California AHMCT Program
University of California at Davis
California Department of Transportation

DEVELOPMENT AND FIELD-TESTING OF A GPS-BASED MOUNTAIN PASS ROAD OPENING DRIVER ASSISTANCE SYSTEM*

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16. Abstract

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Abstract

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Disclaimer/Disclosure

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

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California, the Federal Highway Administration, or the University of California. This report does not constitute a standard, specification, or regulation.

Acronyms and Abbreviations

Acronyms used within this document are defined below.

2D	Two Dimensional
802.11x	Institute of Electrical and Electronics Engineers (IEEE) wireless LAN/WAN standards
8P8C	8 Position 8 Conductor
AHMCT	Advanced Highway Maintenance & Construction Technology
Caltrans	California State Department of Transportation
CD	Compact Disc
COG	Center Of Gravity
COTS	Commercial-off-the-shelf
CRC	Cyclic Redundancy Check
DAS	Driver Assistance System
DC	Direct Current
DGPS	Differential Global Positioning System
DOT	Department of Transportation
DRI	Division of Research and Innovation
DVD	Digital Video Disc
EIA	Electronic Industries Alliance
ESRI	Environmental Systems Research Institute
EU	European Union
GIS	Geographic Information System

GLONASS	GLObal NAvigation Satellite System
GMT	Greenwich Mean Time
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GUI	Graphical User Interface
HDOP	Horizontal Dilution of precision
HMI	Human-Machine Interface
HTTP	HyperText Transfer Protocol
IEEE	Institute of Electrical and Electronics Engineers
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
ITS-4	4th generation ITS technologies
ITS	Intelligent Transportation System
ITS	Intelligent Transportation Systems
LAN	Local Area Network
LCD	Liquid Crystal Display
MDSS	Maintenance Decision Support System
MPRO	Mountain Pass Road Opening Driver Assistance System
NMEA-0183	National Marine Electronics Association GPS communications standard
OEM	Original Equipment Manufacturer
OWL	Web Ontology Language
RDF	Resource Description Framework
RMS	Root Mean Square
RS-232	EIA serial communications standard
SBAS	Satellite Based Augmentation System
SHP	Shapefile

SOAP	Simple Object Access Protocol
SR	State Route
SRS	Software Requirements Specification
TAG	Technical Advisory Group
TNC	Threaded Neill-Concelman
UI	User Interface
USB	Universal Serial Bus
UTC	Universal Time Coordinated
W3C	World Wide Web Consortium
WAN	Wide Area Network
WGS-84	World Geodetic System 84
x86	Commodity Intel, AMD, and compatible microprocessors
XML	eXtensible Markup Language

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Chapter 1

Introduction

1.1 Document Purpose

This document summarizes and details a research project undertaken by the Advanced Highway Maintenance & Construction Technology (AHMCT) Research Center. The Mountain Pass Road Opening Driver Assistance System (MPRO) project was undertaken between May 2005 and December 2007 and was funded by the California State Department of Transportation (Caltrans) Division of Research and Innovation (DRI).

1.2 Definition of Engineering Problem

Caltrans has eight mountain passes that it closes over each winter season, due to large snow precipitation, and opens each spring[1]. These are: Ebbets Pass (SR 4), Monitor Pass (SR 89), Lassen Loop (SR 89), Sonora Pass (SR 108), Tioga Pass (SR 120), June Lake Loop (SR 158), Mammoth Lakes (SR 203), and Lake Sabrina to Aspendell (SR 168). These locations are shown in Google Earth in Figure 1.1 on the following page and in Google Maps in Figure 1.2 on page 3. Opening these passes in the spring is a difficult and dangerous job because of large snow accumulation over the entire winder season. It involves cutting the snow from the top down to the pavement using a small rotary snow blower driving on top of the snowpack. There are few visual indicators (e.g. terrain, snow stakes, trees) of road location, and over time some of these indicators may no longer be available (see Figure 1.3 on page 4)—e.g. due to mandates, snow stakes may not be replaced when they are damaged or destroyed. Generally, experienced operators lead the road-opening effort, and identify the first cut paths in the snow build-up based on their experience and local terrain features and landmarks. For experienced operators, it can be difficult to reliably and repeatably determine the roadway location. For less experienced operators, this

[1]For information on Caltrans winter pass closures see http://www.dot.ca.gov/hq/roadinfo/clsdlst.htm.

task is even more challenging and dangerous. If the rotary plow were steered off course, the vehicle could slide off a steep slope, sink into a creek bed, or damage the blower mechanism due to ingestion of rocks or running into rocks hidden in the snow along the roadside. Existing techniques include probing the snow pack with poles, path staking, and active embedded cable systems, which all have associated drawbacks.

Figure 1.1: Caltrans winter pass closures visualized in Google Earth. KML file available at http://hardhat.ahmct.ucdavis.edu/kml/passClosures.kmz

These annual road opening operations, while difficult and hazardous, are also essential for public safety, mobility, and tourism. In conjunction with Caltrans DRI and the Caltrans Winter Maintenance group, the Advanced Highway Maintenance & Construction Technology (AHMCT) Research Center developed a field-ready and deployable GPS-based mountain pass road-opening rotary plow DAS to guide rotary plow operators to drive and stay over the roadway during the road opening operation. Primary system objectives are increased safety and snow-removal efficiency with minimal capital investment, and decreased environmental impact and costs associated with infrastructure repair. The system was developed to be portable and easily installed, with a small number of units sharable across Statewide mountain pass opening operations. Field-testing was completed under a related project in the spring of 2007 and results indicate the system is ready for widespread use within Caltrans Winter Maintenance Operations. Results also indicate promising benefits for deployment on a wider basis for other functional types of Caltrans vehicles.

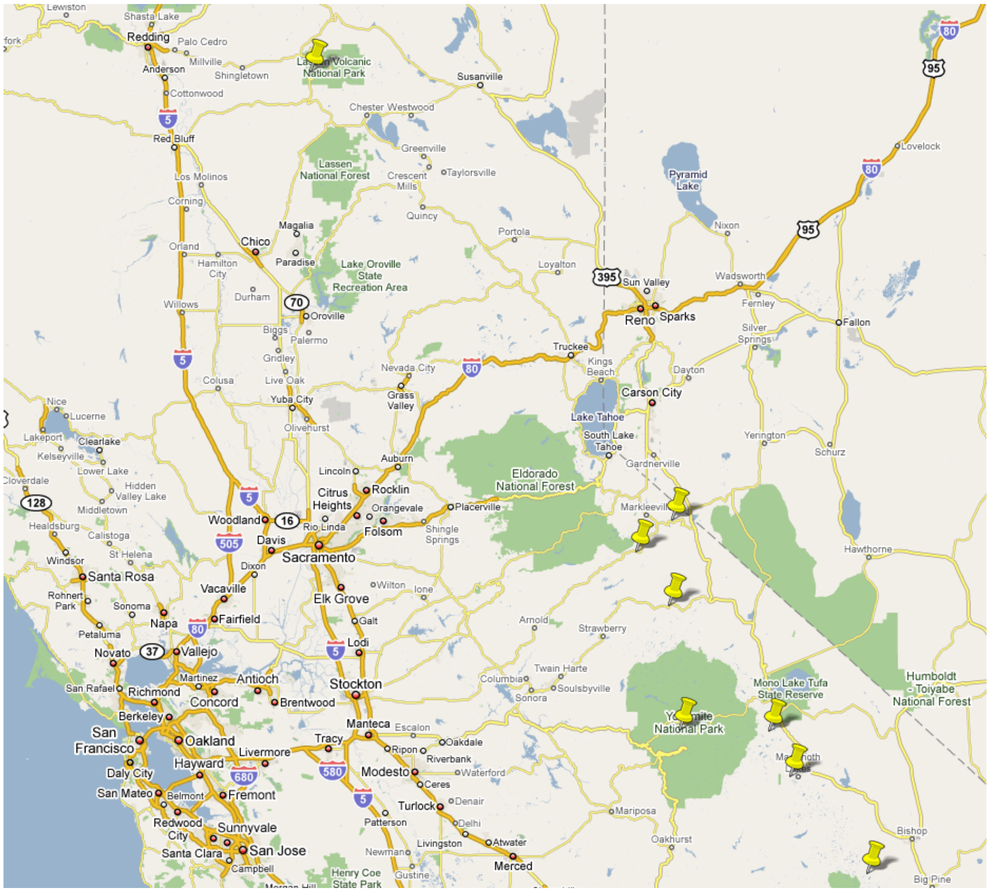

Figure 1.2: Caltrans winter pass closures visualized in Google Maps. Live map available at maps.google.com/maps?q=hardhat.ahmct.ucdavis.edu/kml/passClosures.kmz

1.3 Previous Work in Area

The winter road-opening DAS fits within a larger winter maintenance context. The background information summarized below shaped MPRO requirements (pg. 17) and design (pg. 31). Other methods have been used to locate snow-buried roadways. These are typically infrastructure-based methods. An infrastructure based approach was previously installed by Caltrans on Sonora Pass along SR 108 east of Long Barn, CA. It used an active embedded cable system to assist operators in locating the roadway [9]. With this system, at the start of the opening operation, the crew must dig through the deep snow to locate the cable access point in order to energize the system. Subsequently, Caltrans operators, usually on snowmobiles or on foot, use a cable sensor to determine road location relative to the cable, and mark out a path with stakes. Sometimes there is delay between this marking operation and the subsequent road clearing. On occasion, these markers have been vandalized or removed by recreational snowmobile users, reintroducing uncertainty into the operation.

Most areas have no such system available, leaving the operators to find the road

Figure 1.3: Terrain surrounding SR 108 prior to road-opening operations. Note the single snow stake marking road location.

through their own devices. Techniques include probing the snow with poles and staking a path, or simply relying on operator familiarity with the terrain. Some in Caltrans and other Department of Transportations (DOTs) have expressed reservations over any infrastructure-based approach for vehicle guidance. Fundamentally, infrastructure-based approaches are by nature more constrained in terms of wide-scale deployment due to the costs (money, time, road closures) of installation and maintenance (e.g. broken cable), and typically are also hardware-intensive and demanding in terms of vehicle instrumentation.

In a 1992 Caltrans study by Winter and Caudle [9], GPS was considered and rejected due to technical limitations, with the caveat that "future developments may change this perception." Recent developments have resulted in substantial improvements in accuracy and the availability of alternative methods to obtain differential corrections (see Figure 1.7 on page 8 and Figures 1.8, 1.9 and 1.10).

Land vehicle positioning systems have been developed for variety of applications, including navigation, intelligent vehicle systems, and agricultural and construction machine guidance and controls [2]. Kalman filter-integrated GPS/INS systems are widely used as the primary positioning system for land vehicle positioning systems—this may be augmented by other auxiliary sensors such as digital magnetic compasses, odometers, speed sensors, and vehicle wheel encoders. In many situations, a simple bicycle vehicle model and nonholonomic lateral and longitudinal motion constraints can also be used to improve system accuracy and robustness. These approaches may not work well for rotary snow blowers because their low dynamic, slow moving speed (less that 0.1 m/s) on

Figure 1.4: Rotary plow operating over the roadway during mountain pass opening

a mix of slippery snow and ice. The nonholonomic constraints do not apply in the case of high slip which typically occurs on the snow surface. Hence, wheel encoders or odometry would provide very little performance improvement. The low vehicle dynamics reduces the effectiveness of any low-cost Inertial Measurement Unit (IMU). The Inertial Navigation System (INS) system would effectively be integrating mainly sensor noise and bias. To provide adequate information to guide the rotary plow operator, the internal positioning system must provide vehicle position and orientation. Unlike many other ground vehicles, rotary plow travel direction can be significantly different from (nearly independent of) its orientation because of its independent front and rear steering system. The system design must also consider installation time, complexity, and cost, since the final system is intended to be installed in the field with minimal disruption to normal road opening operation. For example, instrumenting the front and rear steering angles would significantly increase the installation time, and impact the complexity and maintainability of the system in a harsh operating environment. The positioning system will have to be integrated with the control software and a Geographic Information System (GIS) database to provide real-time in-cab information to keep the rotary plow above the road surface.

