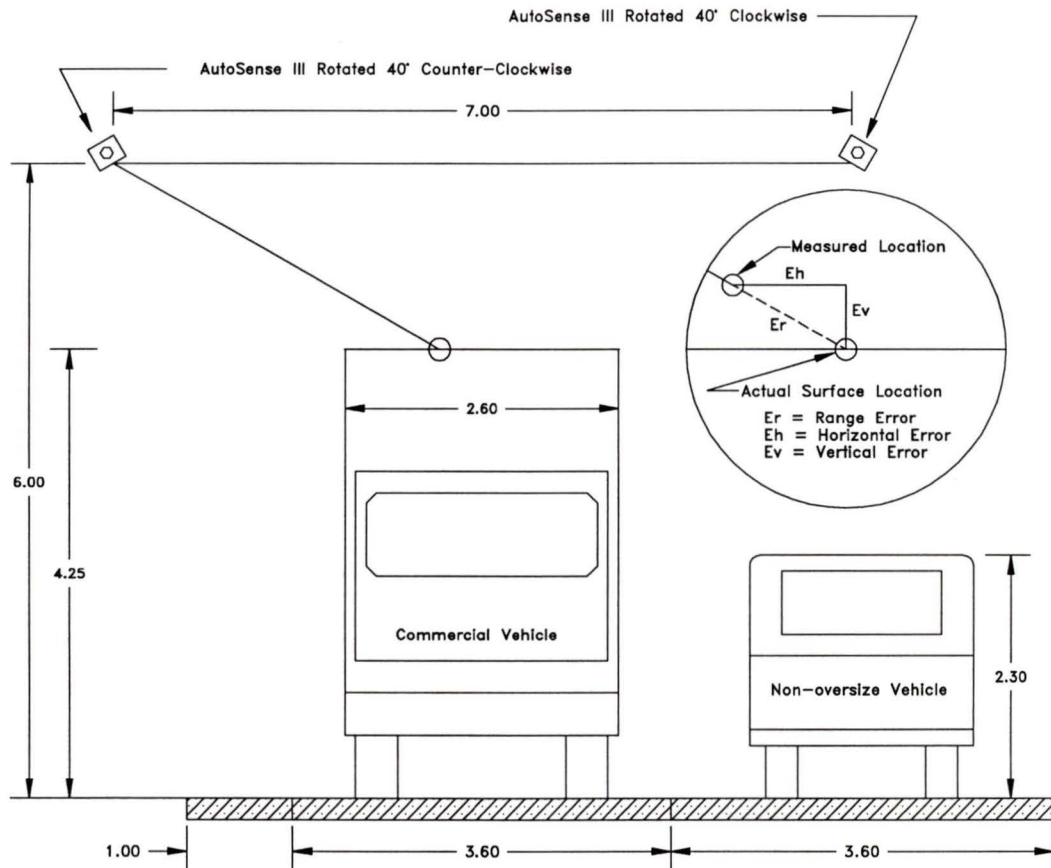


Figure 4.3: Range Error vs. Measurement Error

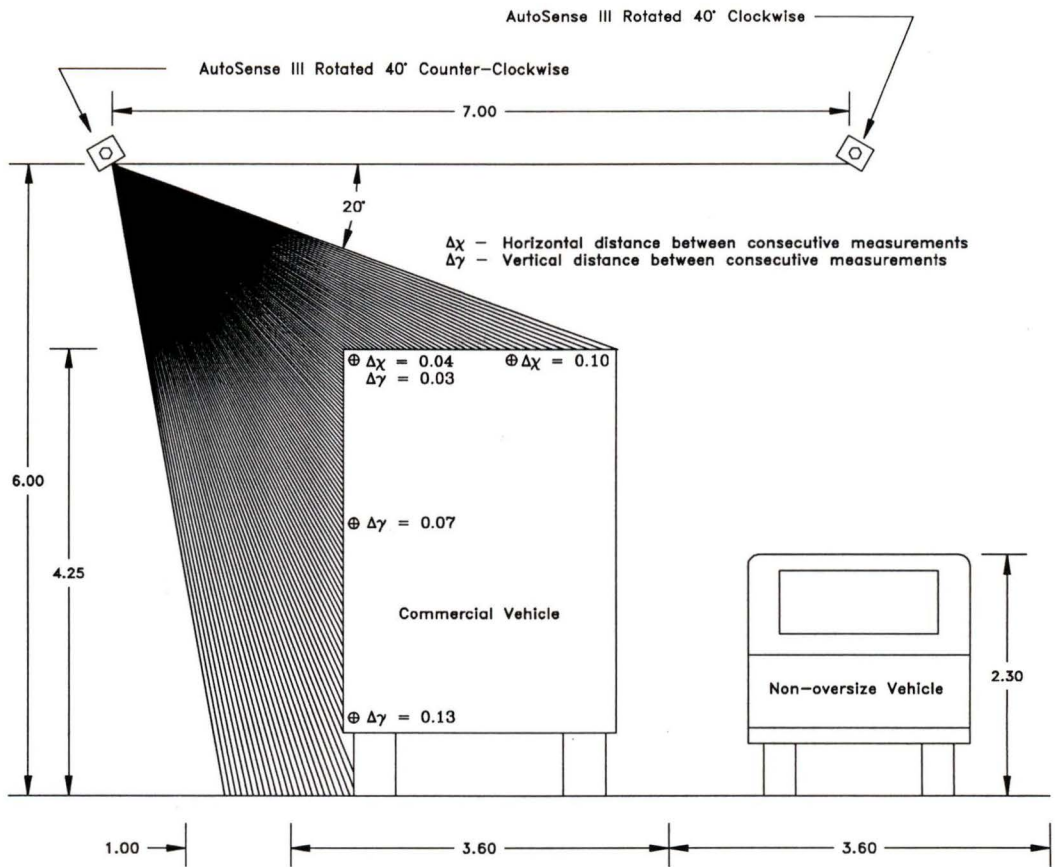


Figure 4.4: Scanning Resolution

4.4.2 Removal of Bad Data with Thresholds and Median Filtering

Fortunately, there are only modest noise and wild data in the range measurements from the Autosense III scanners, and the maximum dimensions of the vehicles can be determined without having to perform large amounts of post-processing or filtering.

In order to deal with the bad range values in the scanned data, it is important to know the reasons why the bad data occurs. Because of the high scan rate, only one measurement is made at each angle per scan. This means that a large number of range values are not averaged to give a mean range at any target point. Based on experimental observation and light reflection theory, bad range values are due to two main factors: 1) the colour of the target surface, and 2) the material and texture of the target surface. In the first case, a very dark coloured vehicle surface or partial surface will absorb the light from the scanner and significantly reduce the intensity of the return signal. The range measurements are based on the travel time of the laser light to and from the target. The exact return time of a low intensity signal cannot be detected easily which distorts the measured travel time. This problem does not occur very often, but has been observed in a couple cases in which a vehicle is painted black. In the second case, glass surfaces or high gloss surfaces such as shiny chrome or aluminum also cause errors in the range measurements. These surfaces will either reflect the laser light almost completely away from the scanner or directly at the scanner, distorting the intensity of the return signal in both cases. The Autosense III scanners have a built-in filtering system which eliminates almost all of the range measurement distortions that occur due to the high-intensity return signals. Low intensity return signals caused by dark coloured surfaces or surfaces which reflect the signal away from the scanner are not as important to eliminate since they will essentially eliminate themselves when it comes to determining the dimensions of a

particular vehicle.

However, occasionally wild data points do exist, and these points need to be filtered. In order to remove this type of erroneous data, two steps are used. First of all, maximum and minimum threshold values are set to eliminate any extreme values or ‘wild’ data. Secondly, a three-point median-type filtering process is used on each scan. This filter uses a window with a size of three data values to look through the linear array of range values starting from the second value and ending with the second to last value. The first and last data points do not require filtering as they are not needed for determining a vehicle’s dimensions. At each data location in the array, the three-point window looks at the range value and its two neighboring range values on either side and ensures that the current data location holds the median value of the three values. The three-point median filter works effectively on the vehicle data by replacing the odd ‘bad’ range value with a neighboring range value without significantly altering the ‘good’ range values. Appendix B lists the C-code for the three-point median filter algorithm.

After processing the data as indicated, the maximum vehicle dimensions can be determined quite accurately. Once the system is installed and calibrated, measurement accuracies are expected to be 15 *cm* for vehicle width and height, and approximately 30 *cm* for vehicle length. The system has not been tested in heavy fog, rain or snow conditions which may cause additional noise to the system.

Chapter 5

Vehicle Speed Measurement

5.1 The Need for Speed Measurement

The AVDMS requires a high-accuracy speed sensor in order to determine the length of vehicles. The Autosense III laser scanners are used for measuring the height and width of vehicles, as well as, measuring the time for vehicles to pass through the scanning system. A speed sensor is required so that the vehicle's length can be calculated as the product of the vehicle speed and the time for the vehicle to pass through the scanning system. Based on the accuracy requirement of the measured vehicle length, the speed measurement system must be able to measure vehicle speeds with accuracy better than 0.8 *km/h*.

5.2 Speed Measurement Investigations

Many companies were contacted about the need for a high accuracy speed measurement system for the AVDMS. The task of selecting an adequate speed sensor was

considerably difficult and time consuming. The speed sensors and systems suggested by many companies were unable to achieve the 0.8 *km/h* design specification, not appropriate for real-time operation due to lack of adequate computer interface, or not cost-effective due to high development, construction and maintenance costs. The various speed measurement methods suggested and investigated were:

- Microwave Doppler and Laser Radar systems;
- Photo-electric sensors;
- Linescan camera methods; and
- Laser range-finding devices.

Each of these methods was investigated and will be discussed below.

5.2.1 Microwave Doppler and Laser Radar Systems

Microwave radar speed sensors are the most common type of vehicle speed measuring device. The sensors transmit a radio frequency around 24 GHz which strikes the moving vehicle and returns at a different frequency due to the relative motion between the sensor and the vehicle. The frequency difference (Doppler frequency) is measured and is directly related to the vehicle's speed. These sensors have been developed mainly for law enforcement, providing an LED digital display of the target vehicle's speed. However, when considering these sensors for the AVDMS there are a number of problems. The radar sensors are accurate to only 0.8 km/h under the best conditions, significant development time would be required to improve the current sensor interface and develop software to work with the current interface, and extra construction costs would be incurred to mount the sensors as they could not be mounted on the overhead

structure. The manufacturers of these sensors stated that it would not be suitable to measure vehicle speeds with these sensors mounted on the overhead structure due to the large angles between the vehicle travel direction and the sensor's detection path.

Testing was done with two of these sensors, the FALCON hand held traffic radar system manufactured by Kustom Signals, and the VH1 Vindicator radar system supplied by MD Charlton. Both of these sensors were tested on the Royal Oak overpass measuring the speeds of vehicles that passed below. It was observed that speed measurements varied largely with the detection path angles at which the vehicles were measured. At short ranges it was difficult to make speed measurements due to the large angle between vehicle travel direction and the sensor's detection path as stated by the manufacturers. These speed sensors work well for vehicles at reasonable distances but in this case, would not necessarily be able to determine the speed for the correct vehicle or determine the speed of the vehicle at the right location. Based on the information provided by the manufacturers and testing, it was determined that the Doppler radar sensors were not suitable for the AVDMS.

Laser radar sensors were also investigated. These sensors emit short pulses of laser light which reflect off the target vehicle and return to the sensor. Speed measurements are made by measuring the 'time-of-flight' of the laser pulses. These sensors can be aimed more accurately at the vehicles than the microwave radar sensors, allowing the angles at which the speeds are measured to be known more accurately. However, the laser radar speed sensors are accurate to only 1 mile/hour, which is also inadequate for the AVDMS.

5.2.2 Photo-Electric Sensors

Two types of photo-electric sensors have also been tested for speed measurement: through-beam sensor-receiver pairs and retro-reflective (or diffuse reflection) sensors. The principle of speed measurement using the photo-electric sensors is as follows. The sensors are mounted along the road, apart from each other by a known distance. Vehicle presence is detected at each location and the time required for a vehicle to pass the known distance is measured. Vehicle speed is simply calculated as the known distance divided by the measured time.

The through-beam arrangement requires a signal sender on one side of the roadway and a signal receiver on the other side. This method is not suitable since there are two lanes of traffic and vehicles in the second lane would interfere with vehicle presence detection in the first lane. Also, the sensors cannot be mounted between the vehicle lanes.

