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Adaptation of Wheeled Mobile Robots to Highway Maintenance Operations*

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Abstract

This paper reviews the important research and development activities in the subject of Wheeled Mobile Robots (WMRs), in order to evaluate their potential use in highway maintenance and construction tasks. It particularly focuses on mobility as an essential feature for highway maintenance and construction application, which concerns wheel type arrangement, kinematics, dynamics, navigation and control. For each of these areas, aspects related directly to the deployment of WMRs in highway maintenance are discussed.

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Chapter 1

Introduction

There has been widespread research on the use of robotics in various applications and recently several authors have discussed the use of robotics in construction (Oppenheim and Skibniewski, 1988; Hasegawa, 1989; Ishikawa, 1988). However, very few works has addressed the use of robotics in highway maintenance.

The importance of highway maintenance lies mainly in the need to protect the substantial investment that has been made in the highway infrastructure. Furthermore, the significance of the maintenance function is seen in the vital need to continue the economic and safety benefits of the road system. In California alone, the State Department of Transportation (Caltrans) spends about $100 million per year maintaining approximately 33,000 lane-miles of flexible pavement (Asphalt Concrete - AC) and 13,000 lane-miles of rigid pavement (Portland Cement Concrete - PCC) (Velinsky, 1993).

There are several important reasons for automating highway maintenance operations through the use of robotics including:

- Highway maintenance activities often involve repetition of the same or similar work cycles (e.g., roadway marking). Robots can readily be programmed to perform repetitive work cycles.
- Highway maintenance activities are dangerous to both public and the traveling public. The use of robots will improve the safety of workers by reducing their exposure time to traffic which consequently improves traveler's safety.
- Current methods for highway maintenance are generally labor intensive, tedious and slow which result in traffic congestion as well as wasting fuel and polluting the air. Robots can alleviate all of these problems. Overall, the use of robots can improve the efficiency and speed of highway maintenance operations which improves their cost effectiveness.

Commercially available robots are not easily suitable for highway maintenance applications because they have payloads well below the weights of many highway maintenance devices. Conventional robots have been used for highway maintenance operations with some modifications. Velinsky (1993) used a SCARA[1] type robot for roadway crack sealing operations. The payload requirements for the crack sealing operations, were well above the payload of the SCARA robot. Hence, a secondary arm was designed that could carry the weight of the sealant applicator. Highway maintenance activities usually require relatively heavy end-effectors to follow a specific path which is also difficult for conventional robots. A WMR designed specifically for highway maintenance and construction operations has the potential to overcome all these problems.

Existing mobile robots tend to be research-oriented vehicles. They have been used for experiments in vision, navigation, ultrasonic detection of obstacles, and path planning.

There are many potential applications of WMRs. Following an agreement reached at the Summit Meeting of Heads of State and Government held in France in 1982, Japan and France initiated joint research programs for the design of multipurpose autonomous mobile robots to replace workers in difficult and dangerous tasks (Zhou, 1991). The French mobile robot projects included:

- automatic maintenance of machine tools;
- automatic cleaning of buses and underground railway stations;
- forestry applications;
- coal mining applications;
- underwater applications including diver assistance;
- maintenance and rescue in nuclear plants.

Some other potential applications of WMRs include: reconnaissance/exploratory vehicles for space, underwater and land use; material handling systems for the office and the factory; intelligent wheelchairs for the handicapped; and, of particular interest to the authors, highway maintenance and construction applications.

This document reviews the important research and latest development activities in the subject of WMRs. This document focuses particularly on an overview of the most prominent WMRs, practical wheel type arrangements, kinematic and dynamic models, navigation, and control. All of these aspects fall within the area of mobility which is an essential feature required for highway maintenance applications.

For each of these areas, aspects related directly to the deployment of WMRs in highway maintenance are discussed. As such, this paper provides a concise yet thorough review of existing work in the area of WMRs to enlighten highway researchers. It additionally discusses those aspects of highway maintenance that differ from conventional work applications and need attention.

[1]SCARA is the acronym for Selectively Compliant Assembly Robot Arm.

Chapter 2

An Overview of the Most Prominent WMRs

This section covers a survey of several WMRs that are described in order of their appearance chronologically. In general, it describes features, purpose of design, time of manufacture, design problems, and further improvements. This overview shows that much work is yet to be done in the areas of control and sensors, and some modifications in system architecture are needed for a WMR that can perform highway maintenance operations (Ravani, Velinsky and West, 1994).

2.1 Shakey

Research on mobile robots began in the late sixties with the Stanford Research Institute's (SRI) pioneering work. Two versions of Shakey, an autonomous mobile robot, were built in 1968 and 1971. The main purpose of this project was "to study processes for real-time control of a robot system that interacts with a complex environment" (Giralt, Chatila and Vaisset, 1984).

Shakey derived its name from its unstable appearance as it attempted to move. A computer organized the vehicle's actions and controlled those actions as the vehicle moved. Information from the vehicle's television camera and other sensory devices permitted the computer to modify its plans while the vehicle was attempting to accomplish a task. This vision system ran very slowly, taking an hour to find a block and a ramp in a single scene. The first computer used in the Shakey system was an XDS-940 with 64k 24-bit word Random Access Memory (RAM). Later, in 1971, a PDP-10 was used.