The novel approach used within the MPRO project applies precision GPS technology for absolute location using longitude, latitude, and altitude in World Geodetic System 84 (WGS-84). To provide maximum system portability and minimal site requirements, the system uses a Satellite Based Augmentation System (SBAS) to provide differential corrections for the GPS solution; as such, the system as implemented does require SBAS

Figure 1.5: Mountain pass opening near completion

subscription service, and Caltrans will need to maintain an annual license for each MPRO system it operates. Associated sensors, control software, and a GIS database are used to provide a real-time in-cab mountain pass road-opening system for rotary plow driver assistance. The complete system horizontal accuracy (decimeter-level) is more than sufficient for the task of positioning the rotary plow accurately above the road (see Figure 1.7 on page 8).

1.4 Trends Within the Research Area

Trends within the research area are crucial because they provide insight into future research directions and provide an indication of future component capabilities and costs.

1.4.1 System Engineering and ITS Trends

Trends are driven by a number of sources. Semiconductor process technology continues to lower power requirements, reduce chip size, and double processor performance about every 18 months. This is simultaneously pushing four trends referred to as 4th generation ITS technologies (ITS-4) [8]:

- Commoditization of sensors

Figure 1.6: Back-country terrain

- Commoditization of processors
- Commoditization of communication
- Decentralization of processing intelligence

These are combined to produce real-time results. Commoditization of software is also a key trend [1].

1.4.2 GPS Hardware Trends

Within the Global Navigation Satellite System (GNSS) domain, a number of trends have been identified related to GPS hardware [6]. These trends are consistent with project goals:

- Continued reduction in size, power consumption and cost of receivers.
- Improved reliability, higher sampling rates, lower-noise observations, better multipath-resistance, all digital processing.
- Decreased cost, especially for middle-tier GPS receivers.

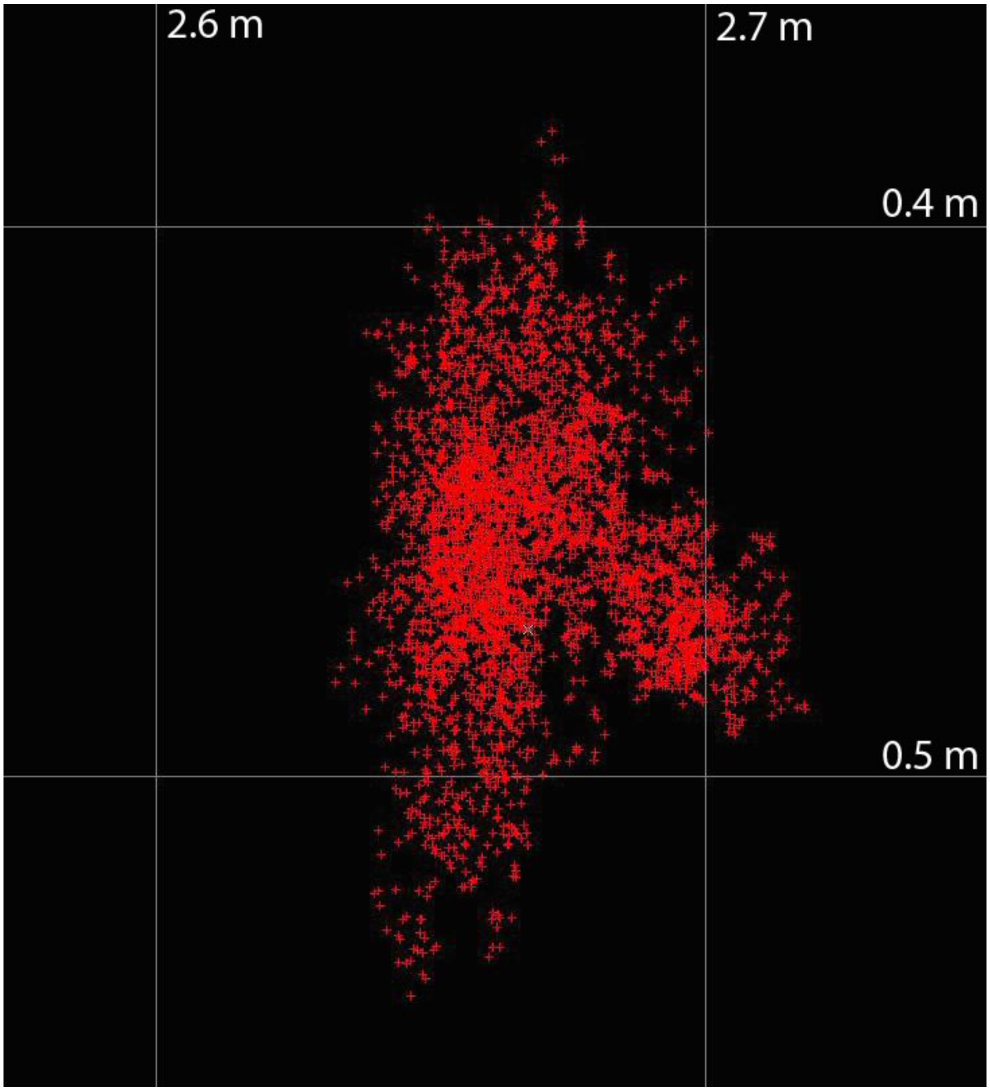

Figure 1.7: Static OmniSTAR HP SBAS Differential Global Positioning System (DGPS) test result in Northern California

- Increased accuracy and reduced latency for kinematic positioning.
- Increased GPS receiver computing power.
- Real-time operation becoming standard across applications.
- Combined GNSS operation of GPS, the European Union (EU) Galileo system, and the Russian GLObal NAvigation Satellite System (GLONASS) system.
- Increased integration of GPS into hardware systems used for navigation and surveying.
- Increased use of Original Equipment Manufacturer (OEM) receivers within products.

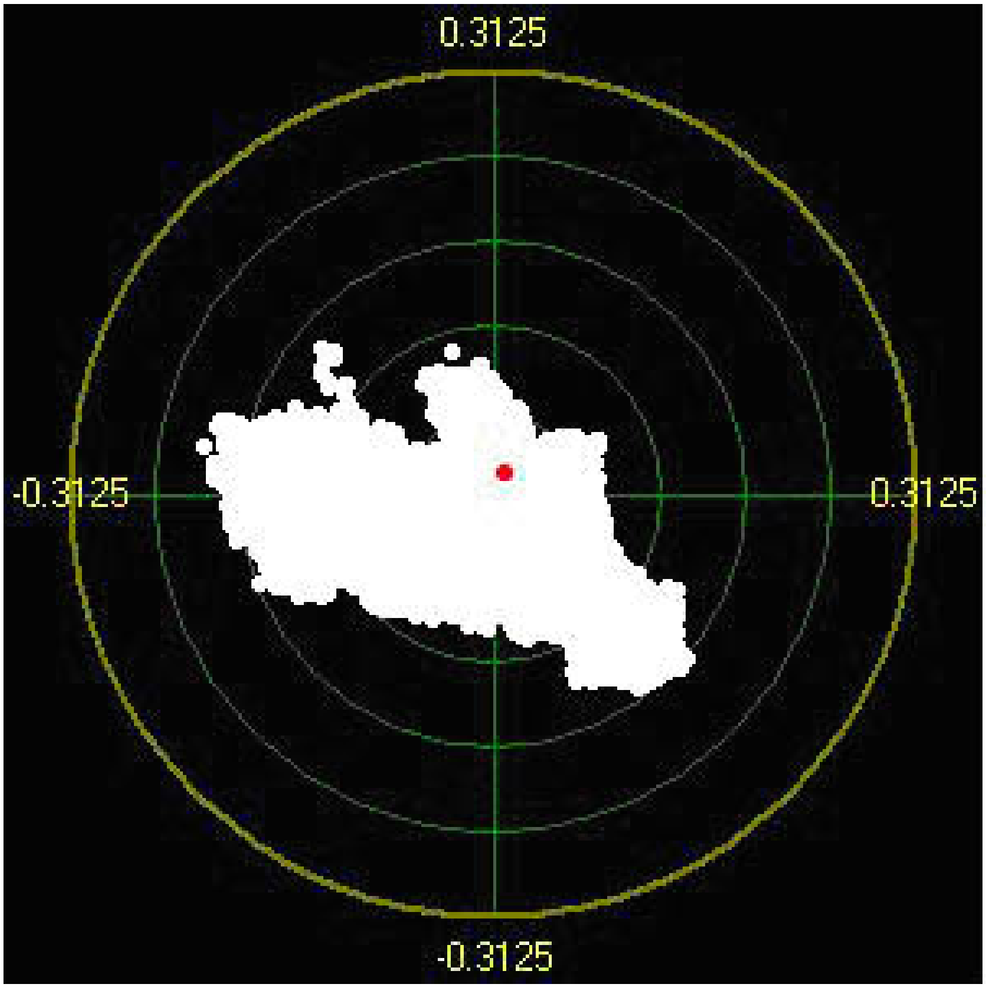

Figure 1.8: Static NavCom StarFire SBAS DGPS test result in Northern California (in meters)

- Improved antennas with decreased multipath susceptibility.

1.4.3 GPS Software Trends

Several trends have been identified related to GPS software [6].

- Increased availability of software for precise navigation and GIS.
- Increased availability of software for special applications.
- Increasing availability of receiver-independent software.
- Increasing use of INS products.
- Increased integration with GPS-associated software such as GIS.

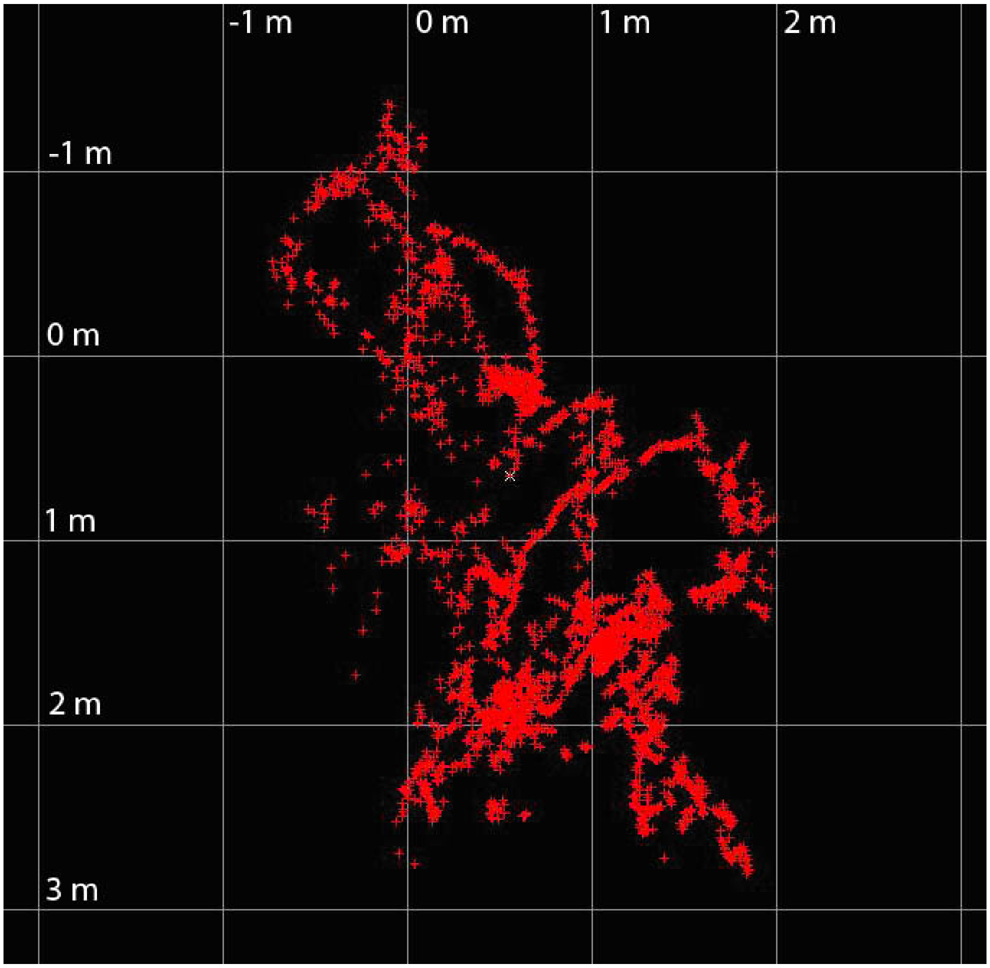

Figure 1.9: Static WAAS DGPS test result in Northern California

1.5 Research Tasks and Progression

Project development is summarized in the tasks in this section. Software development used an evolutionary linear process model, which iteratively followed the sequence of: requirements definition, design, development, and testing [5]. Caltrans Maintenance personnel and management were consulted during each task. Regular meetings were used to discuss project status.