Retro-reflective sensors transmit a focussed infrared signal that reflects off a vehicle and back to the same sensor. Thus, the two lane problem is eliminated. In order to make speed measurement possible using the retro-reflective sensors, many sensors, placed strategically, would be required to ensure the full length of the vehicle was measured. However, it was discovered while testing these sensors that various parts of vehicles do not reflect the signal adequately for detection. It was also observed that the sensor was close to its maximum operating range at 2 to 3 metres from the vehicles. Any dust or dirt build-up, or bad weather conditions would hamper the success of vehicle detection.

There is another concern with using the retro-reflective sensors. In order to measure vehicle speed the sensors would need to be separated by a known distance (not greater than 10 - 20 *m* to eliminate changes in vehicle speed while timing) and the ve-

hicle travel time between the sensors pairs would be measured. For a vehicle travelling at the maximum design speed of 120 km/h (33.3 m/s), the time to pass through a 10 m interval is 0.3 seconds. In order to measure the vehicle speed to within 0.8 km/h (0.22 m/s), the sensors would have to measure the vehicle's time between the sensors to within approximately 2 milliseconds which is faster than the detection speed of the two sensors. Although most vehicles will be travelling slower than 120 km/h , it would not be easy to measure vehicle speed with accuracies much better than 1 km/h using this sensor configuration.

Moreover, the development, construction, and maintenance costs for this multi-sensor system were considered higher than those for a single sensor speed detection system.

5.2.3 Linescan Cameras

Image processing using line-scan cameras was considered early in AVDMS investigations for the purpose of vehicle dimension measurement. After performing some in-lab testing with a high-speed, high-resolution line-scan camera and speaking with experts in the field, the costs and development time required to develop an adequate system were considered too large. When the speed measuring problem persisted, a much simpler line-scan camera system was considered for speed measurement but again rejected for the same reasons.

5.2.4 Laser Ranging Sensors

Schwartz Electro-Optics, the designer and manufacturer of the Autosense III laser scanners for the AVDMS, was approached about the speed sensor dilemma. They proposed further development of their Autosense I unit to achieve speed measurement

Table 5.1: Summary of Speed Measurement Systems

Type	Problems	Benefits
Microwave Radar	Not accurate enough	Inexpensive
Laser Radar	Not accurate enough	Can be accurately aimed
Photo-Electric Sensors	Unreliable / High Cost	
Linescan Cameras	High Cost	
Laser Rangefinding		Most accurate/Easy to interface

accuracies of 0.34 mile/hour (0.55 km/h). The revised Autosense I would be mounted on the same overhead structure as the Autosense III scanners and would measure speed at both the front and rear of the vehicle to obtain a more accurate vehicle speed and also ensure that vehicle acceleration and deceleration are accounted for. This system uses advanced ‘time-of-flight’ techniques and simple geometry to determine the vehicle speeds. More discussion on the laser range-finding speed measurement system is discussed in section 5.3.

5.2.5 Summary of Speed Measurement Alternatives

Table 5.1 shows a tabular summary indicating the main problems and benefits of the various speed measurement systems investigated. The modified Autosense I system which uses laser range-finding is the only speed measurement system considered suitable for use in the AVDMS. There are many benefits to this solution as itemized below.

- Speeds can be measured to 0.55 *km/h*.
- Only one sensor is required.
- Interface allows for simple integration with the existing system.

- Reasonable initial cost.
- Minimal development, construction and maintenance costs.
- The manufacturer and supplier is Schwartz Electro-Optics (SEO), a company on the leading edge of this technology which has proven itself to deliver a quality product, providing the support required to test and integrate their products. Having SEO develop the speed sensor component would also mean that all of the sensor components would be from one source providing easier overall system maintenance.

5.3 High-Accuracy Speed Sensor System for the AVDMS

The AVDMS has been designed such that the height and width of vehicles are measured directly by the Autosense III laser scanners. However, to determine vehicle length, vehicle speed information is required. The vehicle length is the product of the time required for the vehicle to pass under the scanning structure and its speed. Due to the high scan rate (240 *scans/s*) the time required for a vehicle to pass under the scanning structure can be measured to within 1/240 of a second. To measure the length of a vehicle to within approximately 20 *cm* (initial design requirement), the speed of the vehicle must be measured to within 0.5 *km/h*.

5.3.1 System Description

The revised Autosense I developed by Schwartz Electro-Optics will be mounted on the same overhead structure as the Autosense III scanners and will measure speed

at both the front and rear of the vehicle to obtain a more accurate vehicle speed and to ensure the vehicle acceleration and deceleration are accounted for. Figure 5.1 shows a conceptual drawing of the speed measurement system. The two laser beams are used to detect vehicle presence and thus vehicle speed is measured when vehicle presence is first detected by both lasers and again when vehicle presence is no longer detected. The RS422 interface will provide direct ASCII speed data to the computer which allows for simple integration with existing software.

5.3.2 Error Discussion

As shown below, the error in the length measurement depends on two factors, the error in measuring the vehicle passing time($dL1$) and the error in the speed measurement($dL2$).

$$L = v * t \quad (5.1)$$

$$dL = v * dt + t * dv \quad (5.2)$$

where, dL = length measurement error, dv = speed measurement error, dt = timing error. To determine the maximum length error introduced by the error in the timing measurement, we use a maximum design speed of 120 km/h . The Autosense III scans at a rate of 240 scans/s meaning that the timing resolution will be $1/240 \text{ s}$ or 4.17 ms . Theoretically, the accuracy of the vehicle timing at each end of the vehicle will be $1/2$ the timing resolution, resulting in total timing error of 4.17 ms . Therefore, the vehicle length error introduced by a timing error of 4.17 ms is 14.2 cm as shown below. Length error due to the timing error:

$$dL1 = v * dt \quad (5.3)$$

$$= 34\text{m/s} * 4.17\text{E} - 3\text{s} \quad (5.4)$$

$$= 0.142\text{m} \quad (5.5)$$

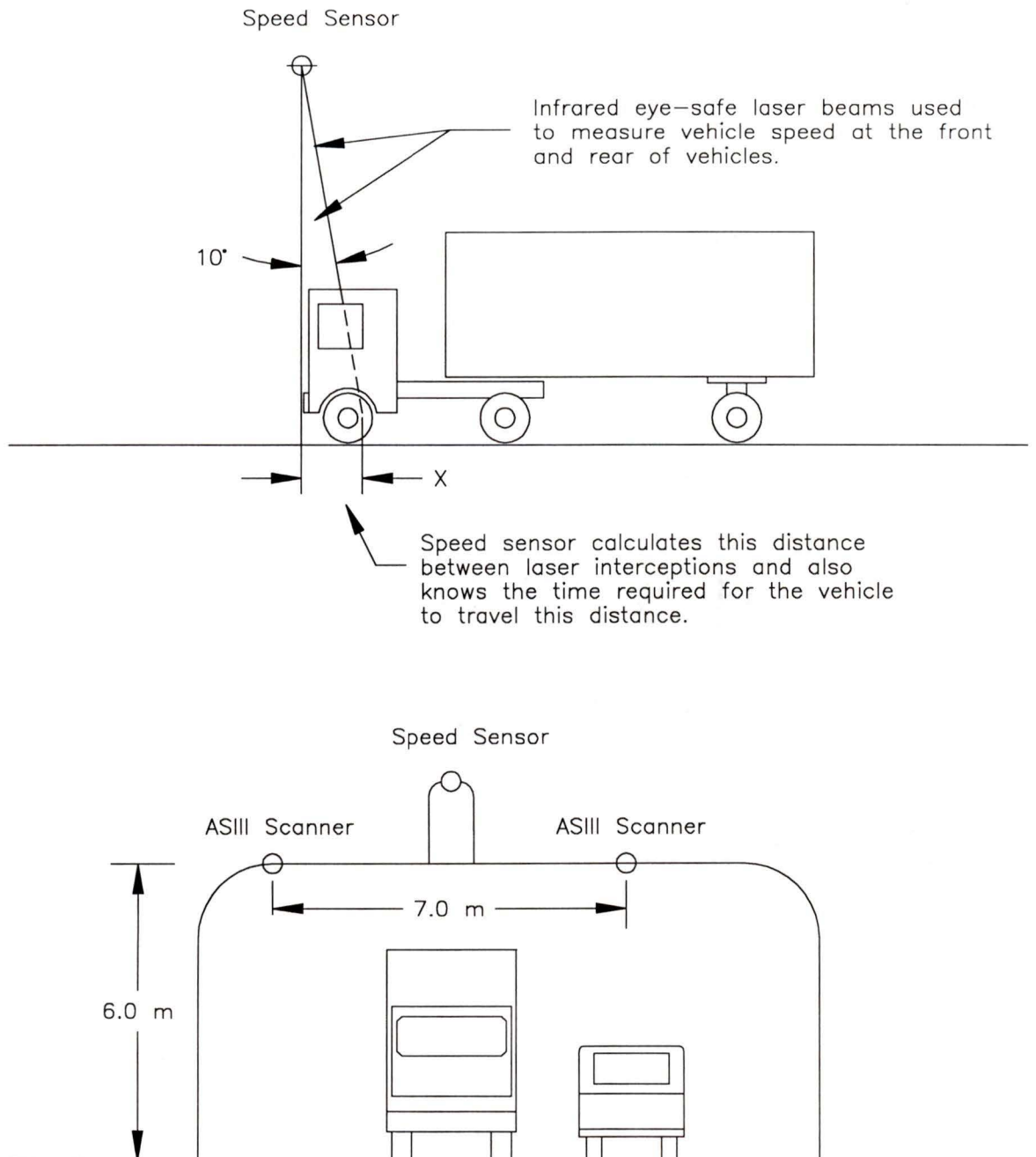


Figure 5.1: Speed Measuring System

To determine the maximum length error introduced by the error in the velocity measurement, we use a maximum design passing time. Using a design vehicle length of 20 *m* and a design speed of 34 *m/s*, the passing time is 0.588 *s*. If we assume that the speed can be measured to within 0.55 *km/h* (0.153 *m/s*), the error introduced due to this speed measurement error will be 9.0 *cm* as shown below. Length error due to the speed measurement error:

$$dL2 = t * dv \quad (5.6)$$

$$= 0.588s * 0.153m/s \quad (5.7)$$

$$= 0.090m \quad (5.8)$$

Therefore, assuming that the speed will be measured to within 0.55 *km/h*, the maximum error in the length measurement will be the sum of the two errors ($dL1 + dL2$) calculated above which is 23.2 *cm*. This error is considered reasonable and will likely be reduced due to vehicles travelling at speeds lower than 120 *km/h* and with most vehicles being shorter than 20 *m*.

5.3.3 Software Development for High Resolution Timing

In order to accurately measure the time for a vehicle to pass through the scanning system, some software development was required to access the 16 bit timer in the PC that ticks at 1.19 MHz. This allows one to get around the lack of resolution in the usual timer for the PC, which runs at only 18.2 Hz. In combination with the contents of the PC's 18.2 Hz clock-tick value, a timer was constructed that runs from 0 to 103090749439 each day. With the high resolution timer, activities can be timed to within approximately 1 microsecond as opposed to worse than millisecond timing

with the normal PC internal timer. Precise frequency values for the timers are as follows:

- PC internal timer interrupt frequency: 18.20648 Hz
- $1/2^{16}$ Overflow timer frequency: 1.19318 MHz

5.3.4 Field Testing the Speed Sensor

The speed sensor has been interfaced with the rest of the AVDMS system and was tested on highway travelling vehicles. This was the first road test for the speed sensor and unfortunately it did not detect the vehicles properly and was unable to make speed measurements. The problem is most likely due to the over-sensitivity of the sensor's receiver. The manufacturer is in the process of testing and adjusting the speed sensor as required. This speed measurement technique has been used by the manufacturer in other functioning products and it will just be a matter of time before the speed sensor is functioning properly.

5.4 Conclusion

The main problem in finding a speed measurement system for the AVDMS was finding a system that could meet the accuracy specification of 0.8 *km/h*. The only system close to this specification is the modified Autosense I which can measure vehicle speeds to 0.55 *km/h*. The modified Autosense I was therefore chosen as the solution for speed measurement.

