Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

Field-Ready GPS-Based Guidance Methods and Systems for Winter Maintenance Vehicles

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16. Abstract

This report documents the research project "Field-Ready GPS-Based Guidance Methods and Systems for Winter Maintenance Vehicles." The primary goal of this project was to identify and test cost-effective methods for installation and use of guidance systems in snow removal vehicles. These systems would allow equipment operators to constantly know exactly where they are on the highway in any type of adverse weather condition including blizzards and white outs. Winter maintenance operations are difficult and hazardous, yet essential for public safety and mobility. The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center investigated three distinct field-ready prototype guidance systems under this research effort: a Global Positioning System (GPS)-based Snowplow Driver Assistance System (DAS), a GPS-based Mountain Pass Road Opening (MPRO) Rotary Plow DAS, and a GPS-based Rotary Plow DAS (for normal rotary plow operations) augmented by side-fire ranging radar. The three systems minimize reliance on external infrastructure for reference trajectories and position sensing, with no need for added reference infrastructure in the roadway. Under this research effort, AHMCT enhanced the MPRO system and performed several seasons of additional field testing with Caltrans personnel. GPS-based snowplow guidance with an enhanced Human-Machine Interface (HMI) was developed and tested in a research vehicle prototype. GPS-based rotary plow operation, based in part on the MPRO system, was investigated, including approaches for integrating GPS DAS with local (range-based) adjustment—testing of this system was deferred as the ranging research in a separate project was terminated before the system development phase. To support the three systems in a unified fashion, AHMCT investigated innovative means to develop the needed base maps (reference trajectories) in an accurate and efficient manner. This report includes discussion of the three systems, implementation details, and testing results.

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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 Aerospace 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.

LIST OF ACRONYMS AND ABBREVIATIONS

AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
ASP	Advanced Snowplow
Caltrans	California Department of Transportation
COTS	Commercial Off–The-Shelf
CRC	Cyclic Redundancy Check
DAS	Driver Assistance System
DGPS	Differential GPS
DOD	Department of Defense
DOE	Caltrans Division of Equipment
DOP	Dilution-of-Precision
DOT	Department of Transportation
DR	Dead Reckoning
DRI	Caltrans Division of Research and Innovation
DTM	Digital Terrain Model
ESC	Caltrans Equipment Service Center
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HMI	Human-Machine Interface
IGEB	Interagency GPS Executive Board
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
LCD	Liquid Crystal Display
MEMS	Micro-Electro-Mechanical Systems
MPRO	Mountain Pass Road Opening
MTLS	Mobile Terrestrial Laser Scanning
NDGPS	Nationwide Differential GPS
NMEA	National Marine Electronics Association
OEM	Original Equipment Manufacturer
PATH	Partners for Advanced Transit and Highways
R&D	Research & Development
RFP	Request for Proposals
RTK	Real-Time Kinematic
SBAS	Satellite-Based Augmentation System
SR	State Route
TAG	Technical Advisory Group
TSI	Transportation System Information
TLC	Time to Line Crossing
TLS	Terrestrial Laser Scanning (fixed)
UTC	Coordinated Universal Time
WAAS	Wide Area Augmentation System
WGS-84	World Geodetic System

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CHAPTER 1: INTRODUCTION

Background and Motivation

Problem

Caltrans is interested in the most cost-effective methods for installation and use of guidance systems in snow removal vehicles. These systems would allow equipment operators to constantly know exactly where they are on the highway in any type of adverse weather condition including blizzards and white outs. Winter maintenance operations are difficult and hazardous, yet essential for public safety and mobility. In the current research, the Advanced Highway Maintenance and Construction Technology Research Center (AHMCT) investigated and developed three prototype guidance systems:

- a GPS-based Mountain Pass Road Opening Rotary Plow DAS,
- a Global Positioning System (GPS)-based Snowplow Driver Assistance System (DAS), and
- a GPS-based Rotary Plow DAS for normal rotary plow operations, augmented by side-fire ranging radar.

Background

Winter maintenance operations, including snow removal, are subject to increased risk. Snowplows and rotary plows (“blowers”) must operate in the worst of conditions, including completely covered roads, very low traction, and complete visual whiteout. In California, the consequences of road run-off are more severe due to the mountainous terrain in which most snow removal operations are performed. Additional danger comes from vehicles and other obstacles obscured due to whiteout, as well as improper visual cues resulting from previous plowing. The operating environment and the nature of the risks indicate a significant opportunity to enhance the safety of the maintenance operator and the traveling public through the appropriate application of field-ready driver assistance technologies.

Previous work on snowplow driver assistance has proven its utility and effectiveness. Research in California has focused on magnet-based lateral guidance, with proof-of-concept and field-testing projects on Interstate 80 at Kingvale and State Route 299 at Burney. Some in Caltrans, as well as in other DOTs have expressed reservations over any infrastructure-based approach for vehicle guidance; in addition, such approaches are deficient for use in rotary plow operations, as they do not truly support operations relative to the guardrail itself. 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 typically are also hardware-intensive and demanding in terms of vehicle instrumentation. GPS-based snowplow guidance solutions have been investigated in the Midwest by Donath and others [1,2,16], where requirements and operating conditions are significantly different from California’s. Some of this work directly benefits the current research, but specific snow and terrain conditions and a broader range of applications require a focus specific to the needs of Caltrans.

Research Approach

The current work builds on AHMCT's experience with Winter Maintenance Vehicle Guidance, our strength in GPS sensing and vehicle integration, and our established Mechatronic hardware and software base [3,11,13,14,22-25].

The research methodology included:

- Formation of a technical advisory group (TAG),
- Survey of literature, products, and standards,
- System requirements definition, including common requirements and application-specific requirements, and
- Development and testing of individual subsystems and systems at varying levels from laboratory prototype to field test.

Overview of Research Results and Benefits

Each of the systems developed provides safety benefits for Caltrans personnel working in particularly hazardous conditions.

For the Mountain Pass Road Opening system, the roadway is obscured by many feet of snow, and there are few if any markers for the edge of the roadway. Snow stakes are not reliably available. Trees can provide a good indication; however, much of the road opening operation occurs above the tree line. Run-off road accidents are a risk, particularly for newer operators. The MPRO system provides clear and reliable indication of the vehicle's position above and heading along the roadway, thus greatly increasing the safety of the road opening.

Whiteout conditions are the greatest risk for on-road snowplowing. The snowplow DAS provides the operator with ability to maintain position in the lane. It also provides collision warning regarding vehicles or similar obstacles ahead of the snowplow. These capabilities enhance the safety of the operation. They also may enable operations in conditions that would otherwise prevent plowing, thus supporting Caltrans mission of Mobility by keeping the roads open, or reducing the time and effort needed to reopen a stretch of roadway after a severe storm.

For the rotary plow operation, there are benefits for safety, based on obstacle detection and warning. However, perhaps the greatest benefit for this operation is the greatly reduced impact on the infrastructure (guardrails) and the blower vehicle. In existing operations, it is common to guide the blower along the guardrail by feel. Over a season, this causes significant damage to guardrails. The corresponding flattening of the guardrails and leaning of posts reduce the guardrails effectiveness for vehicle impact, and the frequency of guardrail repair is increased. By providing the range from the guardrail and allowing the operator to maintain the blower close to the guardrail but without impact, the damage to guardrails can be minimized, and their operational life can be extended, with associated benefits in safety and cost.

Additional benefit of the current research comes from the use of the GPS-based approach. First, this approach eliminates the need to place infrastructure (e.g. reference markers) in the pavement or along the roadside. This removes a cost component, and also eliminates need for maintenance of this added infrastructure. In addition, the commonality of the three applications in terms of the need for and approach to create base maps can yield cost savings through economies of scale for generating this GIS component. Similarly, differential base stations can be shared among the applications in a given range.

The key deliverables of this project include:

- System concepts for the three winter maintenance systems,
- Field or lab prototypes of the MPRO DAS and snowplow DAS,
- Field testing and operator feedback summary information, and
- Test results, analysis, and documentation.

CHAPTER 2:
COMMON BACKGROUND AND SYSTEMS

The detailed discussion for each of the application-specific systems is reserved for Chapters 3 – 5. In this chapter, the common background and common supporting systems are discussed.

The Human-Machine Interface (HMI) is the essential element in all of the systems. From the operator's point of view, the HMI ***is*** the system. The HMI for the two rotary plow operations shares significant commonality, based on a bird's eye view of the roadway. The snowplow HMI differs in that it provides look-ahead and predictive capabilities that are unnecessary in the low-speed rotary operations. The HMI in general combines visual (screen-based), audible, and tactile feedback to the operator. In previous work, AHMCT developed simple and effective means to retrofit any existing driver seat with vibrating tactile feedback without compromising the safety and comfort of the driver's seat. AHMCT has also developed custom display technologies that are very well-suited to the maintenance vehicle environment in general, and to the low-temperature conditions of winter maintenance in particular. For the snowplow and the rotary plow DAS, the HMI includes collision warning / obstacle detection and ranging information.

GPS and Related Technologies Background

Through numerous research efforts, AHMCT has developed significant experience and strength in the understanding and use of the Global Positioning System (GPS) in the highway environment. This includes previous research into vehicle guidance (related to snowplow driver assistance as well as mountain pass opening) with GPS as the primary sensor. AHMCT developed methodologies to survey and efficiently represent roadways and reference trajectories in a Geographic Information System (GIS), and refined these methods on SR 108 near Long Barn, CA. In separate research, AHMCT designed, developed, and is currently working with Caltrans Transportation System Information (TSI) to deploy the GPS Advanced Travel Diary (GPS-ATD) for use in Travel Behavior studies. In this section, we will provide some of the relevant GPS background information and a summary of the state-of-practice and state-of-the-art in this area. We have also developed an extensive capability in the Mechatronic design and implementation of sensors, processors, and tightly-integrated solutions targeted for highway maintenance use (e.g. Donecker *et al* [3]).

Recent technological developments and improvements in GPS, low-cost small Micro-Electro-Mechanical Systems (MEMS) inertial sensors, and low-power embedded computers have converged to make GPS-based vehicle guidance the best choice for field-ready and deployable systems. Each of these technical areas will be discussed in brief detail in this section.

GPS

The Global Positioning System (GPS) is a space-based radio-navigation system consisting of a constellation of satellites and a network of ground stations used for monitoring and control. A minimum of 24 GPS satellites orbit the Earth at an altitude of approximately 11,000 miles, providing land, sea, and airborne users with accurate information on position, velocity, and time anywhere in the world and in all weather conditions, with precision and accuracy far better than other radio-navigation systems available today or in the foreseeable future (see gps.faa.gov). Currently, there are 30 operational GPS satellites in orbits. They circle the Earth twice per day. The space and ground control GPS segments are operated and maintained by the Department of Defense (DOD). In 1996, a Presidential Decision Directive, later passed into law, transferred "ownership" from DOD to an Interagency GPS Executive Board (IGEB), co-chaired by senior officials of the Departments of Transportation and Defense to provide management oversight to assure that GPS meets civil and military user requirements.

