

The OmniMate: A Guidewire- and Beacon-free AGV for Highly Reconfigurable Applications

by

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ABSTRACT

This paper introduces a new Automated Guided Vehicle (AGV) for guidewire-free industrial applications where rapid reconfiguration is required. The AGV, called *OmniMate*, has full omnidirectional motion capabilities, can correct odometry errors without external references, and offers a large 183×91 cm (72×36") loading deck. A patented, so-called *compliant linkage* avoids the excessive wheel slip-page often found in other omnidirectional platforms.

The paper describes the kinematic design and the control system of the platform and explains its unique odometry error correction method, called *Internal Position Error Correction* (IPEC). IPEC renders the OmniMate's odometry almost completely insensitive to even severe irregularities of the floor, such as bumps, cracks, or traversable objects. Dead-reckoning is further enhanced by the addition of a fiber-optics gyroscope.

Because of its extraordinary dead-reckoning capabilities the OmniMate can travel over extended distances while following a pre-programmed path fully automatically. The paper describes an implemented "lead-through" teaching system, in which an operator guides the OmniMate along a desired path, while the OmniMate records the path to memory. Later, in path execution mode, the OmniMate reproduces the path accurately, observing commanded velocities. With this system it is possible and feasible to program or modify a complete path within minutes.

1. INTRODUCTION

Most Automated Guided Vehicles (AGV) use inductive guidewires embedded in the floor or guide-paths painted onto the floor for navigation. Installation of new AGV systems or changing the pathways for existing systems is time consuming and expensive. Some more recent designs don't rely on guide-paths but rather use a variety of beacon- or marker arrangements installed in the environment. These systems are more flexible but they are still somewhat costly to install. This is especially true for beacon-based systems in large installations because the sensors of the AGV have to see at least two or three beacons at any time. Also, the cost of installing beacons is quite high because the beacons' location must be carefully surveyed for accurate navigation.

Almost all AGVs use odometry, i.e., the counting of wheel revolutions to derive position information. Conventionally, odometry is only being used as a secondary navigation aid. It is considered unsuitable as a primary navigation means because it accumulates errors without bound. That is, odometry errors tend to grow over distance traveled. One rough rule of thumb is that a small or medium-sized AGV accumulates at least 10 cm (4 inches) of error for 10 meters of travel over smooth floors.

The OmniMate platform, described in this paper, overthrows the conventional notion that odometry cannot be used as the primary navigation means. Before this can be explained, however, some properties of odometry and its associated errors need to be examined.

Figure 1 shows a typical differential-drive mobile platform. In this design incremental encoders are mounted onto the two drive motors to count the wheel revolutions. A simple set of equations, known as “odometry,” computes the platform’s relative horizontal displacement and change in orientation as a function of the incremental horizontal displacement of the drive wheels. The odometry equations are omitted here but can be found in [Everett, 1995].

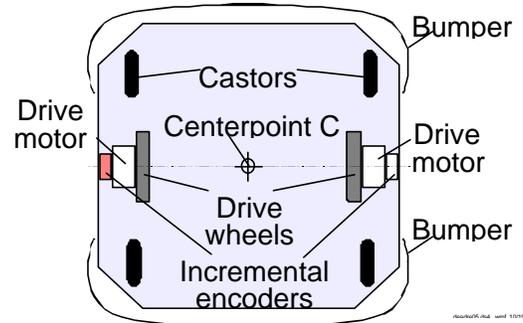


Figure 1: A simple differential-drive mobile platform (bottom view).

Odometry is based on the assumption that wheel revolutions can be translated into linear displacement relative to the floor. This assumption is only of limited validity. One extreme example is wheel slippage: If one wheel was to slip on, say, an oil spill, then the associated encoder would register wheel revolutions even though these revolutions would not correspond to a linear displacement of the wheel.

Besides this extreme case of total slippage, there are several other, more subtle reasons for inaccuracies in the translation of wheel encoder readings into linear motion. All of these error sources fit into one of two categories: (1) systematic errors and (2) non-systematic errors.

1. Systematic errors

- Unequal wheel diameters
- Average of both wheel diameters differs from nominal diameter
- Misalignment of wheels
- Uncertainty about the effective wheelbase (due to non-point wheel contact with the floor)
- Limited encoder resolution
- Limited encoder sampling rate

2. Non-systematic errors

- Travel over uneven floors
- Travel over unexpected objects on the floor
- Wheel-slippage due to:
 - slippery floors
 - over-acceleration

- fast turning (skidding)
- external forces (interaction with external bodies)
- internal forces (e.g., castor wheels)
- non-point wheel contact with the floor

Note that systematic errors mostly related to kinematic properties or imperfections of the platform, but not to interaction with the floor. On most smooth indoor surfaces systematic errors contribute more to the overall odometry error than non-systematic errors. However, on rough surfaces with significant irregularities, non-systematic errors are dominant. Non-systematic errors need to be of primary concern because a single incident with a large bump, crack, or other major irregularity on the floor can cause a very large odometry error. Finally, we note that in order to reduce overall odometry errors, orientation errors are the main source of concern because once they are incurred they grow into lateral position errors without bound [Crowley, 1989; Feng et al., 1993].

Many components of the OmniMate system have been described in previous work. Therefore the descriptions given in the following sections are more concise, while references throughout this paper refer the reader to the relevant in-depth publications.

2. THE OMNIMATE

Omnidirectional vehicles, also called *Multi-Degree-of-Freedom* (MDOF) vehicles, have great advantages for moving in tight areas; they can crab sideways, turn on the spot, and follow complex trajectories. MDOF vehicle designs have been attempted many times, with relevant patents dating back to the 1920s. For strictly manual control or when following a guide path embedded in the floor, many of these designs work adequately. However, under computer control, dynamic errors in wheel orientation and velocity can result in instabilities, excessive wheel slippage, and consequently large position errors in odometry computations.

To overcome these problems we designed the OmniMate, an MDOF mobile platform with full omnidirectional motion capabilities. The vehicle is made from two differential-drive *LabMate* platforms (here called “trucks”) as shown in Figure 2 and Figure 3. The front truck can rotate around rotational joint A, which is attached to the bottom of a rigid loading deck. The rear truck can rotate around rotational joint B, which is connected to a slider assembly. The slider assembly can linearly move along slider bars that are attached at their ends to the bottom of the loading deck. Rotary encoders mounted on joints A and B measure the relative rotation between each truck and the loading deck, while a linear encoder measures the position of the linear slider assembly, from which the distance between the center points of the two trucks can be computed. Additional joints not shown in Figure 3 allow for limited pitch, roll, and yaw motion of the trucks relative to each other, to accommodate uneven ground.