Chapter 6

AVDMS Hardware Configuration

One of the major benefits of the Automatic Vehicle Dimension Measuring System is the relatively simple hardware configuration. Currently, one 66 MHz/80486 personal computer, a high-speed communications board and 4 Megabytes of RAM are all the hardware requirements for operating the AVDMS. The acquired range data from the Autosense III scanners is transferred through a programmable ACB-530 Advanced Communications Board. The ACB-530 is manufactured by *Sealevel Systems Incorporated* located in Liberty, South Carolina, U.S.A.. This board provides the PC/XT/AT with two high-speed sync/async ports and can be used for a number of sophisticated communications applications. The ACB-530 has a number of features [1]:

- Two channels of sync/async communications using the Zilog 8530 SCC,
- DMA supporting data rates greater than 1 million bit per second,
- Selectable Port Address, IRQ level (2,3,4,5,7,10,12,15),
- Selectable DMA channel (0,1,2 or 3),
- RS-530 / 422 / 485 Interface with full modem control,

- Supports TD, RD, RTS, CTS, DSR, DCD, DTR, TXC, RXC, LL, RL, TM and TSET signals,
- Jumper options for clock source and input/output mode,
- Software programmable baud rate,
- Can be installed in any of the PC expansion slots, excluding J8 on the "XT" and portable.

Direct Memory Access (DMA) is required in the AVDMS to access and process the range data at high rates allowing real-time data acquisition and dimension measurement. The RS422 driver allows error free long distance (up to 5000 feet at 9600 baud) data transfer as opposed to RS232 [1]. The ASIII scanners operate at 4800 rpm with three scans per rotation and 121 byte-size values per scan. This means a data rate of 232320 bits per second for each scanner.

The AVDMS control hardware will most likely be mounted in a road-side cabinet not far from the ASIII scanners and speed sensor. The general AVDMS hardware schematic is shown in Figure 6.1.

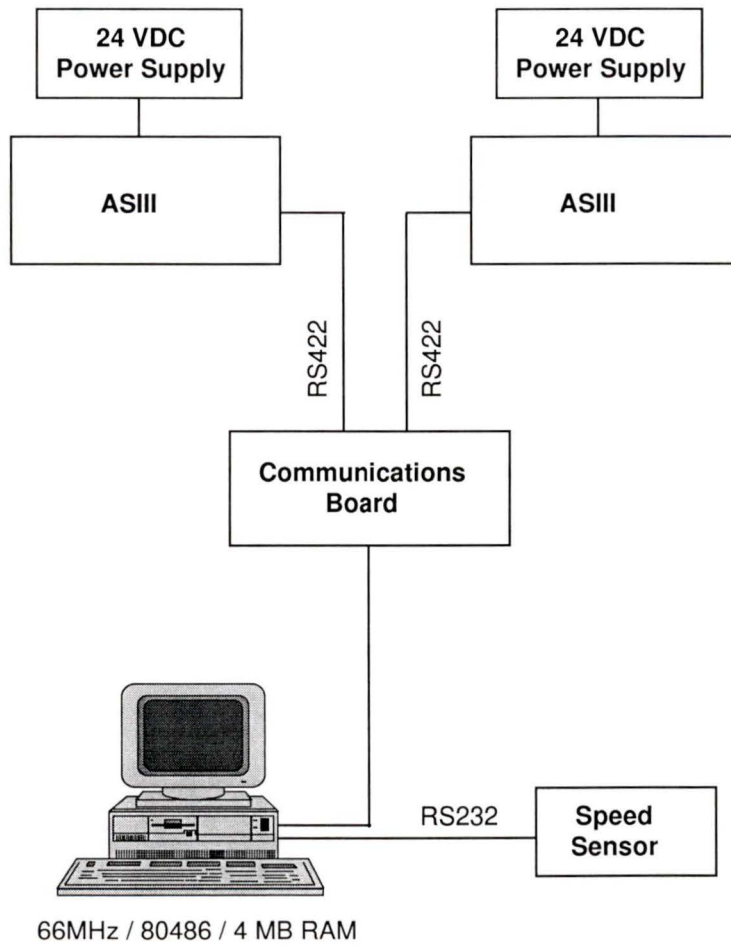


Figure 6.1: AVDMS Hardware Schematic

Chapter 7

AVDMS Functional Modules (Software)

7.1 Overview of AVDMS Software

The AVDMS software package was developed to acquire and process the data from the two Autosense III laser scanners and the speed sensor to measure the dimensions of moving vehicles. It was developed by a team of Computer and Mechanical Engineers from the University of Victoria. AVDMS software acquires and processes range data from two high-speed laser scanning range sensors and a high accuracy laser range-finding speed sensor. The software processes the acquired data in real-time to determine the maximum length, width and height of a vehicle passing through the system at highway speeds.

The software development was divided into two parts. Part I included the acquisition of data from the laser scanners and the speed sensor as well as preparing the acquired data for efficient processing. Part II included processing the range and

speed data to determine vehicle dimensions. The general AVDMS software schematic is shown in Figure 7.1.

7.2 Data Acquisition Software

The data from the Autosense III scanners is handled by a programmable ACB-530 Advanced Communications Board discussed in Chapter 6. Initialization software was required to initialize the ACB-530 board to use two channels with DMA control on each. Separate channels are used for each of the two Autosense III scanners in the AVDMS. A set of 8 memory buffers was set up for each DMA channel to access in a continuous circular fashion. While the AVDMS is in operation, the software monitors the data flow in the buffers and switches between the buffers as required to ensure that data is not lost or over-written. A flowchart of the DMA circular buffer processing is given in Figure 7.2. Furthermore, the flowchart of the subroutines that process the DMA buffers is presented in Figure 7.3. These flowcharts illustrate the procedures for operating the DMA buffers which provide real-time data processing.

Speed sensor data is acquired using an RS232 interface. Serial port interrupt software was developed to capture and store the speed information as it arrives at the serial port. The speed sensor sends vehicle speed information measured at the front and rear ends of each vehicle. The algorithm calculates the average speed of the vehicle and uses the average speed to calculate the vehicle length.

7.3 Data Processing

The raw data acquired from the Autosense III scanners and the speed sensor is processed in real-time by the AVDMS software. The software has the following functional

