DEVELOPMENT OF AN AUTONOMOUS GUIDED VEHICLE
FOR INDOOR PROPAGATION MEASUREMENTS

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ABSTRACT

At Virginia Tech, an autonomous guided vehicle has been developed for use in indoor propagation measurements and for a research/teaching tool in the Computer Integrated Manufacturing Laboratory. A radar system carried by the AGV is being used to perform automated channel sounding measurements in several typical indoor environments. These measurements are aimed at providing insight into design guidelines for reliable premises radio systems. With an AGV, it is possible to obtain very accurate position information during mobile measurements to relate propagation to building geometry. The AGV operates in three modes: manual control, computer control, and learn mode. This paper describes the AGV design strategy, navigation methodology, and a calibration technique used to minimize path errors caused by unequal wheel radii in dead-reckoning navigation. Measurements of vehicle position through use of calibrated dead-reckoning show accurate vehicle position to within a few cm along a 10 m path.

I. INTRODUCTION

Factories are beginning to make extensive use of inexpensive, simple autonomous guided vehicles (AGVs) to transfer work-in-process. Indoor wireless communication for voice, data, and video signals will also become popular in future factories and offices [1]. These technologies promise flexibility and efficiency for the workplace. Conventional mobile robots are generally restricted to fixed guide paths, defined by wire, paint, or magnetic tape. Such restrictions limit their usefulness if the manufacturing process flow changes frequently [2]. Future vehicle systems will be able to move throughout an entire building with dynamic route assignment [2,3,4].

There are complex navigation techniques which rely on artificial intelligence and vision systems on each AGV [5,6]. Simpler methods for navigating vehicles also exist. Optical beacons can provide navigation to AGVs if situated to maintain line-of-sight to vehicles at all times [7]. Retrorreflectors may also be used to enable AGVs to self navigate [8]. Virtually all forms of AGV navigation rely somewhat on dead reckoning, in which distances and trajectories are computed by integrating the distance traveled by one or more vehicle wheels. Dead reckoning is the simplest navigation technique, requiring no hardware outside the AGV. Its major limitation is the accumulation of position error during travel. Because the vehicle described here will be used over relatively short distances in unfamiliar building environments where fixed navigation systems are not in place, a properly calibrated dead reckoning control system provides a flexible and accurate navigation system.

II. ELECTRICAL AND MECHANICAL DESIGN

Figure 1: Photograph of the AGV

Figure 1 shows the AGV, equipped with a microwave multipath receiver. The vehicle has a flatbed that carries equipment 45 centimeters above the floor. A plastic adjustable height antenna mast is mounted on the front of the vehicle. The navigation and control systems fit underneath the flat-bed. The vehicle uses a tricycle design with a hard rubber front wheel and pneumatic tires on the rear wheels. The overall design is similar to that of an AGV developed at Purdue University’s Engineering Research Center for Intelligent Manufacturing [10]. The front wheel contains a steering motor and a drive motor. Each of the two rear wheels has an optical shaft encoder that provides wheel counts that are translated into distance and path curvature information by the personal computer controller. In the computer, a custom adapter card accepts wheel count data and produces control voltages for the motor drive circuitry. Remote commands from a radio modem enter the computer.
through a standard RS-232 serial port adapter card. Exact position information is obtained by time stamping the wheel count data with propagation measurements.

The motor drive system consists of two classical linear proportional analog control loops to control the position of the steering motor and the speed of the drive motor. The steering motor uses potentiometer feedback for position adjustment while the drive motor is equipped with a tachometer to facilitate closed-loop control of its speed. The analog control loops are compensated for optimal step response on the steering and minimal steady-state error on the speed. The PC provides inputs to the steering and drive control boards as analog voltages. Two 12-V, 80-A hr gelled electrolyte batteries power the computer, motors, and other circuitry.

The AGV has a plastic bumper that extends 0.4 m in front of the vehicle. When the bumper is depressed, microswitches activate relays that disconnect the drive power from the motor and drop the back EMF across a braking resistor. This braking scheme stops the AGV from full speed (1 m/s) within a few inches. A manual emergency switch/button can also stop the vehicle. Since the computer disengages power to the motor drive system, the relay will disengage and immediately engage the braking feature.