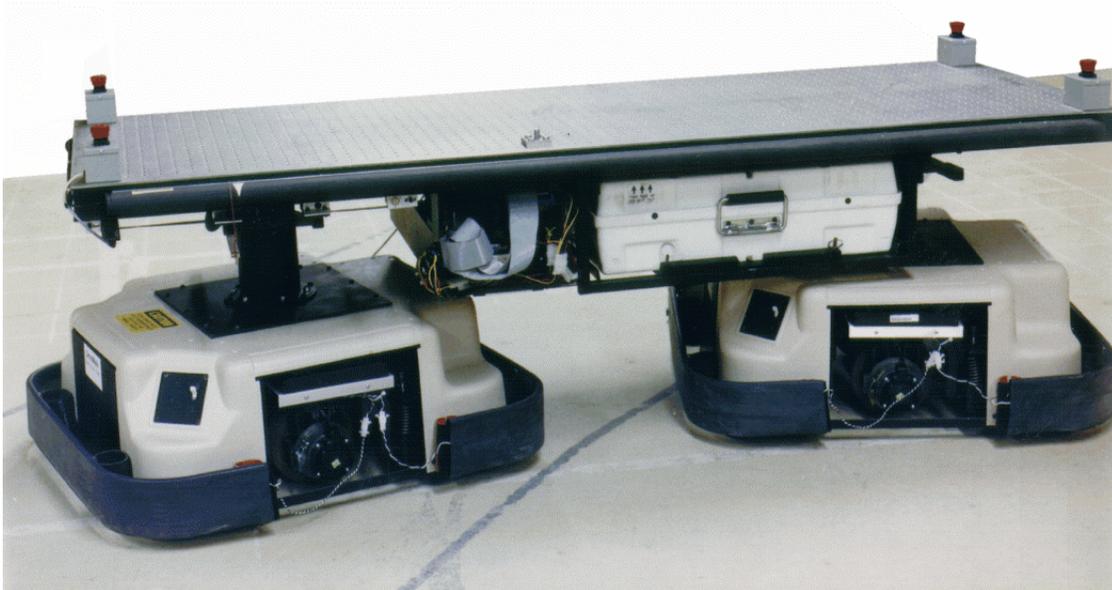


Figure 2: The OmniMate is based on two *LabMate* "trucks" connected by a compliant linkage. This design provides an uncluttered 180×90 cm (72×36-in) loading deck for up to 114 Kg (250 lbs) of payload.

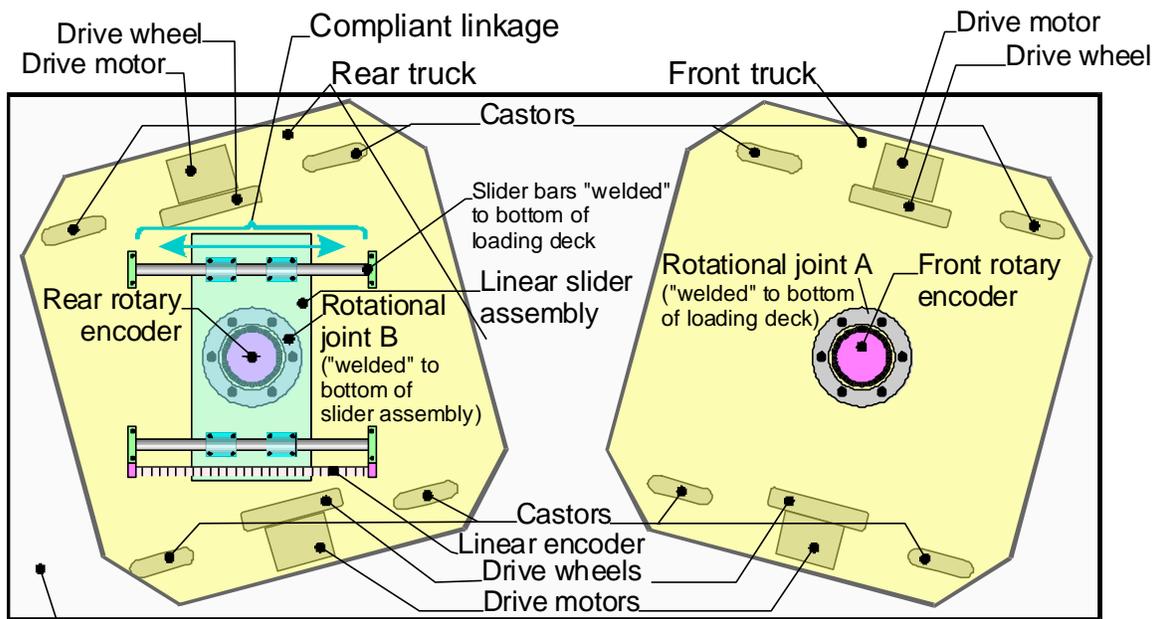


Figure 3: Schematic diagram of the OmniMate mobile platform.

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Because of the linear slider the two trucks can freely move relative to each other. This patented UM design is called “compliant linkage.” The purpose of the compliant linkage is to absorb the inevitable momentary controller errors that can cause wheel slippage in conventional, rigidly-built MDOF mobile robots, as reported by Reister [1991], Killough and Pin [1992], West and Asada [1992], Hirose and Amano [1993], or Pin and Killough [1994].

Figure 2 shows that the OmniMate design provides a completely flat, 180×90 cm (72×36 inch) loading deck that is available exclusively for the end-user’s payload. A 24-Volt auxiliary battery pack, designed to power user-installed equipment and the onboard control computer, is installed underneath the loading-deck. This battery pack can provide 300 Watts for 6 hours. In addition, each of the trucks is individually powered by its own 24-Volt battery pack installed inside of each truck. Control and feedback signals to and from the trucks are passed through slip-ring assemblies. The onboard motion control system runs on a 486/100 MHz PC-compatible single board computer.

The two modified LabMate trucks used in the OmniMate are individually rated at a load capacity of at least 200 kg (440 lbs). With two trucks supporting the payload, the total load capacity is 400 kg (880 lbs). After adding the OmniMate vehicle frame and auxiliary battery pack, there remains a user payload of about 114 kg (250 lbs).

The onboard computer controls and coordinates the motion of the two trucks in a user-transparent manner. This means that the user (or a user-generated high-level control program, such as the path execution program described in Section 7.3) must prescribe the desired translation and rotation of the vehicle only with respect to the loading-deck. The user or the higher-level control program does not need to consider the motion of the two trucks individually, which would result in the desired motion of the loading-deck. A detailed description of the control system is given in [Borenstein, 1995a] and is omitted here.