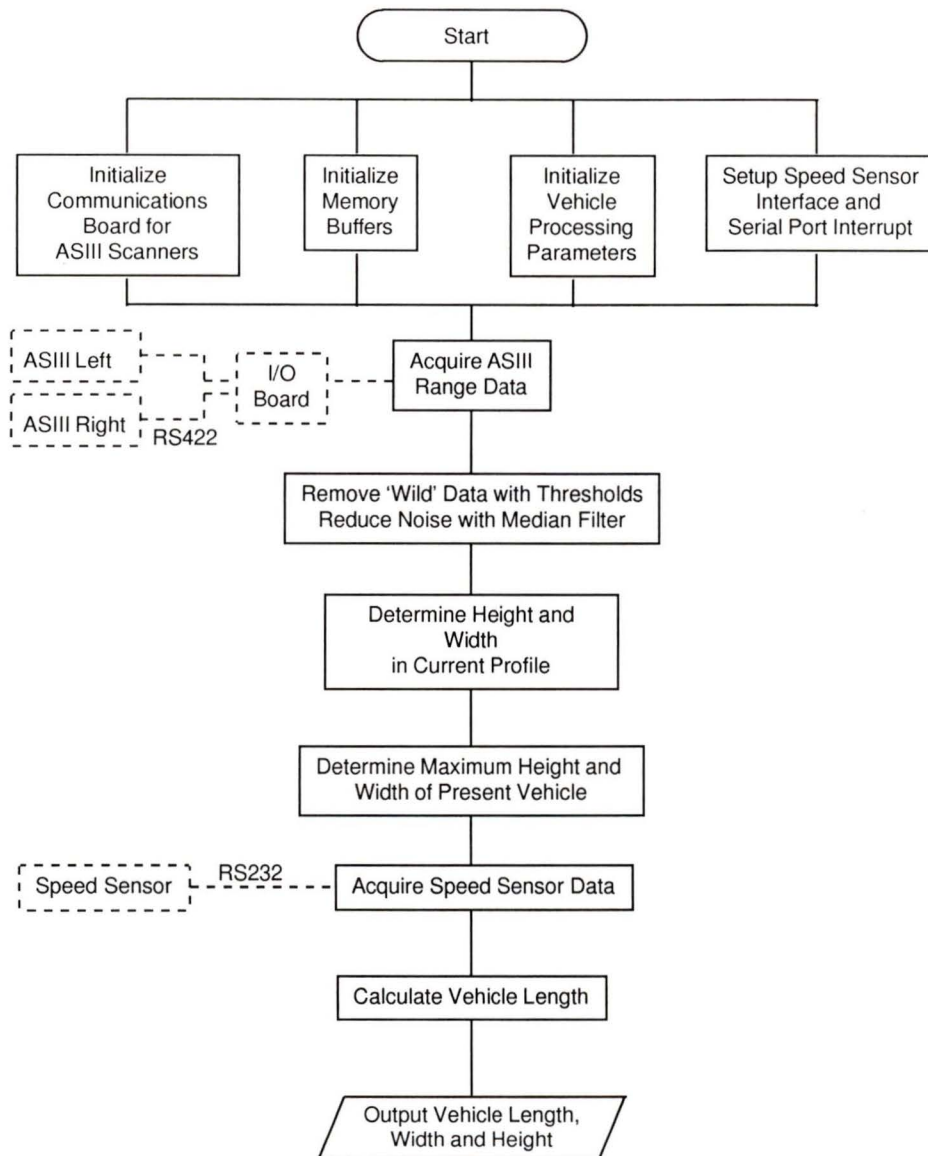


Figure 7.1: AVDMS Software Schematic

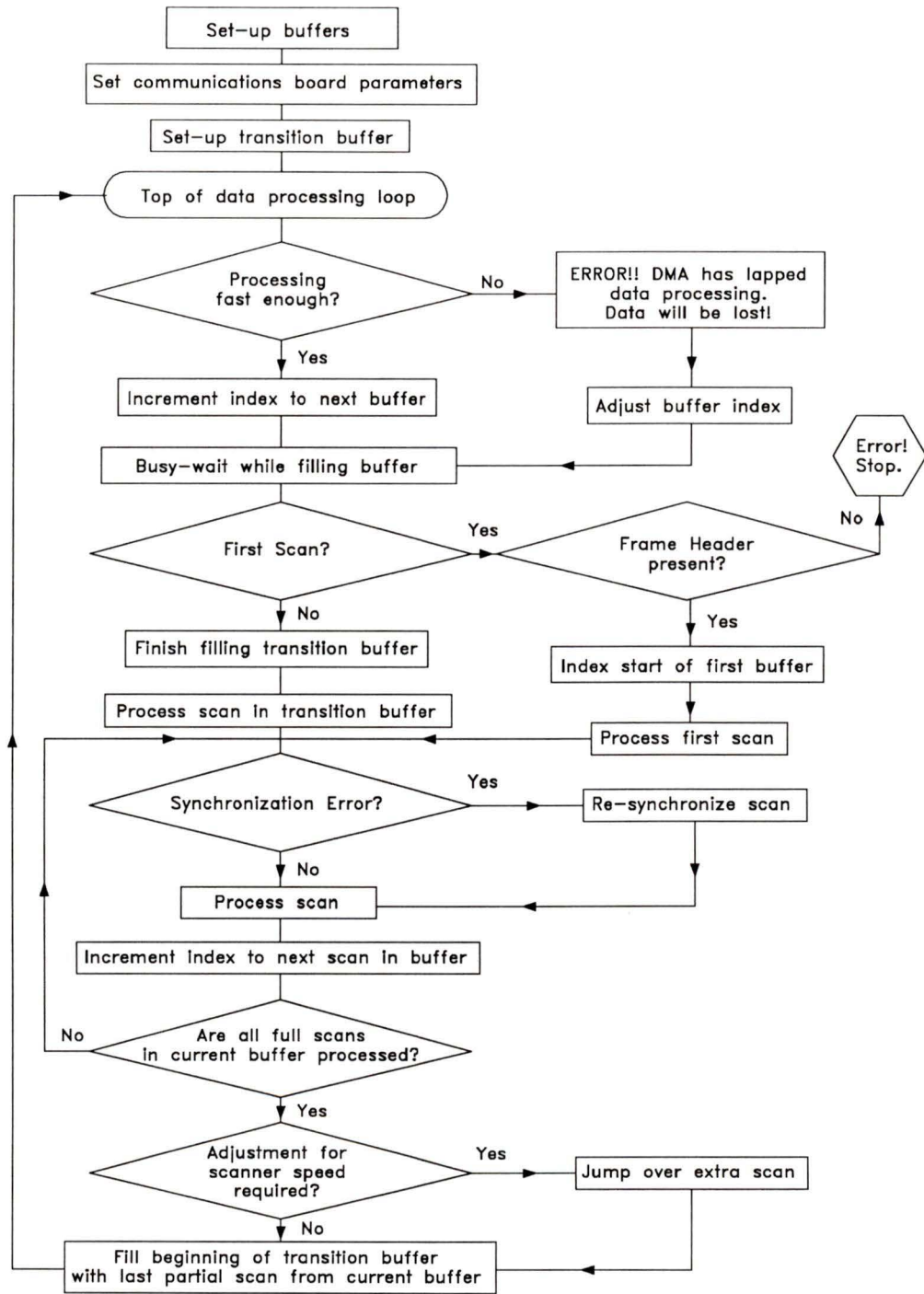


Figure 7.2: DMA Circular Buffer Processing Flowchart

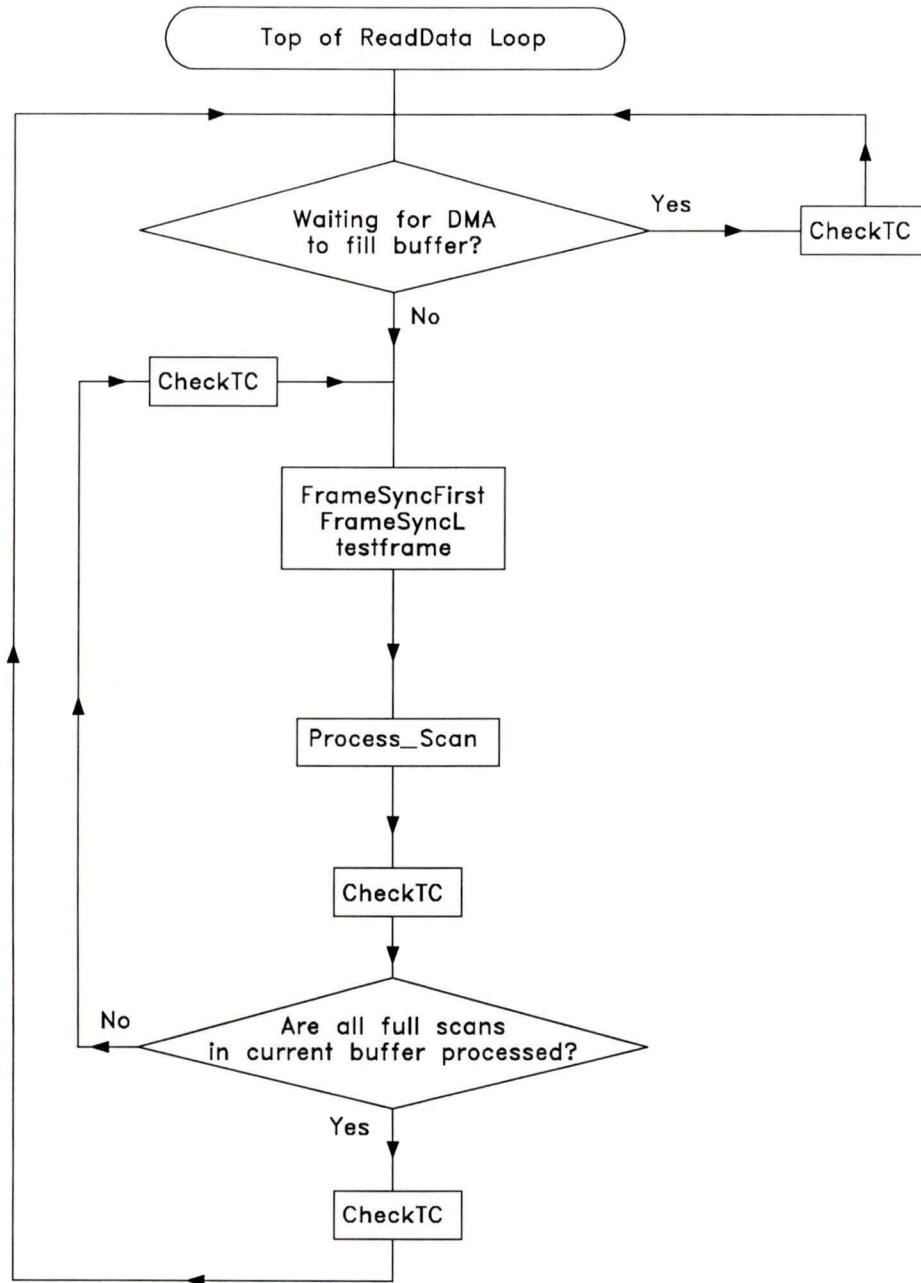


Figure 7.3: Software Modules in Buffer Processing Flowchart

modules:

1. Calculate height of the scanned surface under the profile sensor for each scan.
2. Use Min. and Max. thresholds to remove 'wild' data.
3. Perform three-point median filtering on the height values for each scan.
4. Determine if a vehicle is present in each scan, based upon the elevation change of the scanned surface.
5. Determine the vehicle height after filtering each scan.
6. Calculate the vehicle side location for each scan.
7. Store height and width information for each scan into the vehicle array.
8. Determine when the vehicle is no longer present under the profile sensor.
9. Perform three-point median filtering on the width and height arrays.
10. Determine height and width of the vehicle from filtered arrays.
11. Calculate the length of the vehicle from the sensed vehicle speed and elapsed time during vehicle presence.

The method determines the maximum height and width for each scan, and after the vehicle has completely passed through the system, determines the maximum height and width for the entire vehicle. The vehicle speed and its time to pass through the AVDMS system are measured, and thus its length is calculated.

7.4 Summary of Software Files and Modules

The AVDMS software system was implemented using Microsoft Visual C++. The functionality of various files involved are briefly stated in this section. Due to the proprietary nature of the contract work, the source code and detailed flowcharts are not included in this thesis. Reader may contact the Ministry of Transportation and Highways of B.C. for the technical details.

7.4.1 Project Linked Files

AVDMS.c

- **Read_Data** - This is the main data acquisition module which is responsible for switching DMA buffers and ensuring the buffers are arranged and indexed properly for processing. It also checks whether processing is occurring fast enough to prevent data from being overwritten.
- **Init85230** - The function that initializes the ACB-530 Advanced Communications Board.
- **SetupDMA_AB** - The function that sets up DMA transfers on Ch. A and Ch. B and returns the transfer count from the last buffer filled.
- **FrameSyncFirst** - The function that searches through the current data buffer to locate the first complete scan. The function is used on start up to ensure proper synchronization.
- **FrameSyncL** - The function that searches a given length through the current data buffer to locate the start of a scan. It is used only if a synchronization problem is identified.

- **CheckTC** - The function that monitors the transfer count value of the current buffer to determine if it is time to switch to the next buffer.
- **WaitTC** - A busy-wait version of CheckTC which is used to measure the scan speed of the ASIII scanners.
- **Process_Vehicle** - This module is used to store the height and width data from each scan, identifies when a vehicle has passed through the system, determines the maximum width and height of the last vehicle, calculates the length of the vehicle based on the timing and speed information, and outputs the dimension information.

ProcScan.c

- **Init_AS3_Params** - This is the main routine for handling the user input and calling the other initialization routines below.
- **Get_Init_Values** - This function is used to initialize the global variables by reading the values from the initialization file.
- **Show_Init** - This function is used to initialize and display the global variables by reading the values from the initialization file or by reading from the user specified file.
- **Manual_Init** - This function allows the user to observe the current global variables and make changes to the values. The new values are written to the initialization file.
- **Auto_Init** - This function is used to automatically set the global variables using the scanners.

- **Init_Trig_Arrays** - This function is called during initialization to initialize the cosine and tan arrays used for converting the scan data from the cylindrical coordinate system to the Cartesian coordinate system.
- **Process_Scan** - This function is called by the Process_Vehicle module to determine vehicle presence, maximum height of each scan, and the location of the side of the vehicle based on the location of the fixed scanner. It uses thresholds and three-point median filtering to eliminate undesirable data.
- **Med_Filt_3** - This function performs the three-point median filtering by taking in a pointer to the height values array and uses two or three comparisons to determine the median value for each set of three points through-out the array.

hrt2.c

The program that uses the 8253/8354 timer chip as a microsecond-resolution timer.

dmal.obj

Linkable object-code for DMA commands. This file is compiled for the ‘Large’ memory model.

icom.c

The module contains the code for the interrupt-based communications with the serial port for data acquisition from the speed sensor. It also contains the speed sensor setup routine.

7.4.2 Header Files

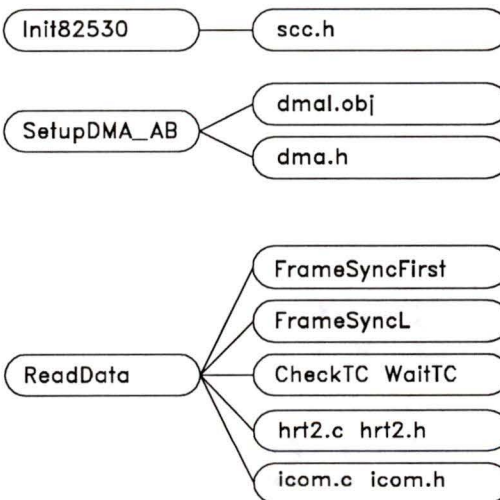
- **ProcScan.h** - This file defines constants and prototypes for **Init_AS3_Params**, **Process_Scan**, and **Med_Filt_3** routines. These routines are used in processing the data to determine vehicle dimensions.
- **scc.h** - This file defines the structure for initializing the serial communications controller and also initializes the values of the structure variable.
- **dma.h** - This file defines constants and prototypes for routines that interface to the 8237 DMA controller.
- **hrt2.h** - This file specifies data types and function prototypes for the High Resolution Timer library (hrt2.c)
- **icom.h** - This file specifies data types and function prototypes for icom.c

Figure 7.4 indicates hierarchy of the stated software system, and the connections to various sub-modules.

AVDMS Software Modules

I. Data Acquisition

AVDMS.c



II. Data Processing

ProcScan.c

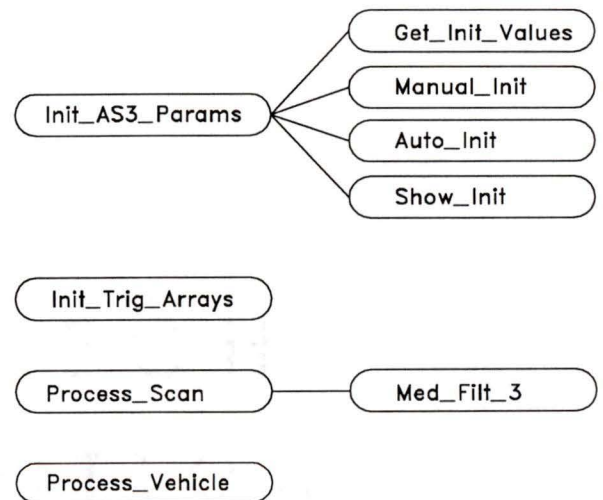


Figure 7.4: Overview of AVDMS Software Modules

Chapter 8

Prototype System and Test Results

The Automatic Vehicle Dimension Measurement System has been tested in its prototype form in the University of Victoria laboratory and on the highway. Unfortunately, failures of the speed sensor have prevented testing of the complete AVDMS system until the submission of the thesis. The ASIII laser scanners have been tested quite extensively, and appear to be performing well. The test results are discussed below. Both the ASIII scanners and the AVDMS software have performed well except for the speed sensor component, as illustrated by the results presented in this Chapter.

8.1 In-Lab Test results

The Autosense III scanners were set up in the laboratory as shown in Figure 8.1 and scanned a surface as shown in the Figures 8.2, 8.3 and 8.4. The solid lines represent the surface and the wall in the background. The dots are the actual range

data measured by the ASIII scanners. The measurements are both consistent and considerably accurate, considering that the laser time-of-flight based range-finding technique is being used at its minimum operating range with maximum range errors.

