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DESIGN AND DEVELOPMENT OF AN INFRASTRUCTURE DIAGNOSTIC VEHICLE (IDV) FOR AHS*

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16. Abstract

This report describes the development of an Infrastructure Diagnostic Vehicle (IDV) for Automated Highway Systems (AHS). The IDV was developed to support inspection-integrated maintenance of AHS. The system is intended to diagnose various aspects of the infrastructure required for safe and reliable operation of an AHS. Currently, the system diagnoses the discrete magnetic marker lateral reference system, checking for missing or degraded markers, as well as for incorrect polarity for information coding. The system also tests communications with roadside beacons and the Transportation Management Center (TMC). In addition, the system allows for easy notification by the operator for other faults, such as debris in the roadway or roadside, using a Differential Global Positioning System (DGPS) receiver and an error logger. The IDV provides health-monitoring inspection of the AHS at highway speed using vision-based lateral control. The current vehicle uses standard cruise control, but could be easily augmented with Intelligent Cruise Control (ICC). The system includes magnetometers, sensing computer, control computer, vision system, communications system, and required actuators. The AHS IDV was demonstrated at the National Automated Highway Systems Consortium (NAHSC) Proof-of-Technical-Feasibility Demonstration in August 1997.

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ABSTRACT

This report describes the development of an Infrastructure Diagnostic Vehicle (IDV) for Automated Highway Systems (AHS). The IDV was developed to support inspection-integrated maintenance of AHS. The system is intended to diagnose various aspects of the infrastructure required for safe and reliable operation of an AHS. Currently, the system diagnoses the discrete magnetic marker lateral reference system, checking for missing or degraded markers, as well as for incorrect polarity for information coding. The system also tests communications with roadside beacons and the Transportation Management Center (TMC). In addition, the system allows for easy notification by the operator for other faults, such as debris in the roadway or roadside, using a Differential Global Positioning System (DGPS) receiver and an error logger. The IDV provides health-monitoring inspection of the AHS at highway speed using vision-based lateral control. The current vehicle uses standard cruise control, but could be easily augmented with Intelligent Cruise Control (ICC). The system includes magnetometers, sensing computer, control computer, vision system, communications system, and required actuators. The AHS IDV was demonstrated at the National Automated Highway Systems Consortium (NAHSC) Proof-of-Technical-Feasibility Demonstration in August 1997.

EXECUTIVE SUMMARY

AHS operation relies upon accuracy in infrastructure parameters. It will be the responsibility of State Departments of Transportation (DOT) to check and maintain the integrity of these newly important components of infrastructure. The AHS Infrastructure Diagnostic Vehicle (IDV) tests and diagnoses problems in magnetic reference markers and roadside communications infrastructure as a demonstration of technology for maintenance of AHS-specific technologies. The AHS IDV was demonstrated at the National Automated Highway Systems Consortium (NAHSC) Proof-of-Technical-Feasibility Demonstration in August, 1997, mandated by the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). The system was developed as part of the California State Department of Transportation's (Caltrans) involvement in the NAHSC demonstration. The AHS IDV (herein referred to as the IDV) is intended to demonstrate the need for and capability of advanced diagnostic systems in an AHS.

Reliable AHS electronic sensing and communication relies upon minimum functionality in various parts of an AHS: embedded magnetic reference markers and roadside communication beacons, for example. Vehicle sensing systems rely on infrastructure components, such as magnetic reference markers for purposes of guidance. Roadside communication beacons must also operate according to specifications, in order to provide necessary Vehicle-to-Roadside Communication (VRC) for system Check-in and Check-out functions. Frequent and rapid inspection of passive reference devices and communications systems will be required to maintain overall system integrity. The IDV assures the functionality and general health of an AHS using appropriate maintenance equipment and inspection procedures. The IDV, equipped with laser-based lane-following capability, travels along the AHS with the main purpose of rapidly testing AHS-specific infrastructure components. In the NAHSC demonstration scenario, the IDV logs system status and communicates any system degradation to a central operations center. Using this information, an automated maintenance vehicle can be dispatched to expeditiously perform the required maintenance task, possibly at traffic speeds.

The IDV is equipped with an array of magnetometers, along with other appropriate sensors, e.g. velocity sensors. With vision-based lateral guidance, and longitudinal control provided by either standard or "intelligent" cruise control, the IDV senses the magnetic markers to verify their presence and qualification as a guidance reference. The system checks the magnetic markers for presence, correct polarity, and field strength. Other specialized reference markers could also be inspected, such as retroreflective paint stripes or radar reflective markers, if such systems are identified as critical to the functionality of an AHS. The IDV also verifies the operation of the roadside data communication devices, using a transponder tag for communication with the roadside beacons that are intended to support AHS Check-in and Check-out functions. Results regarding the health of the roadway and roadside devices are communicated to a central maintenance facility or Transportation Management Center (TMC) via Infrastructure-to-Vehicle (I-V) communication, using a Cellular Digital Packet Data (CDPD) modem. Notification from the IDV that an infrastructure component is missing or malfunctioning can be used to dispatch or schedule maintenance to replace or repair it.

This report is organized as follows. Chapter 2 presents an overview of the magnetic marker diagnostics hardware, algorithms, and software. Similar information for the communications diagnostics is provided in Chapter 3. Chapter 4 describes the internal and external communications architecture used in the IDV computer systems. Chapter 5 briefly overviews the Automated Location Tracking System (ALTS) developed by Lockheed Martin Corporation (LMC). Chapter 6 provides a similar overview of the vehicle automatic control. Both Chapter 5 and Chapter 6 are cursory, as much of the detailed information is proprietary to LMC and its subsidiaries. Chapter 7 describes the system integration for the IDV, an essential aspect in this project. An overview of the NAHSC demonstration is provided in Chapter 8. Chapter 9 provides results and evaluation of the diagnostic package field tests. Finally, Chapter 10 presents conclusions and recommendations for future research.

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DISCLAIMER/DISCLOSURE

"The research reported herein was performed as part of the Advanced Highway Maintenance and Construction Technology Program (AHMCT), within the Department of Mechanical and Aeronautical Engineering at the University of California, Davis and the Division of New Technology and Research of the California Department of Transportation. It is evolutionary and voluntary. It is a cooperative venture of local, state and federal governments and universities."

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LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	Definition
ADC	Analog-to-Digital Converter
AHMCT	Advanced Highway Maintenance and Construction Technology
AHS	Automated Highway System
ALTS	Automated Location and Tracking System
bps	Bits per second
Caltrans	California State Department of Transportation
CC	Control Computer
CDPD	Cellular Digital Packet Data
CLTF	Crow’s Landing Test Facility
CPS	Continuous Positioning System
DGPS	Differential Global Positioning System
DOT	Department of Transportation
DP	Diagnostic Package
DPC	Demonstration Presentation Center
DRV	Debris Removal Vehicle
EMI	Electromagnetic Interference
FLIR	Forward-Looking Infrared Radar
GGF	Golden Gate Fields
GM	General Motors
GPS	Global Positioning System
HMI	Human Machine Interface
I-V	Infrastructure to Vehicle
ICC	Intelligent Cruise Control
IDV	Infrastructure Diagnostic Vehicle
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITS	Intelligent Transportation Systems
ITSA	Intelligent Transportation Society of America
IVI	Intelligent Vehicle Initiative
LAN	Local Area Network
LMC	Lockheed Martin Corporation
MMI	Man-Machine Interface
NAHSC	National Automated Highway Systems Consortium
NAV	LMC Navigation and Control Computer
NCY	North Control Yard
ORV	Obstacle Removal Vehicle
PATH	Partners for Advanced Transit and Highways
POSE	Program Office Systems Engineering
RF	Radio Frequency, or Road Follower (context dependent)
RFI	Radio Frequency Interference
RFS	Richmond Field Station

RTOS	Real-Time Operating System
SCY	South Control Yard
TCP/IP	Transmission Control Protocol / Internet Protocol
TMC	Transportation Management Center
UCD	University of California-Davis
VRC	Vehicle-to-Roadside Communication
WTI	Western Transportation Institute

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CHAPTER ONE

INTRODUCTION

This report documents the Advanced Highway Maintenance and Construction Technology (AHMCT) Center's development of the Automated Highway Systems (AHS) Infrastructure Diagnostic Vehicle (IDV). The document provides motivation, system overview, major subsystems, and functions. It also describes the demonstration of the IDV as part of the Maintenance Scenario in the National Automated Highway System Consortium (NAHSC) Proof-of-Technical Feasibility Demonstration in August, 1997. The document discusses the automatic control as implemented by Lockheed Martin Corporation (LMC), but does not provide the details of this system. The interested reader may consult related reports produced by LMC to obtain detailed descriptions of the vehicle control. Similarly, the LMC Automated Location and Tracking System (ALTS) is overviewed, but details are not provided. Integration of the UC Davis Diagnostic Package (DP) with the LMC vehicle control system is also discussed, along with the development of the system's Human Machine Interface (HMI). Finally, conclusions, lessons learned, and recommendations for future work are presented.

Motivation

AHS operation relies upon accuracy in infrastructure parameters. It is the responsibility of each State DOT to check and maintain the integrity of these critical components of infrastructure. The IDV tests and diagnoses problems of magnetic reference markers and vehicle-to-roadside communication (VRC) systems as a demonstration of technology for maintenance of AHS safety-critical systems.

AHS sensing and communication rely upon minimum functionality in various parts of an AHS: embedded magnets and roadside readers, for example. Vehicle sensing systems will rely upon such infrastructure components as embedded magnets for purposes of guidance. Roadside readers, used for vehicle check-in and check-out, also must operate according to specifications. Frequent and rapid inspection of passive reference devices will be necessary to maintain overall system integrity. This project showed that the accuracy and general health of an AHS can be assured with appropriate maintenance equipment. The IDV, equipped with lane following capability, travels along the AHS with the sole purpose of rapidly testing AHS dependent infrastructure components. The IDV communicates any system degradation to a central operations center, known as the Transportation Management Center (TMC), and an automated maintenance vehicle is dispatched to expeditiously perform the repair task, possibly at traffic speeds. In the planned scenario, the Obstacle Removal Vehicle (ORV) is dispatched in this manner, but no vehicle is dispatched for detected magnetic marker faults. As the controlled vehicles are robust with respect to a small number of magnet failures, and the IDV detects magnet failures at a very early stage, it is sufficient to schedule the repair and/or replacement of faulty magnets at a later time, when AHS traffic is minimal

A General Motors Corporation (GMC) Chevrolet Lumina with LMC vision guidance and steering technology was provided to the AHMCT Center. AHMCT equipped this system with magnetometers, GPS and dead-reckoning, and VRC transponder tag, to support the AHS diagnostics. The LMC control vehicle, without the DP technology, is referred to as the IDV Platform. Using the same technology that other AHS computer-guided vehicles use, the vehicle, equipped with the AHMCT Diagnostic Package (DP), senses the magnetic reference markers to verify their presence and qualification as a guidance reference. Other special markers can be inspected, if such systems are identified as safety-critical components of an AHS. Appropriate sensors must be added to the IDV to support diagnosis of such systems. Also, the IDV verifies operation of the VRC system. In operation, results regarding the health of the roadway and roadside devices are communicated with the TMC. In the NAHSC demonstration, the data was sent to the Demonstration Command and Control (DCC) center and to the Demonstration Presentation Center (DPC) at the exposition site.. Notification that an infrastructure component is missing or malfunctioning is used to dispatch maintenance to replace or repair it.

Observation of the testing and diagnostic operation was provided via cameras. NAHSC demonstration attendants were able to watch the actual testing of embedded magnets and roadside readers as it occurred. In addition, VIP demonstration attendants were allowed to ride in the IDV to directly experience the vehicle's automated control and the AHS diagnostics. Simulated magnet errors were intentionally introduced for the purposes of this demonstration, in order to illustrate the capabilities of the diagnostic system.

Project Overview

The AHS IDV (herein referred to as the IDV) demonstrates the need for and capability of advanced diagnostic systems in an AHS. The system was developed for use in the National Automated Highway Systems Consortium (NAHSC) Proof-of-Technical-Feasibility Demonstration, required by the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). This demonstration was held August 5 - 11, 1997, on the 7.6 mile (12 km) long AHS Test Facility located on the I-15 High Occupancy Vehicle (HOV) lanes in San Diego, CA. The system was developed as part of the California State Department of Transportation’s (Caltrans) involvement in the NAHSC demonstration. The lead contractor on the project was the Advanced Highway Maintenance and Construction Technology Research Center at the University of California-Davis (UCD). AHMCT was responsible for the development of the Diagnostic Package (DP). Lockheed Martin was responsible for the IDV Platform, i.e. the vehicle control automation.

The IDV diagnoses the health and functionality of various components in the AHS infrastructure. Components required for the effective lateral guidance of both platoon and free-agent vehicles are tested. For the NAHSC demonstration scenario, the system diagnoses the magnetic markers (also known as “nails”) used by the PATH-developed automated vehicles. These magnetic markers were also used in demonstration scenarios developed by Honda and Toyota. The IDV checks the magnetic markers for presence, correct polarity, and field strength, as well as correct longitudinal spacing and lateral smoothness. The system includes location tracking and error logging equipment provided by the LMC, known as the Automated Location and Tracking System (ALTS). The IDV communicates infrastructure errors to the TMC via

Infrastructure-to-Vehicle (I-V) communication; using a Cellular Digital Packet Data (CDPD) modem. The IDV also includes an RF reader tag system for Vehicle-to-Roadside Communication (VRC) at system check-in and check-out. The RF tag is used to diagnose the health of the roadside RF beacon used for check-in, another AHS safety-critical function. The general IDV concept is illustrated in Figure 1-1. The actual IDV is shown in Figures 1-2 and 1-3.

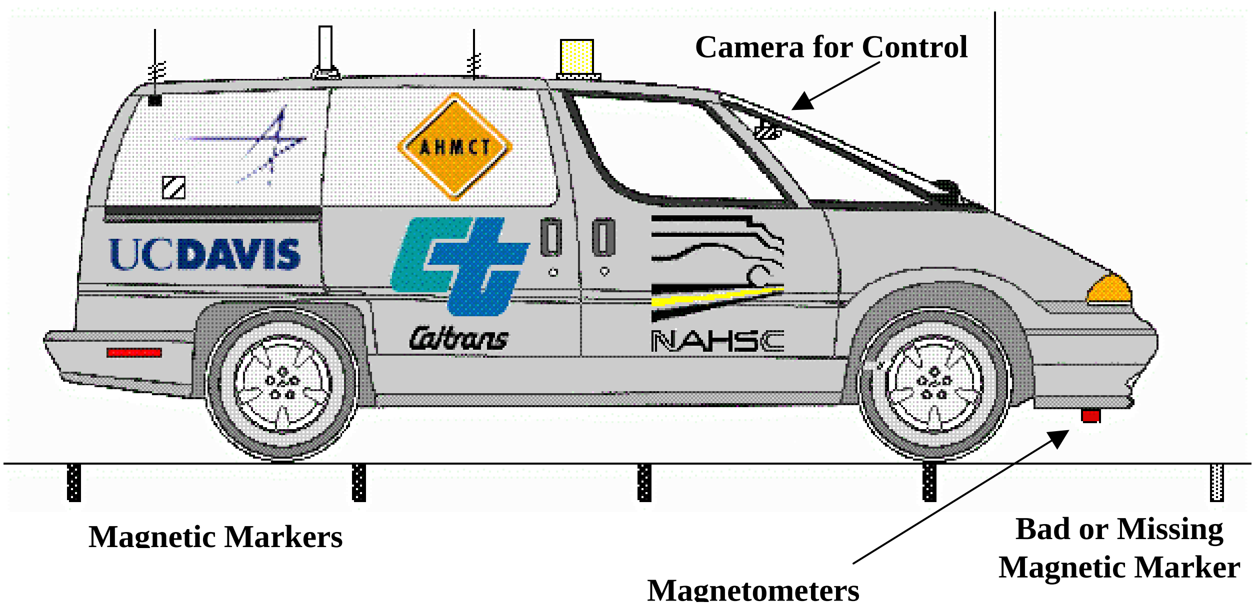


Figure 1-1: Infrastructure Diagnostic Vehicle Conceptual Drawing

The support vehicle as developed by LMC contains the steering actuator, cooling ducts for electronics components, and power bus. The system uses standard cruise control for longitudinal control; note that the speed setting for the cruise control is interfaced to the control computer, allowing the specification of vehicle velocity profiles. LMC integrated their vision-based navigation and control system into the vehicle. This system was originally developed as part of Lockheed's participation in the DEMO II program. The system is capable of automated lateral control (i.e. “hands-off”) at highway speed of 65 MPH (29.1 m/s), as specified for the demonstration. The vehicle also includes LMC’s ALTS package, which will supplies absolute vehicle location, as well as error logging capability. The LMC control system computer provides an Ethernet connection for communications between the control and infrastructure sensing computers using TCP/IP and UDP sockets.

To minimize schedule delays, AHMCT developed the infrastructure Diagnostic Package in parallel with the LMC IDV Platform development. AHMCT used a testbed vehicle which is identical to the IDV platform, with the exception that the AHMCT vehicle does not contain any vehicle automation. The AHMCT testbed includes magnetometers, support computer, Analog-to-Digital Converter (ADC), Real-Time Operating System (RTOS), and all required sensing and communications hardware and software. The system is capable of detecting missing magnets, incorrect polarity magnets, and other magnet errors. The system was tested and validated at two test sites where magnets have been previously installed: a parking lot at the Golden Gate Fields (GGF) race track, and an airport runway known as the Crow's Landing Test Facility (CLTF). This validation was coordinated with the demo vehicle integration, so that the two systems were ready for complete system integration at approximately the same time.

Figure 1-2: Infrastructure Diagnostic Vehicle During Development in Colorado

Figure 1-3: Infrastructure Diagnostic Vehicle During Testing in San Diego

The IDV communicates infrastructure errors to the TMC, and the TMC (or DPC) displays the errors on a map of the I-15 facility. This error display also occurs in the vehicle itself, on the ALTS display. Error display methods were developed to address the constraints of the demonstration facilities, and the needs of the NAHSC to clearly and professionally exhibit AHS functionality to VIPs and the general public. In addition, the rate at which the vehicle will be detecting magnetic markers effects error display. At the nominal operating speed of 65 MPH, with the expected 1.2 m (3.9 ft) spacing between consecutive magnets, the system detects approximately 24 magnets every second, so that information regarding individual magnets cannot be displayed in real time.

Top-Level Roles and Responsibilities

A significant issue to be dealt with early in the project was the determination of the roles and responsibilities of AHMCT and LMC. Here, AHMCT implies both UCD and Caltrans. LMC responsible for its tasks, including the work of any subcontractors. Table 1-1 identifies the major tasks of the project. Each task is briefly elaborated below.

Task	Description	Responsible Party
1	IDV Platform Development and Delivery	LMC
2	DP Development and Delivery	AHMCT
3	Integration of DP on IDV, and Field Testing and Debugging	AHMCT/LMC
4	Demo Site Testing and Scenario Refinement	AHMCT/LMC
5	Dry Run of Scenario	AHMCT/LMC
6	Final NAHSC Demonstration	AHMCT/LMC

Table 1-1: Top-Level Roles and Responsibilities

Task 1

LMC delivered a system including a van (model: 1996 Chevrolet Lumina donated by GMC), required lateral control actuator, sensors (vision system, vehicle sensing, etc.), control computer and software, software for integration with the diagnostic package, power system, I-V communication (CDPD modem), mobile voice radio, ALTS package with GPS, laptop computer for control computer interface, driver controls and displays (human-machine interface or HMI), and magnetometer wiring. Magnetometer cabling was available for direct connection at the computer rack when this stage was complete. LMC reserved space available in the 19” computer rack for the rackmount PC used for the AHMCT Diagnostic Package. The IDV Platform includes methods for system calibration and status diagnostics.

Task 2

AHMCT developed the Diagnostic Package that enables the IDV to sense and diagnose the components of the infrastructure targeted in this project. Embedded magnetic markers have been identified as an essential, safety-critical infrastructure component for lateral vehicle control in the NAHSC demo. The AHMCT DP system was developed on a testbed vehicle (model: 1996 Chevrolet Lumina donated by GMC), and includes three (3) front-mounted magnetometers and required cabling, rackmount computer, analog-to-digital converter, real-time operating system (QNX) and required application software, and communications software to interface to the LMC control computer. The system also includes a Global Positioning System (GPS) receiver with integrated dead-reckoning for absolute vehicle location, as well as velocity sensing. some form of vehicle location unit.

Testing of the DP occurred at the Golden Gate Fields (GGF) test facility used by the Partners for Advanced Transit and Highways (PATH) demo team, as well as the Crow's Landing Test Facility (CLTF). This testing involved high speeds (approximately 40 MPH at GGF and up to 70 MPH at CLTF), longer runs, and, in general, conditions that closely approximate the conditions at the NAHSC demo site. After completion of Task 2, testing and refinement of the DP continued at these test sites.

Task 3

Upon completion of Task 1 and Task 2, the DP was integrated into the IDV Platform. The DP computer was transferred from the development testbed to the IDV computer rack. Other components of the DP testbed, including the magnetometer package, remained with the testbed vehicle, which was used for further development and refinement of diagnostic algorithms. Integration resolved communication issues for between the LMC and AHMCT systems. These issues were considered during Task 1 and Task 2, but some aspects could not be resolved until this stage.

Upon completion of integration in the lab at LMC's facility, the system was transferred to the San Diego demonstration site for further controller refinements on the actual test facility. During this time, further integration of the LMC and AHMCT subsystems continued.

Task 4

Upon completion of Task 3, the IDV was fully operational. Task 4 involved testing at the demo site, final debugging, and refinement and practice of the demo scenario. The speed of operation for the demo was 65 MPH.

Task 5

NAHSC required pre-certification and certification of the system, including dry run demonstration of the demonstration scenario. This task involved execution of the planned scenario at the demonstration site, as well as required documentation and presentations for the NAHSC certification procedures.

Task 6

Task 6 includes dress rehearsals and final demonstration of the IDV, as part of the Maintenance Scenario in the NAHSC demo. Prior to the actual demonstration, three weeks of dress rehearsals were conducted, including passengers. The final demonstration of the IDV occurred August 7 - 10, 1997. Both LMC and AHMCT personnel were required for the rehearsals and live demonstration.

Demonstration Scenario

AHMCT demonstrated AHS maintenance operations using the Infrastructure Diagnostic Vehicle (IDV) and the Obstacle Removal Vehicle (ORV). The two systems together formed the Maintenance Scenario, part of the NAHSC Proof-of-Technical Feasibility Demonstration. The IDV uses autonomous lateral control equipment and conventional cruise control for automated driving. The IDV includes diagnostic equipment to conduct monitoring, physical inspection, and preventive care to preserve the integrity of the AHS infrastructure. These maintenance operations are performed while traveling under automated control at highway speeds. The ORV, developed for AHMCT by Pick-All Inc., demonstrated the automatic removal of debris from the AHS lanes. The following represents the scenario as demonstrated in San Diego. Note that the timing is approximate.

