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DEVELOPMENT OF AN INTEGRATED SURVEY VEHICLE FOR MEASURING PAVEMENT SURFACE CONDITIONS AT HIGHWAY SPEEDS, VOLUME I: TECHNICAL REPORT

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FOREWORD

Pavement management decisions require a reliable and current data base including information on construction, past maintenance, traffic and accident data, traffic loads and weather exposure, current pavement condition and the rate of past and predicted deterioration. Pavement conditions of interest include roughness, skid resistance, rutting, cracking, and structural integrity. Some of these are being measured, some are estimated by survey crews, and some are not measured at all. Measurement of skid resistance is well understood and is standardized. Roughness is measured in two ways, by profiling and by response type methods. The latter is not very satisfactory and the trend is toward profiling. Condition surveys, i.e., at travel speeds, of all the other measurements are still in the development stage. Collecting the required condition data for a large highway network is an expensive undertaking. Measuring methods which will reduce the cost while at the same time improve the data base, i.e., make more frequent data collection affordable, are essential.

This two-volume report provides a detailed design for a survey vehicle for collecting pavement condition data at highway speeds. The design is based on existing technology and includes roughness profiling, measurement of skid resistance, pavement texture, rut depth, and environmental conditions. An outline for a crack measuring system is included, which, however, was not quite operational at the preparation of this report. It is estimated that a prototype system can be constructed for about $520,000.

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NOTICE

TABLE OF CONTENTS

VOLUME I

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

VOLUME I

LIST OF FIGURES (Continued)

LIST OF TABLES

VOLUME I

TABLE OF CONTENTS

VOLUME II

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF FIGURES

VOLUME II

LIST OF FIGURES (continued)

LIST OF TABLES

VOLUME II

LIST OF ABBREVIATIONS AND SYMBOLS

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
A/D	analog/digital
ASME	American Society of Mechanical Engineers
ASTM	American Standards for Testing and Materials
ATS	automatic test sequence
°C	degrees Centigrade
CAD	computer-assisted drafting
CCD	charged coupled device
cm^2	square centimeter(s)
COPES	Portland Cement Concrete Pavement Evaluation System
CPU	central processing unit
DCP	driver control panel
deg	degree(s)
°F	degrees Fahrenheit
FHWA	Federal Highway Administration
ft	foot, feet
g	gram(s)
G	units of gravity; 1 G = 32.2 ft/s^2
gal	gallon
GPS	global positioning system
h	hour(s)
HPMS	Highway Performance Monitoring System
in	inch(es)
in^2	square inch(es)
in^3	cubic inch(es)
I/O	input/output
IR	infrared
IRI	International Roughness Index
IRSV	integrated road survey vehicle
kg	kilogram(s)
kg/kW	kilograms per kilowatts
kHz	kilohertz
km/h	kilometers per hour
kW	kilowatts
l	liter(s)
LAN	local area network
lb/hp	pounds per horsepower
LTM	long-term monitoring
LTPP	Long-Term Pavement Monitoring Program

LIST OF ABBREVIATIONS AND SYMBOLS (Continued)

m	meter(s)
mA	milliamps
mi	mile(s)
mi/h	miles per hour
mm	millimeter(s)
MR	measurement range
MTS	manual test sequence
N	newton(s)
NCHRP	National Cooperative Highway Research Program
OCP	operator control panel
PCC	portland cement concrete
PLC	Programmable Logic Controller
PNG	percent normalized gradient
PSI	present serviceability index
PTI	Pennsylvania Transportation Institute
RAM	random access memory
RMS	root mean square
s	second(s)
SHRP	Strategic Highway Research Program
SIRST	Survey System for Road Roughness, Rutting, and Topography
SN	skid number
SN_0	theoretical skid number at 0 speed
TTL	transistor-transistor logic
V	volt(s)
VDC	volts direct current
VITC	vertical interval time code

CHAPTER 1. INTRODUCTION

CONTRACT OBJECTIVES

The objectives of this contract were to "determine the requirements and operating characteristics for an integrated pavement condition survey system, prepare a design and estimate initial and operating costs." Upon approval of the conceptual design, a detailed system design was prepared.

SCOPE OF WORK

This project involved reviewing available measuring methods and establishing their operational characteristics and compatibility. The proposed integrated system was to use currently available technology, but work currently under development was to be monitored and considered for incorporation into the integrated system. The researchers completed the following tasks:

A. Identified pavement condition data requiring periodic monitoring, the required quality, and the adequacy of the data collection procedures for the integrated vehicle.

B. Identified equipment available or under development for collecting condition data at highway speeds, showing the degree to which the equipment meets the requirements established under A.

C. Prepared a conceptual design(s) for an integrated pavement condition survey system using the equipment identified under B.

D. Prepared the detailed design of the system described in this report.

PAVEMENT MANAGEMENT SYSTEMS

Pavement management incorporates all activities required to construct and maintain a single pavement or the pavements within a system.[1,2] The objective is to obtain the best possible value from available funds by using a systematic approach in the development and analysis of alternative management strategies for the pavement structure. The purpose of this chapter is to document the data necessary to describe the surface condition of pavements as one of the sets of data needed to implement a pavement management system.

Such systems may be categorized as either network-level systems for managing a network of roadway sections or as project-level systems for evaluating a single roadway section independent of other sections in the same network. The data base on all roadway sections must include information about the pavement structure, traffic volume, and the performance history of each section.[3] With such a data base it is possible to determine the current condition of the road network, to identify which sections are in the worst or best condition, and to predict which sections are likely to be in critical condition in the near future.

At the network level, the data base is used primarily for screening, which requires a limited amount of information about each pavement section. At the project level, different pavement designs and maintenance and rehabilitation strategies are compared.[3] Therefore, the pavement structure must be characterized in detail; material properties, soil conditions, and distress modes must be identified. Also, vehicle types and axle loadings as well as traffic volumes must be known. Computer programs developed for project-level management systems may be used to evaluate different design and rehabilitation strategies to determine the lowest total cost solution for a particular set of circumstances.[4]

REVIEW OF DATA BASE SYSTEMS

Most States have implemented some form of pavement management system and have started to develop data bases. Recently, several attempts were made to organize selected pavement data into nationwide data bases.[5,6] These efforts form the logical basis for the type of data that an integrated survey vehicle should be capable of collecting.

Portland Cement Concrete Pavement Evaluation System--COPES

As part of a study to "develop a system for State and nationwide evaluation of concrete pavement performance, and to demonstrate and refine the system in cooperation with state highway departments," a data base called the Portland Cement Concrete Pavement Evaluation System (COPES) was developed.[7] Data on pumping, joint faulting, joint deterioration, and slab cracking were collected in six States. The data base also includes calculated parameters such as present serviceability index.

The project survey data portion of the file contains skid resistance, distress, and roughness data measured by several devices. Distress classification uses visual survey results to generate data adapted from the manual developed by the Construction Engineering Research Laboratory.[8] The data requirements for the COPES data base are summarized in table 1.

Long-Term Pavement Monitoring Program--LTPP

Because only a limited amount of data on roadway deterioration had been collected since the AASHO Road Test, the Federal Highway Administration (FHWA) in cooperation with the American Association of State Highway and Transportation Officials (AASHTO) implemented a long-term monitoring (LTM) pilot study involving eight States.[5] Recently, an extensive long-term pavement monitoring program (LTPP) was begun as part of the Strategic Highway Research Program (SHRP).[9] It is expected that data on design, materials, soils, environment, traffic, maintenance, and cost will be collected on more than 3,000 test sections throughout the United States and Canada. The data collection guide for LTPP can be found in FHWA's "Data Collection Plan for SHRP Long-Term Pavement Performance Studies."[10] The types of data are very similar to those used in the COPES program (table 1), except that the LTPP data base will include deflection information.

Highway Performance Monitoring System--HPMS

The Federal Highway Administration developed the Highway Performance Monitoring System (HPMS) to "assess the physical condition, safety, service, and efficiency of operation of our highway system."[6] Because the HPMS process supports planners at the State and national level, it is a policy-planning tool rather than a project-level program and treats highway condi-

Table 1. Summary of COPES and LTPP pavement condition data requirements.

Pavement Condition Data Requirements	COPES	LTPP
STRUCTURAL RESPONSE		x
ROUGHNESS INDEX	X	X
RUTTING		X
SKID RESISTANCE	X	X
CONDITION (DISTRESS)	X	X
Jointed Rigid Surfaces		
Blowup	X	X
Transverse Joint Spalling	X	X
Longitudinal Joint Spalling	X	X
Joint Load Transfer Deflection		X
Pumping	X	X
Longitudinal "D" Cracking	X	X
Transverse "D" Cracking	X	X
Longitudinal Cracking	X	X
Transverse Cracking	X	X
Crown Breaks	X	X
Reactive Aggregate	X	X
Scaling, Map Cracking	X	
Transverse Joint Faulting	X	X
Continuously Reinforced Rigid Surface		
Transverse Crack Spalling		X
Longitudinal Crack Spalling	X	X
Transverse "D" Cracking	X	X
Longitudinal "D" Cracking	X	X
Pumping	X	X
Scaling, Map Cracking	X	X
Longitudinal Cracking	X	X
Longitudinal Joint Spalling	X	X
Longitudinal Joint Faulting		X
Punchouts	X	X
Construction Joint Deterioration	X	X
Reactive Aggregate	X	X
Flexible Surfaces		
Alligator Cracking		X
Raveling		X
Bleeding		X
Block Cracking		X
Longitudinal Cracking		X
Transverse Cracking		X
Potholes		X
Reflective Cracking		X

tions in very general terms. Therefore, the HPMS data base has little relevance for the current project.

DATA NEEDS

Data collection requirements in the LTPP program have been used as a guide for determining the data to be collected by the survey vehicle. These requirements plus a review of current practice and the research team's experience led to the conclusion that the following categories of data are needed:

- Roughness, longitudinal profile.
- Rutting, transverse profile.
- Skid resistance.
- Surface condition, distress.
- Structural response.
- Environmental data and location identification.

The data requirements for each of these categories must be considered separately at the project and network level (see table 2); these requirements were reported in an interim report on SHRP project H103.[11] In current practice, network-level data are being used to identify pavement sections that no longer adequately serve the public on the basis of functional serviceability using criteria such as roughness or present serviceability index values (PSI).[6] After the sections that require rehabilitation are identified, project-level data are obtained to establish rehabilitation strategies.

Longitudinal Profile (Roughness) Data Needs

Roughness is measured by response-type instruments such as the Mays Meter or by profiling equipment.[11-14] While either type of equipment can be used to calculate PSI, profiling equipment is preferred because it allows in-depth analysis and it is not sensitive to changes in test vehicle characteristics.[15,16]

Table 2. Pavement management data categories.

Type of Data	Importance at Network Level	Importance at Project Level
Roughness	Primary	Limited
Rutting	Primary	Primary
Skid Resistance	Primary	Primary
Surface Condition (Distress)	Limited	Primary
Structural Response	Limited	Primary
Environmental	None	Primary

Roughness data are primarily of interest at the network level. At the project level, roughness information is sometimes used to evaluate the effectiveness of rehabilitation measures. In addition, some agencies require longitudinal profile data as part of the quality acceptance program for new or overlay construction. Profiling devices are more suitable for these purposes.

Transverse Profile (Rutting) Data Needs

At the project level, rutting information is useful for determining the type of rehabilitation required because rutting can be the result of either pavement wear or, for AC pavements, plastic deformation within the pavement structure. Some States currently collect rut depth data at the network level and use the information for selecting and prioritizing projects. Excessive rutting may lead to water accumulation and then to hydroplaning.[17]

Skid Resistance Data Needs

Skid resistance is a primary factor in highway safety and is included in the data collection program of SHRP. Many States pursue very active skid resistance survey programs.[9,18] The widely accepted standard for measuring skid resistance is ASTM Standard E 274.[19] To be useful for inventory purposes, the skid resistance measurements should be corrected for daily and seasonal variations to an end-of-season skid number.[20]

Although skid resistance is traditionally measured at 40 mi/h (64 km/h), there is a definite need to determine in some manner the change in skid resistance with speed.[21] The speed gradient, the change in skid resistance with speed, can be obtained directly from skid tests at several speeds, or it can be estimated from texture measurements or from "spinup" tests in which the test wheel accelerates from lockup to free-rolling.[22]

Surface Condition (Distress) Data Needs

Data that characterize the surface condition of the pavement are currently derived from visual observations and include a large number of specific parameters (see table 1). Distress may be manifested by cracking, raveling, shoving, and other defects.[23] Many types of distress still require evaluation by a human observer, though efforts are underway to automate the interpretation through electronic or photographic imagery.[24-27] Usually one or two persons are required in the field, although a few States use photologging procedures to analyze the distress information from the photographs.[28,29] Photologging is probably more accurate than direct visual evaluation, but it is a costly and time-consuming procedure.

Distress condition survey data are useful at the project level for determining the cause of pavement failure. At the network level, the visual or manual distress information is voluminous and costly to collect. Therefore, simpler procedures are more useful, e.g., assigning qualitative "sufficiency" ratings that categorize pavement sections into "good" or "poor" groups to prioritize them for rehabilitation.

Automated digital imaging equipment will allow analysis of very large amounts of data and may extend the use of distress condition surveys to the network level. If the data can be collected at highway speeds, the data needed at the network and project levels can be obtained in a single survey with different types of analysis applied at the two levels.

Structural Response (Deflection) Data Needs

The structural condition of the pavement is usually evaluated by measuring deflections. At the project level, deflection data may be used in empirical design procedures to determine overlay thickness.[30,31] In more sophisticated, mechanistically based design procedures, deflection measurements can be used to characterize the material properties of the various pavement layers.[32-34] Suitable equipment does not currently exist for network level deflection measurements; therefore, deflection data are collected mostly at the project level (see table 2).

Environmental and Other Data Needs

Environmental data may be required to calculate or adjust certain parameters. For example, pavement temperature is required to adjust skid resistance measurements to an end-of-season value.[22] A number of other data could be included in a pavement condition data base, including those for texture, noise characteristics, cross slope, longitudinal grade, and reflectance. Some of these parameters are outside the scope of this project; others cannot or need not be part of the data base per se, but position or location measurements are required to verify where specific measurements were made.

MEASUREMENT NEEDS

Each of the data needs discussed in the previous section implies a set of measurements. These measurements are discussed in the following paragraphs.

Longitudinal Profile (Roughness) Measurements

Typically, PSI is determined from a vertical measurement taken by a response-type roughness meter with a resolution of 0.125 in (3.2 mm). However, longitudinal profiles are measured by methods that conform to ASTM Standard E 950, which states that a minimum resolution of 0.01 in (0.25 mm) is necessary.[19]

Longitudinal profile measurements are used primarily to calculate roughness index values or other measures of pavement serviceability. The FHWA's Highway Pavement Monitoring Program requires that roughness be measured in in/mi.[5] AASHTO recommends that this measure be obtained from a quarter-car simulation. Routine inventory data can be successfully calculated from profile measurements with an accuracy and precision of ±0.01 in (±0.25 mm). (Exceptions do occur: Documenting Los Angeles "freeway hop" required accuracy and precision of ±0.001 in (±0.025 mm), but such accuracy is not normally required for survey work.[13]) With sufficient resolution, longitudinal profile sensors can also yield information on pavement macrotexture, but devices with such resolution are not within the scope of this project.

Longitudinal profiling systems could also be used to measure faulting in portland cement concrete (PCC) pavements. Faulting is considered excessive when it is greater than 0.25 in (6.5 mm).[7] Therefore, vertical measurements at 3-in (76-mm) intervals and with a sensitivity of ±0.05 in (±1.25 mm) would be adequate. A special software program would be needed to analyze longitudinal profile data to extract this information. Requirements for the smoothness of new construction vary from State to State, but typical specifications call for deviations from a planar surface to be less than 0.125 in (3.2 mm) in a 10-ft (3-m) span.[35] This would dictate that profile measurements have an accuracy and precision of ±0.05 in (±1.25 mm). Table 3 presents an overview of accuracy, precision, and frequency requirements for longitudinal profile measurements.

Transverse Profile (Rutting) Measurements

Transverse profile measurements are needed to establish pavement rutting as a measure of pavement distress and to calculate hydroplaning potential. For this purpose, transverse profiles measured with an accuracy and precision of 0.1 in (2.5 mm) is considered adequate.[36] To compute the hydroplaning potential from transverse profile measurements it is, however, necessary to know the cross-slope of the pavement and it should be certain within 0.01 in (0.25 mm).[37]

Table 3. Measurement needs.

	Measurement				Calculated Parameter		
Measurement	Units	Precision	Accuracy	Frequency	Units	Precision	Accuracy
Structural Response (Deflection)	in	0.001	0.001	50 ft (1,000 ft)*	in	0.001	0.002
Roughness, Longitudinal Profile	in	0.01	0.01	3 in	in/mi	0.1	1.0
Rutting, Transverse Profile	in	0.01	0.01	3 ft	in	0.1	0.1
Skid Resistance	SN	1	1	1 set per 0.25 mi	SN	1.0	2.5
Surface Condition Distress	resolution, in	0.1	0.1	1 set per 0.25 mi	qualitative resolution, in	0.01	0.01

* 50 ft on project basis; 1,000 ft on network basis.

1 in = 25.4 mm
1 ft = 0.305 mm
1 in/mi = 15.8 mm/km
1 mi = 1.61 km

Skid Resistance Measurements

For locked-wheel skid resistance measurements, ASTM Standard E 274 serves as the guide to the method, the required component tolerances, the acceptable accuracy and precision, and calibration procedures.[19] Because the skid number (SN) is speed sensitive, such measurements give only a single skid number during one pass of the survey vehicle and require that the vehicle travel at 40 mi/h (64 km/h). Knowledge of pavement texture, or the parameters that define it, is required if the SN-speed relationship is to be calculated. The measured SN should be normalized for the transient effects of weather, etc., to the end-of-season value. Alternatively, if the SN at other speeds is of interest, the survey vehicle can be operated at those speeds.

Texture can be measured by methods now under development to obtain the information necessary for normalization and the computation of the SN-speed gradient. For the survey vehicle, the spinup method was chosen for obtaining the SN-speed relationship directly. This method is currently being refined in the FHWA study, "Development of an Implementation Package Entitled Skid Resistance Manual" (FHWA Contract No. DTFH61-88-C-00058), which will also establish the limits of necessary and achievable accuracy and precision for it to be used in place of locked-wheel measurements at several different speeds.

Surface Condition (Distress) Measurements

A minimum resolution of 0.1 in (2.5 mm) is necessary to adequately resolve surface features. If the surface is evaluated visually, the resolution is entirely a function of the evaluator's ability to rate and distinguish different features, even if the evaluation is not done directly but from photographs of the pavement surface. Photographs must have an accuracy and precision of 0.1 in (2.5 mm) of the required resolution, whether the photographs are analyzed visually or by some digital technique.

Structural Response (Deflection) Measurements

To fully describe the response of pavements to imposed loads, it is necessary to obtain four or five deflection measurements at 1-ft (.305-m) distances from the applied load so that the deflection basin can be determined. Deflection measurements require a minimum precision and accuracy of ±0.0005 in (±0.0125 mm). An ASTM standard for deflection measurements that is now being developed is expected to call for measurements on flexible and rigid pavements every 500 to 1,000 ft (150 to 300 m) on a network basis and every 200 to 500 ft (60 to 150 m) on a project basis.[38]

Environmental Measurements

Certain environmental data must be obtained at the time of pavement condition measurement. Air or pavement temperature is needed for skid resistance evaluation. These temperatures are measured adequately with an accuracy and precision of ±1.0 °F (±0.6 °C).[22]

Miscellaneous Measurements

Proper spatial identification of the evaluation measurements is necessary when they are collected and transmitted to the data base. Sections of pavement should be marked by geographical coordinates, stations, or the link-node method of location reference. Subsections should also have geographical coordinates, an assigned number, or mileage within a section. Individual measurements should be recorded by date and subsection or by geographical coordinates or mileage within the subsection. Other miscellaneous measurements or data include the name of the operator(s), time of day, vehicle speed, and type of pavement.

CHAPTER 2. EQUIPMENT CURRENTLY AVAILABLE FOR USE WITH THE SURVEY VEHICLE

The purpose of this chapter is to identify equipment available or under development that can be used to obtain the measurements needed to satisfy the data needs outlined in the preceding chapter. Specifications of the identified equipment were evaluated to determine if they could meet the requirements of the data needs and if the equipment is suitable for use in the integrated survey vehicle. In addition, the following questions were asked:

- Are the different measurements compatible and can they be made concurrently?
- What mechanical or electronic interference between the different measurements can be expected?
- What are the minimum acceptable sampling rates for the different measurements?
- What are the expected system and operating costs?
- What vehicle is suitable for the required dynamic performance, space, and power?
- What transducers are available for survey measurements at highway speeds?
- What recent technology in signal processing, data analysis, and recording can be reliably operated on a survey vehicle?

After this project began, NCHRP Synthesis 126, "Equipment for Obtaining Pavement Condition and Traffic Loading Data," was published.[39] It reviews current equipment and data requirements for roughness and texture, friction, surface distress, structural capacity, and traffic volume and traffic weight. The report also discusses equipment, operational characteristics, cost, safety features, and maintenance requirements. Another useful report for the purposes of this project is the FHWA report on the Roadway Evaluation Equipment Workshop held at The Pennsylvania State University in 1984.[40]

Currently available equipment is sufficient to develop an integrated road survey vehicle (IRSV) that can measure rutting (transverse profile), roughness (longitudinal profile), skid resistance, and surface condition. Structural response equipment is not sufficiently developed at this time to meet the requirements of this project; therefore, this capability was not included in the design of the IRSV.

LONGITUDINAL AND TRANSVERSE PROFILES (ROUGHNESS AND RUTTING)

Equipment for measuring longitudinal and transverse profiles is reviewed together because both involve identical methods of measurements; they both measure the distance between vehicle body and pavement.

Measuring Pavement Roughness

To select a device for measuring the road surface profile, features such as accuracy, resolution, and method of operation were considered. Most profiling vehicles use accelerometers to establish body motion. Only the sensors used to measure vehicle-to-road surface distance variations are discussed here. Only noncontact sensors that measure this distance are considered because mechanical sensors have been shown to have limited life and reliability.

Selcom Optocator. This device, which consists of a gauging probe and a central processing unit (CPU), uses a laser light source to create an illuminated spot on the road surface. The gauging probe consists of a laser light source, a camera unit lens and detector, and analog and digital processing electronics. The CPU consists of a power supply, a receiver that collects data from the gauging probe, a data processor, and data output.

The light source is maintained at constant intensity. Because it is switched on and off 16,000 times per second, ambient light will have no effect on the system. The Optocator sees a portion of the scattered light on its detector, which is composed of a photodiode array as shown in figure 1.[14] This device has a fast response for measurements of pavement elevation from a vehicle traveling at normal speeds. It has a measurement range (MR) of 0.3 in (8 mm) (minimum) to 20.2 in (512 mm) (maximum) with a resolution of 0.025 percent of the MR at an accuracy of 0.1 percent. The standoff distance can be

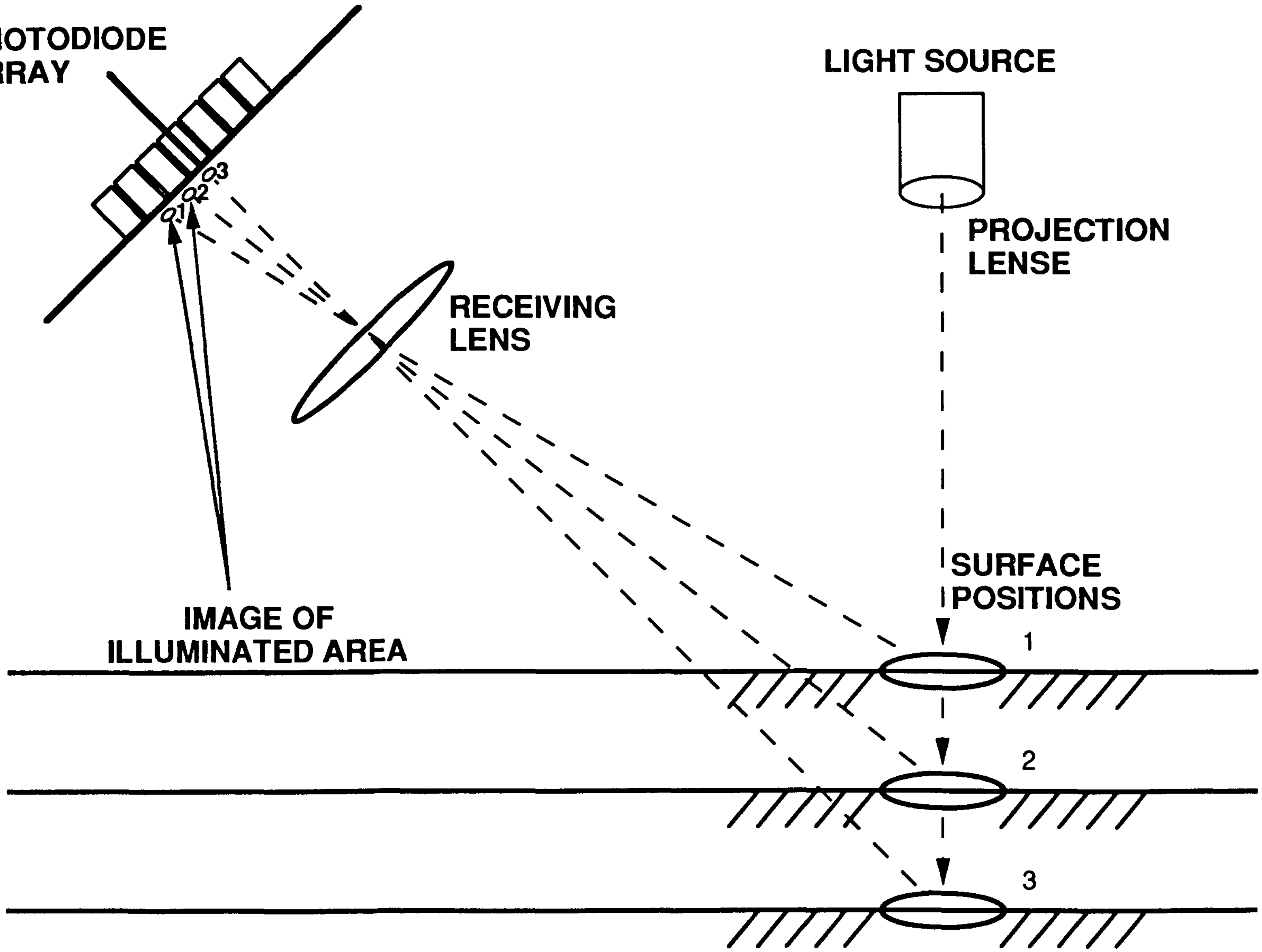

Figure 1. Selcom laser light noncontact lens displacement transducer design.

as much as 40 in (1 000 mm). Since the spot size is only 0.02 in (0.5 mm), the signal must be filtered, or averaged, over an area the size of the footprint of a tire to eliminate macro- and megatexture when it is used for profiling roughness.

IR Sensor. This noncontact device employs an infrared-light (IR) transducer developed in an FHWA project, "System for Inventorying Road Roughness, Rutting, and Topography (SIRST)."[37] Its height measurement concept (figure 2) is similar to that of the Optocator, except that the IR sensor uses two detectors instead of the photodiode array of the Optocator. A change in road height changes the image position on the two detectors, which are placed at complementary angles on either side of the light source. Two detectors are required to eliminate the sensor's sensitivity to color. The latest version of the unit is self-contained and produces both digital and analog signal outputs. The unit requires 12 VDC at 4 amps, and its case dimensions are 3 by 7 by 24 in (76 by 178 by 610 mm). It has a maximum standoff distance of 13-3/4 in (350 mm) and a 3-in (75-mm) measuring range with an accuracy of 0.012 in (0.3 mm). The unit's dual lens assembly produces a 3-in (76-mm) spot. The outputs are not truly linear but are easily linearized in digital computations.

Law White Light Sensor. This device consists of a light source, a projection system, an optical receiver, and a processing unit. The projection system focuses a rectangular light beam onto the road surface. The optical receiver receives an image of the beam diffusely reflected from the road surface. The displacement of the road surface is computed from the measurement of the angle at which the incandescent spot is viewed by the rotating scanner (see figure 3). This device has fast response, a measuring range of 2.83 in (72 mm), a resolution and accuracy of 0.01 in (0.250 mm), and a standoff distance of about 10.5 in (270 mm). The Model 690 digital noncontact road profilometer by K. J. Law Engineers, Inc. incorporates this sensor.

All of the described noncontact devices can be used to evaluate the longitudinal profile of the road as well as the transverse profile. Table 4 compares these devices. Because the white light sensor requires complicated computation to obtain the transverse profile, this device was not considered

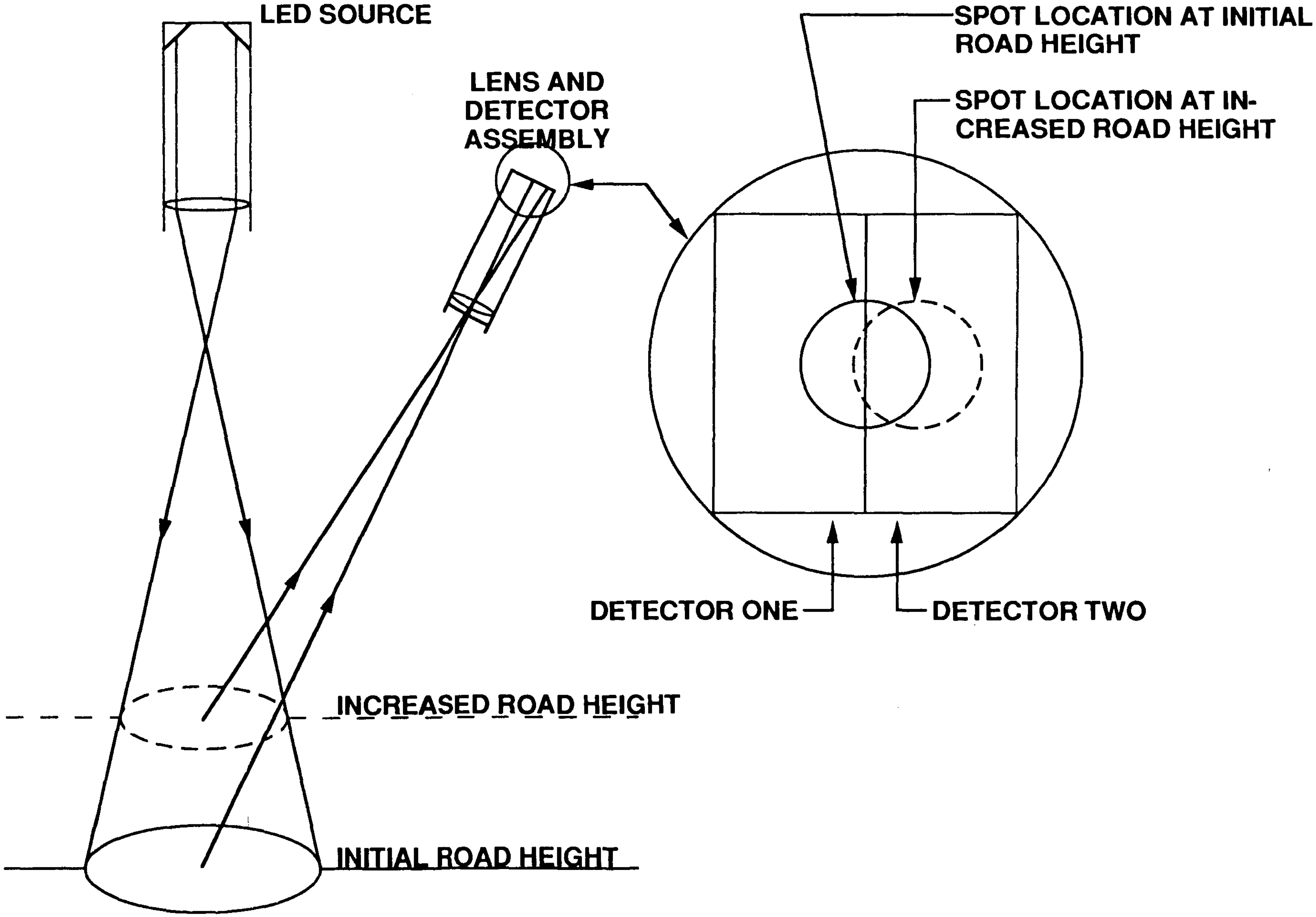

Figure 2. FHWA-SIRST infrared height-measuring technique.

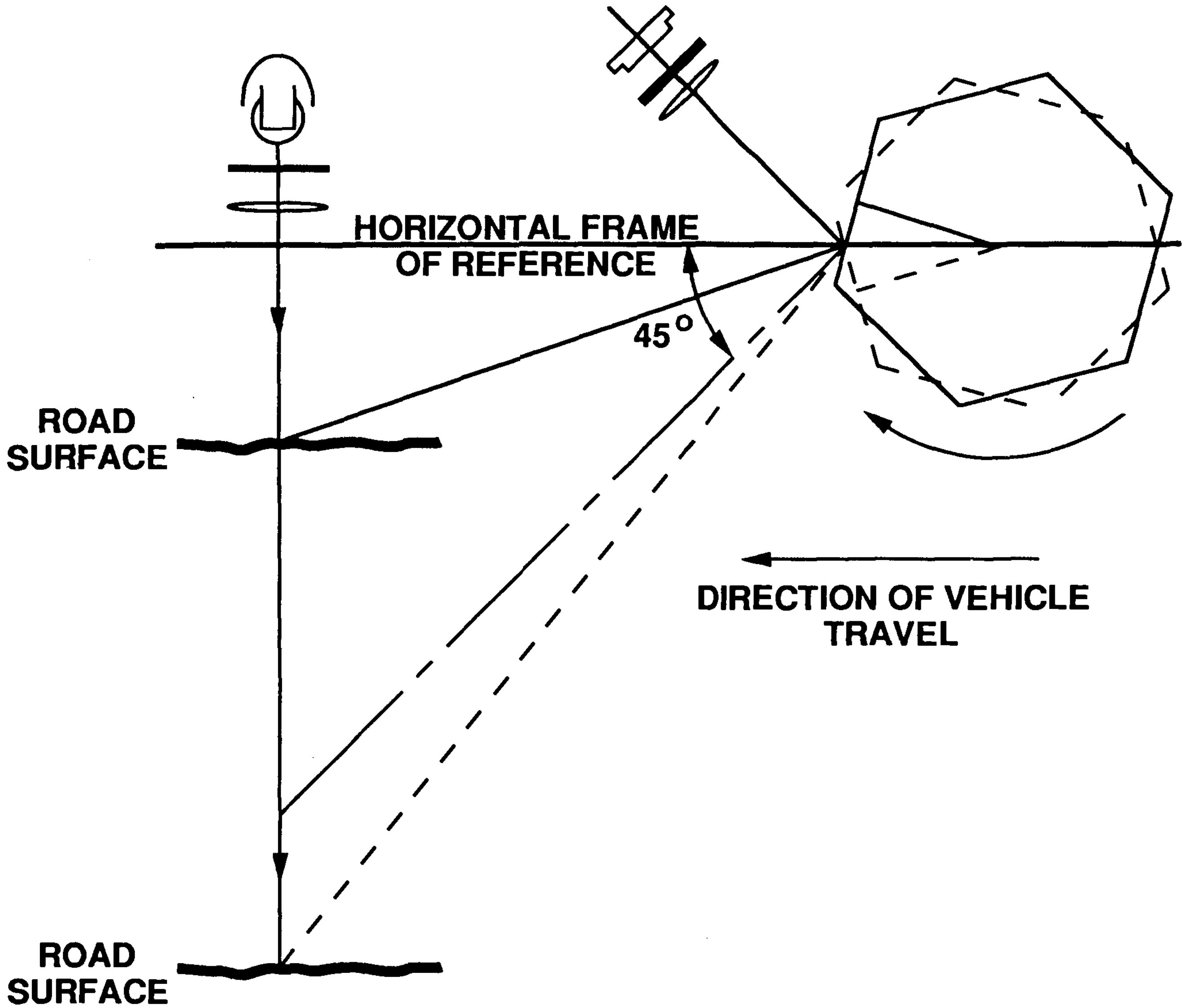

Figure 3. Schematic diagram of the road image optics portion of the Law White Light Sensors.

further. With the other sensors, the accuracy of the transverse measurement depends on the number of sensors employed.

Table 4. Comparison of height sensors.

	K. J. Law White Light	Selcom-Optocator Laser Sensor	FHWA IR Sensor
Normal Operating Speed	Highway Speeds	Highway Speeds	Highway Speeds
Disadvantages or Limitations	Initial Cost and Requires Skirts to Block Ambient Light	Initial Cost and Small Spot Requires Filtering	Color Sensitive and Somewhat Nonlinear
Data Output	Paper Tape or Digital	Paper Tape or Digital	Digital or Analog
Measuring Range	72 mm	80 mm	75 mm
Resolution	0.282 mm	0.25 mm	0.3 mm
Accuracy	0.282 mm	N/A	0.3 mm
Standoff Distance	270 mm	400 mm	350 mm

N/A = Not available
1 in = 25.4 mm

SKID RESISTANCE

Pavement skid resistance or frictional resistance can be determined by several means. The ones considered in this project are: locked-wheel testing according to ASTM Method E 274, sideforce coefficient measurement with a tire rotating at constant speed and yaw angle, a combination of these methods with a texture measurement, and a transient test involving tire spinup.

Highway agencies use locked-wheel testing for the majority of highway testing; the U.S. data base is based on this method. Two tires can be used, the ribbed (ASTM E 501) and the blank (ASTM E 524). The ribbed tire is in general use. However, the use of both tires together is gaining popularity in several States.[18] Measurements with the two tires may be used in an empirical correlation to predict skid resistance-percent normalized gradient (PNG) and the zero speed intercept (SN_0) or to calculate micro- and macrotexture and the skid number at any speed.[22]

A new study indicates that a transient measurement with a ribbed tire can be used to define either PNG and SN_0 or the micro- and macrotexture of the pavement.[34] Lockup of the standard E 501 ribbed tire and subsequent spinup would be sufficient to predict skid resistance as a function of speed from knowledge of the test wheel angular velocity only. With changes in the sensors and instrumentation, the integrated survey vehicle can accommodate either the locked-wheel method, meeting the requirements of ASTM E 274, or the spinup method.