After this initial lab test, another test was performed with the scanners operating at the typical ranges expected for the AVDMS system. This test was used to determine how accurately the Autosense III scanners would measure the height and width of an object of known size. In Figure 8.5, the width of the object indicated by the solid line is 110 *cm* and the height is 82 *cm*. The acquired range data is also shown. From the acquired range data, the object was measured to have a 115 *cm* width, and a 88 *cm* height. This indicates that the measurement errors were 5 *cm* for the object's width, and 6 *cm* for the vehicle's height. These measurement errors are well within the accuracy specification set out for the AVDMS. Although this test was performed indoors on a non-moving object, it gives a good indication of the accuracy that can be expected from the AVDMS. Movement and lighting will not affect the accuracy of the AVDMS. The physical and geometrical properties of the vehicle's surface have the greatest effect on the range results. However, road tests have indicated that even 'tough' vehicle surfaces can be scanned with good results.

8.2 Road Tests Over Pat Bay Highway

The AVDMS prototype system has been temporarily mounted for short testing periods over Pat Bay Highway at the Royal Oak overpass. Photographs of the test site are shown in Figure 8.6. The ASIII scanners and the speed sensor were mounted using the laboratory-built wood fixtures shown in the photographs in Figure 8.6 and Figure 8.7. Although, the design of the permanent mounting structure is not completed yet, it will have a layout similar to that shown in Figure 4.2. The overhead