Time (min)	Activity
00 - 01	IDV performs VRC diagnostic with results to TMC
00 - 01	IDV departs staging area and accelerates to operating speed
00 - 01	IDV initiates marker diagnostic routine
01 - 02	IDV Operator detects road hazard, notifies TMC. IDV continues travel
02 - 04	DRV dispatched by TMC, travels to debris site
04 - 05	DRV retrieves road hazard, continues travel
06 - 07	IDV detects defective magnetic reference, notifies TMC
07 - 08	TMC logs defective magnetic reference for later repair
08 - 10	IDV exits system. Reinitializes subsystems as necessary
12	DRV exits system. Reinitializes subsystems as necessary
12 - 13	Safety factor

Table 1-2: Maintenance Scenario and Approximate Timing

The Infrastructure Diagnostic Vehicle travels the full length of the facility, nonstop at 65 MPH. The IDV, using the LMC control system for lateral guidance, checks all discrete magnetic references for presence, placement, field strength, and correct polarity. The IDV performs a diagnostic check of check-in and check-out facilities. In addition, the IDV uses the LMC ALTS package to notify the TMC of other facility faults.

Facility-mounted cameras monitor vehicle movements. The TMC and/or DPC monitors and displays incoming data from the IDV, and dispatches the ORV to remove the detected debris. Monitors in the DPC display all video coverage in a highly choreographed manner.

After diagnosing the check-in system, the IDV enters the automated lanes, and begins the magnet diagnostics. Upon entering the AHS, the IDV begins automated lane-keeping using the LMC vision system. The operator detects a road hazard (e.g. a muffler or tire) on the shoulder, and enters this anomaly into the system using the ALTS package using a voice command. ALTS automatically notes the location of the debris and sends a message to the TMC using a CDPD modem. The TMC dispatches the Debris Removal Vehicle (DRV) to retrieve the road hazard. The IDV continues its travel, diagnosing the magnets at a rate of approximately 24 magnets per second.

For the purpose of the demonstration, simulated magnet anomalies were introduced. Defective polarity was selected as the anomaly type, as it is most readily simulated in a realistic manner, as discussed in a later chapter. Several such anomalies are simulated and detected, with automatic notification sent to the TMC by the ALTS system. Note that no operator action is required (or possible) for marker errors. The TMC enters this for scheduled maintenance.

IDV Goals

The following goals provided a guideline for the development of the IDV. Goals marked as "Low" indicates goals that were considered essential for successful demonstration of the IDV. Goals marked as "High" were desirable goals, but not essential to the success of the demonstration. The final column in the table indicates that all goals were achieved.

Goal	Low	High	Achieved
IDV identifies missing magnetic markers	x		x
IDV identifies incorrect polarity magnets		x	x
IDV locates magnets using marker count from index		x	x
IDV logs errors and locations to data file for subsequent download	x		x
IDV provides voice comm. to TMC to report errors for maintenance dispatch		x	x
IDV under full automated lateral control at highway speeds, defined as 45 - 65 MPH (20 - 29 m/s)	x		x
IDV under manual or standard cruise control for longitudinal control	x		x
IDV identifies low field strength magnets		x	x
IDV logs errors (magnet and other) using ALTS or GPS data	x		x
IDV operator identifies other faults (e.g. road hazard), reports and locates via ALTS	x		x
IDV automatically sends real-time error notification and location to TMC. Vehicle will be capable of "real-time" two-way communication with TMC.	x		x
IDV capable of required diagnostics under complete manual control	x		x
IDV verifies longitudinal spacing between magnets		x	x
IDV performs rudimentary testing of VRC, including check-in/out readers. Requires coordination with Hughes.		x	x
IDV verifies lateral placement of magnets		x	x

Table 1-3: IDV Goals and Priorities

Interfaces

The two major components of the IDV are the automatically controlled vehicle (the IDV Platform), and the infrastructure sensing system (the Diagnostic Package). Due to geographic and time constraints, these two systems had to be developed in parallel at separate locations. To facilitate the final integration of these two systems, it was critical to clearly define interfaces between the two systems at an early stage.

The link between the AHMCT Diagnostic Package computer and the LMC Control Computer (CC) is based on a direct-wire Ethernet connection using the TCP/IP communication protocol. Communication between the DP and ALTS is also based on TCP/IP. Some communication with the CC is done using UDP/IP, as discussed in the chapter on communications.

Integration was a critical stage for this project. The individual technologies for the IDV Platform and the DP were reasonably well-known to LMC and AHMCT, respectively. However, merging these two systems into a complete and functional IDV was one of the most difficult task in the development of the IDV. Use of loose coupling between the LMC and AHMCT systems and standard communication protocols such as TCP/IP and RS-232 mitigated some of the difficulty of this task, and is highly recommended for future development.

Overview of Report

The remainder of the report provides details of the IDV, in particular for the Diagnostics Package developed by AHMCT. In addition, some results and discussion of the NAHSC demo are provided, along with various test results.

Chapter 2 provides detailed information on the magnet diagnostics, which are the core of the AHMCT DP for the IDV. This chapter includes information on the system hardware, an overview of the concept of lateral control using magnets, and details of the algorithms used for the various diagnostics.

Chapter 3 discusses the diagnostics for the Vehicle-to-Roadside communication system. A brief discussion of the hardware used is followed by the details of the VRC diagnostic algorithms.

Chapter 4 reviews the communications architecture used in the IDV. This includes two aspects: internal communications between various DP processes, and external communications between the DP computer and other systems, i.e. the IDV control computer and ALTS.

Chapter 5 provides an overview of the operation of the Automated Location Tracking System, or ALTS, provided by Lockheed Martin. As noted elsewhere, the details of this system are considered proprietary, and thus the information provided here is from a functional viewpoint, i.e. implementation issues are not discussed.

Chapter 6 discusses the vehicle automation as performed by Lockheed Martin. Again, much of this information is proprietary to LMC, so that only a functional review will be given. Details may be obtained from Lockheed Martin Corporation.

Chapter 7 details the integration of the various subsystems, and discusses the overall functionality of the IDV.

Chapter 8 discusses the demonstration of the IDV at the NAHSC Proof-of-Technical Feasibility Demonstration, as well as providing some user feedback from demonstration attendants.

Chapter 9 presents test results and data, along with evaluation of these results.

Finally, Chapter 10 provides conclusions, lessons learned, and recommendations for future work. Some further technical detail is provided in the appendices.

CHAPTER TWO

MAGNETIC MARKER DIAGNOSTICS

Introduction

Discrete reference markers may be used to provide lateral and/or longitudinal reference for vehicle control in an Automated Highway System (AHS). These discrete markers can be passive or active elements. Examples of these markers include magnets, colored paint marks, retroreflective raised pavement markers, and radar reflective materials. The marker detection system configuration is dependent on the marker type. A marker inspection system has been developed to ensure that all markers are properly installed and maintained. During post-installation and maintenance inspections, the system identifies and locates any marker that is not within the discrete marker specifications. This inspection is performed with little or no operator input in a real-time fashion inside an autonomous or manually driven vehicle. Furthermore, it also performs self-diagnostics on sensors and system health. Any anomaly will be sent immediately and automatically to a Traffic Management Center (TMC). Compared to manual marker inspection, this system reduces risk of marker failure and worker injury, improves reliability of the AHS, and minimizes delays due to highway maintenance. Thus, it lowers liability and cost to institutions and increases availability and efficiency of the AHS.

Currently, the marker diagnostic system is configured to diagnose discrete magnetic markers used in the NAHSC Demo97 on the I-15 HOV lanes in San Diego. However, it can be reconfigured to work in other locations with the change of several parameters. It is programmed to scan for low magnetic field strength markers, bad longitudinal spacing and lateral alignment of markers, missing markers, and marker coding errors. The marker diagnostics are programmed to start after entering the northbound or southbound AHS lane, and terminate automatically before exiting the AHS lane.

Hardware Architecture

The diagnostic system includes an Andrew Corp. Continuous Positioning System (CPS), three Applied Physics Systems APS535 tri-axis fluxgate magnetometers, and a diagnostic computing package with a National Instruments AT-MIO-16H A/D board. The Andrew Corp. CPS is a Differential Global Positioning System with integrated inertial navigation unit and velocity input from the vehicle's transmission encoder. In the current system, the computing unit is an Intel Pentium 166 MHz industrial computer with the QNX real-time operating system (RTOS) and its own hard drive. Detailed equipment specifications and component information are included in the appendix. Figure 2-1 shows the hardware configuration of the entire inspection system.

The marker detection system consists of three magnetometers, an analog-to-digital board, and the marker detection software module. The three fluxgate magnetometers are mounted under the front bumper of the IDV at about 18 cm (7 inches) above the ground as shown in Figure 2-2. Lowering the sensors would achieve a better signal-to-noise ratio. However, they must be high enough so that the rare earth magnetic markers will not saturate the sensors. The sensors are mounted 30 cm apart laterally and have an operating range of ±30 cm from the center of the sensor element.

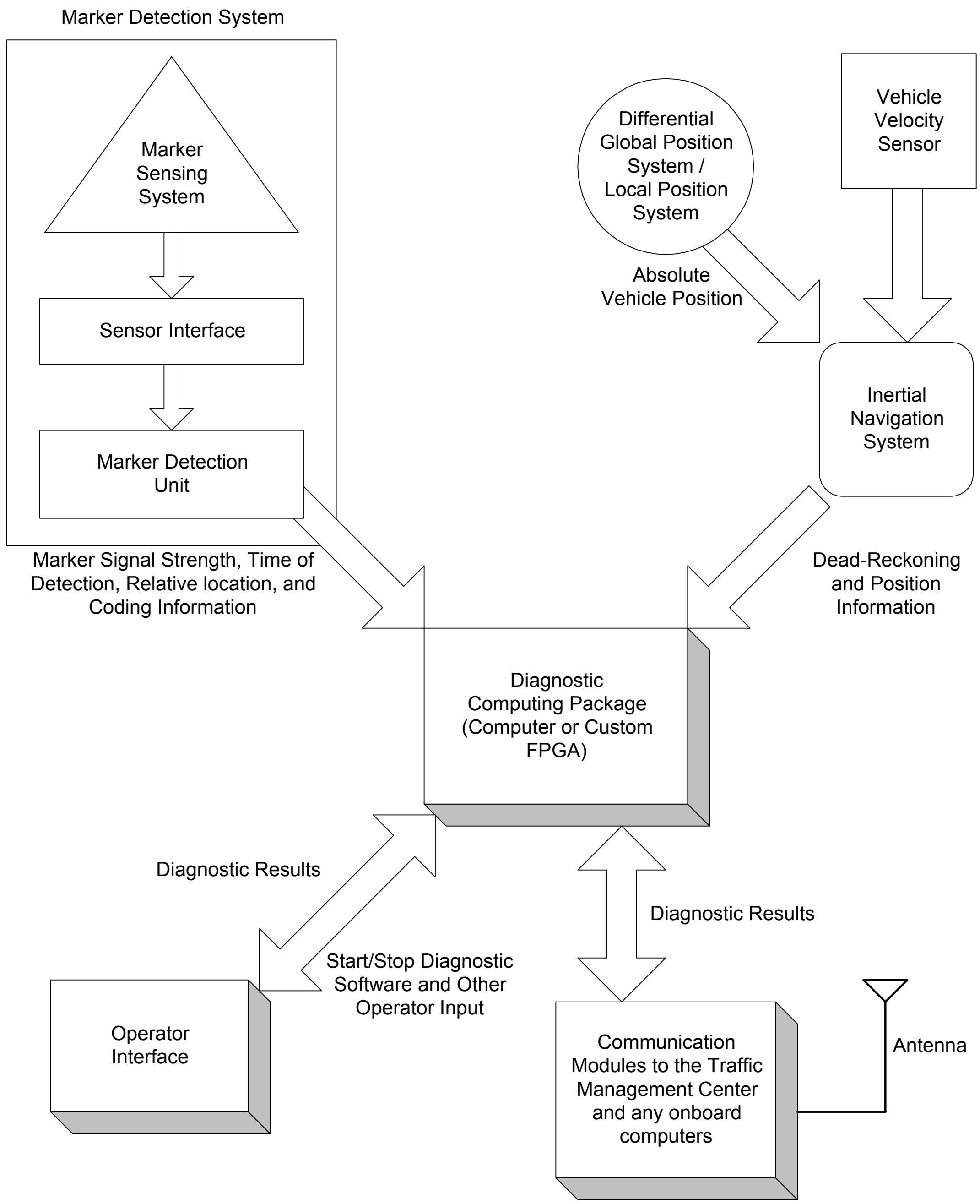


Figure 2-1: Hardware Configuration for the Diagnostic System

Detailed magnetometer specifications and mounting bracket design drawings are located in the appendix. This configuration yields a combined sensing range of ±45 cm from the center of the vehicle. In other words, the diagnostic package can diagnose all magnetic markers when the center of the vehicle stays within ±45 cm from the center of the lane. Thus, the constraint on vehicle control accuracy by either the computer or human operator is reduced through use of multiple magnetometers. However, in the unlikely event that the vehicle deviates out of sensing range, the marker diagnostic software will record any unchecked markers in the log database and resume diagnostics when the vehicle reenters sensing range. Moreover, only two outputs (vertical Y- and horizontal X-axis) of each sensor were used. The ISA bus ATMIO16 analog-to-digital board is the sensor interface that digitizes the analog signals from all three magnetometers at 500 Hz and sends it to the computer. The A/D board is capable of sampling at 1000 Hz, provided that the CPU can process all diagnostic information within 1.0 ms. The marker detection unit is a software module that runs in conjunction with the diagnostic software on the diagnostic computer. It is discussed in more detail in the following section.

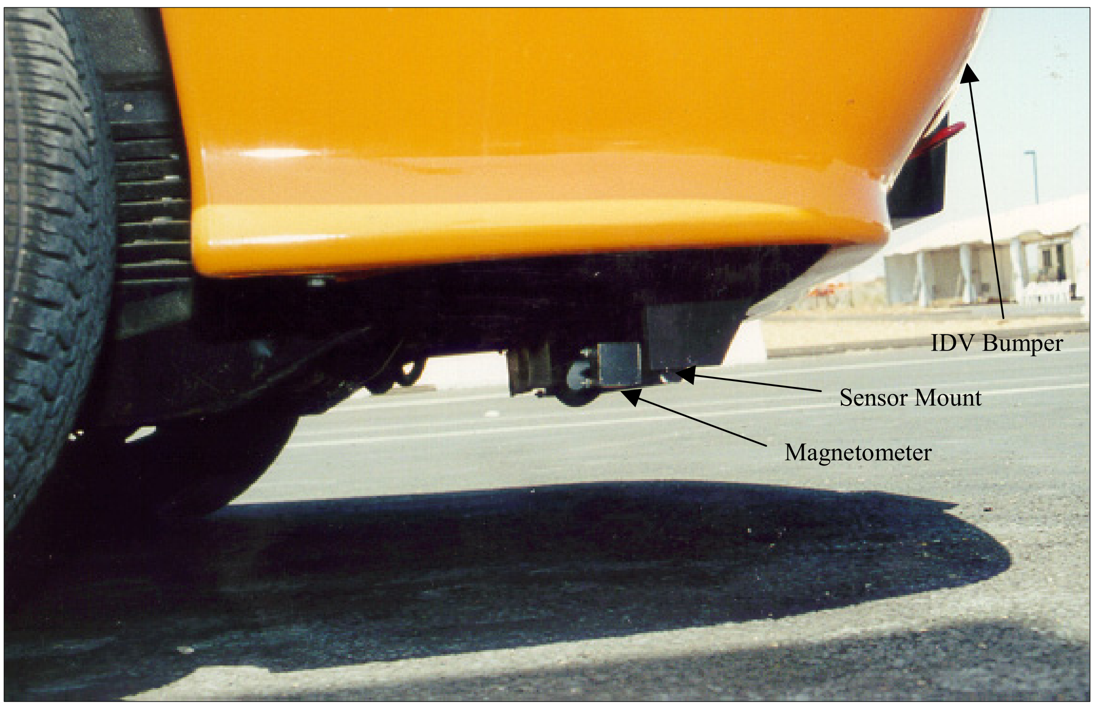


Figure 2-2: Magnetometer Location

The vehicle position reference system consists of the CPS and a conditioned signal, a square-wave pulse cruise-control input signal from the factory transmission speed encoder. The vehicle velocity is obtained indirectly from the vehicle transmission encoder through the CPS. In addition, the CPS communicates with the diagnostic computer through the serial port at 9600 bps. It provides an approximate vehicle location at 10 Hz with 5-10 meters accuracy. The vehicle location error may be reduced by increasing the differential station update rate, reducing distance to the base station, or using a carrier-phase differential DGPS.

Software Architecture

The diagnostic software obtains marker characteristic information (marker detection time, marker position relative to the vehicle, coding information, and marker magnetic field strength) from the marker detection module. Combined with the vehicle position and motion information, a known marker coding database, and highway survey data, the diagnostic software can determine if any marker is not within the AHS specifications. These specifications are: minimum marker magnetic field strength, longitudinal spacing error limits and lateral alignment tolerance of markers, any missing markers, and validity of all coding information from the marker. The diagnostic module also performs self-diagnostics on sensors and system health. All diagnostic results are then sent to the marker repair operations center through the communication module. Results are also displayed to the operator through the Human Machine Interface (HMI). Figure 2-3 provides an overview of the diagnostic algorithm.

Magnetic Marker Detection Algorithm

The magnetic marker detection module reports marker detection time, magnetic field strength, deviation from lane center, and marker polarity. The California PATH program has extensively studied the use of magnetic markers and their detection algorithms. The current marker detection module is based on the PATH algorithm. (1) However, the authors believe a more analytical method based on triangulation may provide higher resolution of marker properties for diagnostic purposes. Nevertheless, the triangulation method was not implemented due to time constraints. Instead, PATH's magnetic marker detection module was ported to the diagnostic package. Figure 2-4 illustrates the marker detection algorithm.

The marker detection module receives digitized analog sensor signals from the ATMIO16 A/D board driver. Therefore, the marker detection module requires that the A/D board driver be started first. QNX on the diagnostic computer is configured to start the ATMIO16 driver after the network card driver at boot-up time. As the system detects magnets, the marker's absolute magnetic field strength is determined by subtracting the earth's magnetic field strength from the detected value. As the vehicle approaches a magnetic marker, the sensor-measured magnetic field strength increases. The vertical component of the magnetic field signal will be at a maximum when the sensor is closest to the marker longitudinally. The vehicle offset from the lane center is calculated through a lookup table using both horizontal and vertical components of the absolute magnetic field at that instant of time. Since the A/D board only samples the signal every two ms and the vehicle is moving at a high speed, the magnetometer may not be directly above the marker at the instant of the digital signal peak. Thus, an error of ±3 cm is introduced in the longitudinal distance calculated when the vehicle is moving at 26 m/s (60 mph). Lower vehicle speed or higher sampling rate will reduce this error. However, the real-time nature of the diagnostic software dictates that the CPU must finish processing all diagnostic information before the next sampling period.

In addition, a new filter subroutine was added to trap and disregard the large ferric objects that can be found frequently embedded in modern highways. These objects behave like weak magnets and can cause error and uncertainty in the marker count. They can be rejected from the diagnosis based on a combination of their significantly lower magnetic strength, a large change in vehicle position relative to the marker, and the longitudinal distance from the last marker. Consequently, a very weak magnetic marker may be mistaken for one of these magnetic objects. However, the diagnostic module will catch this error and flag it as a missing marker. Thus, a missing marker error from the diagnostic module indicates a missing marker or a very weak marker. This is acceptable because a missing marker and a very weak marker are the same from the system safety viewpoint.