Since the AGV has been designed for propagation measurements, the vehicle must be stable enough to support heavy electronic equipment during transport. The vehicle is 79 cm wide to allow for passage through standard 32 inch (81cm) doorways. Stability rules for a three-wheeled vehicle were developed in [9]. To keep the vehicle from tipping over backwards, the center of gravity should be on the front two thirds of the vehicle; for rollover stability, the distance between the rear wheels must be more than twice the height of the center of gravity.

III. NAVIGATION

The AGV uses dead reckoning navigation for guidance. Dead reckoning consists of determining the vehicle's present position from knowledge of its previous position, speed, and heading. Real-time control algorithms have been developed to calculate the necessary drive and steering control corrections to keep the AGV traveling on a desired straight line or turn, based on the results of prior calibration runs. The computer determines the heading of the vehicle via the differences in the path of each of the two wheels. The speed and distance is computed using the sum of the wheel counts, and that the heading error changes only by a small amount between samples. Sampling should be done as fast as possible. On our AGV, wheel counts are sampled at a 100Hz rate, or 200 samples per meter traveled at normal speed.

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Figure 2 shows the vehicle with its coordinate system. The equations for the location of the AGV at any time (in rectangular coordinates) are [9]:

\[
x_j = x_{j-1} + \frac{N}{200} \left( R_1 \Delta n_{1j} + R_2 \Delta n_{2j} \right) \cos \left( \phi_j + \phi_{j-1} \right)
\]

\[
y_j = y_{j-1} + \frac{N}{200} \left( R_1 \Delta n_{1j} + R_2 \Delta n_{2j} \right) \sin \left( \phi_j + \phi_{j-1} \right)
\]

where \( \phi \) is the vehicle's heading angle relative to the X-axis, given by:

\[
\phi_j = \phi_{j-1} + \frac{2 \pi}{N} \left( R_1 \Delta n_{1j} - R_2 \Delta n_{2j} \right)
\]

where \( \Delta n_{ij} \) is the change in the wheel count between samples on the right wheel \( (n_{ij}\Delta n_{ij}) \). N is the number of counts per revolution, and \( R_1 \) and \( R_2 \) are the radii of the respective wheels. Equations (1-3) assume that the steering angle is constant between consecutive samples of the wheel counts, and that the heading error changes only by a small amount between samples. Sampling should be done as fast as possible. On our AGV, wheel counts are sampled at a 100Hz rate, or 200 samples per meter traveled at normal speed.

Figure 2: AGV coordinate system and paths

On Figure 2, \( \theta_1 \) is the polar angle made between the ith desired (predetermined) straight line path segment and the global X-axis, and \( D_i \) is the length of the ith path segment. \( X_i \) and \( Y_i \) are the coordinates of the junction point \( J_i \) that begins the ith path segment. Navigation over several straight line path segments is discussed subsequently.

The vehicle's calculated position and heading (from (1), (2), and (3)) continually generate a steering angle, \( \phi \), to keep the AGV traveling along the desired path. Ideally, \( \phi \) would be zero over any straight path. However, undulations in floors require that \( \phi \) be continually updated. Furthermore, \( \phi \) must be changed near each junction point to steer the AGV onto a new path segment. For the simple case of travel along the X-axis (see Figure 3), the significant perpendicular position error (the perpendicular distance from the path to the vehicle) is \( \Delta Y \), and vehicle heading error is \( \phi \). There may be some small parallel distance error in navigating a junction between paths, but we are more concerned with adhering to the path than with the exact distance traveled. It turns out that the distance error can be made extremely small when the calibration technique in Section 4 is followed.

Forcing the vehicle to stay on a straight path through control of the steering angle is difficult since the vehicle's heading and position cannot be changed instantaneously by changing the steering angle. The AGV must first move over some finite distance to change heading, and then must travel some distance with the new heading to reduce the perpendicular position error \( \Delta Y \). Thus the kinematics require two distance integrations between the steering command, \( \phi \), and the vehicle's cross-track error, \( \Delta Y \) [9]. Richards [9] simulated various first through third order compensation systems with limited success. The simple proportional-differential controller was found by [9] to be most satisfactory. A proportional-differential controller can be implemented on the AGV by
observing that there is an integration between $\epsilon$ and $\Delta Y$, so $\epsilon$ is a derivative of $\Delta Y$. The basic control equation to close the loop on steering is:

$$\phi = -(K_p \Delta Y + K_c \epsilon) + \phi_o$$

(4)

where $\phi_o$ is a small constant calibration factor, computed in (16). The constants are determined empirically to provide the desired dynamic response during navigation. Future research will investigate optimal control techniques. [9] suggests $K_p = 5$ rad/meter and $K_c = 3$ as a starting point if all angles are measured in radians.