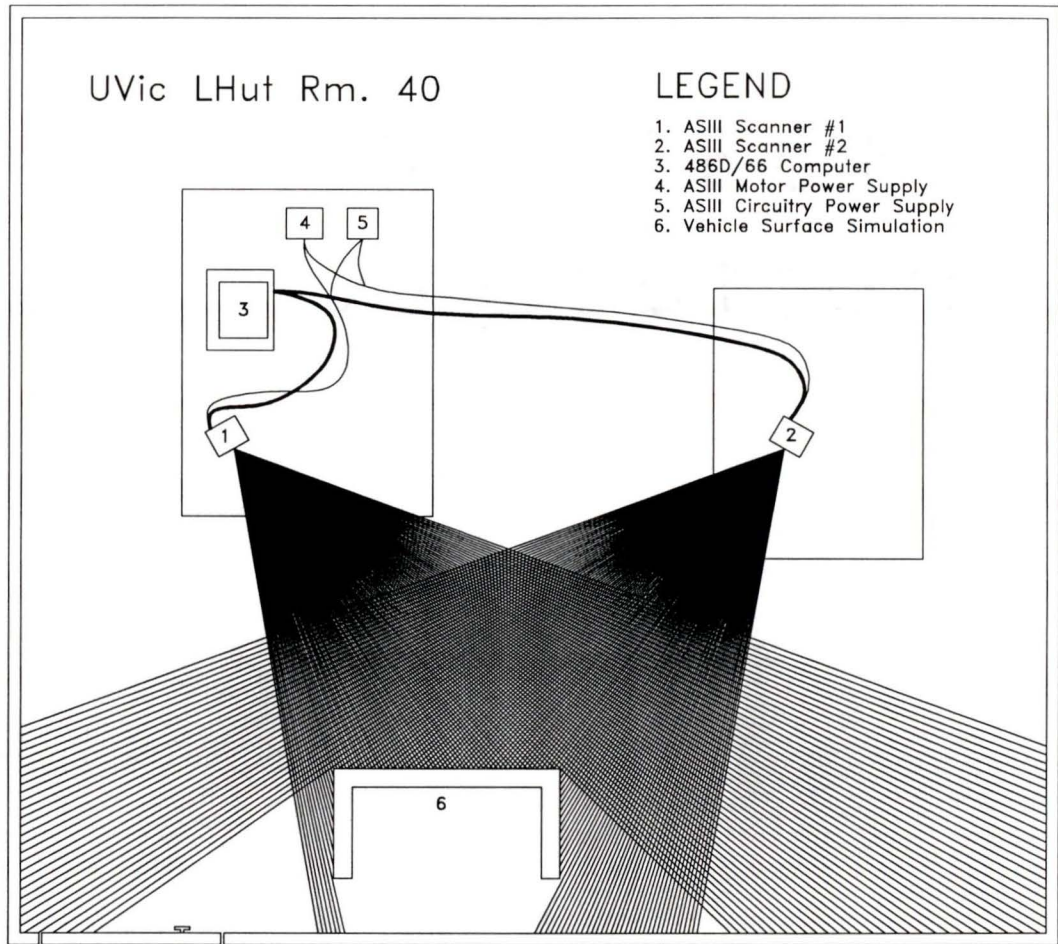


Figure 8.1: UVic Laboratory Setup for Testing the ASIII Scanners

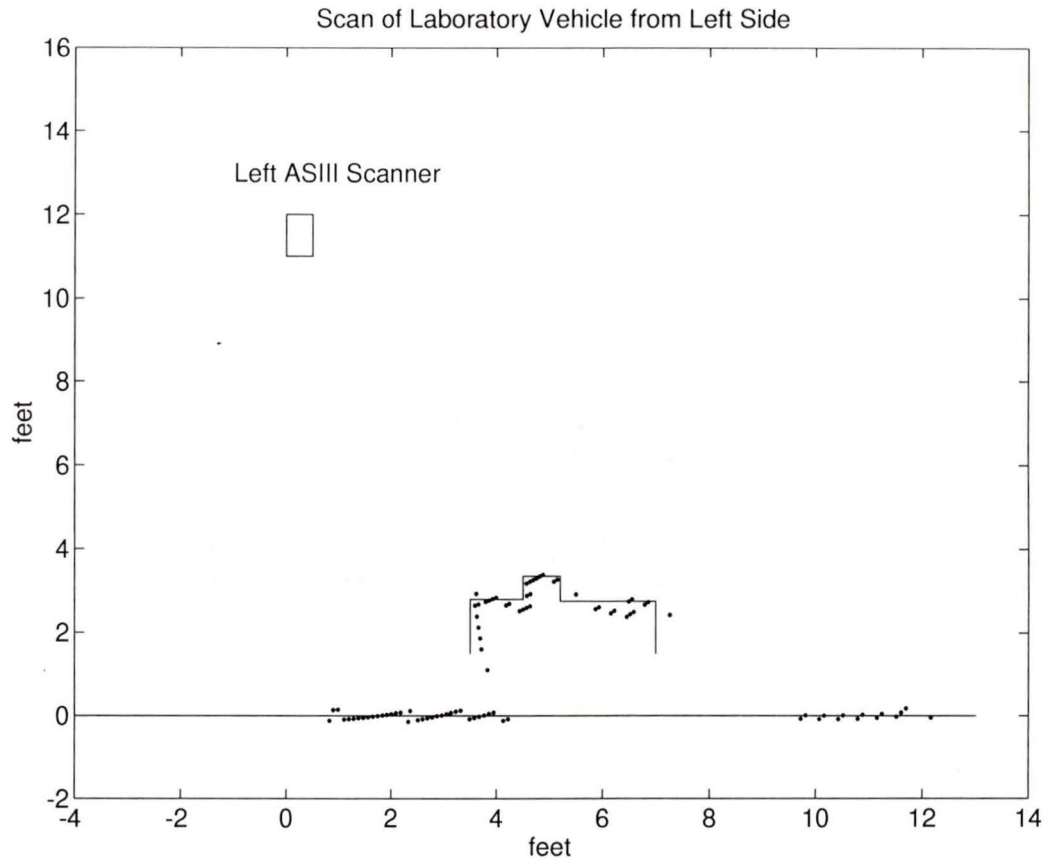


Figure 8.2: Results of Scanning Mock-up Vehicle from Left side ASIII Scanner

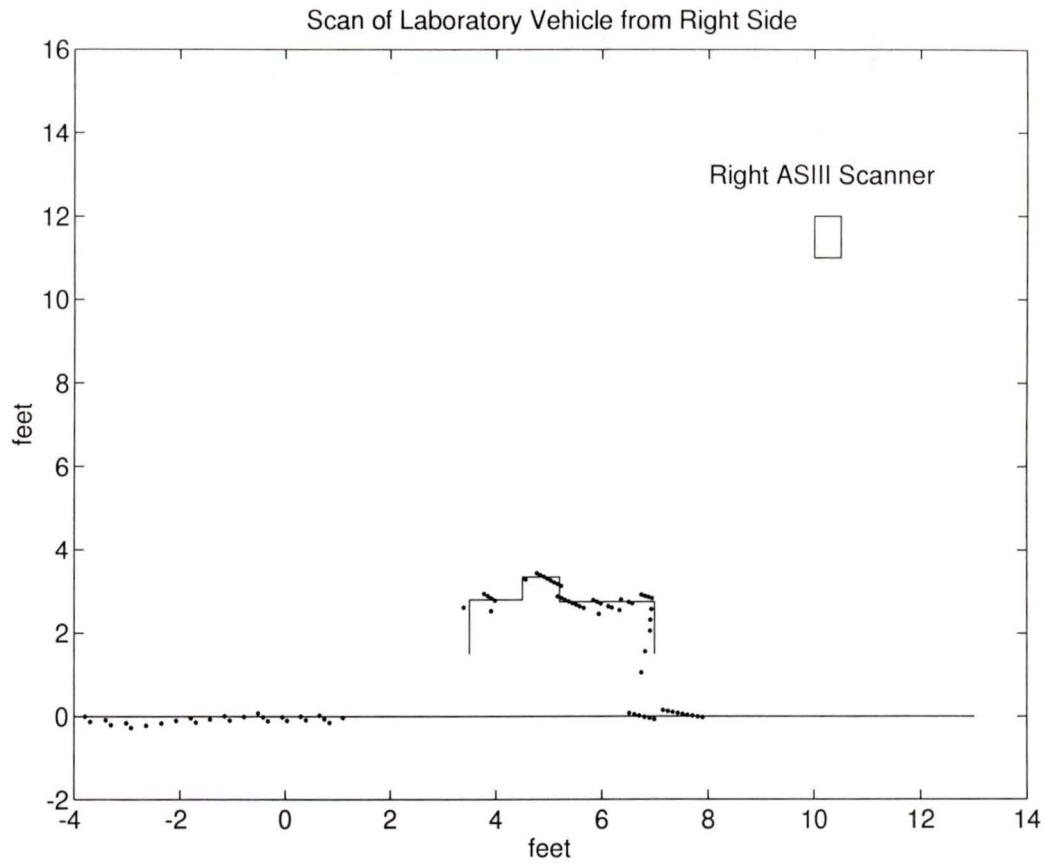


Figure 8.3: Results of Scanning Mock-up Vehicle from Right side ASIII Scanner

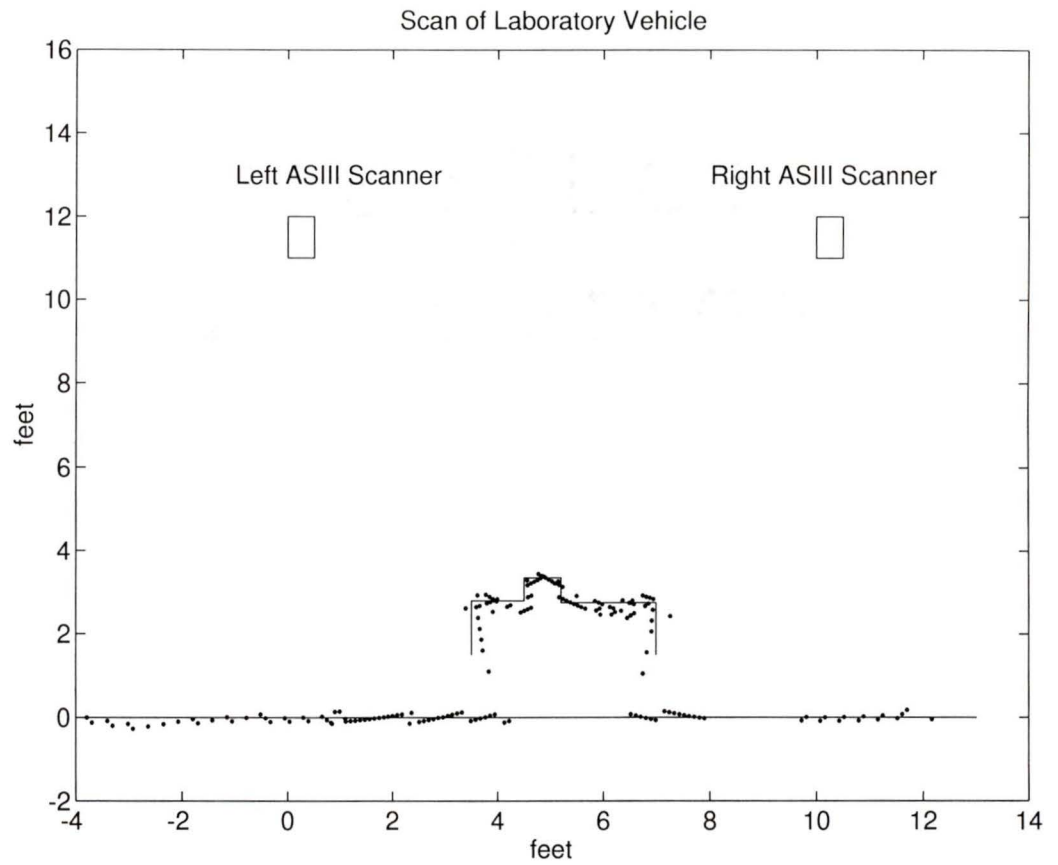


Figure 8.4: Results of Scanning Mock-up Vehicle in Laboratory

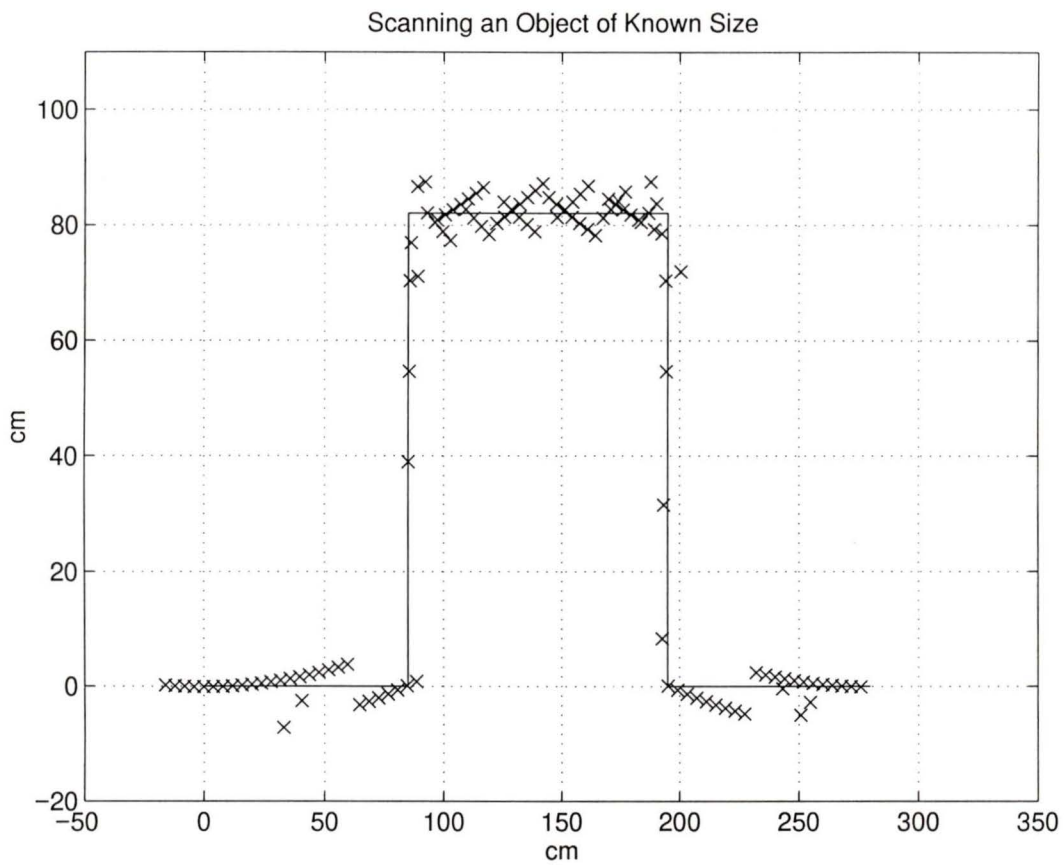
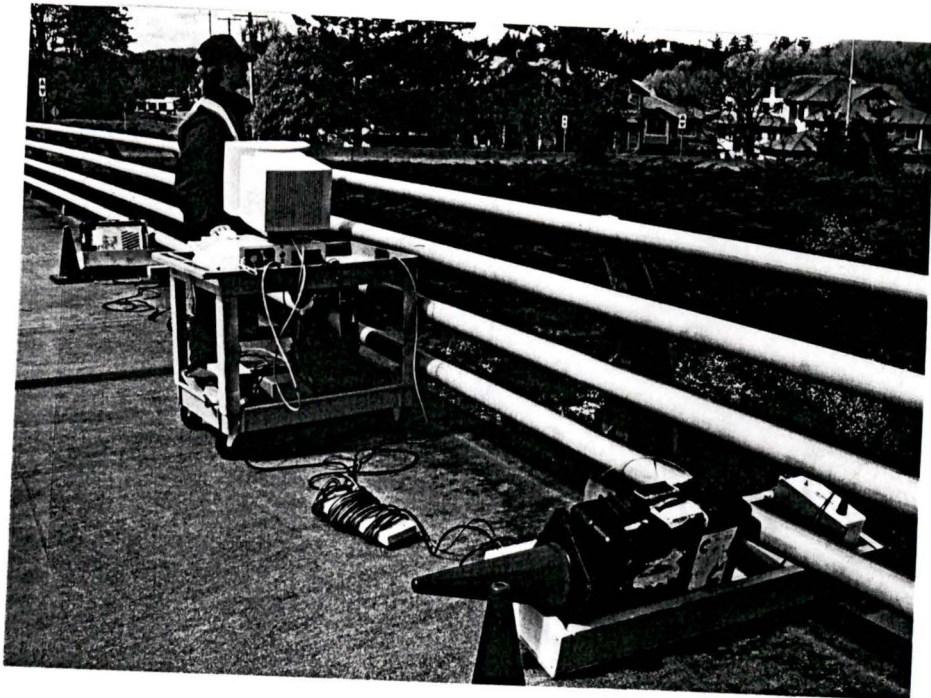


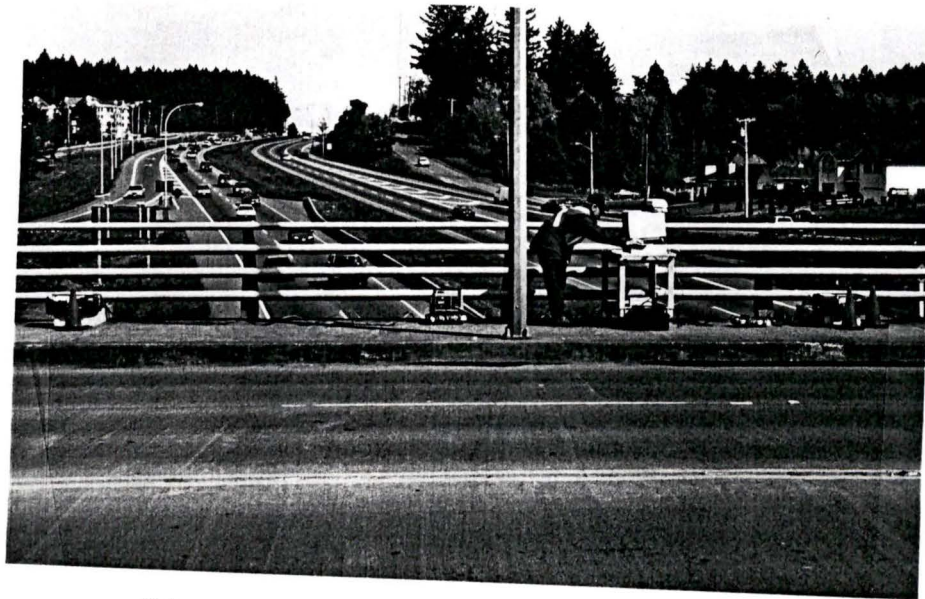
Figure 8.5: Testing the Accuracy of the AVDMS

structure used to mount the ASIII laser scanners and speed sensor will be a standard bridge structure commonly used by the British Columbia Ministry of Transportation and Highways. Covers for the sensors will be provided to protect them from the environment and vandalism.

The Autosense III scanners were tested at Royal Oak overpass many times as indicated in Appendix A. Many of the tests were required during the development stages to determine what improvements or changes were