The principal impact of this research was the awakening of the concept of a machine with intelligence, "a reasoning machine" (Steele and Ebrahimi, 1986).

2.2 The Stanford Cart

The Stanford Cart project (Moravec, 1983), which started about 1973 and lasted until 1981, emphasized perception and control rather than planning, as with Shakey. It was a remotely computer controlled vehicle which used a television camera as its only sensor. The Cart could follow a white line in real-time. The Cart used several kinds of steropsis to locate objects around it in three dimensions and to deduce its own motion. It planned an obstacle-avoiding path to a desired destination based on a model built with this information. The plan changed as the cart perceived new obstacles on its journey.

The system was reliable for short runs, but slow. The Cart moved 1 m every 10 to 15 min, in a lurching manner. After rolling a meter, it stopped, took some pictures, and thought about them for a long time. Then it planned a new path, executed a little of it, and paused again. The Cart made several experimental runs, taking approximately five hours to complete a 20 meters course. Despite many problems, the journeys of the Stanford Cart were unique because they were the first mobile robot journeys through realistic environments using only the mobile robot's intelligence.

2.3 Jet Propultion Laboratory (JPL) Rover

The objective of this program was the development of a nearly autonomous mobile robot for use in space exploration (Steele and Ebrahimi, 1986). The human interaction would be limited to the selection of goals and similar higher level functions. The JPL Rover was then able to analyze a scene of the environment for traversability, generate a planned path to the goal, and follow that path. The mapping system on the JPL Rover was the first to handle storage of large-scale terrain maps. The Artificial Intelligence (AI) path planning techniques were also new, and the hierarchical control system on the JPL Rover is still one of the most sophisticated designed to date. The JPL Rover was also the first mobile robot to carry a robot manipulator.

2.4 The Carnegie-Mellon University WMRs

The Robotics Institute of Carnegie-Mellon University (CMU) is responsible for several research mobile robots, the most recognized of which are Pluto, Neptune, Uranus, and Terregator.

2.4.1 Pluto (CMU Rover)

Pluto (Moravec, 1983) was the first mobile robot built at Carnegie-Mellon University. The design of Pluto began in 1980. The major goals for Pluto included continuing the work on visual navigation that Moravec initiated on the Stanford Cart, as well as providing a high performance platform capable of accommodating a robot arm. Essentially Pluto provided a robot base which had three degrees of freedom: two degrees of translation, and a rotation about the mobile robot's vertical axis. This was achieved by designing all three wheels to be steerable which allowed omnidirectional drive. Each wheel was actually a pair of wheels positioned off-center of the wheel turning axis. The pair was connected via a differential gear. The body of the machine was cylindrical, about 1 m tall and 55 cm in diameter, and weighed about 90 kg. Unlike the Stanford Cart, which depended on a vision system for its position control, Pluto utilized modern microprocessor and motor technologies of the time to provide a high level of closed-loop control of the vehicle. Specifically, the unit had three independently controllable wheel assemblies. Each of these wheels is driven by two servo motors; one for steering and the other for driving. 4000-line incremental optical encoders are employed on all six motors to provide position feedback for the digital servos. Pluto actuator control was handled by six separate Motorola 6805 microprocessors which utilized feedback and desired position information, obtained from a Motorola 68000 microprocessor. This information was then used to send pulse-width-modulation commands to the motors. With this scheme, the robot can be made to turn about its vertical axis in addition to being able to execute linear motion.

2.4.2 Neptune

A new, more simple mobile robot denoted Neptune was designed and built in three months to overcome control problems with Pluto. Neptune was a tricycle design with a single forward wheel providing both the steering and drive. It could travel at 30 cm/s and turned around in a circular space of diameter 1.2 m. The steering wheel could be rotated at 20 deg. Neptune was equipped with a 360 deg ring of 24 sonar range sensors (Elfes, 1987).

Neptune, which has proven to be a very reliable research vehicle, continues to be the test bed for mobile robotic research, including AI command and control schemes.

2.4.3 Uranus

Uranus was the third mobile robot designed at CMU. Uranus had four omnidirectional wheels mounted at the corners of a rectangular frame (Muir and Neuman, 1987a). Each wheel consisted of a wheel hub about which 12 rollers were mounted at an angle of 45 degrees to the wheel orientation. In forward and reverse travel, the wheels worked normally. However, by turning wheels on opposite sides in opposite directions, the robot traveled sideways. The inner hub of each omnidirectional wheel was driven by a brushless DC motor, and its position was sensed by an optical shaft encoder. The position and velocity of each wheel were thus available to the control processor through the interface electronics. The interface electronics also handled electronic communication and pulse-width-modulation for the brushless DC motors. The desired robot position trajectory was communicated to the control processor from an independent off-board processor. A stiff suspension mechanism was built into each wheel assembly.

2.4.4 Terregator

Terregator (Wallace, et al., 1985), the fourth CMU mobile robot, used in several outdoor experiments, including road-following and outdoor sonar navigation. Terregator was a six-wheeled vehicle approximately 1.6 meters long and one meter by one meter square. All six wheels were driven; one motor drives the right side and another the left. Terregator navigated with a vision and navigation algorithm. The aim of this project was to develop vision and intelligence capabilities for a mobile robots operating in the unstructured outdoor world. The robot is equipped with a sonar ring, a color camera, and a laser range finder. Its initial task was to follow roads and sidewalks, while avoiding obstacles such as trees, humans, and traffic.