To date three commercial-grade prototypes of the OmniMate have been built in a collaborative effort between HelpMate Robotics Inc. [HRI] and the University of Michigan’s Mobile Robotics Lab.

3. INTERNAL POSITION ERROR CORRECTION (IPEC)

One unique and seemingly impossible feature of the OmniMate is its ability to measure and correct systematic and non-systematic odometry errors that occur in one truck by using the other truck as a point of reference. Yet, this error correction method works even while both trucks are in continuous, fast motion.

3.1 Physical explanation of the IPEC method

Figure 4 illustrates in physical terms how the IPEC method works. We will consider only the case of straight-line motion, to keep the example simple, although the IPEC method can be shown to work equally well during turning.

In straight-line motion the internal controllers of each truck try to vary the speed of the motors so that each motor generates exactly the same number of encoder pulses. This simple control law works well on smooth floors, but when one wheel encounters a bump (as shown in Figure 4) then this wheel has to travel an extra distance (namely up and down the bump). Yet, as the encoder pulses of both wheels are being kept equal by the controller, the right wheel (in Figure 4) will cover less horizontal distance. As a result Truck A's orientation will change (a fact unknown to Truck A's odometry computation). Truck A is therefore expecting to "see" Truck B along the extension of line L_e . However, because of the physically incurred rotation of Truck A, the rotary encoder on truck A will report that truck B is now actually seen along line L_m . The angular difference between L_e and L_m is the thus measured odometry orientation error of Truck A, which can be corrected immediately. One should note that even if Truck B encountered a bump at the same time, the resulting rotation of Truck B would not affect the orientation error measurement. One should also note that orientation errors are much more severe than linear odometry errors because even a small orientation error will result in the unbounded growth of a subsequent lateral position error.

The unique error correction capability of the OmniMate is documented in video clips available in [Borenstein, 1995V; Borenstein et al., 1996b].

3.2 Formal implementation of IPEC on the OmniMate

The IPEC method performs the following computations once during each sampling interval: At first, trucks A and B compute their momentary position and orientation based on odometry:

$$x_{A,i} = x_{A,i-1} + U_{A,i} \cos\theta_{A,i}$$

$$y_{A,i} = y_{A,i-1} + U_{A,i} \sin\theta_{A,i}$$

and

(1)

$$x_{B,i} = x_{B,i-1} + U_{B,i} \cos\theta_{B,i}$$

$$y_{B,i} = y_{B,i-1} + U_{B,i} \sin\theta_{B,i}$$

where

$x_{A,i}, y_{A,i}$ - position of centerpoint of truck A, at instant i ;

$x_{B,i}, y_{B,i}$ - position of centerpoint of truck B, at instant i ;

$U_{A,i}, U_{B,i}$ - incremental displacements of the centerpoints of trucks A and B during the last sampling interval;

$\theta_{A,i}, \theta_{B,i}$ - Orientations of trucks A and B, respectively; computed from odometry.

Note that the odometry equations that yield U_i and θ_i are well known and not repeated here (see [Everett, 1995]). Also note that we omit the index i in the following equations.

Next, the orientation θ_L of the compliant linkage is computed

$$\mathbf{q}_L = \text{atan} \frac{y_B - y_A}{x_B - x_A} \quad (2)$$

Using the kinematic relations defined in Figure 5, we can now compute the *expected* angles α_{exp} and β_{exp} between the compliant linkage and trucks A and B, respectively.

$$\alpha_{\text{exp}} = \theta_A - \theta_L$$

and (3)

$$\beta_{\text{exp}} = \theta_B - \theta_L$$

Note that the index “*exp*” indicates that the computed angle is *expected*, based on odometry during this sampling interval.

We can now compute

$$\Delta\theta_A = \alpha_{\text{act}} - \alpha_{\text{exp}}$$

and (4)

$$\Delta\theta_B = \beta_{\text{act}} - \beta_{\text{exp}}$$

where α_{act} and β_{act} are the *actual* angles between the compliant linkage and trucks A and B respectively, as measured by the two absolute rotary encoders located at points A and B (see Figure 3 and Figure 5). Non-zero results for $\Delta\theta_A$ or $\Delta\theta_B$ do not only indicate the presence of an odometry error, but they are quantitatively accurate values for correcting these errors. Thus, computing