CRACK DETECTION

Several methods can be used to generate a condition survey from a moving vehicle. These methods are summarized in tables 5 and 6. The first method uses a windshield survey in which a human rater estimates the types and levels of distress while the vehicle is moving. A computerized device records the distance traveled while the rater manually enters locations of high distress. The second method incorporates a laser or other device to measure the distance from the vehicle to the road surface at many discrete points. The cracks are indicated by points of sharp discontinuity. The third approach uses a vision system with either manual or computer processing to analyze the images.

Windshield Survey

In a vehicle in which a computer has been installed, a transducer is attached to one of the vehicle wheels to measure the distance traveled. The operator inputs a starting point marker and then visually rates the road and enters the information. This method can provide discrete information such as the location of high crack areas and a numerical rating of the severity, or it can provide an average rating over a specific distance. The equipment is less expensive than the other methods considered. This method covers more lane miles per day than a walking survey and requires much less effort. If the vehicle travels at normal traffic speeds, it is, however, difficult to obtain

Table 5. Data collection technologies for automated pavement crack detection.

Data Collection Approaches	Merits	Limitations
Rangefinding Methods		
Acoustic (ultrasonic)	• Inexpensive	• Resolution too low (both range and breadth)
Optical (laser)	• Very accurate • Ideal measurement (fewer artifacts)	• Expensive • Too slow to scan imagery (limited mainly to transverse cracks)
Reflective Optical Methods		
Photolog	• Very mature technology • Very high resolution • Historical record	• Automated image processing would require scanning • Post-process only • Non-reusable media
Short-Exposure Video Capture	• Mature technology • Reusable media (video-tape, if post-process) • Readily digitized • Historical record	• Requires shuttered system or phased array of strobe lights • Limited resolution • Complex processing often required
Line Scan	• Less light field uniformity required • Real-time signal processing possible • Medium to high resolution	• Custom hardware design • Complex processing and interface
Flying Spot Laser Scanner	• High transverse resolution • Superior illumination uniformity	• Low longitudinal resolution • May fail to find transverse cracks at highway speeds • Custom hardware design; moving parts • Development not complete
Directed Light Meter (Slit Integration)	• Helps to distinguish cracks from texture • Well suited to real-time processing • Inexpensive hardware	• Custom hardware design • Limited versatility • Finds only transverse and longitudinal cracks • Development currently on hold
Acoustic Pickup Methods		
(microphonic)	• Very inexpensive	• Generally poor performance anticipated • Very susceptible to artifacts

Table 6. Partial list of developers of automated crack detection technologies.

Manufacturer or Researcher	Data Collection Technology	Data Reduction Technology	State of Development	Cost Category*	
Swedish Laser RST	Laser rangefinder	Real-time analog/digital	Available	H,S	Makes several other measurements as well May fail to detect some longitudinal cracks
PCES/Earth Technology	Continuous line scan	Real-time digital	Version 1.0 nearing completion	H,S	Makes several other measurements as well
EKTRON Slit Integration	Directed light meter & integrated line scan	Real-time analog/ digital logging	Currently inactive	L	Statistical device; will not detect diagonal cracks Future versions to retrofit vehicles already in use
VideoComp (Idaho DOT)	Short-exposure video	Post-process digital image processing	Version 1.0 nearing completion	M,S	Videologs done for Idaho and Arizona DOTs Software nearing completion
University of Waterloo	Video	Post-process digital image processing	Study phase	N/A	"Accurate" processing PC-based software delivered to Ministry
Komatsu, Ltd.	Flying spot laser scanner	Post-process digital image processing	N/A	N/A Probably H	Limited speed for detection of transverse cracks Night use only Also measures rut depth and slope variance
MHM Associates	Short-exposure video	Post-process digital image processing	Study phase	N/A	
KLD Associates	Short-exposure video	Post-process digital image processing	Currently inactive	N/A	

* Relative Cost Category: L = Lower ($40,000 to 80,000)
M = Moderate ($80,000 to 150,000)
H = Higher (> $150,000)
S = Available as service
N/A = Data not available

reliable ratings. Also, the method is subjective, as are other methods of manually rating road conditions.

Laser Methods

One or several high-speed pulsed laser devices could be used to measure the return distance of the laser beam and compare it with the return distance of the preceding measurement. A large difference in the two measurements would indicate the presence of a crack or surface discontinuity. This information would then be coupled with a computerized system that would count the cracks or discontinuities and record information indicating their location.

Such methods would accurately indicate the number and location of cracks or discontinuities but only along the path of the laser. An array of lasers would be required to characterize the condition of an entire lane. For each laser, computational speeds are required that are beyond the capability of current hardware. To classify all perturbations wider than 1/16 in (1.6 mm) would require measurements taken at least every 1/16 in (1.6 mm). If the vehicle is traveling at 45 mi/h (72 km/h), this would require more than 13,000 measurements per second for each laser, requiring prohibitive computing capabilities.

Vision System

With this system, one or more cameras are used to record an optical image of the road surface. The image is collected using either a photographic movie camera or a video camera. Location data and other information is collected at the same time. The image is either rated manually at a later time or digitized and processed using digital imagery techniques.

Photographic Survey. Some States are currently using photologging to survey their road systems by recording a windshield view of the road, which is similar to what a driver would see. However, better quality information on pavement condition is obtained from a vertical view of the road surface. Such a system includes a camera that is mounted on a boom attached to the roof of the vehicle for recording a path approximately 12 ft (3.7 m) wide. Photo-logging systems can be interfaced with a computer system from which the information can be downloaded to a data base and recalled for manual classification of the recorded images. A rigid boom with a special camera, a lighting system, a distance-measuring transducer, and a computer are required on the vehicle. High-resolution photographic imagery gives better resolution than video imagery.

The equipment is relatively expensive, but, compared to a manual survey, it saves time and yields improved data. This system still requires manual rating, which requires a significant number of man hours for a road system. Computerized image-processing techniques could be employed, but at a rather high cost in equipment and computing time and at a loss in resolution.

Video Survey. This survey can be conducted using a specially equipped van with one or more video cameras. The data are stored in analog form, and a videotape or on-line image-processing is used to reduce the data to yield only crack information. The camera(s) is mounted perpendicular to the road surface and records images of the road surface. Video recorders (for later processing), an image-processing system (for on-line processing), a computer, a lighting system, and a distance-measuring transducer are required.

This system is better suited to computerized image processing than is a system using photographic methods, but standard video cameras have limited resolution. To continuously record a 12-ft (3.7-m) road with a resolution of 1/16 in (1.6 mm) would require 5 cameras and 5 video recorders. The speed would be limited to 40 mi/h (64 km/h). On-line processing would most likely be beyond current hardware speeds. The cost of the system would be the highest of all systems considered.

Additional Considerations for Vision Systems. Lighting is very important for any vision system. For crack detection, the most important consideration is the position of the light; the lighting angle must be such that surface texture is not confused with cracks. A second consideration is the wavelength of the light. It would be best to choose a wavelength that can compete with sunlight and to have a film or video camera that is especially sensitive to this wavelength. Proper lighting will make identification of the cracks easier for human raters. If computer processing is used and the contrast is high enough, simple thresholding methods can be used to process the image.

A practical solution to the data management problem might be to use some method to signal the likelihood of cracks. If cracks usually occur only at points where pavement roughness is high, a roughness measurement could be used as a trigger to notify the system or operator to begin image processing. The trigger could be a laser crack detector; even though it has poor resolution, it would detect one of the cracks and this would be sufficient to trigger the imaging process.

Gerpho Condition Survey Vehicle

The Gerpho vehicle is equipped with a slit camera that records a continuous image of a 15-ft-wide (4.6-m-wide) cross-section of highway at about 40 mi/h (64 km/h). A hydraulic retractable mast mounted on the roof of the vehicle supports a 35-mm continuously running slit camera. Light sources are mounted on the front of the vehicle, and a hydraulic pump unit operates the mast. The accuracy of this device depends on the focus of the camera and on the grain of the film, but should be well within the accuracy needed to detect cracks.

Idaho Video Condition Equipment

The system consists of a video camera that is vertically mounted on a 16-ft (4.9-m) trailer. The trailer is skirted so that it can be used during the day or night. The recorded image is processed later, when software is used to determine the extent and severity of cracking, spalling, and potholes. The resolution is such that it can recognize 1/8-in (3.2-mm) cracks.

PCES/Earth Technology

The most advanced video system appears to be the PCES system under development by Earth Tech. This system uses four cameras, and the frames are digitized on-board. On-board digital gray-level analysis is used to measure crack lengths and sizes. The system may be available in 1 to 2 years on a service basis.

EKTRON Slit Integration

With FHWA support, EKTRON Applied Imaging (a subsidiary of Eastman Kodak Company) has been developing a lower cost/lower precision system via slit integration and analog processing. A slit-shaped light meter is used to detect transverse cracks, and a linear array is used with a deliberate motion smear to detect longitudinal cracks. Most diagonal cracks and cracks narrower than 1/8 in (3.2 mm) will not be detected. The EKTRON system is intended for use during the day at 40 mi/h (64 km/h). It is intended to sample continuously, but to detect only a statistical fraction of all cracks. Signals from the detectors are analyzed in analog hardware, counted in digital circuitry, and logged via portable computer. The system is designed to report crack density in raw index form. Also, it is designed to be affordable as a retrofit to existing test vehicles ($50,000, excluding the vehicle and the 3,000-watt power source).

Radar

Radar has been used in the past 5 years to determine layer thickness and the location of voids within the pavement structure. A typical radar unit consists of a self-contained vehicle that has two antennae from 6 to 14 in (150 to 350 mm) off the ground mounted behind the unit. With an approximate coverage path of 18 in (460 mm), both wheel paths of a single lane can be evaluated. Penetrating radar can be used to determine the thickness of the individual pavement layers and can reach a depth of 15 in (380 mm) in portland cement concrete and deeper in asphalt concrete. The system requires a trained technician to interpret the output from the radar device.[41]

Infrared Thermography

For the last 5 years, infrared thermography has been used to evaluate pavements and bridge decks. The primary purpose of the evaluation is to locate voids or areas of delamination. It has the potential ability to locate areas where an overlay has separated from the substrate material. The system works on the principle of detecting the thin layer of air between the layers that have delaminated. Since this air warms and cools at a different rate than the surrounding material, it is possible to detect these areas of different temperatures by infrared means. The day should be clear and sunny, and the pavement surface should be dry. A mast on the test vehicle raises the infrared cameras about 14 ft (4.3 m) above the pavement. Signals from the cameras are displayed in the vehicle and recorded on magnetic tape. The maximum speed of the vehicle is about 10 mi/h (16 km/h).[42]

STRUCTURAL RESPONSE (DEFLECTION)

Deflection measurements are an important component of the pavement management data collection activities of many States. At the project level, deflection data are used to characterize the material properties of the layers in existing pavements and in pavement rehabilitation design. Very little use has been made of deflection data at the network level of pavement management, primarily because of the time involved in taking deflection measurements by current stationary methods. Highway Products International (Ontario, Canada) is currently developing a system that measures the vertical acceleration of a vehicle as it travels over pavement sections with different stiffnesses. In preliminary studies, this equipment correlated well with standard deflection equipment. Surface Dynamics Corporation is working on a similar approach.

Current Equipment

Currently, no instrument can measure pavement deflections (such as the measurements obtained by a Falling Weight Deflectometer or Dynaflect) while traveling at highway speeds. The LaCroix Deflectograph and the Curviameter, both French devices, obtain deflection measurements while traveling at slow speeds (5 to 10 mi/h [8 to 16 km/h]). Table 7 provides a summary of the deflection-measuring equipment currently available. Only the LaCroix Deflectograph and the Curviameter (a version of the Deflectograph) offer the capability of taking measurements with a moving vehicle.

Table 7. Summary of deflection-measuring equipment.

	Curviameter and La Croix Deflectograph	Dynaflect	Model 4008 Road Rater	Model 2000 Road Rater	Model 2008 Road Rater	KUAB 50 FWD	KUAB 150 FWD	Dynatest Model 8000 FWD	Phoenix Cal Beam
Principle of Operation	Mechanized Deflection Beam	Steady State Vibratory	Steady State Vibratory	Steady State Vibratory	Steady State Vibratory	Impulse	Impulse	Impulse	Impulse
Load Actuator System	Moving Truck Loaded with blocks/water	Counter Rotating Masses	Hydraulic Actuated Masses	Hydraulic Actuated Masses	Hydraulic Actuated Masses	Two Dropping Masses		Dropping Masses	Dropping Masses
Minimum Load (lb)	Empty Truck	1,000	500	1,000	1,000	1,500	1,500	1,500	1,500
Maximum Load (lb)	Loaded Truck Wheel Weight	1,000	2,800	5,500	8,000	12,000	35,000	24,000	
Static Weight on the Plate (lb)	N/A	2,100	2,400	3,800	5,800				
Type of Load Transmission	Truck Wheels	Two 16-in Diameter Urethane Coated Wheels	Two 4-in by 7-in Pads with 5.5-in Center Gap	Circular Plate 18-in Diameter	Circular Plate 18-in Diameter	Sectionalized Circular Plate 11.8-in Diameter		Circular Plate 11.8-in Diameter	Circular Plate 11.8-in Diameter
Method of Recording Data	Manual, Printer, or Automated	Manual, Printer, or Automated	Manual, Printer, or Automated	Manual, Printer, or Automated	Manual, Printer, or Automated	Manual, Printer, or Automated		Manual, Printer, or Automated	Manual, Printer, or Automated
Type of Carriage	Truck	Trailer	Van or Trailer	Van or Trailer	Van or Trailer	Trailer	Trailer	Trailer	Trailer
Contact Area	N/A	32 in^2	56 in^2	254 in^2	254 in^2	109 in^2	109 in^2	109 in^2	109 in^2
Vibratory Frequency and Range	N/A	8 Hz	5 to 7 Hz	5 to 7 Hz	5 to 7 Hz	N/A	N/A	N/A	N/A
Deflection Measuring System	Inductive Displacement Transducer	Velocity Transducer	Velocity Transducer	Velocity Transducer	Velocity Transducer	Seismic Deflection Transducer		Velocity Transducer	Velocity Transducer
No. of Deflection Sensors	One in each Wheel Path	5	4	4	4	5	5	7	7
Normal Spacing of Sensors	N/A	Center and at 1-in Intervals	Center and at 1-ft Intervals	Center and at 1-ft Intervals	Center and at 1-ft Intervals	Center and at 0.6 to 8 ft		Center and at 0.6 to 7.4 ft	Center and at 0.6 to 7.4 ft

1 in = 25.4 mm
1 in^2 = 6.45 cm^2
1 ft = 0.305 m
1 lb = 4.45 N
N/A = Not available

Equipment Under Development

Highway Products International and Surface Dynamics Corporation are both working on high-speed measuring equipment. The Highway Products system travels at 30 mi/h (48 km/h) and "thumps" the pavement periodically. An accelerometer placed on the loading device measures the response of the pavement, allowing the deflection under the load to be calculated. Deflection basins cannot be determined. The Surface Dynamics equipment is in the design phase; little information on this equipment is available at this time.

The Swedish Road and Traffic Institute is developing a system using 2 sets of 11 laser cameras, 1 set preceding and 1 set directly following a rolling loaded wheel. The differences between the profiles taken before and after the wheel will, with frequent sampling and statistical analysis of the measurements, show the rolling load influence on the road surface (see figure 4). Extensive three-dimensional simulations of the road body and investigations of how various loads, speeds, and temperatures influence the road body are an integral part of this exercise, but the unit has yet to be built.

ENVIRONMENTAL DATA

Many devices are available for measuring environmental data, and many of these are off-the-shelf items. Temperature measurements can be made with standard automotive digital outside and inside temperature equipment. Road surface temperature may be measured using the appropriate radiometers currently in use at various agencies. Similarly, off-the-shelf radiometers may be used to measure solar radiation.

MISCELLANEOUS EQUIPMENT

Test vehicle speed is usually measured by a fifth wheel or is obtained from a calibrated nondriven wheel of the vehicle. Locations of test sites can be defined by inputting landmarks, mile posts, etc., by recording visual observations, or by using a Loran C system.

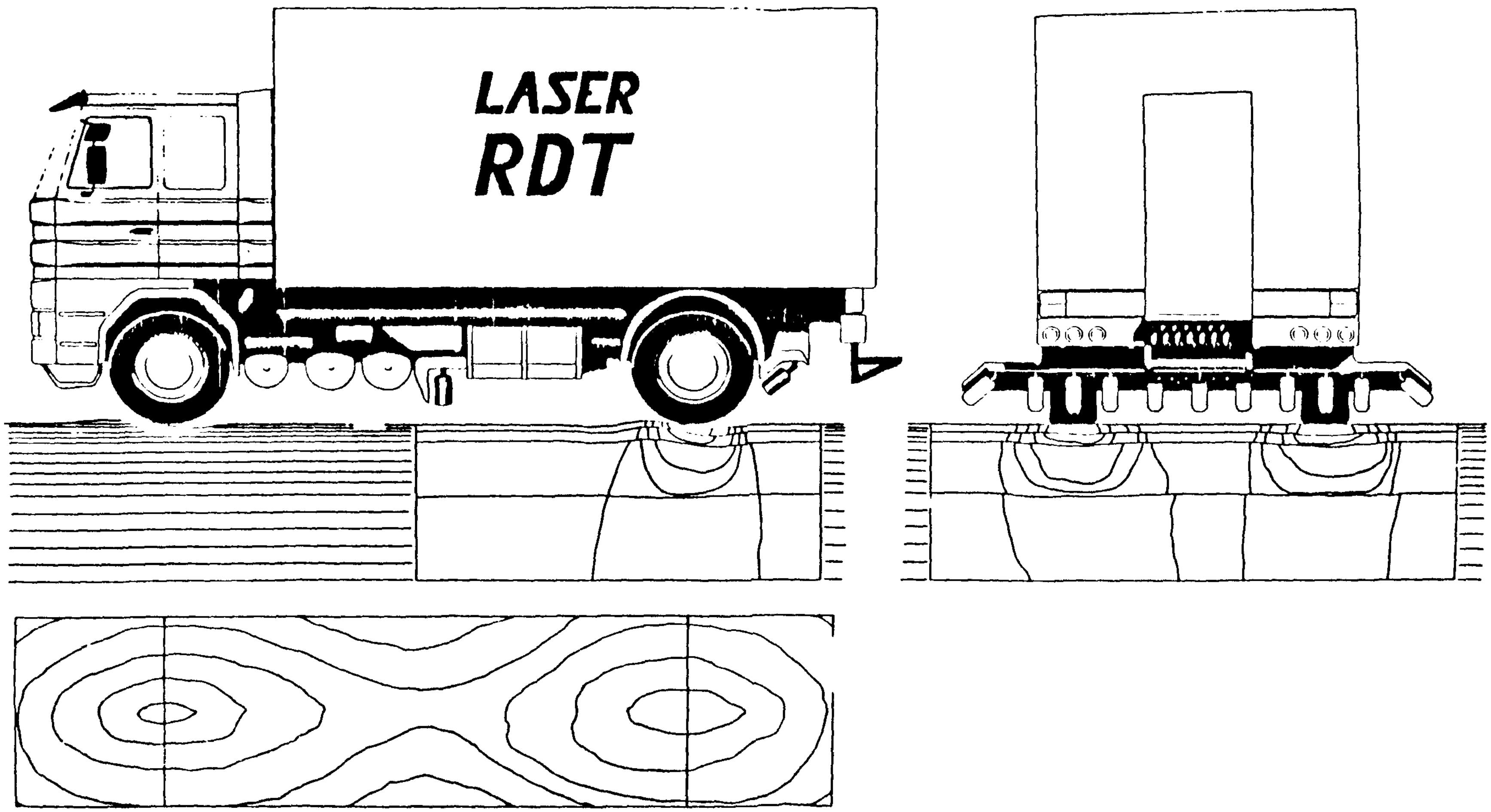

Figure 4. Bearing capacity measurement under development at Swedish Road and Traffic Institute. An early drawing of the Road Deflection Tester (RDT) illustrating the measurement of the principles involved.

SIGNAL PROCESSING, DATA ANALYSIS, AND DATA RECORDING

In the integrated raod survey vehicle developed in this project, microcomputers are used for data acquisition and pre-processing. A microcomputer is also used to coordinate all data collecting, to perform final processing, organization, and recording of data, and to operate the local area network that communicates with the different computers. A wide range of microcomputer software has been developed to perform signal processing, data analysis, and recording, and these programs are available as off-the-shelf items. One of the microcomputers is used as an operating terminal for the system. Each microcomputer can be used as a stand-alone signal processor or data analyzer. They are used to support various recording methods ranging from floppy disks or hard disks to read and write laser disks.

With this acquisition and analysis design, hard card disks are used in each system to store data. These hard card disks are rated for dynamic loads well above 1 g, with peaks up to 5 g. Therefore, these units make excellent mass storage devices or buffers. More details are given later in this report.

CHAPTER 3. OVERVIEW OF THE INTEGRATED VEHICLE DESIGN

Three conceptual designs were developed for the integrated survey vehicle. All designs included equipment for measuring longitudinal and transverse profile, skid resistance, and auxiliary measurements such as environmental conditions and pavement location. Surface distress measurements were included in the final design by including the Idaho crack detection system. The final design also included the FHWA macrotexture-profiling system, which was updated to include standard IBM-PC equipment and off-the-shelf add-on boards. Pavement deflection measurements were not included, although the design anticipates the possibility of adding such equipment when a system is fully developed and proven. The design included the equipment needed for signal processing, data analysis, display, and recording. All transducers were noncontact, with the exception of skid resistance equipment. A list of drawings, a list of IRSV components and their costs, and a list of source programs for the system are contained in appendixes A, B, and C, respectively.

VEHICLE SELECTION

Three types of vehicles were investigated for the conceptual design:

- Utility van.
- Motor home.
- Step van.

A truck-trailer combination was considered initially but was rejected due to its mechanical complexity and poor maneuverability. All three vehicles could accommodate the currently needed equipment, but the first vehicle, a Winnebago Utility Van, offers only enough space for available equipment and does not allow for future additions. The second vehicle, a motor home built by Establishment, Inc., is more spacious (future equipment can be added) and has a V-8 engine as standard equipment. The two units, fully equipped, were quoted at $23,000 and $32,000, respectively. The third vehicle was an Aeromaster (step van) built on a GMC P6T042 chassis with a cost of $28,000.

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The smaller Winnebago van, although accommodating the same basic equipment as the motorhome vehicle, has front-wheel drive and is quite compact. However, the vehicle is underpowered with its current four-cylinder diesel engine. G. F. Hayhoe and J. Grundman showed that the weight-to-power ratio for recreational vehicles with poor to high performance is between 50 and 20 lb/hp (30 and 12 kg/kW).[43] The two Pennsylvania Transportation Institute (PTI) skid testers and FHWA's skid tester have weight-to-power ratios between 20 and 25 lb/hp (12 and 15 kg/kW). Therefore, it was decided that the weight-to-power ratio for the vehicle should be in the mid-20's, which would have required that a 366-in^3 (6-ℓ) V-8 engine be fitted. However, after a complete system was developed, the Winnebago Utility Van was eliminated because it lacked sufficient space for additional equipment. A complete system layout using the motor home eliminated this vehicle due to its weight distribution. At this point, the third vehicle came into play and was chosen for the design. The vehicle is an Aeromaster (step van) built on a GMC P6T042 chassis by Utilimaster of Wakarusa, IN. Figure 5 is an overview of the van. The van has a step-van type body that is 20 ft (6.1 m) long by 93.5 in (2 375 mm) wide by 85 in (2 160 mm) high. It is equipped with a 366-in^3 (6-ℓ) V-8 gasoline engine and has a 203-in (5 156-mm) wheel base and a gross vehicle weight of 26,000 lb (10 000 kg).

Researchers determined that a generator driven by the vehicle engine is totally insufficient and that a standard, auxiliary, gasoline engine powered 115 VAC generator is required. Its output must be sufficient for operating all electronics, air conditioning, and other equipment that is needed now or might be added in the future. The generator is mounted at the rear of the vehicle and is well isolated from the rest of the vehicle and the built-in equipment. The standard air conditioning units are roof mounted and capable of maintaining humidity and temperature levels comfortable for the operators and providing an acceptable operating environment for the electronic equipment (65 to 75 $^{\circ}$F [18 to 24 $^{\circ}$C]) and less than 80-percent humidity) without needing to run the main engine.

Considerable attention was given to the dynamics of the proposed vehicles. Computer simulation studies of the vehicles, their suspension

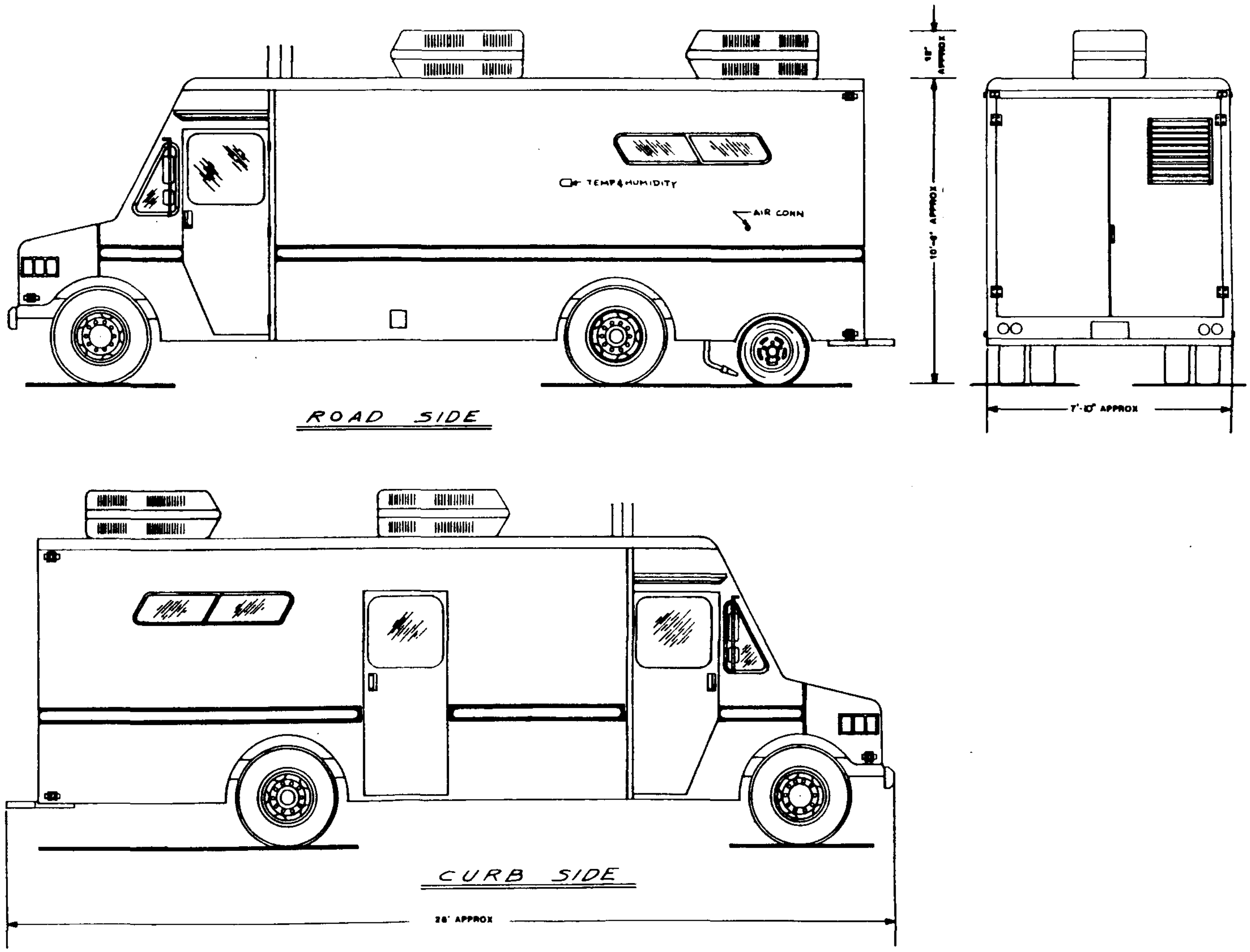

Figure 5. Overview of the vehicle.

characteristics, and the road geometry showed that the vehicle is suitable for both profiling and skid resistance measurements.[44] The skid test wheel will be mounted under the vehicle with a suspension independent from the vehicle (this wheel can be raised). Vehicle leveling is accommodated by automatic leveling air bags on the vehicle suspension. With this system, if skid measurements are made at the same time as profiling, the profile sensors will not be moved out of their operating range. Water sufficient for 4 h of skid testing can be accommodated in the vehicle. A trailer-mounted water tank that would replenish the vehicle tank periodically would be required if water for more than 4 h is desired. (Locked-wheel tests according to ASTM E 274 use about 3 gal [11 ℓ] of water per test.) Estimates for the spinup tester show that the water usage should be about half of the standard E 274 test (as being studied by another FHWA project).

Vehicle operating safety with the skid test wheel in the operating position is improved by an antilock brake system on the vehicle, which can compensate for the unloading of the wheels on the side of the skid test wheel. At the time of this report, antilock brake systems were not yet available on the selected vehicles, but they should be in the near future. The vehicle is specified with an air-bag suspension system and an automatic leveling system. "Development of Integrated Survey Vehicle for Measuring Pavement Surface Conditions at Highway Speeds--Volume II: Technical Details" (FHWA-RD-90-012) gives detailed specifications for the vehicle.

TEST EQUIPMENT FOR THE SURVEY VEHICLE

The overall layout of equipment in the vehicle is given in figure 6. Figures 7 and 8 show the right and left side elevation layouts of the integrated survey vehicle. A brief overview of the equipment for each subsystem is given here; a more detailed discussion and specifications are given later in this report and in "Development of Integrated Survey Vehicle for Measuring Pavement Surface Conditions at Highway Speeds--Volume II: Technical Details" (FHWA-RD-90-012).

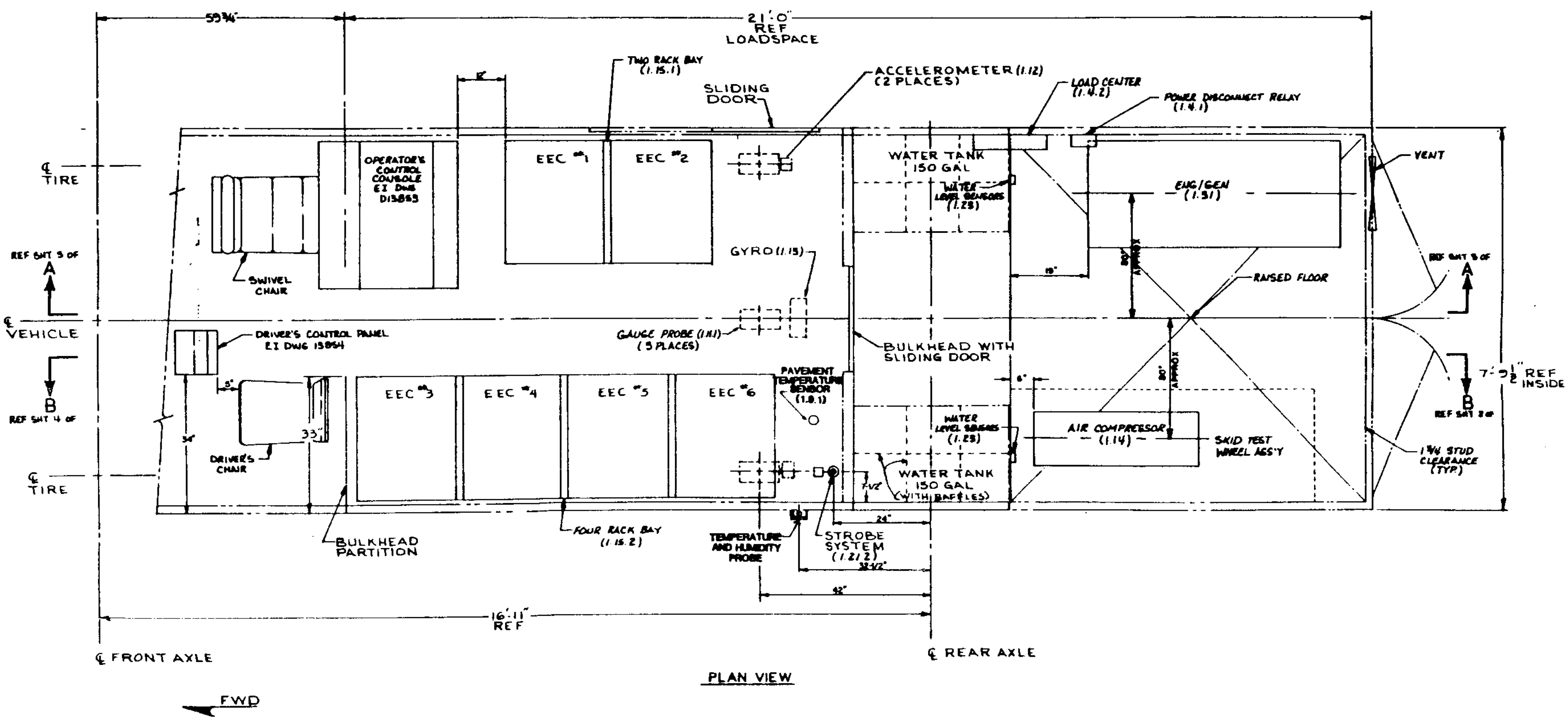

Figure 6. Plan view of equipment layout.

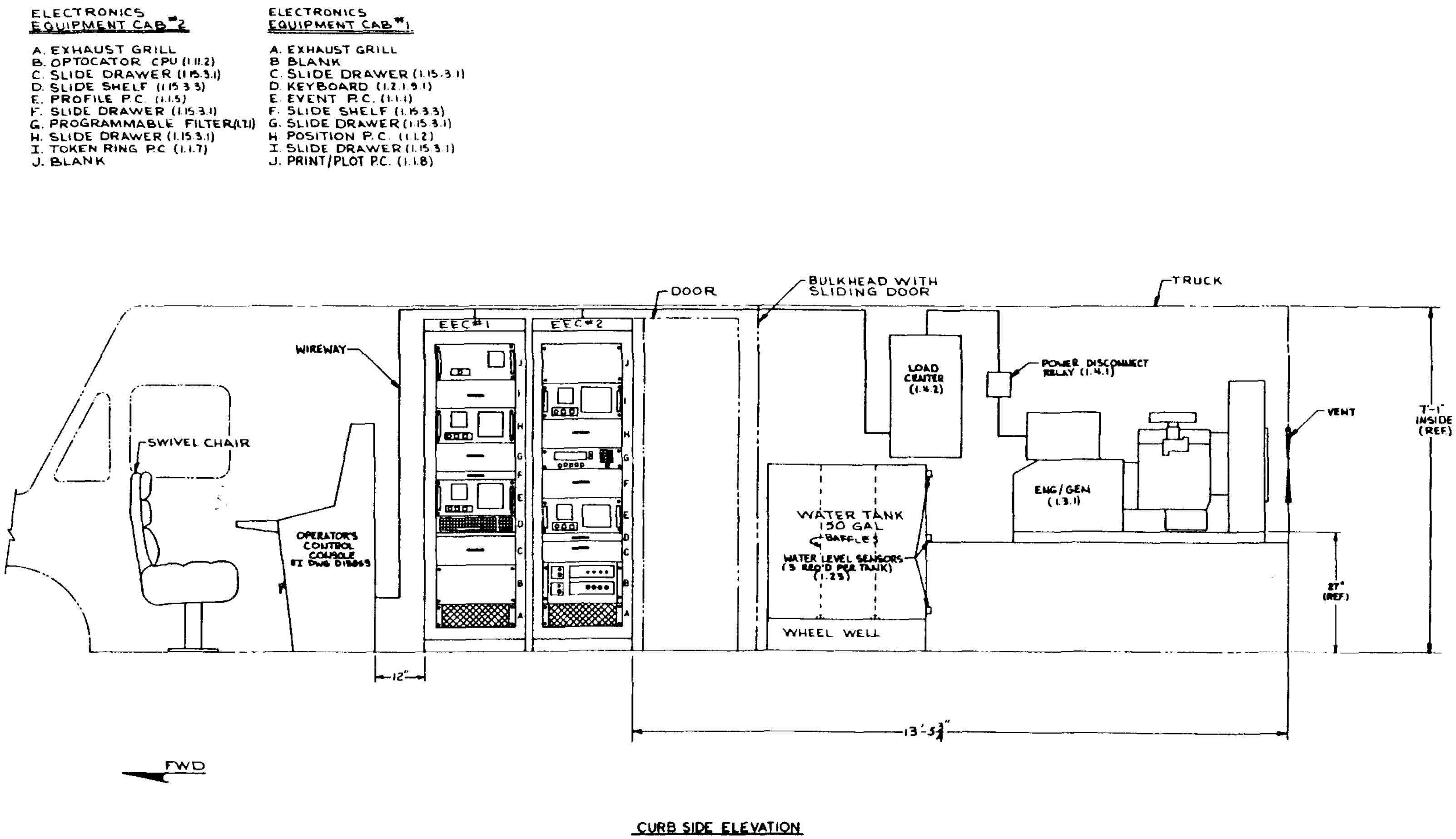

Figure 7. Curb side elevation.