2.5 Unimation Machine

Unimation Corporation was developing an omnidirectional vehicle about the same time CMU was building Pluto (1983) (Carlisle, 1983). In order to minimize the floor space required to turn corners and to eliminate the control problems associated with steering, this vehicle was designed to be omnidirectional and compact. The vehicle had a PUMA 600 robot arm mounted on it. The primary utility of this mobile robot would be in servicing multiple workstations in a manufacturing environment.

Unimation, after researching the different approaches to omnidirectional travel, designed a three-wheeled vehicle. Each of the three wheels was composed of a ring of eight rollers, which were alternated by the length (long and short) of their major axis. The three wheels were configured in an equilateral triangle shape so that by driving different combinations of wheels the vehicle could be made to travel in any direction. Each wheel was driven by a torque motor with one spur gear reduction.

The controller consisted of a repackaged Unimation PUMA series controller. A standard Unimation PUMA teach pendant was used to program both the robot and the mobile base. Instantaneous vehicle motion could be decomposed into two motions: translation of the vehicle center and rotation about the vehicle center. Because there was no direct transformation between the number of wheel revolutions and vehicle position or orientation, vehicle location had to be determined by integrating linear and rotational vehicle velocities in the control loop. Unimation's high-level robot language, VAL I, was used to program the vehicle. The vehicle was programmed using the same instructions and manual control as the PUMA manipulator. Course navigation was done by dead reckoning.

2.6 Hilare

The Hilare project started at the end of 1977 in France. The project's goal was to perform general research in robotics, robot perception, and planning (Giralt, Chatila and Vaisset, 1984). Hilare's main characteristics were: (1) perception provided by a video camera and a laser range-finder mounted on a two-axis scanning system, (2) locomotion provided by two-rear drive wheels, and (3) a computer system which consists of a local minicomputer and a remote time-shared IBM mainframe. Decision-making was a distributed process effected through a high level coordinator in a hierarchical structure. Individual modules consisted of (1) specialized knowledge bases, (2) algorithm heuristics, (3) local error-processing capabilities, and (4) communications. The navigation and motion control system (NMCS) was one of Hilare's specialized decision modules. The basic procedures were routing, navigation, low-level vision, locomotion, position finding, and local obstacle avoidance. Obstacles were defined as polyhedral. Each obstacle projection was represented as an ordered list of segments in counter-clockwise sequence. Trajectories were considered as straight lines between entry and exit segments. A cost function was used to quantify the relative cost of different paths and plan was formed by finding the minimum cost path to the goal. Hilare was also fitted with ten ultrasonic sensors. These sensors were part of a closed- loop-close-quarter navigation system, which took control of the navigation when needed for close range maneuvering.

2.7 Meldog

This mobile robot was equipped with an ultrasonic system and obstacle avoidance capabilities and was developed to serve as a guide dog for blind people (Tachi, et al., 1981). The robot obeyed spoken commands and had a very accurate system of speed and direction control. Communication between the user and Meldog was over a flexible wire link. Control commands such as LEFT, RIGHT, STRAIGHT and STOP, were transmitted by control switches on the harness. Alarms signaling danger from Meldog to the user, were transmitted over the wire link, in the form of mild shocks to the blind person's hand. Ultrasonic transducers were also used in a feedback system between man and Meldog, so they could walk fast or slow, while a distance of 1 m was always maintained between the two. The design of Meldog started in 1979 and finished in 1983.

2.8 Robart-I

Robart-I was built at the Naval Post-graduate School to serve as a feasibility demonstration for wheeled mobile robots; see Everett (1982a; 1982b). Robart was intended to patrol a site in a random manner, sensing fire, smoke, flooding, toxic gas, intrusion, etc., and issued an appropriate warning if any of these conditions were found. This robot did not have any planning capabilities. It was a mobile warning system, whose motion was not goal-oriented;

it was random wandering.

A motion routine was randomly chosen from a preprogrammed set of sixteen routines. Some of these routines would move the robot to a new vantage point, where it might choose to stop and re-enter the surveillance mode. Motion under these circumstances usually involved moving straight ahead, unless it saw an object, in which case it would swerve to one side or the other as appropriate. The robot had a single forward-looking ultrasonic ranging unit, a long-range near-infrared proximity detector that could be positioned by a rotating head, ten short-range near-infrared proximity detectors, and tactile feelers and bumper switches for collision avoidance. Other on-board sensors included an infrared body heat sensor which could detect a person up to a distance of 15 m.

Because of the success of this prototype mobile robot, a second generation unit called Robart-II, was built. It improved upon many of the capabilities and features of Robart-I. Among these modifications was the replacement of the single ultrasonic ranger by an array of sequentially-fired Polaroid sonar sensors. Centered on the forward axis, these units permit beam-splitting to be utilized, thereby increasing the system's horizontal resolution and also allowing course and speed corrections to be made if the robot is to follow a target at a fixed distance.