1.5.1 Task 1: Refine functional requirements and system specifications

Functional requirements and system specifications were developed and refined, incorporating updated Caltrans operator and management input. The defined requirements were used to define hardware and software specifications. An initial meeting was held with Caltrans to facilitate requirements identification for mountain pass road-opening. The proof-of-concept prototype developed previously was reviewed and areas for im-

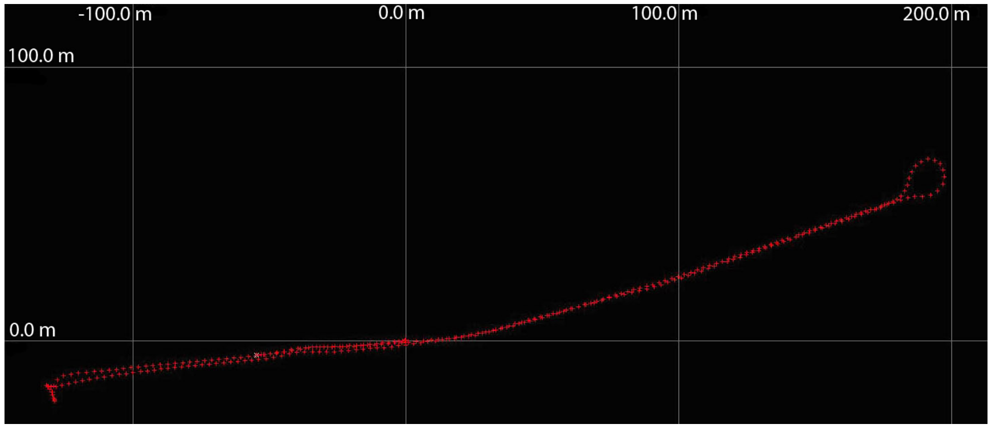

Figure 1.10: Dynamic test result of OmniSTAR SBAS DGPS at Kingvale, California

provement were identified. The definition of the vehicle reference path is also included in these requirements.

1.5.2 Task 2: Enhance and ruggedize portable hardware for ease of installation

In this task the prototype field-installable pass opening hardware was ruggedized and field-readiness was improved. Hardware enhancements identified in Task1 were implemented. The goal is a portable unit that is easily installable on-site for various types of snow blower, in the maintenance yard or in the field. The end result is a ruggedized system ready for wide-scale use by Caltrans, that can be shared among sites and districts for pass opening, yielding a high benefit/cost ratio. Field testing in the Spring of 2006 and 2007 was performed and used as a basis for software and hardware refinement.

1.5.3 Task 3: Refine software for HMI and sensing systems

This task focused on refining the first-generation system software. The software is primarily concerned with the HMI and sensing systems. The HMI was designed to maximize ease-of-use and the clarity of operator presented information. Feedback from Caltrans was incorporated. Field testing was also used to refine the software.

1.5.4 Task 4: Operator training, field demonstration, and field testing

In this task operator training, field demonstration, and field testing were performed. Testing involved unit and integration testing following the developed test plan. Lab testing proceeded field testing. Field testing was performed in conjunction with Caltrans road

Figure 1.11: Back-country terrain

opening schedule for SR 108. Field test results were analyzed. Based on testing, the feasibility of targeting development for additional systems was evaluated.

1.5.5 Task 5: High-accuracy survey updates for test site

Roadway location data at the test site along SR 108 was collected and integrated into the system's GIS. Requirements for the reference path were determined with respect to relevant roadway features. The researchers worked with the Caltrans Office of Land Surveys to develop the reference path.

1.5.6 Task 6: Design reviews

This task performed design reviews using data collected from discussions with Caltrans, training, field testing, and field demonstration. Associated requirements were reviewed and validated. Caltrans management (DRI, Maintenance, Equipment) and operators were involved.

Figure 1.12: Back-country terrain

1.5.7 Task 7: System documentation and final report

This final report and other documentation are the result of this task.

1.6 Deliverables

Project deliverables include:

- Portable road-opening hardware
- Road-opening sensing and in-vehicle HMI software (executable and source code)
- Test plan, results, and analysis (Section 5 on page 45)
- Deployment plan
- System documentation for deployment within the DOT operational framework
- This final report which includes:
  - Test results and analysis (Section 5 on page 45)

Figure 1.13: Back-country terrain that often has 30 feet or more of spring snow cover

- System installation instructions (Appendix A on page 55)
- Usage instructions (Appendix B on page 61)
- Training documentation (Appendix C on page 63)

1.7 Document Scope

This document was developed by the researchers using project documentation, research reports, software and hardware specifications, software development documentation, field and laboratory data, testing, and the guidance and information gained through collaboration with Caltrans management (DRI, Maintenance, Equipment) and operators.

1.8 Summary of Report

Chapter 2 details the project's context, requirements, and goals. The resulting design and architecture are covered in Chapter 3. The system hardware and software implementation structure, languages, libraries, and screenshots are discussed in Chapter 4. Laboratory and field testing are detailed in Chapter 5. Finally, conclusions, analysis, and future work

Figure 1.14: Roadside obstacles

are discussed in chapter 6 on page 51. Appendix A on page 55 details system installation instructions. Appendix B on page 61 details system usage instructions. Appendix C on page 63 contains system training documentation.

Chapter 2

Requirements and Goals

2.1 Introduction

This chapter discusses MPRO (a.k.a. the ”System”) requirements and goals. Requirements defined here are used in the subsequent design and implementation phases. In general, this chapter follows the IEEE SRS standard 830-1998 [4].

2.1.1 Chapter Purpose

This chapter defines MPRO features and functions which are used in the subsequent design, implementation, and testing phases. The intended audience includes: system developers, engineers, project management, the Technical Advisory Group (TAG), Caltrans management and engineers, and other DOT personnel and management.

2.1.2 Product Scope

The requirements defined in this chapter are for a single product referred to here as MPRO. A System architecture block diagram is shown in Figure 2.1 on the following page. MPRO is a mountain pass road-opening Driver Assistance System (DAS) that can be easily installed within Caltrans rotary snow plows. MPRO is a hardware and software system that provides snowplow drives with real-time information including:

- Roadway location
- Roadway orientation relative to absolute north
- Snow blower location relative to the road
- Snow blower heading relative to absolute north

- Snow blower elevation above road
- Post-mile location

Primary System goals are increased safety for road-opening operations, increased snow-removal efficiency, decreased costs associated with infrastructure repair, and thus decreased environmental impact. The System should be portable, and easy to install on various snow blower designs, enabling a small number of units to be shared across Caltrans operations, improving the efficiency and safety of Statewide pass opening operations with minimal capital investment.

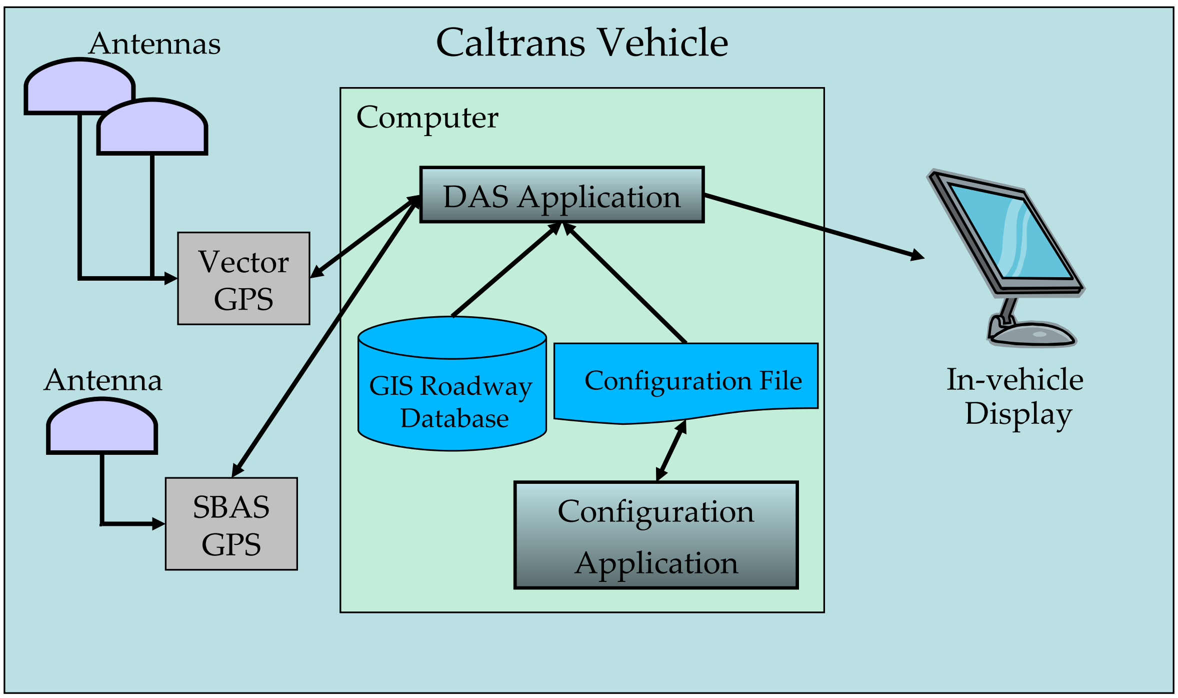

Figure 2.1: MPRO architecture

2.1.3 Definitions, Acronyms, and Abbreviations

MPRO-specific terms are defined here. General acronyms are defined on page ??.

- Customer: the entity providing project funding.
- Supplier: the entity providing the product for the customer.
- User: the entity interacting with MPRO directly.
- Functionality: what the System does.

- External interfaces: System interfaces for people, System hardware, other hardware, and other software.
- Performance: System speed, availability, response time, recovery time, etc.
- Attributes: System attributes such as portability, correctness, maintainability, security, etc.
- Design constraints: outside constraints imposed on the System such as required standards, implementation language constraints, policies, resource limits, operating environment limits, etc.
- Snow blower: a rotary snow blowing vehicle used by Caltrans for mountain pass road-opening operations (see Figure 1.4 on page 5).

2.1.4 SRS References

The following documents are relevant for this chapter. See the References section on page 53 for further background material.

- IEEE Recommended Practice for Software Requirements Specifications, IEEE Std 830-1998 [4].
- Implementing the IEEE Software Engineering Standards [7].

2.1.5 Chapter Overview

Section 2.2 provides background information relevant to requirements definition. Section 2.3 on page 23 defines MPRO functionality, primarily in terms of functional and non-functional requirements. Requirements are grouped by category and numbered for reference elsewhere in the document.

2.2 Overall MPRO Description

This section provides background information that shaped requirements. Requirements are defined in the subsequent section (Section 2.3 on page 23).