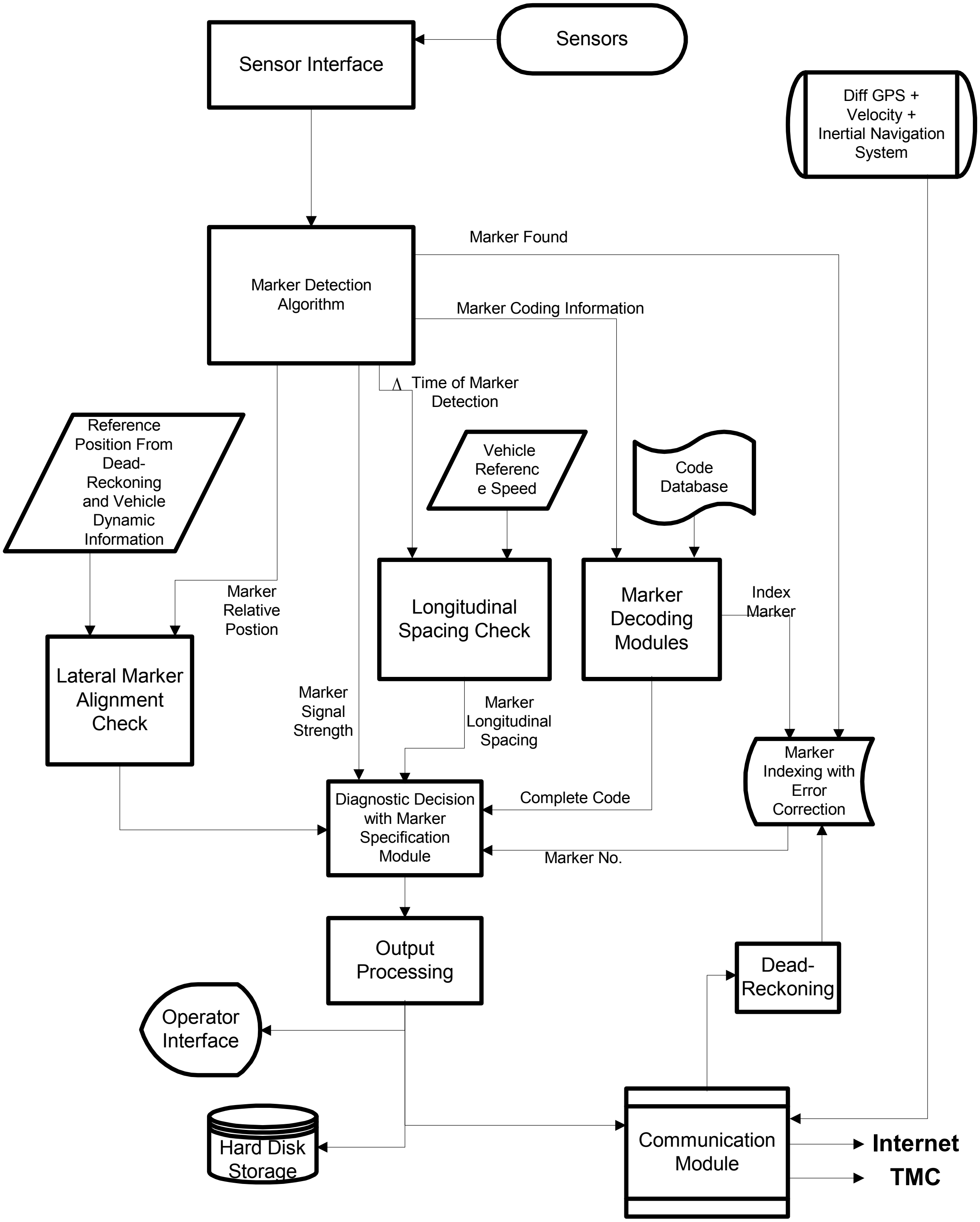


Figure 2-3: Discrete Marker Diagnostic Software Processing Algorithm

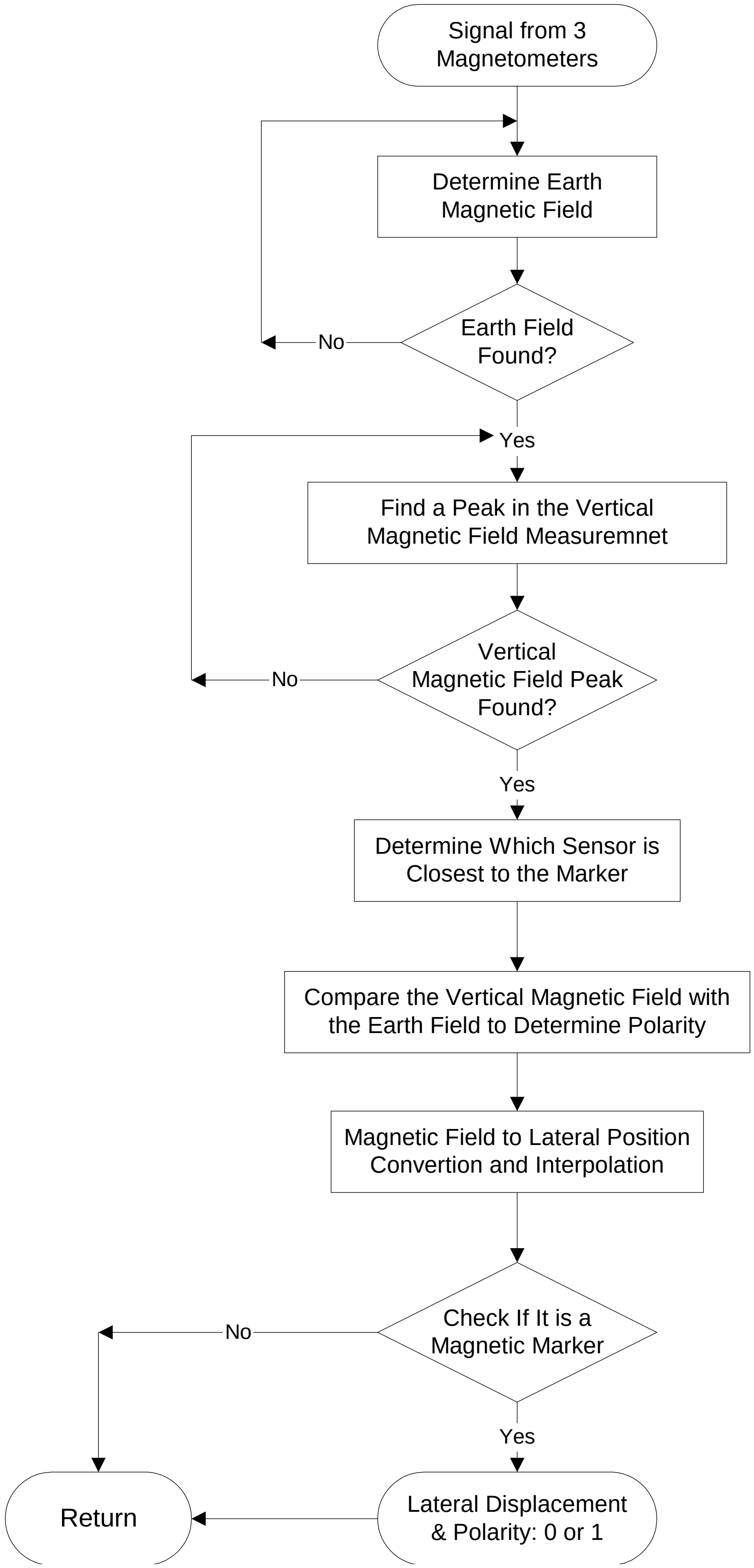


Figure 2-4: Magnetic Marker Detection Algorithm Flowchart

the vehicle position information from the CPS and a sequence of marker polarity coding information, the diagnostic module is programmed to start and stop marker diagnostics at pre-specified locations, without user input. It determines if the markers are within the system specifications. Furthermore, it monitors the sensors and sensor power supply health signals. Any errors are then sent to the HMI through the communication module. In addition, raw data and analysis results are logged to the hard disk (file names sens.dat, ana.dat) for debugging and post-processing.

Sensor and Sensor Power Supply Health Monitoring

The eqpt_check() function performs system health monitoring. Each magnetometer has a sensor health channel output connected to the ATMIO16 A/D board. This output is about 4 volts when the magnetometer is functioning properly, but drops to zero volts on sensor failure. Experiments also show that a magnetometer will be temporarily disabled when it is saturated with a strong magnetic field. In other words, if a magnet is held too close to the sensor for an extended period, the health signal will be zero volts. However, the magnetometer will recover and resume operation shortly after the strong magnet has been moved away from the sensor. Therefore, detection of zero voltage is considered a failure only if this signal remain at zero volts for more than 0.2 seconds (MAX_FAIL_COUNT, constant defined in code). The magnetometer power supply outputs (±15 volts) are also connected to the A/D board through voltage dividers. The voltage dividers are necessary because the maximum voltage input of the A/D board is ±10 volts. The outputs of the voltage dividers are ±5 volts. Thus, the diagnostic module can determine the system health by monitoring these voltages input, and any system health error will be sent to the communication module. This configuration allows the user to determine why the system failed and repair it quickly.

Auto-Start Algorithm

In order to minimize required operator input, the diagnostic module is programmed to start and stop automatically at pre-specified locations. These locations are immediately after the AHS entrance and before the AHS exit, respectively. Using the approximate vehicle location provided by the CPS, the diagnostic module determines if the vehicle is in the South or North Control Yard (SCY or NCY) and loads the correct code diagnostic database. Since the accuracy of the CPS position information is approximately ±5 meters, further information is needed to ensure a consistent starting point, since code checking requires an accurate marker index count. Coding information on the road is used to reference the starting point. Using the CPS information, the diag_autostart() function determines that the vehicle has entered the correct coding area. The system then compares the observed code with the database to determine the exact code endpoint. By comparing a section of code, errors in diagnostic starting point are minimized. However, if the DGPS has sub-meter resolution, as is available in a real-time kinematic carrier-phase tracking unit, such an algorithm may not be required.

Vehicle Out-of-Sensor-Range Detection and Dead Reckoning Algorithm

Since the IDV may occasionally drift in and out of sensor range, dead reckoning and vehicle out-of-sensor-range detection algorithms must be used so that the diagnostic module can operate correctly while the vehicle travels the rest of the AHS lane in sensor range. Furthermore, the diagnostic module must be able to distinguish vehicle out-of-range vs. missing marker errors. This is accomplished by setting the "out_of_range_warning_flag" to true when the vehicle deviation (ycar) is more than 0.4 meters. After that, if the marker detection module does not detect another marker within 2 meters with the "out_of_range_warning_flag" true, the diagnostic module will consider the vehicle to have drifted out of sensor range.

The diagnostic module can calculate how many markers are skipped by integrating the vehicle speed from the CPS when the vehicle drifts out of range. This information (nu_miss) is used to correct the marker index count and log which markers are not diagnosed. Moreover, the accuracy of the result depends on the duration / distance traveled by the vehicle while out of sensor range. Since the IDV does not drift out of sensor range for more than thirty seconds, the error is less than ±one marker. Furthermore, the introduced uncertainty in the marker index count may be corrected using the coding information from the magnets on the road. The code_check() function returns a count adjustment value. A detailed explanation is included in the polarity checking section. Therefore, the chance of misdiagnosing is minimized.

Detail Detection Algorithm of Different Types of Errors

Missing Magnet and Longitudinal Spacing Error Detection

Missing marker and longitudinal spacing errors are detected using the time between marker detection (T1), distance traveled by integrating vehicle speed, and the average time between marker detection of the three previous markers (Tave). If the remainder value of (T1/Tave) is less than 0.6, nu_miss (integer value of T1/Tave) is reduced by one. If the final value of nu_miss is greater than one, nu_miss is the number of missing marker, provided that the "out_of_range_flag" is not "true". Otherwise, the vehicle is out of sensor range, and nu_miss is the number of markers that were skipped. The same algorithm is employed using the integrated distance and nominal marker spacing to perform error checking on nu_miss. If nu_miss is zero, the mark_diag() function checks for any longitudinal spacing error. If the absolute value of the difference between T1 and Tave is less than MAX_DIFF_TIME, a constant defined in sense.h, the marker longitudinal spacing is within the specifications.

Polarity Error Diagnostic

The Code_check() function checks for any polarity errors and returns a counting error adjustment. It is designed to work independently of the coding design and code error correction methods. A simple method of straight comparison between the code table and the polarity read from the road is used. Therefore, the marker index count must be correct in order to have a high diagnostic reliability. When the program encounters a coded section on the road or from the coding table, it will store a pre-programmed number (CODE_LENGTH) of marker polarities from the road before diagnosing the polarities. Once the desired number of markers have been read, the function will shift the marker index back and forth until the total number of polarity errors is minimum when compared with the polarity coding table. The amount the index is shifted to achieve minimum error is called the index adjustment. The algorithm also corrects any counting errors caused by the vehicle going out of sensor range. If the marker coding section length is greater than the pre-programmed code length, the function will continue comparing the polarity with the code table without any shifting.

Weak Magnetic Marker Detection

The Junkmag_check() and pnpoly() functions check for weak magnetic markers and large embedded ferrous objects. Figure 2-5 shows the data collected on the I-15 AHS Lane before filtering out the embedded ferrous objects. B_v and B_h are the vertical and horizontal component of the marker's magnetic field respectively. Each data point represents one magnetic marker. Three distinct bands of data points can be observed from Figure 2-5. The outer-most band represents strong magnetic markers, the rare earth magnets used on the bridge section. Therefore, there are relatively few of these. The center band is the ceramic magnetic markers. The variation of the field strength is caused by the lateral motion of the vehicle and variation in the magnets themselves. The lower band of data points is caused mainly by embedded ferrous objects. Weak magnetic markers will fall into the region between the lower and the center band. This graphic region is defined in the pnpoly() function. If a marker falls within the region, it is flagged as a weak magnetic marker. Embedded ferrous objects are rejected by similar means.

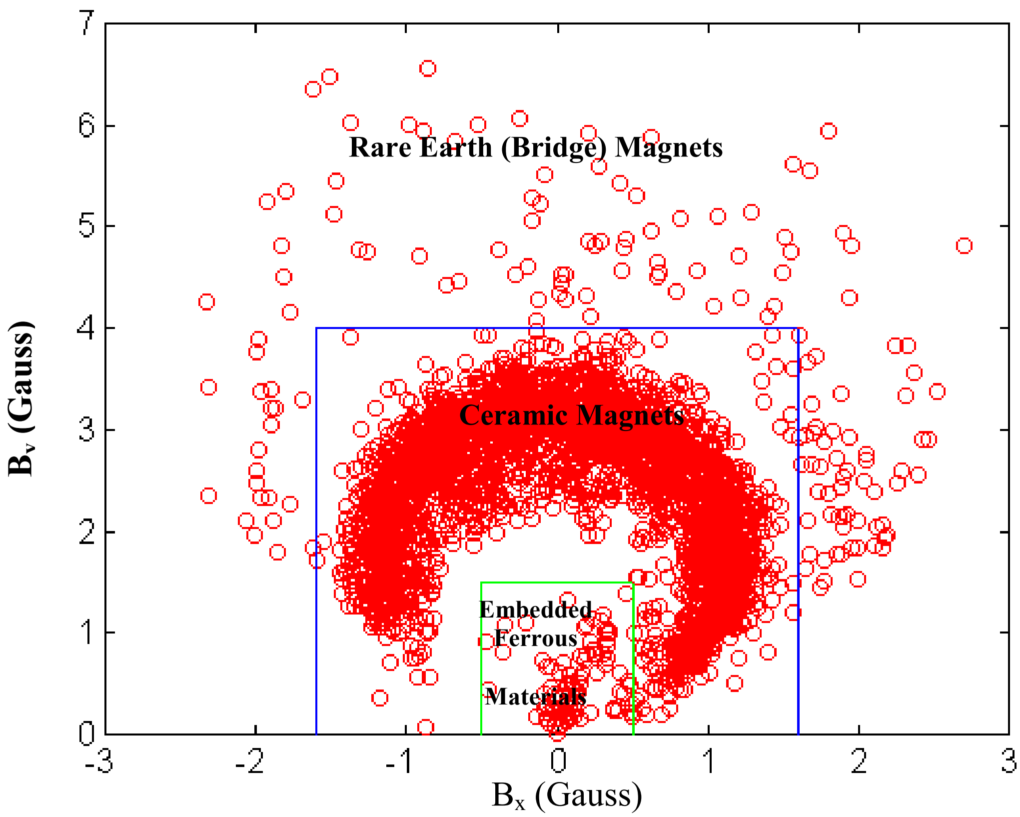


Figure 2-5: Magnetic Marker Field Data, I-15

Lateral Alignment Error

Large lateral misalignment in magnetic marker placement may cause excessive lateral jerk and significantly reduce ride comfort in automated vehicles. Sudden change in lateral deviation is not physically possible in normal vehicle operation. Moreover, computational analysis was used to determine the maximum vehicle deviation under normal operating conditions based on a maximum of 0.3 g lateral acceleration (comfort level) and minimum road radius. The diagnostic module examines the change in vehicle lateral deviation, and, if it is greater than the maximum change possible, the marker will be flagged as misaligned.

CPS and Communication Integration

The diagnostic module interfaces with other hardware or software through the communication module with the exception of the marker detection module. The Msg_gen() function is used to report any error to the HMI. In addition, the vehicle speed data is received from the CPS using the get_cps_data() function. After that, it is checked against the velocity calculated from the marker detection time and nominal spacing, since the CPS unit occasionally produces incorrect results. Erroneous data is ignored, and the last data is used instead. Vehicle speed error must be corrected, otherwise the integrated distance will be inaccurate and cause errors in the diagnosis. In conclusion, redundancy within the system is used to provide error correction in order to yield the highest degree of robustness possible.

CHAPTER THREE

COMMUNICATION DIAGNOSTICS

Introduction

In addition to diagnosing roadway magnets (Chapter 2), the IDV also tests the AHS Vehicle-to-Roadside Communication (VRC) link.

The focus of the IDV communication diagnostic is to test the functioning of the Roadside Reader. In its current application, the Roadside Reader is used to check automated vehicles in to an Automated Highway. This is accomplished by sending a series of handshake messages between the vehicle's transponder and the Roadside Reader. If the Reader receives the correct message sequence from the requesting vehicle, it allows the vehicle to enter the automated lanes.

The IDV communication diagnostic routine is capable of performing a variety of tests on the Roadside Reader to ensure proper function. This chapter overviews the communication diagnostics, specifically the Roadside Reader detection and range analysis. Details of the diagnostic messaging sequence and real-time analysis are presented in Chapter Four.

Vehicle-Roadside Communication

VRC is accomplished using two devices, one in the vehicle and one on the roadside. The in-vehicle device is a Delco transponder and the roadside device is a Hughes Roadside Reader. Both are radio frequency devices that communicate with each other using a pre-defined message set.

Malfunction of the Roadside Reader could result in admission of unsafe vehicles into the AHS, or the rejection of admissible vehicles. The IDV safeguards against such undesirable occurrences by performing a thorough diagnostic check on the Roadside Reader.

Roadside Reader Detection and Testing

The Roadside Reader transmits messages to each vehicle's transponder using an antenna located on either the roadside or an over-the-road structure. The IDV contains a database with the location (latitude and longitude) of each Roadside Reader. The IDV is also equipped with a Continuous Positioning System (CPS) which sends the IDV location to the diagnostic computer at 10 Hz. With this and the database information, an algorithm calculates the distance, in feet, between the IDV and the Roadside Reader location. The IDV begins "listening" for a Roadside Reader message when it has come within about 200 ft. of the expected Reader location. As shown in Figure 3-1, if the IDV passes through the entire range of the antenna, approximately 150 ft., the Reader is tagged defective and an error message is sent to the Transportation Management Center (TMC).

If the Roadside Reader is detected, the IDV monitors the messages passed between the Reader and the IDV transponder. Any errors in the Reader messages are catalogued and sent to the TMC. Otherwise, the Reader is identified as functional, and a status report is sent to the TMC.

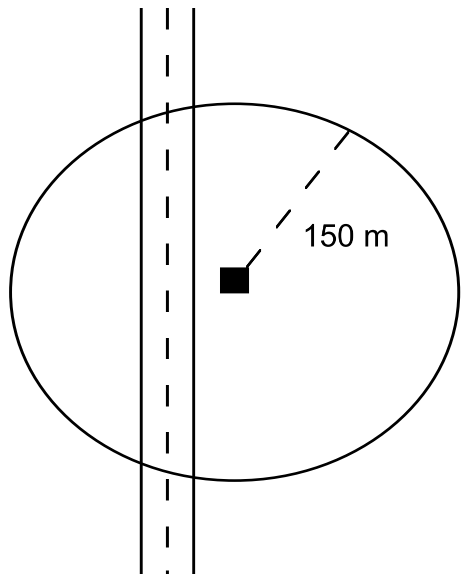


Figure 3-1: Roadside Reader Detection Geometry

CHAPTER FOUR

COMMUNICATION ARCHITECTURE

Introduction

The architecture of the communications program is centered on the concept of real-time operation. The IDV travels at highway speeds, diagnosing infrastructure errors and relaying the information to the TMC. Because of the real-time nature of this diagnosis and the volume of computations necessary to evaluate approximately twenty magnetic markers per second, it is essential that the communications processes do not interfere with the diagnostic routine.

To solve this problem, the program architecture is divided into processes of differing priorities. The main process, with the highest priority, contains the magnet diagnostic routine. All communications algorithms are contained in sub-processes (also called child processes) with lower priorities. The sub-processes are ranked in priority according to their real-time needs in the program. The seven sub-processes, listed in order of decreasing priority are:

- CPS process
- Road Follower send message process
- Transponder diagnostic process
- Status message compiler process
- ALTS socket connection process
- Road Follower receive message process
- HMI Java data process

This chapter presents the architecture of the diagnostic system communications, and programming techniques: child processes and pipes, the main process, and the seven sub-processes.

Communications Layout

The Diagnostic Package (DP) computer communicates with two other computer systems in the IDV: the automated steering control computer (NAV) and the HMI computer (ALTS). Communication with NAV includes lateral deviation measurements and other current roadway information. This is a real-time operation and thus is assigned a high priority. Communication with ALTS includes all status information for both the infrastructure and the IDV, as well as data for the Java-based HMI display. This information is not as time-critical and therefore holds lower priority than communication with NAV.

Communication between the computers is accomplished via sockets, a standard Unix Interprocess Communication method. The program uses both datagram (connectionless) and stream (connection-based) sockets. The type of connection used depends on the information being transferred and the required transmission rate, and is explained in detail in the child process description sections.

Peripherals

The DP communicates with two peripheral devices, the Continuous Positioning System (CPS) and the Delco Transponder. The CPS, designed by Andrew Corporation, incorporates GPS technology with differential correction and dead reckoning based on fiber-optic gyros. The result is a position output (latitude and longitude) ten times per second. The output, a character string based loosely on the standard output of GPS systems, goes to a serial port. Because of the amount of data and the speed at which it must be transmitted, the CPS uses a proprietary message format.

The transponder, designed by Delco, is a small, radio frequency device used to communicate with the Roadside Reader. The transponder is programmed with automatic messaging capabilities and requires no external interface to perform standard check-in/check-out procedures for an AHS. Because the IDV diagnoses the performance of the Roadside Reader, the DP connects to the transponder using a standard serial port. Through this connection, the DP can monitor the messages being sent and received by the transponder, and can send special diagnostic messages to the Roadside Reader. The computer system layout is shown in Figure 4-1.

Communication with each device is facilitated through a separate sub-process. In each sub-process, special care is taken to prevent read/write blocking on the serial port, an occurrence that could seriously inhibit the real-time operation of the DP. The programming techniques used to solve this problem are presented in the detailed description of the sub-processes.

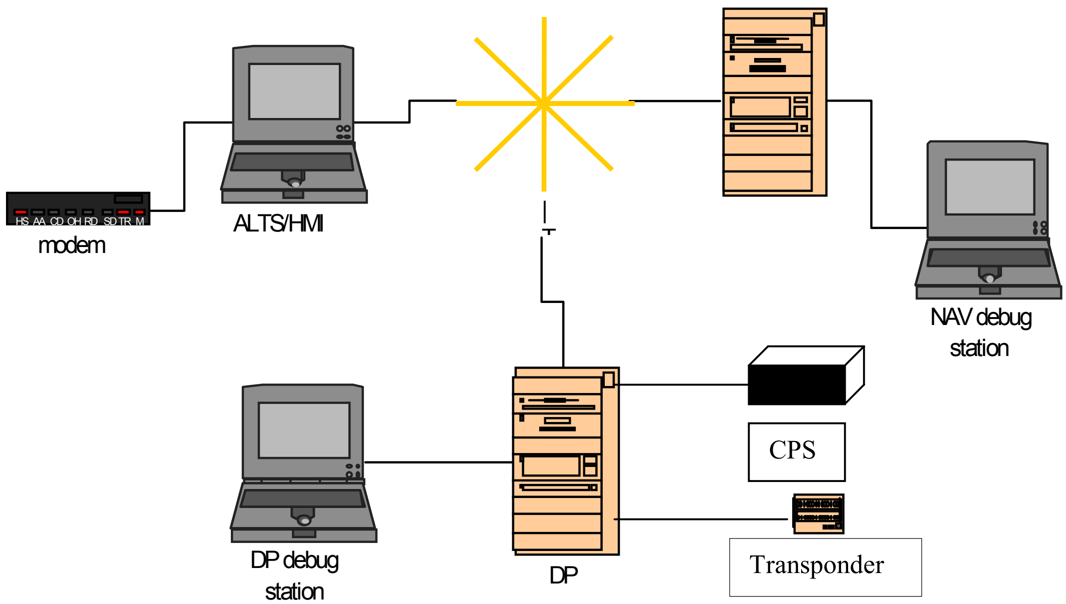


Figure 4-1: Computer Layout

Programming Techniques — Child Processes and Pipes

The main function of the IDV is to diagnose the magnetic markers embedded in the roadway of an AHS. As mentioned previously, this is a computationally intensive, high-speed operation requiring real-time diagnosis. Therefore, the principal emphasis of the communications architecture is to preserve real-time functionality.

The most important programming technique used to accomplish this goal is the use of child processes (sub-processes). A child process is created by a main process (parent process) using the *fork()* command. Once created, the child process is completely independent of the parent process; operations in the child process do not effect the parent process, even though they are written in the same program. QNX allows the programmer to assign different process priorities to each process and sub-process. Using this feature, the main diagnostic process is set to the highest possible priority, and the sub-processes are all assigned lesser priorities.

The DP runs the QNX real-time operating system (RTOS), so that priority levels are always enforced. Even if a sub-process becomes delayed, the main process will continue to diagnose the magnets unabated. This process of decoupling eliminates the possibility of errant communications functions interfering with the main diagnostic process.

Although using sub-processes eliminates the prioritization problem, it complicates communications. Because each process is independent, information cannot be passed using arrays or other simple means. Communication is accomplished using the POSIX *pipe()* function. A pipe is a one-way communication device. Any information written at one end is retrieved and read at the other. This information can be shared as long as the process that created the pipe passes the address of the pipe (much like a file descriptor) to the sub-process. In the DP program, all pipes are created by the main process, which passes the addresses to the sub-processes that need them. This allows the main process to access all pipes when it performs the shutdown routine. This function will be explained in detail in the following section.