GPS receivers collect signals from the satellites in view. They provide the user's position, velocity, and time, and some receivers give additional data, such as distance and bearing to selected waypoints or digital charts after further processing of the positional and time solutions. Without going into full detail, each satellite transmits an accurate position and time signal. The user's receiver measures the time delay for the signal to reach the receiver, which provides a direct measure of the apparent range (called a "pseudorange") to the satellite. Measurements collected simultaneously from a minimum four satellites are processed to solve for the three dimensions of position (latitude, longitude, and altitude in WGS-84 geodetic reference system) and precise time. For more information, see Hoffmann-Wellenhof, et al [7].

Selective Availability (SA) was used to protect the security interests of the U.S. and its allies by globally denying the full accuracy of the civil system to potential adversaries. It was turned off at midnight on May 1, 2000. It is not the intent of the U.S. to ever use SA again. Currently, with removal of SA, accurate position (< 25 m), time, and speed can be obtained throughout the country using small and low-cost GPS receivers. GPS is continuously being modernized with additional radio frequency and transmission power resulting in more reliable and accurate positional and time solution.

Free Nationwide Differential GPS (DGPS) Services

GPS accuracy can be improved by additional information provided by fixed ground GPS monitoring stations. The Wide Area Augmentation System (WAAS) and the Nationwide Differential GPS (NDGPS) are two free differential GPS services available in the United States. Both systems provide improved GPS accuracy (1 to 3 meter) and integrity monitoring services. WAAS vertical accuracy over the United States is illustrated in Figure 2.1—horizontal accuracy (of most interest for vehicle guidance applications) is approximately three times better than vertical, due to geometric configuration. The West Coast has relatively excellent WAAS accuracy and coverage. While these services are not yet sufficient for the types of operations in the current research, they are noteworthy in that they illustrate the strong advances in freely available services. In addition, higher accuracy versions of some of these services have been proposed or are currently in development—such improved versions may be directly applicable in the future.

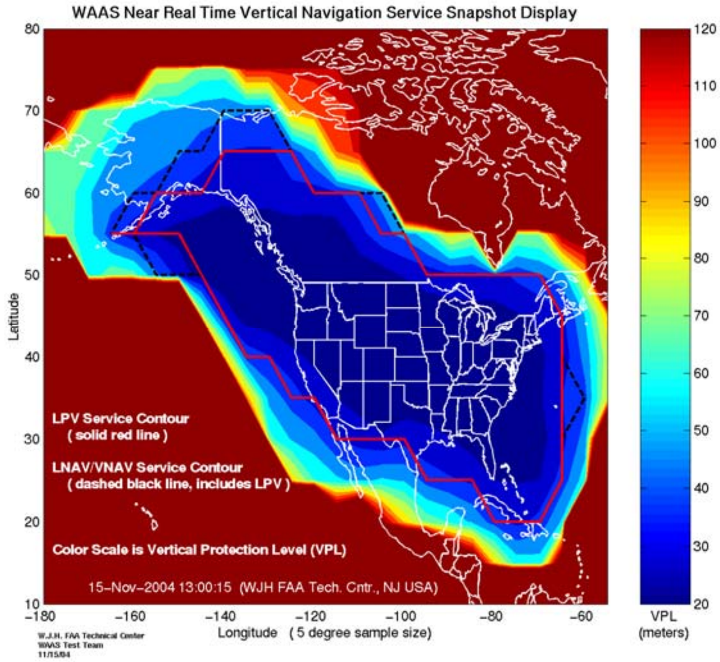

Figure 2.1: WAAS GPS Vertical accuracy map (http://www.nstb.tc.faa.gov/vpl.html)

Real-Time Kinematic GPS

GPS includes several sources of error. Many error sources are correlated between satellites and/or receivers, and can be removed via methods commonly referred to as differential corrections, or Differential GPS (DGPS). DGPS approaches can be broadly classified as code-based and real-time kinematic (RTK). For vehicle guidance applications, code-based approaches are typically not sufficiently accurate, so only RTK is considered in this discussion and in the research.

The RTK approach is based on carrier-phase tracking. The GPS satellites broadcast coded information on multiple frequencies. The carrier wave frequencies are precisely known, and RTK receivers can identify the phase of the incoming signal very accurately, so that the pseudorange can be determined for each satellite with very high precision (sub-wavelength). However, at system startup, the receiver only knows the phase and corresponding position within that wavelength; the receiver does not know the number of full wavelengths *n* between the receiver and each broadcasting satellite. A key feature of the RTK approach is known as ambiguity resolution. Effectively, the receiver intelligently and (these days) rapidly resolves the ambiguity resolution for each satellite, and then knows each pseudorange to very high accuracy. Details will not be discussed here, but are commonly available in the literature [7]. The net result is that, with ambiguity resolution complete, the RTK GPS receiver can provide cm-level (or even sub-cm level) accuracy. There are a number of complicating factors (e.g. satellite signal loss, switchover from one satellite set to another, etc.) which must be carefully considered in vehicle guidance applications, but the key point is that RTK GPS can provide high accuracy position (and velocity) information throughout most of the world, and, when thoughtfully integrated, is an exceptional enabling technology for a wide range of applications in highway maintenance, general transportation, and many other areas.

Satellite-Based Augmentation System

Standard code-based and RTK DGPS systems typically require a fixed base station and some form of radio communication for real-time differential corrections. Of course, for surveying and similar operations, one can always post-process GPS data so that a real-time data link is not required; however, for vehicle guidance and control, real-time corrections are obviously essential. An alternative approach, a Satellite-Based Augmentation System (SBAS), can provide quite high accuracy (~ 10 cm) differential GPS solutions without the need for a fixed base station, and with the real-time data link provided via a satellite-based system. SBAS subscription services are available from a number of vendors, with SBAS-enabled receivers available from multiple providers. Figure 2.2 and Figure 2.3 show test data for two SBAS services, and Figure 2.4 provides similar data for WAAS. SBAS is not appropriate for some applications which require the highest levels of accuracy; however, it is applicable in the Mountain Pass Road Opening (MPRO) system. Areas that typically would need such a road opening system are generally well-suited for SBAS DGPS—they are in high passes, often above the tree line (hence the need for some additional guidance), so that satellite signals will typically have high availability. In addition, SBAS has the strong advantage of removing the need for a fixed (or even temporary) base station, which is an important aspect given the portability and sharing potential of the MPRO system.

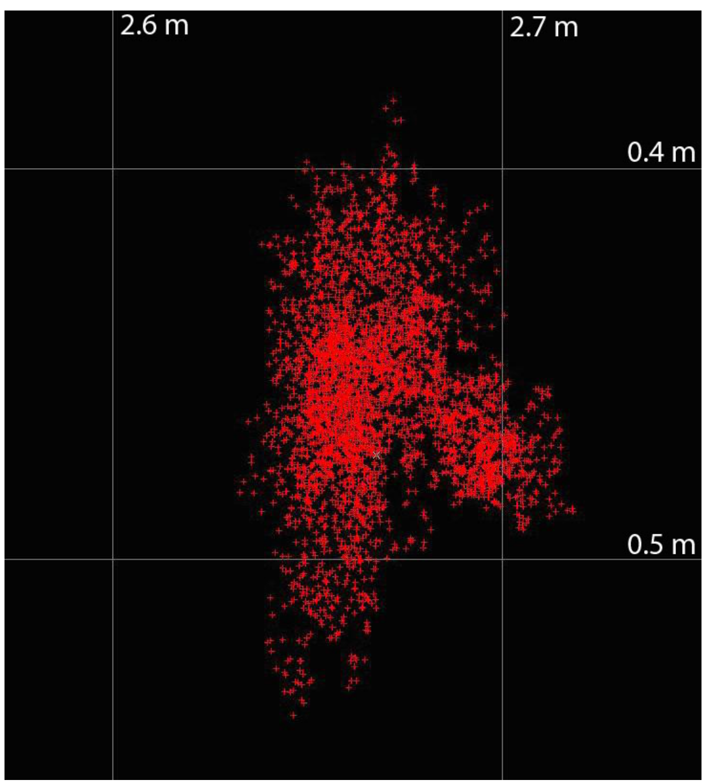

Figure 2.2: Static OmniSTAR SBAS DGPS test result in Northern California.

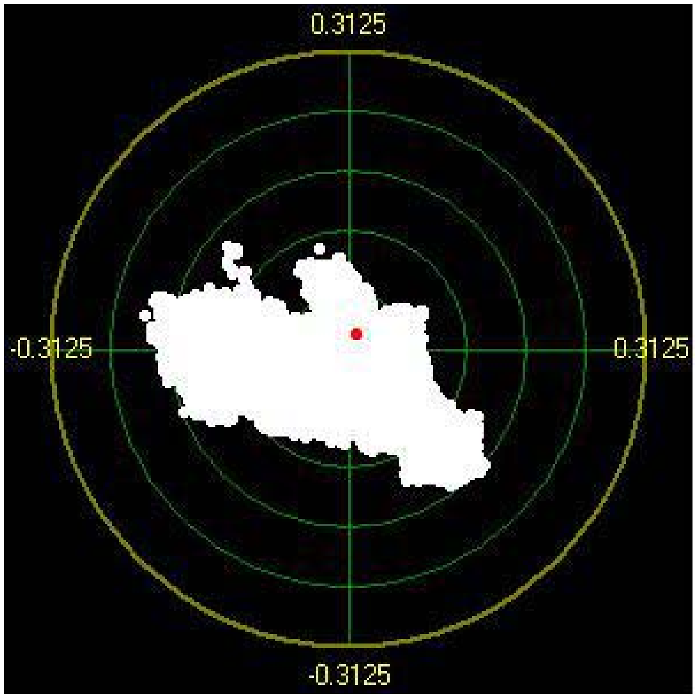

Figure 2.3: Static StarFire SBAS DGPS test result in Northern California (meters)

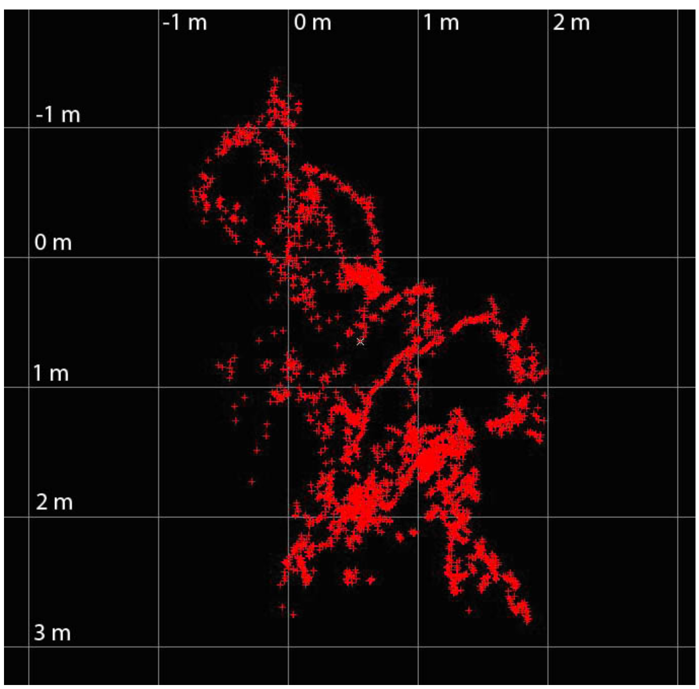

Figure 2.4: Static WAAS DGPS test result in Northern California

GPS Vulnerability Issues and Mitigation

AHMCT is aware of the typical GPS vulnerabilities, and has developed methods to alleviate or mitigate these issues in the demanding winter maintenance environment. Many factors can degrade GPS performance. GPS receivers require a direct line-of-sight to the satellites in order to obtain a signal representative of the true distance from the satellite to the receiver. Therefore, any object in the path of the weak GPS signal has the potential to interfere with its reception. Objects which can block a weak GPS signal include tree canopies, buildings and terrain features. Similarly, the WAAS geostationary satellite signal can also be blocked. Furthermore, reflective surfaces can cause the GPS signals to bounce before arriving at a receiver, thus causing an error in the distance calculation. This problem, known as multipath, can be caused by a variety of materials, including water, glass, and metal. The water contained in the leaves of vegetation can produce multipath error. In some instances, operating under heavy and wet forest canopy can degrade the ability of a GPS receiver to track satellites. Typically, lower-elevation GPS satellites' signals are most likely to be blocked. In this situation, GPS receivers track only the highest satellites in the sky, as opposed to those satellites which provide the best Dilution-of-Precision (DOP)—a measure of the satellite geometry error sensitivity. Thus, the positional accuracy decreases. Unfortunately, there will be locations where a minimum four GPS satellite signals simply are not available due to obstruction such as urban canyon—in these cases, no general GPS solution can be obtained. Methods are available (e.g. combination with inertial measurement unit based dead reckoning) to alleviate these issues and provide a robust solution with maximum availability.