2.2.1 Product Perspective

This subsection places MPRO into perspective with related products. The system block diagram is shown on 2.1 on the preceding page. MPRO is largely a self-contained product. Specific constraints and interfaces are discussed below:

User Interfaces

MPRO will be used by Caltrans snow blower operators. The DAS application requires no ongoing user interaction from the operator. Map zoom-in and zoom-out keys are provided for the operator. The DAS application will start when the vehicle is started and automatically shutdown when the vehicle is turned off. Satellite acquisition can take approximately two minutes at start-up–the system will be available for use following acquisition.

Hardware Interfaces

MPRO uses commodity hardware and is designed to be relatively easy to install and move between different vehicles. Installation hardware consists of the GPS antenna bar and a hardware box containing two GPS receivers and a computer. The System requires a 12-Volt Direct Current (DC) power supply. See Appendix A on page 55 for installation instructions. Existing and future sensors interface to the computer using commodity hardware interfaces such as EIA serial communications standard (RS-232), Universal Serial Bus (USB), or other standard interfaces.

Software Interfaces

The DAS application interfaces with a GIS database, which contains high-resolution roadway position information. The Environmental Systems Research Institute (ESRI) Shapefile (SHP) file format is used to store the roadway position information. An eXtensible Markup Language (XML) configuration file is used to specify System options and is created and edited using a System configuration application. For internal interfaces see the Implementation chapter (pg. 37).

Communications Interfaces

For software installation and maintenance purposes the System may have a standard Ethernet 8 Position 8 Conductor (8P8C) modular jack or IEEE wireless LAN/WAN standards (802.11x) capabilities. No communication interfaces are used for typical operation.

Memory

The in-vehicle computers use commodity x86 hardware, persistent storage devices, and memory. The DAS application requires 1 GB RAM minimum.

Operations

Normal operation of the DAS will be automatic and require very little (if any) ongoing user intervention. The System will use standard commodity software and hardware. Start-up and shutdown will be initiated by the vehicle power system. Satellite acquisition can take approximately two minutes at start-up–the system will be available for use following acquisition.

Site Adaptation Requirements

MPRO is not expected to require adaptation of the winter maintenance yard. The system as implemented does require SBAS subscription service–Caltrans will need to maintain an annual license for each MPRO system it operates. For System installation within vehicles, see Appendix A on page 55.

2.2.2 Product Functions

System functionality can be decomposed into broad categories classified by actor:

- Functionality used by the snow blower operator:
  - The System will start automatically when the snow blower engine is started.
  - The System will shutdown automatically when the snow blower engine is turned off.
  - The System will have an in-vehicle Liquid Crystal Display (LCD) display visible to the operator.
  - The System will depict a Two Dimensional (2D) top-down view of the snow blower in the middle of the screen.
  - The System will depict the position of the roadway relative to the vehicle.
  - The System will depict the vehicle in the operator's frame of reference.
  - The System will have an on-screen compass in degrees indicating which direction relative to absolute north the front of vehicle is pointing (front to rear).
  - The System will have on-screen status indicators that indicate the health of the sensors, computer, and overall system.
- Functionality used to configure, install, and maintain the System:
  - The System will have a configuration application that can be used to specify configuration options.
  - The System will store configuration options in a file which is used by the DAS application at load time.

  - The System will have networking or USB capabilities for loading new software and operating system updates.
  - The System will have application logging capability for tracking and diagnosis of serious error conditions.
  - The System will have the capability of loading new roadway maps for operation in new areas and additional roadways.
  - The System will be relatively easy to install in vehicles.

2.2.3 User Characteristics

MPRO users may require up to one hour of training.

2.2.4 Constraints

Constraints that might impact development options include:

- The capabilities of commodity sensor hardware such as GPS receivers and antennas.
- The speed, power consumption, reliability, and storage capacity of commodity computer systems.
- The physically demanding environment that the rotary snow blower operates in, with extremes in temperature, moisture, vibration, and shock.

2.2.5 Assumptions and Dependencies

Changes in the following assumptions and dependencies may effect the requirements specified in Section 2.3 on the facing page.

- A GPS system will be used for determining real-time vehicle position and orientation.
- Position accuracy provided by the GPS hardware.
- GPS signal interference from natural landmarks such as mountains, trees, and valleys.
- GPS signal interference from man-made landmarks such as overpasses, power lines, etc.
- The accuracy of the roadway GIS database.

- Ongoing System maintenance provided by the customer. For example, dual-antenna GPS heading accuracy highly depends on accurate GPS antenna separation.
- The physical security of System hardware (e.g. the computer, GPS antennas, etc.) installed on the vehicle is assumed to be provided.

2.3 Specific Requirements

This section lists functional and non-functional requirements, which are used in the subsequent design and implementation.

2.3.1 External Interface Requirements

This section specifies nonfunctional requirements specific to System interfaces with the outside world. The outside world includes existing external systems which are used by MPRO and future systems which would be desirable to integrate with MPRO.

User Interface Requirements

Requirement 1: The in-vehicle LCD screen contents shall be visible in bright sunlight conditions.

Requirement 2: Software application ease-of-use is an important non-functional requirement and positively impacts initial and ongoing costs, including training. The DAS application will be easy to use, requiring little if any user attendance.

Requirement 3: The System shall, to the extent possible, use a consistent and common User Interface (UI).

Requirement 4: The System UI shall be designed for an operator using the DAS as a secondary navigation assistance device, with the operator typically glancing at the DAS screen briefly.

Requirement 5: The user is not expected to use a keyboard or pointing device as part of normal system operation.

Hardware Interface Requirements

Requirement 6: Hardware interfaces with sensors shall use standards common to Commodity Intel, AMD, and compatible microprocessors (x86) hardware, such as RS-232, USB, Ethernet, etc.

Software Interface Requirements

Requirement 7: MPRO will use public standards such as XML, Simple Object Access Protocol (SOAP), Resource Description Framework (RDF), Web Ontology Language (OWL), HyperText Transfer Protocol (HTTP), to store data wherever possible.

Communications Interface Requirements

Requirement 8: To the extent possible, existing sensor standards shall be used. For example, National Marine Electronics Association GPS communications standard (NMEA-0183) for communication with GPS devices.

2.3.2 Functional Requirements

All System functional requirements are stated in this section. Functional requirements are intended to be testable as stated.

Functional User Interface Requirements

Requirement 9: The System shall use local time for display purposes.

Requirement 10: The System shall have an in-vehicle LCD display visible to the operator.

Requirement 11: The System shall use a status indicator to depict when system response time is larger than 100 ms (warning) and 250 ms (system unavailable).

Functional DAS Software Requirements, Depiction

Requirement 12: The System shall depict a 2D top-down view of the snow blower in the middle of the screen.

Requirement 13: The System shall depict the position of the roadway relative to the vehicle.

Requirement 14: The System shall depict the vehicle in the operator's frame of reference.

Requirement 15: The System shall depict an on-screen compass in degrees indicating which direction relative to absolute north the front of vehicle is pointing (front to rear).

Requirement 16: The System shall depict sensor and application health with on-screen status indicators.

Requirement 17: The System shall depict the calculated height of the vehicle above the roadway surface (in feet).

Requirement 18: The System shall depict the current calculated highway mile post.

Requirement 19: The System shall depict and distinguish between the front and rear of the vehicle.

Requirement 20: The System shall depict the specified GPS antenna location on the vehicle as a point.

Requirement 21: The System shall depict the location of the center of the vehicle as a point.

Requirement 22: The System shall accurately depict the vehicle moving slowly forward and in reverse.

Functional DAS Software Requirements

Requirement 23: The System shall be capable of receiving GPS position updates at 10 Hz.

Requirement 24: The System shall be capable of receiving vehicle heading updates at 10 Hz.

Requirement 25: The System shall have the ability to display real-time GPS diagnostic information while executing, such as: bytes received, time, number of satellites, Horizontal Dilution of precision (HDOP), differential mode, NMEA-0183 Cyclic Redundancy Check (CRC) parity failures, etc.

Requirement 26: The System shall have the ability to collect and store real-time sensor and system data for later playback and simulation in the laboratory environment.

Requirement 27: The System shall store simulation data (see R26) in the World Wide Web Consortium (W3C) XML file format.

Requirement 28: The System shall have the ability to synchronize the System's computer clock with GPS satellite clocks.

Requirement 29: The System shall support any number of sensor drivers, which are used to interface with existing and future hardware sensors.

Functional Software Configuration Requirements

Requirement 30: The System shall have a configuration application that is used to specify configuration options.

Requirement 31: The System shall store configuration options in a file which is used by the DAS application at load time.

Requirement 32: The System shall be configured so the operator does not need to change configuration options as part of normal operation.

Requirement 33: The System configuration file shall use XML syntax.

Requirement 34: The System shall have networking or USB capabilities for loading new software and operating system updates.

Requirement 35: The System shall have application logging capability for tracking and diagnosis of serious error conditions.

Requirement 36: The System's Configuration application shall allow specification of: agency name, vehicle name, heading source, vehicle dimensions (width, length, Center Of Gravity (COG), GPS antenna position)).

Requirement 37: The System configuration application shall include specification of various sensors attached to the System's computer via hardware drivers.

Requirement 38: The System configuration application shall include specific configuration options for each hardware sensor and associated device specific parameters.

Requirement 39: The System configuration application shall include specification of map layers.

Requirement 40: The System configuration application shall provide the capability of verifying that multiple sensors are not specified as using a single RS-232 communication port number.

Requirement 41: The System configuration application shall provide the capability of specifying multiple GPS and other sensors for simultaneous real-time use.

Functional Software Installation Requirements

Requirement 42: The System software shall install into a single directory.

Functional Hardware Requirements

Requirement 43: The system shall use a GPS receiver for determining vehicle position.

Requirement 44: The GPS hardware shall have maximum standard deviation as follows: latitude 50 cm, longitude 50 cm, altitude 1 m.

Requirement 45: The LCD shall be mounted inside the vehicle cab and not susceptible to noticeable movement due to bumping, vehicle vibration, vehicle shock, and vehicle collision with roadside obstacles encountered during normal operations.

Functional Hardware Installation Requirements

Requirement 46: The System hardware shall use the vehicle's 12-Volt DC power system.

Functional Security Requirements

Requirement 47: The System shall not be connected to a data network as part of normal operations.

Requirement 48: The System's computer's operating system shall be configured to be "locked down" so that files may not be deleted, software installed, etc.

Requirement 49: The System's computer's operating system shall be configured to use access control and passwords and logins as appropriate for the agency deploying the System.

Requirement 50: As part of normal operations, the System shall not allow the operator to connect the system to a data network.

Functional GIS and Map Requirements

Requirement 51: The System GIS shall support spatial queries by distance.

Requirement 52: The System shall have the capability of using new roadway maps that are installed onto the System's computer in the accepted formats (see R53).

Requirement 53: The System GIS shall read maps in the ESRI SHP file format.

Requirement 54: The System shall respond to real-time map queries in less than 100 milliseconds.

Requirement 55: The System shall have the capability to depict relevant map features (e.g. roadway edges, lanes, guard rails, etc.) using points and lines.

Requirement 56: System map accuracy of roadway features (e.g. road edge, lane edge) shall have a mean error of less than 20 cm.

Requirement 57: System map accuracy of non-roadway features (e.g. guard rails, trees, signs, etc.) shall have a mean error of less than 50 cm.

2.3.3 Performance Requirements

Requirement 58: Commercial-off-the-shelf (COTS) hardware, especially commodity hardware, shall be used wherever possible so that System costs (initial and ongoing) are minimized.

Requirement 59: COTS software, especially commodity and open-source software, shall be used wherever possible so that System costs (initial and ongoing) are minimized.

Requirement 60: The system shall depict vehicle heading with enough stability so the operator has reasonable confidence in the system representation of vehicle position.

Requirement 61: System hardware is expected to operate in the physically demanding environment of the rotary snow blower, with extremes in temperature, moisture, vibration, and shock.

2.3.4 Logical Database Requirements

None.

2.3.5 Design Constraints

Requirement 62: The system requires the use of a GPS and associated antennas.