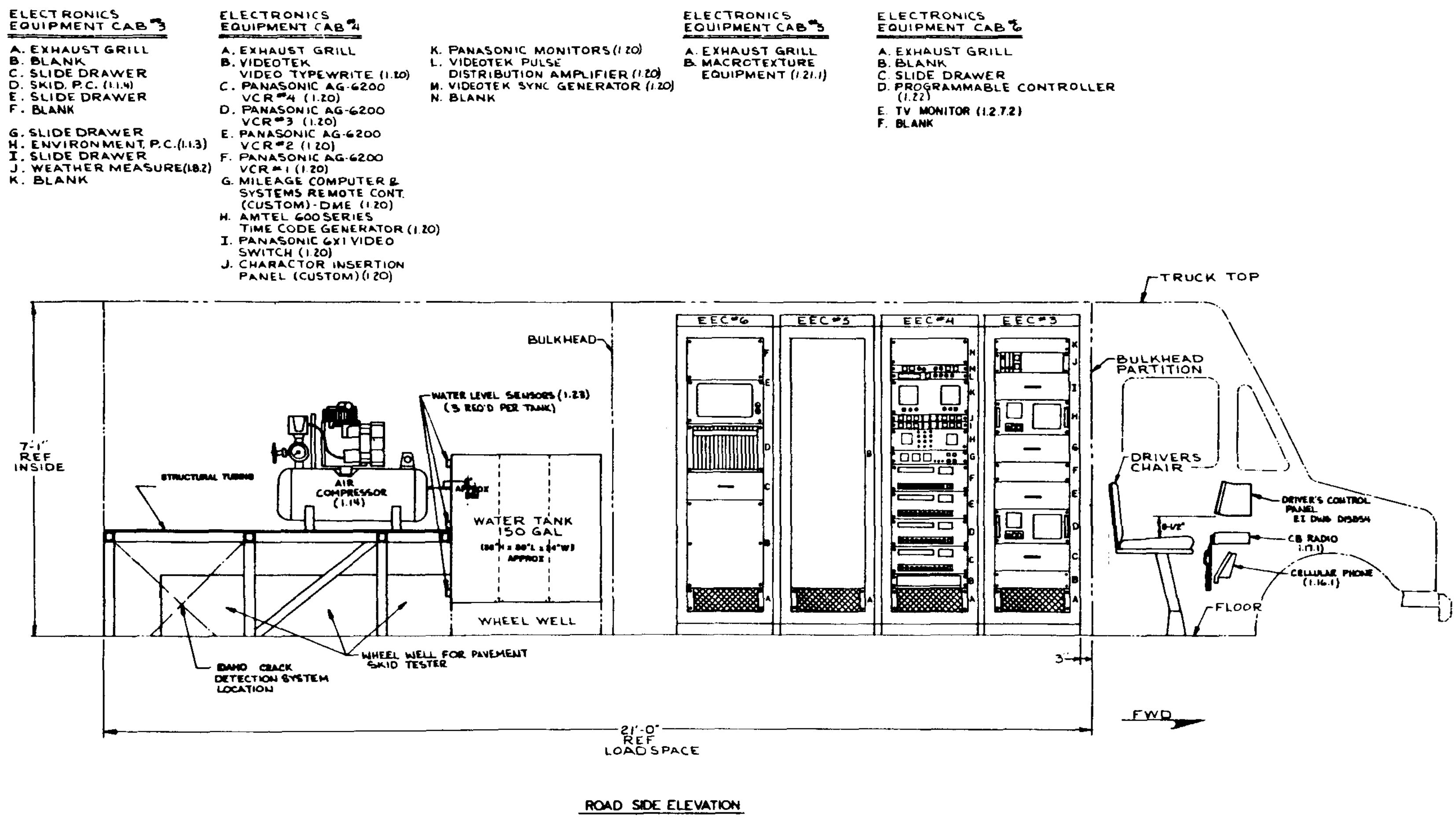

Figure 8. Road side elevation.

Control and Operation

The vehicle requires two persons for most operations, usually one operator and one driver. The operator's duties include system setup and operation. In the fully automatic mode, the system is set up and then the operator only needs to monitor system operations and system output. In the manual mode, the operator selects which systems are to be run and manually starts/stops equipment operation. The driver controls the vehicle and can activate the voice-recognition system to start or stop tests or to act as an event marker. The driver is also responsible for any voice-actuated comments regarding site conditions, start-end descriptions, and test conditions. Figure 9 shows the operator's control panel layout; figure 10 shows the driver's control panel.

A spinup skid test wheel with an ASTM E 501 tire is housed beneath the vehicle in the left wheel path immediately behind the rear wheels. This position minimizes the effect of the skid tester operation on the dynamic stability of the vehicle. This position also places the water sprayed from the nozzles aft of all sensors except the crack-detection system, which is lcoated to the rear of the skid tester. Therefore, except for the crack-detection system, the other systems will not be affected by the spraying of water on the pavement. This also means that skid and crack-detection measurements cannot be obtained simultaneously.

The skid test wheel, located behind the left rear wheel of the IRSV, is mormally carried in a raised position and lowered on the pavement when skid tests are perofrmed. The wheel is loaded with dead weight through an air cylinder. The wheel and the dead weight are lifted to the raised position by means of the air cylinder.

The arrangement of the various measurement systems, proceeding from the front to the back of the vehicle, is:

- Profile system.
- Macrotexture system immediately in front of the rear vehicle tires.

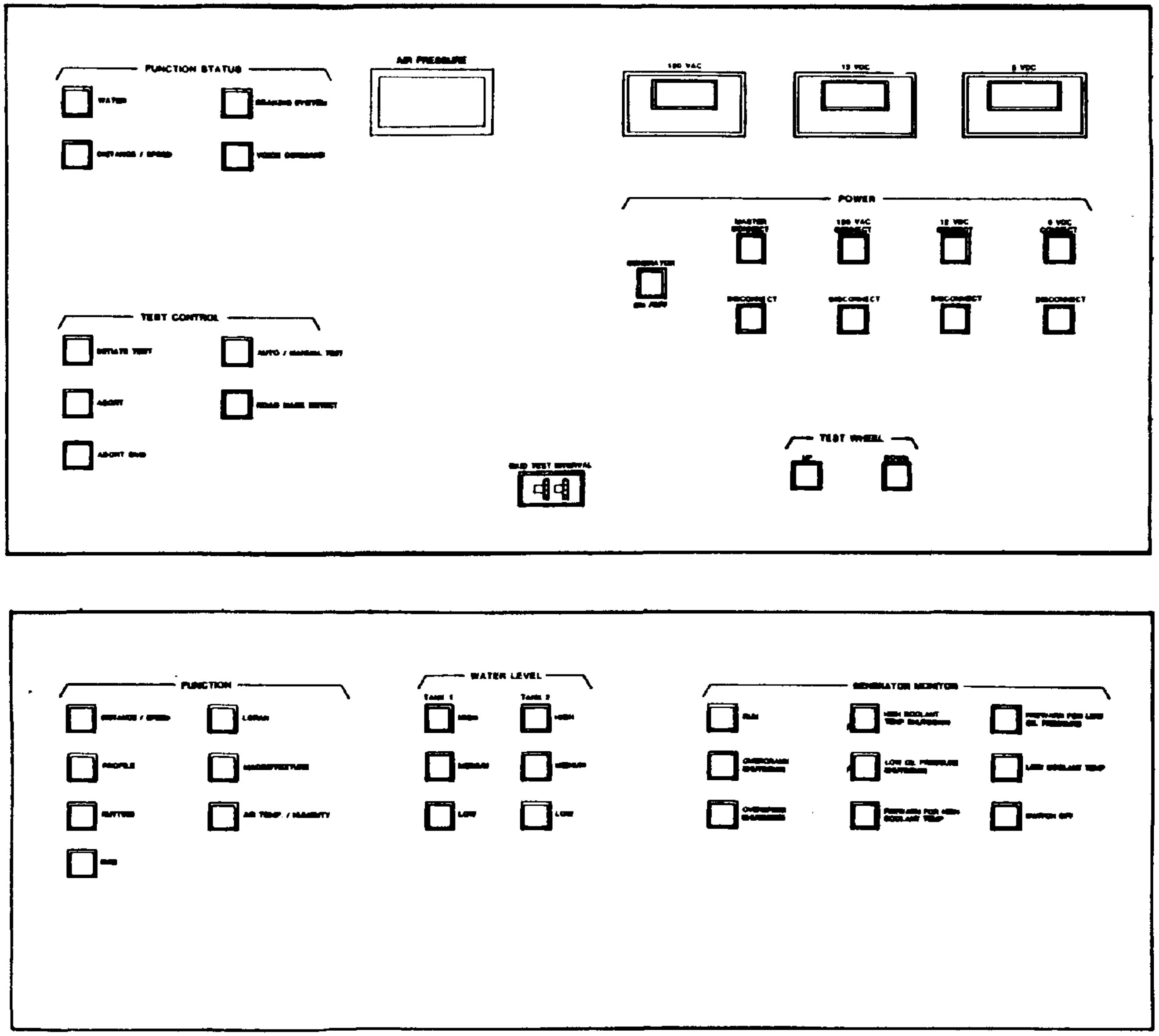

Figure 9. Operator's control panel.

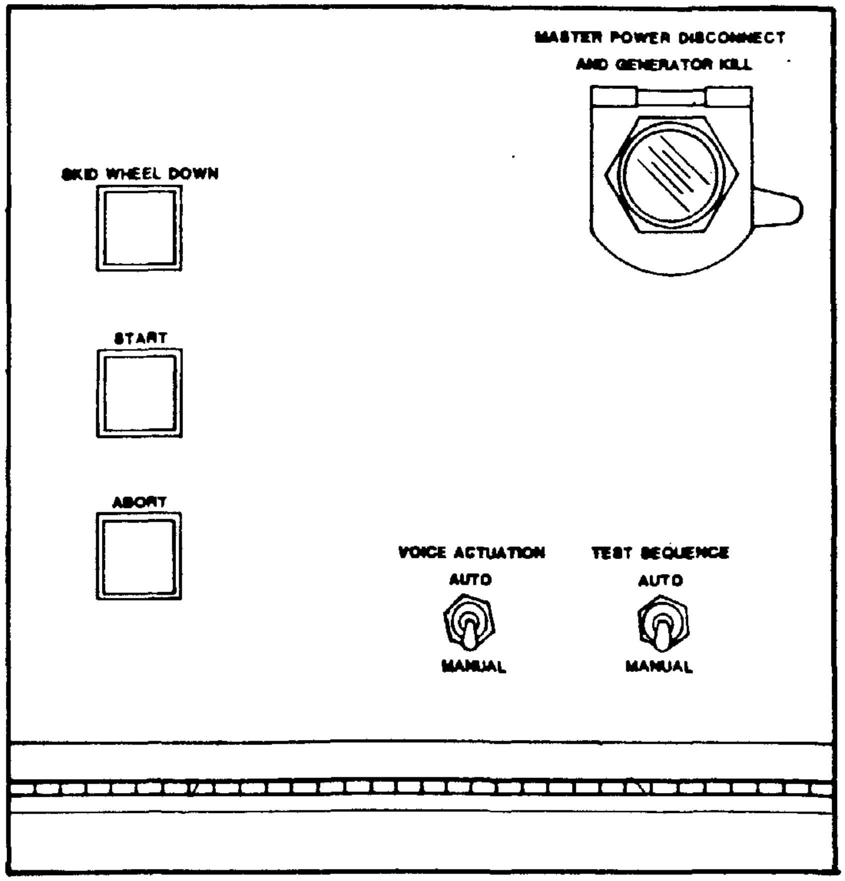

Figure 10. Driver's control panel.

- Skid system immediately in back of the left rear tire of the vehicle.
- Crack-detection system at the extreme rear of the vehicle.

A visual display and an audible back-up warning system notify the driver and operator when the wheel is in the lowered position. The skid computer monitors the vertical loading of the test wheel by monitoring the air pressure during actual testing. The watering system (tank and pump) are located over the rear axle to distribute water weight equally left and right. The water tanks contain baffles to prevent sloshing and the resulting vehicle oscillations. A drive line is established between the vehicle's engine and the watering system pump via the available power take-off unit to allow for flow rates proportional to vehicle speed. If more water is needed than can be provided for on the vehicle, a trailer carrying a water tank is recommended. If this system is required (not specified on current vehicle), an electrically driven pump would transfer water periodically and automatically from the trailer to the vehicle.

The transducers for longitudinal and transverse profiles are mounted on a frame beneath the vehicle. This frame is in line with the front side door (see curb side view, figure 6). The frame is designed to accommodate five height sensors, which can be used for both longitudinal and transverse profile calculations. Three sensors are used in the current design configuration--one in each wheel track and one between the wheel tracks. A transducer, located on the front right wheel, is used to monitor both distance traveled and speed. This sensor also generates a pulse train used in acquiring distance data during testing. Different data acquisition rates are generated by a series of counters in each system computer preset to a count that will correspond to a known longitudinal distance. For skid testing, a thumbwheel switch is provided to facilitate a change of distance between tests.

DATA ACQUISITION, PROCESSING, AND STORAGE

On-board signal conditioning and data acquisition systems are totally self-sufficient and require little or no user intervention; they can operate fully automatically or manually as the need arises. The following systems are used to acquire, process, and store the data and to control the operations of the overall system:

- An event or main system that controls the operation of the overall system. The event system also includes a voice-recognition system.
- A position system used to determine the location of the vehicle. This system is based on the Loran C navigational system.
- An environmental system that records ambient environmental conditions.
- A skid system that captures and reduces the skid data.
- A profile system that captures and reduces longitudinal and transverse profile data.
- A macrotexture system that uses digital vision techniques to measure pavement macrotexture.
- A local area network system that acts as a file system to other data.
- A print/plot system that is used to print or plot the test results.
- A programmable logic controller that is controlled by the Event (main) PC. This system starts/stops the various test equipment, values, etc.

These systems function independently and communicate via the local area network (LAN) computer for data storage. The programmable logic controller controls starting, stopping, and aborting test runs under control of the Event PC in the automatic mode or under the control of the operator in the manual mode. All data storage is performed on WORM (write once-read many) optical disk storage systems with headers and event information by the LAN PC. Raw profile data is stored on a separate WORM by the Profile PC.

Figure 11 is a block layout of the overall system. Each subsystem includes a microcomputer that can be used to control that subsystem. The microcomputers are used to digitize, condition (e.g., filter), and store the signals from the transducers. The processed data are then transferred to the LAN computer for storage.

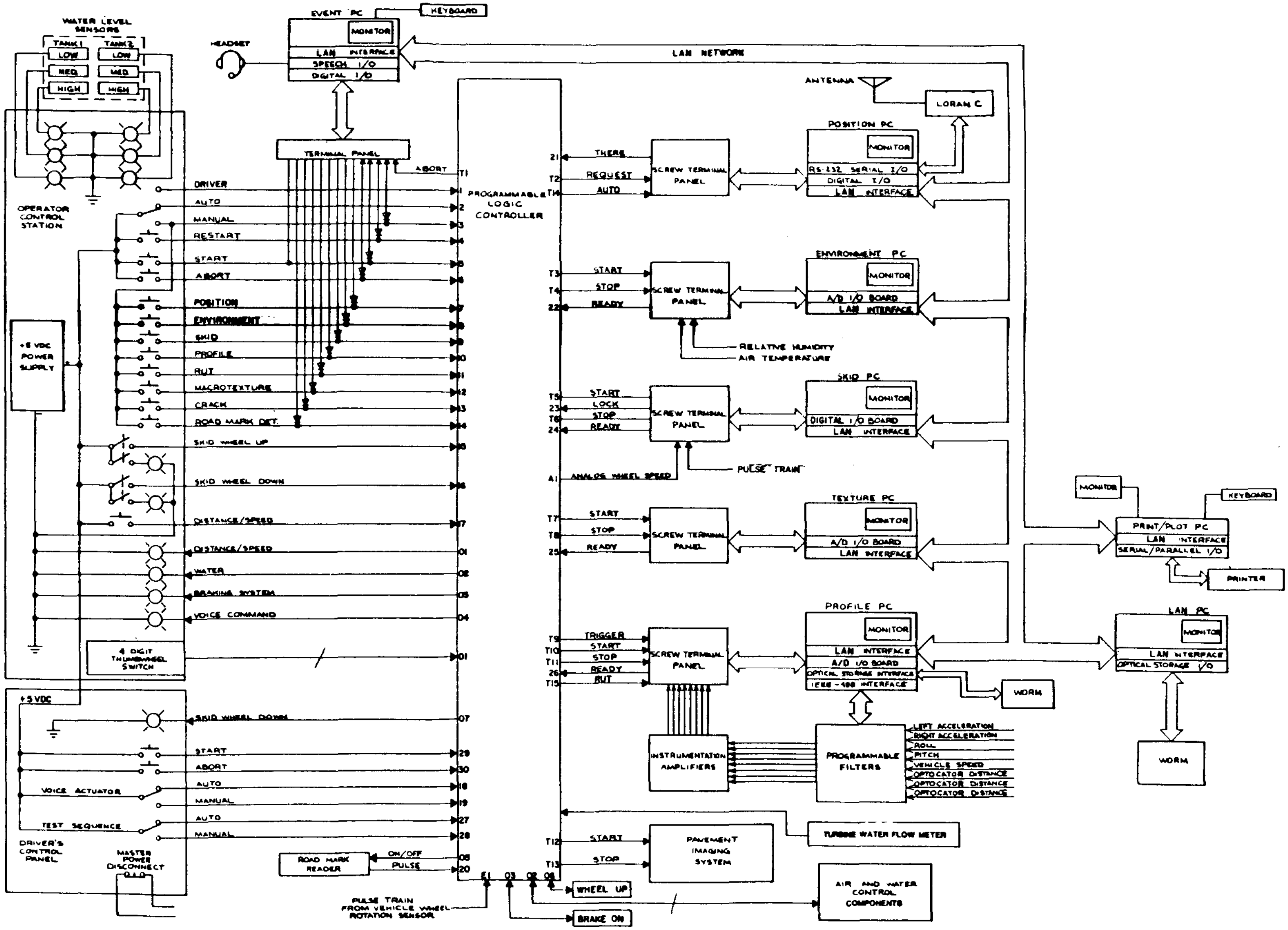

Figure 11. IRSV system block layout.

A keyboard is provided on the Event PC to allow input and to start up the system. In addition, a voice-actuated/voice-recognition system allows the operator or the driver to add comments while driving without physically touching a keyboard. For example, the driver/operator can dictate, "Position, bridge," and the Loran C will automatically record the position of the bridge along with the word "bridge." The Loran C navigation system is incorporated so that the latitude and longitude can be recorded whenever location is requested.

MEASUREMENT SYSTEMS

The profiles are obtained with three Selcom laser distance measuring units and a gyro to give longitudinal profile, rutting, and overall cross slope (see figure 12). These same signals can be used with up to two additional sensors or pitch and roll from a gyroscope for transverse profiles.

Skid measurements are obtained from a wheel that is allowed to spin up from a locked position. The rate at which the wheels spins up as it is released from the locked position is used to calculate skid numbers at slip speeds in increments of 10 mi/h (16 km/h).

Macrotexture measurements are obtained from a vision processing system in which a video camera is used to obtain video images; these images are subsequently digitized and processed by a computer.

The Idaho video crack detection system is included in the survey vehicle for obtaining condition survey data. This system is self-contained in that it is supplied with its own software for processing the video images. With the system, video cameras are used to obtain an image of the pavement, and the images are processed at a later date using hardware and software separate from that contained in the survey vehicle.

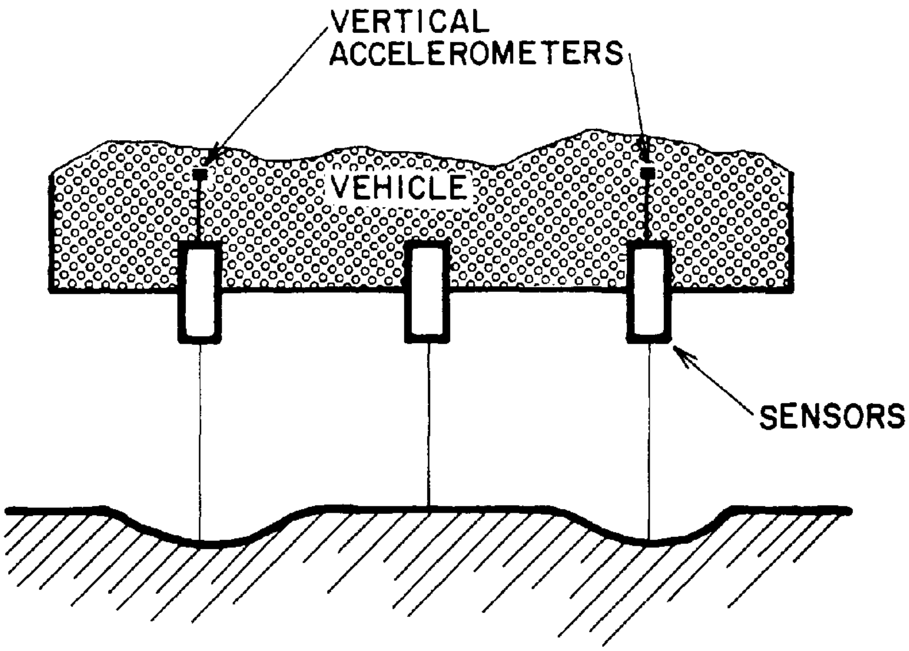

Figure 12. Transverse profile measurement.

CHAPTER 4. LONGITUDINAL AND TRANSVERSE PROFILING

OVERVIEW

The IRSV is intended to measure both the longitudinal (along the length of the roadway) and transverse (perpendicular to the track of the vehicle) road profiles. These measurements are accomplished by the use of three (expandable to 12) optical distance-measuring units located beneath the vehicle. The units can be placed as close as their size allows with no measurement crosstalk. If more than three units are used, additional control boards must be added to the Optocator system and the software must be changed. The Selcom Optocator system provides measurements to a resolution of 0.0025 in (0.064 mm). The influence of vehicle motion on these measurements is corrected for by processing vehicle vertical acceleration, roll, and pitch information as obtained by two accelerometers and a gyro. The distance traveled is measured precisely by a pulse encoder mounted on one of the free wheels. The gyro is used only for the measurement of transverse profile.

Figure 13 shows how the profile/rut subsystem performs data acquisition, data storing, rut computation, profile computation, International Roughness Index (IRI) computation, and the storing of results. The profile/rut subsystem is interfaced with the Main LAN PC to determine the operation parameters (speed, sampling distance, overall length) and with an Allen-Bradley Programmable Logic Controller (PLC) to perform the data acquisition at the correct locations.

MECHANICAL DESCRIPTION

The major mechanical aspect of the profiling system is the structure that supports the Optocator gauge probes, the accelerometers, and the gyro. This structure, located beneath the vehicle, secures the optical gauges so that they have an unobstructed view of the pavement. This structure is secured rigidly enough to the vehicle so that all vehicle motion is sensed by the accelerometers and gyro that are attached to it. The profile/rut subsystem consists of the hardware listed below:

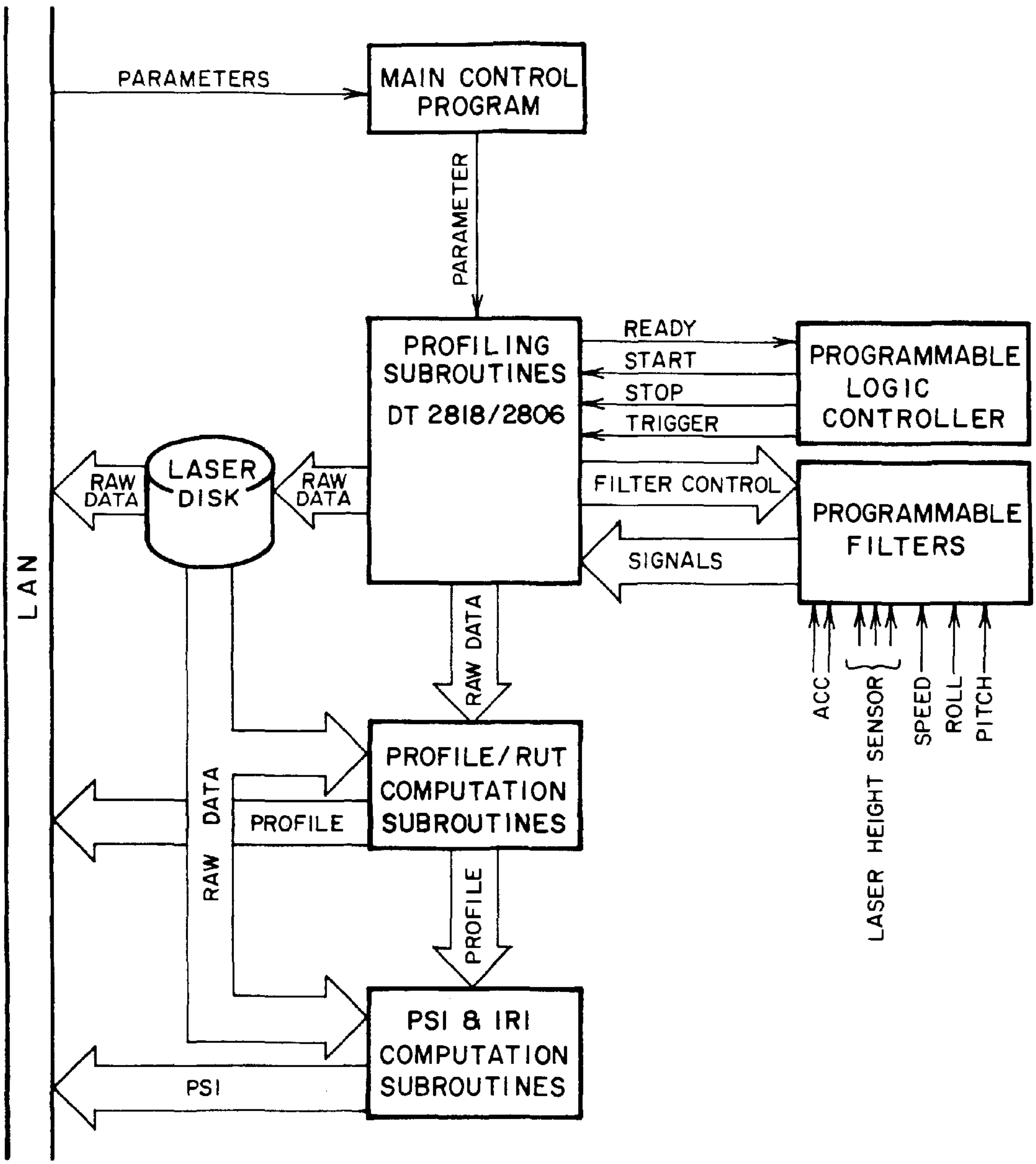

Figure 13. Profile/rut data flow diagram.

- Computer (80386-base with 80387 coprocessor, parallel, serial ports).
- Hard disk.
- Optical Disk Memory Storage (WORM).
- Data Translation DT2801-A Analog and Digital I/O Board.
- Frequency Device Model 9016 Programmable Analog Filter.
- Eight instrumentation amplifiers.
- Null balance accelerometers.
- Selcom Laser distance transducers with processing unit (Optocator).
- Speed pulse to analog voltage converter.
- A roll and pitch gyroscope.

The peripheral devices of the profile/rut computer are connected or configured so that the:

- Hard disk is drive C.
- Optical storage disk is drive E.
- IEEE-488 is connected to the 9016 filter.
- DT2801-A board is connected to one of the 8-bit bus connectors.

ELECTRICAL DESCRIPTION

Two major electronics systems are associated with the profiling system: the Selcom Optocator system and the Profile PC system.

Selcom Optocator System

Figure 14 is a schematic block diagram for the Selcom Optocator system. As shown in the figure, there are three optical probes: one located above the left wheel track, one above the right wheel track, and one above the center of the lane. Each probe is placed so that the bottom face is located roughly 12 in (305 mm) above the road surface. Each probe has a measuring range of 10 in (254 mm), which means that the probes can provide measurements when the face of the probe ranges from 7 to 17 in (177 to 433 mm) above the pavement surface.

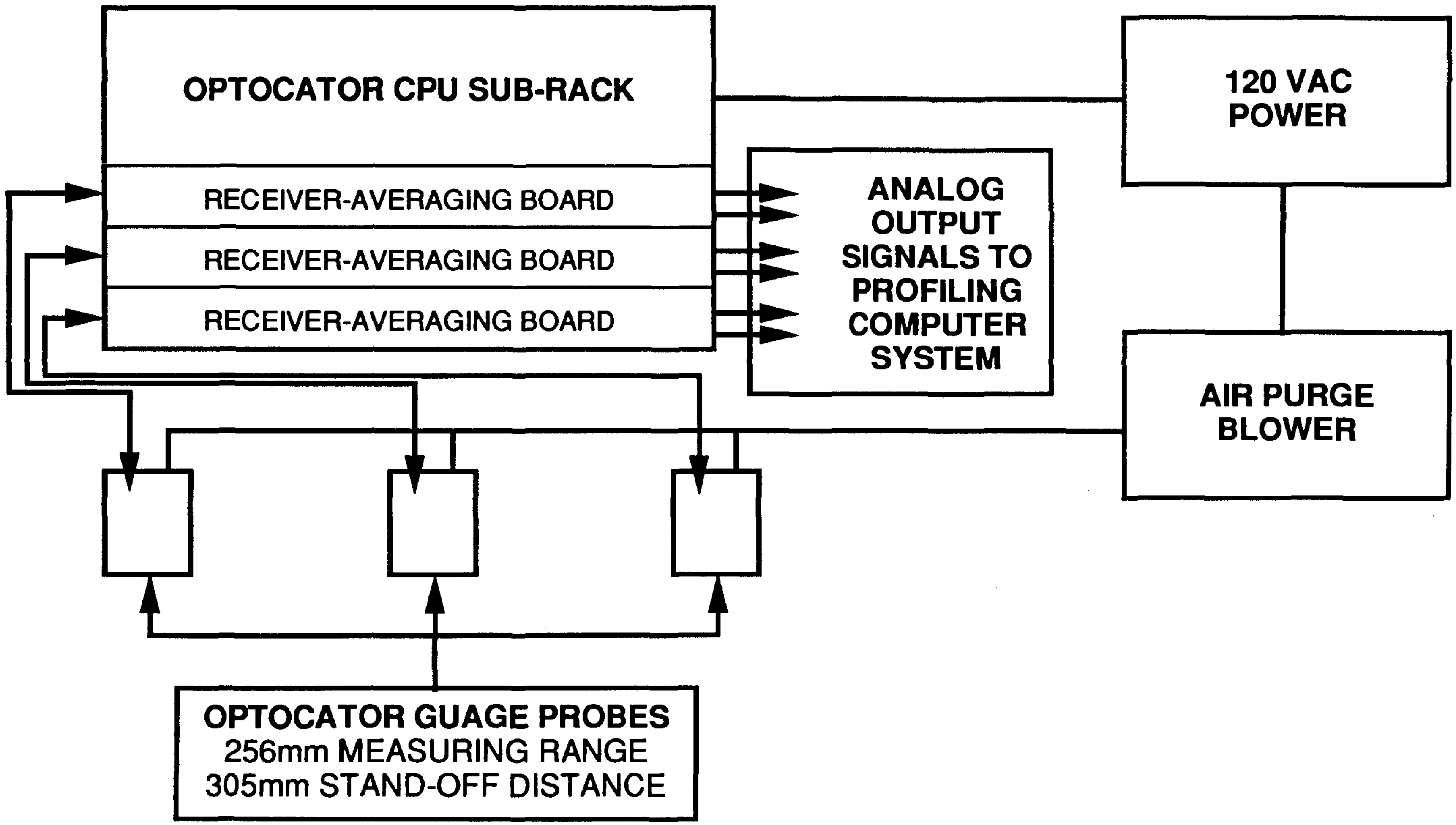

Figure 14. Selcom Optocator distance-measuring system.

A gauge probe uses a laser beam and a photodetector array to measure distances. The beam strikes the road surface at a right angle and part of the reflected light is focused on the sensor array. The gauge probe digitally transmits array photodetector element sensing information to the receiver-averaging board in the Optocator CPU. The probes utilize a 32-kHz sampling frequency that enables the Optocators to acquire 16,000 samples per second.

The receiver portion of the receiver-averaging board receives the serial data from the gauge probe at 16,000 bursts per second and processes each burst of data to derive the measured distance. This data rate is then reduced to a more stable form by an averaging process in the averaging portion of the board.

Distance information is made available by the CPU in both a digital and an analog form. The digital data acquisition option will not be used by the IRSV profile system; instead, distance data will be acquired from the analog signal output ports. The analog output voltage spans 0 to 10 VDC.

Profile PC System

Figure 15 is a schematic block diagram of the Profile PC system. The major components are the computer with its associated DT2801-A Analog and Digital I/O Board, IEEE-488 interface bus, mass memory (WORM) interface, LAN interface, instrumentation amplifiers, and a programmable filter set. Three lasers are considered normal as described below; however, when the fourth and fifth lasers are present, the roll and pitch connections are used for the additional lasers.

The Profile PC system has the most extensive data acquisition requirements of any system in the IRSV. The analog data signals are dynamic in nature and come from different types of sensors with different signal ranges.

The dynamic nature of the analog input signals dictates the need for filtering prior to the DT2801-A analog-to-digital data conversion process. The cut-off frequency of the filters, which is dependent on vehicle speed, is

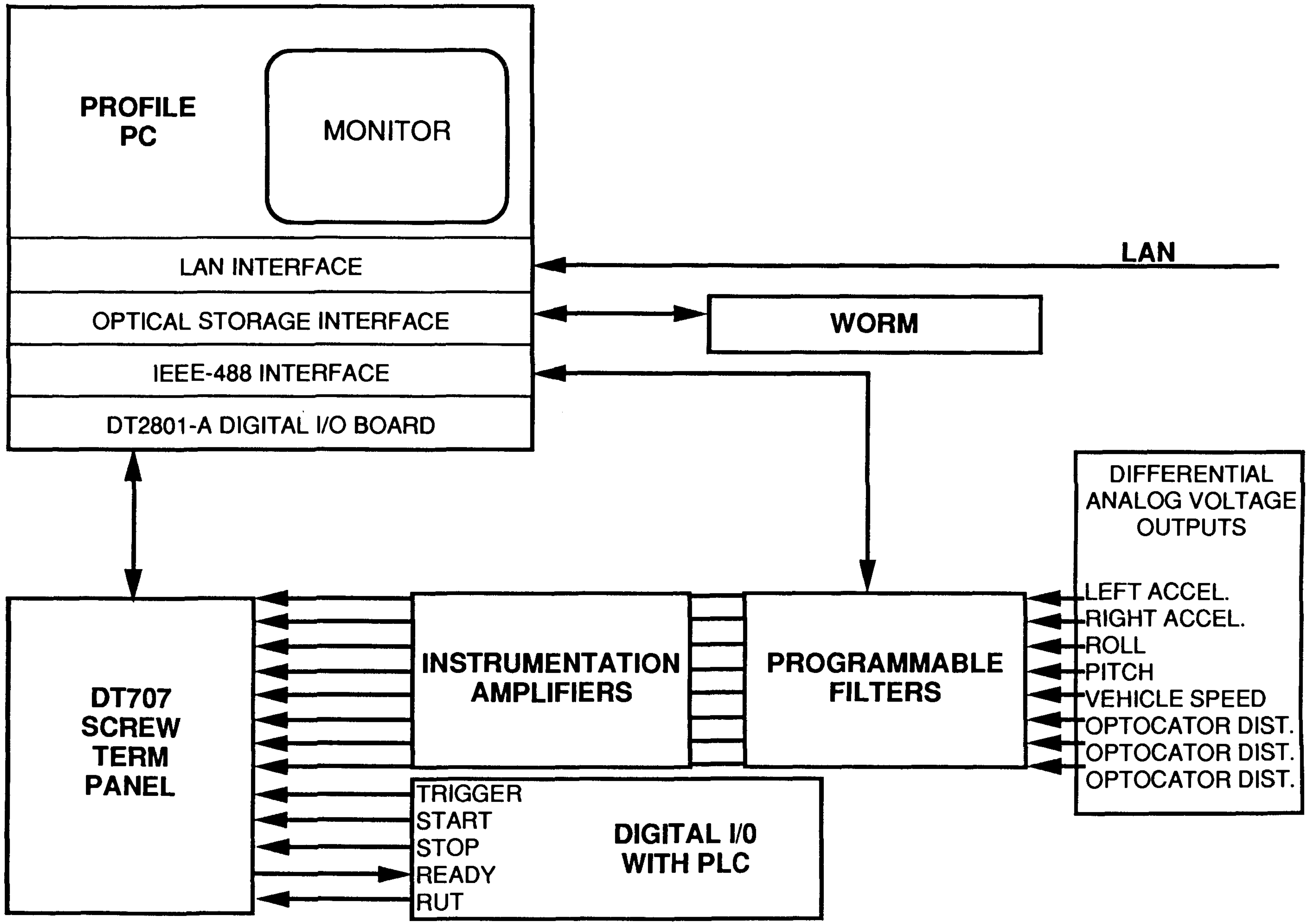

Figure 15. Profile system diagram.

set to eliminate any high frequency noise that may be introduced in the signal lines. Unwanted signals, which are most likely to be harmonics of real data or sensor resonances, can produce erroneous results during data acquisition.

The IEEE-488 interface card enables the computer to communicate with the filter bank. The LAN interface card enables the computer to communicate with the other computers on the LAN. The mass memory interface enables the computer to communicate with the WORM. The instrumentation amplifiers are used so that the DT2801-A can be programmed to read all analog inputs at the same voltage range (-5 to +5 VDC). This feature is important because the Optocator CPU analog output signals range from 0 to 10 VDC, the accelerometers have an output signal range of ±5 VDC, and the gyro output signals range from 0 to 10 VDC. The amplifiers, which can be adjusted for voltage offset and magnitude, make all sensor output signal ranges consistent.

Figure 16 is a schematic block diagram for the fifth-wheel system. The analog output provides accurate vehicle speed information to the Profile PC system. Figures 17 and 18 are schematic block diagrams for the accelerometer and gyro systems. These sensors provide vehicle motion information to the Profile PC that enable it to compensate for vertical motion when determining road profiles.

Cabling

The cabling is shown generically in figure 19. The common ground configuration is assumed. The return wires for the trigger line and all other analog signals are required.