AHMCT has experimentally verified satellite signal availability on Interstate 80 near Kingvale, CA (see Figure 2.5 for a dynamic testing result), as well as on SR-108 at Sonora Pass, east of Long Barn, CA. For SR-108, AHMCT confirmed the availability of the essential SBAS differential correction service during field testing under prior research. In each of these areas, standard GPS satellites and the SBAS satellite signals have high availability, quite sufficient for the GPS-based systems in this research. In addition, AHMCT has investigated complementary sensing (e.g. inertial-aided guidance, complementary filtering, Kalman filtering [20], and local ranging) to augment the primary GPS sensing and to provide robust ongoing operation during short periods when GPS signals may be blocked or otherwise unavailable. For field-deployed systems, it is essential to provide fail-soft operation; i.e. if GPS signals are unavailable for an extended time such that complementary sensors (in particular dead reckoning via inertial sensing) can no longer provide a sufficient safety margin, the systems will alert the operator to resume manual operation without the aid of the driver assistance system. For example, this is implemented in the MPRO system via watchdog timers and related health monitoring of the critical sensing components.

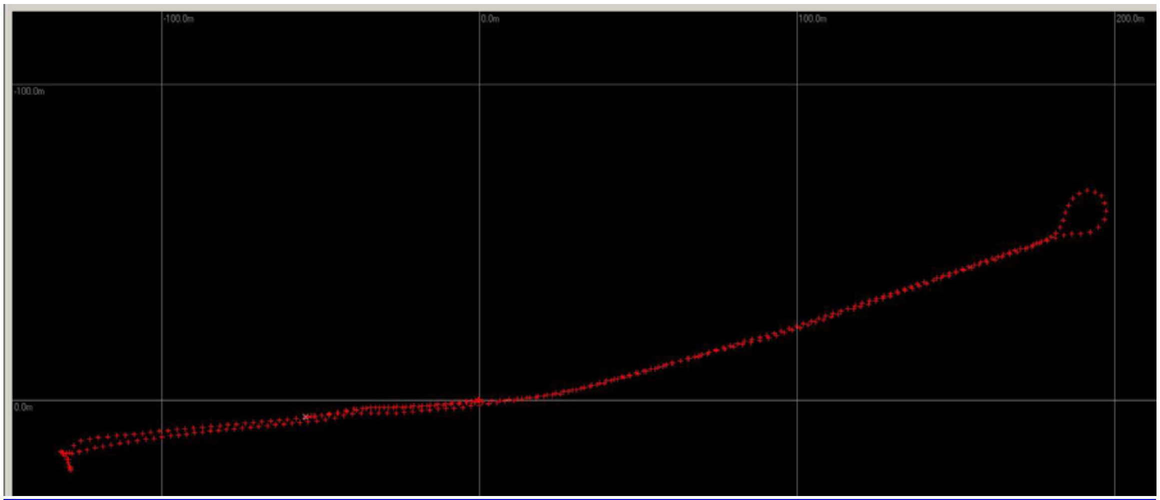

Figure 2.5: Dynamic test result of OmniSTAR SBAS DGPS at Kingvale, California

GPS Sensors

Each manufacturer may have its own signal tracking, positional solution and filtering algorithms. Receivers may perform differently during startup, reacquisition of signal, and in various terrains such as urban canyons and under tree canopies. Nevertheless, most GPS receivers output positional and time solution in ASCII text standard National Marine Electronics Association (NMEA) 0183 format via an RS232 serial port. NEMA output sentences contains Coordinated Universal Time (UTC) date and time, latitude, longitude, and altitude in the WGS84 coordinate system, geoidal separation, number of visible satellites, speed, heading, horizontal DOP, and solution status. Some GPS receivers give additional information such as estimated positional accuracy. Moreover, most receivers can also communicate solution data using proprietary binary communication protocols at a higher baud rate, allowing more data or more frequent updates.

Most GPS users would still not know where they are given their position in latitude, longitude, and altitude—with this raw data, most users can only tell whether they are in the northern or southern hemisphere. A digital map or a Geographic Information System (GIS) database is required to determine the user's state, city, and street location. In the special case of vehicle guidance, a centimeter-level accuracy digital map is required. The GIS component is an essential part of the research, as it provides the high-precision reference information to support GPS-based driver assistance and guidance. This component, also referred to as a base map, is discussed below, including methods to generate it.

Each GPS receiver has its own power-on sequence where it downloads almanac data (such as GPS satellite orbital information) before establishing a positional and time fix. This start-up time is referred as cold start time (typically between 45 sec to 5 min). Some receivers have a "sleep" mode in which the receiver keeps all the almanac data in memory using a low-power consumption mode. Thus, the long start time may be eliminated. Furthermore, keeping the receiver on may eliminate the cold start time. In addition, the reacquisition time, the time to reacquire the satellite signal lock when the signal was temporarily blocked, varies from 1 to 3 seconds for different manufacturers. Moreover, GPS receivers perform differently in GPSchallenged areas like urban canyons or heavily wooded areas. Their size and power consumption varies as well. These factors have been examined in this research, along with methods to alleviate these issues and provide a robust solution with maximum availability.

Low-Cost Inertial Sensors for Dead Reckoning

Dead reckoning (DR) is a navigation method used in ships, aircraft, and, more recently, mobile robots. Essentially it is used to estimate an object's position based on the distance traveled in the current direction from its previous position. A simple dead reckoning system measures and estimates heading and speed, then integrates to obtain position. For a vehicle, heading could be measured by compass and/or gyro, and the speed may be obtained through accelerometer or wheel rotational speed. DR will provide position information if GPS is not available for a short period of time. Since DR relies on integration of sensor measurements, error increases as usage duration increases—this is referred to as drift. The error can be corrected with a positional update from the GPS receiver.

Small and low-cost MEMS gyro and accelerometer chips (see e.g. Figure 2.6) now make low-cost DR possible. In addition, MEMS gyros and accelerometers can measure vehicle acceleration, detect lane changes, and provide dead-reckoning to increase GPS availability in a complimentary fashion. Combining these technologies, a system can collect positional and temporal data automatically and accurately with high availability.

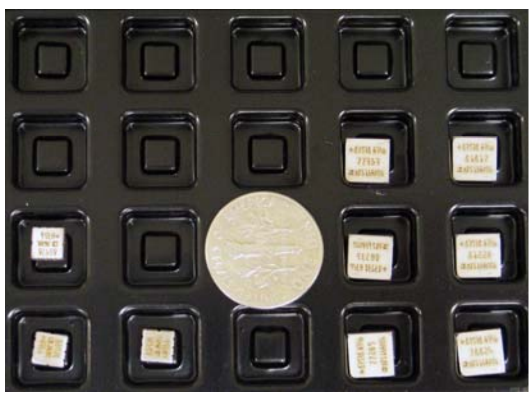

Figure 2.6: Analog Devices MEMS gyro and accelerometer chips, with dime to provide scale reference

Supporting Systems

The GPS-based approach of the current research does not require any added reference infrastructure in the pavement or on the guardrails. This provides a significant advantage in terms of maintainability. This section overviews, the required support systems: base maps for position reference, and differential base stations. All of the systems will use World Geodetic System (WGS-84) latitude / longitude / altitude coordinates for their operation. The goal is to unify the required support as much as possible, while still exploiting and supporting the unique characteristics of the three applications.

Accurate As-Built Roadway Base Map

The roadway base map provides the positioning reference for any of the GPS-based guidance systems. This base map must be generated for each system installation site. The base map would need updates for any significant redesign of the roadway, i.e. anything that changes the roadway configuration. For the one-time and the needed updates, AHMCT has investigated appropriate and efficient methodologies, including simple driving and recording of lane centerline positions (effective for the MPRO operation) and fixed terrestrial laser scanning (TLS) and mobile terrestrial laser scanning (TLS and MTLS).

In general, the base map must be as accurate as the machine control requirements. For MPRO operations, the requirement is to keep the operator over the roadway; for this application, it is sufficient to drive the route and record a lane centerline, although the higher precision MTLS approaches would certainly be applicable as well. The rotary plow guidance map horizontal accuracy requirement is ~ 10 mm, and the snowplow guidance horizontal accuracy is ~ 50 mm. The new geo-referenced 3D laser scanning technology (TLS and MTLS) provides the most suitable survey solution for this application. For the rotary plow application, which occurs over limited areas and requires higher accuracy, fixed TLS is more appropriate at this time. For snowplow guidance, MTLS would be the ideal choice, as data is collected at approximately highway speed and provides the level of accuracy needed, with the appropriate system configuration. The dense geo-referenced 3-D point clouds capture all features of the roadway area accurately and rapidly, thus a surveyor can go back to the point clouds and perform virtual survey of any point and surveys of any dimension that was not conceived before the physical survey, all in the safety of the office. The 3-D point clouds may be used to generate a 3-D terrain model for use in any machine guidance applications. It should be used in this case since different machine guidance applications require accurate measurement of different features, some of which are unknown at this time. Other data may be extracted to produce current survey deliverables such as a Digital Terrain Model (DTM). In summary, the geo-referenced 3-D laser approach will provide the detail and accuracy required for the GPS-based guidance applications, and it will provide data needed by Caltrans for other envisioned applications, including the demanding requirements of Caltrans Design.

Figure 2.7: Example 3D laser scan point cloud supporting base map generation

The existing industry 3-D laser scanning survey standards (including scan density) in conjunction with the accuracy requirements of Digital Terrain Model (DTM) survey (7 mm vertical and 10 mm horizontal) would yield adequate base map survey requirements. The final point cloud density depends highly on range and geography. The laser scanner operators are experienced in setting the proper scan density for the required accuracy. It should be no less than 100 mm x 100 mm. Higher scan density may be required for proper registration and geo-referencing. Caltrans now has the in-house ability and equipment to perform fixed TLS. For MTLS, Caltrans currently contracts out services, and there are existing bid requests to provide a basis for future contracting. In addition, the Caltrans Surveys manual now includes a chapter for TLS and MTLS.