required. Results from the April 19, 1995 road test are included in Figures 8.8-8.14. These figures show a sample of the data collected by the Autosense III scanners. All of the data points plotted in these images are range data points measured by the Autosense III scanners and the location of these points in three-dimensional space is known. From the quality of these 3D images, it is apparent that the dimensions of the vehicles can be determined accurately by analysing the acquired range data. The software system developed in this work fully utilizes the acquired range data to interpret the 3D dimensions of the moving vehicles in real-time. The images below were captured before the speed measurement system was integrated with the Autosense III scanners. Therefore the length scale is shown in terms of the number of scans.



(a) AVDMS System Layout for Road Test



(b) View of AVDMS Setup and Pat Bay Highway

Figure 8.6: Photographs of Road Test Site over the Pat Bay Highway

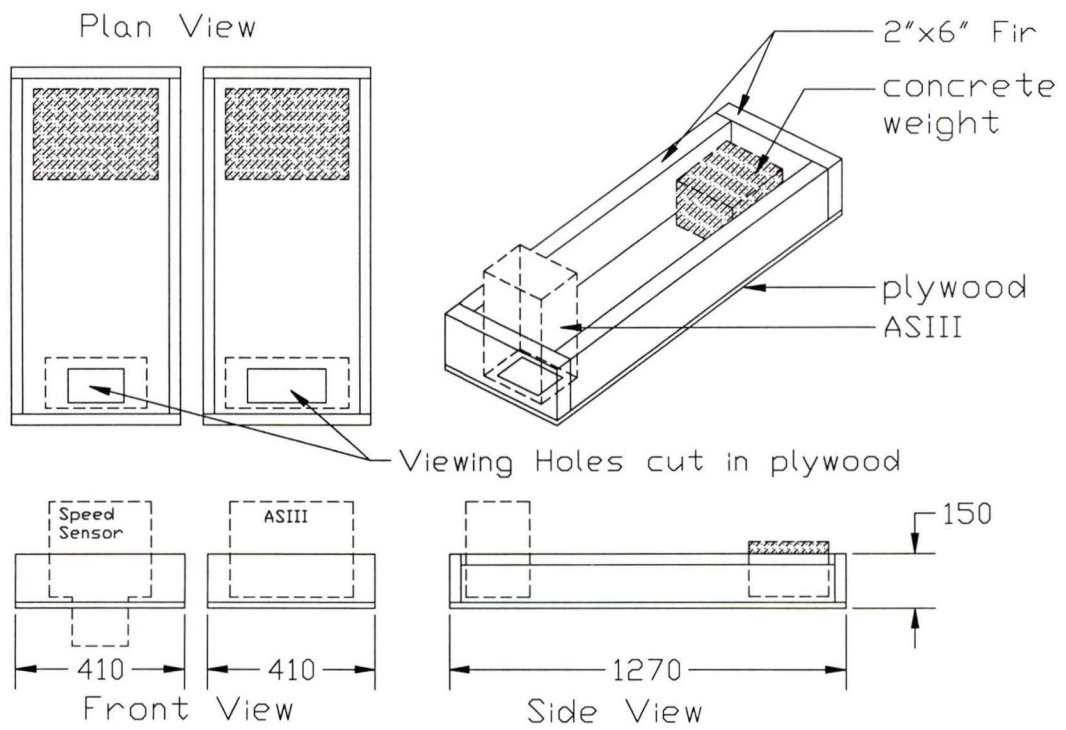
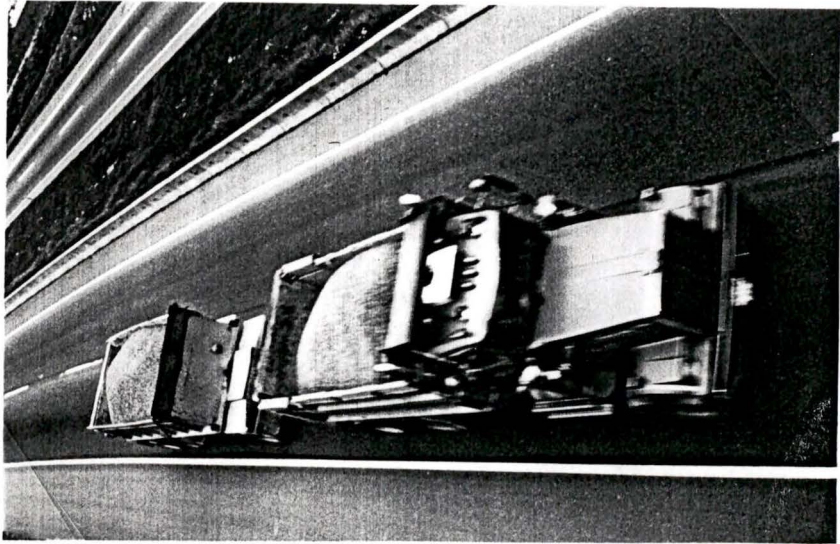
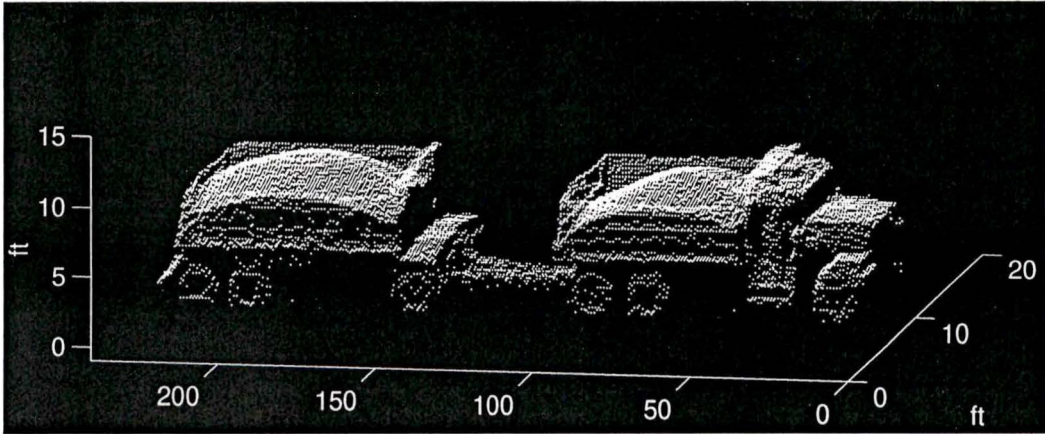