2.9 Sentry

Sentry was developed by Denning, a commercial mobile robot manufacturer (Steele and Ebrahimi, 1986). Sentry was a cylindrical shaped robot approximately 1.2 m high and 0.7 m diameter, weighing approximately 170 kg and had a maximum speed of 5 km/h. The robot had three wheels, all of which have synchronous drive and synchronous steering. As an operating system, the robot ran OS-9, a UNIX-like real-time operating system. The sensors were a ring of 24 Polaroid ranging devices placed at a height of 0.75 m for object detection. From multiple scans, the sensor program produced a map of its surroundings including obstacles and walls. Internal communication was provided by RS-422 synchronous data link on a multi-drop back plane, and external communication was done via RS-232C.

2.10 Mars Rover

In the 1970's, there was a Mars Rover research program at the Jet Propulsion Laboratory (JPL) sponsored by the National Aeronautics and Space Administration (NASA). The program ended in 1979. Recently, there has been revived interest in planetary rovers. A JPL study and a workshop have helped to define the characteristics for a Mars Rover for the 1990s. Work is continuing with plans for a 1998 launch and numerous issues are still being addressed (Wilcox and Gennery, 1987).

2.11 Construction Mobile Robots

Oppenheim and Skibnieski (1988) have performed a survey of the significant research and development activities in construction robotics. Among the numerous robots discussed, several employed wheels for locomotion and these were used in numerous applications. Construction robots are, in general, not commercially marketed. There have been significant attempts to robotize a number of narrow applications using WMRs, including:

1. Surface Finishing: a fireproofing spray robot by Shimizu Construction Company, and a concrete slab finishing robot by Kajima Construction Company. The latter was designed to smooth the surface of a wet concrete floor after pouring. It was equipped with gyrocompass, travel distance sensor, and self-navigation logic that enabled it to determine its position and made automatic adjustments to its path (Groover, et al., 1989).

2. Structural Element Placement: a reinforcement-placing robot developed by Kajima Construction Company.

Articles by Hasegawa (1988; 1989) give insight into the progress being made in introducing robotics and automation into the construction industry. He believes that recent progress in robot technology is breaking through the barriers to robotization in the construction industry. Hasegawa listed some of the construction robots developed in Japan.

A number of mobile robots have been developed for concrete distribution and finishing. The Multi-Purpose Traveling Vehicle (Shimizu) (Oppenheim and Skibniewski, 1988) with a multi-function capacity for clearing, has been developed for grinding of concrete slab surfaces. The CFR-1 (Shimizu) is a board-setting robot which sets and fixes ceiling and wall boards. Tile and wall inspection robots such as Exfoliated Wall Tile Detector (Kajima), and Self-Climbing Inspection Machine (Zhou, 1991) are also in current use in industry.

Chapter 3

Practical Wheel Arrangement

In mobile robot design it is of prime interest to define the wheel arrangement, which affects both the kinematic and dynamic characteristics of the vehicle. The mechanical configuration of most WMRs falls into two categories: steered-wheel and differential-drive. The steered-wheel configuration typically consists of a fixed rear axle and a single-steered (and often driven) front wheel. An advantage of differential-drive mobile robots is the ability to turn with zero radius, hence making maneuvering easier either in a cluttered environment or while following a path.

There are basically three types of wheels that are used in WMRs: conventional, omnidirectional, and ball wheels.

The conventional wheel is the most widely used. It is usually mounted on a steering link to provide an additional Degree-Of-Freedom (DOF). Muir and Neuman (1987b) defined this DOF as rotational slip. It allowed the vehicle to travel along a surface in the direction of the wheel orientation, and to rotate about the point of contact between the wheel and the floor.

The omnidirectional wheel has three DOF. Unlike the conventional wheel, it has rollers mounted around the periphery of the main wheel, which enables movement along the wheel axle. The ball type wheel is the most maneuverable and it has three DOF without slip.

Winters and Velinsky (1992) reviewed several WMR wheel types and categorized them based on three types of wheel arrangements. Among the listed WMRs: Shakey, Newt, Hilare, and Robart-II are conventional two-DOF; Neptune and Stanford Cart are steered conventional two-DOF; Uranus, the Unimation robot, and Rover are omnidirectional.

Gentile and Mangialardi (1992) examined nine different types of wheel arrangements. The characteristics of each of the nine arrangements were assessed in terms of stability and dexterity in relation to a minimum radius of curvature during locomotion over a plane surface. Parameters were suggested for evaluating the stability and dexterity characteristics of the various arrangements.

West and Asada (1992) designed an omnidirectional spherical tire that allowed the vehicle to maneuver in an arbitrary direction from an arbitrary configuration on a plane. The authors suggested that this type of design significantly simplified control problems and improved positioning accuracy. The two translational motions were found to have a positional accuracy of within one percent and were not affected by each other or variations in floor friction. Vehicle rotation was found to be less accurate due to tire slip problems.

The conventional wheel arrangement, as used by Newt, for example, had two DOF. The advantage of this arrangement was that it was simple to build. The other conventional wheel arrangement, such as the Stanford Cart and Neptune, had two DOF, yet they cannot follow any arbitrary path in a plane. This was due to their constrained turning radius. The omnidirectional wheel arrangement, as used by Uranus and Unimation robot, had three DOF. The disadvantage of this arrangement was its complexity. Although difficult to implement, it allowed unconstrained motion in any direction which means there were no singularity points.