Requirement 63: The System shall be designed with standard software engineering practices.

Standards Compliance

Requirement 64: To the extent possible, existing standards shall be used. For example, NMEA-0183 for communication with GPS devices, and W3C XML for data file formats.

2.3.6 Software System Attributes

Requirement 65: System software code shall be internally documented with comments.

Requirement 66: System software code shall be internally decomposed into modules, classes, and properties.

Reliability

Requirement 67: The System shall internally use Universal Time Coordinated (UTC) / Greenwich Mean Time (GMT) to represent time.

Requirement 68: GPS NMEA-0183 messages shall use CRC parity checking.

Availability

Requirement 69: The installed hardware and software system will operate with little or no user intervention, to the extent possible.

Requirement 70: The System shall start automatically when the snow blower engine is started.

Requirement 71: The System shall shutdown automatically when the snow blower engine is turned off.

Security

Requirement 72: In a production environment, the System design and implementation will prevent it from being disabled either accidentally or intentionally.

Requirement 73: The physical security of System hardware installed on the vehicle are assumed to be provided by the customer/user.

Maintainability

Requirement 74: The System will be implemented using higher-level languages and standard software engineering practices.

Requirement 75: The System shall be implemented in English.

Portability

Requirement 76: To the extent possible, the software system shall be implemented to be portable across operating system platforms. This may not always be possible due to performance and cost trade-offs.

Requirement 77: To the extent possible, the hardware system shall be implemented to be portable and shareable across various vehicles.

Requirement 78: To the extent possible, the hardware system shall be implemented to be easy to install in various vehicles.

2.3.7 Other Requirements

None.

Chapter 3

Design and Architecture

The design uses Caltrans-specified requirements to create a blueprint for the implementation. Specific requirements are referenced where appropriate (e.g. R1). The general design approach was to specify a prototype system based on a general framework, here tailored to mountain pass road-opening. The design evolved from an earlier-generation prototype. The implementation of the design is discussed in the next chapter.

3.1 Architectural Design

Relationships between major hardware and software structural elements are discussed in this section.

3.1.1 Hardware

Packaging

Major hardware elements to be packaged are:

- System computer
- GPS receivers
- GPS antennas
- LCD display

The system cabling includes low-loss GPS co-axial antenna cable and analog video cable to the LCD.

Relevant requirements are: R6, R61, R69, R70, R71, R73, R77, and R78. Based on these requirements, the GPS receivers and computer were packaged together into a single installable box. The System box was mounted on a platform attached to a display boom arm (see Figure 4.2 on page 40, Figure 4.3 on page 41). The GPS antennas were mounted onto a single antenna bar (see Figure 4.4 on page 42, Figure 4.8 on page 44).

Vehicle Heading Components

Determination of vehicle heading is a crucial system function in this application. Relevant requirements include R13, R14, R15, R19, R22, R24, and R60. An initial design combining a magnetic compass, GPS track, and software algorithms was discarded for a number of reasons including magnetic interference, difficulty in distinguishing between forward and reverse vehicle motion (R22), and GPS position variation at slow speeds. A satisfactory solution was found using a dedicated dual-antenna GPS that provides true heading in addition to vehicle track.

3.1.2 Software

In the broadest sense, the system collects data from sensors, synthesizes the data, and presents it visually to the operator. Major software elements are:

1. The DAS application
    - Sensor drivers
    - Simultaneous communication with sensors
    - DAS display
        - Compass control
        - Height bar control
        - Status lights control
        - Map control
    - Data synthesis
2. The DAS configuration application
3. The DAS configuration file

3.2 Interface Design

3.2.1 Human Machine Interface

The operator is expected to use the DAS as a secondary navigation device. Relevant requirements are: R2, R3, R4, R5, R70, and R71. Little or no keyboard or pointing device use is necessary, minimizing any distraction from using the system.

3.2.2 Interface Between Components

Interfaces between software components are between binary Microsoft .Net modules. Interfaces between hardware components use commodity hardware standards (R6). The interface between the vehicle and DAS system is a 12-Volt DC power supply (R46).

3.3 Application Level Design

MPRO consists of two applications with specific functionality:

- MPROApp: responsible for reading the configuration file, interfacing with in-vehicle sensors, initializing the sensors, collecting the sensor data, synthesizing data, and presenting the DAS UI to the operator.
- MPROConfigApp: responsible for reading and writing the DAS configuration file.

3.4 Library Design

Shared modules containing class definitions, implementations, interfaces, and static methods are used by both system applications. Shared modules correspond to architectural elements (see Section 3.1.2 on the preceding page). Modules which share functionality among applications and between modules within each application are also used.

3.5 Data-Level Design

An object-oriented design was used (see Figures 3.1–3.3). Small-grained classes are defined for physical quantities such as: Angle, Speed, and Temperature. Container classes are also used such as Sensors, which is a group of Sensor objects. Class hierarchies are used, e.g. starting with the base class: Sensor, SerialDevice, GPS, NovAtel. In general, containment is preferred over deep hierarchies. The system design supports the addition of any number of sensors, and specialization of existing sensors (R29). The following class hierarchies are used:

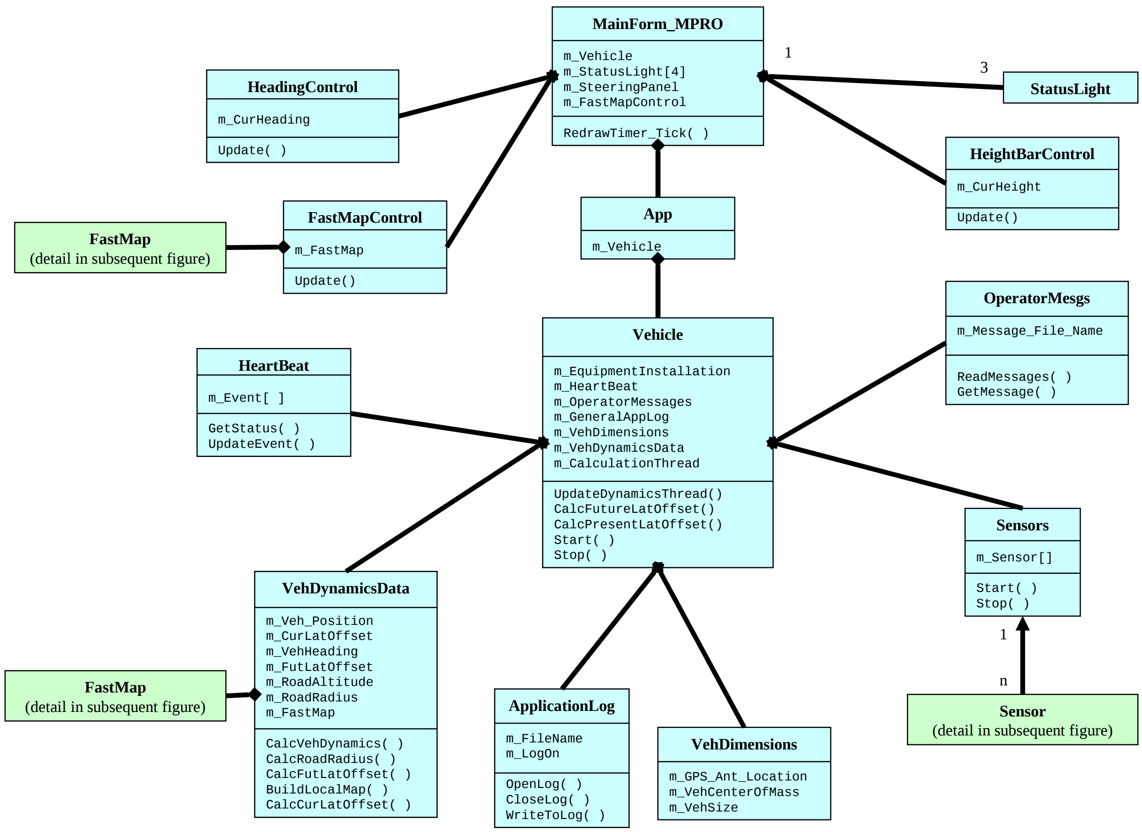

Figure 3.1: MPRO top-level class diagram

- Sensors: this hierarchy represents the relationships between sensor drivers from the general to specific. Classes are: Sensor, SerialDevice, GPS, NovAtel, and Vector.
- Mapping elements: this hierarchy represents relationships between shapes in the DAS mapping module. Classes are: Shape, Point, Rectangle, Line, Polygon, and Circle.
- Mapping layers: this hierarchy represents classes within a single map. Classes are: Layer, LayerTree, and LayerArray.
- Vehicle: this hierarchy describes a general Vehicle class, which contains all sensors and physical vehicle properties. The specific capabilities of the rotary snowplow vehicle are represented in the subclass VehicleMPRO.