Signal Conditioning

As shown in figure 19, signals from all transducers are first properly processed by the Optocator's own processing unit. Then the signals are amplified or shifted to the proper voltage range (±5 V). These signals also have to be properly filtered to avoid aliasing during digital data acquisition. This is accomplished by the programmable filters. The filter cutoff frequency depends on the vehicle speed because the Optocator sampling

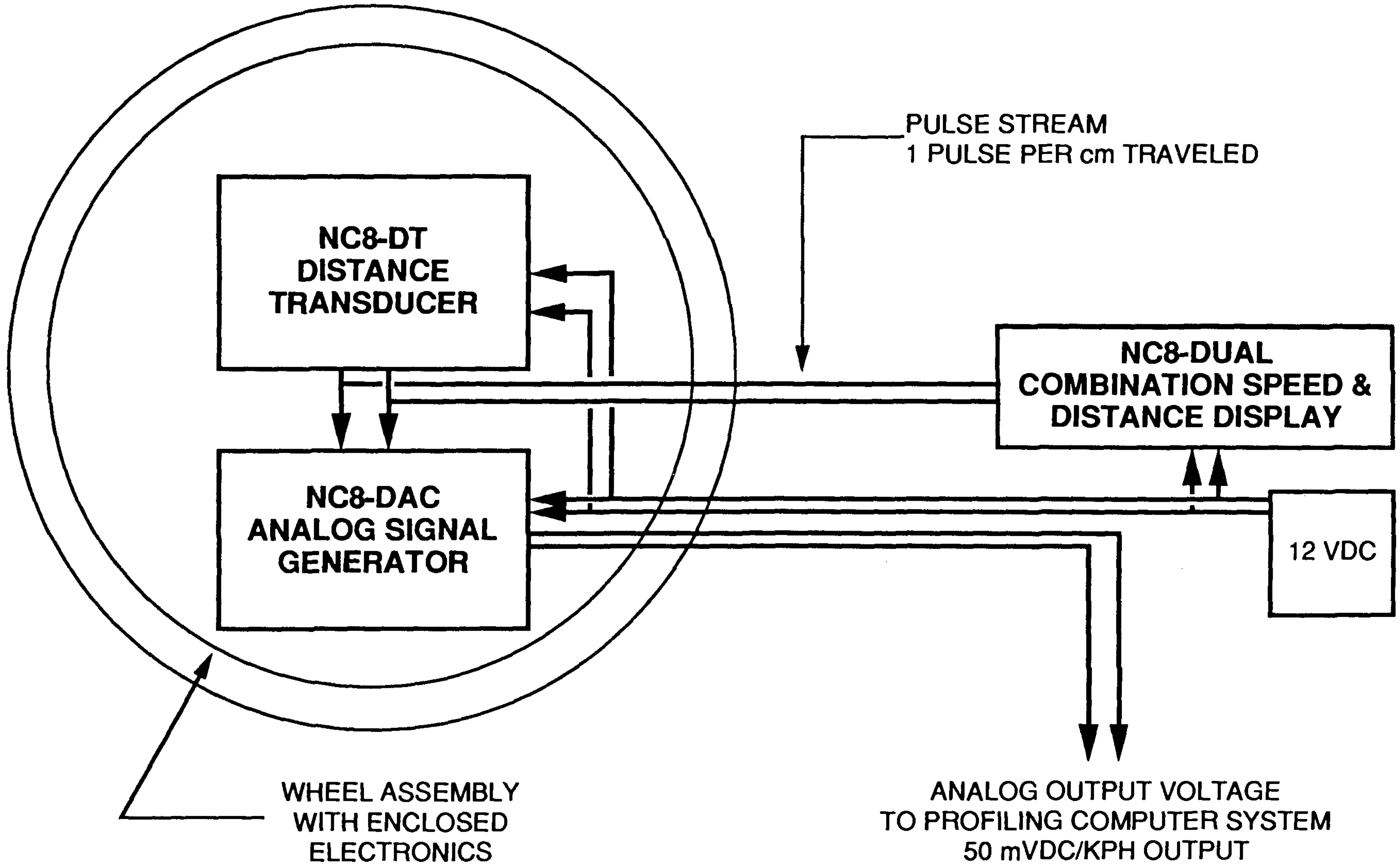

Figure 16. Fifth-wheel system diagram.

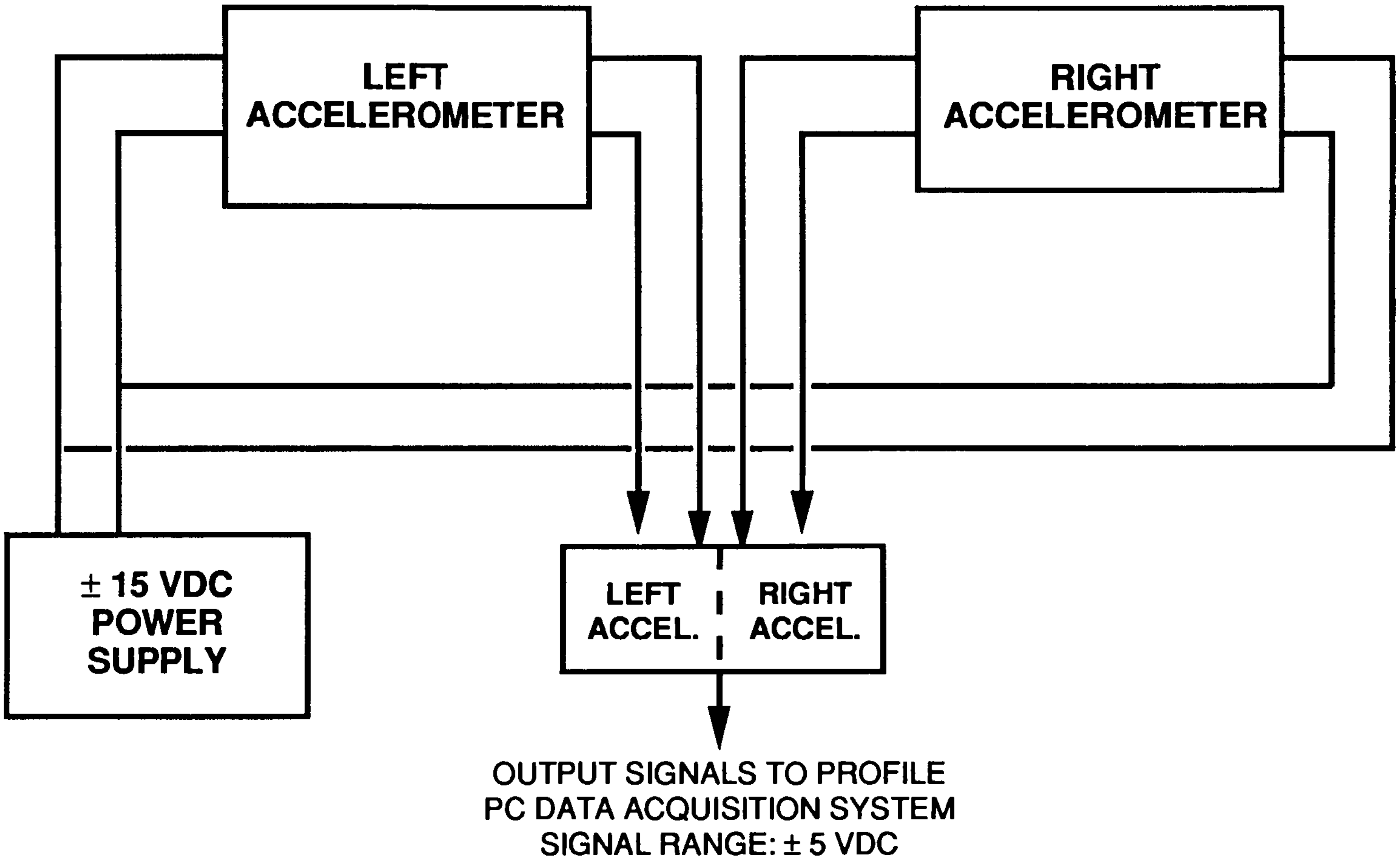

Figure 17. Accelerometer wiring schematic.

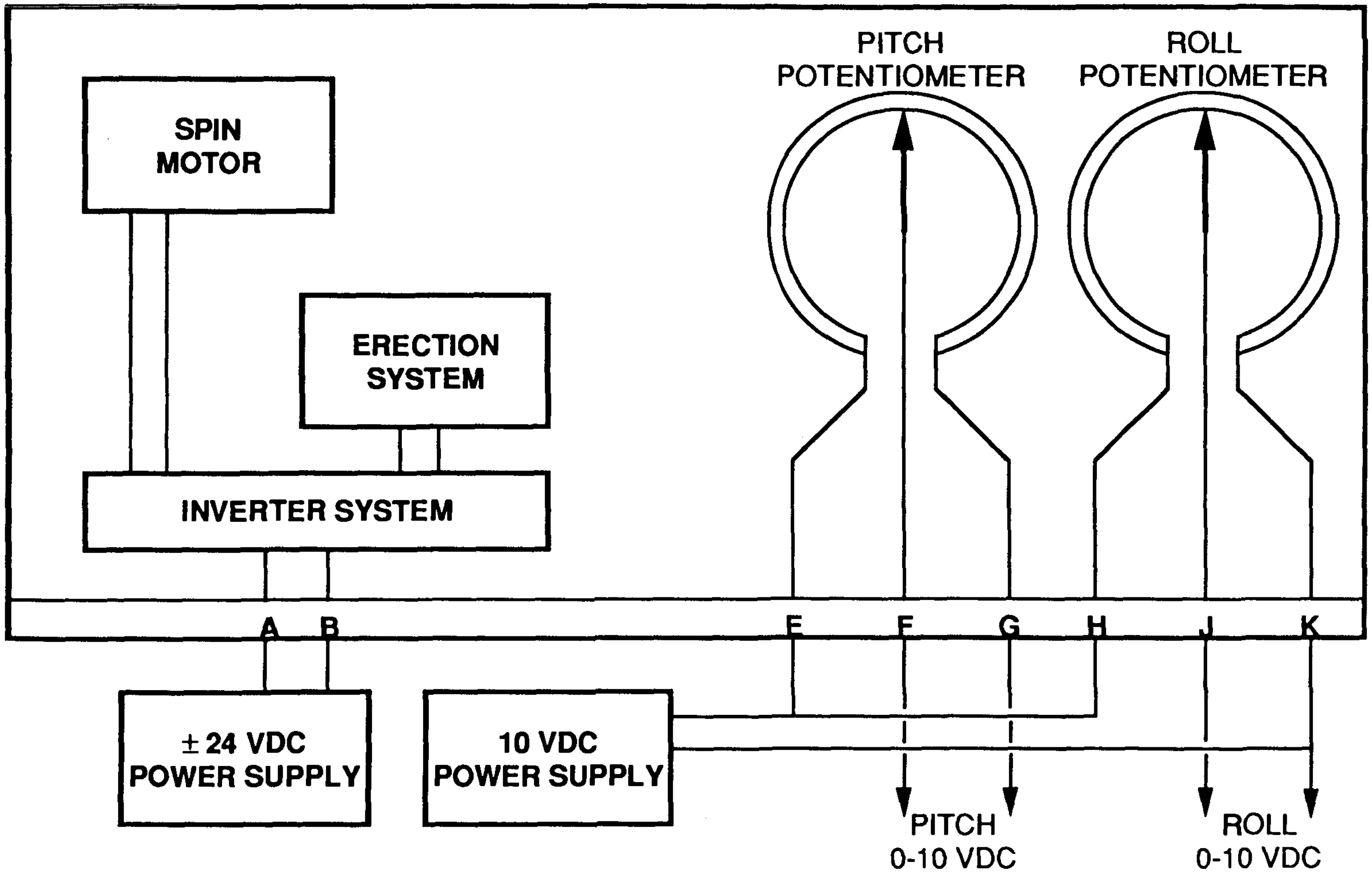

Figure 18. Gyro schematic diagram.

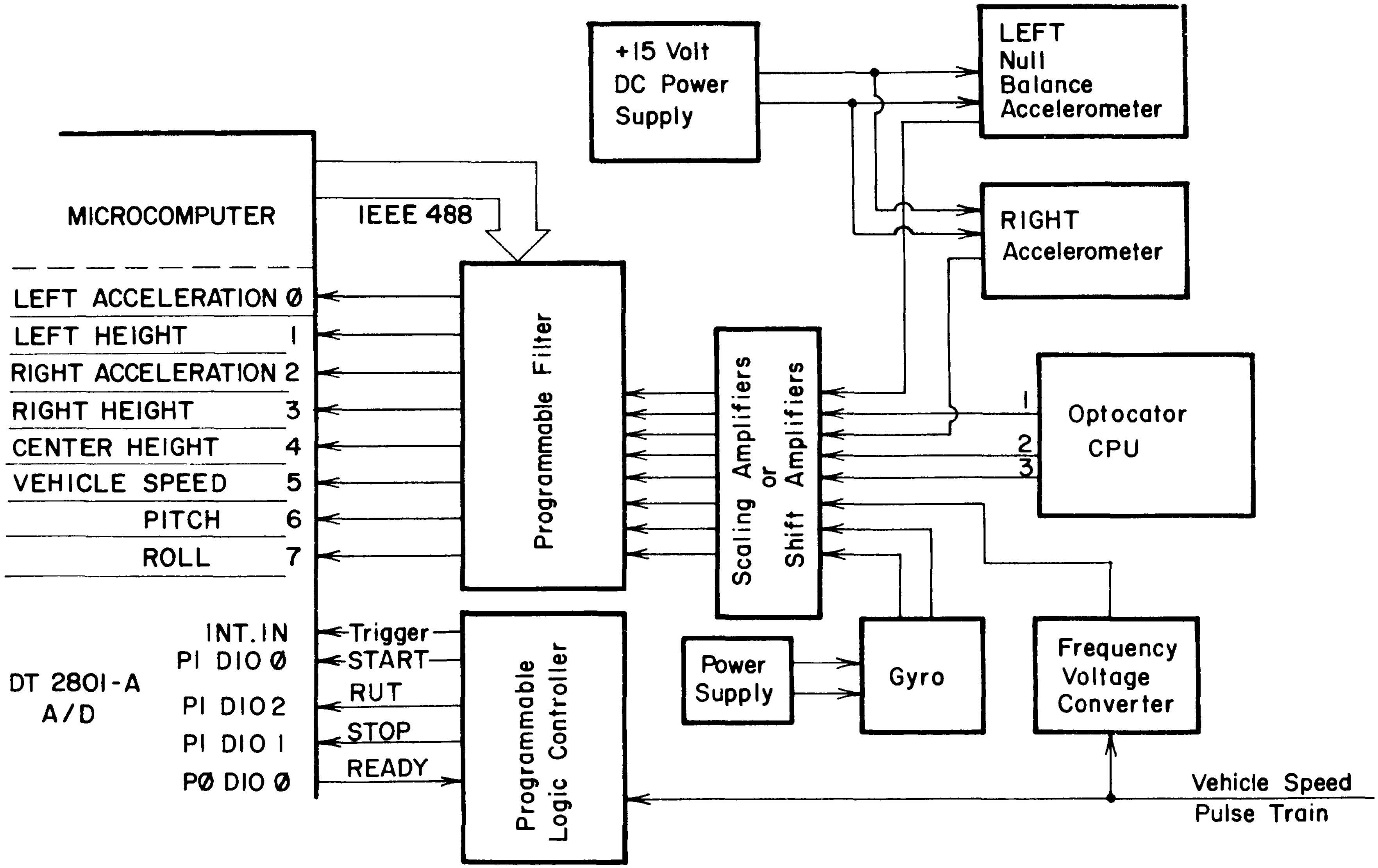

Figure 19. Flow diagram for profiling system.

distance is fixed. The computer acquires these signals sequentially and stores them on laser disk for later processing. Signals are acquired and recorded on the trigger line's rising edge. The performance of data acquisition is controlled by the PLC through the digital I/O ports and external trigger input.

Instrumentation Amplifiers Setup

The A/D channel configuration of DT2801-A is shown in table 8. The voltage range of DT2801-A's analog channels is configured as -5.0 to +5.0 V. Thus, the accelerometer signals have to be amplified by a factor of two; the signals from laser height sensors have to be shifted -5.0 V; the analog speed signal has to be shifted -4 V; and the gyro's signals have to be amplified as specified in table 8. This configuration has to be followed strictly to be consistent with the written software and to obtain proper calibration.

The digital channel configuration of DT2801-A is shown in table 9. This is the status information transferred between the Profile/Rut PC and the PLC. The trigger line from the PLC is connected to EXT. INT. (External Interrupt).

DATA ACQUISITION AND INFORMATION TRANSFER REQUIREMENTS

The Profile PC system acquires the following data with each measurement:

- Optocator gauge probe distance from one to three probes.
- Vehicle acceleration from two sensors.
- Vehicle roll or a fourth probe.
- Vehicle pitch or a fifth probe.
- Vehicle speed.

Based on the measurements performed, the Profile PC derives the longitudinal profile and then calculates the IRI and PSI values and/or the rutting and/or data for transverse profile. The computer stores these profiles, along with the associated time and date, in mass memory (WORM) and makes this information available to the LAN.

Table 8. A/D channel configuration of Profile/Rut PC.

A/D Channel	Transducer	Sensitivity	Start
0	ACC1	10 V/G	0 V = 0 G
1	Laser1	-1 V/in (0.04 V/mm)	-5 V = +5 in
2	ACC2	10 V/G	0 V = 0 G
3	Laser2	-1 V/in (0.04 V/mm)	-5 V = +5 in
4	Laser3	-1 V/in (0.04 V/mm)	-5 V = +5 in
5	Speed	1 V/10 mi/h (0.62 V/10 km/h)	4 V = 0 mi/h (4 V = 0 km/h)
6	Roll (Laser 4)*	2 V/10 deg	0 V = 0 deg
7	Pitch (Laser 5)*	2 V/10 deg	0 V = 0 deg

* Channels 6 and 7 may be used for gyroscope input (design configuration) or may be used for laser input. If laser input is used then the sensitivity and start values should be changed to the same as Channels 1, 2, and 3.

Table 9. Digital configuration of Profile/Rut PC.

Port 0	Bit 0	----------	READY
Port 1	Bit 0	----------	START
Port 1	Bit 1	----------	STOP
Port 1	Bit 2	----------	RUT
EXT.INT.		----------	Trigger Pulse Train

Data

The data flow diagram of the data transfer scheme is shown in figure 13.

Data Collected. Five types of data are collected in the Profile/Rut PC system: the vehicle's vertical acceleration, the vehicle's height relative to the pavement, the forward speed of travel, and the vehicle's pitch and roll. Two acceleration signals (left and right), three height signals (left, center, and right), one speed signal, one roll signal, and one pitch signal are recorded whenever a pulse is present on the trigger line. The trigger is based on distance traveled and is preprogrammed into the PLC.

Data Files. The data files contain only raw data stored in the following sequence: left accelerometer, left height, right accelerometer, right height, center height, speed, pitch, and roll voltages.

Format. To save storage space, the data is stored in binary format. To read this data, the file has to be opened in binary format. For raw data, eight 2-byte integer values are stored for one sample. For longitudinal profile, two 4-byte real values are stored for every 6.0 in (0.15 m) traveled. For transverse profile, one 4-byte real value is stored for every 3.0 ft (0.915 m) traveled. These values were set per ASTM Standard E17 950, but can be changed manually by changing the parameters in the setup file to acquire as many as 12 samples per ft (0.15 m).[19]

Structure. The raw data for the longitudinal and transverse profiles are stored in binary format in a single unstructured file as a single string of numbers. The computed longitudinal profile is stored in a file with the extension .PRF. This file contains eight columns of original raw data in integer format, and two columns of left and right profiles in real format. PSI and IRI values are stored in a file with the extension .PSI. This file contains three columns: the first column contains length measurements in 0.1-mi increments; the second column contains PSI values; and the third column contains IRI vlaues. Transverse profile data, or rut depth, are stored in a separate data file in one-column real format.

Software

The profiling task includes raw data acquisition, data summary processing, profile/rut computation, IRI computation, and PSI computation. Because the computer's memory is limited, these tasks are programmed separately and run sequentially after the prior task has been completed. The required programs are DATACQ.FOR for data acquisition and testing, VANAL.FOR for data processing, and PROFCOM.FOR for profile/rut, PSI, and IRI computations and result storing. Some parameters have to be passed between the three programs because the three tasks are related.

A list of filenames is created during the data acquisition stage. This list of filenames is used during the processing of the data so that the raw data may be properly located and recovered from the WORM disk. These separate programs are described below.

Data Acquisition. The profile control program, DATACQ.FOR, requires a number of subroutines, as shown in figure 20. This program acquires the raw data and stores the data in mass storage (WORM disk). The data acquisition program uses many PCLAB routines to access the DT2801-A board. The program flow diagram is shown in figure 21.

The capacity of the profile control program is currently limited to a sampling size of 30,000 for each of 8 channels. This limit is due to the memory limitation of DOS. If the operating system is upgraded and a larger FORTRAN compiler is adopted, the sampling size can be as large as computer memory will allow.

Data Summary Program. As stated earlier, memory limitations dictate that the entire profiling task be divided into three subtasks performed by separate programs. The second task is the processing of raw data for computig the profile. Because the profile computation consists primarily of the integration of an acceleration signal, profile drifts are introduced due to the integration constant, no matter how small the drift of the raw signal. Therefore, a pre-process program to find the mean values of all raw

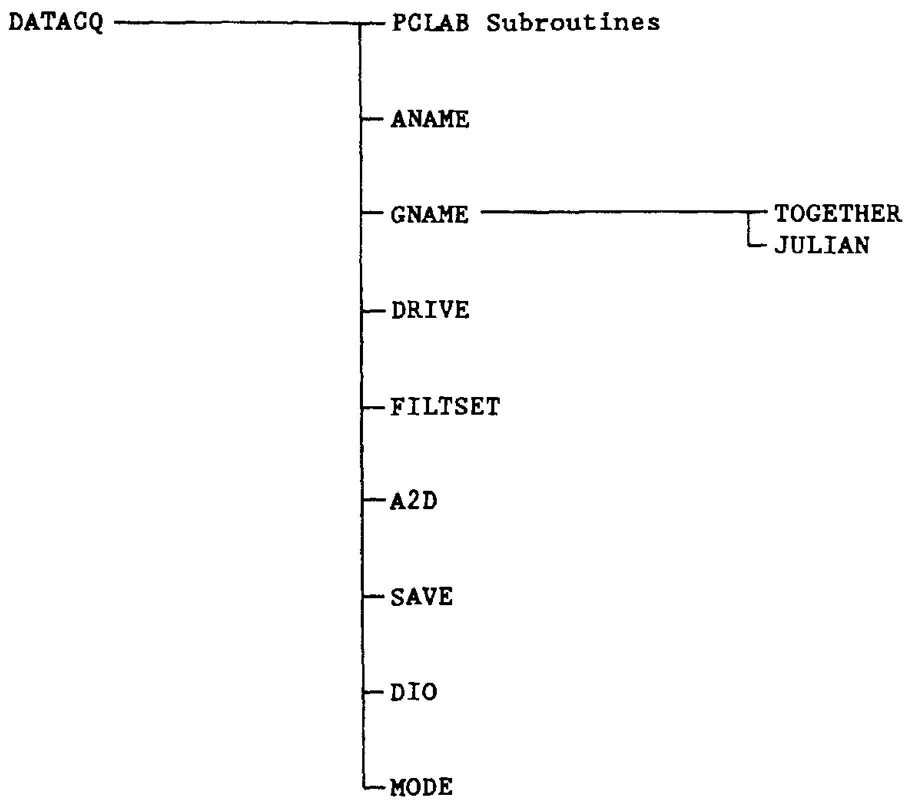

Figure 20. Profile system data acquisition program structure.

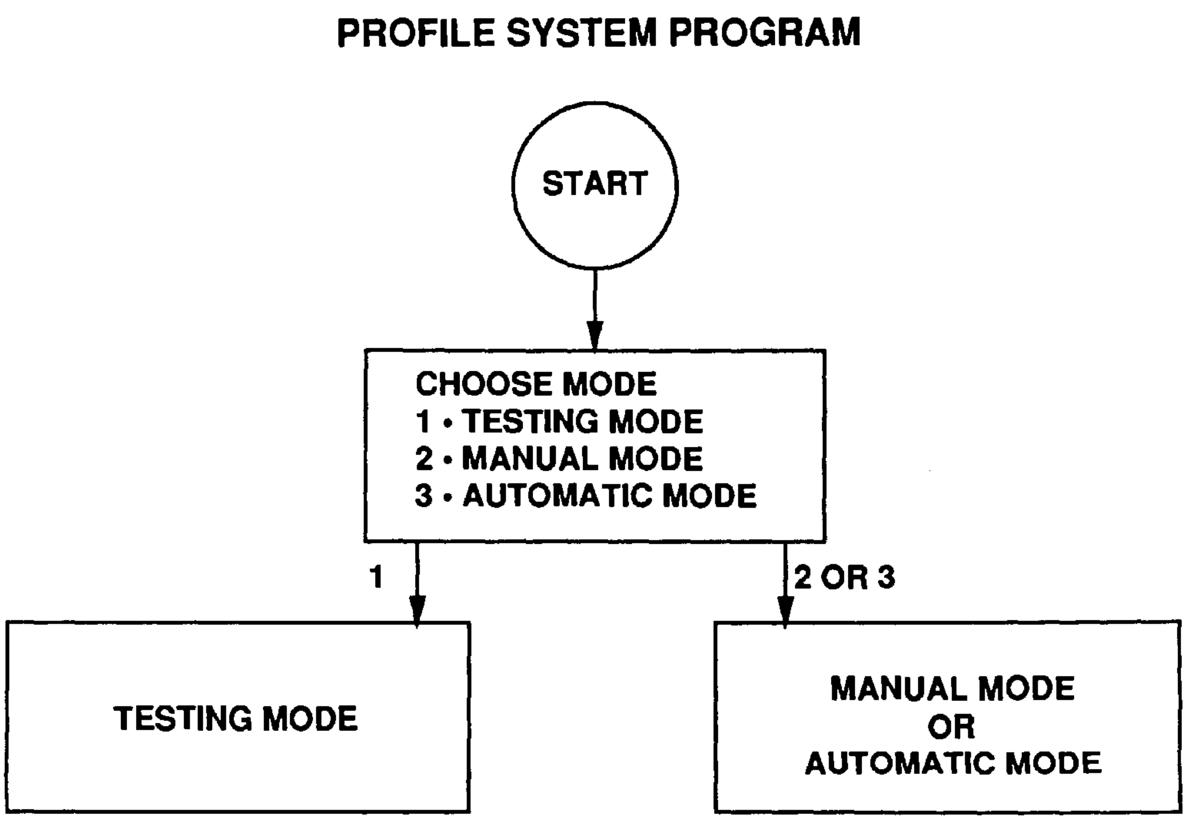

Figure 21. Flow diagram for profile system data acquisition program.

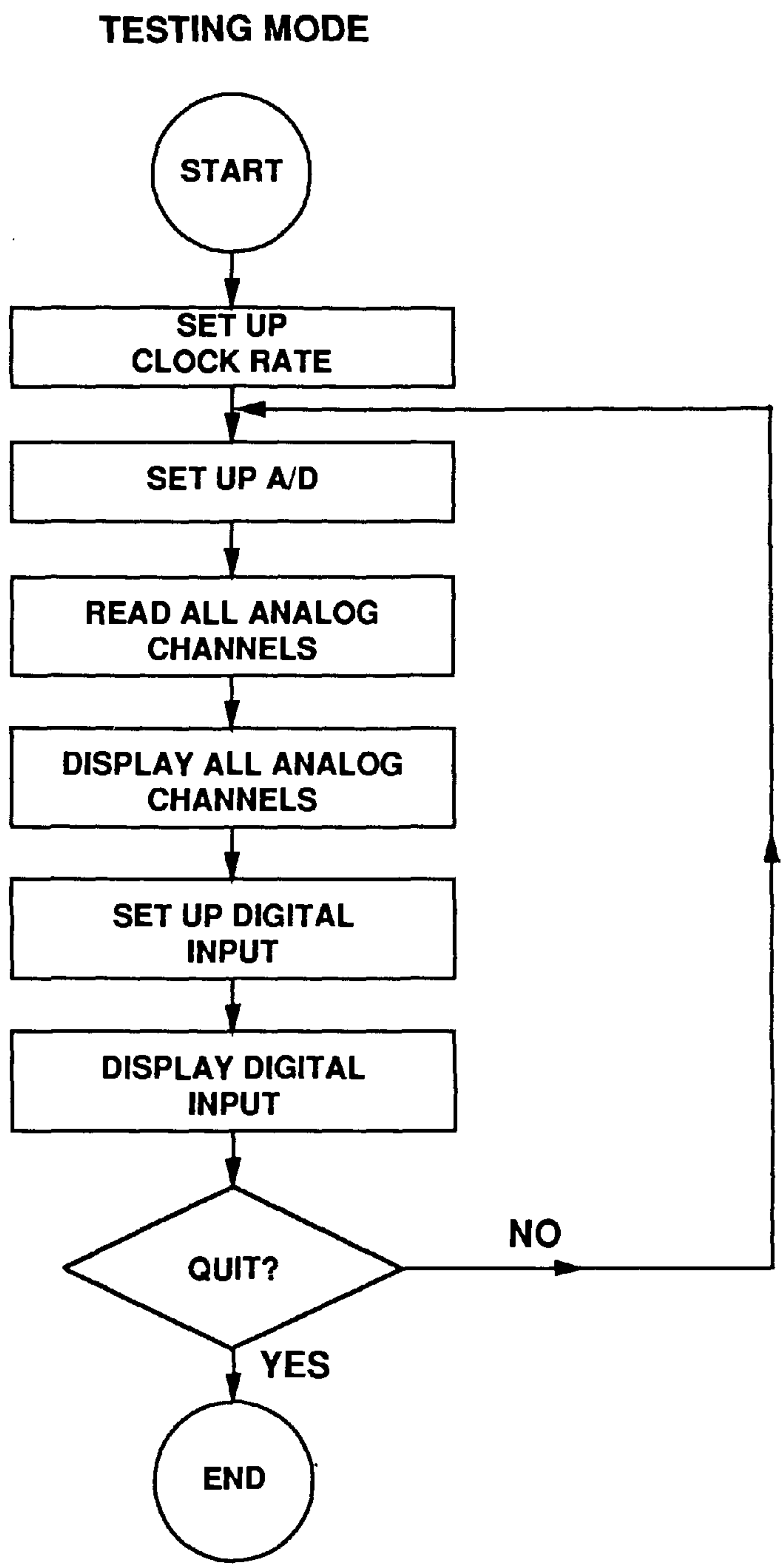

Figure 21. Flow diagram for profile system data acquisition program (continued).

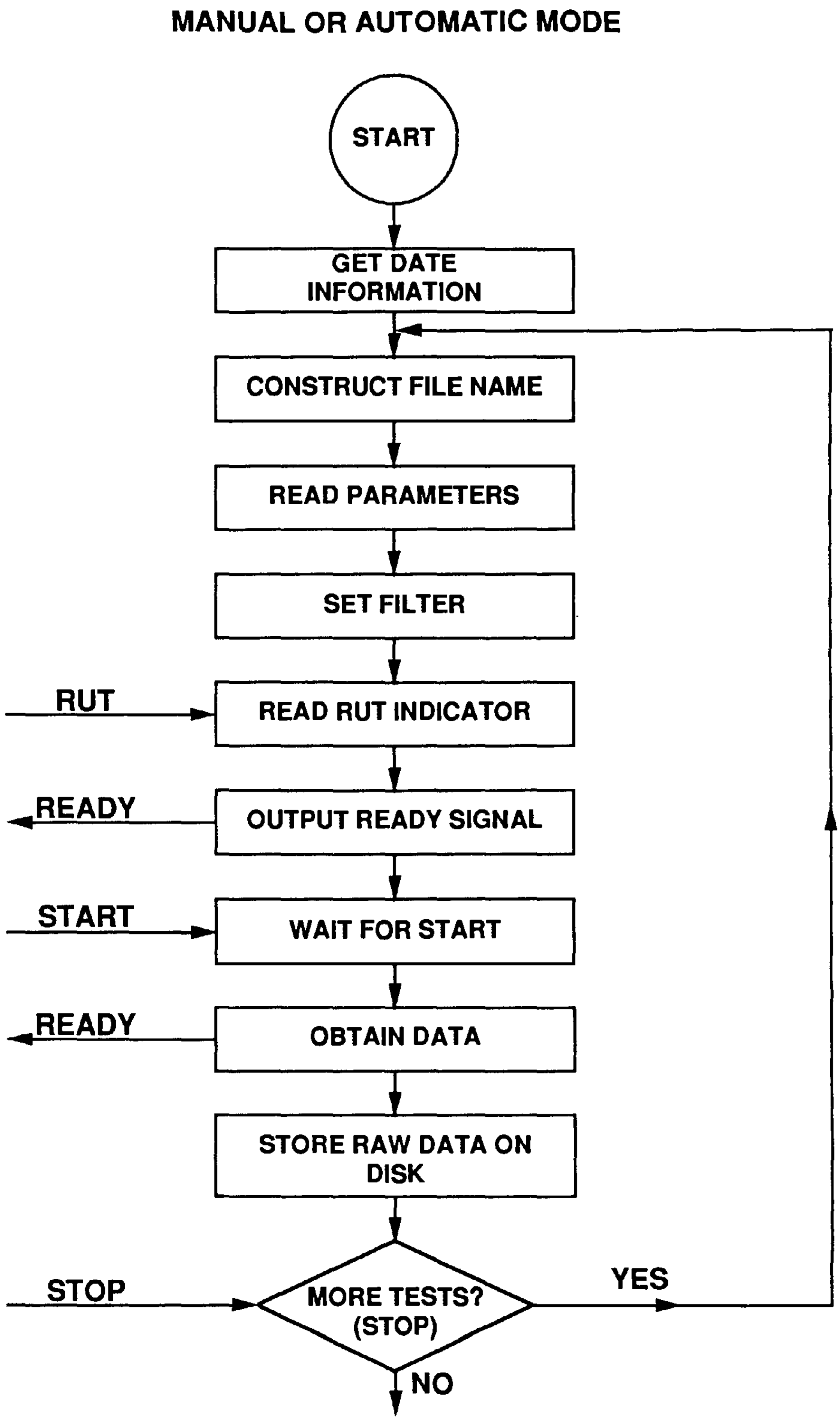

Figure 21. Flow diagram for profile system data acquisition program (continued).

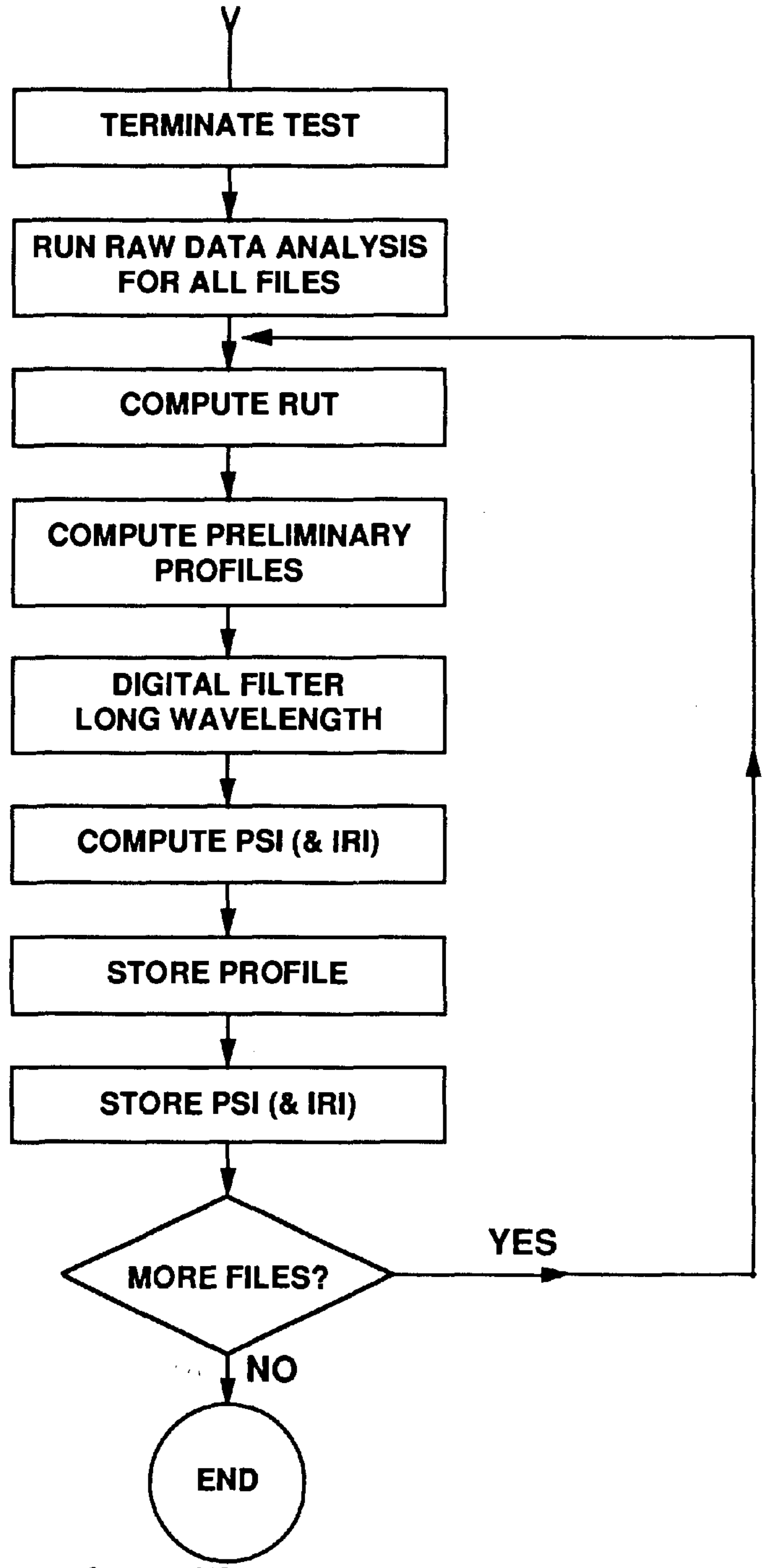

Figure 21. Flow diagram for profile system data acquisition program (continued).

acceleration signals is used to reduce the profile drift. This program, VANAL.FOR, requires no other subroutines. The flow diagram of VANAL.FOR is shown in figure 22.

Profile Computation. The profile/rut computation program, PROFCOM.FOR, requires a number of subroutines, as shown in figure 23. This program also computes IRI and PSI while the profile is still in the memory. Again, the capacity of the program is related to the memory size of the computer system. The program only handles a sample size of 30,000. The flow diagram of PROFCOM.FOR is shown in figure 24.

There are many calibration constants in this program, and they have been fixed to be consistent with the setup of both the transducer and instrument amplifiers. These constants are particularly important for profile computation. The constants are defined in a separate FORTRAN source code listing. If the calibration is changed, then these constants will have to be changed to be consistent with the system.

Storage Method. The raw profile data is stored on the WORM disk. After processing, the processed data is also stored on the WORM disk. The Event (Main) PC accesses this WORM disk through the LAN. The profile subsystem also needs data acquisition parameters from the Event (Main) PC. This information transfer is accomplished by sharing the same virtual disk drive.

Auxiliary Files. The inputs and outputs of each program are summarized in table 10. The output of each program has its own particular format. The output of the data acquisition program consists of raw data files and a file containing a list of file names. The output of VANAL.FOR is a separate file that contains a list of file names and control data used later in the profile computation. The outputs of PROFCOM.FOR are profiles and PSI lists. These files are named in the format:

YYDDDnnn.EXT

where

YY is a two-digit number of year.