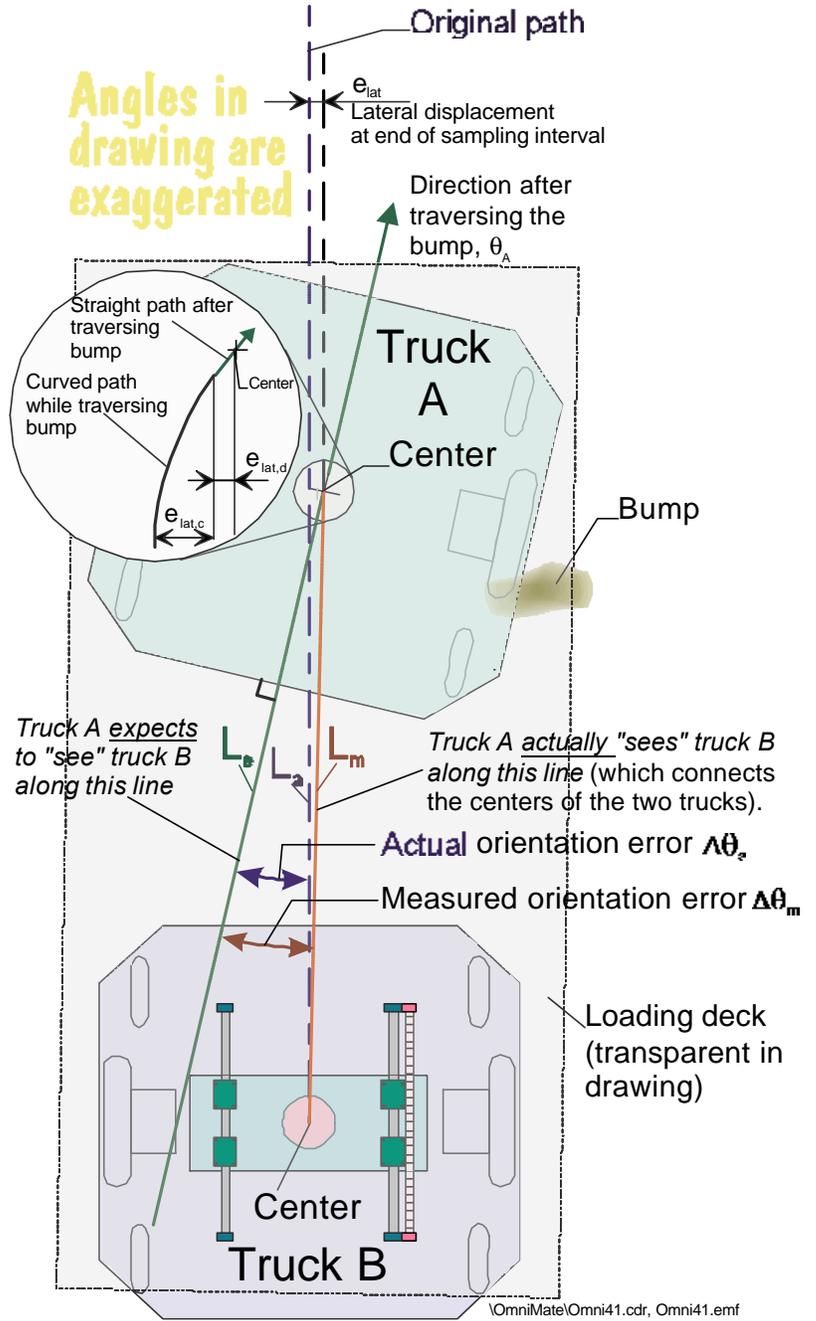


Figure 4: After traversing a bump, the resulting change of orientation of Truck A can be measured relative to Truck B.

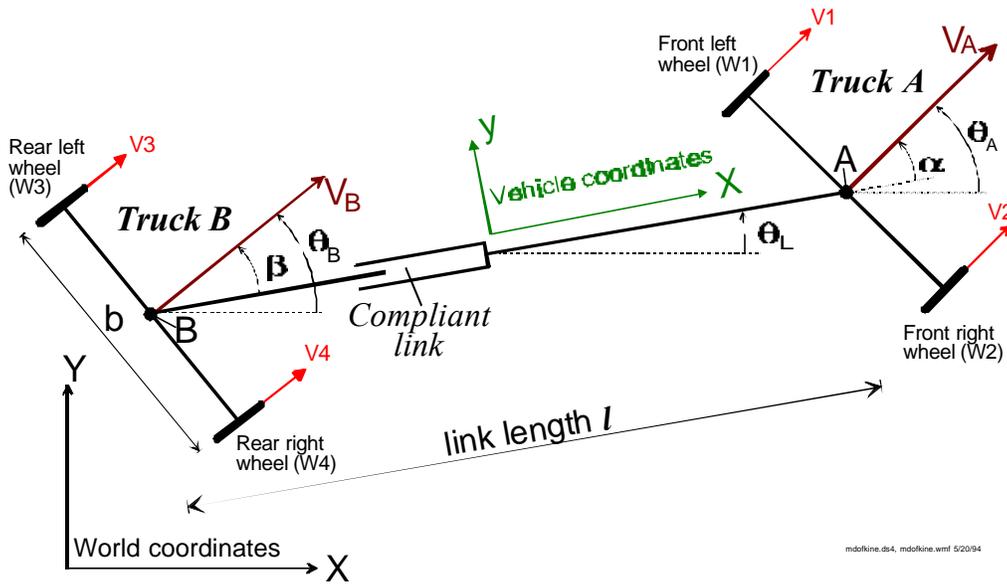


Figure 5: Kinematic definitions for the OmniMate.

$$\theta'_A = \theta_A + \Delta\theta_A$$

and

$$\theta'_B = \theta_B + \Delta\theta_B$$

yields the *corrected* orientations for truck A and truck B.

4. EXPERIMENTAL RESULTS WITH IPEC

In order to test the odometric accuracy of the OmniMate with Internal Position Error Correction (IPEC) the vehicle was programmed to run five laps along a rectangular path in clockwise (cw) and counter-clockwise (ccw) direction, according to a benchmark test protocol called *UMBmark* [Borenstein and Feng, 1996]. The total length of the rectangular path (i.e., for one lap) was 18.5 meters (60 ft) and the platform performed a total of four 90°-turns in each lap (see Figure 6). Traveling at a maximum speed of 0.3 m/s (11.8 in/s) during straight segments, the platform slowed down near corners but didn't stop. In a second experiment consisting of an additional five laps each

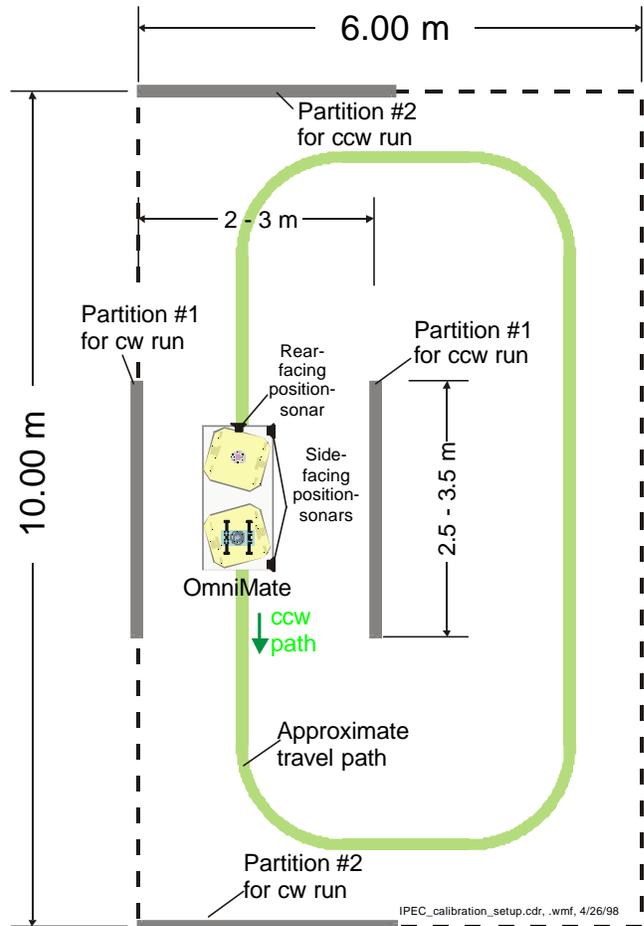


Figure 6: Setup for running IPEC experiments.

in cw and ccw direction 20 artificial 9-mm diameter bumps were placed under the OmniMate’s wheels to test the vehicle’s ability to correct non-systematic odometry errors. After these runs (i.e., a total of 20 laps) the whole experiment was repeated but with the OmniMate’s error correction *disabled*, for comparison.