Differential GPS Base Station

For the required sensing accuracy, each of the GPS-based guidance systems will require a level of differential GPS corrections. The accuracy requirements differ significantly between the operations, pointing to different solutions in each case. However, the higher accuracy solutions would cover all needs, in areas that combine two or more of the applications.

The MPRO operation requires the least accuracy, with a 10 cm correction being more than sufficient. This can be conveniently provided via a Satellite-Based Augmentation System (SBAS). This removes need for any differential base station infrastructure at the pass opening site, and maximized system portability and minimizes site requirements. However, the system does require SBAS subscription service, and Caltrans will need to maintain an annual license for each MPRO system it operates. On the other hand, as the system is portable, and pass opening operations may occur at different times in each pass, one consideration is sharing of the MPRO system among multiple passes, to maximize benefits.

The normal snowplow operation must maintain the snowplow within a lane, as the operation typically occurs while the road is open, i.e. in mixed traffic conditions. A higher-accuracy in-vehicle (rover) GPS unit will be needed. In addition, high-accuracy corrections with high availability and low latency are essential. These requirements point to use of Real-Time Kinematic (RTK) differential corrections. Through prior AHMCT work and additional Caltrans-sponsored research, an RTK base station has been established in the Kingvale area.

For the on-road rotary plow operation, i.e. clearing snow from the shoulders in close proximity to guardrails, precise positioning will also be required. Here, the requirements are driven by several factors: First, the rotary plow must cut the snow close to the guardrail so that remaining snow does not collapse back onto the roadway. Second, the rotary plow must not deviate into moving traffic. Third, the rotary plow should not impact the guardrail, thus avoiding damage to the guardrail and the rotary plow, minimizing maintenance costs and extending infrastructure lifetime. The first two requirements dictate high-accuracy rover GPS and high-accuracy RTK differential corrections. The third requirement adds the need for local range sensing between the rotary plow and the guardrail, as will be discussed in detail in Chapter 5.

CHAPTER 3: MOUNTAIN PASS ROAD OPENING (MPRO) DAS

Overview

The Mountain Pass Road Opening (MPRO) DAS is the most mature of the three systems discussed in this report. It was developed and field-tested in a previous research project [21]. The system was further ruggedized based on prior testing results and operator feedback. In the current project, the system was field-tested during the opening of SR 108, Sonora Pass, over four seasons.

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 3.1 and in Google Maps in Figure 3.2. 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 3.3)—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 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.

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 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 continued on the current project through Spring 2009, and results indicate the system is ready for widespread use within Caltrans Winter Maintenance Operations. The approach used in the MPRO system is applicable for on-road rotary plow operations, with suitable modifications for virtual compliant tracking of guardrails distance, as discussed in Chapter 5.

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

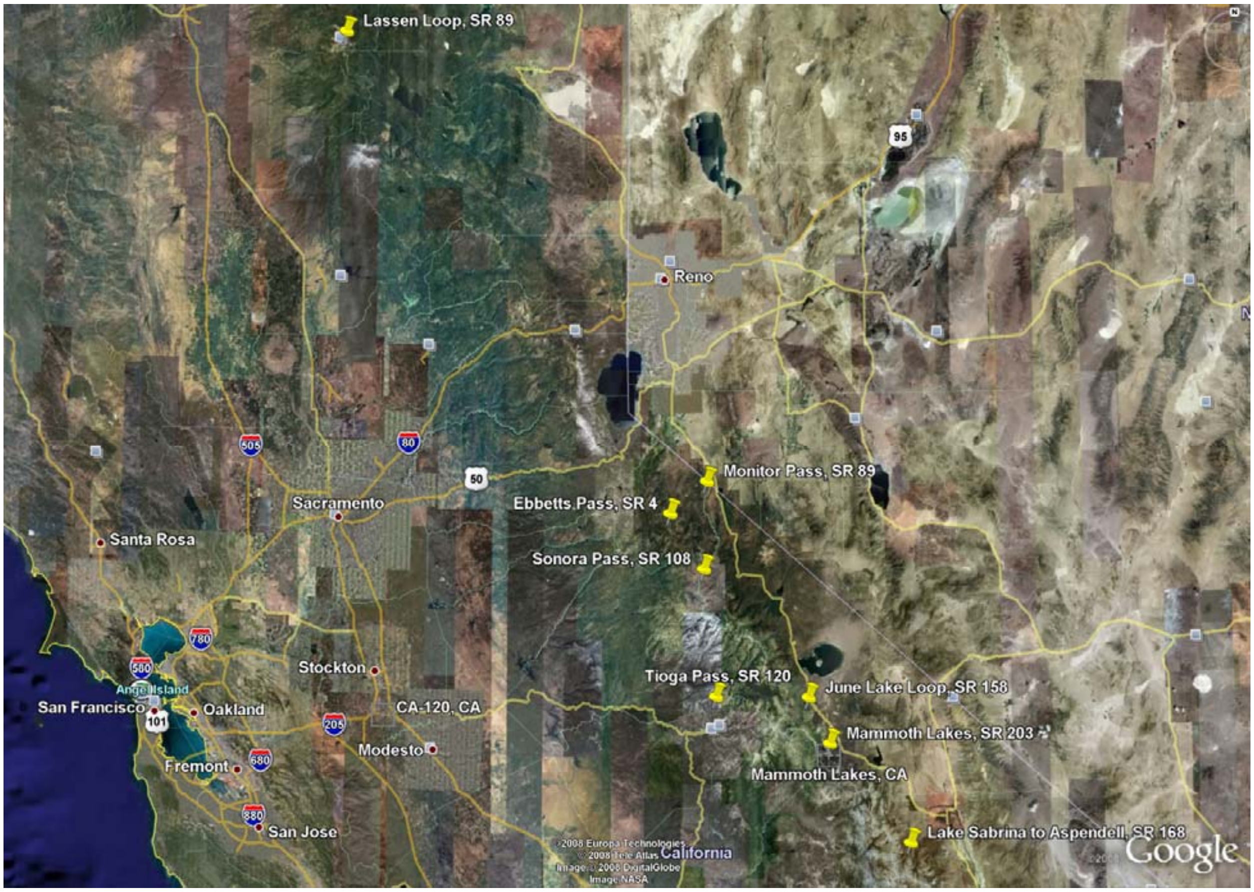

Figure 3.1: Caltrans winter pass closures visualized in Google Earth

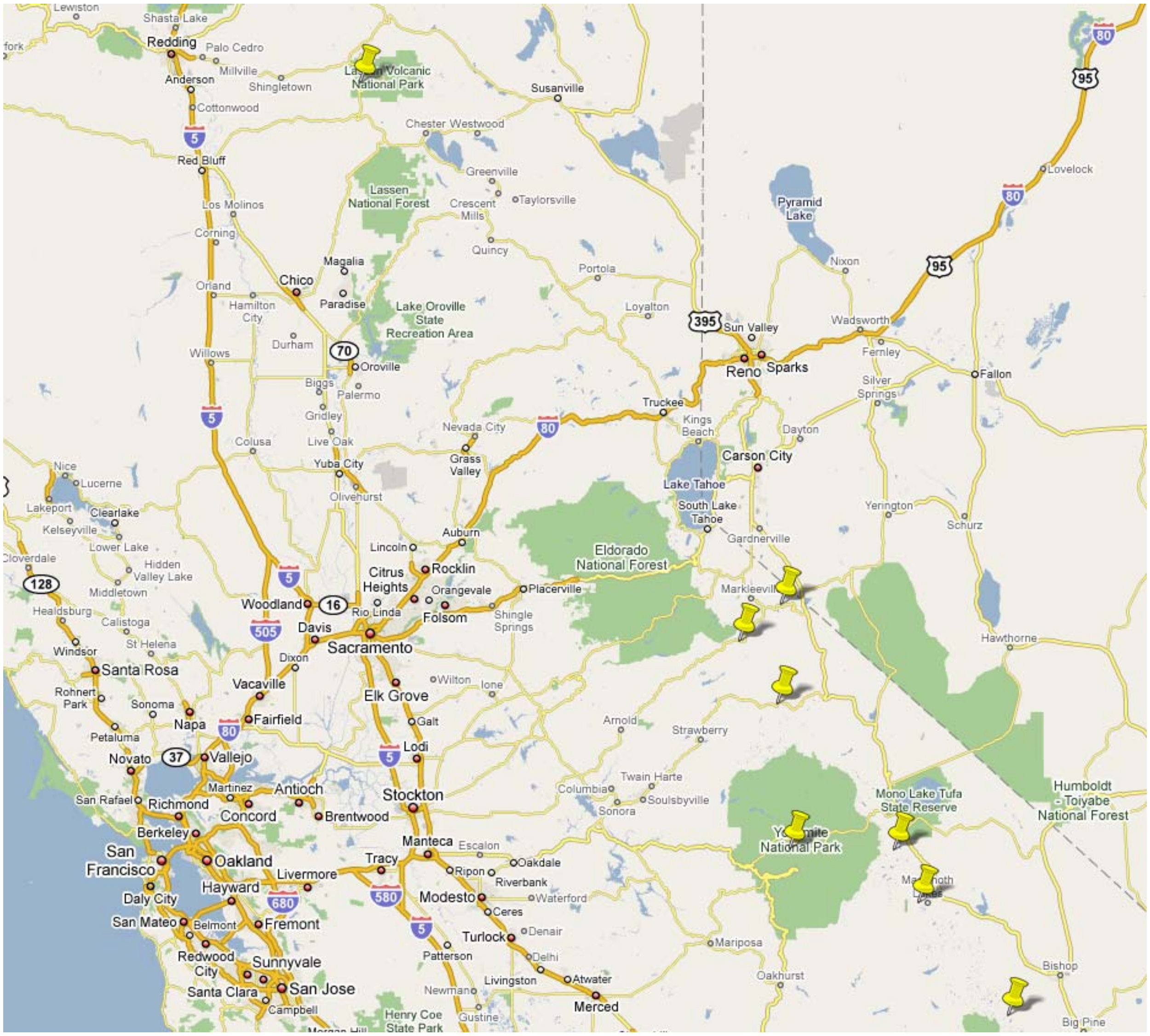

Figure 3.2: Caltrans winter pass closures visualized in Google Maps

Figure 3.3: Terrain surrounding SR 108 prior to road-opening operations

This DAS system allows the operator of a small rotary plow to safely and efficiently work on top of deep (30 – 40 feet) snow build-ups, in order to reopen mountain passes that are allowed to close over each winter. This system provides a bird's-eye view of the roadway with the vehicle location and heading clearly illustrated. Additional information, e.g. landmarks, is provided to help operators have a context for their location along the route. This system is portable, with easy field installation, calibration, use, and removal. As such, it is feasible to share the system between passes and between Districts within Caltrans, yielding cost advantages. The system uses GPS as the primary sensor for driver mountain pass road opening driver assistance. It includes (see Figure 3.4 for a system configuration diagram):

- A GPS receiver to provide accurate (~10 cm) vehicle location in WGS-84 latitude / longitude / altitude coordinates, suitable for integration with the GIS noted below. The mountain pass opening operation is suitable for RTK GPS incorporating SBAS differential corrections, i.e. no base station is required. For SBAS, currently an annual service fee is, but there are significant advantages due to removing the need for establishing and maintaining a fixed base station at each site.
- A GPS-based compass to determine vehicle heading. Note that the pass opening operation is typically too slow to effectively derive heading from single antenna GPS data. However, the system has been augmented to include a dual-antenna vector GPS unit that directly provides accurate heading data that is not subject to magnetic interference.