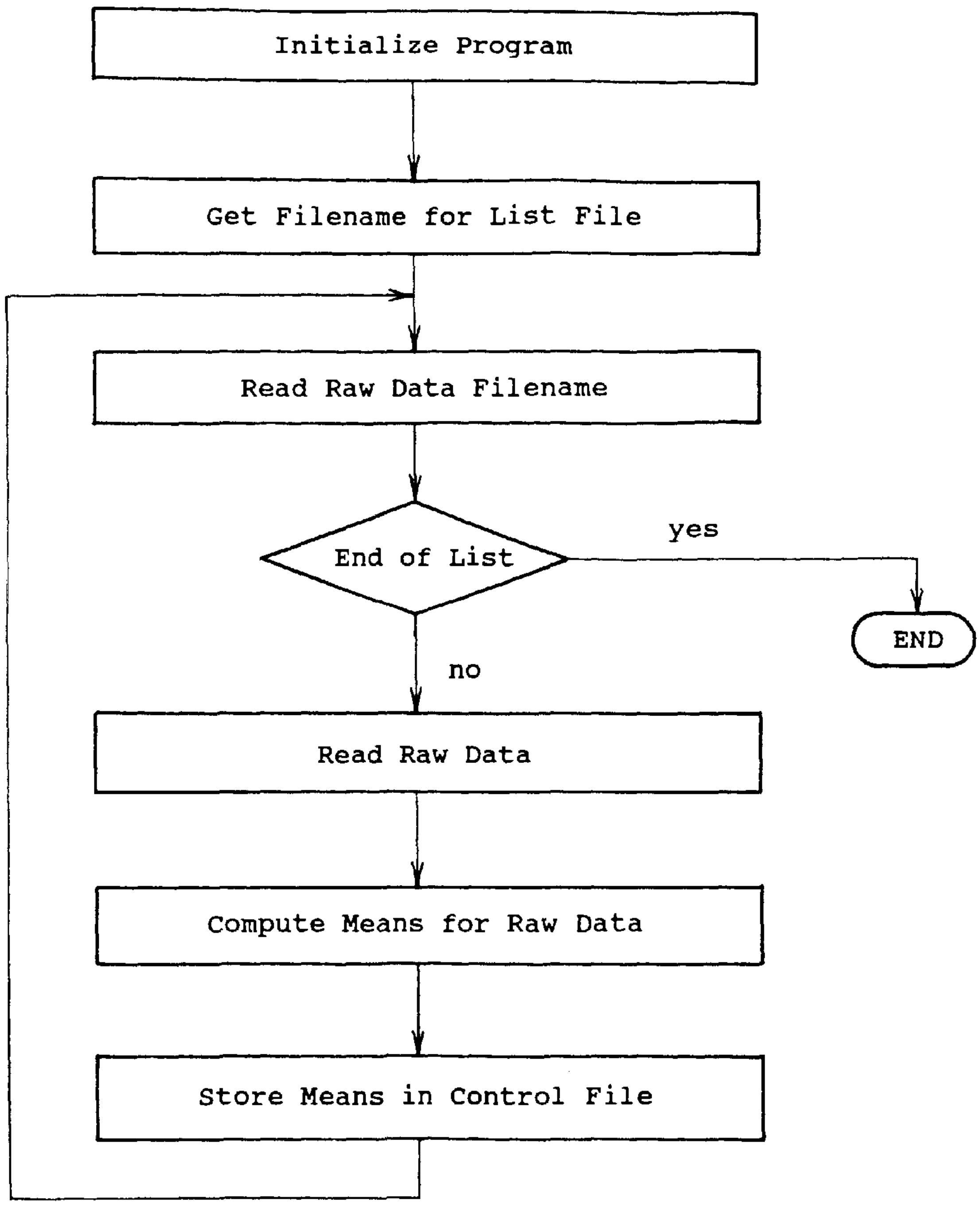

Figure 22. Data processing program flow diagram.

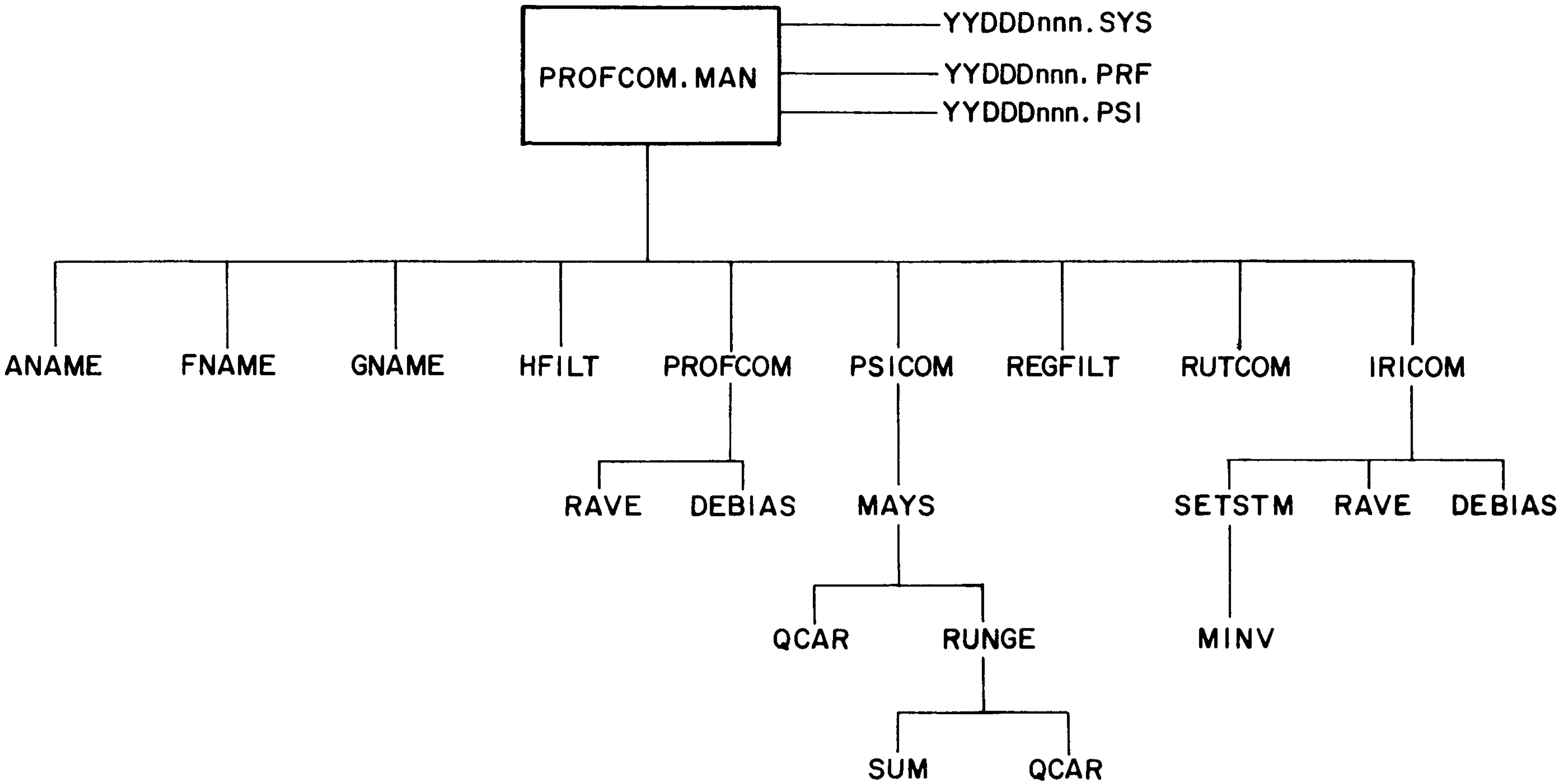

Figure 23. Program structure of profile/rut computation program, PROFCOM.FOR.

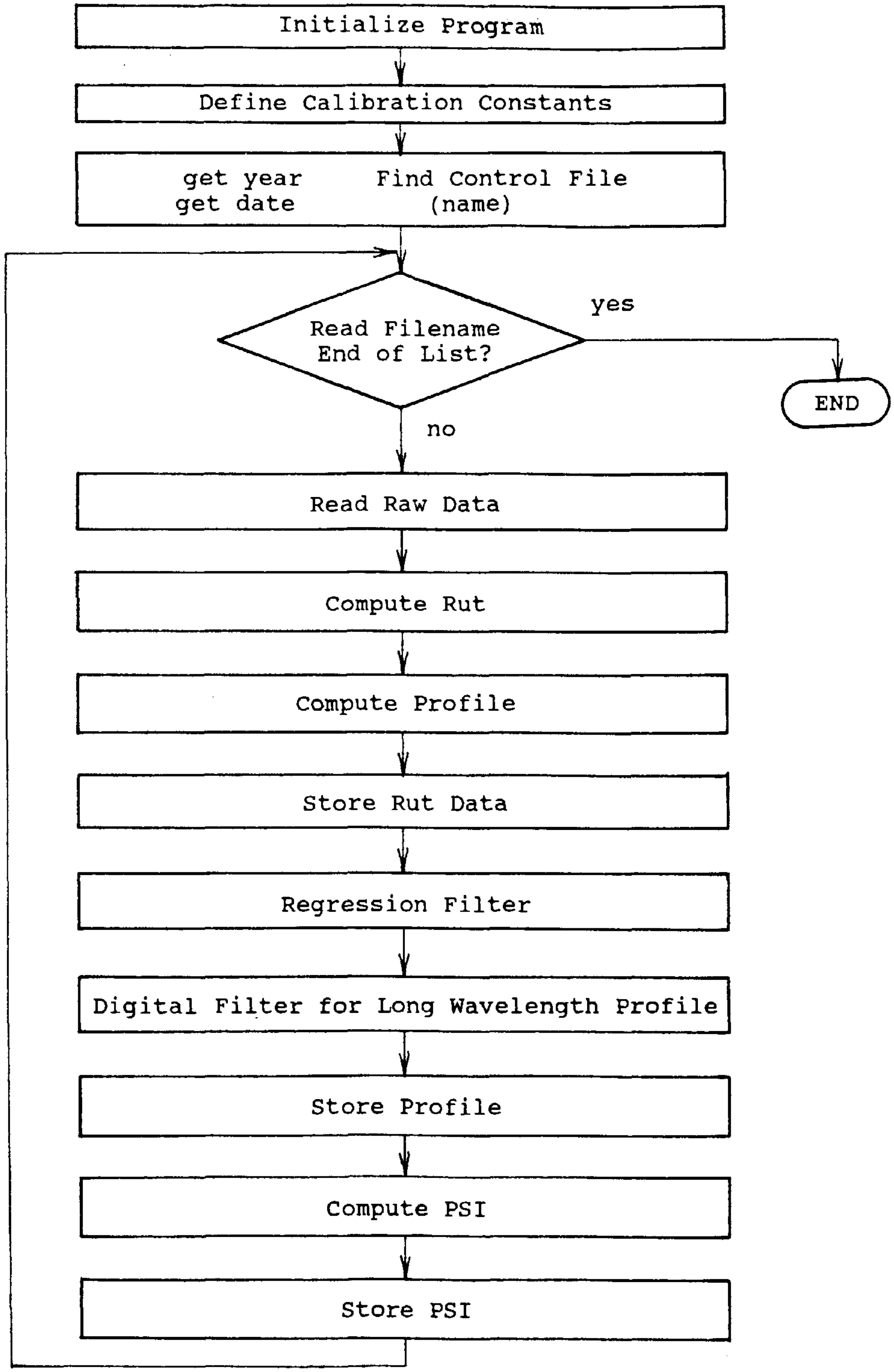

Figure 24. Profile/rut computation.

DDD is a three-digit number of Julian date of the year.

nnn is the profile sequence number of the day.

EXT is a three-letter extension representing attributes:

- .LST is file list produced by DATACQ.
- .RAW is raw data.
- .SYS is the control list produced by VANAL.
- .PRF is profile.
- .PSI is Present Service Index, and International Roughness Index.

Table 10. Input and output of each subprogram.

Program	Input	Input Location	Output	Output Destination
DATACQ	DATACQ.SYS	LAN	file list	LOCAL DRIVE
	FILTER.SYS	LOCAL DRIVE	raw data file	LOCAL
VANAL	file list	LOCAL DRIVE	control file	LOCAL
	raw data file	LASER DRIVE		
PROFCOM	control file	LOCAL	PSI list	LAN
	raw data	LASER DRIVE	Profile	LAN

Note: LASER DRIVE can be acccessed by the LAN.

Initialization. The three main programs, DATACQ.FOR, VANAL.FOR, and PROFCOM.FOR, are provided on a floppy disk as a series of subroutines. The subroutines must be linked together to form the three main programs. After they are linked together, they must be compiled with the FORTRAN compiler. The compiled programs are then linked to the PCLAB FORTRAN Library and to the PTI Library. This execution procedure refers to Microsoft FORTRAN 5.0.

PCLAB Setup

Before running any program in the Profile/Rut PC system, the DT2801-A board must be properly configured. This program constructs a system file that contains specifications such as board type, single-ended or differential input, unipolar or bipolar, voltage range, base address, etc. In this system, the configuration is: DT2801-A, differential input, bipolar, 5.0-V range, and base address: 2EC hexadecimal.

TEST AND CALIBRATION

Two systems have been provided for calibrating the profile distance transducers. In the first, a bracket is fitted to the vehicle so that a 2.0-in-wide (51-mm-wide) by 1.0-in-thick (25-mm-thick) aluminum bar is mounted transversely across the vehicle and positioned directly under the gauge probes. A 0.250-in-thick (6.35-mm-thick) ±0.001-in (±0.03-mm) aluminum plate and a 1-in-thick (25-mm-thick) ±0.001-in (±0.03-mm) aluminum plate are then used to provide calibration blocks for calibrating the gauge probes and checking the system. The plates provide three positions: neutral, plus 1 in (25.4 mm), and minus 1 in (25.4 mm). The CALIBPRF program is then used to calibrate the system with the three positions.

The transverse aluminum bar serves as a reference that is rigidly fixed with respect to the vehicle chassis and the gauge probe. This is in contrast to using the ground or floor of a garage as a reference. Such a reference is not fixed with respect to the gauge probes and, in general, is not level. By sliding the stainless steel block on the aluminum bar for a step change of 1.000 ± 0.001 in (25.400 ± 0.003 mm), the distance between the probe and the measured surface is provided.

In the second method, to test and calibrate the profilometer, two plates (1/4 in thick and 1 in thick [6.4 mm and 25.4 mm]) are prepared as above. In this procedure, the plates are placed directly on the ground and used as known heights for checking system calibration. Placing the two plates on the ground offers an easy technique that can be repeated daily. The transverse, vehicle-mounted bar would be used less frequently as a reference technique.

The two plates are used in conjunction with the CALIBPRF program and the procedures specified by the menu in the program. The flow diagram for CALIBPRF is shown in figure 25.

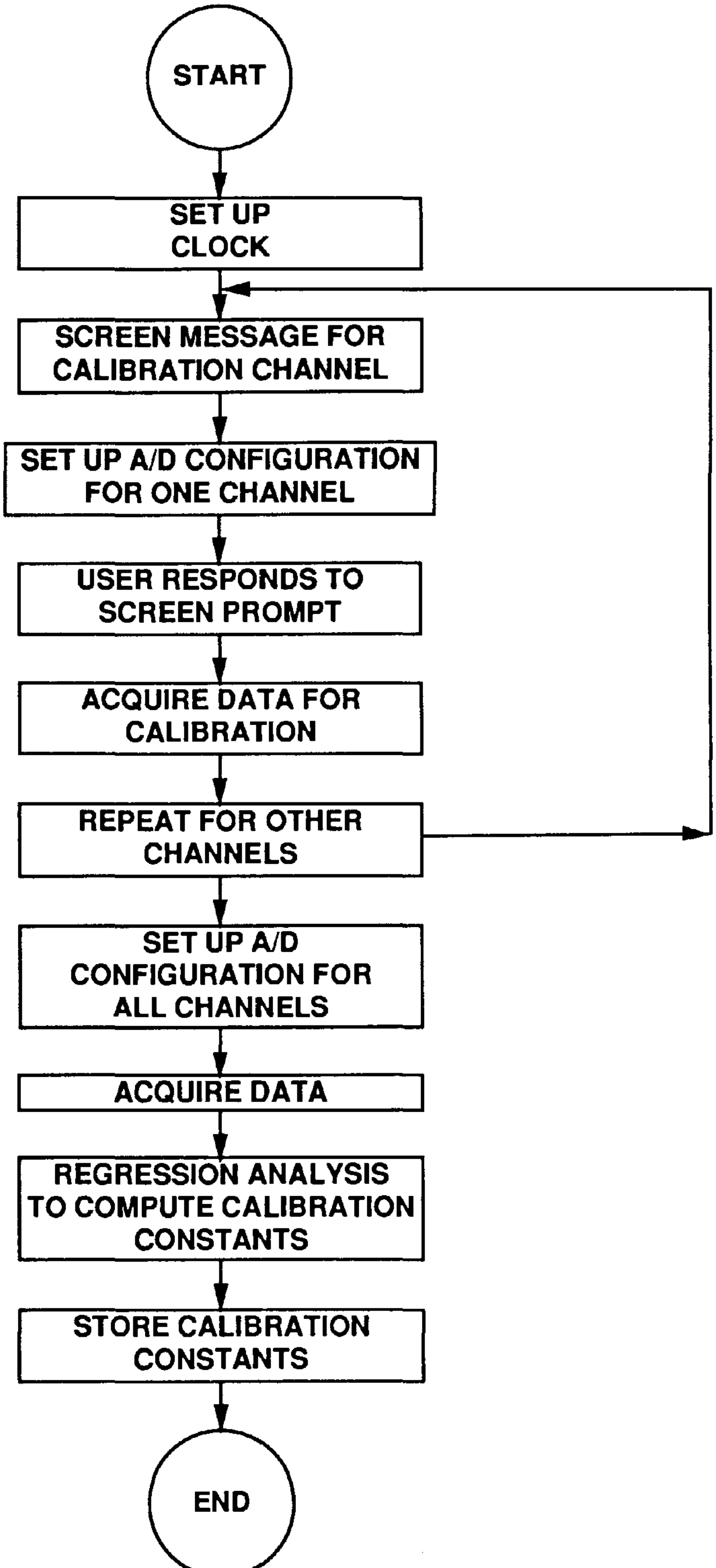

Figure 25. Flow diagram for profile system calibration program.

CHAPTER 5. SKID RESISTANCE MEASUREMENT

OVERVIEW

The road survey vehicle utilizes the spinup method for skid testing. In this method, the time interval between the pulses generated by the skid-wheel encoder after the skid-wheel brake has been released is measured. A layer of water is laid down on the road surface ahead of the tire per ASTM E 274. The skid testing process is shown in block diagram form in figure 26.

MECHANICAL DESCRIPTION

Personal Computer

The computer for the skid subsystem is based on a 80286-based CPU installed with a hard disk and a Data Translation DT2801-A analog/digital data acquisition board. The computer is interfaced with the programmable logic controller (PLC) to properly control locking the wheel, watering, releasing the brake, starting data acquisition, and recycling. The computer provides skid numbers with their slip speeds.

Skid Tester

The skid test wheel assembly consists of an ASTM Standard E 501 test tire mounted on a 15 x 6 JJ rim attached to an automobile wheel assembly (spindle with an integral wheel speed encoder), a brake rotor, and a brake caliper. This wheel assembly is supported by an articulated arm that can be raised and lowered by the vehicle operator or controller. The skid test assembly is weighted with dead weight so that the wheel is loaded to 1,085 lb (4826 N).

The articulated arm that supports the test wheel and the wheel assembly is raised and lowered by a pneumatic cylinder as it pivots about its attachment point on the vehicle frame. Electrically operated valves control the venting and filling of the air system.

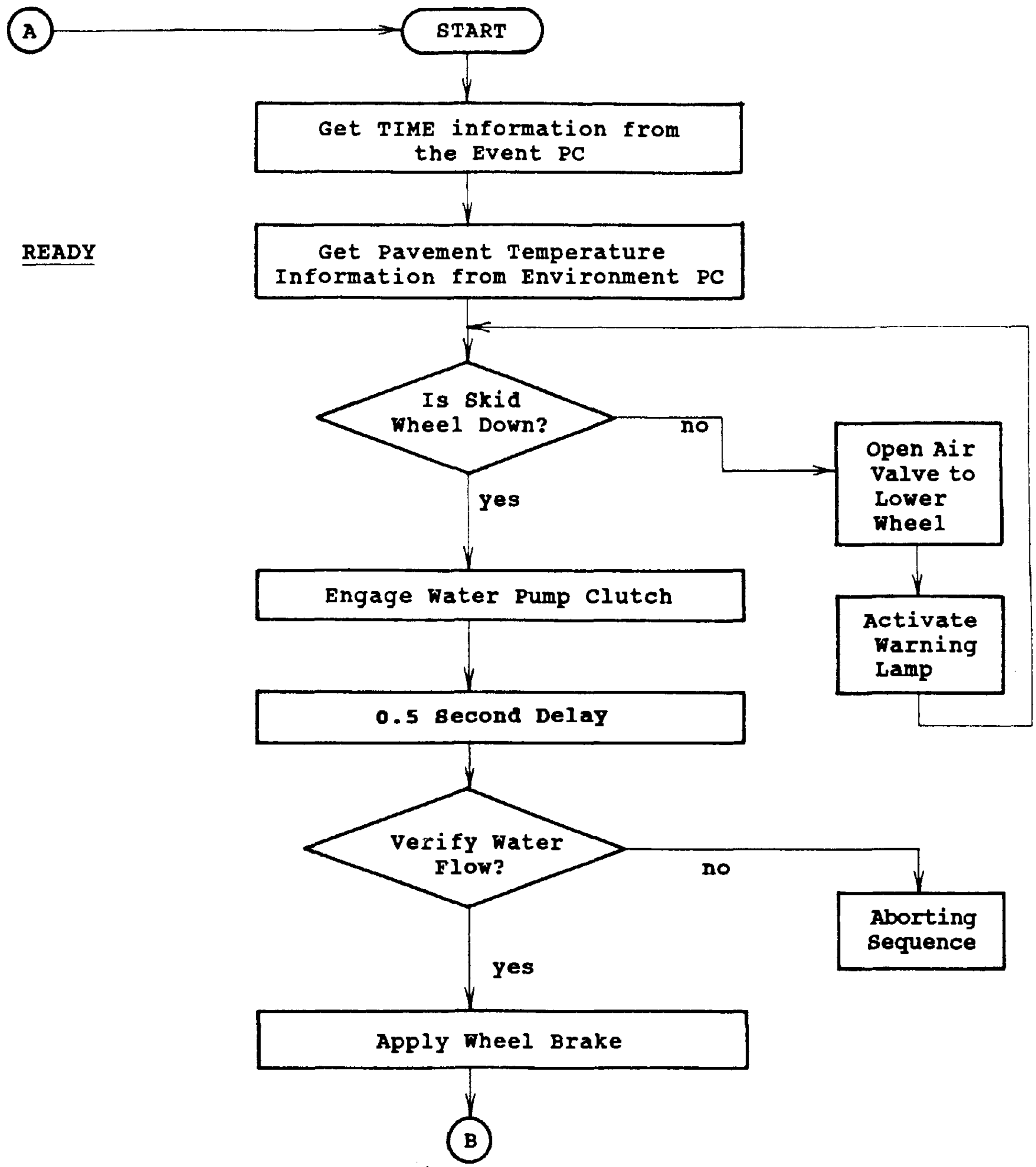

Figure 26. Skid test control procedure.

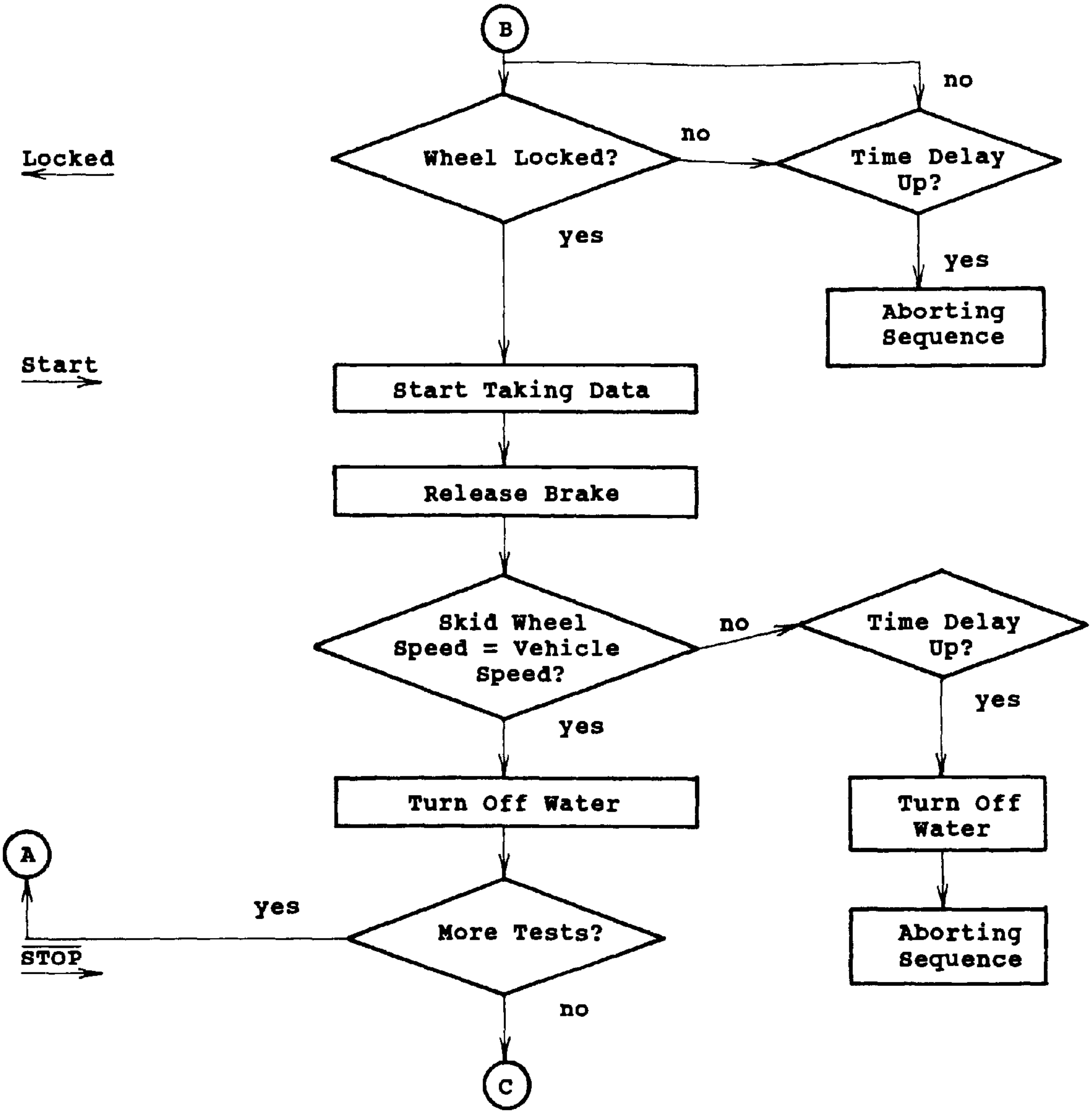

Figure 26. Skid test control procedure (continued).

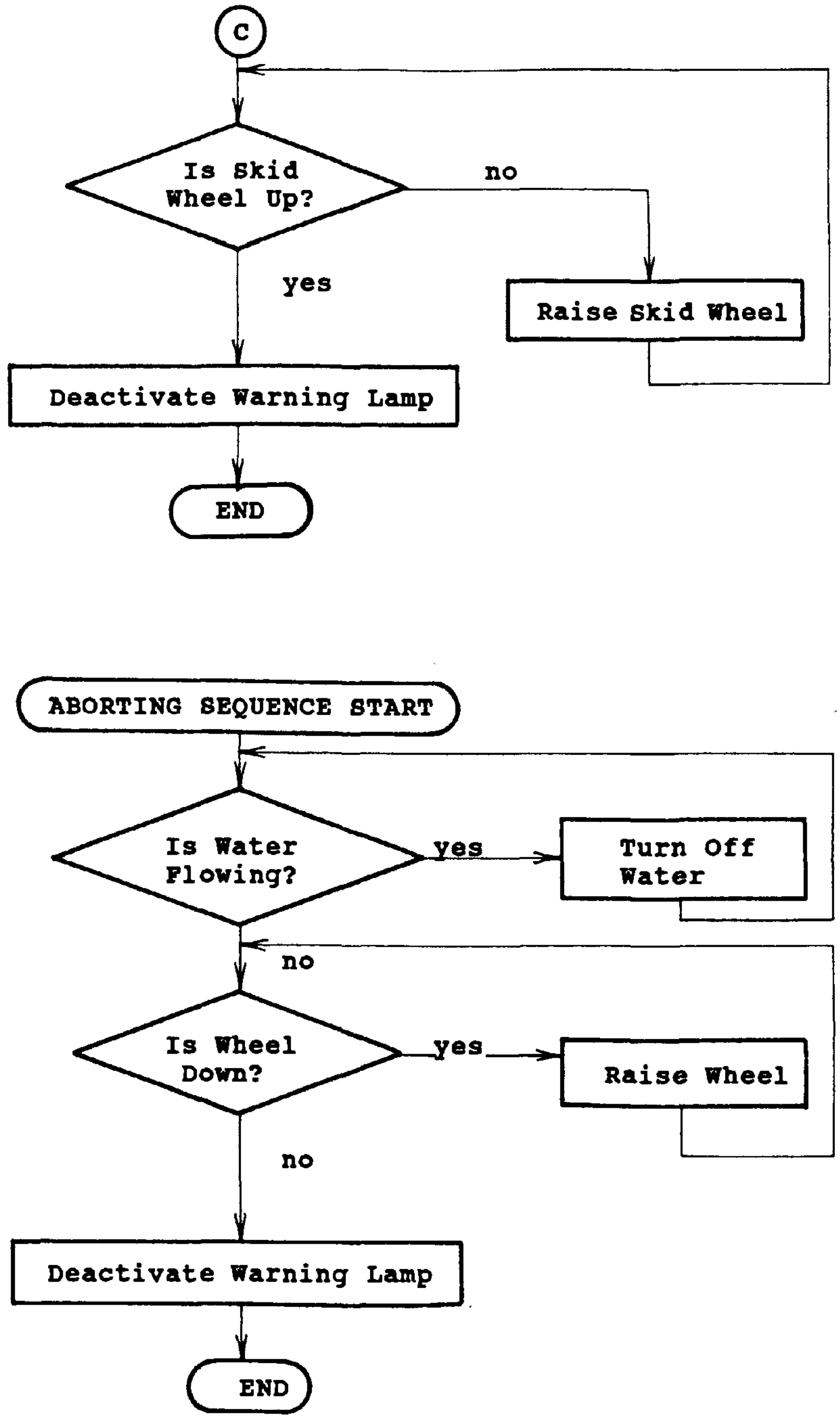

Figure 26. Skid test control procedure (continued).

A water spray nozzle designed and located according to ASTM Standard E 274 is positioned so that water is applied to the pavement just ahead of the test tire. The water pump is operated by a power take-off from the transmission so that the water flow rate is proportional to vehicle speed. An electrically operated clutch controls the power take-off unit. A water flow sensor is placed before the outlet of the nozzle to verify that water is flowing after the clutch is engaged.

The wheel bearing, brake rotor, and brake caliper are standard parts such as those found on the rear wheels of the Pontiac 6000 STE automobile. The wheel bearing, designed by the New Departure Hyatt division of GM, utilizes an integral wheel speed encoder.

ELECTRICAL DESCRIPTION

The schematic diagram of the Skid PC system is shown in figure 27. The major components are the computer and the associated analog and digital I/O board that enables it to acquire data and communicate with the PLC. The computer communicates with the other computers via the LAN network and with the PLC via the analog and digital channels of the DT2801-A analog and digital I/O board.

One of the differential analog voltage input channels of the DT2801-A is used to acquire skid test wheel speed data. The PLC, which counts the pulses generated by the speed-sensing system in the test wheel bearing, produces an analog output voltage at a level that is proportional to wheel speed.

The integral wheel speed sensor that is used in the skid test wheel bearing is a variable-reluctance sensor that produces a sinusoidal waveform, whose frequency and voltage are directly proportional to wheel rotational speed. This mechanism consists of a magnetized, toothed wheel that rotates at a speed proportional to wheel speed. As each wheel tooth crosses the coil assembly, a voltage pulse is produced.

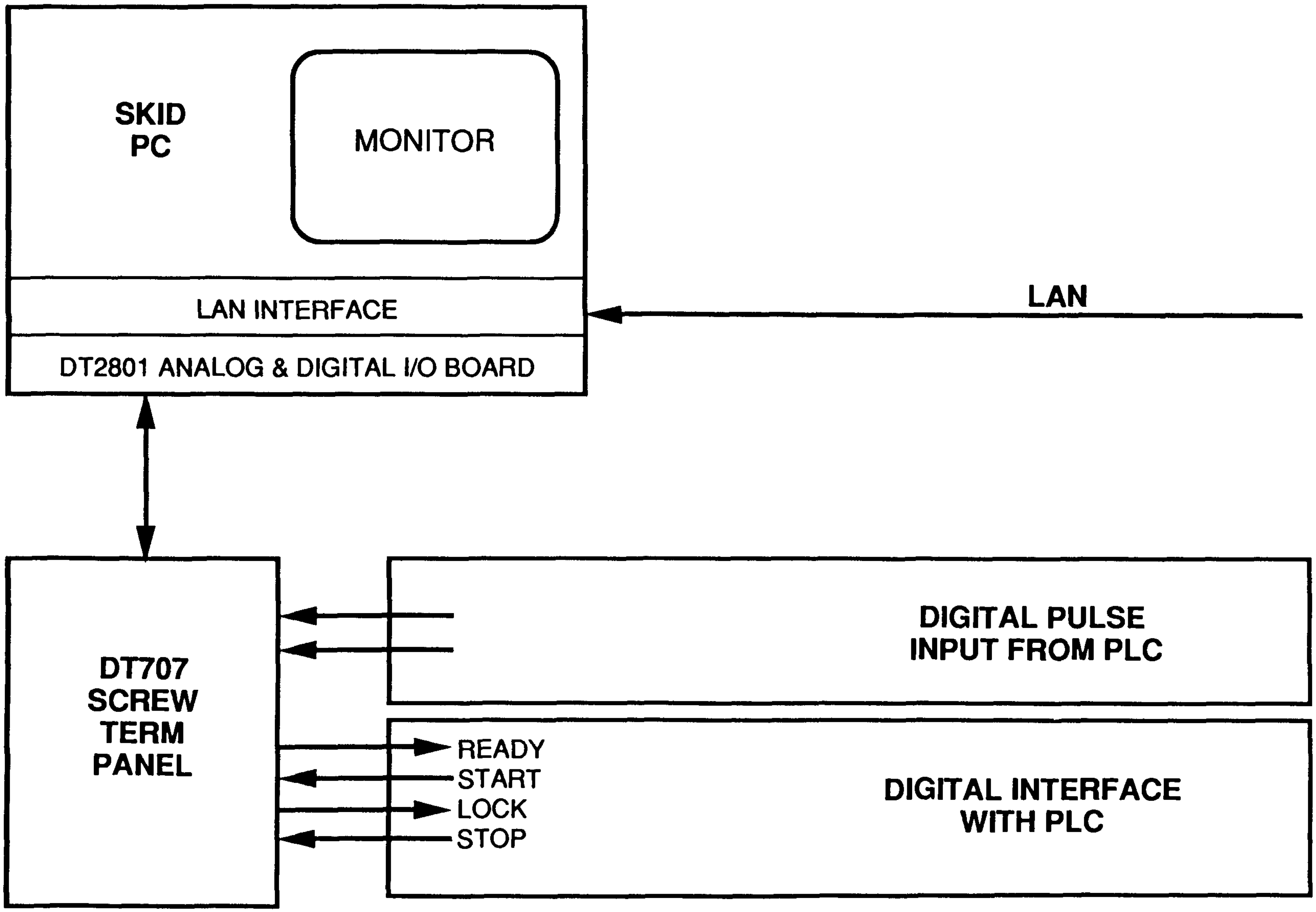

Figure 27. Skid system diagram.

The sensor produces a sinusoidal waveform as the wheel rotates, producing 48 complete cycles per revolution. Wheel speed is determined by counting cycles (N cycles per unit time correspond to N/48 wheel revolutions per unit time).

The 16 digital I/O lines of the DT2801-A are programmed so that the computer has access to one 8-bit input word and one 8-bit output word. Four of these bits are used to enable the PC to communicate with the PLC. Two output word bits are used to send the READY and LOCK signals to the PLC. The LOCK signal informs the PLC that the test wheel is locked and that the wheel can be released for spinup. Two input word bits are used to receive the START and STOP signals from the PLC. Utilizing these four digital lines, a handshaking process is feasible that enables the PC to monitor the skid test wheel speed. This handshaking is needed for test coordination and data acquisition.

Cabling

The cabling of the skid subsystem is shown in figure 28; the figure illustrates the generic connection of signal flow. Common ground wiring for all transistor-transistor logic (TTL) signals, and return wire is required for the EXT. INT. signals from the skid wheel encoder.

Conditioning

Conditioning of the signal from the skid wheel is required. The output signal from the skid wheel encoder is a sinusoidal waveform of 48 cycles per revolution. A conditioner is used to convert the sine waves into TTL pulses at zero crossing, which then produces 96 pulses per revolution. This conditioning hardware is not available in any commercial product; it is supplied as part of the spinup skid tester.