A typical highway maintenance operation that could employ a WMR is pavement crack sealing. This operation involves four different tasks, including: routing, debris removal, heating and sealing. Of these tasks, routing is the most demanding due to its excessive forces and severe vibrations. With this task in mind, we note that the wheel type configuration must produce enough tractive force to overcome the router blade's resultant force. Furthermore, a Wheeled Mobile Robot, for the purpose of highway maintenance tasks, requires a high degree of maneuverability, e.g., to follow the arbitrary nature of pavement cracks.

While the omnidirectional wheel has the advantage of having three DOF, it is more difficult to construct due to the intricate shape of the wheel. It also does not necessarily generate adequate friction force to drive the WMR forward while the router is in operation. Similarly, the ball type configuration cannot generate adequate friction force, and it has the further disadvantage of being difficult to actuate.

It can be concluded that a differential-drive wheel configuration using pneumatic or semi-pneumatic tires has a particular advantage due to its ability to turn with zero radius, making maneuvering easier while the WMR performs highway maintenance operations. This type of design also eliminates the control problems associated with the steering wheel type configuration. Finally, the pneumatic tires are able to absorb vibrations due to routing and road roughness while maintaining tractive capabilities.

Chapter 4

Kinematics and Dynamics of Wheeled Mobile Robots

A comprehensive treatment of the kinematics of steered-wheeled, differential-drive, omnidirectional, and ball-wheeled mobile robots can be found in a paper by Muir and Neuman (1987b). They introduced a methodology for the kinematic modeling of wheeled mobile robots, and included a detailed literature study noting the most prominent work. In another paper Muir and Neuman (1987a) applied the developed methodology to Uranus, an omnidirectional wheeled mobile robot which they have developed. The significance of their approach is in wheel slip detection, a phenomenon that has been ignored by many researchers[1]. Muir and Neuman used a method to calculate the wheel slip. The shortcoming of their method is in a case where all four wheels slip simultaneously in such a manner that the equations-of-motion remain consistent; this approach will fail to detect wheel slip.

The kinematic models used by most researchers are based on a rolling model which fails due to slippage of the wheels. There are two distinct cases in which slippage cannot be ignored. The rolling model can fail to be a good approximation because of large forces, both inertial and external. This mode of failure of the rolling model is associated with either quick maneuvering or high working loads. The second mode of failure is that the steering and driving controls of the wheels are not compatible with ideal rolling. This incompatibility can arise at any speed.

Hamdy and Badreddin (1992) developed a dynamic model for RAMSIS, the wheeled mobile robot of the Swiss Federal Institute of Technology at Zurich. The derivation is based on the Newton-Euler method and considers the robot as a multi-body system. Two forms of the model were developed: a linear sixth-order model that assumes perfect rolling of the two driven wheels, and a nonlinear tenth-order model, that allows slip to occur between each wheel and the ground. The non-linearity comes from the suggested relation between the slip

[1]The research carried out at AHMCT at UC-Davis incorporates a complex tire model which accounts for both longitudinal tire slip as well as tire slip angle. Such modeling is essential for high speed and/or high load applications.

speed of each wheel and the force generated as its point of contact with the ground[2]. Hamdy and Badreddin's dynamic model accounted only for slip and tire forces in the longitudinal direction, while side slip was assumed zero and lateral tire forces were neglected.

The kinematic model simply predicts the position and orientation regardless of external and internal forces. It also assumes that there is no tire slip. A WMR for highway maintenance application tends to be heavy and/or fast. It also can have large external forces exerted upon it (e.g., router forces). For these reasons, the kinematic model is insufficient for predicting a WMR's position and orientation. A dynamic model can more accurately predict the behavior of a WMR because it is sensitive to external and internal forces. It is usually essential to incorporate an accurate tire model which allows for both longitudinal and lateral slip.

[2]The authors are not aware of any other paper which uses dynamic modeling to estimate the slip magnitude and correct the sensed forward navigation.

Chapter 5

Navigation

Navigation is a fundamental requirement of autonomous mobile robots. Navigation can be broadly separated into two distinct approaches: reference and dead reckoning, as discussed in (Cox and Wilfong, 1990). Reference guidance refers to navigation with respect to a coordinate frame based on visible external landmarks.

Dead reckoning is the process of position determination by measuring wheel rotations. Usually the rotations of one wheel on each side of the vehicle are measured, and the results are processed to determine both position and orientation. Although the equipment cost for dead reckoning is low, it inevitably suffers from error accumulation due to wheel slippage, uncertainty of the wheel radius, and separation of effective wheel contact points. Dead reckoning and reference navigation are complementary and combinations of the two approaches can provide a very accurate positioning system.

Ren and Walker (1986) suggested a number of equations which determined the magnitude of location errors for a circular arc path and a straight line path. Due to these errors a secondary location technique was proposed and tested. It involved using a narrow light beam along some areas of the path. The vehicle had one sensor array at the front and one at the rear. Based on where the light struck the sensor arrays the vehicle's exact position and heading were determined, and dead reckoning errors corrected. The test vehicle showed position errors of ± 5 mm and a heading error of ± 0.5 deg.