- A high-accuracy GIS database representation of the roadway (lane centerlines, relevant roadside infrastructure, on and off-ramps, etc.) which provides a reference to determine the vehicle's location above the road, heading vs. the road direction, and approximate height above the road.
- An in-vehicle display to provide the bird's-eye view of the vehicle location and heading vs. the roadway, and landmark information to provide a sense of overall position along the route.
- The required embedded computing, real-time software, and power systems to support this mountain pass road opening driver assistance system.

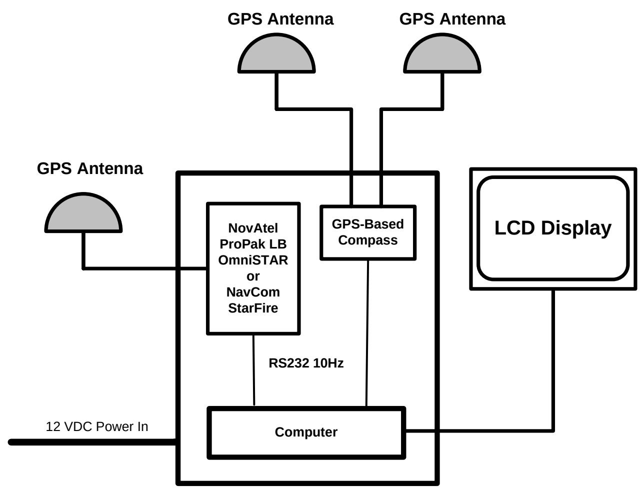

Figure 3.4: MPRO system configuration

System Architecture and Hardware

This system provides an overview of the MPRO architecture and hardware. Software details were presented in the final report of related previous research [21].

The overall MPRO architecture is provided in Figure 3.4. An example screen shot of the MPRO DAS display is shown in Figure 3.5. The derivation of the information content from the sensing systems is noted below.

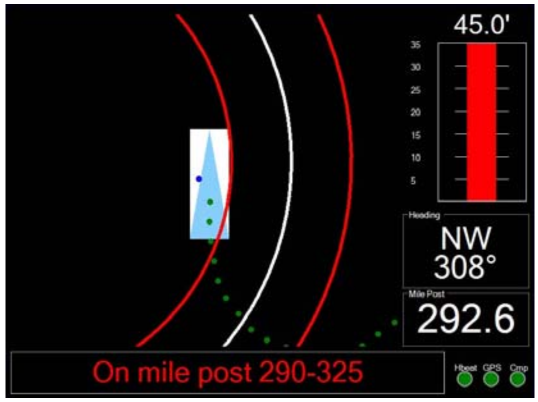

Figure 3.5: The MPRO DAS display

The system determines vehicle location using the Global Positioning System (GPS). Accuracy of uncorrected GPS is not sufficient for this application. To safely find the road center and keep the vehicle over the road, sub-meter accuracy is crucial. However, many locations do not have the necessary differential base station to provide this level of accuracy. To achieve the accuracy desired while avoiding additional infrastructure, the current system uses a Satellite-Based Augmentation System (SBAS) to provide differential corrections, and achieves 4 inch (10-cm) accuracy. This is more than sufficient for the current task, and the SBAS signal is available continent-wide.

Vehicle heading vs. the road heading is also essential, so that the blower operator can continue moving along the road. A dual-antenna GPS-based compass provides the heading of the vehicle, which allows display of vehicle vs. road heading.

The system also provides height above the roadway, as well as text-based information indicating how far along the current pass opening has advanced, e.g. milepost readings. The GPS again provides this information. Underlying the GPS sensing, a key part of the system is the Geographic Information System (GIS) base map, which includes information on the roadway location (centerline, shoulders, lanes), as well as roadside features, including signs. From this GIS, the system can determine location along the road, and provide the operator with milepost numbers, as well as text messages for familiar local landmarks, upcoming intersections, and system status.

To assure safety, the system includes a watchdog feature, and status indicators for all sensing systems. The status indicators provide an immediate indication of the function of the system, e.g. whether the GPS receiver sees enough satellites, whether differential correction information is available, etc. The watchdog subsystem monitors the overall code execution, and provides a pulsing heartbeat. In the rare circumstance of a system freeze, this heartbeat would also stop, and the operator could tell that the system was no longer reliable. In normal conditions, if the sensing degrades (e.g. due to loss of satellites) beyond an acceptable level, the operator is notified and the system will not provide faulty guidance information.

Figure 3.6: LCD, and system box containing computer and GPS receivers

MPRO hardware is responsible for providing sensor data to software applications, executing DAS software applications, and displaying driver assistance information for the operator. MPRO hardware includes the system box and display installed inside the rotary plow cab (Figure 3.6), and the antenna bar (Figure 3.7 and Figure 3.8). The computer, power backup battery, power supplies, GPS receiver for position, and GPS receiver for heading were packaged together into a single system box. Inside the system box, the GPS receivers and computer are connected using EIA serial communications standard (RS-232) serial communication, and the GPS protocol is the National Marine Electronics Association GPS communications standard (NMEA-0183) GPS communications standard (NMEA-0183) with an 8-bit Cyclic Redundancy Check (CRC) to verify message integrity. The system box was mounted on a platform attached to a display boom arm (see Figure 3.6), and installed inside the rotary plow cab. NovAtel and Hemisphere GPS receivers were used, along with OmniSTAR XP SBAS service for decimeter-level corrections. The GPS antennas were mounted onto a single antenna bar (see Figure 3.7 and Figure 3.8) to be installed on the roof of the rotary plow cab as a single unit. The antenna bar ensures that the spacing of the GPS antennas for heading determination is fixed on every installation. The only cabling connection between the vehicle and the DAS is for the 12-Volt Direct Current (DC) power supply. Hardware model numbers are shown in Table 3.1. The final system is usually installed in the field in a couple of hours. The only field software configuration is to input the vehicle dimensions and antenna location relative to the vehicle.

Figure 3.7: GPS antenna bar

Figure 3.8: Caltrans rotary snow blower with GPS antenna bar

Figure 3.9: System installation showing LCD screen location

Table 3.1: Implementation hardware details

Hardware	Model	Manufacturer
GPS receiver 1 (SBAS, position)	OEM-4 ProPack-LB-HP	NovAtel
GPS receiver 2 (heading)	Crescent Vector	Hemisphere GPS
Computer	MB890	IBASE
LCD screen	Tflex-G212P	Argonaut
LCD arm	RAM- VB-122-SW1	Ram Mount
GPS 1 antenna	GPS-600-LB	NovAtel
GPS 2 antenna	CDA-3RTK	Hemisphere GPS
GPS antenna bar	Custom	AHMCT
System box	Custom	AHMCT

System Testing on SR 108, Sonora Pass

AHMCT researchers tested the prototype during the Spring 2005 (prior contract) and 2006 openings of Sonora Pass on State Route 108, north of Yosemite, CA. Additional field testing by Caltrans Maintenance personnel occurred in the spring of 2007, 2008, and 2009 with support of AHMCT. Based on results and operator feedback, providing GPS-based driver assistance for mountain pass opening is feasible and effective, and holds great promise for enhancing the safety and efficiency of this operation.

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 rode 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.

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.

Figure 3.10: The mountain pass road opening operation in progress

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 hand-held 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 Original Equipment Manufacturer (OEM) GPS board to reduce wasted space.

Higher-accuracy and more detailed maps are also needed to meet the high user expectation. 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 3.11: Caltrans plows complete clearing a segment of the pass

CHAPTER 4:
GPS-BASED SNOWPLOW DAS

Overview

The snowplow DAS provides driver assistance to allow the snowplow operator to work safely and efficiently in low-visibility conditions, a.k.a. whiteout conditions. Functionally, this system is similar to the RoadView Advanced Snowplow [14,23-25]; however, the previous system was infrastructure-based, which introduces certain known drawbacks. The current system uses GPS and inertial sensors as the primary sensors for driver assistance. The design includes:

- A GPS receiver to provide high-accuracy (sub-decimeter level) vehicle location in World Geodetic System (WGS-84) latitude / longitude / altitude coordinates, suitable for integration with the GIS noted below. The snowplow operation requirements indicate a need for fixed base-station RTK differential GPS (DGPS).
- Associated support sensors (vehicle speed, inertial measurement unit, etc.) to augment the GPS in a complementary fashion (i.e. to provide strengths where GPS is weakest, and to take advantage of the strengths of GPS).
- An off-the-shelf radar system to provide forward collision warning.
- A high-accuracy GIS database (base map) representation of the roadway (lane centerlines, relevant roadside infrastructure, on and off-ramps, etc.) which will provide a reference to determine the vehicle's location along the road and within the lane via the GPS receiver. Methods for development of this base map are discussed in Chapter 2.
- An in-vehicle display to provide a look-ahead view of the upcoming roadway, the snowplow's position in the lane, and landmark information to provide a sense of overall position along the route.
- Other human-machine interface (HMI) components to guide and/or alert the operator in the noisy in-cab environment. Examples include vibrating seat (left or right side) for lane-departure warning, and similar approaches for collision warning to augment display-based warning.
- The required embedded computing, real-time software, and power systems to support this snowplow driver assistance system.

System Architecture and Hardware

To expedite development and facilitate research on GPS DAS methodologies and HMI improvements, the snowplow DAS was implemented and tested using a research prototype system.

Figure 4.01: Prototype snowplow DAS test vehicle

Figure 4.02: Road lane base map for testing the display systems.

Figure 4.03: Driver's view of the modified DAS HMI in the prototype system

Snowplow Research Focus: Reduced Operator Glance Time

A significant portion of the effort in the current research was committed to reducing the frequency and duration of the operator's need to glance at the visual display. This was in part through the use of tactile feedback for collision warning. Additional effort and testing was committed to display imagery redesign, including prototype testing to document the improvements in glance frequency and duration. This redesign was based on analysis and simulation, with testing performed on an AHMCT support research vehicle [18].

To develop a theoretical understanding of underlying issues in the design of the driver assistance system for the snowplow operation, AHMCT developed a mechanics-based model of the snowplowing operations [17] and a stochastic dynamic model of the human–in-the-loop steering dynamics of the vehicle [6]. These models have allowed development of simulation tools that can be used in evaluating different elements of the driver assistance system at the design stage, i.e. before hardware implementation.

In the snowplow driver assistance system, sensor data provides information that is fed back into the display system which shows the roadway lateral position of the vehicle. The snowplow operators can use the display system for lane-keeping in whiteout conditions when the level of snow in the air or on the roadway creates a condition where the roadway and lane boundaries are not visible through the snow. This is especially the case in the initial road opening or first plowing of the snow from a roadway or roadway lane.