Using pipes as a method of communication poses a problem because pipes are set for read/write blocking, i.e. whenever a *read()* function is called on a pipe and nothing is in the pipe, the processor will pause (or block) at that point in the code until something enters the pipe. Likewise, if a *write()* function is called and the pipe is full, the program will block until sufficient space in the pipe is emptied. For a program such as this one, where real-time operation is critical to program success, the dangers of such occurrences are obvious.

To prevent read/write blocking, the DP uses the *fstat()* function. The *fstat()* function checks the pipe to see how much data it holds, without blocking. If *fstat()* indicates a potential block condition, the function using the pipe continues on without reading or writing the pipe. This allows the program to flow smoothly and ensures effective real-time functionality.

Main Process

The main process of the diagnostic program contains the magnet diagnostic routine and the command structure of the communications architecture. This command structure creates all pipes, starts all the sub-processes, coordinates communication of information from the diagnostic process, and facilitates the shutdown of all processes.

The main process coordinates sending all magnet diagnostic specific information to the communication sub-processes. This information includes:

- All status information—sent to the status message compiler process
- Vehicle lateral position—sent to the Road Follower send message process
- All magnet data—sent to the HMI Java data process
- Vehicle direction of travel—sent to the transponder diagnostic process

All information except for vehicle direction of travel is passed via pipes. Because of the small amount of data needed to indicate direction of travel (one byte per diagnostic run) this information is passed using a POSIX *signal*. A signal is, in essence, a “yes” message that can be sent between processes. In this case, if the vehicle is headed south, the signal is sent. If it is heading north, no signal is sent. This decision occurs during the diagnostic run initialization stage and, thus, is complete before the actual run takes place. Using a signal instead of a pipe reduces overhead and decreases initialization time.

In addition to sending out information via pipes, the main process receives information via pipes. A pipe links the main process to the CPS process, constantly sending vehicle position information to the main process. This information is sent at ten Hz. Since the main process loops every two ms, it reads the data faster than it is generated. A special function examines the data in the pipe and updates every time there is new data. The main process uses this information to tag status messages with location data.

The flow of information from the main process to the sub-processes is shown in Figure 4-2.

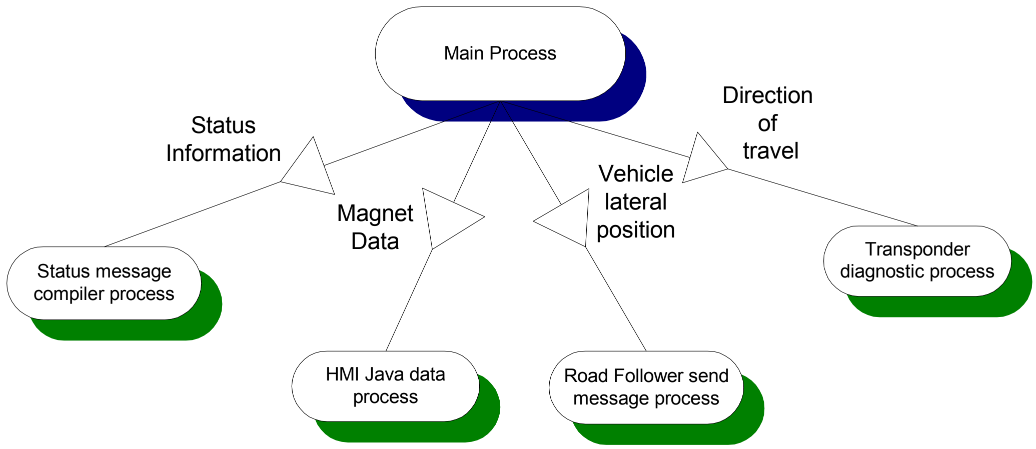


Figure 4-2: Flow of Information from Main Process to Sub-Processes

Once the main process exits, due to receiving the "end of program" signal from the operator, or due to an error, the program enters the Exit Routine. This routine takes care of shutting down all sub-processes, saving data to disk, and restarting the program if it is in Restart mode.

CPS Process

To track position on the roadway, the IDV uses the Andrew Corporation CPS, which gives the vehicle's latitude and longitude ten times per second. This information is used by the transponder sub-process and the main magnet diagnostic process. The CPS sub-process receives the data from a standard RS232 connection, then passes the information, via pipes, to all processes that need it.

The CPS routine is a looping function that repeats until it receives the end of program signal from the main process Exit Function. For each iteration, the function reads in the data string from the CPS, checks the message to make sure it is valid, parses the message, and sends the appropriate information to the processes that need it.

The CPS data is received in string form as shown in Figure 4-3:

```
$PAND,10RMC,163038.7,A,3832.35703,N,12145.05585,W,12.23,310.41,271997,0,-01.0,0000*2C
```

Figure 4-3: CPS Example Data

The checksum at the end of the string is created by taking the bit-wise exclusive OR of the string up to the * sign. After reading in this string, the CPS routine calculates the checksum using its own routine, then compares the two answers to verify the validity of the message.

After checking the message's validity, the CPS routine checks that the right message format has been received. The CPS is capable of generating two message types: a one Hertz message pair; and a ten Hertz message. The one Hertz message pair is the standard output of any GPS receiver, two messages sent per second which include latitude, longitude, and a variety of other parameters. The ten Hertz message was designed by Andrew Corp. specifically for the IDV. Because of the rapidity of message generation, it was not possible to send the standard message pair, so this message eliminated data fields irrelevant to the IDV.

Because of the hardware layout of the IDV, it is not possible for the diagnostic program to automatically change the CPS message. The CPS outputs its message through a serial port, which passes through a serial splitter. This device multiplies the signal and sends it to all computer systems in the IDV. Because the message passes through the splitter, a message cannot be sent directly back to the CPS. Therefore, if the wrong message is being sent to the DP, the program shuts down and requests the operator to change the CPS output message.

As its next task, the CPS routine filters out any message indicating a radical (not physically realizable) change in velocity of the IDV or a wildly inaccurate latitude or longitude measurement. This prevents erroneous messages sent by the CPS from causing the diagnostic program to misdiagnose a magnet error.

Once these checks have been passed, the CPS routine concatenates two data strings, one for the main process and one for the transponder process. These messages are then passed through their respective pipes. The data sent is also saved to a log file. The CPS loop then starts over from the beginning.

Road Follower Send Message Process

The IDV automated steering used a vision-based control system designed by Lockheed Martin, as discussed in Chapter Six. Because the magnet information was already being acquired by the magnet diagnostic routine, some work was done to incorporate that data into the control algorithm of the IDV. This approach would lead to a redundant control system that improves control accuracy and reduces accident risk due to failure of one of the automated control methods.

The Road Follower (RF) send message sub-process sends the appropriate vehicle data, including lateral offset from center and upcoming road curvature, to the Lockheed Martin control computer (NAV). The connection used is a datagram socket, which is connectionless. Overhead is lower than for a connected socket, and speed is greater. Information is sent for each magnet, which averages 23 magnets per second at 60 mph. Although this function was operating correctly, it was not used during the NAHS Demo '97 in San Diego, as there was not sufficient testing time to assure safe and robust controller operation in this mode.

The RF send message function is a very simple routine that reads in data sent by the main process through a pipe, translates the string data into *float*, reformats the information to Big-Endian format, and sends the information over the socket to NAV. The message sent contains four datum: vehicle lateral offset from centerline; upcoming road curvature; distance (meters) to the upcoming curvature; and the program's confidence in the lateral offset data. This data is sent in one array of four *float* variables. Converting the data from QNX Little-Endian to VxWorks Big-Endian data format was accomplished using a simple byte-swapping routine.

This routine is a looping process that repeats until it receives the "end of program" signal from the main process Exit Function. Once the signal is received, the routine closes all sockets and exits.

Transponder Diagnostic Process

As discussed in the previous chapter, the IDV diagnoses Roadside Reader using the onboard Delco transponder. The transponder routine is the sub-process dedicated to performing that task.

Because the transponder diagnostic routine relies on knowledge of the location of the Roadside Reader, it has a pipe connection to the CPS process to obtain instant updates of the IDV's position. The routine is complicated by the fact that it needs every update of the vehicle's position. This means that it must repeat the entire loop every iteration. This is accomplished by having a series of conditional statements that evaluate the various aspects of the diagnosis. The logical flow of the routine is presented in Figure 4-4.

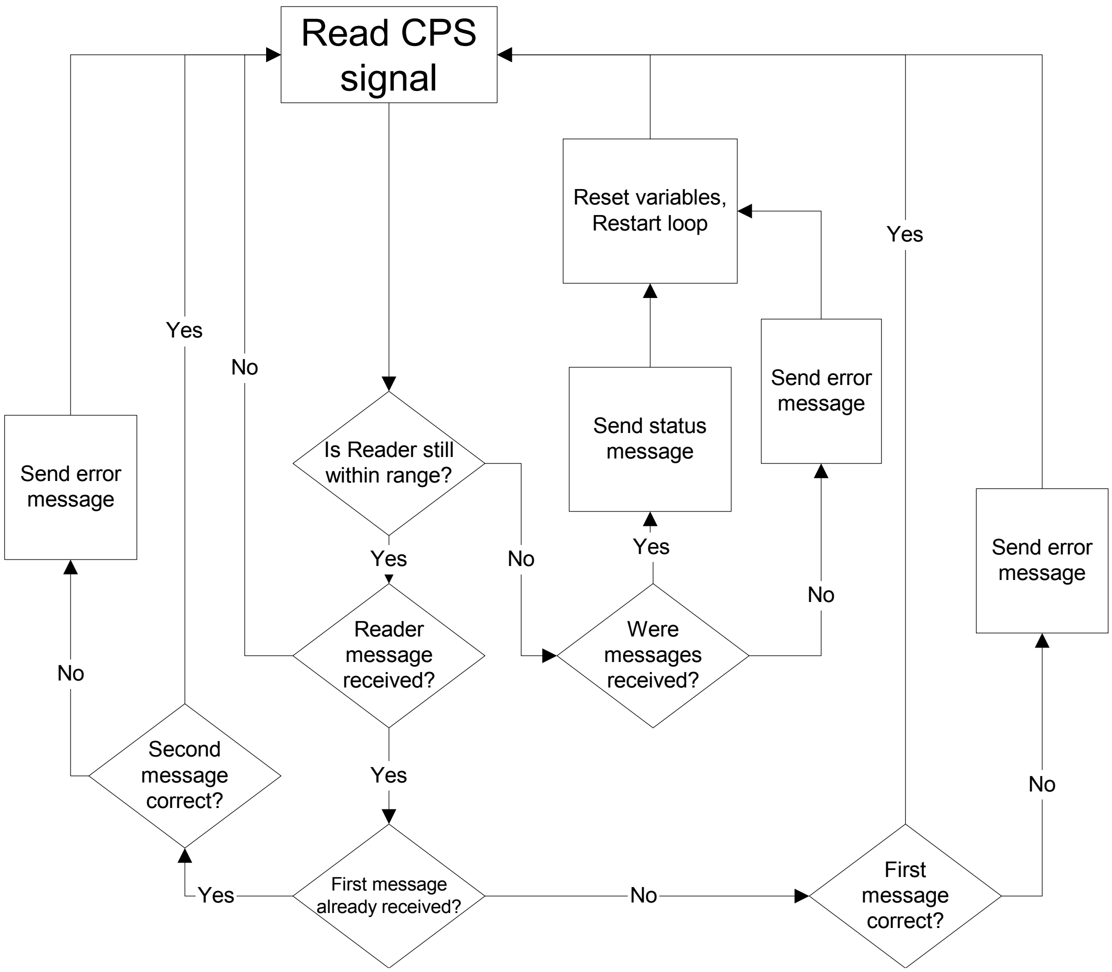


Figure 4-4: Transponder Routine Flowchart

In its first stage, the program loops while analyzing the position data until it determines the vehicle is within approximately 300 m of a Roadside Reader. The routine then "listens" for any messages received by the on-board transponder from the Roadside Reader. Two standard messages should be received for a standard check-in. While it is waiting to receive those two messages, the routine is constantly checking the IDV's position to make sure it hasn't gone out of range before receiving the messages. If the IDV does exit the expected range before receiving either message, an error message indicating no response from the Roadside Reader is sent to the TMC.

Once the first message is received, the routine listens for the second message. If the second message is not received before exiting the expected range, an error message stating that only one message was received is sent. If the second and final message is received, a status message indicating the Roadside Reader is functioning correctly is generated.

This completes the transponder diagnostic, and the routine begins to loop again, waiting for the next Roadside Reader to come within range. One additional, non-critical goal of the transponder diagnostic that was not implemented in the Demo, was to evaluate the effective range of operation of the Roadside Reader. To accomplish this task would have required the use of a second transponder and involved having Hughes Corporation program the Roadside Reader with a special series of diagnostic messages. Due to time and equipment constraints, this part of the diagnostic was not operational for the Demo, but the concept is complete and is discussed in the following paragraph.

To evaluate the range of operation of the Roadside Reader, a second transponder with a special series of messages programmed into memory operates at the same time as the normal check-in transponder. Once the range transponder receives the initial contact message from the Roadside Reader, the routine tags that GPS location to memory and sends out a special range message. Once the Roadside Reader receives this message it sends out a message continually until it loses contact with the range transponder. Once contact is lost, the final location of the IDV is logged and the initial and final latitude/longitude values are sent to a routine that calculates the distance in meters the vehicle traveled while in communication with the Roadside Reader. This information is appended to the status message as the effective range of the Roadside Reader.

Status Message Compiler Process

Because of the variety of status messages the IDV generates and the frequency with which they are sent out, a separate sub-process was written to format the data supplied by the main program into a standard format to be sent to the HMI. The routine loops continuously, reading messages from the main process and sending formatted messages to the ALTS socket routine until it receives an "end of program" signal from the main process.

The diagnostic routine in the main process evaluates all magnets in the roadway and sends status updates every 25 magnets if there are no errors, and at each instance of an error. The status/error information is sent via a pipe to the status message compiler process in comma-delimited form consisting of coded information. A sample message is shown in Figure 4-5.

1,1,245,2,121.5492,58.2342,11.244532

(status indicator, # of magnets, magnet index #, magnet confidence, lat., long., time)

Figure 4-5: Sample Status Message Sent from the Diagnostic Process

This format was selected for brevity to reduce the amount of data that would have to flow through the pipe. Once the status message compiler process receives the information, the raw data is manipulated and concatenated into a more human-readable format. This is done using a *switch()* statement which compares the various category labels used in the message, then performs the necessary compilation depending on the type of message needed.

The structure of the messages sent to the ALTS system is outlined below.

(IDV) DP status messages. Sent on startup and if any hardware malfunctions

(S) **S**tatus

1) Magnetometers OK
2) Transponder OK
3) Diagnostic Computer OK
4) CPS Signal OK

(M) **M**agnetometer errors

1) Magnetometer malfunction

(G) ma**G**netometer error

1) Mag. 1 malfunction
2) Mag. 2 malfunction
3) Mag. 3 malfunction

2) Magnetometers out of range
3) Data acquisition hardware failure
4) Data acquisition program failure

(T) **T**ransponder errors

1) Transponder not responding
2) Transponder messaging error

(D) **D**iagnostic computer errors

1) Program malfunction

(C) **C**PS signal errors

1) CPS message format wrong
2) CPS signal not being received

Expected status message at startup:

$PDPIDV,S,1234,M,,G,,T,,103242.27*<checksum>

S,1234 All systems OK

103242.27 System time

(AHS) AHS status messages. Messages sent at roughly 1 Hz.

(S) **S**tatus

1) Vehicle entrance accepted
2) Roadside Reader OK
3) Magnets OK
4) Vehicle entrance denied

(R) Reader **R**ange (in meters, integer value)

(N) **N**umber of magnets diagnosed

(V) **V**RC errors

1) Handshake incomplete
2) No signal received
3) Messaging error

(M) **M**agnet errors

1) Missing magnet
2) Low field-strength magnet
3) Incorrect polarity
4) Lateral alignment error
5) Longitudinal alignment error

(A) **A**lignment offset (in meters, decimal value)

(I) **I**ndex # of first magnet

(C) Index # **C**onfidence level

± 1,2,3,4,5 markers

Example messages:

$PDPAHS,S,3,R,,N,25,V,,M,,A,,I,512,C,2,N,12045.191406,W,3829.367676,110309.421875*<checksum>

S,3,	Magnets OK
R,,	Range not applicable
N,25,	25 magnets diagnosed
V,,M,,A,,	no errors
I,487,	First magnet in series has index # 487
C,2,	Confidence = $\pm$ 2 magnets
N,12045.191406	latitude (North)
W,3829.367676	longitude (West)
110309.421875	Time, Local 11:03:09.421875

(LANE) AHS lane message. Message is sent when a lane segment # change is detected.

(S) lane **S**egment

0-15, lane ID #

(D) lane **D**irection

N,S,E,W

Example messages:

$PDPLANE,S,13,D,N,110309.421875*<checksum>

S,13,	Lane ID # = 13
D,N,	Direction = North
110309.421875	Local time, 11:03:09.421875

Once the appropriate message has been compiled, it is sent via a pipe to the ALTS socket connection process, which actually sends the message to the ALTS computer.

ALTS Socket Connection Process

Due to the uncertain nature of the connection between computer systems and the possibility of a delay in the connection, the socket connection between the DP and ALTS is contained in its own sub-process. This eliminates the possibility of any delay being introduced in the magnet detection and diagnostic routine.

The ALTS socket connection process is a very simple looping routine. The routine first opens a stream socket connection with ALTS at system startup. Once a connection is established, the process begins to loop, reading from a pipe. All messages received in the pipe are evaluated using a bitwise exclusive-OR to generate a checksum, which is appended to the message. The message is then sent immediately to ALTS. The process then loops again, waiting for the next message. The process loops until interrupted by an “end of program” signal from the main process.

Road Follower Receive Message Process

This function parallels the RF send message process, except its purpose is to receive messages from the RF. The routine establishes a datagram socket connection with the RF, then loops and waits to receive a message. Any message received is converted from Big-Endian to Little-Endian using the byte swapping routine, then the data is concatenated in string format and passed through a pipe to the main process. The DP never used this function.

HMI Java Data Process

The final process after evaluating, compiling, and transmitting the data was to display it for the user on the HMI. Data displayed for the user include current vehicle deviation from center, cumulative magnet polarity, cumulative magnet B-field information, cumulative vehicle deviation from center.

Display of this information was made possible by a Java program running on the DP. The program runs in Microsoft Internet Explorer, receiving data from files using Java classes. Each image is updated by reading from a designated file and displaying the current information. The HMI Java data process performs file updates.

The process works by reading a pipe from the main process. At each iteration, magnet information in comma-delimited form is sent down the pipe. The HMI process takes that information and separates it into the various information it needs to display the desired output. Then, all information is written to its designated file, to be read by the Java program. This is a continuous operation that is done throughout the length of diagnostic operation. The process loops until it receives an “end of program” signal from the main process.

Summary

The IDV successfully demonstrated all phases of its operation at the National Technology Feasibility Demonstration, Demo ’97, in San Diego, August of 1997. All elements of the communication package architecture were implemented as described above and functioned as expected. The success of the IDV in the demo is the clearest indication available of the program architecture's effectiveness. All diagnostic evaluations were completed in real-time, with no delays due to communication efforts, indicating that the process decoupling was successful. Although several areas were noted where improvements could be made on future projects, the IDV performed as desired on the projected tasks for the demonstration, making the project a success.

CHAPTER FIVE

AUTOMATED LOCATION TRACKING SYSTEM

Introduction

The Automated Location Tracking System (ALTS), a main component in the IDV, is used to achieve the following tasks:

- Continuously track the location of the IDV and display it on a screen map inside IDV.
- Locate road debris and anomalies.
- Help in locating defective magnetic markers when they are detected by the Diagnostic Package.
- Report all findings to the TMC.

A GPS unit is used to determine the location of the IDV, anomalies and defective markers. A wireless modem is used for communication with TMC.

The GPS Unit

GPS is a satellite-based radio navigation system that can determine position and velocity. Simultaneous observation of four satellites permits determination of the 3-D coordinates of the receiver in the WGS-84 geodetic coordinate system, which can be transformed into the State Plane Cartesian coordinate system. The GPS unit used in the IDV is an Andrew Corporation Continuous Positioning System (CPS). The CPS unit integrates a GPS receiver with differential correction signal (DGPS) and dead-reckoning to guarantee a continuous and relatively accurate position reading, even with temporary satellite signal blockage. The CPS unit interfaces with the serial port of a PC, the vehicle odometer signal, reverse light, and 12 volt power supply, as shown in Figure 5-1.

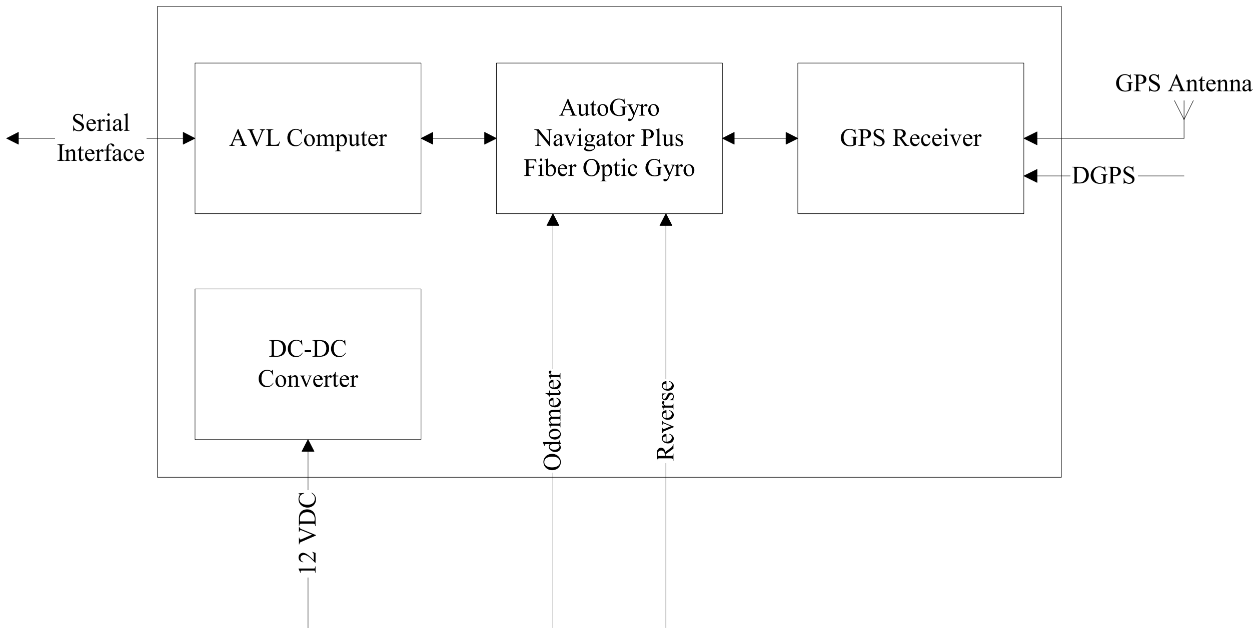


Figure 5-1: CPS Unit and Interfaces

<u>CPS Interface With IDV Components</u>

The 10 Hz CPS RS232 signal is split in three ways, as shown in Figure 5-2, to:

- ALTS Computer
- DP unit Computer
- Vehicle Control Computer (GPS is not currently used for vehicle control)

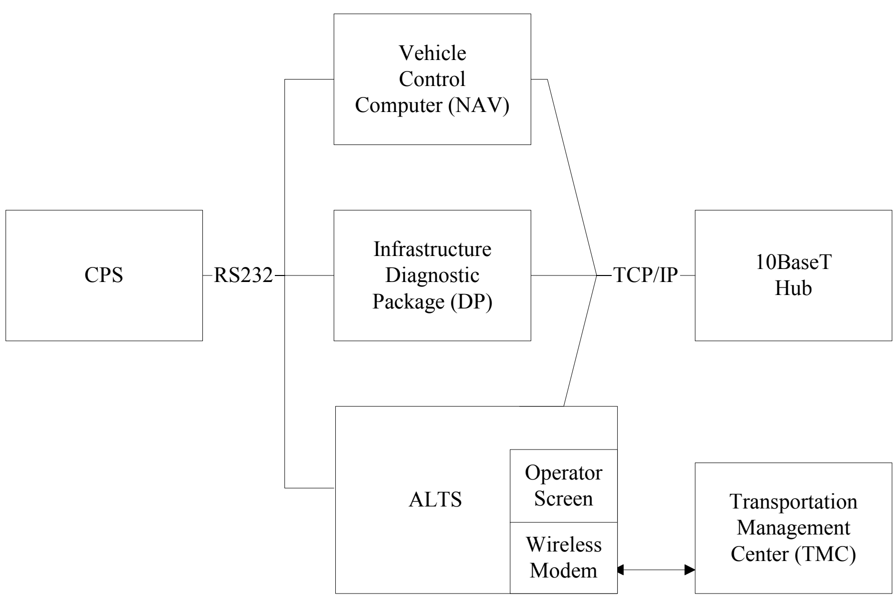


Figure 5-2: CPS and ALTS Communications

ALTS Visual Display of IDV Location

A digital road map of the highway is stored in ALTS computer and displayed on the operator's screen. ALTS reads the CPS signal, at one (1.0) Hz, to determine the IDV position and then updates the screen. The operator's screen shows the road map with a trace of the IDV location on it.