Kanayama, et al.(1988) presented a control strategy for dead reckoning navigation for two vehicle arrangements. In one arrangement the drive/sensor wheels were on opposite sides of the vehicle with their axes passing through the center of the vehicle. Steering was done by rotating the wheels at different speeds. The wheel velocities were based on the path curvature $\kappa(s)$, where s was the distance along the path. The second arrangement was a tricycle-type vehicle. Here the steering was done by the front wheel, and the rear wheels were the drive/sensor wheels. No vehicle dynamic model was used in the development of the control algorithm. The current vehicle state was compared to the path desired state to determine the errors in position and heading. The required velocity and yaw rate were determined by filtering these errors through a Proportional-Integral Derivative (PID) controller. Errors due to dead reckoning were not accounted for in the system.

Sugimoto, et al.(1988) found that errors due to wheel slippage can be decreased if the measuring wheels are not the drive wheels. Drive wheels have a higher tendency to slip. Hence, they designed a vehicle where the drive wheels and the measuring wheels were coaxial, but they were not at the center of the robot. In this application, the robot was designed to travel in hallways to deliver mail on several floors of an office building. Sugimoto investigated two methods for correcting dead reckoning errors. The first method used Optical Range Finders (ORF) at the front and rear of the robot along with mark boards precisely located along the wall. The distance to the wall was measured by the ORF's at the front and rear. These distances were then used to calculate the precise position and heading of the robot. The second method used sonar to measure the distance to the wall. The advantage here was that nothing needed to be added to the hallways. Sonar also had a longer sensing range than the ORF's. The tracking errors using sonar were reported to be ± 5 mm and ± 0.4 deg.

Culley and Baldur (1988) presented a new approach to dead reckoning navigation using a single non-drive wheel located at the center of the vehicle. The wheel was allowed to rotate about the vertical axis of the vehicle as well as move vertically to match changes in the terrain.

Ayache and Faugeras (1989) describe a scheme whereby a dead reckoning solution is updated by comparing vision images taken at each navigation interval. A range image is obtained via trinocular stereo, the vehicle moves an estimated distance D, and another range image is sensed. Corresponding points in the two images are determined, taking into account the noise and measurement uncertainty, and a Kalman filter uses the corresponding change in range to refine the initial estimates of the vehicle's motion D. The process is iterated until satisfactory convergence is obtained. The system not only refines the vehicle's position estimate but also constructs a model or map of its environment as it navigates.

Drunk (1988) used ultrasonic and optical sensors for environment sensing, obstacle avoidance, and trajectory planning. Local navigation was performed using dead reckoning, and the ultrasonic range sensors were used for position updates. The updates occurred when the vehicle was near known fixed objects, such as walls, and interior and exterior corners. The vehicle was similar to Kanayama's tricycle vehicle described earlier, except the front wheel was also the drive wheel. The vehicle avoided obstacles by stopping and waiting until the path was clear. The optical sensors were used to measure distances, for high accuracy vehicle positioning and docking maneuvers.

Permi and Besant (1983) reviewed various guidance techniques that can be used by mobile robots and Automated Guided Vehicle (AGV), including: dead reckoning, position referencing beacons, inertial navigation, ultrasonic imaging and optical stereoscopic vision. The relative advantages of these individual methods were discussed.

Elfes (1987) developed a sonar-based mapping and navigation system for a mobile robot operating in an unknown and unstructured environment. The system uses sonar range data to build a multilevel description of the robot's surroundings. Sonar readings are interpreted using probability profiles to determine empty and occupied areas. Range measurements from multiple points of view are integrated into a sensor-level sonar map, using a robust method that fuses the sensor information in such a way as to cope with uncertainties and errors in the data. The resulting two-dimensional maps are used for path planning and navigation. From these sonar maps, multiple representations are developed for various kinds of problem-solving activities.

The subject of triangulation and trilateration (within the reference guidance system) deals with position estimation based on the simultaneous measurement of the range (trilateration) or bearing (triangulation) to three or more known landmarks. Torrieri (1984) presents a thorough derivation of the principal algorithms for several common forms of triangulation/trilateration-based location systems, as well as an analysis of their performance. In the simplest case, the vehicle identifies at least three known reference points, and then, when the distance (trilateration) or angle (triangulation) to each point is measured, simple trigonometry allows calculation of the vehicle's position. The accuracy of such a system is dependent on the measurement error and the geometric relationships between the vehicle and landmarks. Torrieri (1984) also addressed the problem of determining a vehicle's position from simultaneous measurements of sufficient observables to solve the navigation equations uniquely.

Cox (1990) described a mobile robot navigation system in which an *a priori* map of the environment was provided. The vehicle sensed its environment using an infrared range-finder. The range data points were matched to the map using a novel matching algorithm that solved the correspondence problem by associating data points with their closest (Euclidean) line segment and then applying a least-mean-square optimization procedure to determine the vehicle's position. The vehicle used dead reckoning between matches and the independent estimates were optimally combined. The Kalman filter was not explicitly used, but equivalent results were obtained.

Crowley (1989b) described a navigation system based on ultrasonic sensing and Kalman filtering. A Kalman filter combined all available measurement data with prior knowledge about the system and measuring devices to produce an estimate of the desired variables in such a manner that the error is minimized statistically. For additional information on Kalman filter analysis, Maybeck (1990) provides an overview.

The literature review shows that the majority of autonomous and semi-autonomous vehicles use dead reckoning as their navigation method, while other vehicles include vision systems, infra-red systems, and sonar systems. Table 1 presents the advantages and disadvantages of the various navigation systems normally used by WMRs.