Original Snowplow DAS Display

The Lateral Positioning Assistance Display system used in the RoadView Advanced Snowplow (ASP) [14,19,24] is shown in Figure 4.1. This display system has five icons consisting of the Predictor, the Current Lateral Position Marker, the Lane Delineation Identifiers (Ticks), the Roadway Edge Identifiers and the radar-derived Obstacle Bars displayed in a section on the left side of the display.

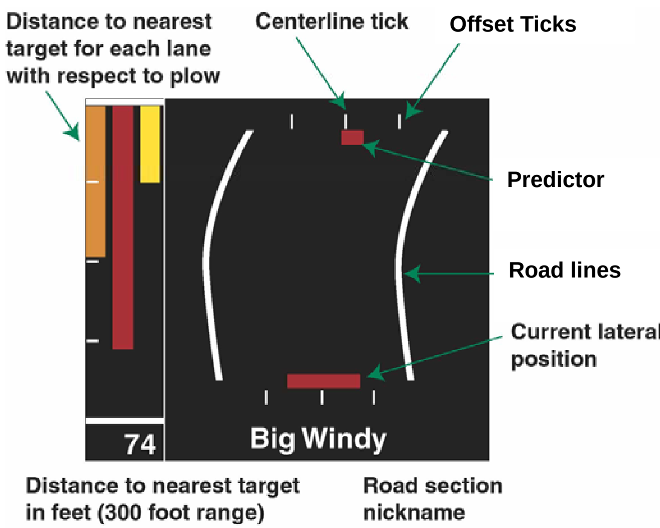

Figure 4.1: The original RoadView DAS display

The Predictor is a major component of the lateral assistance display. This marker or icon shows future lateral position of the vehicle 20 m ahead corresponding to the magnitude and the direction of the steering wheel angle, δ. When the steering wheel is turned right, the Predictor icon moves right. The current lateral position of the snowplow is shown at the bottom of the display by the Current Lateral Position Marker. The graphics is representing a displayed distance of 20 m (66 ft) with a lane width between the "curbs". The locations of the Road Line Markers are computed using an internal map database of road curvature. It is assumed that a driver can steer by positioning the Predictor at any desired future location. The internal dynamics then steer the vehicle to the predicted position. The bars in the left section of the display are activated using radar for collision avoidance with vehicles, trees, guardrails and other obstacles as the snowplow goes around turns on the roadway.

The display of Figure 4.1 was installed in the ASP and RoadView DAS vehicles. The system proved to be very effective, except that the field experience indicated driver fatigue with use of the system. This motivated a theoretical investigation to understand and isolate the parameters associated with the cause of the driver fatigue.

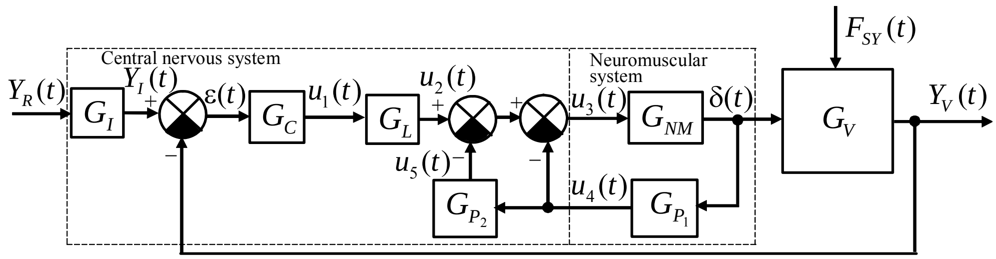

Figure 4.2: Control system model for lateral displacement of the snowplowing vehicle

Simulation of the Driver-in-the-Loop Response

In order to simulate the response of the display-based driver assistance system, a simple deterministic version of the driver-in-the-loop steering dynamics model that we have developed in [5] was used to perform a computational evaluation. Figure 4.2 shows a control system for lateral displacement of the snowplowing vehicle, where G_{NM} represents a second-order neuromuscular system of driver's arms [15]. The input of G_{P_1} is the output of the neuromuscular system, $\delta(t)$, the driver's steering input to the vehicle. The input of G_{P_2} is the output of G_{P_1}. G_{P_1} and G_{P_2} represent feedback of variables, derived from the motion of human limbs and muscle tissue; they are referred as proprioceptive feedback elements. G_L is a pure time delay element, representing human signal processing delays. G_{NM}, G_{P_1}, G_{P_2}, and G_L represent high-frequency compensation to the vehicle model. G_C is the PD controller, which represents low-frequency compensation to the vehicle model. Controller G_C is realized by a human driver and its output signal $u_1(t)$ represents a visual guidance cue. G_I is a preview element, including first-order filter and time advance factor, which represents the advancement of input, corresponding to a single constant "look-ahead distance" or "aim point" depending on forward speed. Look-ahead distance is about 21.3 m (70 ft) at 32-48 km/h (20-30 mph), which corresponds to about 1.5 s. G_V is the vehicle model. $F_{SY}(t)$ is the lateral component of the plowing force acting on the vehicle. $Y_R(t)$ is the desired lateral displacement of the vehicle, and $Y_V(t)$ is the actual lateral displacement. This model, illustrated in Figure 4.2, is described by the following differential equations [15].

$$G_C: \quad u_1(t) = K_y\left(T_3 \frac{d}{dt}\varepsilon(t) + \varepsilon(t)\right), \quad G_{NM}: \quad \frac{d^2}{dt^2}\delta(t) + 2\xi\omega_n \frac{d}{dt}\delta(t) + \omega_n^2\delta(t) = \omega_n^2 u_3(t) \tag{4.1}$$

$$G_{P_1}: \quad \frac{d}{dt}u_4(t) + \frac{1}{T_1}u_4(t) = K_1 \frac{d}{dt}\delta(t), \quad G_{P_2}: \quad \frac{d}{dt}u_5(t) + \frac{1}{T_2}u_5(t) = K_2 u_4(t) \tag{4.2}$$

$$G_I: \quad T_4 \frac{d}{dt}Y_{Ii}(t) + Y_{Ii}(t) = Y_R(t), \tag{4.3}$$

where $Y_{Ii}(t)$ is the output signal of the inertial part of the preview element G_I. In Figure 4.2, $Y_I(t)$ is the full output signal of the preview element [15].

The relationship between the steering angle $\delta(t)$ and the lateral displacement of the vehicle $Y_V(t)$ is described by:

$$\begin{aligned}&\frac{d^4}{dt^4}Y_V(t) - a_3\frac{d^3}{dt^3}Y_V(t) + a_2\frac{d^2}{dt^2}Y_V(t)\\&= b_2\frac{d^2}{dt^2}\delta(t) + b_1\frac{d}{dt}\delta(t) + b_0\delta(t),\end{aligned} \tag{4.4}$$

The driver parameters were selected based on recommendations in [15]. The vehicle model is detailed in [6], with simulation parameters shown in Table 4.1. The coefficients of (4.4) are $a_2 = 19.77$, $a_3 = 8.95$, $b_0 = 28.99$, $b_1 = 5.07$, and $b_2 = 0.642$. Here, a deterministic approach was used to demonstrate the response of the display-based driver assisted system with plow off the ground ($F_{SY}(t) = 0$). Since the plowing force is stochastic in nature due to disturbances in the road surface finish, changes in snow density during snow plowing due to possible ice packs and dirt in snow, etc., a stochastic approach needs to be used for studies with plow on the ground [6]. Simulation showed that the driver glancing at the display system increased human processing time delay (dead-time) in lane keeping, and reduced system stability, resulting in driver fatigue and decreased safety.

Table 4.1: Simulation Parameters

Symbol	Value	Description
K_y	1	Compensator gain
T_3	2.5	Compensator time constant, sec
ξ	0.707	Damping coefficient, neuromuscular system
ω_n	10	Natural frequency, neuromuscular system, Hz
K_1	1	Partial gain, proprioceptive feedback element 1 (total gain is $K_1 \cdot T_1$)
T_1	2.5	Time constant of the proprioceptive feedback element 1, sec
K_2	10	Partial gain, proprioceptive feedback element 2 (total gain is $K_2 \cdot T_2$)
T_2	1.4	Time constant, proprioceptive feedback element 2, sec
T_4	0.1	Time constant, preview element, sec

Pure time delays or dead-time of 0.15 s and more were used to evaluate the effect of the driver glancing at the display system in lane keeping. A 0.15 s pure time delay, according to [15], is considered to be a normal human signal processing delay when a driver looks at the road through the windshield. Bode diagrams of the open-loop system without and with the 0.15 s dead-time are shown in Figure 4.3 and Figure 4.4, respectively. The time delay case used a second-order Padé approximation of the time delay. Comparing the Bode plots of Figure 4.3 and Figure 4.4, it is clear that, as anticipated, increasing time delay in the loop does not change magnitude, but does change phase of the response significantly, reducing phase and gain margins, and therefore, negatively impacting the stability of the system.

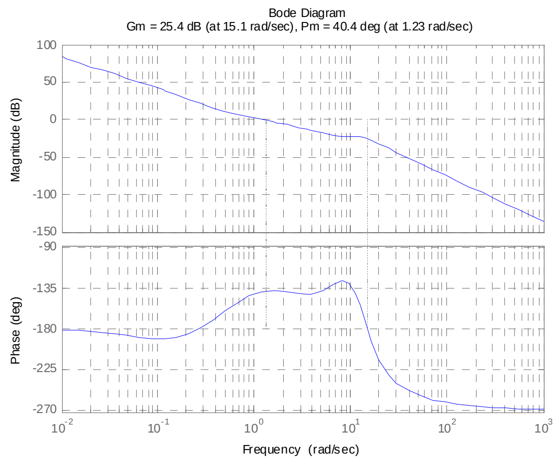

Figure 4.3. Bode diagram of the open-loop system without a time delay element

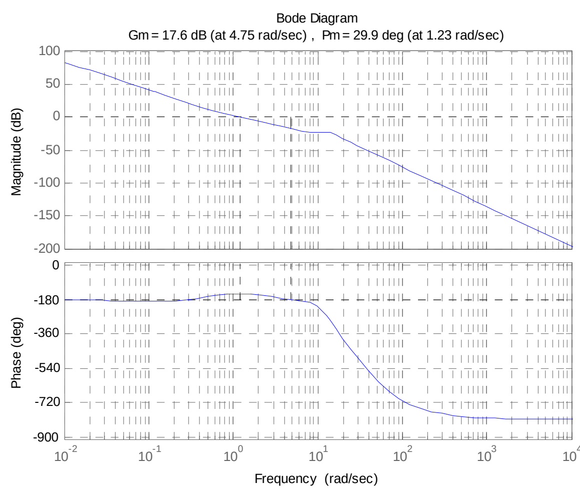

Figure 4.4: Bode Diagram of the open-loop system with 0.15 sec pure time delay (second-order Padé approximation of the time delay was used)

The idealized reference signal is shown in Figure 4.5(a). The actual lateral position of the vehicle with 0.15 s dead-time in the loop is shown in Figure 4.5 (b). When the driver starts paying attention to the display or other devices in the cabin during the maneuver, dead-time obviously increases. Figure 4.5 (c) shows lateral position of the vehicle with 0.45 s dead-time, while Figure 4.5 (d) shows the same with 0.55 s dead-time. As can be seen from this figure, tracking the idealized reference signal is not satisfactory. With dead-time above 0.6 s, the system becomes unstable.