At the beginning and end of each lap an onboard “sonar calibrator” (a device that uses three ultrasonic sensors to measure the distance between three points on the platform to nearby walls) was used to measure the absolute position and orientation of the vehicle. Comparing this absolute (or “true”) measurement to the position and orientation determined from odometry at the end of each lap allows computation of what we call the *Return Position Errors* defined as

$$\epsilon x = x_{\text{abs}} - x_{\text{calc}} \tag{6a}$$

$$\epsilon y = y_{\text{abs}} - y_{\text{calc}}$$

and the *Return Orientation Error*, defined as

$$\epsilon \theta = \theta_{\text{abs}} - \theta_{\text{calc}} \tag{6b}$$

where

- $\epsilon x, \epsilon y, \epsilon \theta$ - Return Position/Orientation Errors
- $x_{\text{abs}}, y_{\text{abs}}, \theta_{\text{abs}}$ - Absolute position and orientation of the platform as measured by the sonar calibrator
- $x_{\text{calc}}, y_{\text{calc}}, \theta_{\text{calc}}$ - Position and orientation of the robot as computed from odometry.

After determining the odometry errors at the end of each lap, the odometry system was re-initialized with that data (i.e., odometry errors were not allowed to accumulate from lap to lap).

Noting the return position and orientation errors after each lap, errors ϵx and ϵy were plotted in Figure 8 and Figure 9, and errors $\epsilon \theta$ were plotted in Figure 7 and Figure 10. It is evident from these results that the OmniMate’s error correction provided consistently one order of magnitude greater accuracy than that obtained from running the same vehicle without IPEC.

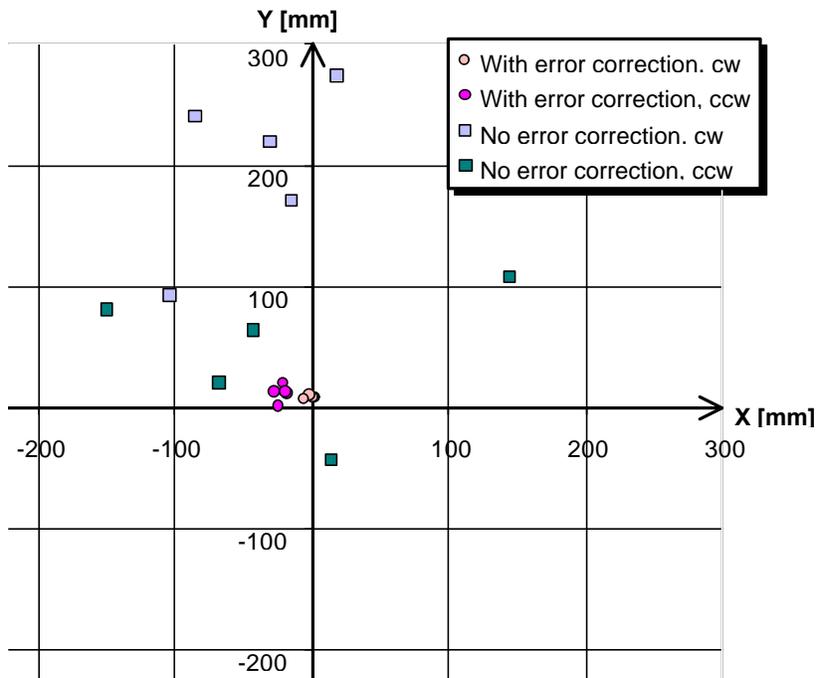


Figure 8: OmniMate return position errors after completing the 18.5 m rectangular path on a smooth concrete floor *without* bumps.

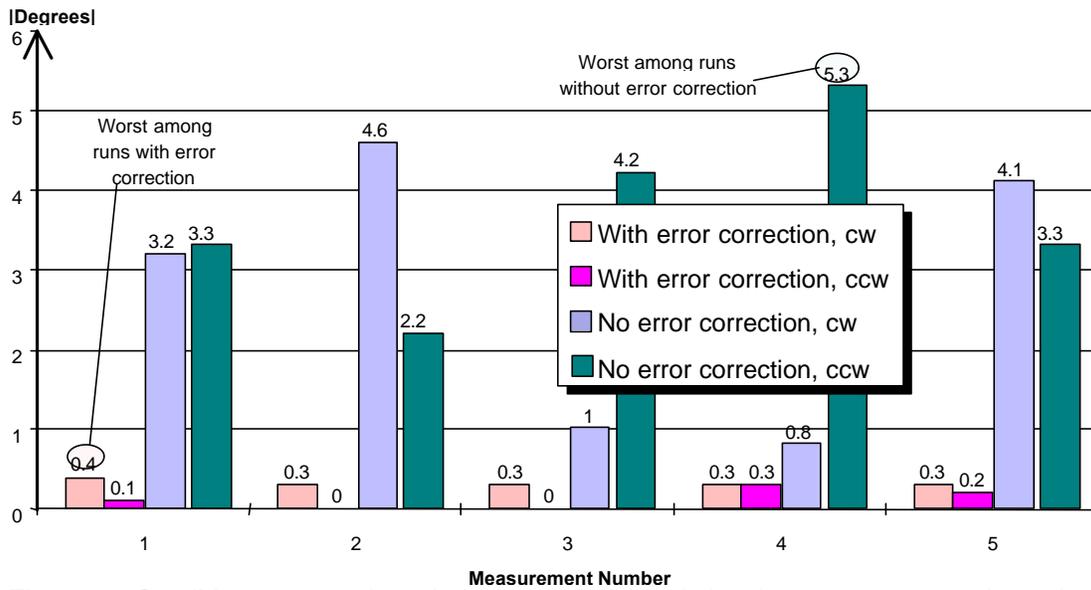


Figure 7: OmniMate return orientation errors after completing the 18.5 m rectangular path on a smooth concrete floor without bumps.