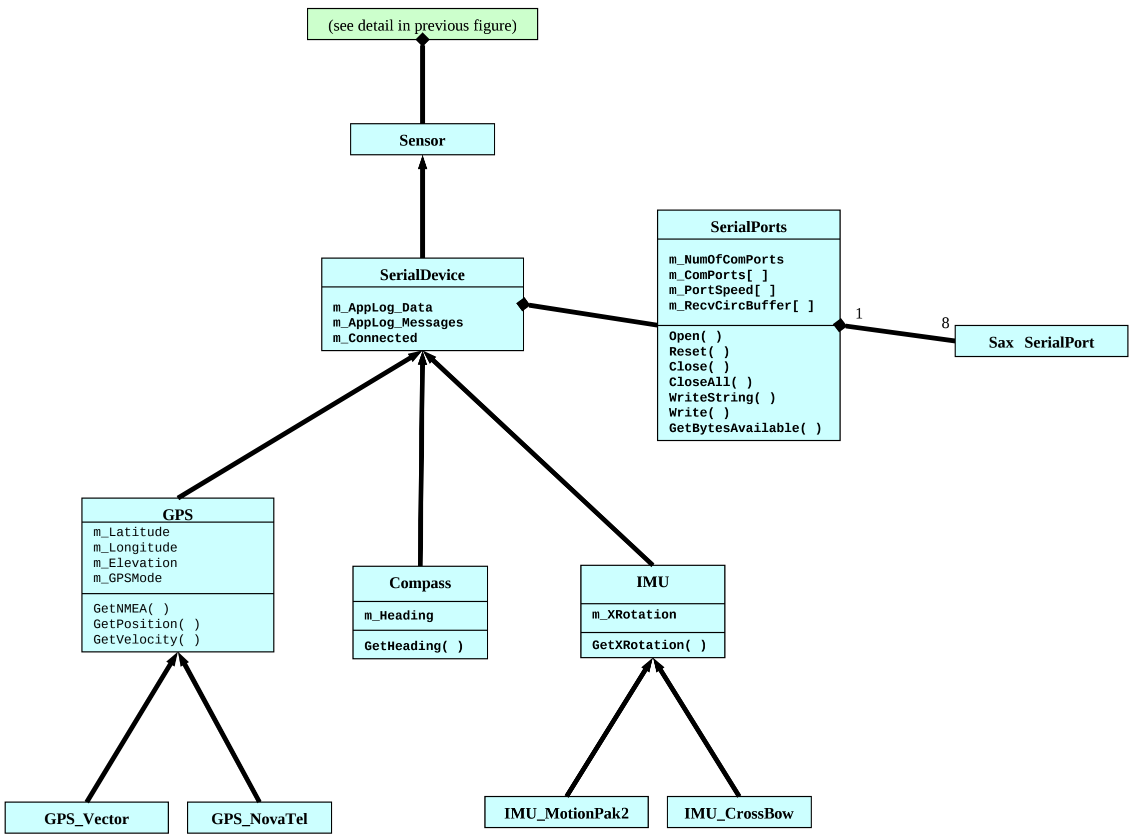

Figure 3.2: Sensor class diagram

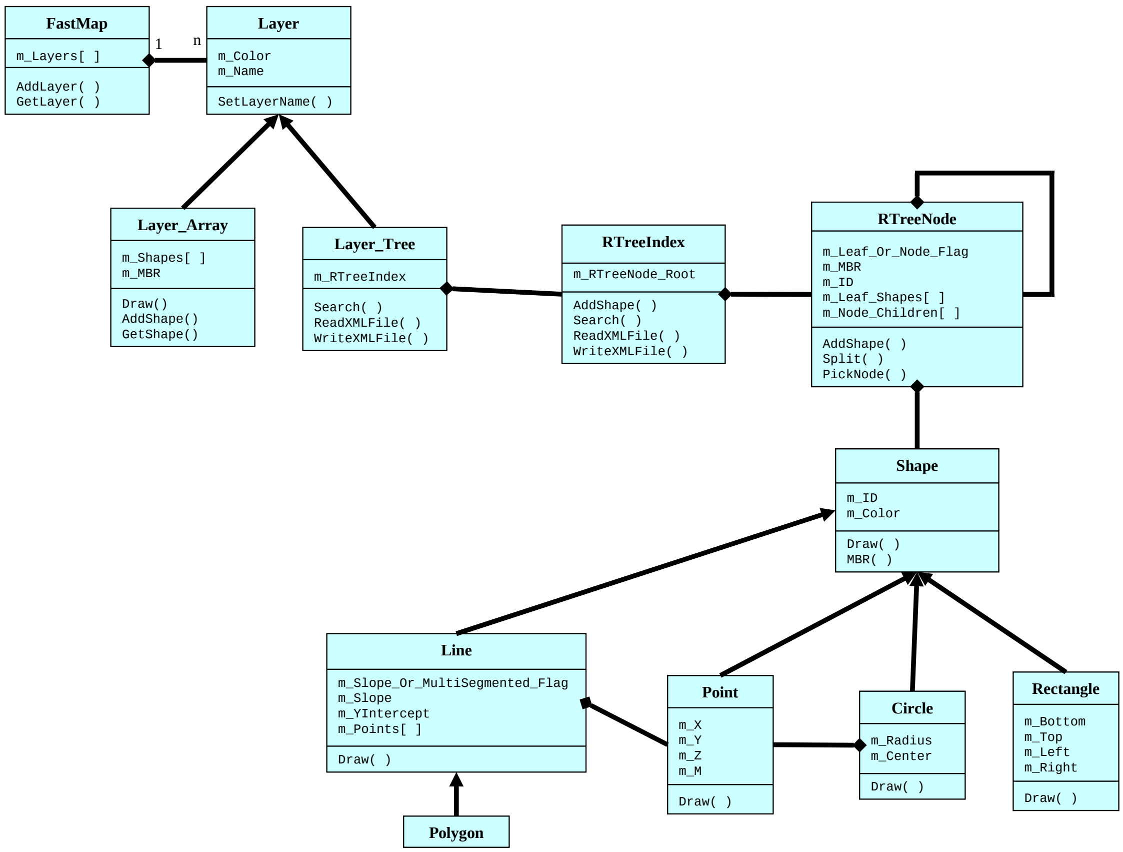

Figure 3.3: FastMap class diagram

Chapter 4

Implementation

The implementation executes the design and fulfills specified requirements. The implementation consists of software and hardware components installed within a Caltrans rotary snowplow (Figure 4.1). MPRO uses commodity hardware and software (R58, R59).

Figure 4.1: Caltrans rotary snow plow used for road opening operations

4.1 Hardware

MPRO hardware is responsible for:

- Providing sensor data to software applications.
- Executing DAS software applications.
- Displaying driver assistance information for the operator.

All hardware (Table 4.1) is installed within the snowplow. This includes sensors, the System box and display (Figure 4.2 on page 40), and antenna bar (Figure 4.4 on page 42, Figure 4.8 on page 44). The System box contains the computer (Figure 4.3 on page 41), GPS receiver for position, and GPS receiver for heading. The GPS receivers and computer are connected using RS-232 serial communication. The GPS protocol is the National Marine Electronics Association GPS communications standard (NMEA-0183) with an 8-bit CRC to verify message integrity. Model numbers are shown in Table 4.2 on the facing page. NovAtel[1] and Hemisphere[2] GPS receivers were used, along with OmniSTAR XP SBAS service for decimeter-level corrections.

Table 4.1: Implementation hardware

#	Hardware	Location	Description
1	GPS Receiver 1	System box	Position sensor, NMEA-0183 compatible
2	GPS Receiver 2	System box	Heading sensor, NMEA-0183 compatible
3	Computer	System box	Runs DAS applications, connected to sensors
4	System box	Cab	Contains GPS receivers and computer
5	LCD screen	Cab	Displays running DAS application
6	LCD arm	Cab	Holds LCD in a fixed position
7	GPS antenna 1	Roof	Antenna for GPS 1
8	GPS antenna 2, 3	Roof	Antennas for GPS 2
9	GPS antenna bar	Roof	Mounting point for GPS antennas 1, 2, 3

4.2 Software

MPRO is implemented using custom-developed software and off-the-shelf commodity software libraries. Together, these applications:

- Read data from sensors installed in the vehicle.

[1]For NovAtel see http://www.novatel.com
[2]For Hemisphere GPS see http://www.hemispheregps.com

- Synthesize sensor data.
- Present a unified on-screen depiction of the vehicle and roadway.
- Provide a Graphical User Interface (GUI) system configuration utility.

4.2.1 Off-the-Shelf Software

Off-the-shelf software packages were used wherever possible. These packages execute on the x86 hardware specified above.

- Application development libraries:
  - Sax.Net CommStudio: this communications library was used to communicate with sensor hardware via RS-232 within the custom-developed C++ and C# applications.
  - ESRI's MapObjects 2.1: this GIS library was used within the custom-developed C++ and C# applications.
  - Microsoft .Net library, version 1.1.
- Operating system:
  - Microsoft Windows XP SP2 was used for the in-vehicle operating system.
- Procedural languages and platforms:
  - Microsoft's Visual Studio 2003 with C# and C++ were used on the Windows XP platform.

Table 4.2: Implementation hardware details

#	Hardware	Model	Manufacturer
1	GPS Receiver 1	OEM-4 ProPack-LB-HP	NovAtel Inc.
2	GPS Receiver 2	Crescent Vector	Hemisphere GPS Inc.
3	Computer	MB890	IBASE
4	LCD screen	Tflex-G212P	Argonaut
5	LCD arm	RAM-VB-122-SW1	Ram Mount Co.
6	GPS 1 antenna	GPS-600-LB	NovAtel Inc.
7	GPS 2 antenna	CDA-3RTK	Hemisphere GPS Inc.
8	GPS antenna bar	Custom	AHMCT
9	System box	Custom	AHMCT

Figure 4.2: LCD, and System box containing computer and GPS receivers

4.2.2 Custom-Developed Software

Custom software applications and shared modules were developed, consisting of approximately 31,000 lines of code.

Applications

The following custom applications were developed in a combination of C++ and C#:

- MPROApp: the primary DAS application (see Figure 4.5 on page 43). It reads the DAS configuration file, initializes sensors, reads real-time data from sensors, synthesizes data, and provides the DAS user interface. Configuration data is read from an XML file on start-up. The application is written in C#.
- MPROConfigApp: enables editing of the associated XML configuration file which is used to specify sensor communication details, directory locations, and other configuration data (see figures 4.6 on page 43 and 4.7 on page 44). The application is written in C#.

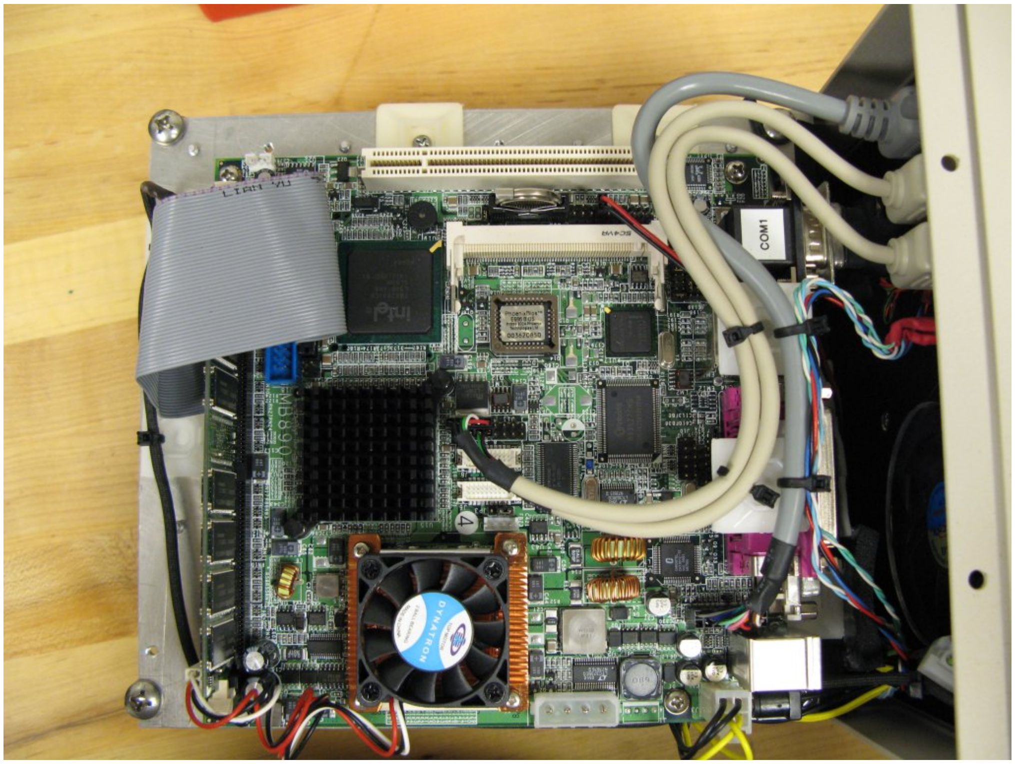

Figure 4.3: System main board, commodity hardware

Shared Modules

Sharable modules are used by DAS applications and were developed in C++ and C#, providing common access to functionality between applications and between modules within a single application.

- App: root Application class and functionality.
- Common: this library contains classes and static methods common to all applications. Example common classes include: Angle, AngleFilter, AppLog, CircularByteBuffer, ConfigFile, Contract, Filter, HeartBeat, MinMaxDouble, PositionFilter, Registry, SignalFilter, Speed, Temperature, among others. Many of these classes contain their own unit test methods.
- FastMap: 2D mapping functionality.
- HeightbarControl: height above pavement visual control.
- MPROLib: functionality common to MPRO modules.
- Sensor: sensor classes, including the base class and derived classes specific to each hardware sensor, e.g. the Vector GPS. This was implemented in C#.
- SensorCPP: sensors implemented in C++.

Figure 4.4: GPS antenna bar

- Sensors: sensor container class.
- SmallHeadingControl: heading visual control.
- StatusLight: status light visual control.
- Vehicle: base vehicle class.
- VehicleMPRO: derived Vehicle class with functionality specific to MPRO.