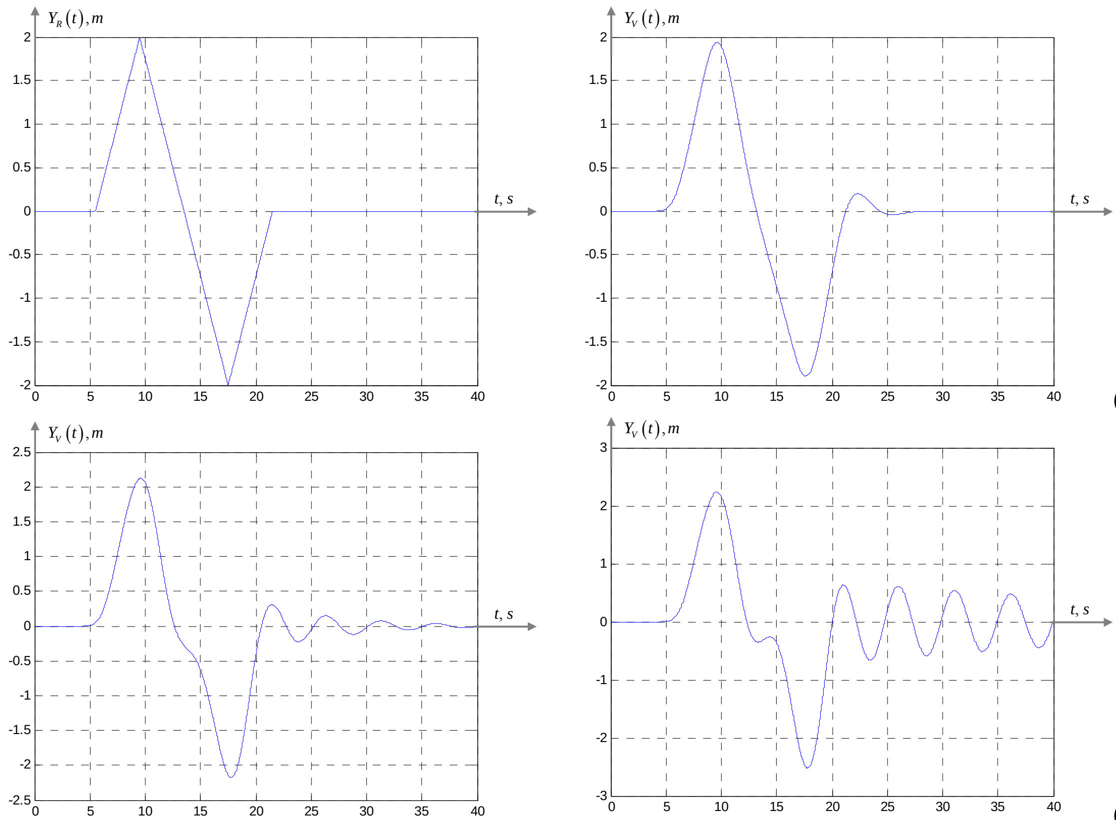

Figure 4.5: (a) Idealized reference signal $Y_R(t)$. Lateral position $Y_V(t)$ of the vehicle with pure time delay of (b) 0.15 sec, (c) 0.45 sec, and (d) 0.55 sec.

To improve safety and decrease driver fatigue, the display system was modified, making it Event-Driven and Prompting. These modifications include the addition of Event-Driven caution signals and flashing arrows on the display warning the driver before the vehicle crosses the lane boundaries. The hypothesis was that these display modifications would significantly reduce human signal processing time delay in glancing at the display, enhancing stability of the whole system, reducing driver fatigue, and improving safety.

The Improved Event-Driven Prompting Display System

The simulation results clearly demonstrate that increasing the human signal processing time delay (dead-time) due to paying attention to the Lateral Assistance Display significantly reduces the stability of the whole system, and as a result, has a negative effect on safe driving on the road. The Lateral Assistance Display therefore needs to be modified to reduce the time delays involved in the driver dividing attention between the windshield and the display. In order to achieve this, the display system was modified to make it into an Event-Driven Prompting Display. The idea is to prompt the driver when an event is triggered, therefore focusing attention of the driver to the display from the windshield only at such times rather than having the driver keep glancing back and forth between the display and the windshield. The event that would trigger the prompts for the driver is defined to be when the vehicle lateral position gets close to crossing the lane boundary on either side; the driver prompts are designed in the form of flashing visual arrows and audible alerts from the HMI. A criterion of time to line crossing (TLC) was used to trigger the prompts with a threshold of 2.5 s. The Event-Driven Prompting Display is meant to be used only in whiteout conditions, and by design it does not issue false alarms to the operator. I.e., the system issues alerts if and only if the defined lane boundary crossing criteria are met, and in whiteout conditions, these criteria always require an alert.

The improved display system is shown in Figure 4.6. In this display system, the Predictor triggers events prompting driver attention to the display (hence, Event-Driven). When the Predictor gets close to a lane boundary, the system triggers the appearance of a flashing yellow arrow (hence, Prompting) on the display (as shown in Figure 4.6) at the approaching boundary line. This action is augmented with a beeping sound, with a specific tone for each (left and right) lane line so the driver knows which side of the lane they are approaching, again prompting the attention of the driver to glance at the display. The arrow points to the direction where the driver needs to steer the vehicle for safe lane-keeping.

Figure 4.6: The modified Event-Driven Prompting Display

Comparative Field-Testing of the Two Display Systems

To evaluate the performance, this modified display system was tested in comparison with the original display system in actual on-the-road testing. In this section, the results from experimental testing of the two Lateral Assistance Display Systems are presented. The testing was performed in a Chevrolet Suburban equipped with the same sensor-based Driver Assistance System as the Advanced Snowplow. This eliminated the need to bring snowplow vehicles off-line, and facilitated the process of integrating other test equipment into the vehicle. The interior of this Chevrolet Suburban was retrofitted with cameras to detect the visual field of the drivers to determine the times that they are glancing at the display as compared to the windshield. The two display systems were used in turn during testing.

Four experienced drivers took part in the testing of the Display Systems. To make the experiment as close as possible to the real whiteout conditions in snow removal, no markings of the lane centerline or the lane boundaries were made on the road, so that such lane delineation marks would not be visible by the drivers through the windshield – a condition similar to the whiteout condition in snow removal. The drivers could only see the lane centerline and lane boundaries on the Lateral Assistance Display Systems. The task for the drivers was to drive the vehicle on the road lane, trying to stay in the lane and use the Display Systems for navigation as necessary. The length of the lane was 1.3 km. The lane width was 3.6 m. Each driver drove the vehicle twelve times – six times with the Display System without modifications and six times with the Display System with the modifications.

Figure 4.7 shows the experimental setup for testing the display systems. The following three recordings were simultaneously done on one series of images: 1) The view of the Lateral Assistance Display to count the number of times the vehicle crossed the lane boundaries; 2) Drivers' face and eye location, allowing determination of the number of times and duration of each that a driver looked at the display; 3) The road view through the windshield - this provided auxiliary visual information about the vehicle position on the road. The three video signals could then be reviewed simultaneously on a monitor, each in its own quadrant of the display. Data extracted to compare the Display Systems included: number of times vehicle crossed the lane boundaries; number of times drivers looked at display; and duration of time drivers spent looking at display.

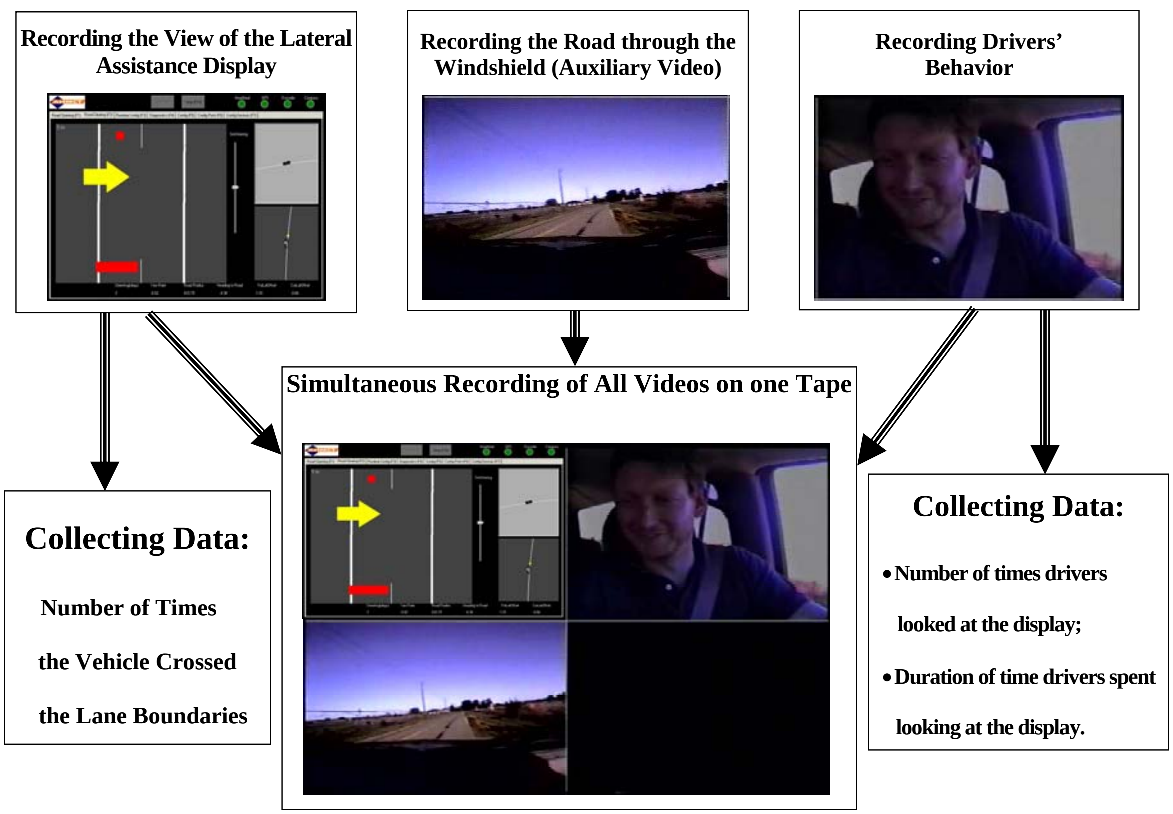

Figure 4.7: Experimental setup used in testing the Lateral Assistance Display Systems

Figure 4.8 shows the average number of times the vehicle crossed the lane boundaries. Figure 4.9 shows the average number of times drivers looked at the display. Figure 4.10 shows the average time duration drivers spent each time they looked at the display. Figure 4.11 shows the total time duration drivers spent looking at the display in four runs. As can be seen from

Figure 4.8− Figure 4.11, all parameters are significantly reduced with the modified Display System, allowing drivers to spend more time focusing on traffic, improving safe driving conditions on the road. Data in Figure 4.8 clearly show improvement in the stability of the system as the number of times the drivers crossed the centerline of the lane reduced significantly. This would enhance the safety of the snowplowing operation. Results of Figure 4.9 show a drastic reduction in the number of times that the drivers looked at the display with the modified system. This shows that the prompting function of the new display played a key role in easing up the requirement for the driver to keep looking at the display—this can potentially significantly reduce driver fatigue. The results in Figure 4.10 and Figure 4.11 show a reduction in the average and total duration in looking at the modified display. This indicates that the modified display more clearly prompted the driver to the type of steering action they have to make for lane keeping as compared to the original display system.