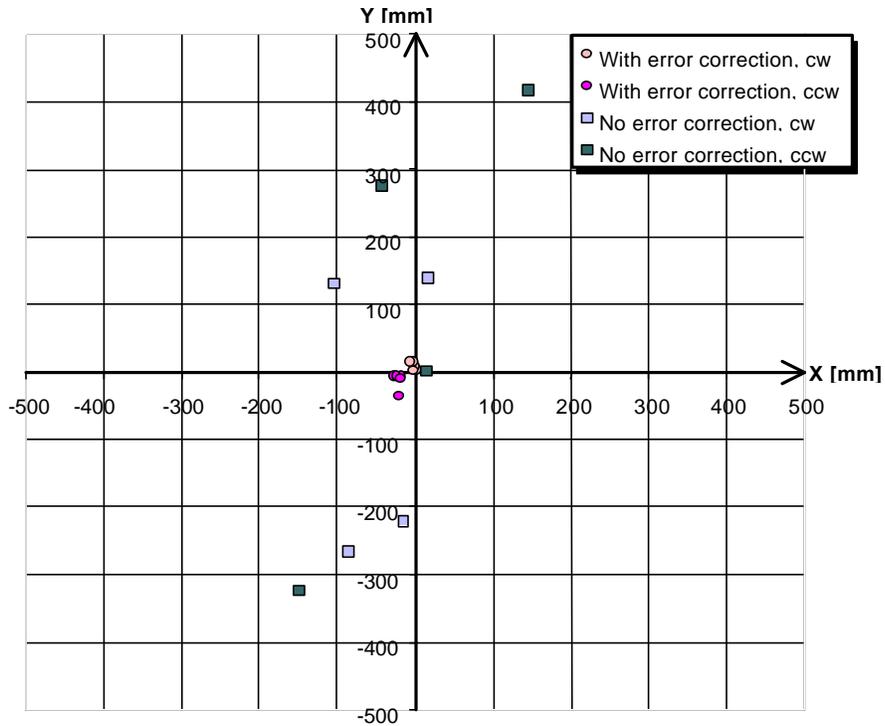


Figure 9: OmniMate return position errors after completing the 18.5 m rectangular on a smooth concrete floor *with 20 artificial 9-mm bumps*.

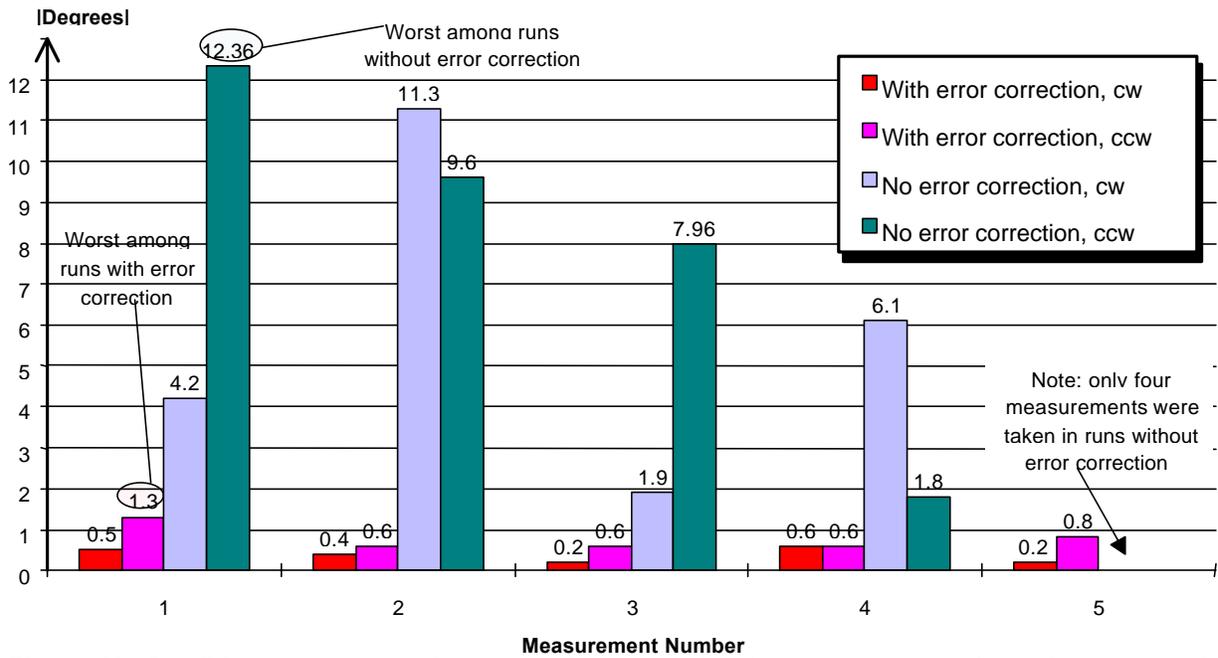


Figure 10: OmniMate return orientation errors after completing the 18.5 m rectangular path on a smooth concrete floor *with 20 artificial 9-mm bumps*.

5. GYRO-ENHANCED IPEC

Despite the good experimental results obtained with the IPEC method implemented on the OmniMate, there are some shortcomings. IPEC detects and corrects conventional systematic and non-systematic odometry errors. However, it introduces new systematic errors of its own (see more detailed discussion of these in [Borenstein, 1995b]). Systematic errors, we recall from Section 1, are directly related to the kinematic properties of the vehicle but mostly unrelated to the unpredictable interaction with the environment. For this reason, it is possible to measure these systematic errors and devise calibration factors that can be implemented in the control software (see [Borenstein and Feng, 1996] for a comprehensive analysis of this subject).

In the experiments described in the proceeding section the OmniMate and its IPEC parameters were very carefully calibrated, resulting in almost complete elimination of all systematic errors introduced by IPEC. In industrial applications, however, it may not always be feasible to maintain precise calibration of each vehicle. Calibrated properties may also change as a result of collisions or overloading.

To overcome this problem we integrated a high-precision fiber-optics gyroscope (in short: “gyro”) with the OmniMate’s IPEC control system. The gyro is the KVH E-core RD2100, previously made by Andrews Corp. under the name Autogyro (see Figure 11). Specifications for the KVH E-core RD2100, as published by the manufacturer, are shown in Table I.



Figure 11: The KVH E-core RD2100 fiber-optics gyroscope. (Courtesy of [KVH])

Table I: Technical specifications for the E-Core RD2100 fiber-optics gyroscope. (Courtesy of [KVH])

| Performance | | RD2100 |
|------------------------------|---------------------------------|----------------|
| Input Rate (max) | \pm $^{\circ}$ /sec | 100 |
| Resolution | $^{\circ}$ /sec | 0.004 |
| Scale factor | $^{\circ}$ /bit | 0.000305 |
| Nonlinearity | %, rms | 0.5 |
| Full Temp | %, p-p | 2 |
| Bias Stability | | |
| Constant Temp | $^{\circ}$ /sec, 1 | 0.002 |
| Full Temp | $^{\circ}$ /sec, p-p | 0.2 |
| Repeatability | $^{\circ}$ /sec, p-p | 0.002 |
| Angle Rand. Walk | $(^{\circ}$ /hr)/ Hz | 5 |
| | $^{\circ}$ / hr | 0.08 |
| Bandwidth | 3 dB, 45 $^{\circ}$ phase shift | 100 |
| Power Requirements | | |
| +9 to +18, or +18 to +36 VDC | watts | 3 |
| Physical | | |
| Dimensions | cm (L×W×H) | 11.2×10.8× 4.3 |
| | in (L×W×H) | 4.41×4.27×1.69 |
| Weight | kg | .34 |
| | lb | .75 |