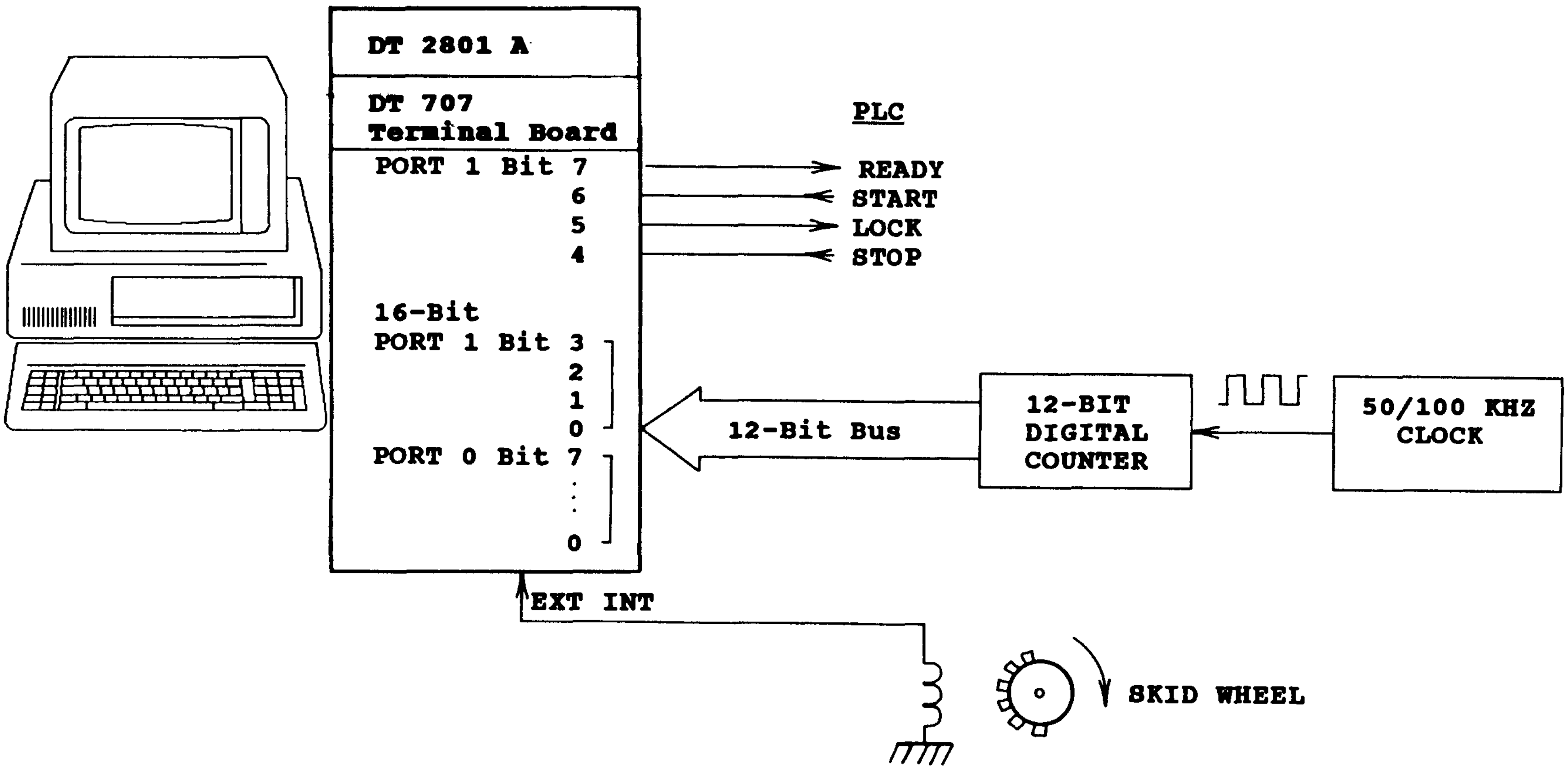

Figure 28. Skid test PC digital interface.

DATA

Data Collected

The only data collected in this system is the accumulated number of counts on the 62.5-kHz clock/counter board. The angular speed of the skid test wheel is measured by using the encoder mounted on the test wheel and a 62.5-kHz custom-designed clock/counter board. The encoder produces a sinusoidal analog signal that creates 48 complete sine waves for each rotation of the wheel. The clock/counter board converts these 48 sine waves into 96 0-5 VDC square waves. Using PCLAB, the leading edge of each pulse is used as a trigger to read the accumulated number of counts produced by the 62.5-kHz clock. By subtracting the number of counts on successive readings and dividing by 62.5 kHz, the angular speed of the wheel can be calculated.

The number of counts is recorded through the digital inputs whenever a pulse is present on the external interrupt line of the DT2801-A board. The data is stored in a memory array until the skid test run is finished. With this information, the system computes the angular speed and acceleration of the skid wheel, which are then used as part of the regression equation to find the skid number. The data flow diagram is shown in figure 29.

Data Files. Data files generated by the Skid PC contain two types of data. The first type of data is skid numbers with their slip speeds. The second type of data is the raw data associated with each test run.

The size of the data files depends on the speed of the spinup process. If the pavement is slippery, time to spinup will take longer, and more pulses (more turns) will be produced and more data will be collected.

The clock/counter board has a finite turn-around time due to the limitation of the 12-bit digital counter. After the counter exceeds 4,095, it starts from 0 again so that the maximum number of counts between any two pulses is limited to 4,095.

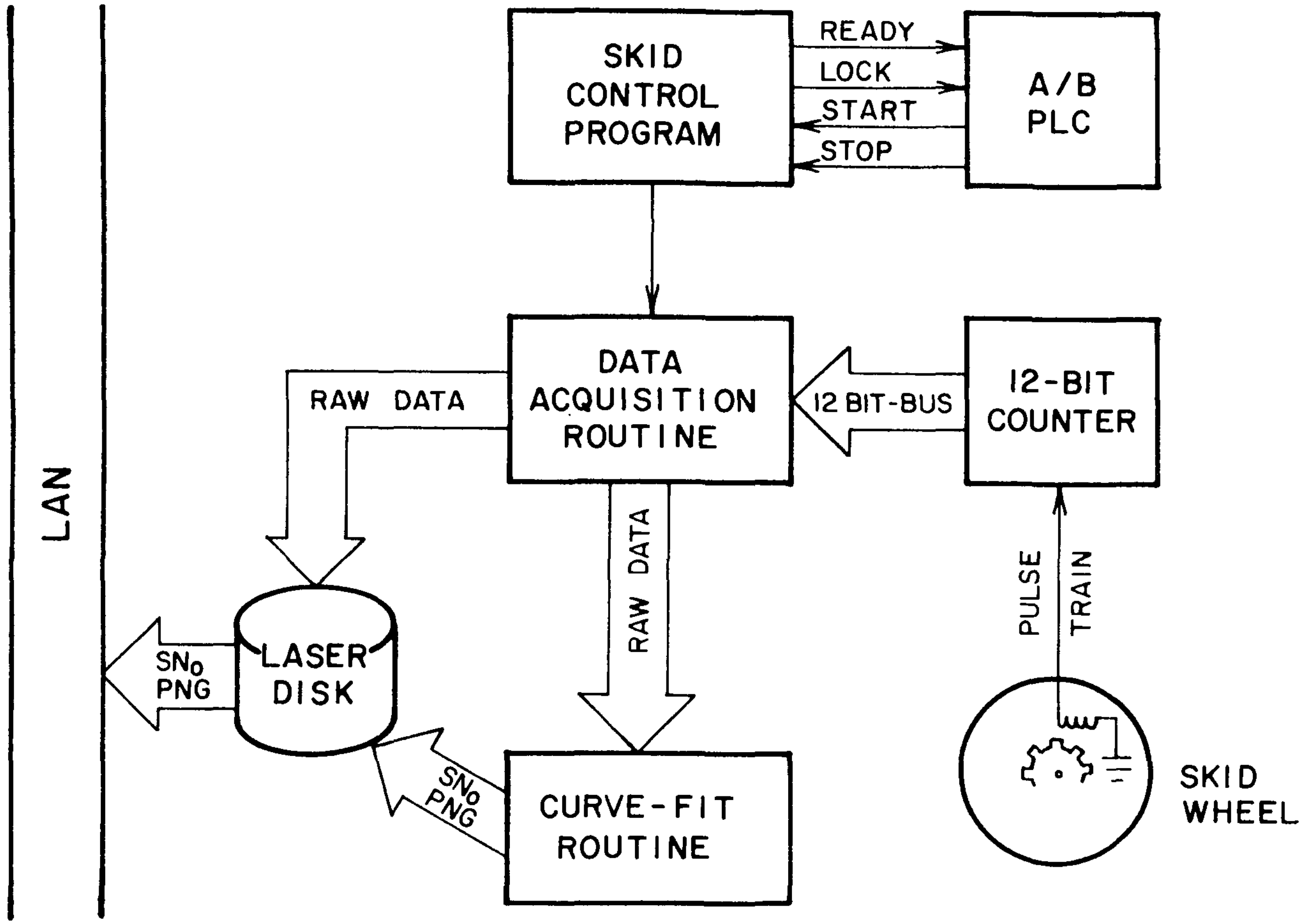

Figure 29. Data flow digram for skid subsystem.

The raw skid data consists of a single column of four-digit integer numbers in ASCII format. This represents the number of accumulated 62.5-kHz counts (0-4,095) read from the clock/counter board. The reduced skid data are contained in a second file. This file contains two columns of data: slip speed and skid number in real format (FORTRAN format 2F6.2). The skid number and raw data can be viewed from the console if the TYPE command is issued.

SOFTWARE

A flow chart of the software is shown in figure 30. The program is interfaced with the PLC to execute the skid test sequences.

File Names

The data files are named by the date and sequential number of test on that day. The first five letters of the file name are the number of the year and Julian date (for example, 89001 represents January 1, 1989). The next three letters are the sequential number of the test for that date. This is consistent with the Julian format used for the profile system.

Routines

There are routines that are called in the main program in addition to the PCLAB utility routines. These routines are used for acquiring the raw data and computing the skid numbers. The structural diagram of these routines is shown in figure 31.

An auxiliary file, SKIDATA.SYS, contains the mode of operation and number of skid runs for each site. Each run consists of the average of a number of spinups of the test wheel. The vehicle speed will be detected by the Skid PC and recorded as a reference. This auxiliary file can be altered by running the configuration disk.

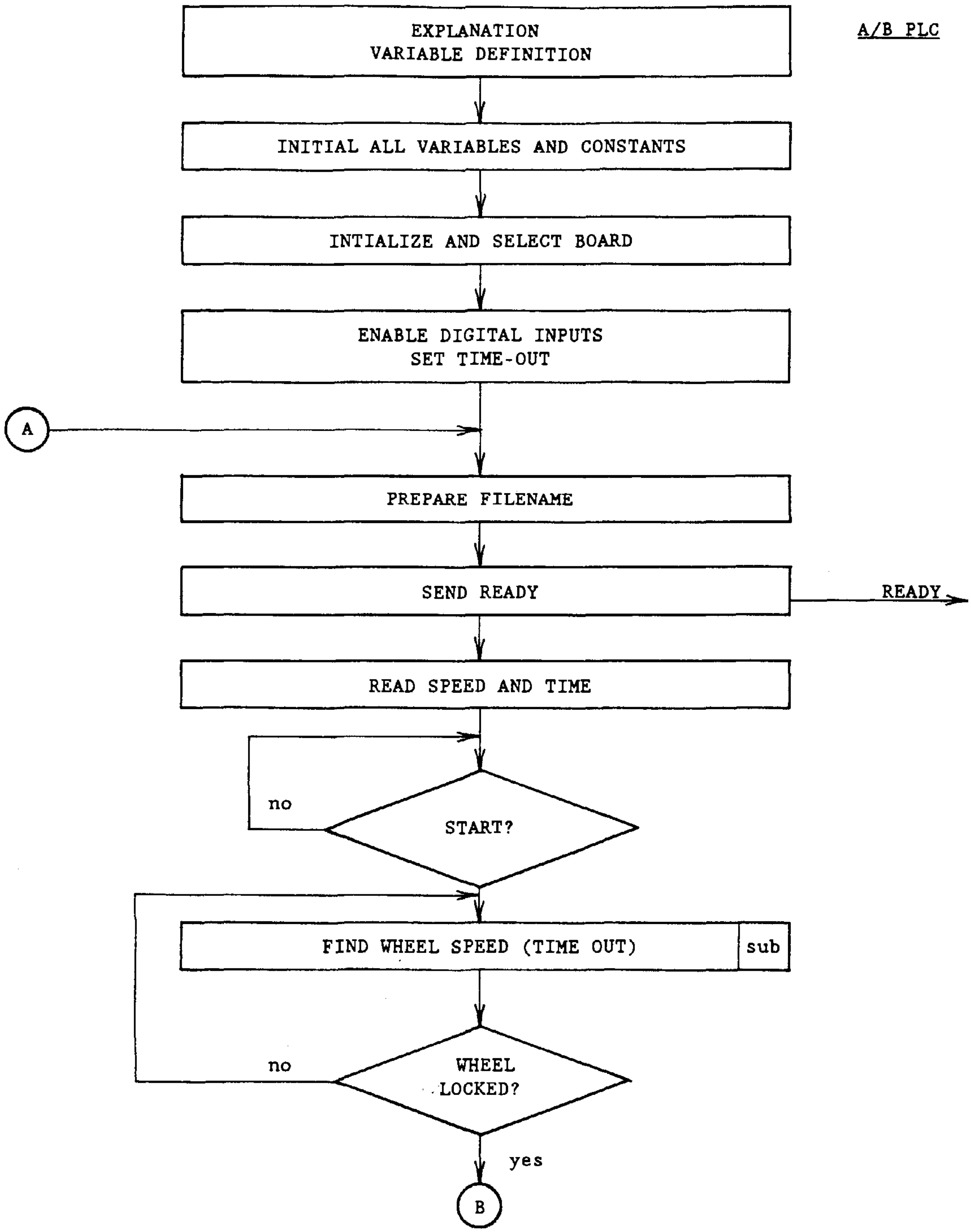

Figure 30. Skid subsystem running program block diagram.

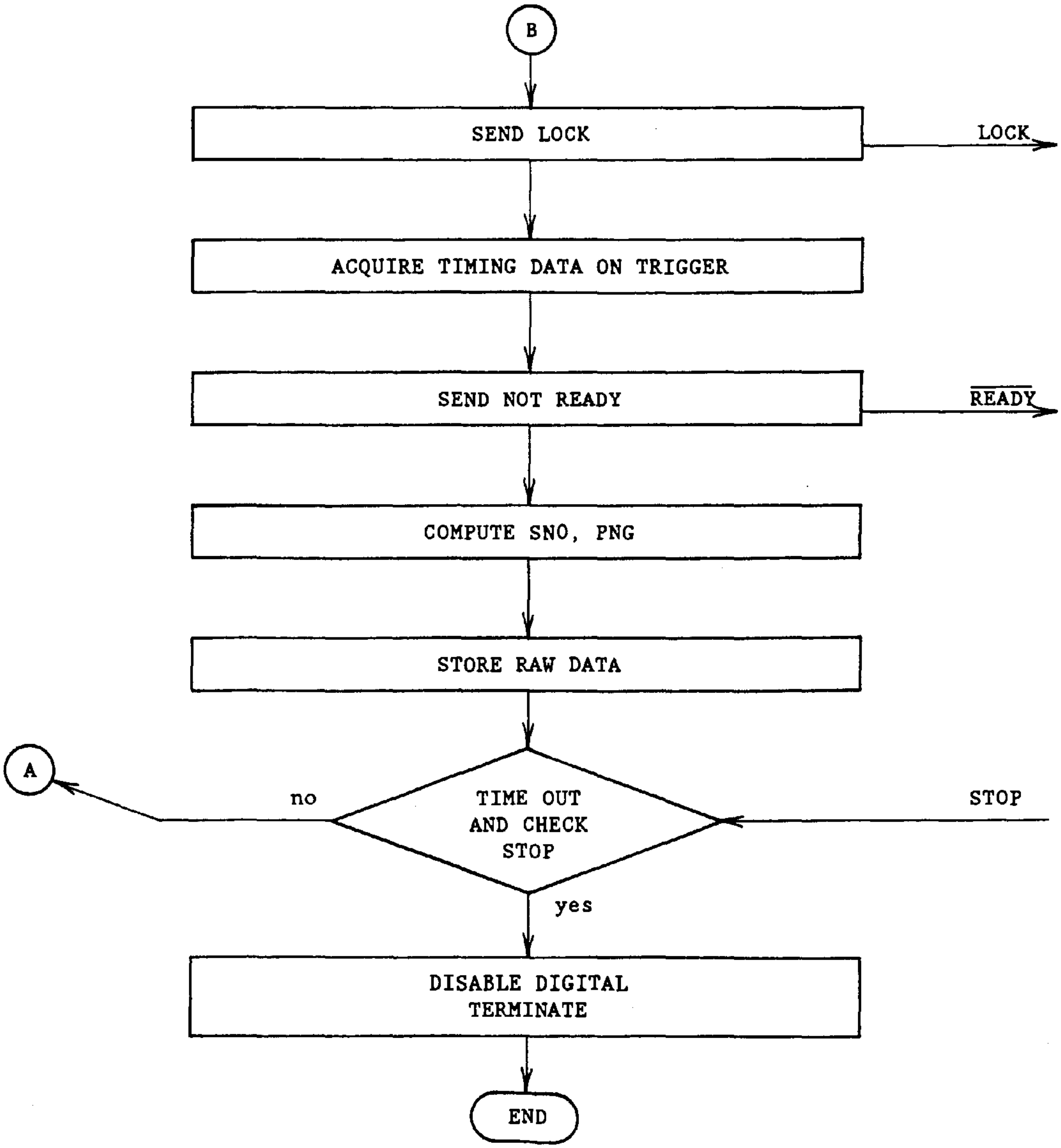

Figure 30. Skid subsystem running program block diagram (continued).

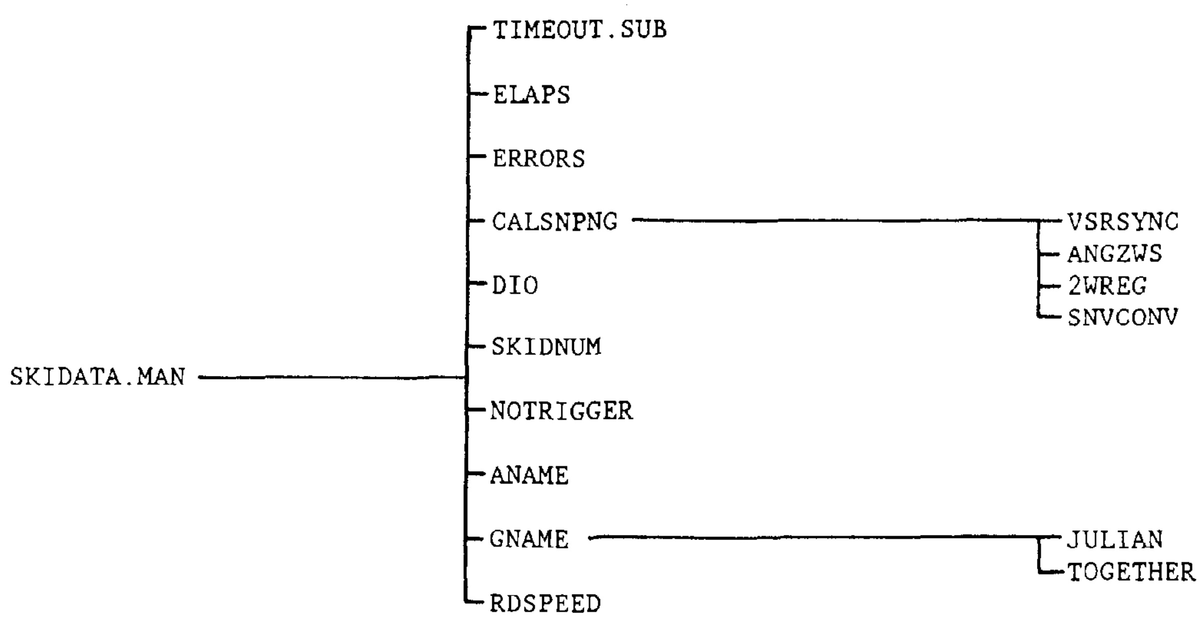

Figure 31. Subroutines required for SKIDATA.MAN.

Initialization

The skid program requires that the DT2801-A board be configured as board number 1. (Refer to the PCLAB manual for details.) The system boots up and runs the SKIDATA program using an AUTOEXEC.BAT file.

Computational Method

Computing skid numbers from raw data involves several steps. First, the raw data is converted to angular speed, as described previously. Second, the angular accelerations are calculated with proper consideration of the phase shift caused by differentiation. Third, the skid numbers for a given spinup are computed using the following equation:

$$SN(V_i) = \frac{(I/R)\ W(V_i)}{mg - (I/L)\ W(V_i)} \qquad (1)$$

where

I = Inertia of rotational assembly

R = Rolling equivalent radius of tire (i.e., R = Loaded center to road height)

L = Articulated arm length

$W(V_i)$ = Angular acceleration of skid wheel at slip speed V_i

mg = Load on skid wheel

$SN(V_i)$ = Skid number of slip speed V_i, where the subscript i represents i measurements (slip speeds)

The skid numbers, $SN(V_i)$, computed using equation (1) are then used to determine SN_0 and PNG. The values of SN_0 and PNG are then used for computing the skid number at any speed, $SN(V_i)$:

$$SN(V_i) = SN_0 * EXP(-PNG * V_i/100) \qquad (2)$$

TEST AND CALIBRATION

Tests and calibrations are carried out per ASTM Standard E 274, except that calibration for friction force or torque is omitted because the spinup system eliminates the need for measuring these parameters.

The moment of inertia of the test wheel is needed to calculate the individual skid numbers. Because the moment of inertia cannot be measured directly, some indirect measure is required. This can be done by attaching a torsional spring with a known stiffness to the spindle. This torsional spring-mass system is then excited by rotating the wheel approximately 10 degrees and then releasing the wheel. The moment of inertia, I_G, of the wheel can then be calculated as follows:

$$I_G = \frac{K_T}{\omega_n^2} \qquad (3)$$

where

I_G - Mass moment of inertia of the wheel

K_T = Torsional stiffness of spring

ω_n - Frequency of oscillation

No other special calibration is needed for the spinup tester. A method for calibrating the downward force of the wheel is given in ASTM E 274. There is no calibration required for the encoder: it is mechanically calibrated at the factory and cannot be field calibrated.

MACROTEXTURE-MEASURING SYSTEM

Overview

The macrotexture-measuring system is intended to measure the deviations of a pavement surface from a true planar surface. By applying image-processing techniques to a strip of light that is projected on the pavement, characteristic dimensions of pavement wavelength and amplitude are made. Features as small as 0.020 in (0.5 mm) can be resolved with this sytem.

Mechanical Description

The FHWA macrotexture-measurement system consists of two major parts:

- The image capture system, which consists of a strobe light, the optics that focus the light into a strip onto the pavement, the acoustic device that senses when the image capture system is in focus, the charged coupled device (CCD) camera, and the mechanical supporting frame.
- The image-processing system, which consists of a 640 x 480 frame grabber board, a monitor, and software.

Figure 32 is a schematic of the image capture system, and figure 33 is a block diagram showing the hardware for the system. The strobe flashes for a duration of 20 μs or less so that the image is not blurred by vehicle motion. The optics collect and direct the light into a concentrated 1/2-in-wide (12.7-mm-wide) strip on the surface of the pavement. The acoustic system measures the distance to the pavement, which determines when the focusing is correct and transmits the information to the software. (Images are taken only when the focus is correct; there is no active focusing mechanism.) The camera then captures the image of the lighted pavement for processing by the image-processing system.

When viewed from directly above (from the light source), the two edges of the light strip appear as straight lines. However, as the viewing incidence changes (e.g., differs from the perpendicular), the texture of the pavement becomes evident in the jaggedness of the light edges. Hence, the camera is oriented at about 45 degrees to the road surface, with the image raster lines running perpendicular to the strip of light. Thus, the program must correct for this angle, which is accomplished by a correction factor determined during calibration.

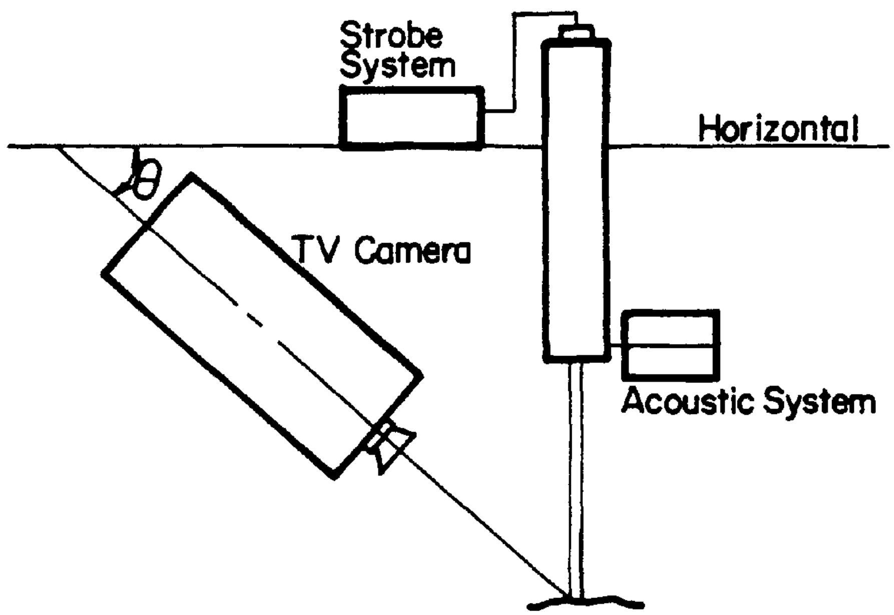

Figure 32. Schematic of the image capture system.[45]

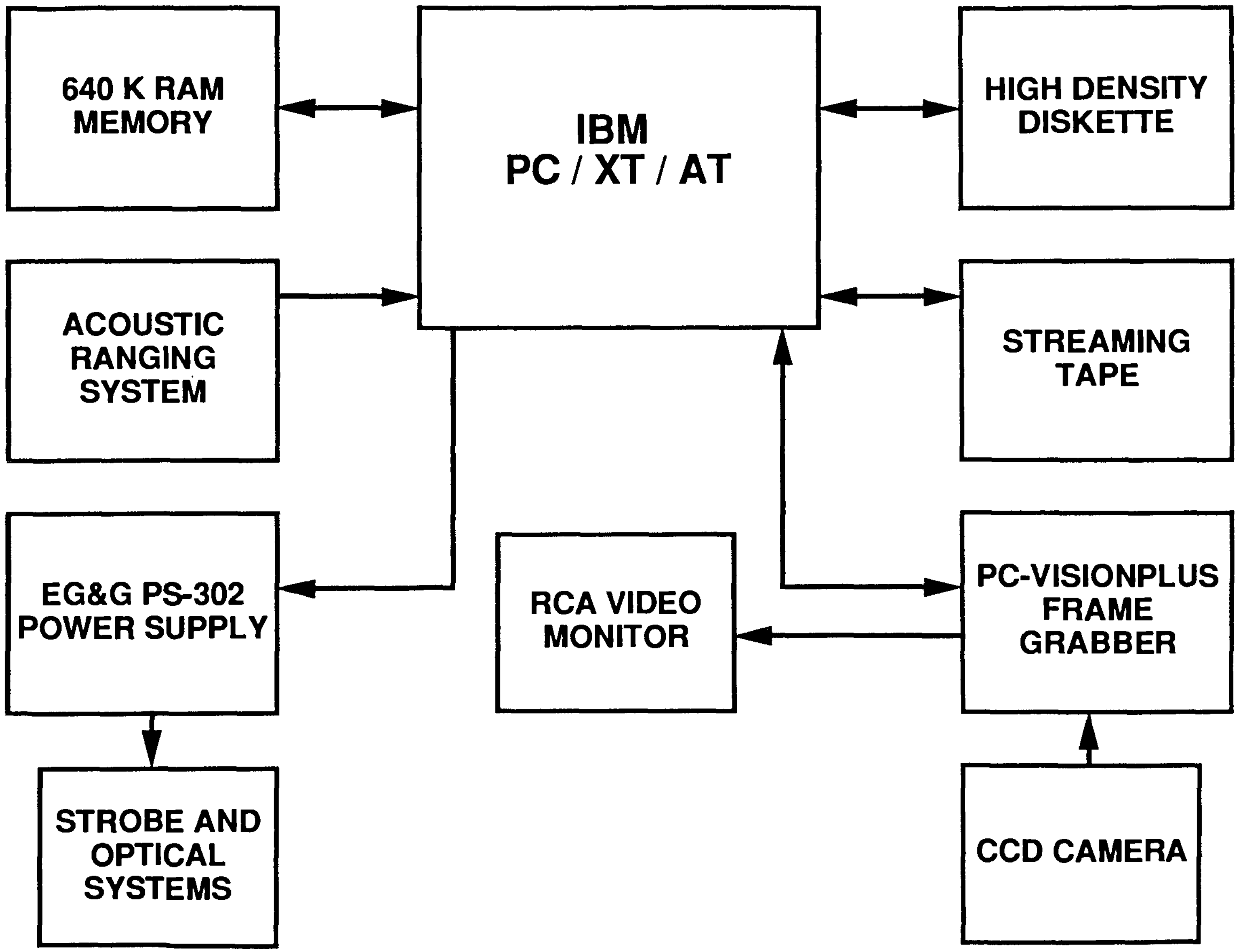

Figure 33. Block diagram showing hardware for macrotexture-measuring system.

Electrical Description

The Macrotexture PC communicates with the PLC over the digital I/O lines of the DT2801-A digital I/O board, providing instructions regarding the starting/stopping of the data acquisition and the general control of the macrotexture system. The image-processing system examines the video pixels to determine a transition from a light area (illuminated by the strobe) to a dark area (unilluminated by the strobe). The pattern of light-to-dark transitions is an effect of the macrotexture pattern.

The design of the image-processing system is based on a frame-grabber or vision board mounted in the 80286-based Macrotexture PC. The video image is processed in the system, and the trailing and leading edge pixels are used to calculate the macrotexture of the pavement surface. The functions of this system are to coordinate the image capture process and then to analyze the image to determine macrotexture.

Unlike the original PTI macrotexture system, a CCD camera will be utilized. This camera is more sensitive than the original camera.

Data Acquisition

The software for the macrotexture measurement scheme consists of one main program and a collection of functions that perform such necessary tasks as I/O operations to read the status of the rangefinder, initialize the vision software, acquire frames, etc. (see figure 34). This software serves two functions. First, it acquires the number of frames specified by the operator or as directed by the master control program and stores the edge pixels on the disk as two arrays of leading and trailing edges. Second, after finishing the on-line acquisition, it goes through the edge pixel arrays and calculates the root mean square (RMS) values for each pair of edges of each frame.

Main Program. The main program performs the following functions, in the order listed:

1. All global variables are declared.

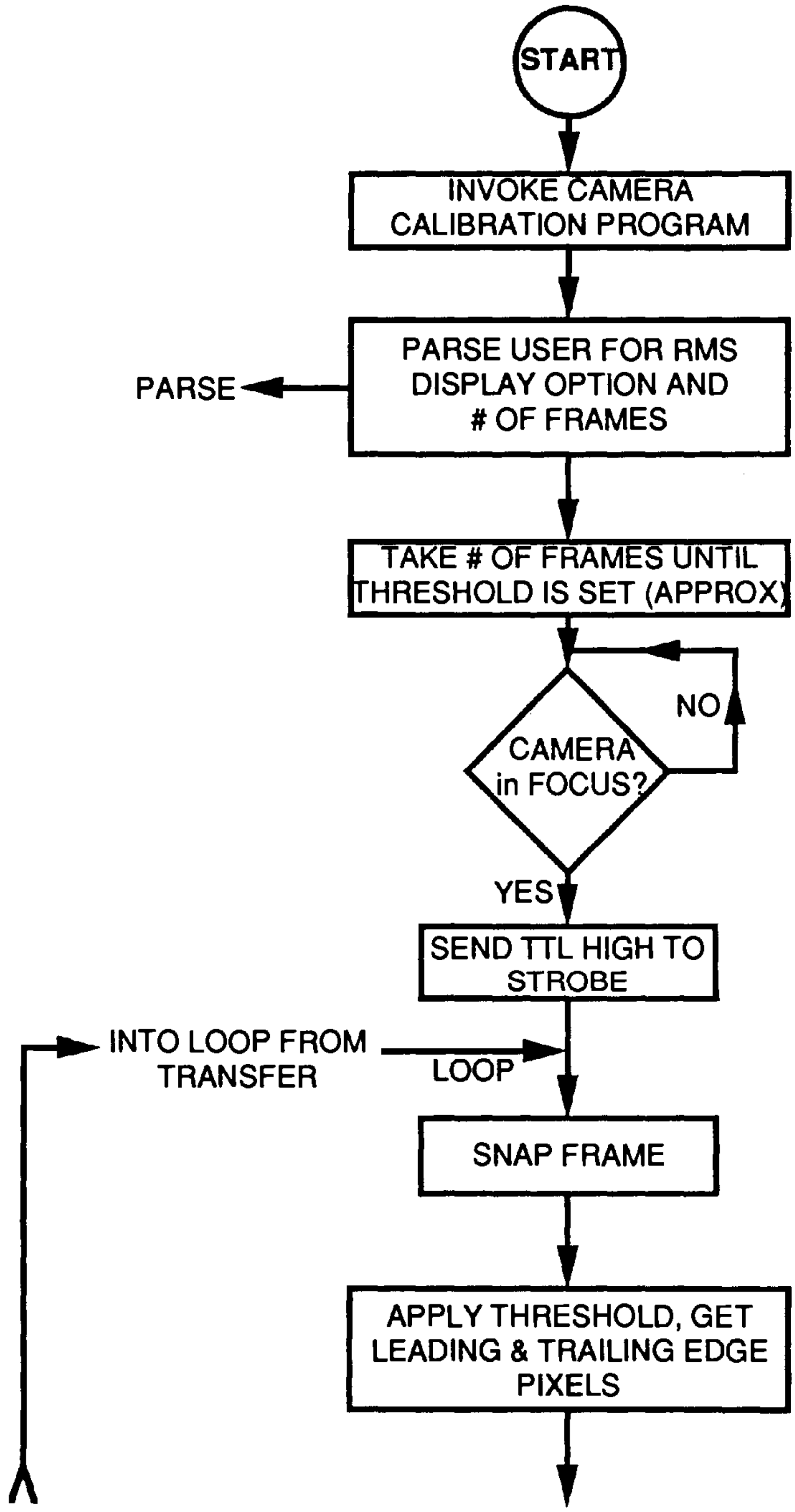

Figure 34. Schematic of the image capture software.

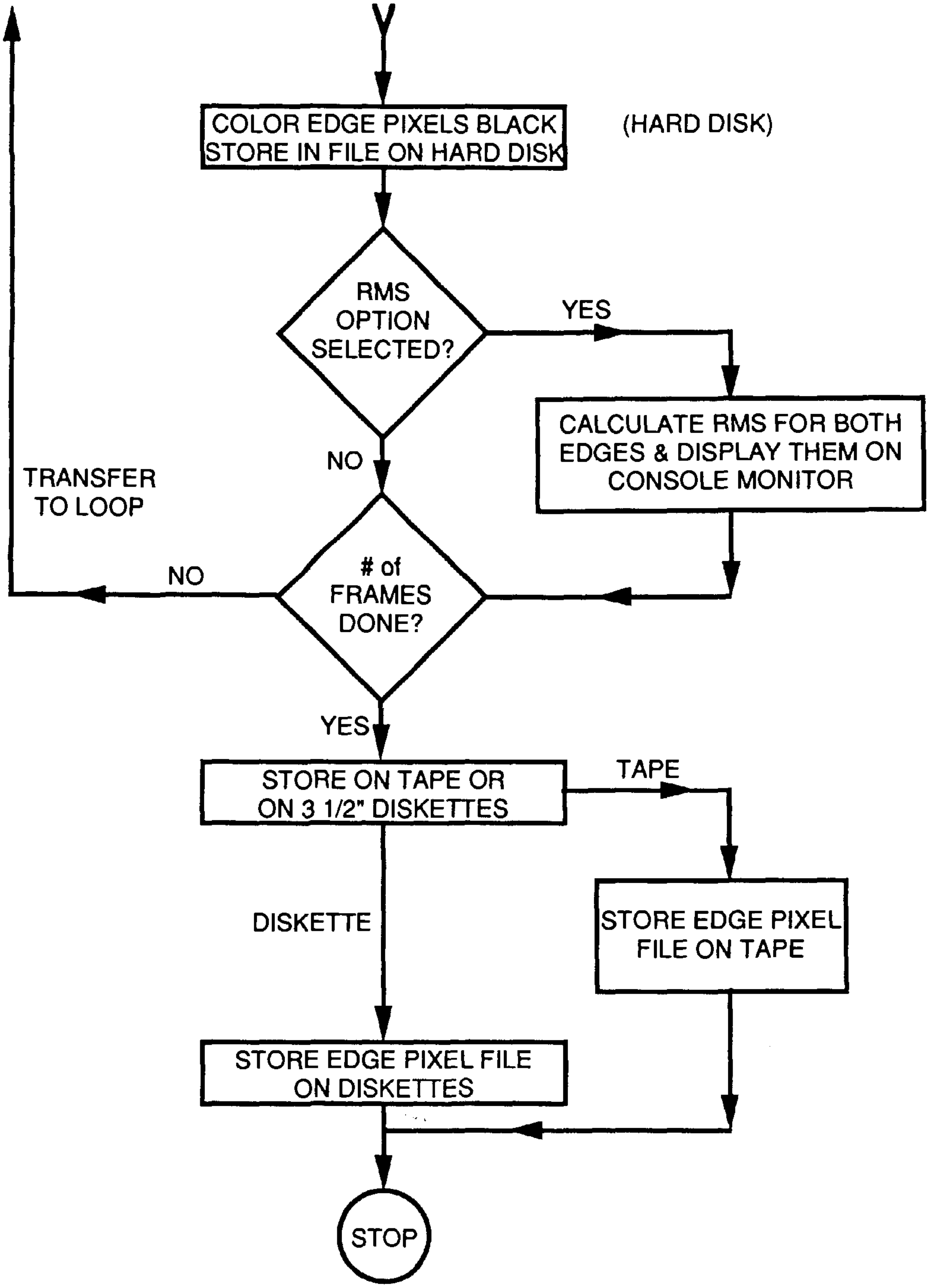

Figure 34. Schematic of the image capture software (continued).

2. The main idea of the program is printed so that the user can become familiar with the program.

3. The ITEX-PC software for the vision card is initialized.

4. After sending a ready signal, the program waits for a start signal from the Event PC.

5. The parallel port is read for checking the "in focus" status of the camera. (The rangefinder sends a TTL high signal if the camera is in focus.)

6. If the camera is in focus, the strobe is fired and the camera acquires a frame.

7. The frame is scanned for pixels with values greater than a specified threshold, and these candidate pixel coordinates are stored in a file.