ALTS Debris and Anomaly Locating

ALTS uses a voice recognition system to identify and GPS to locate debris and anomalies that the operator sees on the road. The operator states the type of debris or anomaly identified. A voice recognition algorithm analyses the command, recognizes, and records the type of debris or anomaly and its GPS location. Next, ALTS sends a message to the TMC via the Cellular Digital Packet Data (CDPD) wireless modem. Finally, the TMC dispatches an obstacle removal or other maintenance vehicle to the specified location.

DP Defective Magnetic Marker Locating

The DP continuously detects the magnetic field and polarity of the magnetic markers on the highway. If a marker is missing, the DP sends that marker number and its GPS location to ALTS via the 10BaseT hub, as discussed in detail in Chapter 4. ALTS then sends the message to TMC. The marker location accuracy with the Andrew CPS unit is ±5 markers. If a polarity error is detected, the DP algorithm compares the detected marker polarity pattern with the database stored in the DP computer, using a shift-and-compare algorithm. If the detected pattern and the database pattern match, then the detection process "slipped", and the DP algorithm adjusts the tracking process and continues. If the pattern and database tables do not match, the polarity on that marker is wrong. Again, the DP sends the marker number and its GPS location via TCP/IP to ALTS, which sends the appropriate message to the TMC.

Coordinate System Transformation

The location of markers, beacons and control points is usually given in the State Plane coordinate system (NAD-83 or NAD-27), where the grid coordinates are Northing & Easting. GPS receiver location is usually given in the geodetic coordinate system (latitude & longitude). Calculation of distance between two points requires conversion of the GPS location to State Plane Cartesian coordinates. Off-the-shelf computer programs can compute this transformation quickly. However, due to the real-time nature of the diagnostic process, the transformation formulas are incorporated in the DP algorithms.

The following formulas are used to transform from GPS (latitude, longitude) to NAD-83 State Plane (Northing, Easting) coordinates. California is divided into six different zones. Each zone has many constants and tables. For example, the San Diego area is in zone # 6. The relevant constants are provided below.

ϕ = Latitude reading of GPS receiver.

λ = Longitude reading of GPS receiver .

$$\boxed{\begin{array}{c}\text{Northing:} \quad y = R_b - R\cos(\theta) + N_b \\ \text{Easting:} \quad x = C - R\sin(\theta)\end{array}}$$

R_b = 9,836,091.7896 meter (zone #6 constant)

N_b = 50,000 meter (zone #6 constant)

C = 2,000,000 meter (for zone #6 constant)

R = radius of Earth at the measured point. Acquired from table based on the Latitude reading ϕ. (Interpolate to account for seconds)

$\theta = L\,\Delta\lambda$

$\Delta\lambda = \lambda - \lambda_{mc}$

L = 0.549517575763 (zone #6 constant)

λ_{mc} = Longitude of the Central Meridian = 116^{o} : 15' (zone #6 constant)

CHAPTER SIX

VEHICLE CONTROL AUTOMATION

This chapter provides an overview of the vision-based control system used in the IDV. As this system was developed by Lockheed Martin Corporation, only overview information is provided here. The interested reader is referred to reports and documentation available from LMC directly.

Overview

The control system used in the IDV was originally developed for use in LMC's Unmanned Ground Vehicle (UGV) DEMO I and DEMO II programs. For these ARPA sponsored research programs, vision-based control was used to automatically drive a HMMWV (HummVee) Surrogate Semiautonomous Vehicle (SSV) in military operations. The military genesis of this control system yielded characteristics that distinguish it from other vision-based road followers demonstrated in San Diego. The IDV controller was based on this existing, proven technology, in order to meet the very restrictive development schedule for the demonstration.

Many vision-based road followers can be classified as line followers. I.e., the purpose of the vision system is to identify one or more (usually two) lane lines, and use this information to determine vehicle location with respect to the roadway, and subsequently to determine the appropriate control input to the steering actuator. While such controllers perform commendably on well-maintained and well-marked roadways, they cannot track poorly marked or unmarked roads, or in an off-road environment. The road-follower used in the IDV is not a line-follower; it is a training-based controller that uses template matching to determine the best steering angle for a given roadway image. The controller uses neural networks for some aspects of its operation. The controller determines the most distinguishing features for a given roadway type, and then matches the current roadway image with a set of templates to determine the appropriate steering angle. The main benefit of this system over line-followers is that it can operate on any road-type for which it has been trained, including dirt roads and other off-road situations. In fact, this controller can operate in any environment in which there are distinguishing characteristics that can determine the appropriate steering command.

The controller is split into two separate computers, as shown in Figure 6-1: the Road-Follower (RF) and the Vehicle (or Navigation) Controller (VC). The RF system is a Sparc 5VT CPU, running Unix, while the VC is a Sparc 5V CPU running the VxWorks real-time operating system. The RF is responsible for generating steering commands based on the camera image. The VC takes the steering commands from the RF, and issues commands to the steering hardware through the vendor-supplied steering electronics. In addition, the VC interfaces with the OEM cruise control to set the vehicle desired speed, thus supplying high-level automated longitudinal control. As obstacle avoidance and braking were not part of the scenario demonstrated by the IDV, brake actuation was not included, but could be added in the future. The hardware for the control system is shown in Figure 6-2, while the circuitry for manual override is shown in Figure 6-3. Figures 6-1 through 6-3 were supplied by LMC during design review meetings. Note that the optional obstacle detection and lane change maneuver functional blocks were not implemented.

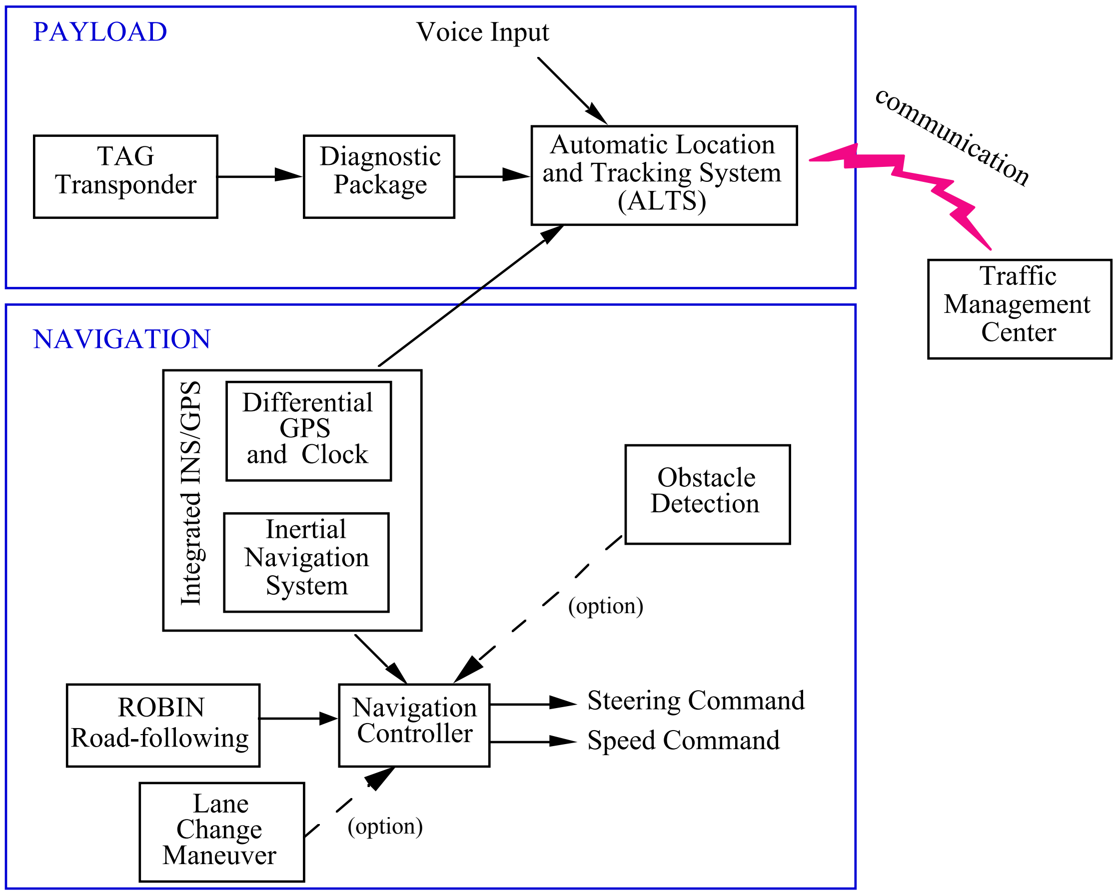


Figure 6-1: IDV Functional Layout

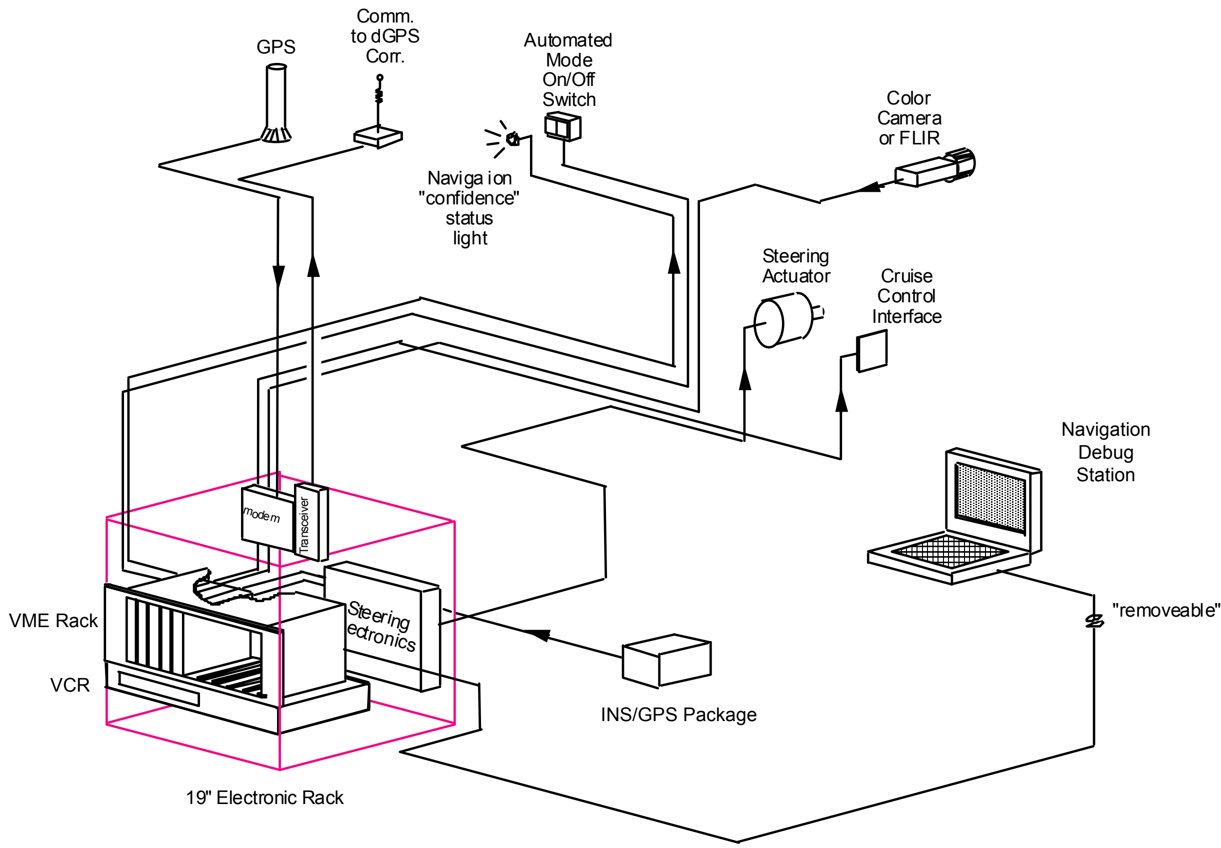


Figure 6-2: IDV Controller Hardware

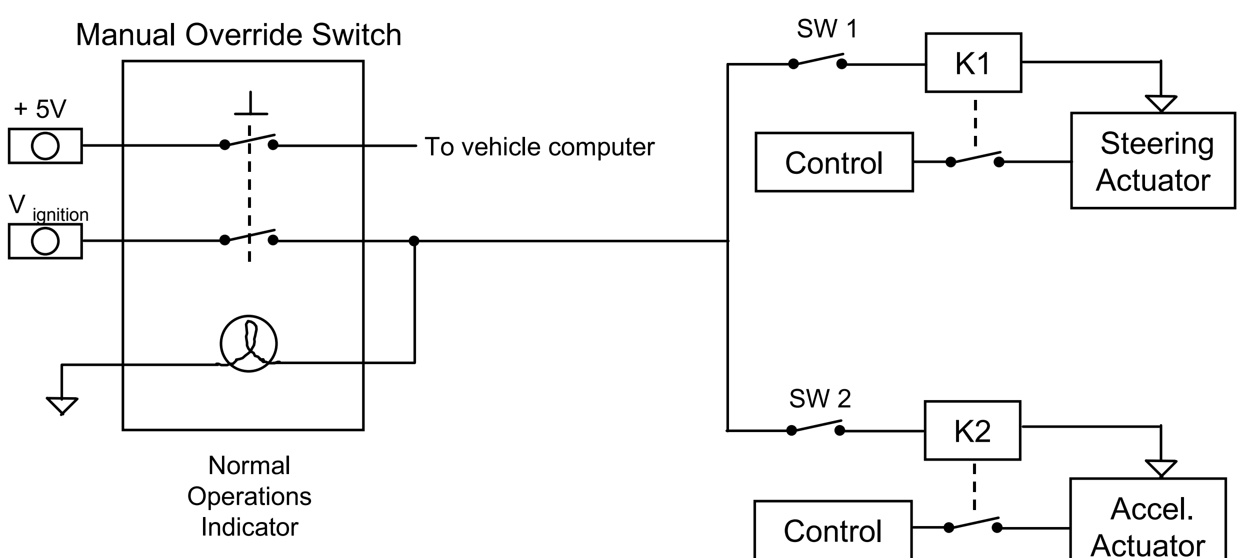


Figure 6-3: IDV Manual Override Circuitry

Training

In the training session, the operator drives the vehicle in a normal, manual fashion, with one exception: the operator should not cut corners in the manner that most human drivers do; instead, the operator should attempt to track the lane centerline at all times. The controller must be trained for each road type (*not* each road), and for each type of lane on a given road. In the future, it is anticipated that the controller will be able to automatically select from a set of road and lane types, and then choose a template set for automated driving which is most appropriate for the given circumstances. As long as the training session includes the most severe left and right turns that will occur in automated driving, the training session will generate a template set of images and associated steering commands that should allow the vehicle to automatically steer along any similar type of road.

As the operator drives the vehicle during the training session, the frame grabber acquires images from the camera, and sends these images to the road-follower computer. This Road-Follower (RF) computer and associated software, referred to as ROBIN, first performs a pixel reduction of the selected windows in the raw image, in order to reduce storage and computational requirements. The reduced images are stored, along with associated steering commands as sensed from the operator input. The images are analyzed to determine the most distinguishing characteristics for the current roadway type. This information is then used to reduce the input image dataset to a set of templates with associated steering commands. This template / steering command database then constitutes the "network" which is used to automatically steer the vehicle along this type of road. For the I-15 test corridor, the distinguishing feature was the stark contrast between the nearly white Portland Cement Concrete (PCC) lane and the nearly black Asphalt Concrete (AC) shoulder. This feature was much more prominent and useful for lane tracking than the actual lane markings.

Automated Steering

With the push of a single button on the IDV steering wheel, the operator can engage automatic steering. At this point, the system will use the video camera input to determine the correct steering angle, and command the steering actuator to the correct setting.

The system operates on the video input essentially in the same way that it does during training. Thus, the system acquires camera images, performs pixel reduction of the selected windows, and generates the appropriate reduced image for the current roadway network. This reduced image is then compared against the stored templates in the roadway network database. The closest match is found, and the associated steering angle is used to automatically steer the vehicle along the lane centerline. The steering command is smoothed through low pass filtering and interpolation techniques. The nominal controller sampling period is approximately 40 milliseconds. However, this period is dependent upon the complexity of the input scene, and can sometimes reach 80 ms.

This controller works well in most situations, and can also address degraded situations. For example, if the vision-based Road-Follower detects that the input image cannot be matched to any of the learned templates, it "loses confidence" in the input image. This can occur for several reasons, including shadows beneath overpasses. Such anomalous images are averaged out during the training session, and thus cannot be a part of the template set. When the system detects low confidence, it first moves auxiliary windows further out in the camera image, in an attempt to "see" past the shadows. If this fails, the controller then resorts to a smoothed steering command history in order to steer the vehicle through this section of roadway. If the system does not regain confidence, i.e. it cannot match the roadway image to available templates, for a period exceeding some threshold, the controller will sound an audible alert, light a warning light, and return control to the human operator.

As with all other automated vehicle controllers at this current time, the human operator is the ultimate safety mechanism. The operator is expected to be aware, alert, and prepared at all times to diagnose the safety of the situation, and to act according to best judgment to assure safe operation of the automated vehicle. For cases where minor operator corrections are needed, the IDV steering actuator allows introduction of manual torque in order to adjust the steering command, and move the vehicle back to lane centerline. For emergency situations, the operator can overtake the steering wheel without application of excessive torque. When the steering actuator controller detects a manual override, it ramps down its internally controlled torque to zero, so that the operator does not introduce an overshoot in steering, as would be the case if the actuator controller immediately removed its torque in a step command. This safety feature was not available in some of the other scenarios demonstrated in San Diego.

Compliant Control Modification Using Magnet-Based Lateral Offset

The lateral offset information obtained from the magnets can be used to assist with the vehicle lateral control. Here, the basic algorithm developed is provided.

The concept is a form of compliant control. Typically, compliant control is viewed in the context of an external force operating on a system, such as a robot, with the controller responding to this force by modifying the position of the system in an advantageous manner. Here, a more general notion of compliant control applies. The IDV vision-based controller selects a steering angle based on its analysis of current vehicle lateral offset and upcoming curvature. The lateral offset of the vehicle as measured by the magnetometers is then used to create a "virtual" force that modifies the output of the controller to help keep the vehicle centered in the lane. The magnitude of this adjustment is parabolic, subject to a maximum value. The sign of the adjustment is determined from the sign of the input steering curvature command as determined by the vision-based road follower, and the sign of the lateral offset as measured relative to the magnets. If the signs differ, the road-follower command is increased by the compliance term, as the road-follower is taking the correct action. When both are of the same sign, the steering command is reduced, as it appears to the compliant controller that the road-follower is taking incorrect action. The net effect is that the vehicle is maintained near lane centerline more often, and returns to the centerline more quickly. The adjustment term is shown in Figure 6-4, where x is the lateral offset (m), y is the input steering curvature command (1/m) from the road-follower, and z is the adjustment component (1/m). Figure 6-5 shows that actual output steering curvature command. Note that the parameters shown were empirically determined during testing, and represent only a working example, not an optimal choice.