$$\phi = -(K_p (y_j \cos \theta_i - x_i \sin \theta_i + C_i) + K_d (\epsilon_j - \epsilon_i)) + \phi_o$$

(5)

As the vehicle approaches the next $J_i$, a new $\epsilon_i$ is inserted into (5) and a new $C_i$ is computed according to:

$$C_i = x_i \sin \theta_i - y_i \cos \theta_i$$

(6)

where $x_i$ and $y_i$ are the initial coordinates for the new path segment. $C_i$ defines a new origin to force the perpendicular position error to zero if the vehicle is on the new path. The vehicle has only a heading error (the $K_d$ term) when starting on a new path segment.

IV. CALIBRATION

The entire dead-reckoning approach requires knowledge of the exact radius of each rear wheel for accurate navigation. A small difference in wheel radii can cause significant differences between actual and desired vehicle position over just a few meters of travel. Because the rear wheels are pneumatic tires, their radii change slightly over different operating conditions due to differences in inflation and vehicle loading.

A simple calibration technique is used to determine the rear wheel radii. The rear wheel radii cannot be measured directly since an error of less than 3% in the measurement will cause a substantial (i.e. several meters) navigation error. The vehicle is aligned parallel to a chalk line and the steering angle, $\phi$, set to zero, i.e. straight ahead. The vehicle is then programmed to move a distance of several meters without any change in $\phi$. Ideally, the AGV will travel straight ahead and remain the same distance from the line. If all the error sources that cause the AGV to deviate from a straight path are constant, the actual path will be either a straight line or an arc of a circle with large radius.

$$\alpha = \tan^{-1} \left( \frac{\Delta Y}{\Delta X} \right)$$

(7)

$$AB = \sqrt{\Delta X^2 + \Delta Y^2}$$

(8)

where $\alpha$ is the angle that segment AB makes with the line. From the isosceles triangle $ABC$,

$$\theta = 2\alpha$$

(9)

where $\theta$ is the angle between the initial and final positions of the AGV on a circle centered at $C$ with a radius of curvature $r_c$. Solving for $r_c$,

$$r_c = \frac{\Delta X^2 + \Delta Y^2}{2\Delta Y}$$

(10)

After calculating $r_c$ and $\theta$ from the calibration run, the rear wheel radii and a steering offset that will cause the AGV to travel a straight path can be calculated. The rear wheel radii are determined based on the information that each wheel traveled an arc determined by the angle $\theta$ and a radius of curvature $r_c \pm W/2$. This gives,

$$(r_c - \frac{W}{2}) \beta = \frac{2\pi}{N_1} R_r N_{r_1}$$

(11)

$$(r_c + \frac{W}{2}) \beta = \frac{2\pi}{N_1} R_r N_{r_2}$$

(12)

where $\beta$ is positive and $N_{r_i}$ is the total number of counts on the right wheel during the run. Simplifying in
terms of measured values and solving for each rear wheel radius gives,

\[ R_r = \frac{N (\Delta X^2 + \Delta Y^2 - W \Delta Y) \tan^{-1} \left( \frac{\Delta Y}{\Delta X} \right)}{2 \pi N \Delta Y} \quad (13) \]

\[ R_t = \frac{N (\Delta X^2 + \Delta Y^2 + W \Delta Y) \tan^{-1} \left( \frac{\Delta Y}{\Delta X} \right)}{2 \pi N \Delta Y} \quad (14) \]

The exact wheel radii from (13) and (14) are the most important results of the calibration run. The calibration data also yields a steering calibration factor, found from this general formula that gives the radius of curvature from any steering angle:

\[ \rho_c = \frac{L}{\tan \phi} \quad (15) \]

Equating (10) and (15) with \( \phi = \phi_s \) and simplifying gives

\[ \phi_s = \tan^{-1} \left( \frac{2 L \Delta Y}{\Delta X^2 + \Delta Y^2} \right) \quad (16) \]

where \( \phi_s \) is the alignment angle required for the AGV to travel a straight path i.e. an offset for the steering. This angle is used in (5) along with additional corrections calculated in real time from \( x_i, y_i \) and \( \epsilon_i \) to keep the vehicle travelling on a straight line. This calibration technique allows for compensation of differences in wheel radii, and steering offset caused by possible misalignment of the steering motor.