Many highway maintenance operations require applications of materials, such as bitumen, paint, sealant or raised pavement markers (Ravani, Velinsky and West, 1994) to the roadway, which requires a storage and retrieval system. This requires a truck which can provide power and air generation for the WMR and maintenance operations. Therefore, the use of a WMR for highway maintenance operations is only feasible if it is used in conjunction with a support truck. Hence, the idea of tethering the WMR to a support vehicle through a linkage mechanism was investigated by Winters and Velinsky (1992). The linkage mechanism is a passive device incorporating an encoder mounted on each joint. This allows the position of the WMR to be calculated relative to the support vehicle. The literature review did not locate any previous use of this type of technique to aid in the navigation of WMRs.

Navigation method	Advantages	Disadvantages
Dead reckoning	Low cost, compact size	Error accumulation
	Low computation time	Wheel slip, uncertainty in wheel radius
Vision	Accurate positioning	Computation intensive
	Absolute positioning	Outdoor lighting, vibration
		Expensive, bulky
Infra-red	Absolute positioning	Sunlight, vibration
	Accurate positioning	
	Medium cost	
	Compact size	
Sonar	Absolute positioning	Reflections, noise and vibration
	Accurate positioning	
	Medium cost	

Table 5.1: The comparison of various navigation methods

The main advantage in using a linkage mechanism is lack of error accumulation due to its absolute error positioning determination. The shortcomings of the linkage mechanism are several, including: potential for linkage deflection, linkage jamming, and resonance due to tool induced vibration which cannot be ignored. However, the popular methods of navigation such as dead reckoning, infra-red optics, and sonar would be prone to errors in the hostile environment of a highway site, and would not meet the needed accuracy and reliability for a navigation system in highway maintenance applications.

Chapter 6

Control

In general, WMRs are required to fulfill a specific task defined by a human operator in a partially known environment using noisy sensors. As the autonomy of the WMR increases, the demands for safe operation also become increasingly important. This imposes stringent requirements on the real-time control of a WMR. Generally, the control is required to be fast and thorough, while maintaining robustness under all operating conditions. Usually, these requirements cannot be met by a single-level control-loop. More sophisticated adaptive, self-tuning and/or hierarchical controllers are sought which are computationally simple enough to run in real-time but still can achieve the performance requirements. Also, the control structure as well as the computation architecture should be tailored to be fail-safe, fault tolerant, and handle exceptions.

The review of literature shows that there are generally two types of control architectures for WMRs. Badreddin (1992) describes them as vertical/behavior decomposition and horizontal/functional decomposition. In his earlier work Badreddin (1989) proposed an alternative architecture, called "Recursive Nested Behavior Control" (RNBC). This architecture is paired with the so called "Functional-Unit" decomposition which emphasizes the realization aspects of the software and hardware to achieve an asynchronous processing in a robust and efficient way. Badreddin (1992), briefly highlights the main properties and the implementation of the RNBC control structure and the associated Functional Unit-decomposition.

In brief, a WMR's control structure should at least meet the following requirements:

1. Programmability: a useful robot should be able to execute a variety of tasks without the need for changing its hardware or software. The tasks should be given to the robot at an abstract level (all detail need not be specified), and the robot should be able to interpret them adequately, according to its measured state and environment.

2. Robustness: the robot should not depend on a unique subsystem for all its actions, but should be as redundant as possible in terms of sensors and functions. This calls for some decentralization of control.

3. Coherent behavior: the robot's behavior must be coherent with its mission, plan, or

objectives. Its reactions to environmental stimuli must be guided by these objectives.

4. Autonomy, adaptiveness and reactivity: these notions are related. Environment conditions are variable, imperfectly known and evolving over time. Therefore, the robot should be

   - *autonomous*, i.e., capable of accomplishing tasks by itself and managing its various subsystems;
   - *adaptive*, i.e., capable of modifying its behavior according to the actual circumstances it encounters. This requires reasoning capacities to detect situations and produce/select the adequate behavior.
   - *reactive*, i.e., capable of *timely* detection of events and reacting to them according to the context and the task.

The control structure of a mobile robot must have both decision-making capacities and real-time capabilities and the robot must react in a timely fashion to events.

De Camargo and Alami (1991) developed a control system for Hilare-II which was composed of a set of interacting modules which implemented the robot primitive functions and other processing functions, and a central control system on top of this layer. The purpose of the central control system was to interpret the task using global knowledge, and to ensure a coherent and goal-oriented robot behavior.

A significant amount of research has been published in tracking control method for a nonholonomic WMR with abundant simulation results. Tsumura (1981) proposed a method in which the reference point sequence is stored in memory. In each cycle of the locomotion control, the reference point and the future position of the robot is compared for determining the next steering. Kanayama (1988) proposed a method using straight line reference for the robot's locomotion instead of a sequence of points. Its velocity and steering control method had some similarities to the one proposed by the same author in another paper (Kanayama,, et al., 1990). Crowley (1989a) developed a locomotion control system whose organization had a three layered structure. The concept of "virtual vehicle" was defined. It was useful for constructing a system which was robot independent. In its command system, independent control of linear and rotational motion was possible, thus enabling smooth clothoid curves. Kanayama and Miyake (1986) suggested that smoothness of path is essential for WMR control, because unsmooth motions may cause slippage of wheels which degrades the WMR dead reckoning ability. Singh (1989) used an inverse kinematic and a quintic polynomial method for compensating errors in vehicle tracking. In the latter method, the current point and a future reference point were interpolated by a smooth curve.