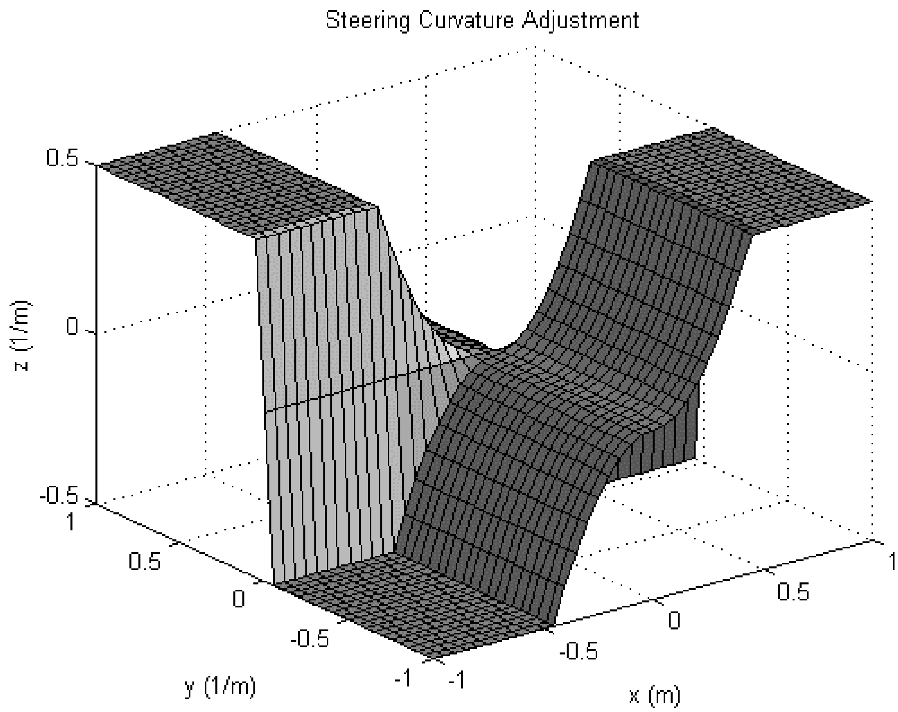


Figure 6-4: Steering Curvature Adjustment Component

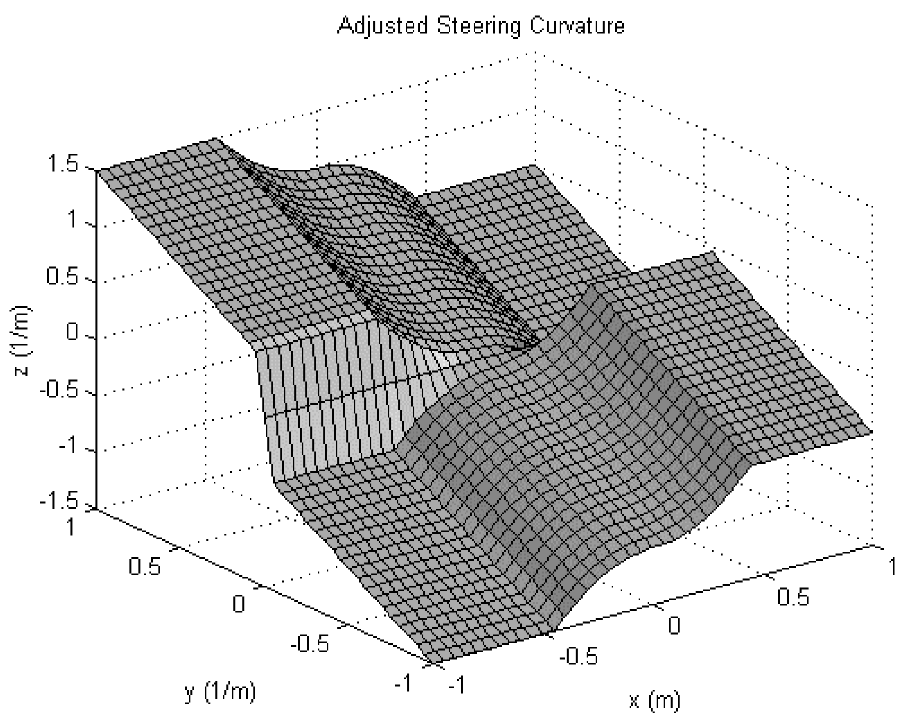


Figure 6-5: Adjusted Steering Curvature

The method discussed was implemented and tested successfully during testing on the I-15 corridor. However, problems related to the communications link between the DP and the RF prevented use during the final demonstration. Specifically, this communications link used an Ethernet UDP socket to send the adjustment signal to the RF, which can introduce non-deterministic delay into the real-time control loop. This, in combination with the variable cycle time of the road-follower, means that the magnetic adjustment information could build up, and be applied at delayed intervals, leading to deterioration in control performance. This problem can be addressed using the known technology of shared-memory between the various systems, thus removing the Ethernet communications link from the controller.

Longitudinal Control

Due to the nature of the maintenance scenario, the longitudinal control system for the IDV was relatively primitive. As the IDV operated as a solo vehicle on the I-15 test corridor, there was no need for tight control of vehicle speed, as is required in platoon vehicles, for example. In addition, as obstacle avoidance was not part of the maintenance scenario, the IDV did not require brake actuation. Low-level throttle and brake actuation, along with methods for obstacle detection and avoidance, would need to be added to the IDV for use in an actual automated highway system. For the current demonstration, the Vehicle Control computer was simply interfaced to the OEM cruise control system. A speed profile could be set by the computer, and the VC would electronically "push" the right buttons in the cruise control system in order to set the vehicle speed to loosely follow this speed profile. Once the system converged on the correct steady-state speed, the VC would then just allow the cruise control to operate as in any normal passenger vehicle. As the cruise control system in the Lumina was somewhat inefficient, the operating speed of the vehicle varied substantially (up to 10 MPH) in the steeper sections of the I-15 test corridor. However, for the purpose of the NAHSC demonstration, this high-level, minimal capability longitudinal control was sufficient.

Lateral Control Issues

As noted above, this controller worked well in most situations. However, during testing and demonstration, certain issues for future consideration were noted. Some of these issues were addressed by the development team at the time of the testing. Some remaining outstanding issues are discussed here.

Weight distribution created serious problems for the lateral controller. Because the road-follower was programmed to follow a single edge, specifically the right roadway edge, shifts in weight that changed the pitch of the vehicle were particularly problematic. The pitch of the vehicle during the training session effectively sets the look-ahead distance of the window that is used to select roadway features for template matching. Thus, this distance is set by the weight distribution at the time of training. When this distribution is significantly shifted, as it was during certain demonstration runs, the effective look-ahead distance is changed; typically, it is shifted farther out from the vehicle. With minimal geometric reasoning, it is clear that without knowing the change in the look-ahead distance, this will cause the road-follower to perceive a lateral shift in the vehicle. The resulting symptom is that the vehicle tracks off centerline, typically to the right, by an amount dependent on the weight shift and resulting vehicle pitch. This problem was partially alleviated by stiffening the relatively soft suspension. Additional instrumentation to detect vehicle pitch (and roll) was considered, along with software modifications to compensate for the sensed deviation. However, this approach was not pursued due to time constraints. In addition, a simpler solution may remove this problem, as well as making the controller more robust; this solution is discussed below.

In a similar manner, if the lateral weight distribution shifts significantly, vehicle and camera roll angle introduce problems. Here, if the roll is large enough, the virtual window used to detect the distinguishing roadway features may be shifted enough that it no longer contains useful information. This can also occur in the case of significant pitch. This problem was not encountered as frequently as the pitch problem, but can be solved using similar techniques.

In general, the system could be much more robust. It should be more robust to variations in weight distribution, external lighting, road conditions, etc. If this controller is used in future research, addressing these robustness issues should be a primary concern. The system is of course also subject to some of the problems inherent in vision-based vehicle control, including weather, lighting, roadway obscurity due to sand and snow. As noted above, shadows under bridges and overpasses can cause problems. Also, the need to train the system for each type of road to be encountered is a burden; however, this burden is matched by the corresponding capability to track more road types (and non-roads) than line-follower systems. Ability to automatically select the best template set from a large library of previously taught road types would be very useful here.

One improvement that would address many of these issues, particular those related to weight distribution, is to have the system track both edges of the lane or road. With this single improvement, the issues of vehicle roll and pitch may be nearly eliminated. When two edges are available, it is a trivial matter to distinguish a lateral lane shift from a change in look-ahead distance as caused by vehicle pitch, for example. Thus, the system will be able to accurately detect its position within the lane for a wide range of weight distributions. Other situations that lead to degraded vehicle tracking may also be alleviated by this improvement.

CHAPTER SEVEN

SYSTEM INTEGRATION

This chapter provides a review of the approach used for overall system integration of the AHS Infrastructure Diagnostic Vehicle. Much of this information is covered in greater detail in other chapters of this report. However, the intent here is to provide a higher level view of the system, with emphasis on interfaces between individual subsystems. Communications issues are touched on briefly, but are discussed in detail in a previous chapter.

Functional Architecture

The overall IDV functional architecture is presented in Figure 7-1. The architecture is split into two on-board functions, labeled "Payload" and "Navigation" The Payload portion represents the true operational intent of the IDV, i.e. it is the portion responsible for all infrastructure diagnostics. The Navigation portion is responsible for automated control of the vehicle, and acts as a support system for the diagnostic functions. Of course, the automated vehicle control is a major component when demonstrating the full functionality of the IDV.

The main component of the Payload portion, and of the IDV in general, is the Diagnostic Package (DP). This system is responsible for all automatic infrastructure diagnostics, including Vehicle-to-Roadside Communication used during system check-in, and the magnetic markers used for lateral vehicle control in some demonstration scenarios. The diagnostic package consists of an industrial PC with required input/output hardware, flux-gate magnetometers for magnet diagnostics, and interfaces to other subsystems. As defined in the functional architecture, the RF TAG transponder and HMI are the remaining subsystems. The RF transponder is used for vehicle check-in, as with other AHS demonstration scenarios. In addition, the transponder is used by the DP to diagnose the functionality of the check-in system. The Automatic Location and Tracking System (ALTS) portion of the HMI provides voice input and recognition for operator identified infrastructure anomalies, such as debris. It also receives status and error information from the DP for VRC and magnetic marker diagnostics. Finally, ALTS provides the real-time communications link to the Transportation Management Center (TMC) via a Cellular Digital Packet Data (CDPD) modem.

The Navigation portion provides automatic vehicle control, including complete automation of steering (lateral control) and high-level automation of the OEM cruise control (longitudinal control). The ROBIN Road-Follower is a vision-based neural network control system that processes that input video image and, using stored data from training sessions, generates the appropriate steering command for the current image. This steering command (actually a curvature command) is sent to the Navigation Controller via an Ethernet UDP socket. The Navigation Controller, a real-time system, converts this curvature command to the appropriate signal for the vehicle steering actuator. The Navigation Controller also adjusts the vehicle speed set-point in the cruise control system. The optional functions shown (obstacle detection, lane change) were not implemented for the demonstration.

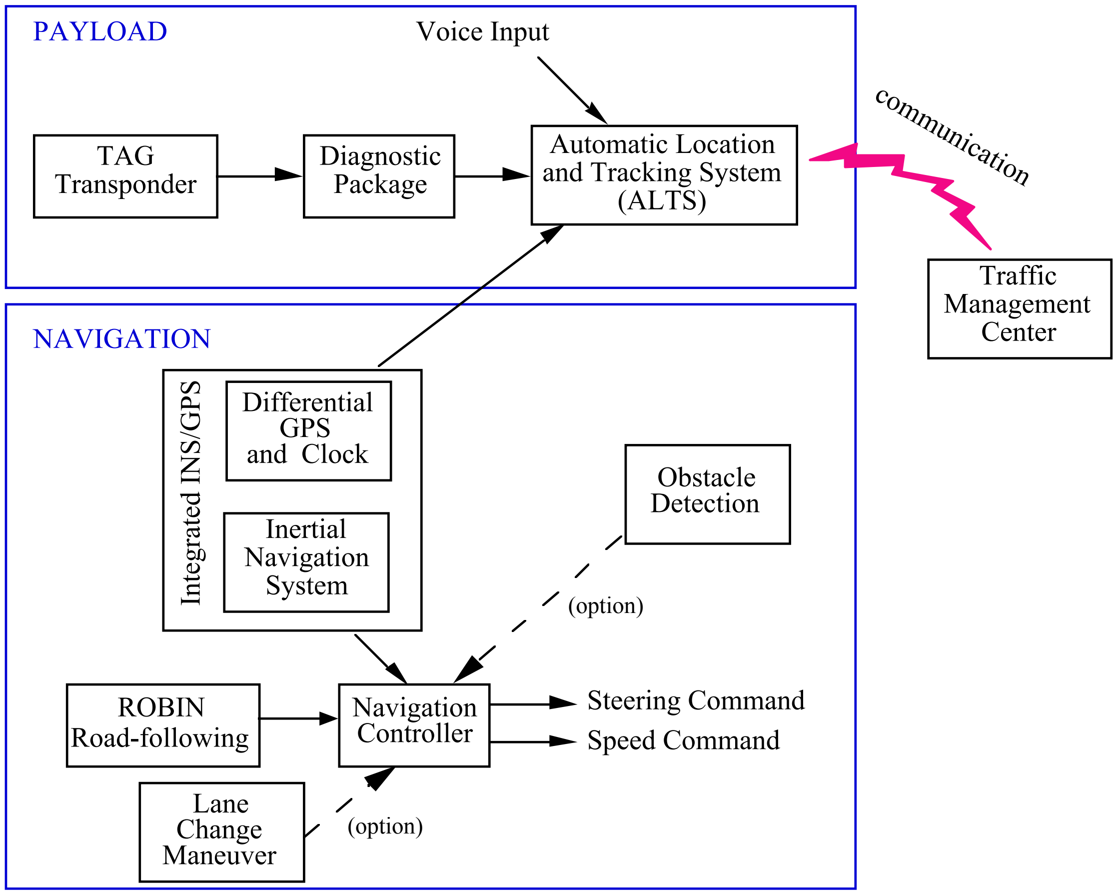


Figure 7-1: IDV Functional Architecture

The TMC provides a vital link in the overall maintenance scenario. When the operator identifies debris in the system and inputs this information into ALTS via voice command, ALTS tags the debris location with GPS coordinates and automatically notifies the TMC. Upon notification that there is debris in the AHS, potentially a safety hazard, the TMC immediately dispatches the Obstacle Removal Vehicle (ORV) to expeditiously remove the debris. The TMC also logs magnet anomaly data and enters it for future scheduled maintenance and repair. Note that while the INS/GPS subsystem is shown under Navigation, it is also an integral part of the diagnostics.

Physical Architecture

The system block diagram and associated hardware are shown in Figures 7-2 and 7-3, respectively. The computer systems, VCR, GPS, and other electronics are installed in a 19" rack in the rear of the Lumina minivan. The various computers in the system are tied together by the 10BaseT hub, and communications occurs via TCP/IP and UDP/IP sockets.

The DP computer, an industrial PC with Intel Pentium CPU, communicates with the transponder by RS-232 serial link, while the APS 533 magnetometers are sampled through analog-to-digital converters on a National Instruments ATMIO-16.

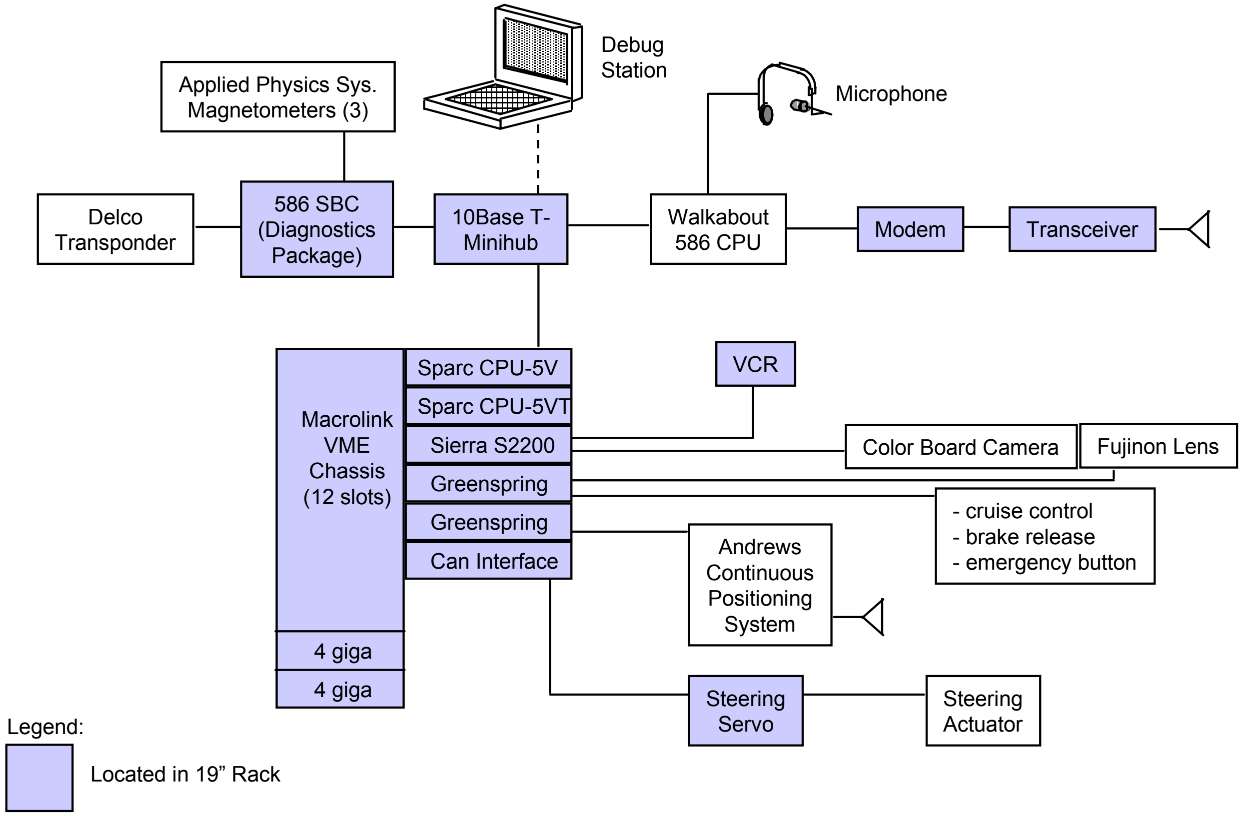


Figure 7-2: IDV Block Diagram

The HMI and ALTS system is installed on a desktop Pentium-based PC. User input to ALTS is by way of voice commands using the microphone on a headset. ALTS is a Windows program, including a graphical user interface (GUI). User interaction with the HMI occurs by way of a touch-screen, which also serves as the main display of the IDV. Much of the data displayed in the IDV was for demonstration purposes, and would not be required in a deployed system. ALTS communicates status and error information, as well as vehicle telemetry, to the TMC by way of a wireless Cellular Digital Packet Data (CDPD) modem.

The Road-Follower (RF) and Vehicle-Controller (VC) computers, both based on Sparc CPUs, reside in a VME chassis. The RF provides file services to the VC by way of NFS. The frame-grabber interfaces with the VCR and the color and low-light black and white cameras to provide images to the RF vision-based controller. I/O boards are included for RS-232 communications to the GPS and for communication to the cruise control system and operator interface buttons. In addition, the VC includes an interface to the fiber optic Controller Area Network (CAN) bus (SAE J1583), which is used to send commands to the steering actuator.

The GPS system includes differential corrections provided by an FM signal. In addition, the GPS unit provides dead reckoning of vehicle position using pulses from the odometer in combination with the output from an internal yaw rate gyro. The GPS unit outputs information in a modified NMEA format. This ASCII text is sent, by way of an RS-232 port, to a splitter box, which distributes the signal to the DP, RF, and HMI computers.

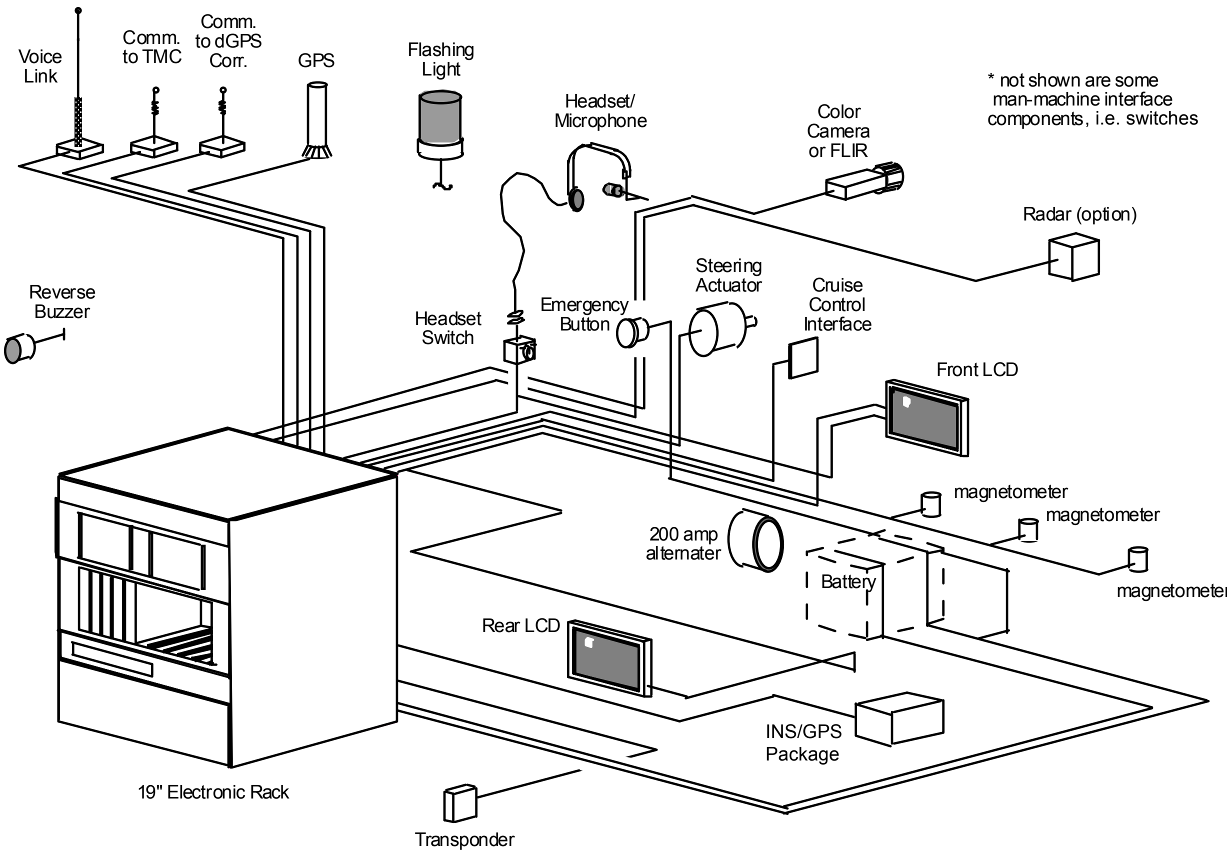


Figure 7-3: IDV Hardware Components

The power system provides both AC and DC power to the various components. Power is supplied by an increased capacity alternator, as the standard Lumina alternator could not provide sufficient current. An inverter provides AC power for those systems that require it. Where possible, computers and other systems were purchased with or converted to DC power, to increase system efficiency.

The physical layout of the components is illustrated in Figure 7-4. Here, the rack components have been represented horizontally in the rear of the vehicle, for clarity. These components include the DP, RF, VC, and HMI computers, GPS and INS, communications hub, steering actuator controller, and associated power electronics. In addition, the rack houses the VCR for image capture, along with a video patch panel that allows a variety of input and output configurations for the vision system. In particular, the system can be configured so that pre-recorded video can be used as the input to the vision-based road-follower, which will then attempt to control the vehicle based on this recorded image. In fact, initial development and testing of the IDV road-follower occurred at Lockheed Martin's facilities in Denver, Colorado, using video footage of the I-15 test facility. Additional components in the rear of the vehicle include battery backup (over two hours), and tool storage compartments. Twisted-pair Ethernet cable connections and AC power outlets are located in several convenient locations throughout the vehicle; this greatly facilitated development and testing of the system.