V. CALIBRATION TEST RESULTS

Several experiments were performed to determine the improvement offered by using the calibration procedure for measuring wheel radii and steering alignment, as opposed to using a coarse estimate of these variables.

One experiment involved calibrating the AGV first with no load, then with approximately 15kg of equipment on the bottom shelf centered over the rear wheels. As measured by calibration, the radii of each rear wheel decreased by approximately 0.4\% (440 \( \mu \)m) after loading. If the old radii were used after loading the AGV, a distance error of 0.4\% (4 cm on a 10 m path) would accumulate. Equations (2) and (3) show that the calculation of \( \epsilon \) (and thus \( y_i \)) is very sensitive to the difference between the radii of the rear wheels. Since the rear wheel radii did not decrease even after loading, there is error in the perpendicular position measurement also. This was borne out by five 10-meter test runs along the X-axis (\( \theta = 0 \)). In either the loaded or unloaded case, use of the corresponding radii measured during calibration consistently resulted in actual perpendicular position error of less than 1cm after a 10m run. The calculated \( \Delta Y \) on the vehicle was always forced to zero. In comparison, when calibration data from the loaded case were used in navigation of the unloaded AGV, consistent perpendicular position errors of 5 cm after the 10 m run occurred. On a different and slightly uneven floor, errors of about 5 cm accumulated even with the correct calibration.

Another test determined if feedback from position to steering (5) was necessary to track a straight line, or if simply using \( \phi_s \) as a constant steering angle (open loop) would be acceptable. Without feedback, even on the same floor as the calibration, errors in the measured \( \Delta Y \) were as great as 13 cm after 10 m of travel. Accurate navigation requires \( x_i \) and \( y_i \) to match the vehicle's actual position, and the vehicle's calculated position to match the desired position. Calibration and steering feedback achieve these objectives within the constraints of the road surface.

VI. OPERATIONAL MODES

The vehicle's software allows operation in three different modes: manual control mode, programmed control mode, and learn mode.

In manual control mode, a joystick or PC keyboard input provides velocity and steering control in both the forward and reverse directions. In this mode, it is possible to easily move the vehicle between various measurement locations.

The programmed control mode causes the vehicle to follow a pre-programmed path that uses a custom high level instruction set. Typical AGV paths along hallways and around corners may be programmed by sequentially combining straight paths of various lengths (\( D_i \)) and new heading (\( \phi_i \)) instructions. Programs are stored as text files on floppy disks for future and repeated use. Alternately, path programs can be transmitted to the AGV by radio from a dispatching computer and executed remotely.

In learn mode, the vehicle is traversed along a desired path by a joystick input similar to manual mode. The computer stores the traversed path as calculated by measurement of the shaft encoders. The traversed path is resolved into a sequence of straight segments and stored in a file that can be read by the programmed control mode. The vehicle can then be returned to its initial position where the retrieved path data can then recreate the original path at constant speed. An advantage of learn mode is that the user can quickly and simply program a desired path in a new environment by using the AGV to measure the local geometry. For propagation measurements, the path may be learned under manual control by a person, and then re-run during measurements without a person standing near the vehicle, thereby eliminating the variation in channel characteristics due to people near the antenna.

VII. CONCLUSION

In this paper, we developed the basic geometry of dead reckoning navigation, with a particular emphasis on the use of a calibration run to yield exact wheel radii and steering correction factors for use in navigation. These techniques were used on an actual AGV and measurements were taken under operating conditions to determine navigation accuracy. We found the major limitation in dead reckoning comes from improper estimates of wheel radii. This can be compensated for with a calibration run, but the tire radius may still change due to dynamic conditions such as redistribution of vehicle weight duringcornering,
and inexact manufacturing of the tires themselves. In industrial environments, slippery and uneven floors and debris will also cause slight errors. Nevertheless, we have been able to consistently achieve accuracies of 5 cm over a 10 m path using a very simple control.

For planned propagation experiments which utilize this AGV, see “Indoor Propagation Measurement System at 1.3 and 4 GHz” by D.A. Hawbaker and T.S. Rappaport elsewhere in this Proceedings.

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REFERENCES