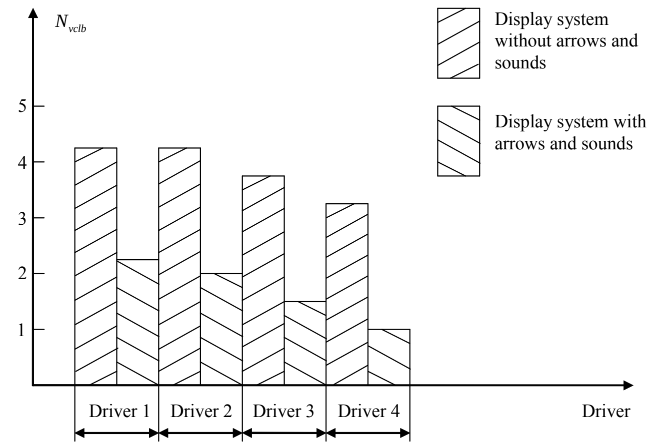

Figure 4.8: Average number of times the vehicle crossed the lane boundaries

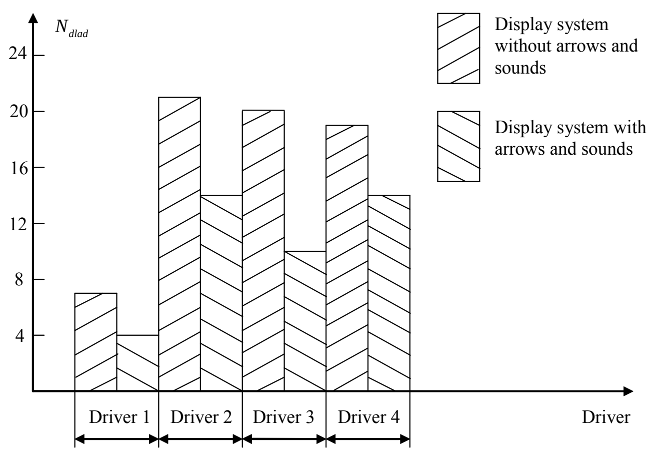

Figure 4.9: Average number of times drivers looked at the display

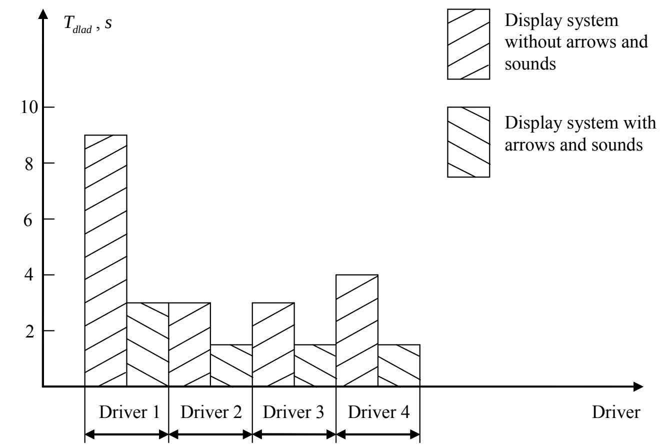

Figure 4.10: Average time duration drivers spent each time they looked at the display

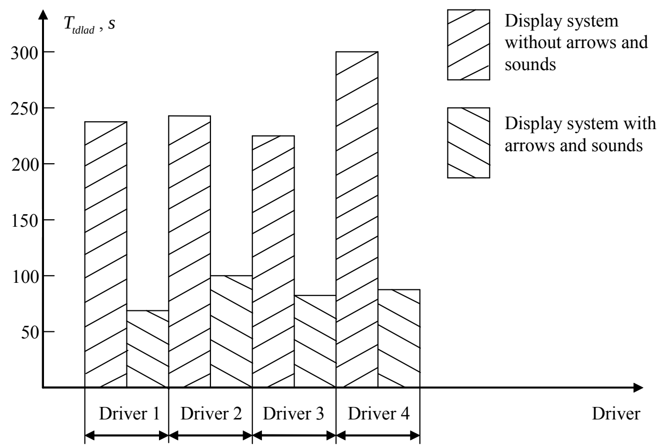

Figure 4.11: Total time duration drivers spent looking at the display in four runs

These results clearly demonstrate a significant benefit achieved by redesign of the DAS HMI, including revised imagery as well as audible feedback. The current implementation did not include tactile feedback.

CHAPTER 5:
GPS-BASED ROTARY PLOW DAS

This system is intended to provide driver assistance to allow the operator of a large rotary plow operating on the road (i.e. normal operations to remove built-up snowbanks from the shoulder) to safely and efficiently remove snowbanks, to operate very near to but not touching the guardrail, and to avoid impacting or ingesting obstacles obscured in the snowbank. This includes driver assistance in the form of relative positioning information vs. the guardrail location, as well as integrated collision warning. The system would benefit from forward and side-fire radar developments. These developments were occurring in a separate project, but that project was terminated prior to prototype development [4]. These AHMCT custom-developed radar systems would have provided range to the guardrail, and range and heading to buried obstacles. As these are key components of the GPS-based rotary plow DAS, essential for field operation, the current research did not include a field implementation stage. This chapter describes the system concept, and provides a view of the approach that would allow integration of the GPS-based DAS for global positioning with the side-fire radar for virtual compliant control to fine-tune the plow's position relative to the guardrail. GPS is the primary sensor for rotary plow driver assistance, and the system concept includes:

- A GPS receiver to provide high-accuracy (cm-level) vehicle location in World Geodetic System (WGS-84) latitude / longitude / altitude coordinates, suitable for integration with the GIS noted below. The rotary plow operation requires the best accuracy available from current GPS, and should be based on a fixed base-station RTK GPS receiver. AHMCT and Caltrans have already installed such a base station near Kingvale, CA, providing a key component required for this system.
- Associated support sensors (vehicle speed, inertial measurement unit) to augment the GPS in a complementary fashion (i.e. to provide strengths where GPS is weakest, and to take advantage of the strengths of GPS).
- Custom-developed AHMCT side-fire radar system to provide range from the rotary plow to the guardrail [4]. This local ranging is a key benefit of the system concept, and would provide a strong enhancement over previous approaches which were referenced vs. the roadway, and assume a known relative guardrail position. This range information would be provided to the operator via the in-vehicle HMI. However, the local range can be intelligently combined with the global trajectory information provided by the GPS / GIS components. With this ideal sensor suite, one can develop a virtual compliant controller to automatically guide the rotary plow along the global trajectory while adjusting the position locally based on the range sensor data, which acts as a virtual force on the vehicle [9,10,12]. Automated control was outside the scope of the current research, but the possibility is noted here for future reference.
- A high-accuracy GIS database representation of the roadway, in particular the shoulder and guardrail locations as well as relevant roadside infrastructure, on and off-ramps, etc., which provides a reference to determine the vehicle's location along the road and on the shoulder via the GPS receiver.
- An in-vehicle display to provide the distance to the guardrail. The operator would use this as a primary indication to adjust the vehicle position relative to the guardrail.

- Other human-machine interface (HMI) components to guide and/or alert the operator in the noisy in-cab environment. In this noisy and challenging environment, it may be most appropriate to use vibrating seat for obstacle warning.
- The required embedded computing, real-time software, and power systems to support this rotary plow driver assistance system.

The rotary plow DAS would use a bird's eye view display very similar in layout to the display used in the MPRO DAS. Key differences would relate to the distinct nature of the two operations. First, for the rotary plow DAS, height above the roadway is not an issue; thus this component would be removed from the HMI. The critical components for the rotary plow DAS would be related to obstacle and guardrail ranging. A component related to obstacles ahead of the rotary plow would be added to the HMI, likely using the space freed up by the height above roadway component. In addition, and as a primary feedback element to the operator, lateral range between the vehicle and guardrail would be provided to the operator. While this component could be included on the LCD screen, it is more appropriate to place this critical information in the most convenient location for the operator, as it would be the primary feedback means for steering the rotary plow. AHMCT developed custom LED-based display technologies that are well-suited to provide this ranging information to the operator. One of these LED-based displays could be mounted within the rotary plow in a manner that provides a simple and low-cost Head-Up Display (HUD) reflected by the windshield in the operator's field of view. In this manner, the range data is readily but unobtrusively available to the operator while they maintain their focus out the window as in current operations.

The same technologies noted here for a rotary plow DAS can be leveraged to provide full automated control of the rotary plow. Of course, such an application must be carefully considered when applying full automation in an environment exposed to public traffic. Other considerations must be factored in, particularly the need for full automation vs. the driver assistance approach, and the likelihood of needing an operator in the vehicle as a fail-safe backup even in the fully automated approach. Under prior research with AHMCT, the California Partners for Advanced Transit and Highways (PATH) investigated infrastructure-based rotary plow automated control. AHMCT researchers have, via simulation, investigated approaches for GPS-based automated control [8].

As noted previously, the ranging elements that are key to the rotary plow DAS were being developed in a separate research project. After that project started, the need for such a system was re-evaluated by Caltrans end users and management. At this time, Caltrans determined that such a system would not currently be cost-beneficial. In response, AHMCT halted research work and expenditures on that project [4]. With this key technology needed for field testing of the rotary plow DAS, this part of the current research remains at the concept stage.

CHAPTER 6: CONCLUSIONS AND FUTURE RESEARCH

Key contributions of this research project included:

- Unified elements in support of winter maintenance Driver Assistance Systems (DAS), including approaches for GIS base map development, representation.
- Identification of application-appropriate methods and systems for RTK DGPS corrections, including infrastructure-free SBAS approaches for MPRO DAS operations, and fixed base station RTK DGPS approaches for snowplow and rotary plow DAS operations.
- Conceptual operations and architectures for the three application areas.
- Further hardening and enhancements of the MPRO system.
- Field testing and operator feedback for the MPRO system.
- Significant enhancements to the snowplow DAS HMI, leading to reductions in glance time and frequency, with associated improvements in safety and operator fatigue. These improvements were demonstrated in prototype testing with multiple operators.

The safety improvements of each of the systems can be significant. Operator feedback from the MPRO field testing has been quite positive. AHMCT factored in operator suggestions for improvements in its iterative development of the system. Mobility benefits are also achieved via the snowplow DAS, due to extended operational capabilities that can either keep the roadway open, or lead to reduced time to reopen the roadway after severe storms. Finally, the rotary plow system would achieve both safety and cost improvements by reducing the damage to guardrails and the corresponding need to frequently repair this critical infrastructure component.

AHMCT is supporting related Caltrans research on tightly-coupled differential corrections methodologies. This work, being performed by UC Riverside researchers, should lead to significant improvements in GPS accuracy and availability. AHMCT also expects to work together with the University of Minnesota to evaluate its GPS-based snowplow system in the context of Caltrans operations. This system has seen field deployment in Minnesota and Alaska.

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