On the OmniMate the gyro is mounted rigidly to the bottom of the loading deck, which, in turn, is rigidly connected to one side of the compliant linkage. Thus, the orientation of the loading deck, of the compliant linkage, and of the gyro are always identical. At the beginning of a run the initial orientation of the gyro, $\theta_{G,0}$, is set equal to the initial orientation of the compliant linkage, $\theta_{L,0}$

$$\theta_{G,0} = \theta_{L,0} \quad (7)$$

The gyro outputs rate-of-rotation data, ω_G , at sampling intervals $T_s = 100$ ms. This data is integrated in the onboard computer and added to a variable θ_G that represents the current orientation of the gyro

$$\theta_{G,i} = \theta_{G,i-1} + \omega_{G,i} T_s \quad (8)$$

The orientation of the gyro, and hence, of the compliant linkage (which represents the vehicle orientation) at time $t = nT_s$ can be expressed as

$$\theta_{G,n} = \theta_{L,0} + \sum_{i=0}^n \omega_{G,i} T_s \quad (9)$$

Merging the gyro data with the IPEC-corrected odometry data is now straightforward:

We substitute for Eq. (2)

$$\theta_{L,i} = \theta_{G,i} \quad (10)$$

The physical significance of this approach is that the orientation of the OmniMate platform is exclusively determined by the gyro, while the position of the two trucks, and thus, of the platform, is determined by IPEC-enhanced odometry. Furthermore, the gyro-based orientation measurement is fed back to the two trucks (by means of Eqs. (3) and (4)), resulting in greater accuracy of the odometric position computation.

6. EXPERIMENTAL RESULTS WITH GYRO-ENHANCED IPEC

The gyro-enhanced IPEC method was extensively tested at our lab. Experiments similar to those described by Figure 6 in Section 4 resulted typically in return position/orientation errors similar to those depicted in Figure 8 - Figure 10 for “plain” IPEC (i.e., without gyro enhancement). This is not surprising, because the plain IPEC results were obtained with a carefully calibrated vehicle and were “near-perfect.”

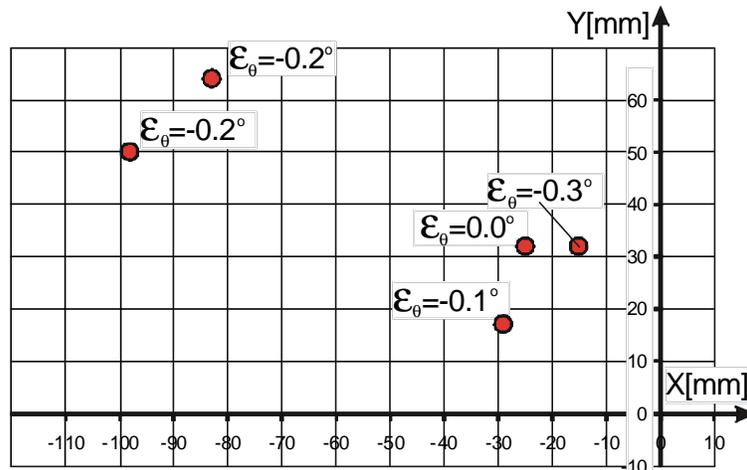


Figure 12: Plot of OmniMate return position errors for five runs along the path of Figure 13. Corresponding return orientation errors ϵ_{θ} are shown next to each data point.

In order to obtain a more practice-oriented set of experimental results, we intentionally degraded the calibration parameters in IPEC, thus creating conditions more likely encountered in industrial applications. We also increased the total travel distance of the test path to 40 meters, as shown in Figure 13. Finally, we pre-programmed the path so as to include sideways and diagonal crabbing elements, which we suspected might introduce further odometry errors.

Results from five consecutive runs along the 40-meter path of Figure 13 are shown in Figure 12. Along the corridor segment of the path 20 bumps like those described in Section 4 were introduced. In addition, we arbitrarily *kicked* the leading truck, resulting in clearly noticeable wheel slippage.

As is evident from these results, extended travel with gyro-enhanced IPEC is possible with only small odometry errors. With this capability in mind, we developed a new feature, believed to be unique to the OmniMate, as discussed in Section 7.2.

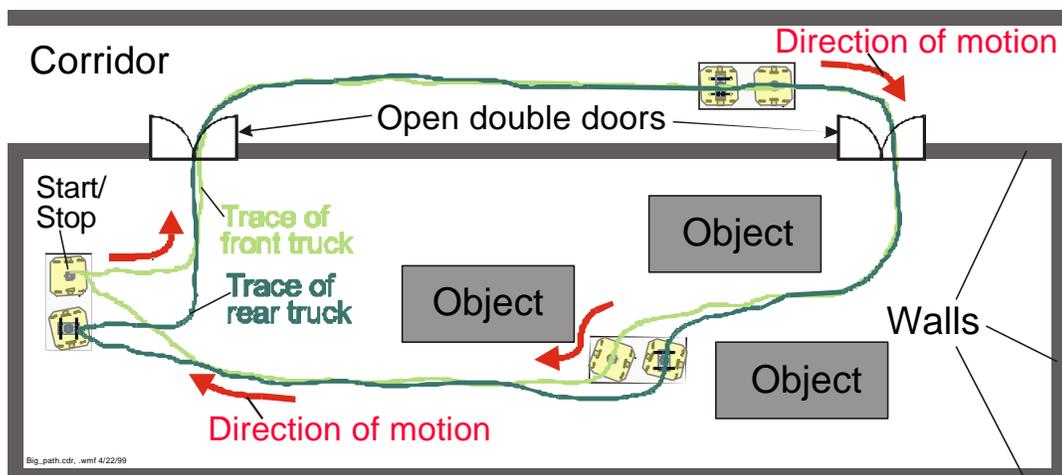


Figure 13: 40-meter extended path for testing gyro-enhanced IPEC. Resulting return position/orientation errors are shown in Figure 12.

7. EMPLOYING THE OMNIMATE

Almost all of the functions of the OmniMate, and especially the motion modes described later in this section, can be invoked under (a) autonomous computer control, or (b) under computer-assisted joystick control. This dual functionality is important because new paths are most conveniently taught by lead-through teaching with the joystick (see Section 7.2). The joystick used for manual control of the OmniMate is shown in Figure 14. It is an off-the-shelf 4-channel radio control dual-joystick typically found in use with model airplanes or cars. Functions assigned to the left-hand and right-hand joysticks on the transmitter differs for each motion mode, as explained below.