8. If the RMS option has been invoked, the RMS values for the leading and trailing edges are calculated and displayed.

9. When the specified number of frames has been acquired, the program loops back to step 4 until a stop signal is received from the Event PC.

Functions. Steps 2 through 7 each represent separate functions; the main program simply invokes one, all, or some of them as required. Note that this type of modular programming is eminently suited for later modifications. A brief description of each of the six functions follows:

- Function Print_Message. Displays the idea of the program. Note that, in a run, this function is invoked only once.

- Function Init_itexpc. This function performs the following initializations for the vision card and software:

  - Informs the card of the hardware settings of the Register-base address, the Memory-base address, and the frame configuration (SINGLE or DUAL). Note that the current configuration is set for an IBM PC-XT with the Register-base at 300 (hex), the Memory-base at A0000 (hex), and SINGLE frame model. All these values can be changed in both the hardware and the software.

  - Sets the dimension of the image screen in the single frame mode as 640 by 480-pixel resolution. Each pixel has a grey scale variation of 8 bits, i.e., 0 to 255.

  - Initializes all the registers.

- Initializes the look-up tables for all three RGB channels.
- Sets the synchronization to external mode so that the vision card is synchronized with the camera.
- Clears the screen to black.

- Function In_focus. This function simply keeps reading the parallel port until a high signal is obtained from the rangefinder, signifying that the camera is focused. The TTL high signal from the rangefinder is expected in the third data bit of the parallel port.

- Function Fire_strobe. This function sends out a TTL high signal in the fourth data bit of the control byte of the parallel port when the camera is in focus. This signal is fed to the amplifier of the strobe.

- Function Edge_pixels. This function scans the frame buffer to locate the leading and trailing edge pixels by a thresholding operation. The threshold has to be set on a trial-and-error basis for each change of condition of the operation, once for every run at the start of the session. Because the threshold is set during run-time (as an input operation), re-compilation is not necessary. The candidate edge pixels are then stored in a file.

- Function RMS. This function interrogates the two edge pixel arrays and calculates the root mean square value of the vertical coordinate for every horizontal coordinate within a default or specified window. The RMS values are then displayed on the screen. Note that the search window can be changed by changing the include-file COORDS.H and recompiling the main program (TEXTURE.C) and the POSTPROC.C program using the command MSCC FILENAME (without an extension).

Testing

The software has been tested with the vendor-specific hardware complement as described in "Development of Integrated Survey Vehicle for Measuring Pavement Surface Conditions at Highway Speeds--Volume II: Technical Details" (FHWA-RD-90-012). The hardware, including the camera and strobe light, was installed in a vehicle and interfaced with an 80286-based PC and the specified vision board. The leading and trailing edge video was displayed on a TV monitor, and an RMS macrotexture was computed for several pavement surfaces.

A more sophisticated calibration scheme will be necessary when the system is built. A suggested technique would be to select several artificial surfaces with known macrotexture and to use the system to determine the macrotexture of these surfaces. Such surfaces may consist of commercial sandpaper of given grit size or a series of grit sizes epoxied to a steel plate.

A scheme for testing the software was developed and is presented in "Development of Integrated Survey Vehicle for Measuring Pavement Surface Conditions at Highway Speeds--Volume II: Technical Details (FHWA-RD-90-012).

CHAPTER 6. VIDEOCOMP CRACK-DETECTION SYSTEM

DATA COLLECTION EQUIPMENT

During the last 3 years, VideoComp has developed a crack-detection system that includes hardware and data collection and analysis software. The system features a modular design (both hardware and software). System modularity is very important because it allows new equipment to be incorporated easily into the overall system and also simplifies systems maintenance. As the data collection system has evolved, VideoComp has been able to introduce new cameras, recorders, and time code equipment without having to reconfigure the entire system.[46,47]

VideoComp designed and implemented its data collection system following these assumptions:

- The safety of the public and the data collection crews is imperative.
- Collected data should be reliable and of high quality.
- Data should be collected in a consistent manner over time.
- The data collection method should be cost effective.
- The system should be modular, which would allow new and improved equipment to be incorporated into the data collection system.

These assumptions have resulted in the selection and use of certain types of equipment and the adoption of a data collection philosophy that accents safety, timeliness, reliability, repeatability, and cost-effectiveness. Performance characteristics, requirements, and limitations of the VideoComp data collection system are itemized below:

- Pavement condition data are collected using CCD cameras and stored on VHS videotape. While the resolution of video cameras is limited compared to photography, video is less expensive, more flexible, and is developing rapidly in terms of resolution. An extensive amount of analog data can be gathered for each test section and stored on videotape. (In the near future, VideoComp plans to begin assessing the feasibility/desirability of editing each videotape, selecting data of interest, and transferring those extracted data to another

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storage medium, either CDROM or laser disc. The original videotapes will be retained and placed in archives.)

- To promote safety and to allow data collection at highway speeds, the maximum legal width of the data collection vehicles is 9 ft (2.75 m). Three CCD high-speed shuttered cameras are positioned 7 ft (2.14 m) above the road surface with each camera covering an area 4.5 ft (1.37 m) wide (using a 12.5-mm lens) and 3.38 ft (1.03 m) long (see figure 35). In addition, a fourth camera (with a 6.5-mm lens) is positioned centrally to provide a wide-angle view of the entire lane. Since the current state-of-the-art video cameras have 384 by 491 lines of resolution, the width of the smallest detectable strictly transverse crack will be 3/32 in (2.10 mm). In practical terms, with the current CCD camera resolution, cracks equal to and greater than 1/8 in (3.18 mm) can be resolved. Total field of vision (subtracting camera overlap essential for subsequent processing of videotapes) is 12.5 ft (3.81 m).

- All the cameras are synchronized to a common timing system so that video fields can be matched in subsequent image processing and surface mapping. Camera video outputs are time coded with SMPTE Time Code and Mileage in one-thousandths of a mile increments. A modified EVERTZ EV-600 Block Modular Time Code System is used to insert vertical interval time code (VITC) in SMPTE format. This unit also inserts user bits from the distance-measuring device into time code. The time code system also provides readout of selected recorders or output with superimposed mileage and frame count.

- Time- and mileage-coded video signals are routed through a title insertion switch and applied to the videotape recorders. Title generation is done on a FOR-A TV typewriter character generator.

- The video recorders used by VideoComp are industrial-grade VHS format, which allows up to 2 h recording time (Panasonic AG-6200). Outputs of each video recorder are monitored in the systems vehicle with selectable remote monitoring in the tow vehicle. Distance measuring, control of the recorders, and control of the time code generator and other instrument systems are accomplished through a custom-fabricated microcomputer system with remote terminal and status display mounted in the vehicles. Control and monitoring consists of a control and data entry keyboard with lamp and video status display. In addition, a microphone is provided for audio notes, which are transmitted to all video recorders simultaneously.

- Other essential equipment includes a 6-kW generator, high-intensity halogen lighting, a power distribution system, and safety lights.

VideoComp feels that the CCD video camera has great potential as a cost-effective and accurate data collection device. Currently photography has better resolution, but surface condition data are not easily extracted from the film, and cost improvements and technical advances are unlikely. With

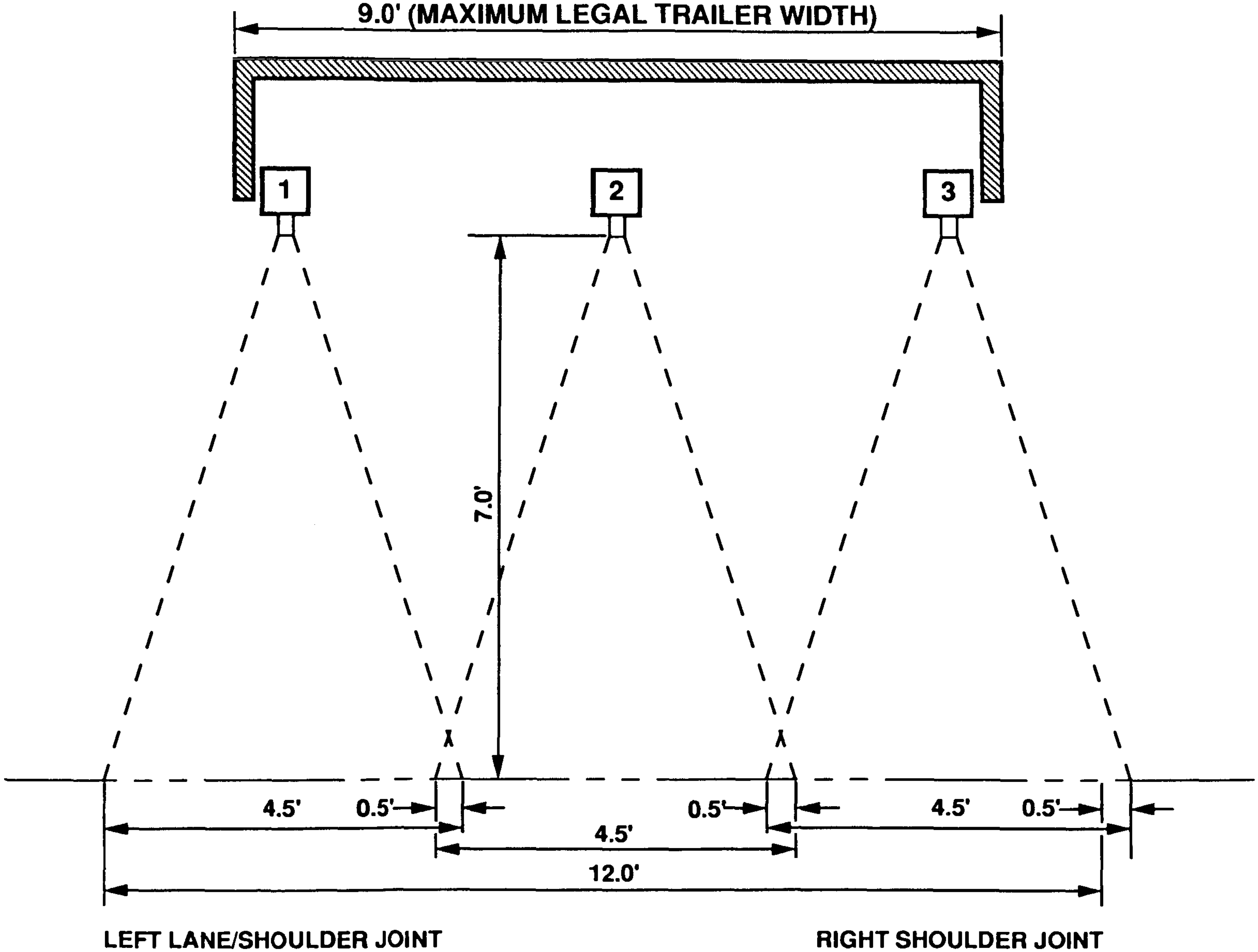

Figure 35. Cross-section view of cameras.

this equipment, the resolution of 3.57 by 2.10 mm and 12.5-ft (3.81-m) width may seem too coarse. However, cracks as small as 1/8 in (3.18 mm) have been resolved sufficiently for determining relative crack size, type, and extent. The current CCD video camera resolution is likely to at least double within the next few years. All work currently undertaken with existing equipment is easily adapted to higher resolution cameras. Better resolution can be attained with existing equipment (more cameras positioned closer to the roadway surface), and the IRSV was designed to accomplish this.

COMPUTER ANALYSIS OF VIDEOTAPES

The videotapes are digitized frame by frame. The cracking data are extracted from the digitized frames using image analysis software. The separate frame-cracking data are summarized to each one-thousandth of a lane mile. These one-thousandth-mile sections may then be summarized for longer lengths, depending on the intended use of the data.

For project analysis, all the cracking data are summarized by crack type, severity level, and length. To provide a good audit trail and to develop plans and quantities for a rehabilitation project, the cracking information is passed to a computer-assisted drafting (CAD) program for graphic display. Table 11 is an example of crack classification of one-tenth of a mile (1.61 km) of Idaho Interstate. Figure 36 is the graphical representation of that same length of roadway.

For network analysis, a cracking index can be derived from the videotapes. Since it is too time consuming to examine every video frame of the entire network, sampling strategies are being developed so that it will be possible to extract a cracking index by examining a portion of each lane mile.

Table 11. Example of crack classification of one-tenth of a mile of Idaho Interstate.

MACS: 001010 DESCRIPTION: I-84
LANE: TRAVEL LANE
SURFACE TYPE: CONCRETE
FROM M.P. 12.624 TO M.P. 12.723

SUMMARY - LONGITUDINAL CRACKS

SEVERITY CLASS (WIDTH)	TOTAL LENGTH (FEET)	AREA LENGTH*WIDTH (SQUARE FEET)	IMPACT AREA LENGTH*(WIDTH+8") (SQUARE FEET)
VERY SLIGHT (-1/4")	.0	.0	.0
SLIGHT (1/4" - 1/2")	8.2	.3	6.4
MODERATE (1/2" - 3/4")	141.6	7.0	113.2
SEVERE (3/4" - 1")	114.4	7.8	93.6
VERY SEVERE (1" +)	426.3	50.9	370.6

SUMMARY - TRANSVERSE CRACKS

SEVERITY CLASS (WIDTH)	TOTAL LENGTH (FEET)	AREA LENGTH*WIDTH (SQUARE FEET)	IMPACT AREA LENGTH*(WIDTH+8") (SQUARE FEET)
VERY SLIGHT (-1/4")	.0	.0	.0
SLIGHT (1/4" - 1/2")	.0	.0	.0
MODERATE (1/2" - 3/4")	.0	.0	.0
SEVERE (3/4" - 1")	.0	.0	.0
VERY SEVERE (1" +)	.0	.0	.0

1 in = 25.4 mm
1 ft = 0.305 m

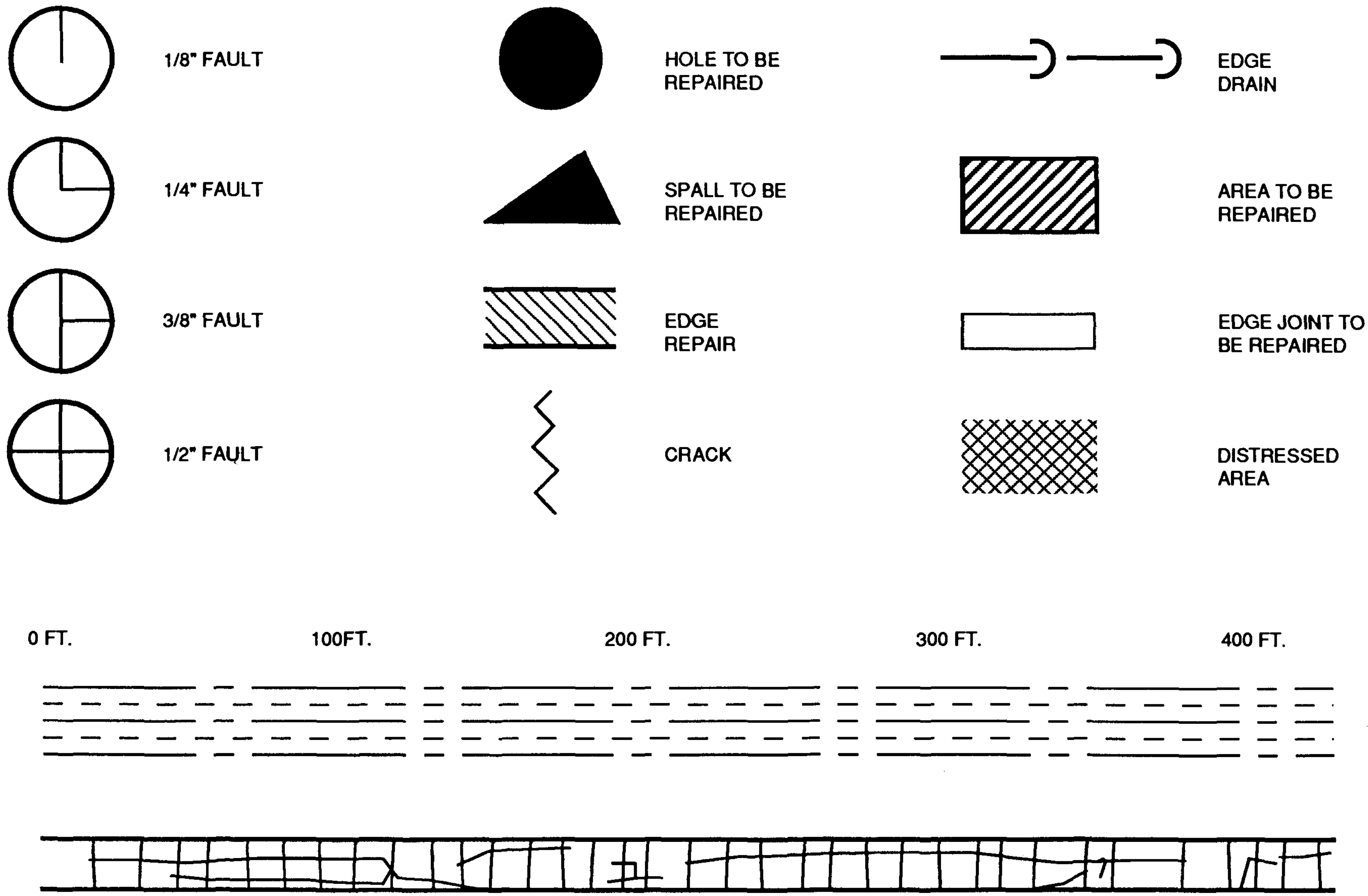

Figure 36. Graphical representation of cracking in section of roadway as produced by crack-detection system.

CHAPTER 7. ENVIRONMENTAL CONDITIONS MEASUREMENT SYSTEM

OVERVIEW

The IRSV Environment PC system uses commercially available humidity-measuring and noncontact temperature-measuring sensors to determine the outside air relative humidity and the road surface temperature, respectively. This data is required in support of the skid number calculation that the SKID system performs.

MECHANICAL DESCRIPTION

A humidity sensor probe and a remote temperature sensor are located beneath the vehicle. The signal conditioning equipment for these sensors are located inside the vehicle at the middle of the vehicle on the driver's side. The Environment PC is located in EEC1.

ELECTRICAL DESCRIPTION

A schematic diagram of the Environment PC system is shown in figure 37, and the environmental measurement sensor system block diagram is shown in figure 38. The major components of this system are the PC, the humidity-sensing system, and the pavement temperature-sensing system. Two means of communication are utilized: the LAN for intercomputer communications and the analog and digital I/O channels for communicating sensor and control data.

The humidity-sensing system, with its sensor probe and associated signal conditioner unit, produces a voltage that is input to one of the analog input channels of the DT2801-A analog and digital I/O board. This voltage ranges from 0 to 5 VDC and represents relative humidity levels of 0 to 100 percent.

The remote temperature-sensing system consists of a temperature sensor placed in series with the power supply (vehicle battery), digital indicator, and instrumentation amplifier. Thus, the 4 to 20 mA current loop is

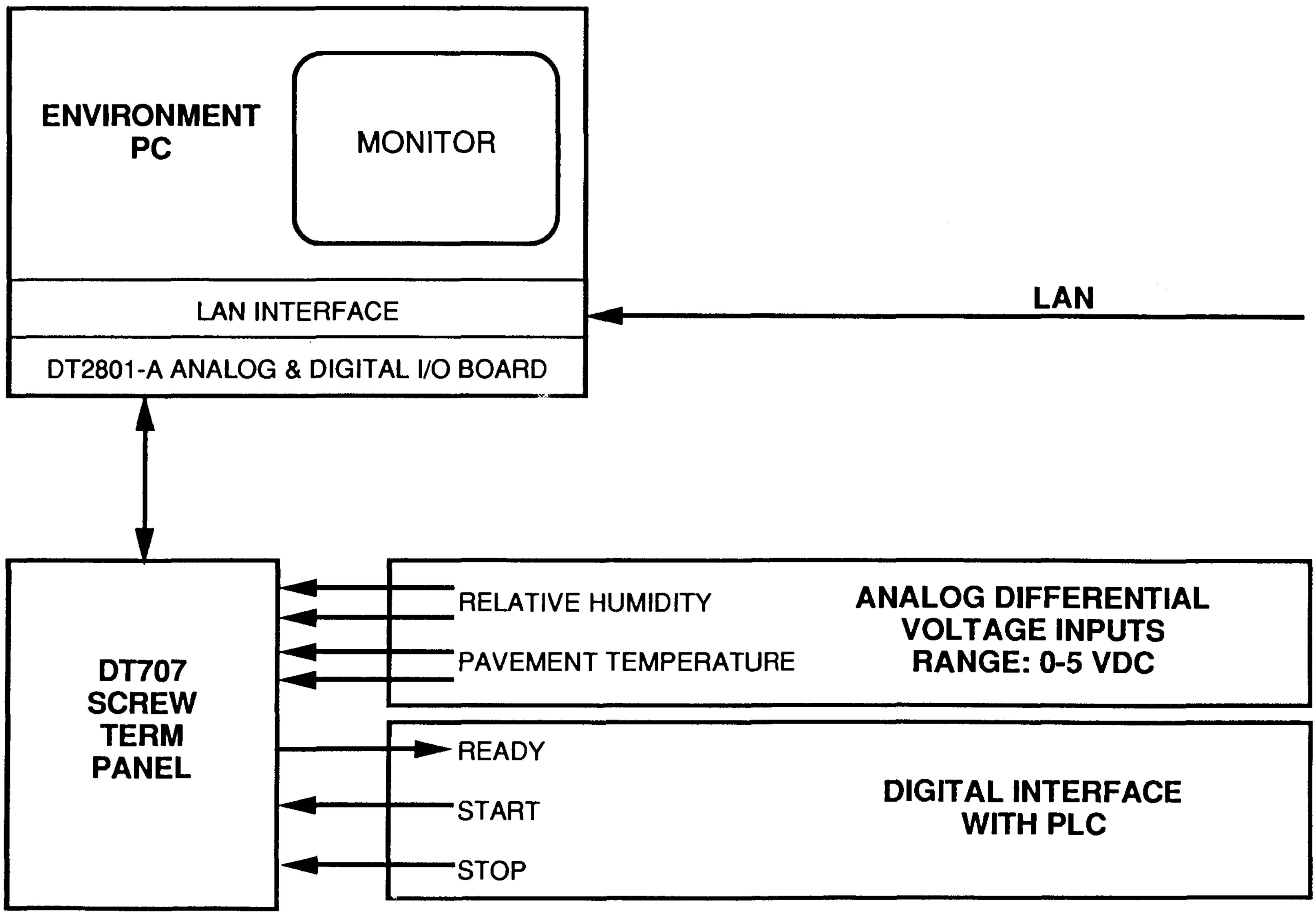

Figure 37. Environmental measurement system.

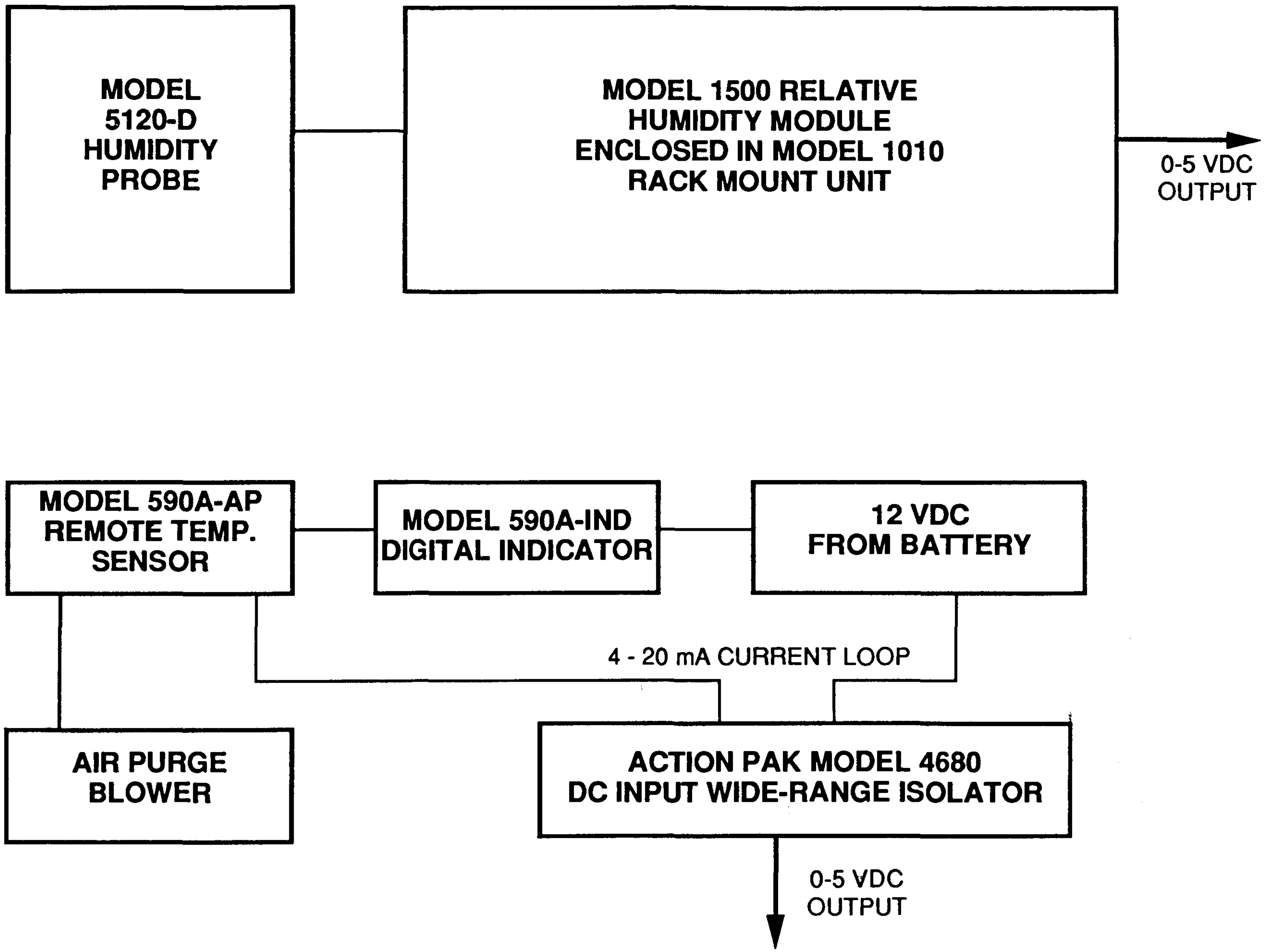

Figure 38. Environmental measurement sensors.

transformed into a differential output 0 to 5 VDC signal, which is consistent with the relative humidity signal. The A/D conversion channels of the DT2801-A are programmed to read input voltages with a range of 0 to 5 VDC.

The 16 digital I/O lines of the DT2801-A will access one 8-bit input word and one 8-bit output word. Three of these bits will be used to enable the PC to communicate with the PLC. One output word bit will be used to send the READY signal to the PLC. Two input word bits will be used to receive the START and STOP signals from the PLC. By using these three digital lines, a handshaking process that enables the PC to acquire environmental data as necessary is realizable.

DATA ACQUISITION

The Environment PC will acquire outside air relative humidity and pavement surface temperature data upon demand and will store the acquired information, along with information on the time of day that the data is acquired, in its memory.

TESTING

The air temperature-measuring system may be calibrated directly by immersing the sensor in a water bath of known temperature. A secondary thermometer in the water bath can be used as a reference, or the water bath may be controlled at a known temperature.

CHAPTER 8. POSITION SYSTEM

OVERVIEW

The vehicle geographic location system utilizes the Position PC and a Loran C to determine the IRSV location. A GPS can be used in place of a Loran C system but its cost is around 20 times more than the Loran C system. In all but the very mountainous areas, the Loran C has very good accuracy.

MECHANICAL DESCRIPTION

The Position PC occupies EER 1, position H. The Loran antenna is located on top of the IRSV.

ELECTRICAL DESCRIPTION

The Position PC system schematic diagram is shown in figure 39; the major components are the PC and the Loran C. The PC uses three methods of communication: the serial interface port with the Loran, the LAN interface with other computers, and the digital I/O ports with the PLC.

One of the PLC output channels represents the Position "Request" command line. This output line is electrically connected to the input line of the Position PC. This PC digital input is one of the PC digital input word bits.

When the PLC sets the request line high, the PC requests the geographical location of the Loran. The Loran then transfers the position information to the Position PC through the serial line. The Position PC then transfers this information to the LAN, where it is stored indexed with time.

DATA ACQUISITION AND INFORMATION TRANSFER REQUIREMENTS

Each time that the PC receives the geographic location information from the Loran, it logs the position, along with the associated time of day, into its memory. This information is utilized during the data compilation process

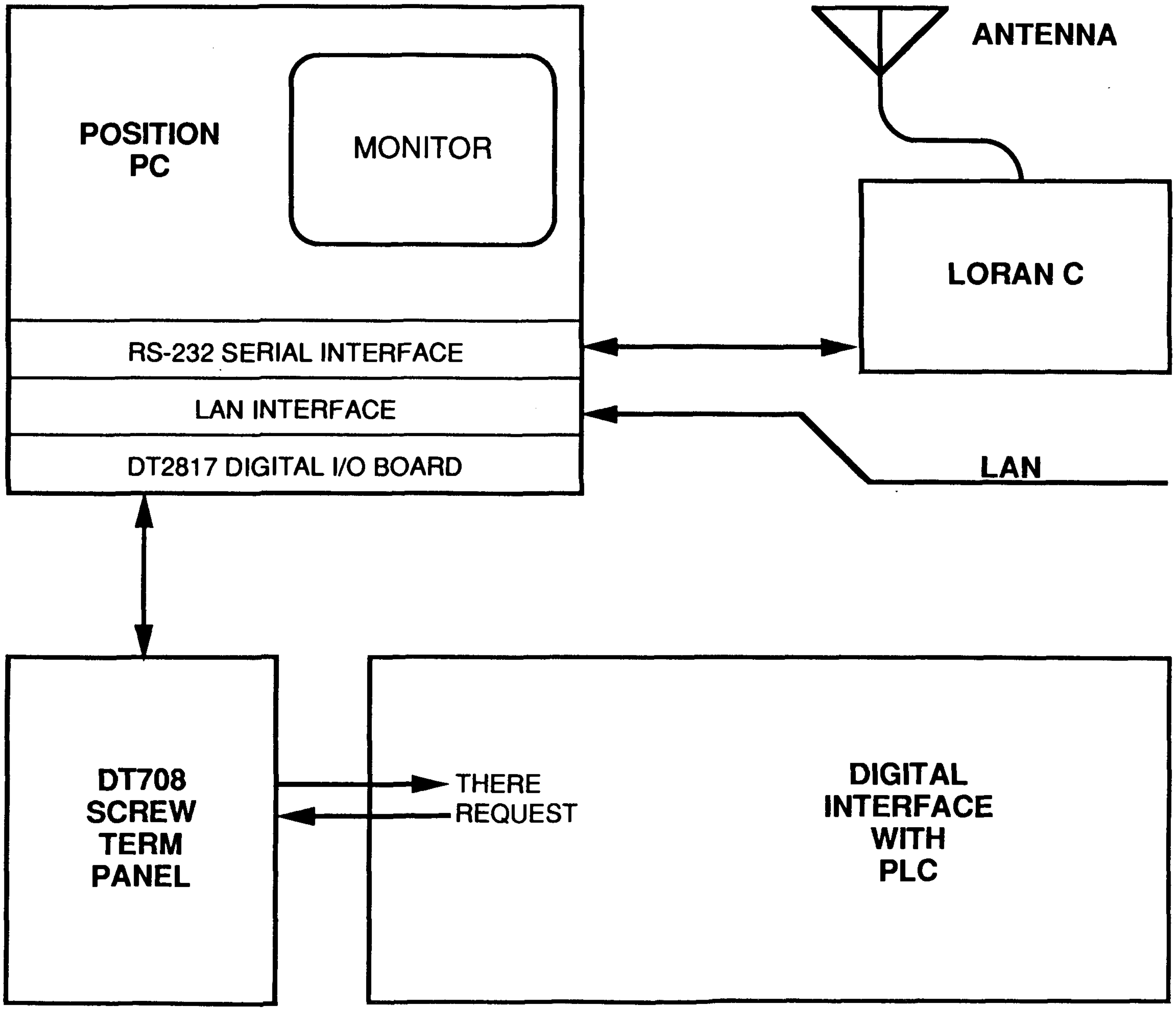

Figure 39. Block diagram for position system.

at the end of the road survey run so that road measurements and analyses can be associated with the appropriate geographical location.

CHAPTER 9. SYSTEM CONTROL EQUIPMENT

There are several miscellaneous systems in the IRSV and they are described in this chapter. These systems include:

- Event (main) system that controls the other PC and the overall operation of the IRSV.
- Operator control panel or the master control that gives control to the event system in the auto mode or provides all control of the IRSV in the manual mode.
- Driver control panel that provides, at the option of the operator, minimum control by the driver and voice operation.
- Programmable logic controller that provides all logical steps of the IRSV.

EVENT (MAIN) SYSTEM

Software Overview

The Survey Vehicle Control Software allows the operator to control several personal computers from a single interface. This software is intended to be user friendly and easy to modify. The main interface for this software is to the PLC. The operator enters a command at the keyboard or into the microphone provided. Using the microphone produces the same results as typing a command on the keyboard. This program then parses the command and initiates the appropriate action. If the program does not recognize a given command, the computer will beep and no action will be taken. The results of most commands would be to set an output line high to signal the PLC to begin a particular test. This output line will stay high until the shutdown command is given, which will set the shutdown line high until the restart or continue command is given. A log file is created to monitor the daily activities of the Survey Vehicle Control Software. Provisions were also made to shutdown all tests immediately.

This software was designed to be self-contained and modular. The operator of this software has the option of recording comments in a file that

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are automatically indexed with time or creating files with site information that can be used by the other personal computers collecting data.

Program Requirements

Hardware. The survey program operates on an IBM-PC or compatible computer (640K RAM) with an EGA monitor and an appropriate graphics card. The PC requires a DT2801-A board to communicate with the PLC. All communications with the PLC consist of digital I/O signals through a 16-conductor ribbon cable provided with the board. The controlling PC is connected to the other acquisition PCs through the specified LAN. This network will appear to the controller PC as a hard drive unit to which the other PCs have access.

Software. The controller PC requires MS DOS 3.0 or higher. The survey software requires a Microsoft Basic compiler V6.0 along with the PC-LAB V3.01 data acquisition software. The compiler and acquisition software is needed to run the survey program as well as to make modifications to it. The network software is also required on the controller PC even though communications to the PLC are digital.

Method of Operation

To start the survey software, type SURVEY at the DOS command prompt. (Note: The same command can be spoken into the system microphone with the same effect.) After the program has started, a command prompt appears on the screen. This prompt appears whenever the control software is waiting for input. First, to get a list of valid commands, type COMMANDS. The system will print out a list of valid commands along with a short description of each. To end the control software and return to DOS, type DONE. (Only type this command at the end of the day when all the other software has been shut down.) The commands are listed below in alphabetical order with a complete description of their actions.

AUTO: Switches control back to the Event PC from the control panel.

COMMANDS: Prints to the screen a list of all valid commands for this program as well as a short description of each command.

COMMENT: Allows the operator to enter a comment into the log file. The log file contains all commands issued indexed with time. The COMMENT command will prompt the operator to enter a comment, which will be recorded along with the time of day. The computer automatically generates a new file for comments each day.

CONTINUE: Restarts the previous test sequence without the need to re-enter the test parameters.

CRACK: Allows the operator to begin the crack test. This command will set the corresponding digital line high to the PLC.

DONE: Terminates the control software and returns to DOS.

MANUAL: Puts the vehicle in manual mode and allows commands to be entered from the control panel.

MARKER: Signals the PLC to wait for road markers before beginning a test. Some tests will require the extra precision of the road markers.

MOVE: Moves all files from the LAN drive to the WORM drive. This command would usually be issued at the end of the day.

POSITION: Sets a digital line high to signal for a position reading from the Position PC.

PROCESS: Signals the other computers to begin postprocessing of the data. The Event PC creates a file on the LAN called PRFSTAT.SYS. The Profile PC checks for this file and then begins processing. The Profile PC will erase this file when it is finished processing to signal the Event PC to resume control.

PROFILE: Sets a digital line high to start the profile test.

RESTART: Sets the shutdown line low so that the entire system can be restarted.

RUT: Sets a digital line high to start the rut test.

SETUP: Prompts the user to enter site information, which is written to the network drive file, DATACQ.SYS, so that other PCs may use this information.

SKID: Sets a digital line high to start the skid test.

SHUTDOWN: Signals the PLC to shut down all tests immediately. (Note: This command will not end the survey program.)

START: Allows the operator to begin more than one test at the same time. The operator first types the name of the test to begin, and then types START. Valid tests are crack, rut, profile, texture, skid, and temperature.

STATUS: Reads the status of the 16 I/O lines in the control PC and prints their status to the screen. The status is also recorded in the log file.

TEMP: Signals the PLC to begin temperature and humidity tests.

TEXTURE: Signals the PLC to begin the texture test.

Communication Method Utilizing the Digital I/O Ports

The PCs use discrete digital input and output lines to communicate with the programmable controller. These digital I/Os are realized in the PLC through the use of the I/O ports of discrete I/O modules and in the PC through the use of digital I/O port bits of either the DT2801-A or the DT2817 computer interface card. Both utilize TTL logic levels: 0 VDC represents logical state 0; 5 VDC represents logical state 1.

The computer interface cards have either two (DT2801-A) or four (DT2817) 8-bit digital I/O ports, and each is programmed as either an input port or an output port. For the purposes of this discussion, it will be assumed that Port 0 is an input port and Port 1 is an output port (additional ports are employed as necessary).

In the PLC, each discrete digital I/O line can serve as either an input or an output line. Each of these lines that are used for computer digital communication will be electrically connected to one bit of an I/O port in a computer interface board.

Figure 40 illustrates the digital interface between the PLC and the PC. In all cases, a screw terminal panel will facilitate the connection to the PC. The eight lines that terminate in the PC digital interface port form a byte of data. Not all lines need be connected to a port, only those that are necessary for the application. Unused lines are treated as logical zeros.

The eight bits of the input word are seen by the computer at Port 0, and are arranged as follows:

Port 0: DB7 DB6 DB5 DB4 DB3 DB2 DB1 DB0

where DB7 is the most significant bit and DB0 is the least significant bit.