Figure 8.7: ASIII Sensor Mounts (units in mm)

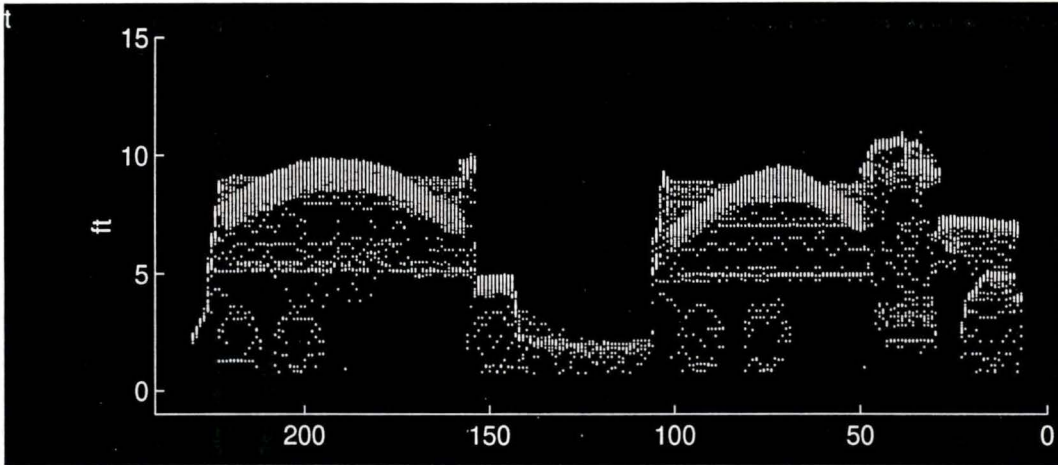


(a) Photograph of the Vehicle

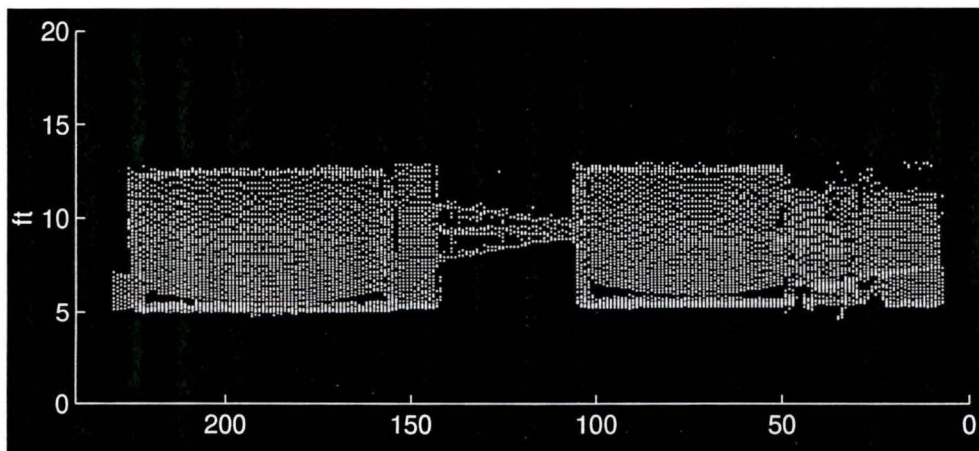


(b) Acquired Range Data of the Vehicle

Figure 8.8: Dump Truck with Pup Trailer Loaded



(a) Side View

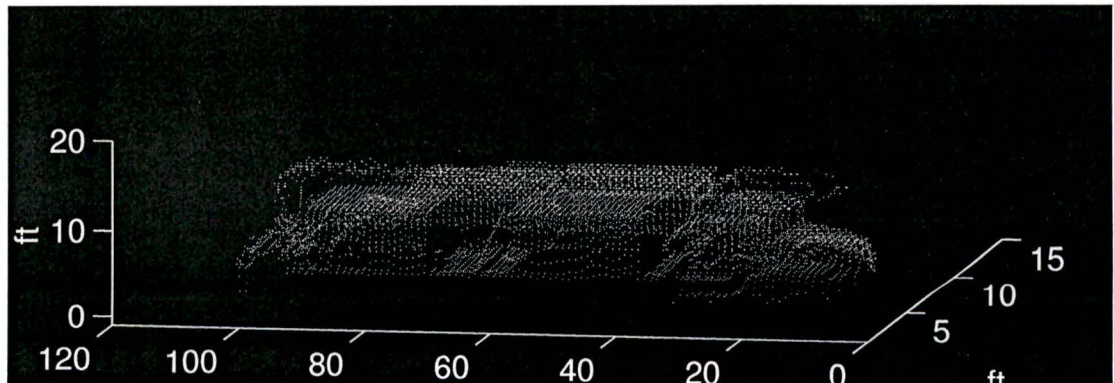


(b) Top View

Figure 8.9: Side and Top Views Of Dump Truck

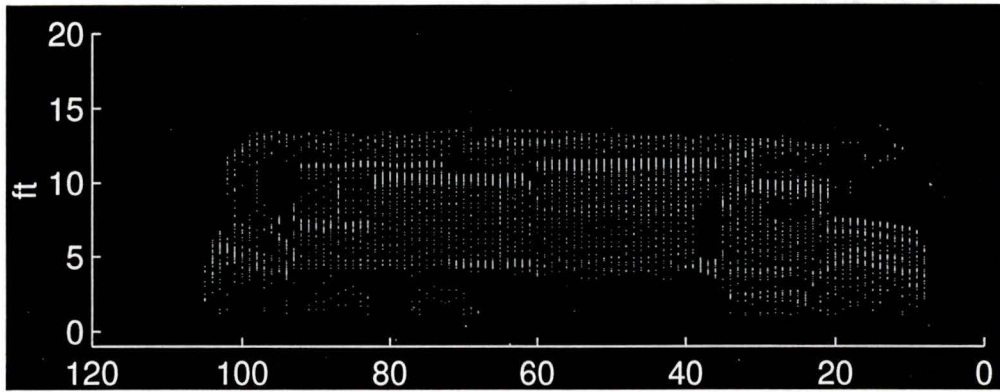


(a) Photograph of the Vehicle

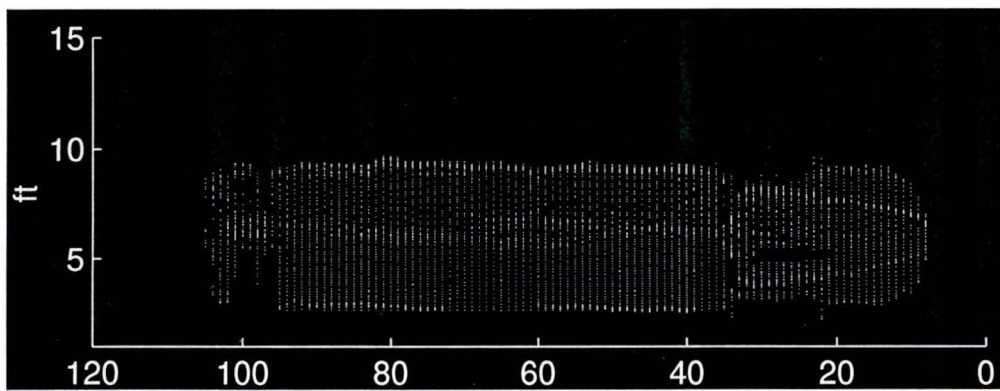


(b) Acquired Range Data of the Vehicle

Figure 8.10: Flatbed Lumber Truck

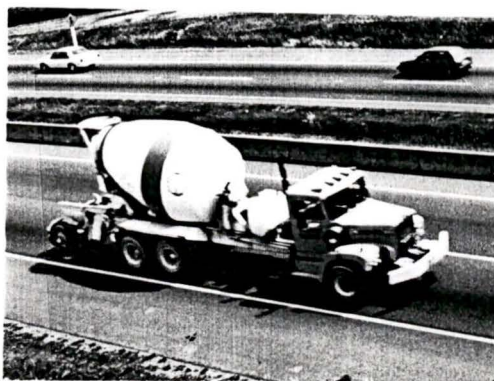


(a) Side View

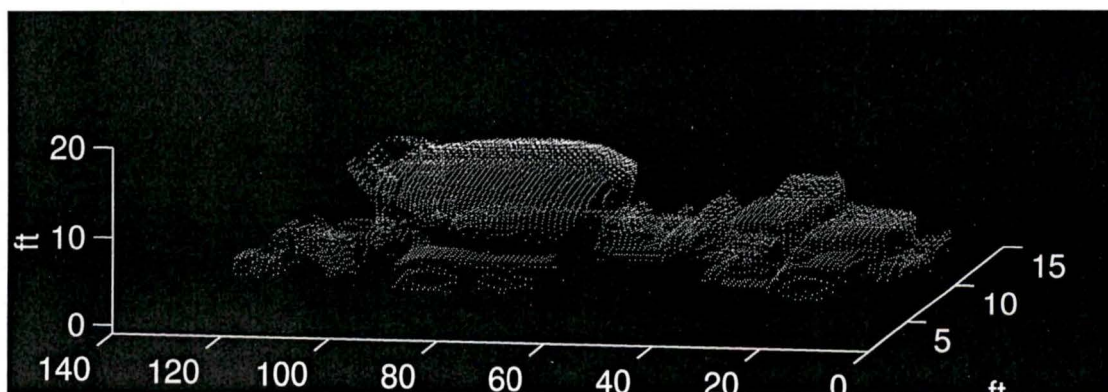


(b) Top View

Figure 8.11: Side and Top Views of Lumber Truck

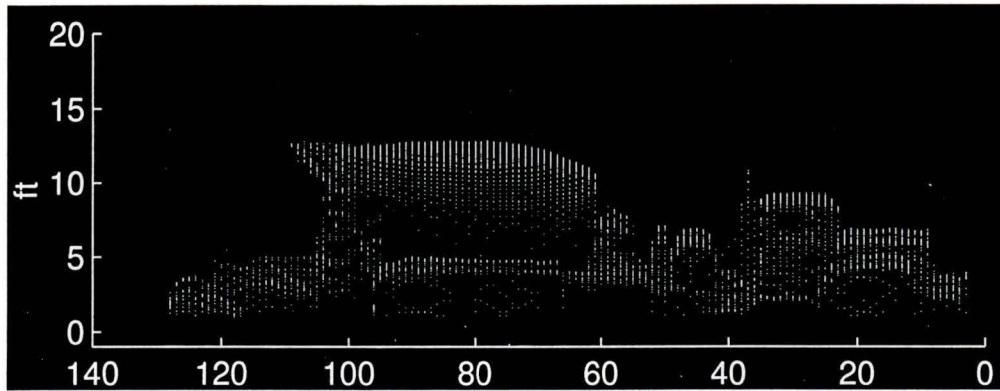


(a) Photograph of the Vehicle

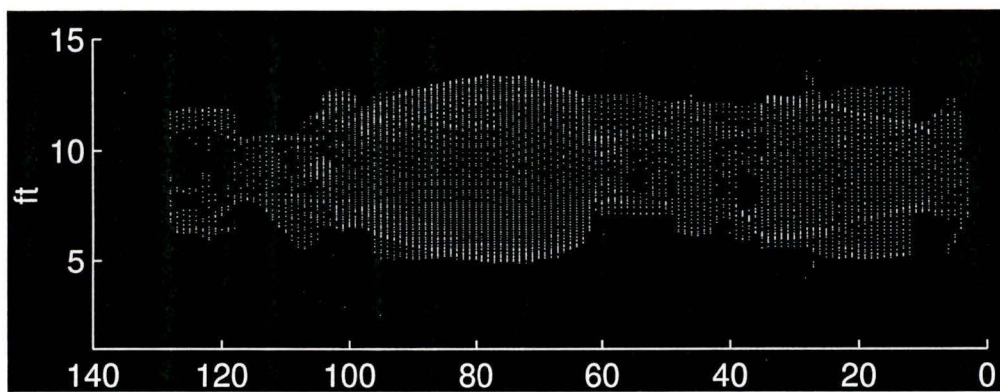


(b) Acquired Range Data of the Vehicle

Figure 8.12: Concrete Truck

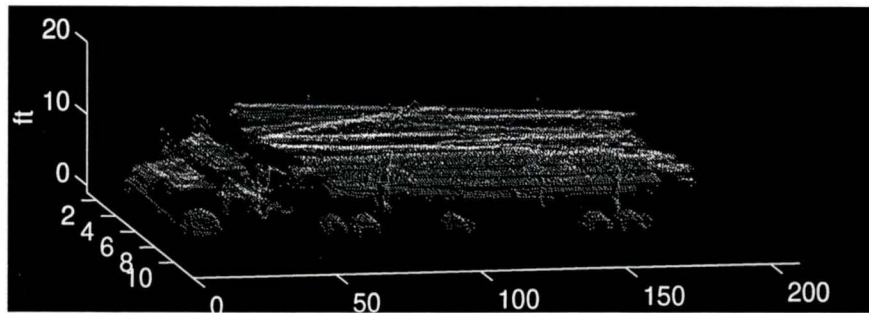


(a) Side View

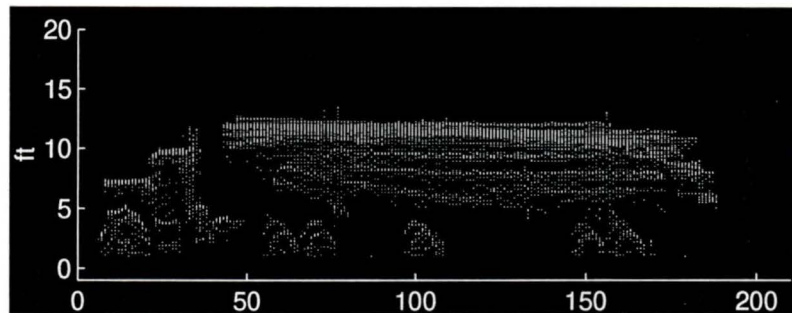


(b) Top View

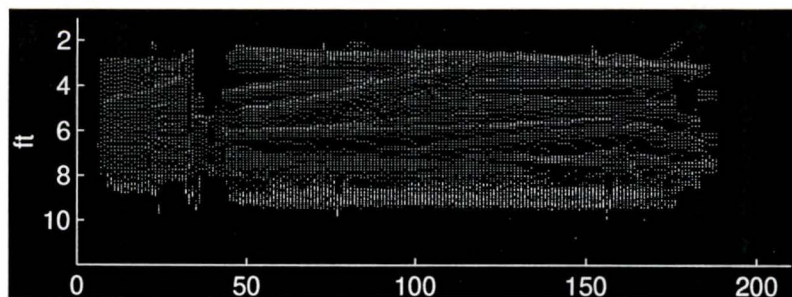
Figure 8.13: Side and Top Views of Concrete Truck



(a) Perspective View



(b) Side View



(c) Top View

Figure 8.14: Loaded Logging Truck

Chapter 9

Other Potential Applications and Future Work

During the tenure of this research, many companies, organizations and individuals have expressed interest in the Automatic Vehicle Dimension Measurement System (AVDMS) project and its application of laser range-finding devices. The AVDMS has demonstrated the capability and usefulness of the technology in a high-speed scanning application to acquire three dimensional range data. The accuracy of the range data can be varied by changing the scan rate. In applications where higher accuracy is required, the scan rate is reduced to allow more measurements at each location. Using the “time-of-flight” based rangefinding technique accuracies are about 1 *mm* at best. For example, a single-shot resolution of 1-8 *cm* can typically be achieved at ranges up to 50 *m*. However, the final precision of the distance measurement can be greatly improved by averaging, the improvement being proportional to the square root of the number of measurements averaged. By averaging 100 successive measurements the final resolution can be improved to the millimetre level. The measurement time is only 100 microseconds for each projected point at a measurement rate of 1 MHz [2].

Therefore, the “time-of-flight” based laser range-finding technique may be suitable for range sensing applications that do not require accuracy better than 1 *mm*.

Currently, shipyards in Great Britain, Spain, the USA, and Finland are using a laser range-finding device as a measurement and guidance system to reduce costly extra fitting and correction work during ship hull construction [2]. Range-finding sensors are also being developed for robots and autonomous vehicles to provide information on depth and surface orientation and to aid in navigation and handling tasks [6].

Due to the superb quality of the range images acquired by the ASIII range finders, the technology has a great potential to serve as the data acquisition tool for the development of an automated vehicle recognition and classification system. This would require geometric model generation and multiple-view fusion which are discussed in Section 3.3, as well as, pattern recognition research. The research also contributes to the better understanding of range-finding devices and their capabilities. The developed technology can be applied to many of the applications where fast-moving objects have to be scanned under hostile outdoor environments.

Chapter 10

Summary

In the last few years, much research and development has been carried out on Intelligent Vehicle-Highway Systems (IVHS) due to increased demand on the current transportation infrastructure. One aspect of IVHS is the development of automatic vehicle classification systems.

The Automatic Vehicle Dimension Measurement System (AVDMS) has been developed by a team of Engineers at the University of Victoria and the British Columbia Ministry of Transportation and Highways. The research and development included in this thesis forms the main part of the AVDMS project. The developed system allows vehicles to be classified based on height, width, length, or overall volume. The AVDMS consists of two high-speed infrared laser scanners, an infrared laser vehicle speed sensor, a high-speed data acquisition board, and an 80486 computer to process the data.

In this thesis, vehicle dimension measurement methods have been discussed, as well as, the processes which led to the selection of the range sensing solution for the AVDMS. Background on range sensing techniques and range data processing have

been provided. A brief overview of geometric model generation and multiple-view fusion was included to help the reader understand range sensing applications and the possibilities for other related applications of this technology. The reader has also been provided with a detailed look at vehicle dimension measurement, including description and specifications of SEO's sensors and scanners, and technical details on the AVDMS method of range data acquisition and vehicle dimension measurement. The vehicle speed measurement problem has been reviewed including an overview of the investigations, a description and comparison of the different measurement methods, and a detailed look at the speed measurement solution. The layout of the AVDMS hardware configuration was presented, as well as, descriptions and flowcharts of the AVDMS software. Results of the AVDMS prototype testing in the laboratory and on the highway with a number of highway travelling vehicles have been provided to demonstrate the capability and usefulness of the system. A number of potential applications for the technology used in the AVDMS have been discussed, as well as, possible future development of the AVDMS.

The AVDMS is to be installed on the approach causeway to the Tsawwassen ferry terminal at Tsawwassen, British Columbia, where it will measure the maximum length, width, and height of commercial and oversize vehicles travelling at speeds up to 120 *km/hr*. Vehicle height and width will be measured to within 15 *cm* and vehicle length to within 30 *cm*. This information will be used for determining the fare for each vehicle based on its volume. Volume is calculated as the product of a vehicle's dimension maximums, that is, the maximum height, width, and length measured by the AVDMS system. The measurements and calculations are made in real-time as each vehicle passes through the system helping reduce queue sizes at the toll booths and improving efficiency.

The automatic real-time vehicle dimension measuring system (AVDMS) developed

in this work is the first system capable of automatically measuring the dimensions of vehicles travelling at highway speeds. The AVDMS system demonstrates new capabilities of laser range-finding devices. The development of this technology may lead to many other applications in the areas of intelligent transportation systems and advanced manufacturing.

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Appendix A

Record of Autosense III Road Tests

Table A.1: Autosense III Testing and Development History

Development Description	Date
ASIII scanners arrived at UVic lab	April / 94
ASIII scanners tested in UVic lab	April-August/ 94
ASIII scanners tested at Royal Oak	April 21 / 94
ASIII scanners tested at Royal Oak	June / 94
ASIII scanners tested at Royal Oak	August 9 / 94
ASIII scanners sent to SEO for improvements	August 12 / 94
ASIII scanners returned after improvements	Sept 28 / 94
ASIII scanners tested in UVic lab	Oct. / 94
ASIII scanners returned to SEO (Failure #1)	Nov. 14 / 94
ASIII scanners received at Uvic after repair	Dec. 17 / 94
ASIII scanners tested in UVic lab	Dec. / 94
ASIII scanners returned to SEO (Failure #2)	Jan. 9 / 95
ASIII scanners received at Uvic after repair	Feb. 8 / 95
ASIII scanners tested at Royal Oak	Feb. 22 / 95
ASIII scanners returned to SEO (Failure #3)	Feb. 24 / 95
ASIII scanners received at Uvic after repair	April-June / 95
ASIII scanners tested at Royal Oak	April 19 / 95
ASIII scanners tested at Royal Oak w/ spd. sensor	June / 95

Appendix B

C-Code for the Three-Point Median Filter

```

/*****
/*  ** Med_Filt_3 **
/*
/*   This function performs the median filtering by taking in a pointer
/*   to the height values array and doing comparisons rather than sorting
/*   to speed up the filtering process.
/*
/*****

unsigned Med_Filt_3(double *height_ptr, double *filt_ptr, unsigned array_size)
{
    double f_array[10];
    unsigned f_index,i;
    double *filt_vector;

    f_index=0;
        *filt_ptr++ = 0; /* set the first value in the filtered array to 0 */

    for (f_index = 1; f_index<array_size-1;f_index++ /* first and last value not changed */
    {
        filt_vector = height_ptr++; /* initialize vector to be filtered */
        for (i=0;i<3;i++)
        {
            f_array[i] = *filt_vector++;
        }

        if (f_array[0] >= f_array[1])
            if (f_array[0] == f_array[2])
                if (f_array[1] >= f_array[2])
                    *filt_ptr++ = f_array[1]; /* order was 321 */
                else
                    *filt_ptr++ = f_array[2]; /* order was 312 */
            else
                *filt_ptr++ = f_array[0]; /* order was 213 */
        else
            if (f_array[0] >= f_array[2])
                *filt_ptr++ = f_array[0]; /* order was 231 */
            else
                if (f_array[1] >= f_array[2])
                    *filt_ptr++ = f_array[2]; /* order was 132 */
                else
                    *filt_ptr++ = f_array[1]; /* order was 123 */
    } /* bottom of 3-pt median filter loop */

    f_index = array_size-1; /* the last value */
        *filt_ptr++ = 0; /* set last value in filtered array to 0. */

    return 1;
}

```

Figure B.1: C-Code for the Three-Point Median Filter

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