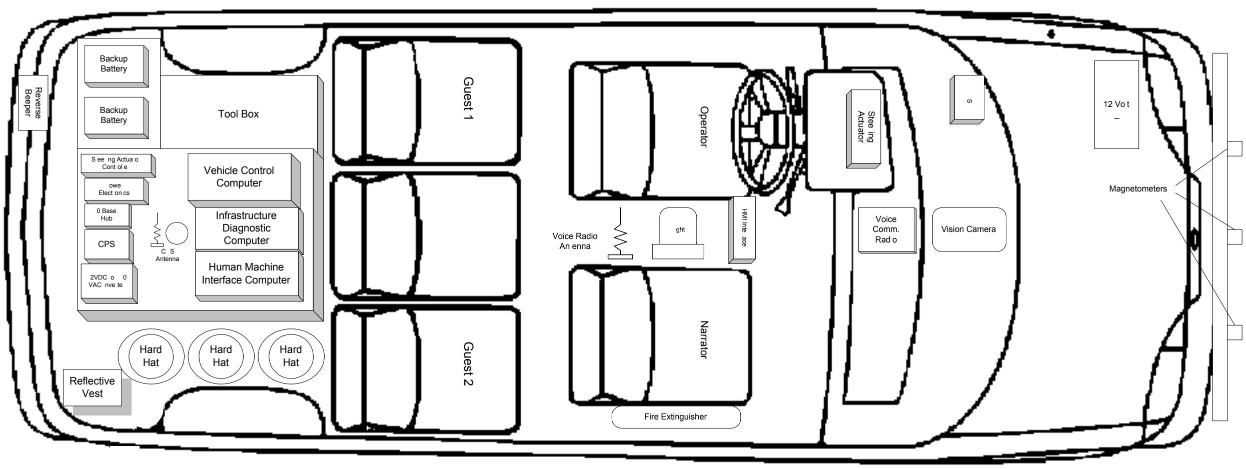


Figure 7-4: IDV Component Layout

The operator / narrator area includes the buttons for automatic vehicle control operation, as well as the flat-panel LCD touch-screen and headset used for the Human Machine Interface. Master power, along with LED status indicators, are located on an overhead panel for convenient access and viewing by the operator. Further status LEDs are located in the instrument panel, providing the operator with clear indication of the status of the automated vehicle control system. Audible alarms are also included as part of the safety warning system. The color and low-light black and white cameras are mounted in the front windshield, approximately at the location of the rear-view mirror. The RF transponder is mounted in the front windshield, near the camera mount. In addition, a standard voice radio unit is located beneath the front passenger seat, for use in demonstration coordination and for emergency communications. A fire extinguisher is also located in the front area. The steering actuator is located within the steering column, and is not accessible from the passenger compartment.

Several components are mounted externally. Antennas for the GPS receiver, GPS FM differential corrections, and voice radio are distributed along the centerline of the roof. As the Lumina minivan body is plastic, a ground plane was installed between the roof and the headliner within the vehicle. An amber rotator light is also mounted on the roof, along with a reverse beeper under the rear bumper, to comply with maintenance vehicle requirements. Finally, the magnetometers, the most critical components in terms of infrastructure diagnostics, are mounted underneath the vehicle. A custom magnetometer mount bar supports the three magnetometers in a location behind the vehicle bumper. This bar also provides routing for the sensor cables, and is designed for break-away if the sensor bar impacts obstacles, including curbs and speed bumps. With this capability, the expensive sensors are protected from excessive impact forces.

The front and rear of the 19" electronics rack can be seen in Figures 7-5 and 7-6, respectively. Note that for Figure 7-5, the middle seat has been removed. This figure illustrates the relative space required by the major subsystems. The VCR is located at the top of the rack. Below this is the VME enclosure, containing the Road-Follower and Vehicle Control computers. Next is the industrial PC, i.e. the Diagnostics Package. Finally, at the bottom of the rack, is the HMI and ALTS computer. In the rear view, Figure 7-6, one can see the video patch panel at the top left, the rear of the VME system, including the 10BaseT hub, and the laptop computer that provides an operator interface for the Road-Follower and Vehicle Control computers. This laptop is not required during system operation. The battery backup compartment is located in the lower left enclosure, marked by the AHMCT logo. The GPS receiver and power electronics are located within the rack, behind the panel with the Lockheed Martin logo.

Figure 7-5: IDV Rack, Front View

Figure 7-6: IDV Rack, Rear View

Human Machine Interface

The Human Machine Interface (HMI) supports two main functions: automated driving, and infrastructure diagnostics. The components of the interface are shown in Figure 7-7. All controls for automated driving are located on the steering wheel, within easy reach of the operator. The Human Machine Interface components, specifically the touch-screen flat-panel display and the headset, are centrally located, so that either the operator or the narrator can manage the infrastructure diagnostics. For the demonstration, the narrator operated the HMI. For a deployed system, only a single operator would be required, and this operator would manage all vehicle functions, along with all diagnostic functions.

Automated driving requires minimal input from the operator. The human driver merely brings the vehicle to a minimum operating speed and, with the vehicle reasonable oriented and centered within the lane, pushes a single button on the left side of the steering wheel to engage automated lateral control. With the push of a button on the right side of the wheel, automatic longitudinal control is also initiated. The steering wheel buttons used for control of the radio in a standard Lumina were selected to support these tasks. Any of the three left buttons will engage the steering system, while any of the three right buttons will engage computer-based cruise control. If an emergency situation occurs, the operator can simply push the horn (the center portion of the steering wheel), and steering is returned to the human operator. Finally, the operator can provide small adjustments to the automatic steering system using small torque on the steering wheel, and can also completely override the automatic lateral control system through a larger, but not excessive, overtake torque. The control system status LED panel, seen through the steering wheel, above the standard instrument panel provides immediate feedback to the operator regarding actuator operation, road-follower confidence, and vehicle operational status.

Figure 7-7: IDV Operator Console

The Diagnostic Package operator interface can be seen between the front seats. It consists of the flat-panel LCD touch-screen and the headset microphone. The touch-screen provides a control panel for the Diagnostic Package, shown in Figure 7-8, and visual display of the DP data collection, shown in Figure 7-9. This display also presents information for the ALTS program, as shown in Figures 7-10 through 7-12. The headset supports voice-input of infrastructure anomalies for ALTS; when the operator uses phrases from the supported vocabulary, ALTS recognizes the anomaly type, marks the location of the anomaly with GPS data, and transmits this information to the TMC. The voice radio controller is mounted to the LCD panel support column.

The DP control panel consists of a number of buttons, shown in Figure 7-8, which are programmed to issue text macros to control DP functions. Button functions are shown in Table 7-1. These buttons are programmed in the PowerTerm terminal emulation program, and are stored in the file ptfunc.ini. When a mouse is available, these buttons can be programmed by right-clicking on the desired button. When using a touch-screen, this option is not available, and direct editing of the text in the INI file is required. Two example entries are provided here, for future reference. The first is straightforward, and the second illustrates entries which issue control characters. The entry is formatted with the pad number, which refers to the row and column of the button, the button label, and the macro string to be sent to the remote computer.

- pad 9 2 "pwd" {send "pwd\n"}
- pad 8 4 "CTRL-C" {send ^C}

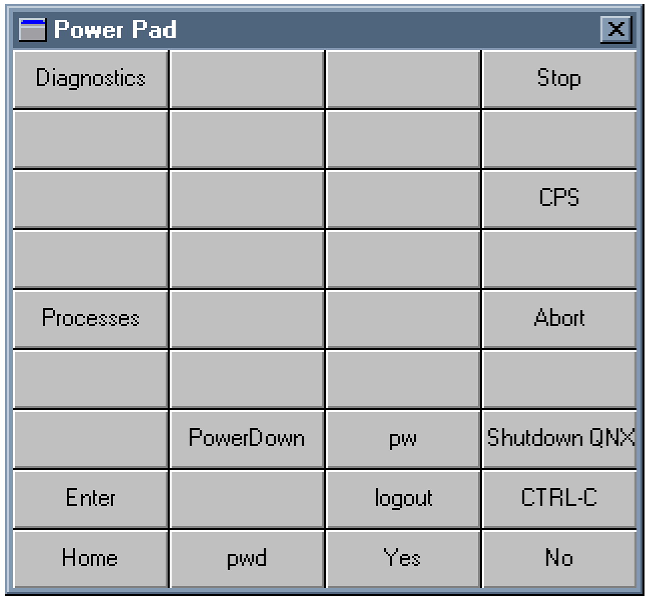


Figure 7-8: Diagnostic Package Control Panel

Button Label	Function	Macro String
Diagnostics	Start diagnostic program	mark&\n
Stop	Stop diagnostic program, save data	terminate\n
CPS	Verify CPS output / data rate	cps test\n
Processes	Show running QNX processes	ps\n
Abort	Halt diagnostic program, don't save data	terminate\nclean_up\n
PowerDown	Shutdown QNX OS	echo shutdown\nshutdown\n
Shutdown QNX	Begin shutdown process by changing to administrator	su\n
Enter	Send "Enter" key	\n
logout	Return to login prompt	exit \n
CTRL-C	Send "CTRL-C" (break) key	^C
Home	Change to home directory	cd\n
pwd	Show current directory	pwd\n
Yes	Send "y" key for queries	y\n
No	Send "n" key for queries	n\n

Table 7-1: DP Control Panel Functions

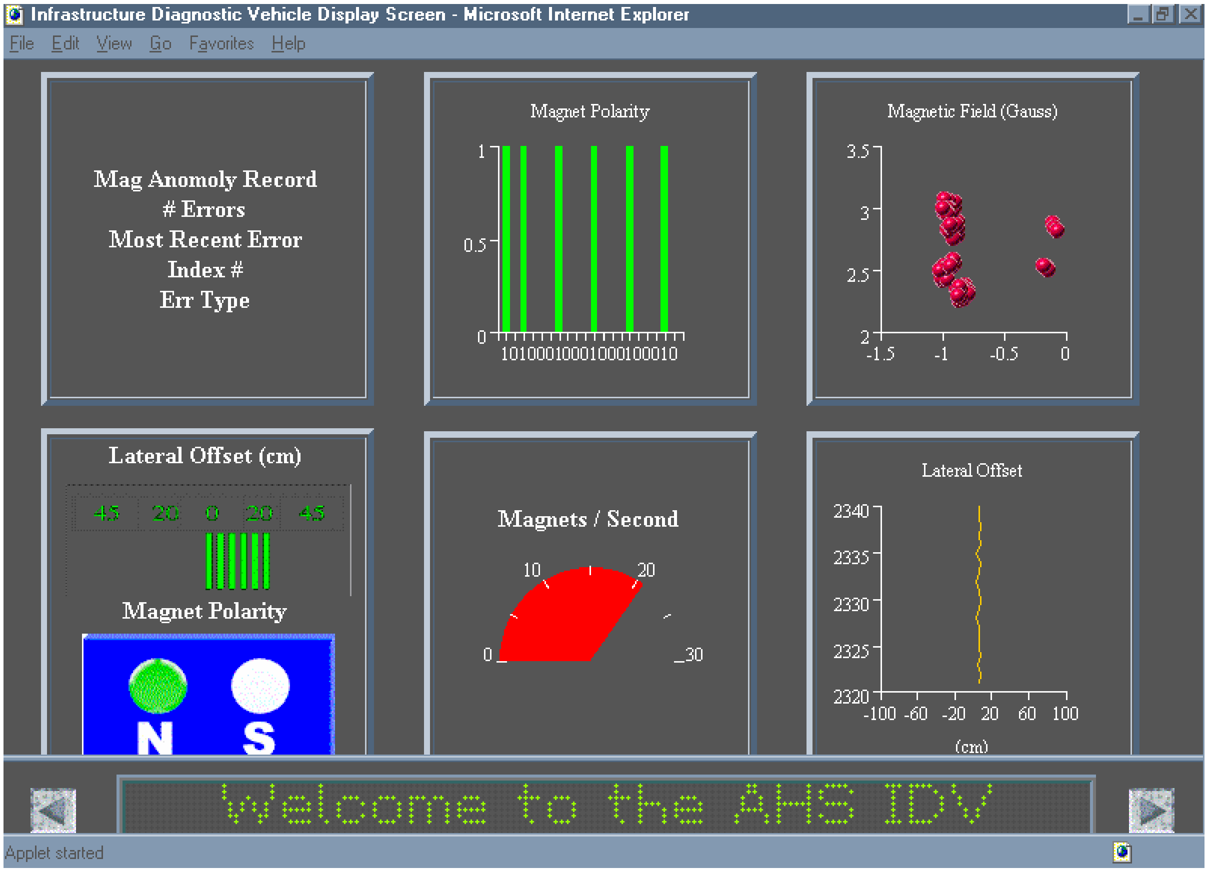


Figure 7-9: Diagnostic Package Human Machine Interface Data Display

The HMI includes a graphic display of magnet diagnostic data. This display is shown in Figure 7-9. The display was developed in a rapid fashion using open standards to interface to the DP computer. All communication occurred over TCP/IP sockets, or using simple file transfers. Typically, the DP updates data files containing the relevant magnet status information, and the HMI screen applets obtain this data through calls to file transfer functions. The individual display components are programmed in Java, an object-oriented, distributed, platform-neutral, network-savvy programming language that is widely used for simple Web programming. The applets are then grouped into a display using standard Web page programming in Hypertext Markup Language (HTML), with layout controlled using tables. Additional screen control is supported with the inclusion of JavaScript functions.

The object-oriented nature of Java, combined with the ability of HTML to combine small applets into one integrated screen, helped in the rapid development of this display screen. In addition, use of Web client/server technology greatly simplified the amount of custom code required. Because of the open nature of this architecture, some components were based on commercial off-the-shelf (COTS) applets. The applets seen in two right top and bottom panels use charting applets from the JavaChart development package, from Visual Engineering. The LED text information applet at the bottom of the screen is a freeware applet found on the Web. Thus, custom applets were required only to display the current lateral offset and current magnet polarity, shown in the lower left applet pane. The upper left pane is a simple text based table component, which provides information on the quantity, type, and location of magnet anomalies.

Specific details for the various panels should be clarified. The magnet polarity history (panel 1-2) illustrates the coding for the previous 20 magnets (approximately one second worth of data), with a bar indicating a "one" or "north" polarity, and no bar indicating a "zero" or "south" polarity. The magnetic field history (panel 1-3) shows the magnetic field (B_y vs. B_x) for the last 20 magnets. Panel 2-1 contains two applets: current lateral offset in centimeters, and current magnet polarity. The current polarity will typically show the default magnet polarity (north), and will flash between polarities when the vehicle traverses coded sections of roadway. Panel 2-2 provides the rate at which magnets are being diagnosed; at a vehicle speed of 60 MPH (27 m/s) and magnet spacing of 1.2 m, the system typically diagnoses 22 magnets per second. The final applet, in panel 2-3, illustrates the history of the vehicle lateral offset relative to the magnetic markers, with the vertical axis representing the current marker index number. This information is mainly provided to evaluate the performance of the vision-based vehicle control, but also can provide the operator visual indication of large non-random shifts in magnet location.

Figures 7-10 through 7-12 provide sample screens from the ALTS program, discussed in a previous chapter. Here, the screens are shown to indicate the feedback available to the operator during diagnostic runs on I-15. Figure 7-10 shows the overview GIS screen for I-15, with the GPS-sensed location of the IDV illustrated by the icon of a car. This display uses the MapObjects software library, from ESRI, along with GIS data for I-15 and the surrounding surface streets. MapObjects provides much of the needed GIS capabilities, including zoomed images, shown in Figure 7-11. Aerial photographs of the region were provided by Caltrans. These photos have been tagged with GIS coordinate data, and incorporated into the ALTS displays. As seen in Figure 7-12, the operator can replace the simple graphic background shown in Figures 7-10 and 7-11 with the aerial photograph of the current region that the vehicle is diagnosing. This allows the operator to better correlate diagnostic information with physical location. Other ALTS displays, not shown here, provide text-based feedback of GPS location, anomaly information based on either automatic detection by the DP or on voice-recognition of operator input, and overall status of the diagnostic system itself.

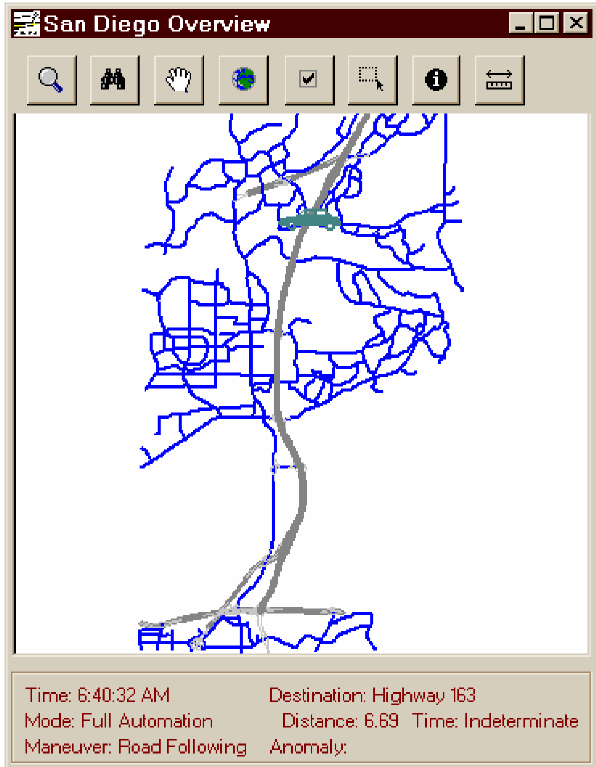


Figure 7-10: ALTS GPS/GIS Overview Screen for I-15

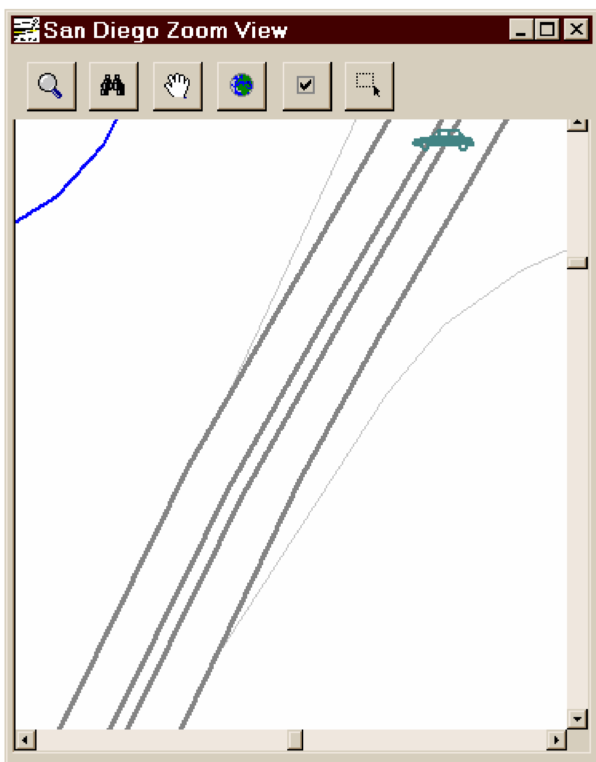


Figure 7-11: ALTS GPS/GIS Zoomed Screen

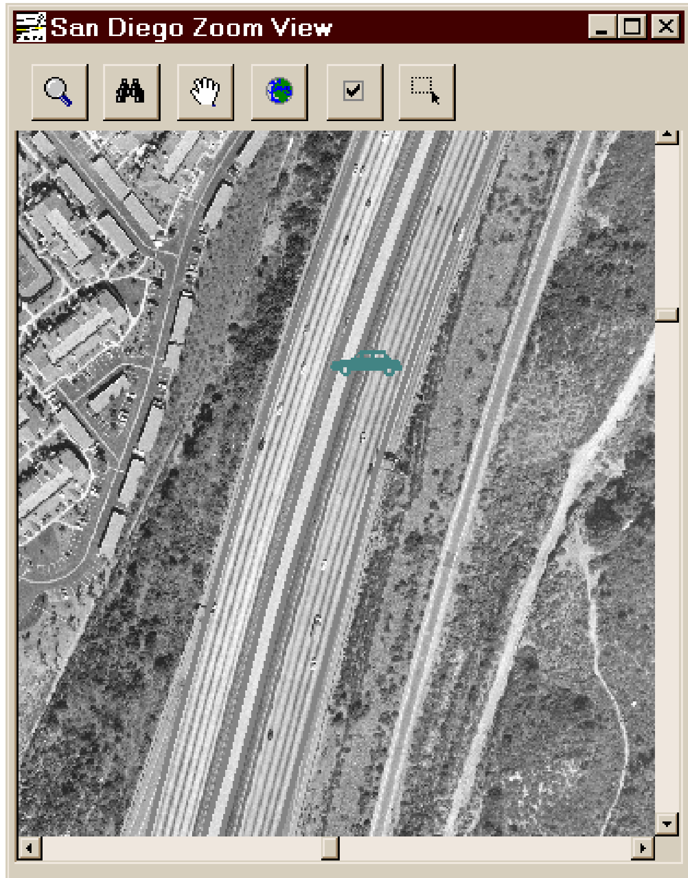


Figure 7-12: ALTS GPS/GIS Zoomed Aerial Map

CHAPTER EIGHT

NAHSC DEMONSTRATION

The AHS Infrastructure Diagnostic Vehicle (IDV) was the key system in the Maintenance Scenario, one of seven demonstration scenarios presented at the National Automated Highway Systems Consortium (NAHSC) Proof-of-Technical Feasibility Demonstration held August 7-10, 1997, in San Diego, California. This demonstration was mandated by Congress in the Intermodal Surface Transportation Efficiency Act of 1991, better known as ISTEA. The demonstration was held on the 7.6 mile (12 km) long AHS test facility located on the I-15 High Occupancy Vehicle (HOV) lanes near San Diego, CA. The IDV was developed as part of the California State Department of Transportation's (Caltrans) involvement in the NAHSC demonstration, in conjunction with Lockheed Martin Corporation. The IDV demonstrates the need for and capability of advanced diagnostic systems in an AHS.

The NAHSC was selected by the United States Department of Transportation to lead in the development and demonstration of an AHS. This program was been established to pursue the technically challenging, long-term goal of having a fully operational vehicle-highway system that automates the driving process. The NAHSC demonstration is a direct response to ISTEA, Part B, Section 6054(b):

> The Secretary (of Transportation) shall develop an automated highway and vehicle prototype from which future fully automated intelligent vehicle-highway systems can be developed. Such development shall include research in human factors to ensure the success of the man-machine relationship. The goal of this program is to have the first fully automated roadway or an automated test track in operation by 1997. This system shall accommodate installation of equipment in new and existing motor vehicles.

The 1997 AHS demonstration was a full-scale live vehicle exhibition, integrating the latest technological achievements of the participants of the NAHSC. The event also included an exposition providing stand-alone demonstrations, static equipment displays, computer simulations, and educational literature. The DP development platform, essentially the IDV without automatic vehicle control, was demonstrated at this exposition.

Here, the Maintenance Scenario, including the IDV and the Obstacle Removal Vehicle (ORV) is presented, along with the results from the live vehicle demonstration.

Maintenance Scenario

As with all the scenarios at the NAHSC demonstration, the Maintenance Scenario demonstrates one form of advanced vehicle control. However, this is not the main intent of this scenario. The Maintenance Scenario demonstrates the ability of a State Department of Transportation or other organization to effectively inspect and maintain an automated highway system. Based on previous studies, including detailed questionnaires to highway maintenance organizations, deployment and maintenance of an AHS raises significant concerns in this segment of the stakeholders. With frozen or dwindling budgets, maintenance of existing systems is difficult at best. The addition of sensors, communications, and reference systems to the infrastructure stirs up serious anxiety regarding available budget, manpower, and technical skill to locate, install, inspect, and maintain such systems. Here, this demonstration shows that the same technologies used for vehicle automation can provide the tools to support DOT operations for an AHS, and actually enhance the ability of the DOT to maintain current as well as future infrastructure systems.