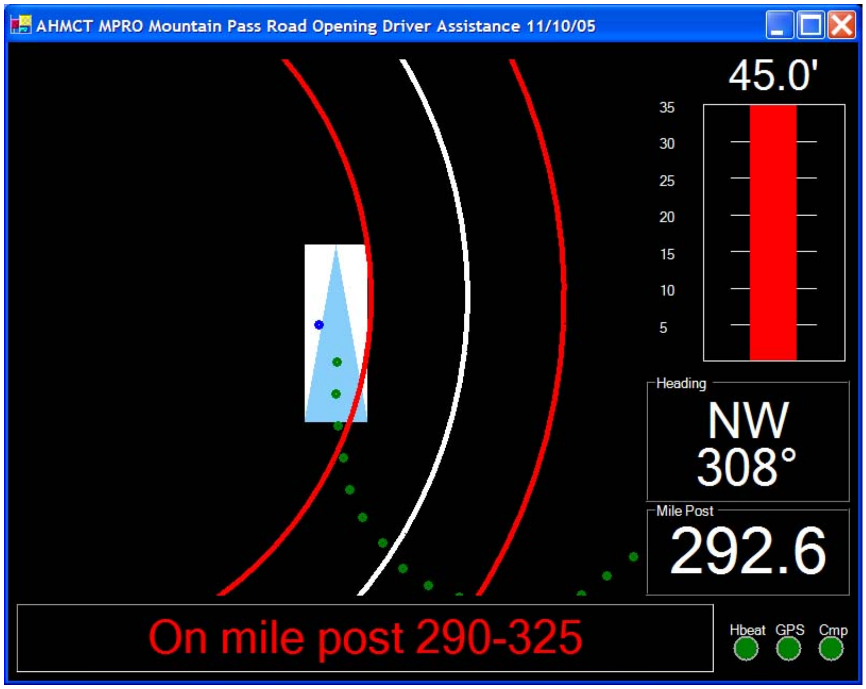

Figure 4.5: DAS application system screenshot

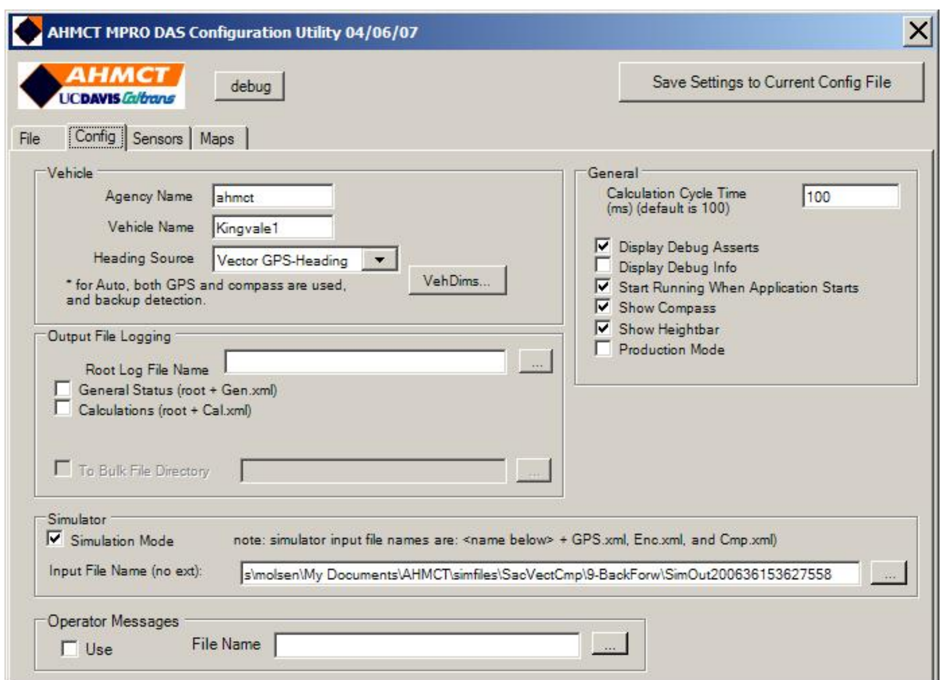

Figure 4.6: DAS configuration application screenshot

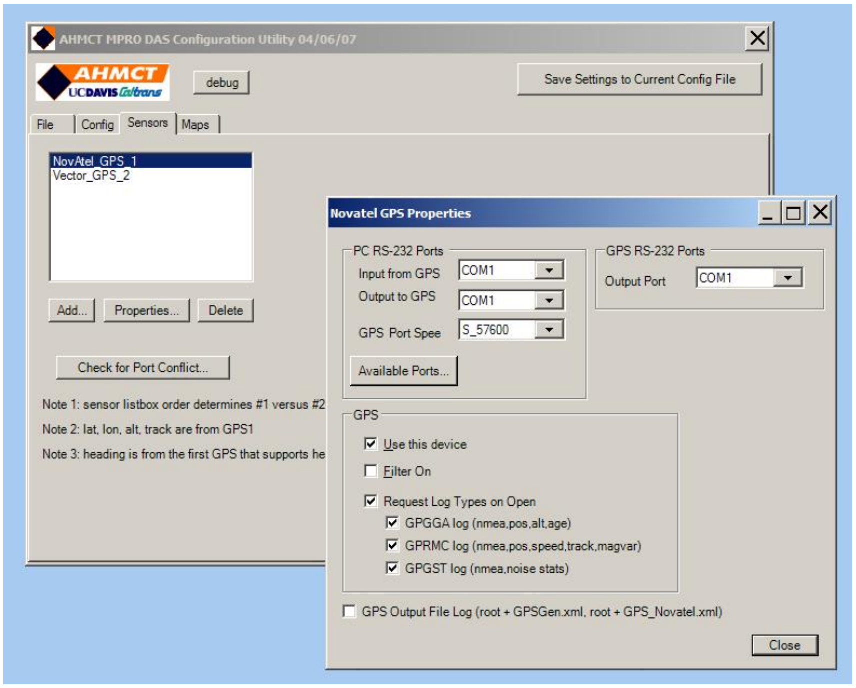

Figure 4.7: DAS configuration application screenshot

Figure 4.8: Caltrans rotary snow blower with GPS antenna bar

Chapter 5

System Testing

Testing consisted of laboratory testing and field-operational testing (Figure 5.1). Essential to testing was the ability of the system to capture real-time sensor data to files, for later simulation in the laboratory (R26, R27). This capability was used to collect in-field sensor data and for subsequent defect investigation and removal in the laboratory. The simulation capability was also used for regression testing of existing functionality as new functionality was added. The overall testing goal was to verify functional (testable) requirements.

Figure 5.1: System installation showing driver's view during testing

Example condition pseudocode fragment for design-by-contract:

```
double SignalFilter(int order)
{
   // preconds
   Contract.Verify("SignalFilter.pre.1",order>0);
   // method code here
   // postconds
   Contract.Verify("SignalFilter.post.1",retval>=0);
   Contract.Verify("SignalFilter.post.2",retval<100);
   return(retval);
}
```

Example unit test cases for the method SwitchEastNorth() in the Angle class:

```
// SwitchEastNorth
Contract.Verify("SwitchEastNorth.1",Angle.SwitchEastNorth(0)==.25);
Contract.Verify("SwitchEastNorth.2",Angle.SwitchEastNorth(.25)==0);
Contract.Verify("SwitchEastNorth.3",Angle.SwitchEastNorth(4)==-3.75);
```

Figure 5.2: Example condition pseudocode for design-by-contract, and example unit test cases for Angle class method

5.1 Laboratory Testing

Laboratory testing was used during development while new functionality was being developed. Laboratory testing typically progressed using unit, integration, and system testing, repeated iteratively.

5.1.1 Unit Testing

Software unit testing, the primary form of software testing used here, was performed during development as new functionality was developed, and applied test cases and *ad hoc* manual verification to test specific methods, classes, and modules. In general, the design-by-contract approach was used during development. Precondition and postcondition statements were used extensively throughout the code. Invariant statements were also used. Contract and invariant failures were logged during program execution. This facilitated detection of anomalous conditions in the code base much closer to the source of the problem, rather than as a side effect somewhere else in the code. An example precondition and postcondition pseudo-code fragment is shown in Figure 5.2; here, the precondition is verifying that the argument to the method SignalFilter is larger than zero. Figure 5.2 also shows example unit test cases for the method SwitchEastNorth() in the Angle class.

5.1.2 System Integration Testing

Laboratory integration testing was performed during development and following development completion. This involved testing at the application level, typically running specific simulation cases and visually verifying the behavior of the applications. Some test cases were developed for integration testing. System testing in the laboratory involved the hardware sensors (GPS), antennas, computer, and DAS applications. The MPRO system was installed in an AHMCT test vehicle. Sensor data was captured for later laboratory simulation, iteration, and defect removal. Integration testing was done at the application level, typically running specific simulation cases and visually verifying the behavior of the software applications. Some test cases were developed for integration testing. A number of scenarios were tested: slow-speed turns, system position accuracy relative to fixed known roadway locations, slow backing and turning, and longer distance roadway tests.

Testing of the GPS-based orientation sensor was performed by mounting the dual GPS antennas on a beam which was then rotated. Testing of the heading subsystem was particularly important (see Figure 5.3 on the next page). System performance due to tree canopy interference was assessed, both for positional and heading accuracy. Heading accuracy of the Vector GPS is specified as 0.15 degrees (Root Mean Square (RMS)) at 0.5 m antenna separation [3]. This accuracy was informally verified during field testing. The larger the antenna separation, the higher the accuracy of the heading solution. However, this also increases the time to achieve heading solution after lost of GPS satellite signal, and decreases solution availability and reliability, due to the need for ambiguity resolution. Here, an 0.8 m antenna separation was selected for a balance of accuracy, solution reliability, and availability. Three SBAS services (NavCom StarFire, OmniSTAR HP and XP) with corresponding GPS receivers were tested for their performance and decimeter-level accuracy confirmation. A site survey was performed by driving the road opening route with SBAS GPS to confirm SBAS signal availability while simultaneously mapping the roadway.

5.2 Field-Operational Testing

In the Spring of 2007 and 2008, the System was installed and tested in a Caltrans rotary snow blower (Figure 5.4 on page 49). System testing was performed both on-road and above-road on top of the snow. Testing under a wide range of circumstances was a goal. During testing, an AHMCT development engineer would ride along with the rotary plow operators during the road opening operation to observe the operation and system performance as well as gathering operator feedback on the system. The effects of GPS satellite signal blockage due to trees and terrain was examined. Future field testing will compare the system's position and orientation solution with a solution provided by a recently-purchased Novatel **SPAN!** (**SPAN!**) GPS/INS and Inertial Explorer post-processing software.

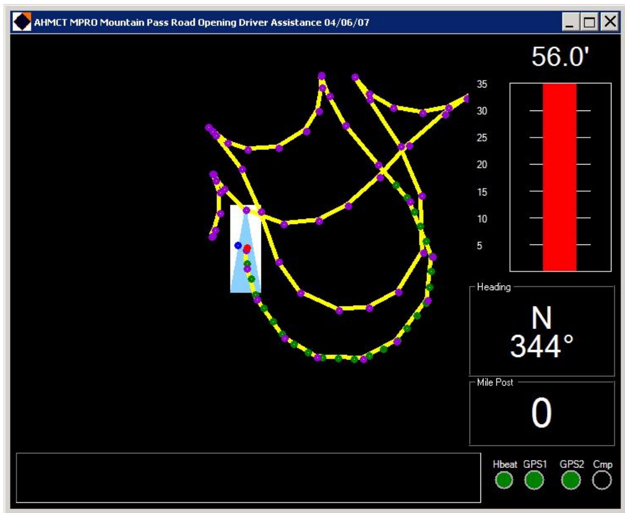

Figure 5.3: On-road testing of the heading subsystem, including backing maneuvers

5.3 Operator Feedback

Operator feedback was generally positive. Over several years' testing, the system was easily integrated into a variety of snow-blower cabs without interference with the equipment operation or the operator's visibility. Thus the system meets the "do no harm" criteria. The white snow and sunlight created a bright background that can produce significant glare on the LCD. Various LCD models were tested. The current high-brightness LCD model can be easily viewed under such challenging conditions. It is fairly compact, so it does not obstruct the operator's field of view.

Users found the information on the vehicle position and heading relative to the road and absolute position along the road (post-mile location) useful. They found the vehicle height above the road / elevation information and system health indicators to be interesting but not critical. Due to intermittent availability of the Rolba snow-blower, the system was not always installed on the "right" snow-blower, i.e. the type that is usually used to operate on top of the snow pack; in these situations, the effectiveness of the system was reduced simply due to the operational characteristics of the vehicle.