Kanayama (1988) proposed the use of a reference and current postures for vehicle control, the use of a local error coordinate system, and a Proportional Integral (PI) control algorithm for linear/rotational velocity rules in an earlier locomotion control method on the Yamabico-II robot. Nelson (1988) proposed a locomotion control method for a WMR with a front steering wheel, in which they also used the error coordinate system. They adopted a linear function in control rules for steering and linear velocity.

A new control rule was suggested by Kanayama (1990), for determining WMR linear and rotational velocities, which were different from both of (Kanayama, Nilipour and Lelm, 1988; Nelson and Cox, 1988). This method was useful to the class of autonomous vehicles in which (a) dead reckoning capability was provided, (b) reference path specification and current position estimation (through dead reckoning) were given separately, and (c) high precision in positional control was mandatory. This method was implemented on the autonomous mobile robot Yamabico-II which has been developed at the University of Tsukuba, the University of California at Santa Barbara, and the Naval Postgraduate School.

Kanayama (1993) applied group theory to describe the motion and odometry error analysis for Yamabico-II. Group theory provided an algebraic structure that made motion calculations more transparent. The periodic detection and reduction of odometry errors allowed the autonomous mobile robot to work for a sustained period with great precision. Several experiments were conducted in which odometry corrections were performed in real-time using landmarks with known configurations. In the worst case average odometry error was ± 2.54 cm in distance and ± 1.04 deg in orientation over a 914 cm course.

Among the control structure elements, programmability adds flexibility to robotic applications, including WMRs used for highway maintenance. The capability to reprogram a WMR allows a broad range of tasks to be performed repetitively. For instance, in pavement markings Kochekali and Ravani (1994) used simple mathematical functions to define the boundaries of all English letters used in roadway markings. These mathematical representations of the boundaries were used to generate an automatic trajectory for the end-effector of a robot (e.g., paint gun) to follow and also to ensure uniform paint distribution over the entire roadway marking. A programmable WMR can be used for painting individual letters, words and even sentences while the control point (e.g., paint gun) follows various programed trajectories.

Robustness which requires some decentralization of control may prove useful for a WMR operating in the hostile environment commonly encountered during highway operations. Reactive control mechanisms are highly specialized, and more general world knowledge and reasoning ability is required to address a variety of situations. In general, autonomy, adaptiveness and reactivity all add costs to the system and complicate the control problem. A WMR for highway maintenance operations is not necessarily required to perform complex behavior such as learning how to avoid obstacles or how to reach a fixed target. However, these applications require fast path following and trajectory generation. For instance, the crack sealing application requires a path planning system that can take data representing roadway cracks from an external sensor, extract connected crack paths, and link paths together to form a trajectory for the WMR to follow.

In highway maintenance applications in which the tasks are complex, a supervisory-controlled teleoperator can perform much better than an autonomous WMR since human intelligence is far superior to artificial intelligence at the present time. In a supervisory-controlled teleoperator, the computer assists the operator by executing tedious or repetitive parts of the task and by providing automatic sensory feedback control functions (Wampler, 1988).

In general, a control system for highway maintenance requires the integration of a variety of sensing and actuating systems which synchronously perform tasks in real-time. These systems are required to act in a coordinated manner for the WMR to perform the highway maintenance tasks. In such a situation a modular control architecture can improve the versatility and maintainability of the control system (Ravani, Velinsky and West, 1994).

Chapter 7

Conclusion

Of the previously developed WMR, most were predominantly research-oriented vehicles. In general, the prototype WMRs have been custom-made, they are costly, and are able to perform only a limited number of tasks. While early WMR concepts can be applied, highway maintenance automation requirements dictate the development of new WMR approaches. To avoid problems associated with the use of robots in highway maintenance operations, the use of a WMR working in close proximity to a support vehicle, which provides power, materials, etc., appears promising. This concept has been introduced by Winters and Velinsky (1992).

In this report, the mobility requirements of a WMR for highway maintenance operations were discussed. This involves several subareas such as wheel type arrangement, kinematics, dynamics, navigation and control.

Several different wheel types and configurations were reviewed for their potential use in a highway maintenance WMR, and a configuration suitable for these activities was proposed a differentially steered, pneumatic tire WMR. Based on WMR modeling, it is apparent that a dynamic model incorporating a detailed tire model is essential for a highway maintenance WMR's path prediction due to the large loads and potentially high speeds expected.

Advantages and disadvantages of various methods of navigation were summarized herein. Based on these navigational concepts, the idea of tethering the WMR (Winters and Velinsky, 1992) to a support vehicle through a linkage mechanism for both the delivery of power and materials to the WMR and the accurate measurement of the WMR's position relative to the support vehicle.

The control system of conventional WMRs were reviewed and the requirements for a WMR control system for highway maintenance operation were suggested. Such a control system should be modular incorporating a supervisory-controlled teleoperator.

In summary, highway maintenance tasks have received minimal attention yet could benefit greatly from advanced automation and robotics. Based on the unique requirements of these activities, WMRs appear most suitable.

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