The IDV illustrates the ability to perform on-the-fly inspection of advanced infrastructure technologies at highway speed. The capability of detecting and accurately locating any flaws in the lateral reference system or communications infrastructure frees the DOT from costly, time-consuming manual inspection of such systems. Any degradation in the systems can be found well before it could lead to actual performance or safety issues for the AHS traveling public. Thus, this system allows the DOT to manage the system more effectively, and provides a much higher level of safety and performance. In addition, the ability to perform such inspections and to localize and repair or replace degraded infrastructure should lead to reduced liability for the associated maintenance organization.

In a similar manner, the Obstacle Removal Vehicle (ORV), shown in Figures 8-1 and 8-2, addresses some existing DOT concerns regarding AHS operation. In particular, the ORV provides a quick and safe method to remove debris and obstacles from the AHS right-of-way, without endangering the maintenance worker. The operator can remotely retrieve and remove debris from the system without leaving the safety of the vehicle cab. Rapid deployment of the ORV in conjunction with notification from the IDV or other vehicles means that debris is removed from the system as early as possible. Although AHS-equipped vehicles will have obstacle avoidance capability, removal of debris and obstacles is a critical function to enhance safety and efficiency of the system. The best form of obstacle avoidance is a complete lack of obstacles, and preventing vehicles from swerving to avoid such obstacles will prevent corresponding reductions in overall system safety and throughput.

The following provides descriptions of the vehicles used for the Maintenance Scenario, along with a timeline for an example run on I-15. An overview of the I-15 demonstration corridor is shown in Figure 8-3.

Figure 8-1: AHS Obstacle Removal Vehicle (ORV), Rear View

Figure 8-2: AHS Obstacle Removal Vehicle (ORV), Side View

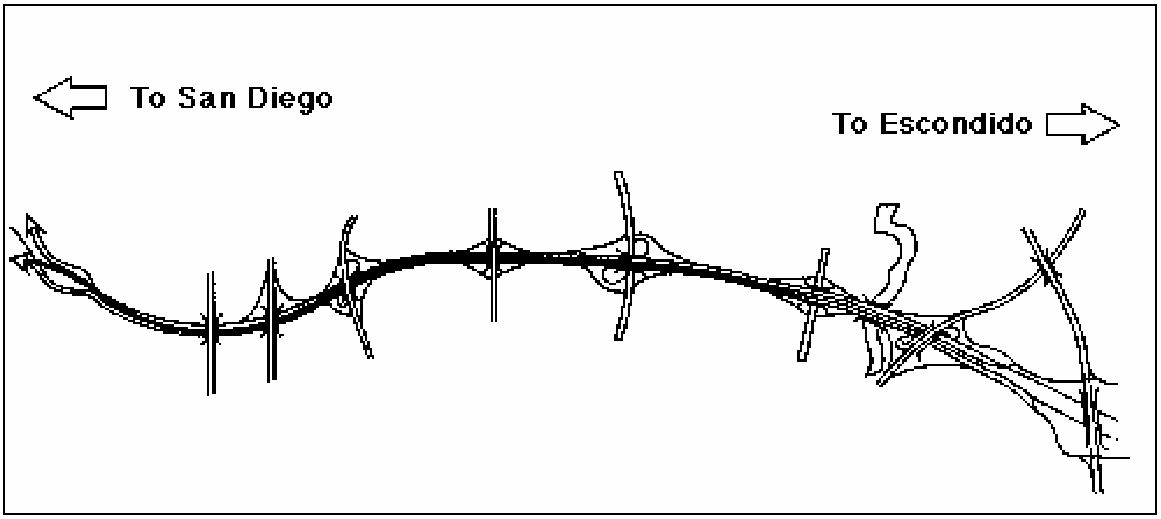


Figure 8-3: AHS Demonstration Site Layout

Vehicles Used

1. Infrastructure Diagnostic Vehicle (IDV):
   Vehicle Type: 1996 Chevrolet Lumina Minivan
   Occupants:
   (1) Operator
   (1) Narrator
   (2) Passengers
2. Obstacle Removal Vehicle (ORV):
   Vehicle Type: Volvo Xpeditor Truck
   Occupants:
   (1) Driver

Table 8-1: Approximate Scenario Timing

Time (min)	Activity
00 - 01	IDV departs staging area and accelerates to operating speed
00 - 01	IDV performs VRC diagnostic with results to TMC
00 - 01	IDV initiates marker diagnostic routine
01 - 02	IDV Operator detects road hazard, notifies TMC. IDV continues travel
02 - 04	ORV dispatched by TMC, travels to debris site
04 - 05	ORV retrieves road hazard, continues travel
06 - 07	IDV detects defective magnetic reference, notifies TMC
07 - 08	TMC logs defective magnetic reference for later repair
08 - 10	IDV exits system. Reinitializes subsystems as necessary
11 - 12	ORV exits system. Reinitializes subsystems as necessary
12 - 13	Safety factor

Magnet Anomaly Simulation

As part of the Maintenance Scenario in the NAHSC demonstration, it was desired to exhibit some infrastructure anomalies, particularly in the magnetic marker lateral reference system. After extensive consideration and negotiation among consortium members, a marker polarity coding error was selected as the anomaly to be detected. One major motivation for this choice is the ability to effectively simulate such an error through software, without the need to modify the infrastructure. Infrastructure modification was not an option, as the magnets were used by other scenarios for their lateral vehicle control. An additional benefit for this type of error is that it can be simulated in a manner so that the IDV's diagnostic software truly detects the error, without knowledge of the use of simulated data.

The algorithms used for polarity diagnostics are described in detail in Chapter 2. In essence, the system senses the incoming binary data stream generated by interpreting magnet polarities as ones and zeros, and compares this with the polarity table used to install the magnets. Note that the magnets were all installed with the correct polarity, as verified manually during the installation process. However, for the purposes of the demonstration, a few polarity bits were toggled in the table used by the Diagnostic Package. Thus, from the point of view of the DP, it appears that there are genuine polarity coding errors at these locations on the highway, while in fact the errors are actually intentionally introduced in the data table itself. In this way, the DP detects "true" errors in the infrastructure.

Results and User Feedback

The Maintenance Scenario passed certification for inclusion in the demonstration on July 12, 1997. During the following three weeks (July 17 - August 2), demonstration dry-runs and rehearsals occurred. In this time, the scenario, script, and displays were all refined in preparation for the demonstration. Additional user screens were developed to display diagnostic status and results.

The IDV executed more than 4,000 miles of automated travel in the period of test, development, and demonstration. Much of this automated mileage was, to quote Christine Johnson of the U.S. DOT, was "flawless." During this time, the diagnostic package algorithms were tested and refined, and were flawless by the time of the demonstration. In fact, the IDV magnetic marker diagnostic algorithm detected and logged the locations of the magnet installation errors. These locations were verified when Caltrans repaired and replaced these magnets.

The IDV was well-received by nearly all riders, both during dress rehearsals and during the actual demonstration. Rider demographics for the IDV were excellent, being spread among many nationalities, many federal and state government organizations, both genders, public and private sector, etc. Riders included several high-ranking members of the U.S. DOT FHWA, current and former members of congress, lobbyists in the transportation industry, and high-ranking corporate officials. A significant number of riders were from foreign countries, including Russia, the Netherlands, and particularly Japan. One Japanese rider from MITI was very intrigued by the IDV demonstration. This led to a visit to AHMCT by a Japanese congress composed of several universities, Ministry of Construction, Ministry of Trade, Nissan Motor Co, Mitsubishi Electric Corporation, Oki Electric Industry Co., the Japanese Highway Industry Development Organization (HIDO), Hitachi Cable, and the Association of Electronic Technology for Automobile Traffic and Driving (JSK). These organizations have expressed sincere interest in membership in the proposed AHMCT Industrial Consortium. In part based on participation in the IDV and the maintenance scenario, GM has also expressed interest in the Consortium.

AHMCT's participation in the NAHSC demonstration has also led to further opportunities for cooperative research efforts. Current work includes development of an Advanced Snowplow Driver Assistance System. This project includes subcontract with PATH and the Western Transportation Institute (WTI), as well as partnership with the Arizona DOT (ADOT). A projected follow-up phase, including full vehicle automation of a snowplow, is expected to lead to a multi-state partnership within a year. In addition, the current project generated opportunities in both the Intelligent Vehicle Initiative (IVI) and Intelligent Transportation Systems. IVI work will include various AHMCT technologies, including infrastructure diagnostics, collision warning systems, lane position and departure sensing, and driver assistance, a.k.a. vision enhancement. ITS work will be in the area of Advanced Construction and Maintenance (ACM) as applied to future transportation systems.

The IDV narrator conveyed the concept that the IDV would be used for diagnostics after an initial installation, after natural disasters, such as earthquakes, and at some regular interval, which would be determined statistically. A recurring theme in the questions and feedback from the riders in the IDV related to the required frequency of diagnostics. This is currently an open question requiring further research to determine. Issues include level of required reliability, tolerance of control systems for marker defects, anticipated marker failure rates, etc.

As part of the maintenance scenario, the ORV demonstrated the significant reduction of time required to remove obstacles and debris from the system. With easy identification of debris performed by the IDV operator, including a voice input of the debris type and GPS tag of location, the TMC can quickly dispatch the closest available ORV to the site. The ORV can remove the obstacle at low speed, without the operator leaving the vehicle, and with minimal disruption to the traveling public. Thus, the system can be returned to full functionality and safety in a much shorter time than would be possible using current manual operations.

In summary, the IDV and ORV demonstrate that the application of Advanced Construction and Maintenance (ACM) techniques, including on-the-fly inspection and debris removal, can greatly enhance the capability of an AHS, or other advanced transportation systems. The systems clearly demonstrate to the State and Federal DOT stakeholders that the overall cost of implementing such systems can be reduced through use of ACM. In fact, it is clear to many that successful and cost-effective deployment and operation of any infrastructure-based advanced transportation systems will require ACM.

CHAPTER 9

TEST RESULTS AND EVALUATION

Introduction

Most of the field testing and system integration of the IDV was performed on the I-15 HOV lanes in San Diego. However, some initial field tests and integration of the Diagnostic Package and the CPS were performed at Crow's Landing and the Golden Gate Fields parking lot. The automated vehicle control system, Diagnostic Package, CPS, and HMI were tested for limitations, robustness, consistency, and reliability. In addition, simulated failures of key control system components were used to test the effectiveness of the corresponding safety override procedures. Quick and accurate execution of the safety override procedures requires in-depth knowledge of the vehicle control system and its performance strengths and weaknesses. Because of this necessity, the IDV logged more than 150 hours of field tests on the I-15 HOV lane. Many passengers were taken for rides, and their feedback on the vehicle control, ride comfort, Diagnostic Package, and the HMI was incorporated to the improve the system. Giving rides to a variety of people proved extremely valuable. Several system weaknesses were identified and corrected early, leading to a successful demo.

The automated vehicle control system can be operated independently of the Diagnostic Package, HMI, and CPS. Attempts were made to improve the performance of the vision-based control system with vehicle lateral deviation data obtained from the magnetic markers. However, this effort was never fully implemented because of time limitations.

Many of the DP functions were tested in detail. Specifically, the socket communication from the Diagnostic Computer to the HMI and the serial communication link from the CPS to the Diagnostic computer were tested. In addition, error and performance data for the CPS were collected and analyzed and the code table used for the AHS construction was verified by experimental means. Finally, each diagnostic algorithm was tested individually, and then the whole package was tested as an integrated system. The Demo scenario was run repeatedly to determine system reliability.

Vehicle Control Performance

The IDV automatic control was acceptable for use in the demonstration. However, the system would require significant improvement, or complete revision, for a deployed maintenance vehicle. The specific vision-based control algorithm was not sufficiently robust in the highway environment. This deficiency stems from the genesis of the Road Follower algorithm as a DOD system meant to track a variety of roads at low speed. The system performance is acceptable for any trained road type, but is not exceptional in any conditions. It is strongly affected by geometric issues, such as vehicle pitch and roll. This is a common issue for vision-based vehicle control, but was exacerbated here because the IDV only "looked at" one lane edge. Without data for both lane lines, the system cannot distinguish vehicle pitch from lateral deviation. Other vision-based systems in the NAHSC demonstration performed more reliably, due to highway-specific lane-tracking algorithms, multiple cameras, and redundant lateral sensors. This problem must be addressed prior to deployment of this type of automated vehicle control system. Additional problems, including excessive motion of the steering wheel while under automatic control, were due mainly to hardware problems, which could be easily addressed given sufficient development time. Further details of the controller performance are discussed in Chapter 6, or can be obtained from Lockheed Martin Corporation.

Diagnostic Package Performance

The Diagnostic Package performed well and to our satisfaction. The communication and diagnostic modules work well together. The overall diagnostic success rate was about 95%. The current authors believed that the failure rate may not be reduced further without fundamental changes in hardware, along with associated software changes. The weakest link in the DP is the CPS unit. Transponder diagnostics and the marker diagnostic “auto-start function” relied heavily on the accuracy and precision of the CPS unit, which prove to be an unreliable system. Failure in any of the two routines is considered a failure in the diagnostic.

Communication Module Performance

The IDV communication module demonstrated excellent performance during the Demo. Unlike the other modules in the DP program, the communications module has relatively few evaluations to complete, so once the code was complete the module functions with equal facility in any situation. The program architecture was designed using sub-processes for all the communications functions so they would be completely independent of the diagnostic routine’s time-dependent process. This independence allowed the individual communications processes to function robustly without interfering with any of the other processes.

The only diagnostic communication process was the Transponder diagnostic routine. This routine functioned well at low speeds, around 10 mph, but had problems at higher speeds. The unreliability of the routine at high speeds was due not to a deficiency in the program, but rather to the high amount of radio frequency (RF) shielding material used in the IDV. Because of the shielding, the transponder signal was very difficult to pick up by the road-side antenna. This issue should not pose a problem in the future, as more robust instrumentation would reduce the need for RF shielding in the vehicle. Improvements in the transponder and roadside reader systems, as well as their placement, should also increase reliability.

Diagnostic Module Performance

Magnetic marker polarity diagnostic is one of the key diagnostic package features demonstrated in the Maintenance Scenario. To simulate polarity error, the correct code table used for the AHS lane construction was modified to inject errors into the table. Four polarity errors at different sections of the lane were injected into the code table. Table 9-1 shows the errors injected to the table. The marker indexing numbers are the same as those used in the construction of the AHS lanes. The marker polarity coding was also experimentally verified by data collection over several test runs. The DP polarity-checking feature works well. It consistently finds the 4 "simulated" errors in the northbound run. However, it failed to find the last "simulated" error in the southbound run 50% of the time. This minor partial failure was caused by the inability of vehicle automated control system to maintain the vehicle within the sensor range consistently in the section of the AHS facility where the last "simulated" error was located. Nevertheless, the polarity checking routine does not function without errors. Sometimes, the signal processing fails to differentiate embedded ferric objects (noise) from magnetic markers (signal), which causes an error in the marker index count. When such an error occurs in the middle of a coded section, the polarity-checking routine will usually flag a large amount of polarity errors. Otherwise, the diagnostic module can always find the "simulated" errors at the exact marker indices consistently.

	Marker Index #	**Original Polarity**	**Final Polarity**
Northbound Run	111640	0	1
East HOV Lane	10670	0	1
	10099	1	0
	8050	1	0
Southbound Run	9912	0	1
West HOV Lane	10087	1	0
	11779	0	1
	11880	1	0

Table 9-1: Simulated Polarity Error Injected

The DP auto-start feature is the least reliable DP function. It relies heavily on the accuracy and precision of the CPS unit. The CPS unit sometimes fails to provide vehicle position information within the error limit that the auto-start function can handle. The auto-start reliability rate varies from 90 to 95%. Possible remedies include increasing the differential update rate, replacing the DGPS unit with a carrier-phase DGPS unit, and having direct access to sensor data from the wheel encoder and gyros. Simply replacing the CPS with a well-designed integrated dead-reckoning and DGPS unit may solve the problem.

The current resolution of the diagnostic module in diagnosing marker field strength, lateral alignment, and longitudinal spacing is limited by the accuracy of the marker detection routine. A new analytical method of vehicle positioning based on triangulation may be developed to improve the accuracy of the marker detection. This approach does not require any calibration for different types of magnetic markers, and is less sensitive to variance in magnets and their installation. Furthermore, it allows exact determination of the marker strength. This new marker detection routine would allow the diagnostic module to differentiate good and bad markers if a stricter AHS system specification is imposed.

CHAPTER TEN

CONCLUSIONS AND FUTURE RESEARCH

As noted in Chapter 8, the IDV and ORV demonstrate that the application of Advanced Construction and Maintenance (ACM) techniques, including on-the-fly inspection and debris removal, can greatly enhance the safety, efficiency, and capability of an AHS, or other advanced transportation systems. The systems clearly demonstrate to critical State and Federal DOT stakeholders that the overall cost of implementing such systems can be reduced through use of ACM. In fact, it is clear that successful and cost-effective deployment and operation of any infrastructure-based advanced transportation systems will require ACM.

The IDV executed more than 4,000 miles of automated travel in the period of test, development, and demonstration. Much of this automated mileage was, to quote Christine Johnson of the U.S. DOT, was "flawless." The diagnostic package algorithms were flawless by the time of the demonstration. Participants in the IDV demonstration have expressed significant interest in the AHMCT center, including interest in participation in the AHMCT Industrial Consortium. The excellent results obtained in the NAHSC demonstration have also led to current and future cooperative research opportunities with various research organizations, State and Federal DOT, as well as national transportation societies. Exposure of the technologies developed by AHMCT have also increased national awareness of the need for Advanced Construction and Maintenance (ACM) technologies in support of current and future transportation systems.

Future research includes the need to identify the required frequency of infrastructure diagnostics. Issues include level of required reliability, tolerance of control systems for marker defects, anticipated marker failure rates, etc. Additional research on the lateral control of an IDV is also warranted. As in the current system, it is undesirable to rely on the infrastructure being diagnosed as a critical component in the vehicle control. However, the current vision-based controller suffered from some limitations, and more reliable control would be needed in a deployed system. In addition, the Automated Location and Tracking System, while conceptually very useful for this and other maintenance activities, was flawed in its implementation. With current improvements in GPS, GIS, and voice recognition technologies, a similar but more robust system could be developed, which would be of general use in highway maintenance. Similarly, the diagnostic data display screens were developed in a very rapid fashion using Java as a rapid prototyping environment. While the screens were visually appealing, they were not always functional, due to flaws in the currently available version of Java. It is now clear that Java was not sufficiently robust at the time of the demonstration, and that similar screen should be developed using a more well-established programming environment, ideally using C or C++. Finally, the communications architecture used in the IDV, while ideal for the current system, could be further developed to be a more general architecture for use in any advanced maintenance vehicle, or even as the communications architecture in general passenger vehicles.

APPENDIX

Diagnostic Package (DP) Computer Power Supply Specification.

The DP computer power supply connector is located at the rear of the computer. It is a 6 pin Amphenol 97-3102A-14S-6P. The mating connector should be Amphenol 97-3106A-14S-6S.

Pin Configuration:

Pin	**Voltage**
A	+ 12 VDC
B	- 12 VDC
C	+ 5 VDC
D	- 5 VDC
E	Ground / Return
F	Ground / Return

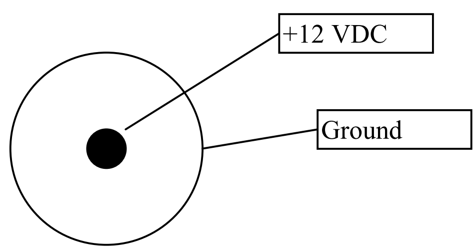
Each voltage supply is individually fuse protected with a 1¼" x ¼" fuse. Diagnostic LEDs are installed for trouble shooting purposes. Each voltage input has a corresponding column of green LED, fuse, and red LED. If the red LED located near the bottom is illuminated, the on/off switch has been turn on and there is power coming into the system. These diagnostic LEDs do not check if the voltage supply is correct. However, if the polarity is incorrect, the LEDs will not be illuminated. If the green LED located near the top is illuminated, power is being supplied to the computer system. If a red LED is on and the corresponding green LED is off, the fuse is probably burnt out.

Specifications of the Magnetometer Power Supply unit.

The magnetometer power supply unit serves two purposes. First, it converts +12 VDC to +/-15 VDC to the magnetometers. Second, it provides the A/D board with a ribbon cable interface with the proper pin-out.

The green LED illumination indicates proper function of the magnetometer power supply unit. Otherwise, the micro-fuse inside is most likely burnt out due to a short circuit or improper connection to the magnetometers.

The magnetometer power supply unit requires +12 VDC input. Location of the input connector is shown below. Note: the inside pole is +12 VDC and the outside is ground.



The connector at the end of the cable that runs to the magnetometer mount is an Amphenol 97-3102A-22-14S and the mating connector is Amphenol 97-3106A-22-14P. The connector on the magnetometer mount is 97-3102A-22-14P and the mating connector is 97-3106A-22-14S.

Pin configuration of cable between magnetometer power unit and magnetometer mount

	Magnetometer Power Unit 97-3102A-22-14S Pin	Magnetometer Mount 97-3102A-22-14P Pin
Pair 1 Data (Right Mag. X-axis) Ground	A (Green) B (Red)	A B
Pair 2 Data (Right Mag. Y-axis) Ground	C (Orange) D (Black)	C D
Pair 3 Data (Center Mag. X-axis) Ground	E (Brown) F (Black)	E F
Pair 4 Data (Center Mag. Y-axis) Ground	G (Yellow) H (Black)	G H
Pair 5 Data (Left Mag. X-axis) Ground	J (Green) K (Black)	J K
Pair 6 Data (Left Mag. Y-axis) Ground	L (Blue) M (Red)	L M
Pair 7 -15 Volt +15 Volt	N (White) P (Red)	N P
Pair 8 Data (Right Mag. Health) Ground/Return	R (Red) S (Black)	R S
Pair 9 Data (Center Mag. Health) Ground/Return	T (Blue) U (Black)	T U
Pair 10 Data (Left Mag. Health) Ground/Return	V (White) U (Black)	V U

Magnetometer Connector	Magnetometer Power Unit 97-3102A-22-14S Pin	A/D adapter 50 pin
Pair 1 Data (Right Mag. X-axis) (Pin E) Ground (Not connected at Mag)	A (Red) B (Orange)	3 1 & 2 are ground
Pair 2 Data (Right Mag. Y-axis) (Pin D) Ground (Not connected at Mag)	C (Yellow) D (Green)	5 1 / 2
Pair 3 Data (Center Mag. X-axis) (Pin E) Ground (Not connected at Mag)	E (Blue) F (Purple)	7 F
Pair 4 Data (Center Mag. Y-axis) (Pin D) Ground (Not connected at Mag)	G (Grey) H (White)	9 H
Pair 5 Data (Left Mag. X-axis) (Pin E) Ground (Not connected at Mag)	J (Black) K (Brown)	11 K
Pair 6 Data (Left Mag. Y-axis) (Pin D) Ground (Not connected at Mag)	L (Red) M (Orange)	13 M
Pair 7 -15 Volt (Pin K) +15 Volt (Pin H)	N (Yellow) P (Green)	N/A N/A
Pair 8 Data (Right Mag. Health) (Pin A) Ground/Return (Pin B & G)	R (Blue) S (Purple)	15 S
Pair 9 Data (Center Mag. Health) (Pin A) Ground/Return (Pin B & G)	T (Grey) U (White)	17 U
Pair 10 Data (Left Mag. Health) (Pin A) Ground/Return (Pin B & G)	V (Black) U (Brown)	4 U