When the computer reads the input word, it performs functions based on the data that is read. Likewise, the eight bits of the output word are presented by the computer at Port 1, and are arranged as follows:

Port 1: DB7 DB6 DB5 DB4 DB3 DB2 DB1 DB0

where DB7 is the most significant bit and DB0 is the least significant bit.

The computer writes an output word to Port 1, as programmed, based on the logical ones that are to be input to the PLC. The PLC scans its input lines, like the PC scans the input word, to determine the state of its input commands and acts on them accordingly. The various input and output commands that are utilized during IRSV testing control are summarized in table 12.

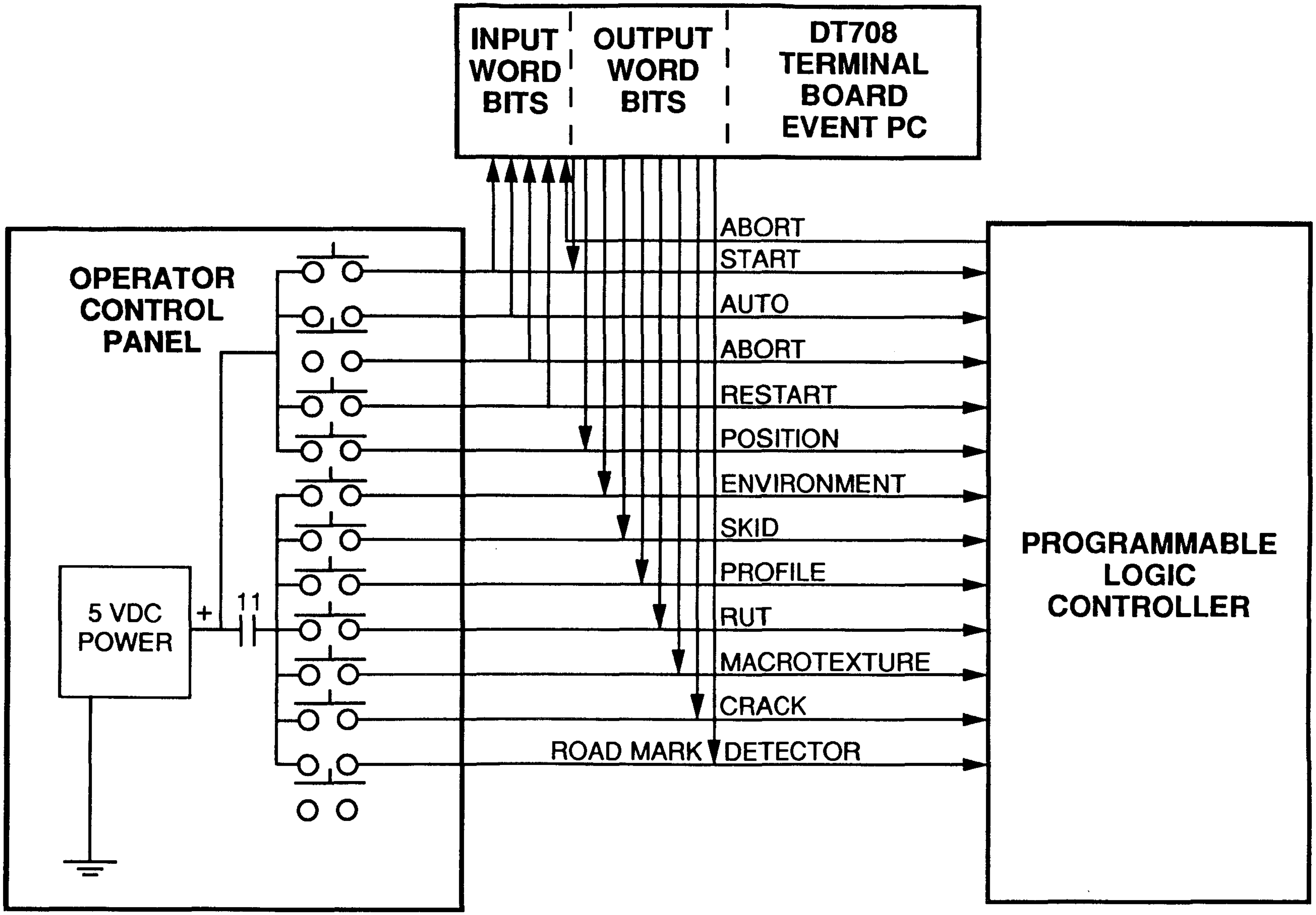

Figure 40. Interface between Event (Main) PC and PLC.

Table 12. PC/PLC digital communication scheme.

	Port 0 Bits (PC Output)	Port 1 Bits (PC Input)
Position PC	D D D D D D D D	D D D D D D D D
	B B B B B B B B	B B B B B B B B
	7 6 5 4 3 2 1 0	7 6 5 4 3 2 1 0
THERE	0 0 0 0 0 0 0 1	0 0 0 0 0 0 0 0
REQUEST	0 0 0 0 0 0 0 0	0 0 0 0 0 0 0 1
Environment PC	D D D D D D D D	D D D D D D D D
	B B B B B B B B	B B B B B B B B
	7 6 5 4 3 2 1 0	7 6 5 4 3 2 1 0
READY	0 0 0 0 0 0 0 1	0 0 0 0 0 0 0 0
START	0 0 0 0 0 0 0 1	0 0 0 0 0 0 0 1
STOP	0 0 0 0 0 0 0 0	0 0 0 0 0 0 1 0
Skid PC	D D D D D D D D	D D D D D D D D
	B B B B B B B B	B B B B B B B B
	7 6 5 4 3 2 1 0	7 6 5 4 3 2 1 0
READY	0 0 0 0 0 0 0 1	0 0 0 0 0 0 0 0
START	0 0 0 0 0 0 0 1	0 0 0 0 0 0 0 1
LOCK	0 0 0 0 0 0 1 0	0 0 0 0 0 0 0 0
STOP	0 0 0 0 0 0 0 0	0 0 0 0 0 0 1 0
Profile PC	D D D D D D D D	D D D D D D D D
	B B B B B B B B	B B B B B B B B
	7 6 5 4 3 2 1 0	7 6 5 4 3 2 1 0
READY	0 0 0 0 0 0 0 1	0 0 0 0 0 0 0 0
START	0 0 0 0 0 0 0 1	0 0 0 0 0 0 0 1
STOP	0 0 0 0 0 0 0 0	0 0 0 0 0 0 1 0
TRIGGER	0 0 0 0 0 0 0 0	0 0 0 0 0 1 0 0

Table 12. PC/PLC digital communication scheme (continued).

	Port 0 Bits (PC Output)								Port 1 Bits (PC Input)							
Macrotexture PC	DB7	DB6	DB5	DB4	DB3	DB2	DB1	DB0	DB7	DB6	DB5	DB4	DB3	DB2	DB1	DB0
READY	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
START	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
STOP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Crack PC	DB7	DB6	DB5	DB4	DB3	DB2	DB1	DB0	DB7	DB6	DB5	DB4	DB3	DB2	DB1	DB0
READY	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
START	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
STOP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0

System Functional Descriptions

Event (Main) System

Overview. The Event (Main) PC provides complete test sequence control during the automatic test sequence (ATS) mode of the IRSV operation. During ATS, the test sequence is loaded into the Event PC, as programmed onto a floppy disk, prior to test startup. The Event PC then automatically initiates the various tests according to the information it has been given.

Mechanical Description. The Event (Main) PC is located in EEC 1, position E. The voice-recognition system processing box is located in the driver's control panel.

Electrical Description. The Event (Main) PC system diagram is shown in figure 41. The major system components are: the computer (an 80286-based machine, including a floppy disk drive, hard disk, serial and parallel interface port, keyboard, monitor, and Data Translation DT2817 Digital I/O Board), the voice board, and the digital I/O connections.

The voice board is a speaker-dependent, isolated-word recognizer with a 400-word vocabulary. To use the speaker-dependent recognizer, a user must first "train" the system to his or her voice for each word or phrase in the vocabulary. From these spoken words, voice templates are stored in the system's memory and saved on disk for everyday use. Voice input capabilities are added to existing programs by using the utility program supplied by the vendor to enter the vocabulary and to train the system. After this is done, the vocabulary and voice templates are saved on the diskette for future use. The output of the voice board is passed to the operating system as if the data were typed at the keyboard. It is this method of keystroke emulation that permits the voice board to add voice input to existing or off-the-shelf programs. The commands are user definable, and each user may create up to 400 commands for each application program. Commands are structured in groups of menus. Menus are linked together to form submenus or extension menus. Each menu may contain as many as 400 commands.

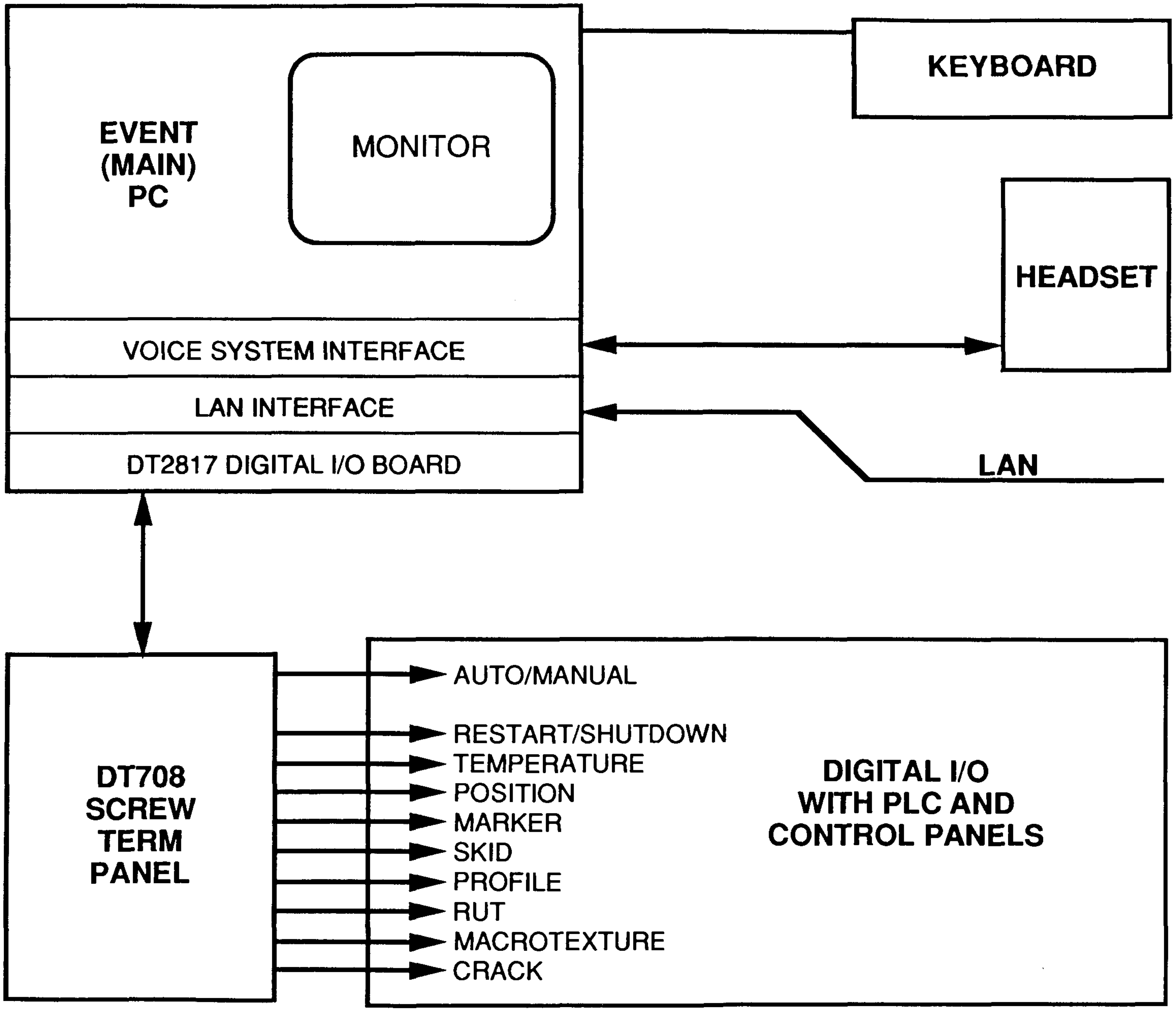

Figure 41. Block diagram showing Event (Main) PC and relationship to PLC.

The digital I/O lines of the DT2817 I/O card (this card has a total of 32 digital I/O lines) are utilized for the computer interface with the PLC. The computers constantly scan the digital input lines of the PLC to determine whether a command has been issued.

The computer output lines (shown in figure 41 by the lines whose arrowheads point away from the computer) are tied into the associated command inputs of the PLC. That is, when the computer is in the automatic mode of operation, as established by a high "auto/manual select" input to the computer I/O board, the computer will initiate the appropriate test command by bringing the appropriate control line high.

Data Acquisition and Information Transfer Requirements. The Event system will not acquire any data. It will, however, have the automatic test sequence control data stored in it for obvious reasons.

The computer will also use stored data to recognize the voice patterns of the particular driver at the wheel. Every driver will undergo a training session and create a database, which will be stored on a floppy disk. This data base will contain the driver's voice patterns for the words that make up the voice board vocabulary.

OPERATOR CONTROL PANEL

Overview

The Operator Control Panel (OCP) allows the vehicle operator (not the driver) to interface with the IRSV systems through the use of push-button and thumbwheel switches, indicators, and displays. The operator can select between the automatic test sequence (ATS) and manual test sequence (MTS) modes of operation, intervene in the testing processes, and control the vehicle support functions.

If the ATS mode of operation is selected, then the event system has primary control and the operator can do little more than abort the testing, restart the testing, enable the road mark detection system, or deactivate the

ATS. During MTS, on the other hand, the operator has complete control over test sequence actuation.

Additionally, the OCP enables the operator to ensure that systems are functioning properly. The operator can control the motor generator operation, determine the status of the generator support systems, and check the displays of parameters that data that are being input to the data acquisition systems.

Electrical Description

Figure 42 is a schematic diagram of the major interface between the OCP, the Event PC, and the PLC. This diagram shows how test activation switches are disabled when ATS is selected.

Data Acquisition and Information Transfer Requirements

Digital information transfer occurs when OCP control switches are actuated or when indicator lamps are illuminated, which indicates that commands are being sent to the Event PC in the PLC, or control or status commands are being received from the PLC.

DRIVER CONTROL PANEL

Overview

The Driver Control Panel (DCP) duplicates the "abort," "start," "auto/manual test sequence," and "skid wheel down" indicator light functions of the OCP. Additionally, the DCP provides a "auto/manual voice control" selector switch that controls the voice-recognition feature. The functions are limited so that the driver will have minimal distractions.

Electrical Description

All devices in the DCP will be connected in parallel with those corresponding features of the OCP except for the "auto/manual voice control," which will serve as a digital input to the Event PC.

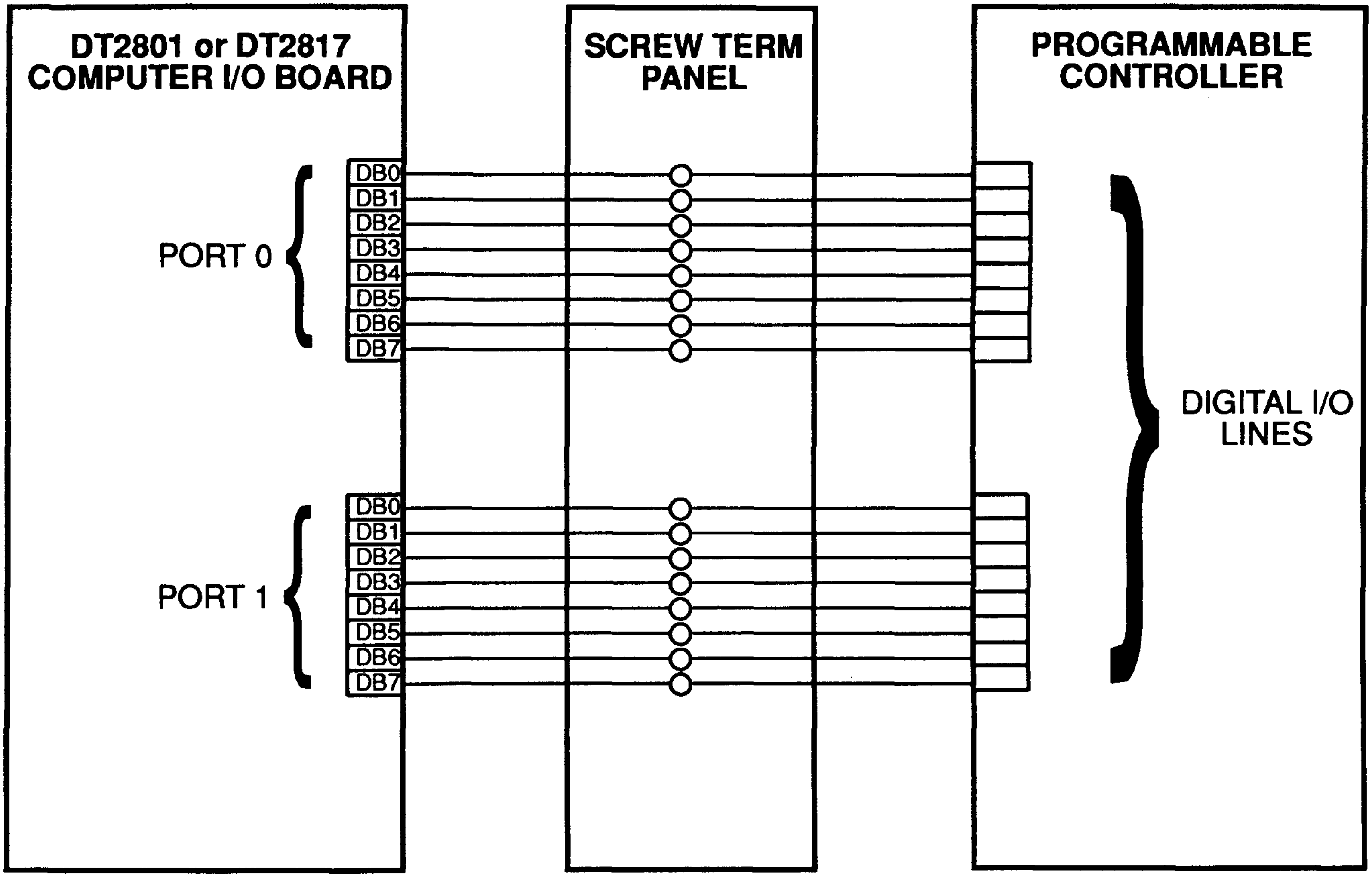

Figure 42. Communication between operator control panel, Event PC, and PLC.

PROGRAMMABLE LOGIC CONTROLLER

Traditional Controls

With the traditional methods of machine control, sensing devices located on the machine detect changes in the machine's condition. For instance, a part arriving at a work station contacts and closes a limit switch, the sensing device. As a result, a signal goes to the control panel.

At the control panel, the signal enters a bank of relays or other devices such as solid-state modules. Circuits within the control panel open or close causing additional signals to control output devices, such as the water pumps and brakes. For example, a relay may energize a clamp, which secures the part at the work station.

Systems run by programmable controllers operate in the same way. Input sensing devices report machine conditions; output devices respond to commands. Wiring between the machine and the controller provides electrical paths from the sensing devices to the controller and from the controller to the output devices. However, instead of wiring relays together to produce a desired response, the programmable controller can be instructed how to respond.

A typical programmable controller system usually consists of a processor, input (input modules), output (output modules), and a power supply. The processor is divided into two sections: the central processing unit and memory. The CPU makes decisions about what the processor is to do according to a user-written program. Memory stores programs, messages, and information in the data table that the CPU may need to make its decisions.

Data is stored and examined in a memory area called the data table, which is divided into smaller sections according to the type of information to be stored. These sections are called the input image table, the output image table, and timer/counter storage. The input image table reflects the status of the input terminals. The output image table reflects the status of bits controlled by the program. The purpose of the output image tables is to control the on or off status of the output devices wired to output module terminals. If an output image table bit is on (1), its corresponding output device is on (energized); if a bit is off (0), its corresponding output device is off (de-energized). Output image table bits are controlled by user program instructions. Timer and counter instructions are output instructions, which provide many of the capabilities available with timing relays and solid-state timing and counting devices. Usually conditioned by examine instructions, they keep track of timed intervals or counted events according to the logic of the rung.

Program storage, where instructions to the programmable controller are stored, takes up the most memory. This set of instructions, or program, consists of a set of statements. Each statement does two things: it describes the conditions that must exist for any action to occur, and it describes the action to be taken.

The third area of memory, message storage, begins after the end statement of the user program. Two alphanumeric characters can be stored in a word.

CHAPTER 10. SUMMARY

An integrated road survey vehicle (IRSV) has been designed, and a detailed description of the hardware and software required to build the vehicle is presented in this report. Detailed drawings, components required to build the vehicle, specifications for the components, and a listing of the software developed for the IRSV are given in "Development of Integrated Survey Vehicle for Measuring Pavement Surface Conditions at Highway Speeds--Volume II: Technical Details" (FHWA-RD-90-012).

The IRSV has been designed to provide the following road survey data while traveling at highway speeds of 40 mi/h (62 km/h):

- Longitudinal profiles with provisions for computing roughness in in/mi (mm/km), International Roughness Index (IRI), and Present Serviceability Index (PSI).
- Transverse profiles with provisions for computing rut depth in each wheel track in inches (mm).
- Skid numbers at different slip speeds using the spinup tester.
- A quantitative measurement of the macrotexture of the pavement surface in terms of the RMS.
- A cracking inventory based upon an off-vehicle analysis of video imaging.

In support of the measurement systems, a number of ancillary systems have been provided. These include:

- An environment system for measuring humidity and air and pavement temperature.
- A position system that gives the coordinates of the vehicle so that the data may be referenced to geographical coordinates.
- A voice-recognition system for recording key features as the vehicle traverses the test sections.
- A print/plot system that allows the data to be printed or plotted on-board during the testing.

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- A local area network (LAN) that is used as a file to store the data that is collected by the various systems.

Control of the overall system is maintained by the Event (Main) PC system and the programmable logic controller (PLC). Each of the subsystems consists of a separate subsystem, facilitating system upgrading, component replacement, and maintenance while offering excellent operational flexibility. Each of the subsystems contains a personal computer (PC) which is based on either an 80286- or 80386-based central processing unit (CPU).

A great deal of specialized software was written for the system. A complete listing of this software can be found in appendix C.

COST ESTIMATES

Detailed cost estimates for the construciton of the IRSV are given in "Development of Integrated Survey Vehicle for Measuring Pavement Surface Conditions at Highway Speeds--Volume II: Technical Details (FHWA-RD-90-012). The total cost to construct a system that includes transverse and longitudinal profiling, skid and macrotexture measurements, and a crack detection system is estimated to be approximately $521,167. The cost estimate is based on list prices for the various components. Competitive bidding would likely reduce the cost of many of these components. The IRSV includes a sophisticated data acquisition system and ancillary systems such as a Loran C position system, a voice-recognition system, and an environmental measurement system.

The exact cost of the system will depend on the bidding strategies of the contractors that bid on its manufacture, the number built, and the expected status of the vehicle after construction. We suggest that the full deployment of the vehicle be accomplished in two stages: (1) building and debugging the operation of the vehicle and (2) establishing the operating parameters of the vehicle and refining the data processing and handling to be consistent with the operating parameters. This later stage would require approximately $100,000 to $200,000 in funding.

The operating costs for the vehicle (excluding operator's time but including maintenance costs) should be approximately the same as operating a fleet of vehicles of the same design. Based on conversations with a major fleet operator and the experience of others in operating a similar test vehicle (skid and profile testers), the operating cost of the IRSV would be $2.00/mi. This figure includes fuel, lubrication, and other chassis maintenance.

A 10-year life cycle is anticipated for the vehicle and its components with a 10 percent, or $50,000, salvage value at the end of 10 years. Over the life of the vehicle, certain components will have to be replaced as a result of wear and breakage, and an average cost of $5,000 per year is allocated to the maintenance and replacement of the test equipment within the vehicle.

To fully appreciate the operating cost of the vehicle, some estimate of down time and productivity must be made. Assuming that the vehicle is used 50 percent of the time to acquire data and that the remainder of the time is used in travel time, maintenance, and other down time, the vehicle could monitor 35,000 miles of pavement per year (8 h/day x 50 percent productive time x 220 working days x 40 mi/h [64 km/h]). Assuming that an additional 5,000 miles are traveled in moving to the test locations, total travel time would be approximately 40,000 miles per year.

If the vehicle is in service for 500,000 miles (50,000 miles per year for 10 years), major engine and chassis maintenance will be required, and this is estimated as $15,000. Salaries for the two operators are estimated, after overhead and fringe benefits, as $100,000 per year ($20,000 base salary with a loading factor of 2.25). A summary of the overall costs is as follows:

Initial capital cost	$521,167
Major vehicle maintenance	$15,000
Salvage value at end of 10 years	($50,000)
Average yearly cost of vehicle	$48,617

Yearly cost for operators	$100,000
Yearly vehicle operating costs	$80,000
Yearly maintenance cost for equipment	$5,000
Total yearly cost for operation	$233,617
Total cost per mile assuming 35,000 miles of pavement are tested per year	$6.67

The above summary neglects the cost of money and life-cycle costing. If these factors are considered, the cost per mile for operating the system is $7.23/mi.

Although the initial cost of the vehicle may seem high, the cost per mile for a survey that produces longitudinal and transverse profiling, skid and macrotexture data, and a computerized video survey is very modest.

APPENDIX A. LIST OF DRAWINGS AND ASSOCIATED EQUIPMENT

DWG. NO.	NO. OF SHEETS	TITLE
D13863	1	TITLE SHEET AND LIST OF DRAWINGS
D13844	1	VEHICLE PROFILES
D13859	1	CHASSIS ARRANGEMENT
D13859D1	1	WATER TANK DETAIL
D13862	3	ELECTRICAL EQUIPMENT ARRANGEMENT
D13856	1	PAVEMENT SKID TESTER
D13856D1	1	SKID TESTER DETAIL
D13861	1	VEHICLE OPTOCATOR SUPPORT BRACKET ASSEMBLY
D13860	1	AIR AND WATER DIAGRAM
D13851	2	CONTROL AND DATA ACQUISITION SYSTEM SCHEMATIC BLOCK DIAGRAM
D13852	1	POWER DISTRIBUTION DIAGRAM
D13853	2	OPERATOR'S CONTROL STATION
D13854	1	DRIVER'S CONTROL PANEL
D13864	3	DETAILS OF TEXTURE SYSTEM

APPENDIX B: LIST OF VEHICLE COMPONENTS AND THEIR COSTS

1. EVENT SYSTEM

Total for Event PC Sub-System		$11,009
Materials for Assembly of Event System	$ 400	
Labor for Assembly of Event System: 20 h @ $80/h	$ 1600	
Total for Materials and Labor for Event System		$ 2,000
Total Estimated Cost for Event System		$13,009

2. POSITION SYSTEM

Total for Position PC Sub-System	Total	$ 9,315
Total for LORAN C Sub-System		$ 1,335
Materials for Assembly of Position System	$ 1,000	
Labor for Assembly of Position System: 20 h @ $80/h	$ 1,600	
Total for Materials and Labor		$ 2,600
Total Estimated Cost for Position System		$13,250

3. ENVIRONMENTAL SYSTEM

Total for Environmental PC Sub-System		**$10,235**
Total for Pavement Temperature Measurement Sub-System		**$ 1,290**
Total for Environmental Measurement Sub-System		**$ 2,790**
Materials for Assembly of Environmental System	**$ 300**	
Labor for Assembly of Environmental System: 35 h @ $80/h	**$ 2,800**	
Total for Materials and Labor		**$ 3,100**
Total Estimated Cost for Environmental System		**$17,415**

4. SKID SYSTEM

Total for Skid PC Sub-System		$11,195
Total for Air Compressor		$ 1,500
Total for Water Level Sensor		$ 1,680
Total Turbine Water Flow Meter		$ 1,390
PSU Spin-up Skid Tester		$50,000
Fabricated Aluminum Water Tanks 2 ea @ $5,000	$10,000	
Materials for Assembly of Skid System	$ 2,500	
Labor for Assembly of Skid System: 200 h @ $80/h	$16,000	
Total for Materials and Labor		$28,500
Total Estimated Cost for Skid System		$94,265

5. PROFILE SYSTEM

Total for Profile PC Sub-System		$17,790
Total for Instrumentation Amplifiers		$ 2,496
Total for Programmable Filters		$11,600
Total for Non-Contact Distance Measurement Sub-System		$53,900
Total for Accelerometer		$ 2,000
Total for Gyro		$10,700
Materials for Assembly of Profile System	$ 5,000	
Labor for Assembly of Profile System: 75 h @ $80/h	$ 6,000	
Total for Materials and Labor		$11,000
Total Estimated Cost for Profile System		$109,486

6. MACROTEXTURE SYSTEM

Total for Macrotexture PC Sub-System		$13,250
Total for Macrotexture System Hardware		$12,000
Materials for Assembly of Macrotexture System	$ 2,000	
Labor for Assembly of Macrotexture System: 80 h @ $80/h	$ 6,400	
Total for Materials and Labor		$ 8,400
Total Estimated Cost for Macrotexture System		$33,650

7. LOCAL AREA NETWORK SYSTEM

Total for Local Area Network PC System		$15,170
Materials for Assembly of Local Area Network System	$ 200	
Labor for Testing Software Programs and Installing LAN Network PC System: 150 h @ $80/h	$12,000	
Total for Materials and Labor		$12,200
Total Estimated Cost for Local Area Network System		$27,370

8. PRINT/PLOT SYSTEM

Total for Print/Plot PC System		$11,682
Materials for Assembly of Print/Plot System	$ 400	
Labor for Assembly of Print/Plot System: 25 h @ $80/h	$ 2,000	
Total for Materials and Labor		$ 2,400
Total Estimated Cost for Print/Plot System		$14,082

9. PROGRAMMABLE LOGIC CONTROL SYSTEM

Total for Programmable Controller System		$16,010
Materials for Assembly of PLC System	$ 1,000	
Labor for Assembly of Programmable Logic Control System: 40 h @ $80/h	$ 3,200	
Total for Materials and Labor		$ 4,200
Total Estimated Cost for Programmable Logic Control System		$20,210

10. POWER DISTRIBUTION SYSTEM

Total for Voltmeters		$ 420
Total for Electrical Power Generation		$10,215
Total for AC Power Control and Distribution Sub-System		$ 945
Total for DC Power Sub-Systems		$ 325
Materials for Assembly of Power Distribution System	$ 1,000	
Labor for Assembly of Power Distribution System: 95 h @ $80/h	$ 7,600	
Total for Materials and Labor		$ 8,600
Total Estimated Cost for Power Distribution System		$20,505

11. GENERAL VEHICLE HARDWARE/ELECTRICAL COMPONENTS

Total for Electronics Equipment Cabinets	$ 9,364
Total for Cellular Phone Sub-System	$ 825
Total CB Radio Sub-System	$ 124
Total Road Mark Detector	$ 272
Total Vehicle Speed Sensor	$ 7,500

Materials for Assembly of General Vehicle Hardware/ Electrical Components	$ 3,000	
Labor for Complete Wiring of Vehicle, Installation of Equipment Racks and Installation and Wiring of Consoles: 600 @ $80/h	$48,000	
Total Materials and Labor		$51,000
Total Estimated Cost for General Vehicle Hardware/Electrical Components		$69,085

12. CRACK DETECTION SYSTEM

Total for Idaho Crack Detection Sub-System		$50,000
Materials for Assembly of Crack Detection Sub-System	$ 2,000	
Labor for Assembly of Crack Detection System: 40 h @ $80/h	$ 3,200	
Labor for Installing System: 8 h @ $80/h	$ 640	
Total for Materials and Labor		$ 5,840
Total Estimated Cost for Crack Detection System		$55,840

13. VEHICLE

Total for Vehicle	$28,000
Modification of Vehicle to Include Carpet False Floor, Fitting of Chair for Operator, etc.	$ 5,000
Total Estimated Cost for Vehicle	$33,000

APPENDIX C. LIST OF SOURCE PROGRAMS

ENVIRONMENTAL SYSTEM

TMPHMD.BAS--BASIC source code for data acquisition.

DOY--subroutine to determine the day of the year in julian calendar.
WRITEDATA--subroutine to write environment data files.

TMPHMD.EXE--compiled executable code for data acquisition.
CNFGENV.BAS--BASIC source code for the setup utility program that creates the data file CNFGENV.DAT read by TMPHMD.EXE at execution.

SKID SYSTEM

SKIDATA--acquires data, computes skid numbers, and stores data and skid numbers.

ANG2WS--computes angular speed and acceleration of test tire.
CALSNPNG--calculates skid numbers: SN_0 and PNG.
ELAPS--collects the timing data for the spinup test.
ERRORS--describes the error messages.
LINREG--linear regression routine to compute the skid parameters.
NOTRIG--detects if the spinup wheel is locked.
RDSPEED--reads vehicle speed.
SKIDNUM--computes the skid number from SN_0 and PNG.
SNVCONV--converts the angular acceleration into skid numbers for different slip speeds.
TIMEOUT--determines the waiting period for NOTRIG routine.
VS2SYNC--time synchronization routine for differentiation computation.

CNFGSKD--sets the operating parameters for data acquisition.

PROFILE SYSTEM

DATACQ.FOR--performs data acquisition.

A2D--performs acquisition of raw profile data.
ANAME--creates filename from 2 character strings.
DIO--performs digital output for communication with PLC.
DRIVE--attaches the disk drive assignment to filenames.
FILTSET--sets the analog filter bandwidths on each channel.
FNAME--creates filename for data files.
GNAME--gets the julian calendar date for use in the filename.
HPFILT--performs digital high pass filterr to provided array.
MANU--allows manual of operating parameters.
MINU--matrix increase routine.
MODE--erases screen.
PCLAB--routines from PCLAB for data acquisition.
TESTING--performs real-time I/O verification for all channels.
TOGETHER--subroutine to combine characters into string.

PROFCOM--performs profile computation.

ANAME--creates filename from 2 character strings.
DEBIAS--removes DC shift in signals.
FNAME--creates filename for data files.
GNAME--gets the julian calendar date for use in the filename.
IRICOM--IRI computation subroutine.
MAYS--simulates mays meter response to profile for computing IPM.
PSICOM--performs PSI and IRI computation.
QCAR--performs Q-CAR simulation.
RAVE--function for real array averaging.
REGFILT--performs removal of long wavelength due to integration.
RUNGE--performs third order Runge-Kutta integration.
RUTCOM--performs rut computation.
SETSTM--initializes quarter car matrix (static transition matrix).
SUM--performs sum computation for RUNGE routine.
TOGETHER--subroutine to combine characters into string.

VANAL.FOR--performs data processing.

ANAME--creates filename from 2 character strings.
FNAME--creates filename for data files.
GNAME--gets the julian calendar date for use in the filename.
TOGETHER--subroutine to combine characters into string.

CALIBPRF--calibrates the profile computation constants for all sensors.

CNFGPRF.FOR--sets up the operating parameters for data acquisition.

MACROTEXTURE SYSTEM

TEXTURE.C--collects and stores data.
CALIBRAT.C--sets system height to correct standoff.
POSTPROC.C--reads data and processes data.
CNFGMTX.C--parses the user for input data and creates a data file TEXINPUT.
AUTOEXEC.BAT--runs all macrotexture programs in order.
CONFIG.SYS--system configuration file required for vision software.

MASTER CONTROL PROGRAM

SURVEY.BAS--master control program for survey vehicle.
INIT--initializes the system and file I/O.
MARKER--signals the controller to wait for road markers.
START--starts a predetermined group of tests.
SKID--begins the skid test.
TEMP--begins the temp test.
PROFILE--begins the profile test.
RUT--begins the rut test.
TEXTURE--begins the texture test.
CRACK--begins the crack test.

POSITION--begins the position acquisition.
SHUTDOWN--shuts down the entire system immediately.
RESTART--restarts the entire system.
DONE--ends the data acquisition program.
COMMENT--enters comments into a comment file.
MANUAL--allows for manual operation from the control panel.
AUTO--returns control to the Event PC.
STATUS--displays the value of the status register I/O lines.
COMMANDS--prints all valid commands for the program.
DIGITAL--handles all digital I/O with the PLC.
SETUP--creates a data file on disk for other programs.
DOY--calculates the day of the year.
MOVE--moves all files from the LAN drive to the WORM drive.
PROCESS--signals other systems to begin data processing.
CONTINUE--restarts the system with the previous parameters.

COMMERCIALLY AVAILABLE PROGRAMS

PCLAB (Version 3.01).
MS DOS (Version 3.1).
Microsoft BASIC Complier (Version 6.0).
Local Area Network Software.
Vocalink--Supplied with Video Digitizing Hardware.
Vocalkey--Supplied with Video Digitizing Hardware.
Miscrosoft FORTRAN Complier (Version 4.01).
Microsoft C Compiler (Version 5.1).

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7. Author(s) J. C. Wambold, W. E. Meyer, D. A. Anderson		8. Performing Organization Report No.
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15. Supplementary Notes

FHWA contract manager (COTR): Dr. Rudolph R. Hegmon (HNR-20)

16. Abstract

The objective of this study was to develop an integrated survey vehicle for measuring pavement surface conditions at highway speeds. This was accomplished by determining the requirements and operating characteristics for such a system, preparing a design, and estimating initial and operating costs.

This volume contains a review of the data and measurement needs for pavement condition surveys. The equipment available and under development for this purpose are identified with emphasis on measurements at highway speeds. Three potential survey vehicle designs are presented: the first uses off-the-shelf components, the second uses state-of-the-art components, while the third anticipates the addition of equipment still in development. The final design that was selected incorporates all three types of equipment. A complete, detailed design for the vehicle and the test equipment was prepared and each subpart discussed. Operating procedures for the survey vehicle are established and given in this report.

This volume is the first in a series. The other volume is:

VOL. No.	FHWA No.	Short Title
2	RD-90-012	Integrated Survey Vehicle--Technical Details

17. Key Words Pavement surveys, pavement management, macrotexture, crack detection	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	170	

Form DOT F 1700.7 (8-69)

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

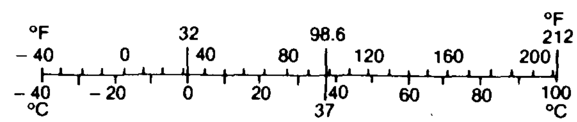
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)