User expectations were formed, in part, by the recent availability of consumer handheld navigation devices. These devices, tailored for the mass consumer market, are inexpensive, very small and robust, and provide sufficient accuracy for effective consumer navigation. The MPRO system should integrate these recent advances in packaging and processing power to meet these user expectations, in addition to providing existing MPRO GPS precision. User expectation can also be managed through better user training, to a certain extent. The system size and power could be reduced using the latest generation of CPU and smaller form-factor computer boards. Size reduction also requires enhanced integration with the OEM GPS board to reduce wasted space.

Higher-accuracy and more detailed maps are also needed to meet the high user ex-

Figure 5.4: System installation showing LCD screen location

pectation. Users would also like to see turn-out area detail in the map. While the users perceived the heading as accurate, in some cases currently users can visually identify position inaccuracy of the system either due to GPS or base-map inaccuracy. Although the GPS and map in the MPRO system do meet the initial accuracy requirements for the system, any small discrepancy which can be visually detected by the operator will reduce user confidence in the system. Having a centimeter-level accuracy map will reduce such discrepancies.

The remaining area of improvement is the GPS positional accuracy and robustness—this presents a significant challenge due to signal blockage by tall trees and terrain. Due to the mountainous terrain, GPS systems typically can only receive signal from 4 to 6 GPS satellites, compared to 7 to 9 satellites in areas with open sky. The reduced number of satellite signals degrades positional accuracy and availability. As a result, the user can occasionally observe a discrepancy between the vehicle position relative to the road as shown by the system vs. what they can detect with their own eyes. The positional solution availability will improve as overall GNSS systems are modernized and/or deployed, as more satellites and signal frequencies are added. However, this modernization process will take about a decade to complete. Nevertheless, this area must be continuously improved in order to gain full user acceptance and resulting deployment.

Figure 5.5: Preparation for field-operational testing of the DAS installed in a Caltrans rotary snow blower

Chapter 6

Conclusions and Future Work

6.1 Conclusions

This report documents the Mountain Pass Road Opening Driver Assistance System (MPRO). The project developed an infrastructure-free GPS-based Mountain Pass Road Opening Driver Assistance System (MPRO) for installation within Caltrans rotary snowplows used during winter maintenance and pass opening operations. This system has the following attributes:

- Infrastructure-free solution: unlike infrastructure-based solutions (e.g. active embedded cable systems, path staking, etc.) MPRO requires no infrastructure modifications, maintenance, or repairs. This should reduce winter maintenance costs, and increase the probability of deployment.
- Low cost: MPRO was implemented using commodity hardware and software. This lowers initial and ongoing system costs.
- Portable: MPRO was designed to be easy to install and sharable between vehicles. This lowers initial system costs.
- Easy to use: MPRO was designed to require no operator interaction with the system while it is operating. This reduces training costs and increases safety.
- Accuracy: MPRO was designed to be accurate, with horizontal position accuracy at decimeter-level and vehicle heading accuracy of 0.15 degrees RMS.
- System flexibility: the System software architecture can integrate different sensor types (e.g. pavement temperature, friction sensors, etc.) and supports multiple simultaneous sensors.

Laboratory testing, field testing on-road, and field testing above-the-road confirmed the utility and accuracy of MPRO. The GPS derived heading was found to be accurate and stable while the vehicle was stationary and in motion–a crucial property for a rotary snow blower application. Testing of the satellite differential system also confirmed desired horizontal position accuracy. Testing results indicate the system is ready for widespread use within Caltrans Winter Maintenance Operations. In addition, system testing revealed system improvement opportunities. Installation time and ease was judged to be sufficient, but could be improved with further miniaturization of commodity components such as the computer and GPS receivers.

6.2 Future Work

To address high user expectations, the system should be improved in the following areas for enhanced user acceptance:

1. Smaller system size and power usage,
2. More detailed and accurate base-map, including turn-out areas,
3. Improved positional accuracy and availability in GPS-challenged areas such as deep canyons and terrain with tall trees.

The first two tasks are technically achievable with currently available technologies and COTS parts. However, the final task is technically very difficult to achieve with the current GNSS systems, and remains the biggest obstacle to final deployment.

Semiconductor process technology continues to drive innovation in electronic systems. The future will continue to bring lower power requirements, reduced chip size, and faster processors, resulting in more powerful systems such as real-time in-vehicle DAS. The authors anticipate that it will be soon cost-effective for all winter maintenance vehicles to use some type of DAS–some specialized for particular applications such as pass clearing, others for more general on-road vehicles. MPRO's general software architecture makes it a strong candidate for use in other applications. Hardware costs can be lowered further–the dual GPS receiver solution provides high accuracy for both heading and position; however, other less demanding applications might be satisfied by a single GPS receiver at lower cost. Other applications might also benefit from additional functionality and communications capabilities. For example, accumulating vehicle position information for future analysis. Future work is anticipated to involve fusion of additional sensor data, integration of other information sources and decision support, such as Maintenance Decision Support System (MDSS) functionality.

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Appendix A

System Installation Instructions

This appendix describes installation of the MPRO DAS system in a vehicle. This includes hardware installation, software installation, system configuration, and system testing. System installation time is estimated to take between two and six hours, depending on the installer's experience, and the specific installation vehicle.

A.1 Hardware Installation

System hardware installation consists of preparing the vehicle, installing the hardware, and testing the hardware.

A.1.1 Preparation

System Hardware Inventory

The system hardware includes:

1. Three GPS antennas.
2. The GPS antenna mounting rail and associated hardware.
3. The System hardware module which contains the GPS receivers and computer.
4. The System hardware module mounting hardware.
5. The DAS LCD display, keyboard, and pointing device.
6. Associated data and power cables.

Installation Tools

The following installation tools are required, others may be necessary depending on the vehicle:

1. Socket set, including ratchet
2. Tape measure
3. Wire cutters
4. Vehicle electrical wire
5. #2 Phillips screwdriver
6. Slotted (Flat-tip) screwdriver
7. Cordless drill / driver and drill bits
8. Multi-meter
9. Assorted terminal lugs (size depending on vehicle type and power source)
10. Heat-shrink / wire loom
11. Fasteners, including assorted 1/4-20 bolts and nuts, flat and lock washers, and self-tapping hex washer-head screws
12. Terminal crimpers
13. Tie wraps

A.1.2 Preparing the Vehicle

In preparation for hardware installation, view Figures A.1 on page 58, 4.4 on page 42, and 4.8 on page 44.

1. Locate a 12-Volt DC power source within the vehicle. This power source needs to be tied to (dependent on) the state of the ignition.
2. Locate the mounting position inside the vehicle for the System module and LCD display.
3. Locate the antenna bar mounting location. The bar can be mounted either laterally (a.k.a. transverse, across vehicle, default setting) or longitudinally (along vehicle, requires software configuration change). Each antenna must be connected to the System module with 50 Ohm coax cable using Threaded Neill-Concelman (TNC) connectors on both ends, and cable length of 20 to 25 ft.

4. The GPS antenna cables can be routed through the passenger-side window or any available cable pass-through opening into the vehicle cab.

A.1.3 Installing the Hardware

Hardware installation steps are as follows:

1. Wire the 12-V DC power source to the System module install location.
2. Install the System module, bolting the unit securely to the vehicle.
3. Mount the antenna bar, with the antennas. Note the two identical antennas (used for vehicle heading) are mounted on the ends of the bar, with the unique antenna mounted in the middle. The heading antennas should be mounted exactly 1 meter apart. If a different mounting distance is used, measure the antenna separation distance as accurately as possible—it will be used later during software installation. Antenna separation should be between 0.5 and 1 m, with 0.8 m as the default / recommended separation.
4. Connect the three cables between the System unit and antennas, keyboard, and LCD.
5. Some installations will require fabrication of an antenna bar adapter plate or bracket.

A.1.4 Testing the Hardware

At this point, the hardware should be installed in the vehicle, and the vehicle's 12-Volt system connected to the system module.

1. Turn the system on.
2. The system should boot to Windows XP as usual.
3. Complete system testing is performed after the DAS software is installed (below).

A.2 Software Installation

1. Locate these Digital Video Disc (DVD)s and Compact Disc (CD)s: Windows XP, ESRI MapObjects, Sax Communications Package, and the MPRO DAS system CD.
2. Install Microsoft Windows XP.
3. Turn off automatic system updates.

Figure A.1: Close-up view of antenna bar installation

4. Install Microsoft .NET 1.1 library.
5. Install ESRI MapObjects
6. Install the Sax Communications package.
7. Locate the MPRO DAS software installation CD.
8. Install the DAS software by creating a directory named:

   `C:\program files\mpro`

9. Copy the contents of the MPRO DAS CD to the directory just created.
10. Create a shortcut within the system Startup folder to the DAS application (MPROApp.exe) located in the directory just created.
11. Reboot the system. The DAS application will start after the system reboots.

A.3 Configuration

1. The DAS system comes with a configuration file with default values that will work in most cases. If an antenna separation distance other than 0.8 m is used, you must

use the configuration application (MPROConfigApp.exe) and specify a different distance.

2. Measure the size of the vehicle (width and length), and antenna location (center antenna) relative to the rear driver's corner of the vehicle. Enter these values in the DAS configuration application, saving the newly modified configuration file.

3. Close the DAS application and restart it.

4. The DAS system CD should come with the map layers you are interested in–if not, contact the AHMCT Research Center.

A.4 System Testing

1. If the instructions above have been followed, turning the vehicle on will start the DAS system. The computer will boot, and the DAS application will start.

2. Verify that the status lights in the lower right corner of the screen are green. If not, isolate the problem to the specific GPS receiver. If the system status light is green, everything is working.

3. It will take the system approximately two minutes to register visible satellites for full positioning information. The GPS status lights may be yellow during this time.

4. At this point, driving the vehicle forward will result in the DAS displaying trailing dots behind the vehicle on the screen, which are 1 m apart.

5. Verify that turning the vehicle to the right shows the on-screen vehicle turning to the right. If not, check your configuration file.

A.5 System Troubleshooting

1. Are the GPS antennas connected correctly?

2. If vehicle heading does not appear to be accurate, press the F10 key within the DAS application. This will bring up a diagnostics screen. Click the 'GPS diagnostics' button. Click the 'calculate antenna separation' button. The value displayed on the screen should match the value that is specified. If not, remeasure the antenna distance.

3. Antennas should be mounted longitudinally by default. Use the configuration program to specify transverse if they are mounted transverse.

4. If the vehicle is displayed at a 90 degree offset, adjust the heading offset in the configuration application by +90 or -90 degrees, and re-test.

5. If a cabling problem is suspected, check the raw NMEA-0183 received from both of the GPS receivers via the GPS diagnostics screen. Also verify that no NMEA-0183 CRC errors are being generated.

Appendix B

System Usage Instructions

B.1 System Startup

- Starting the vehicle will start the DAS.
- It will take the system approximately two minutes to register visible satellites for full positioning information. The GPS status lights may be yellow during this time.

B.2 System Operation

- If the system status light is green the system is operating normally.
- The system status light continuously shrinks and grows ("heartbeat") to give an on-screen indication that the system is functioning.
- If an on-screen GPS status light is red, the GPS heading or position signal has been lost.
- It is normal for GPS signal strength to become weaker under heavy tree cover or in a deep valley, where fewer satellite signals are available.
- System position accuracy is about 1 - 2 ft, and varies depending on satellite visibility.

B.3 System Shutdown

- Turning the vehicle off will automatically turn the DAS system off after about two minutes.

Appendix C

System Training Instructions

The system has been designed to be easy to use, with no keyboard or mouse entry required by the system during operation. The following training resources may help operators and maintenance personnel:

- See the System Usage Instructions (Appendix B on page 61).
- General information about the GPS system may be helpful. For example, see http://en.wikipedia.org/wiki/GPS.
- To facilitate debugging problems, press the F10 key while the DAS is operating–this will bring up a diagnostics screen with further real-time information.
- AHMCT will provide initial training to maintenance personnel for a given Pass, and will facilitate broader deployment within Caltrans by training Caltrans to provide further training ("train the trainers").