Figure 14: Naming convention for the OmniMate 4-channel RF joystick.

7.1 Motion modes

Because of its unique kinematic design the OmniMate can perform many operations in several different motion modes. The two most important motion modes are “Crab” and “Follow-the-Leader” (FTL). Each of these modes has advantages and disadvantages under certain operating conditions. Together, the availability of these modes enhances the usability of the OmniMate in real-life environments. Several other modes of operation are also implemented but not described here. The OmniMate’s control system implements these motion-modes and provides smooth, fluent motion at speeds of up to 0.5 m/s. The OmniMate is physically capable of a maximum speed of 1 m/s, but most of the experiments reported in this paper were conducted at a maximum speed of 0.5 m/s.

Crab mode -- In this motion mode the onboard computer controls and coordinates the motion of the two trucks. This is the most versatile control mode as it affords the greatest maneuverability. However, the maximum speed under Crab mode is limited to 0.5 m/s).

Under autonomous computer control, a higher-level program can call Crab mode and specify a desired translational velocity vector, as well as a desired absolute orientation of the loading deck. If the current orientation differs from the desired one, the onboard controller rotates the vehicle during motion until the desired orientation is reached.

Under joystick control the right-hand joystick is used to control the translational forward/backward (Y1) and the sideways (X1) motion of the OmniMate. The left-hand joystick (X2) is used to change the orientation of the loading deck.

Follow-the-Leader (FTL) mode – In this motion mode the rear truck follows exactly the trajectory of the front truck. This minimizes the space requirements for the OmniMate when traveling through con-

defined space. From a control point of view, this mode is more stable and speeds of up to 1 m/s are permissible. Sideways or diagonal crabbing is not possible under this mode (by definition), so translational control with the joystick (X1) is disabled.

7.2 Lead-through teaching

In lead-through teaching mode a human operator defines a desired trajectory by leading the OmniMate manually (i.e., using the RF joystick) along a path. The OmniMate automatically records intermediate way-points at distance intervals of 100 mm. After completion of a lead-through teaching session the way-points are saved as a named pathfile for later execution. The automatic execution of a previously taught (or otherwise generated pathfile) is called “*pathfile execution*.”

During lead-through teaching the operator has control options that go beyond controlling the three basic Degrees-of-Freedom with the RF joystick. Most notably there are three distinct operating modes that can be changed at any given time and while the platform in motion. We will call these three modes “*path modes*” to distinguish them from the motion modes (Crab and FTL, as discussed above) and because they are only available during lead-through teaching and subsequent path execution.

The left-hand forward/backward joystick (labeled “Y2” in Figure 14), which is not used in conventional crab control, is used to select either one of these three modes. When Y2 is fully pulled toward the operator, then Mode 1 is selected. When Y2 is in its centered (neutral) position, Mode 2 is selected. When Y2 is pushed fully away from the operator, then Mode 3 is selected.

Mode 1: In this path mode the OmniMate uses the “Crab” mode of motion at a preset, very low maximum speed ($V_{\max} = 240$ mm/s). This means that although the operator controls the actual speed with the right-hand joystick as during conventional crabbing, the maximum speed is limited to $V < V_{\max}$.

Mode 2: In this path mode the OmniMate also uses the “Crab” mode of motion but at a higher maximum speed of $V_{\max} = 360$ mm/s.

Mode 3: In this mode the OmniMate uses the Follow-the-Leader (FTL) mode of motion while its maximum speed is limited to $V_{\max} = 500$ mm/s. Recall that in FTL-mode the rear truck always follows the trajectory of the front truck, and that the operator basically controls only the front truck in this motion mode.

The purpose of the three modes is not so much to control the behavior of the platform during lead-through teaching, but rather to specify the behavior of the platform during subsequent automatic path execution. For this purpose the currently selected mode is always recorded into the pathfile along with each via-point. How these three modes are taken into account and why they are defined the way they are will be explained in Section 7.3 below.

Additional operator commands are possible during lead-through teaching. One set of commands allows truck alignment while the vehicle is standing. In truck alignment mode both trucks can be com-

manded to “face” forward, backward, left, or right. This is useful when maneuvering in very tight spaces.

After completing a lead-through teaching session the recorded way-points, operating modes, truck alignment commands, and other special commands are stored in a so-called “*pathfile*” that might look like the one shown in Table II. A pathfile is a plain ASCII text file and it can be edited manually after it has been recorded by lead-through teaching. Editing may be desirable in order to smooth out some segments in which the operator controlled the platform poorly during lead-through teaching.

7.3 Automatic path execution

Automatic path execution is the compliment to lead-through teaching – it executes a path that was previously stored in a so-called “*pathfile*” during lead-through teaching.

The onboard computer executes the pathfile by reading one line at-a-time from the pathfile and issuing an appropriate motion command to the lower-level controller. In the current implementation only two motion commands are needed for pathfile execution. These commands are called *Crab_pass_abs()* and *FTL_pass_abs()*. Under either motion command the front truck always aims at reaching the next via-point. For *Crab_pass_abs()* the OmniMate will also try to align itself with the recorded orientation. For *FTL_pass_abs()* the rear truck will aim at following the trajectory of the front truck. Which motion command is selected for each pathfile line depends on the path mode that was in effect when the pathfile was recorded. The relation between path modes and motion modes is the same as described in Section 7.2.

It is important to understand that for neither path mode the front truck will pass through the specified coordinates with absolute accuracy. Instead there is a tolerance distance specific to each of the three path modes, as summarized in Table III. The reason for these varying tolerances and speeds is that at higher speeds it

Table II: Editable lines of a typical pathfile

| X0 [mm] | Y0 [mm] | Theta[0] [deg] | Path- mode | D_dist [mm] | D_time [ms] |
|-------------------------|------------|-------------------|---------------|----------------|----------------|
| Right (-align trucks) | | | | | |
| 658 | 3700 | 90 | 1 | 101 | 1092 |
| 759 | 3700 | 90 | 1 | 101 | 1312 |
| 850 | 3700 | 90 | 1 | 100 | 3959 |
| Forward (-align trucks) | | | | | |
| 850 | 3800 | 90 | 2 | 101 | 1694 |
| 850 | 3900 | 90 | 2 | 102 | 1505 |
| 850 | 4000 | 90 | 2 | 103 | 1115 |
| 850 | 4100 | 90 | 2 | 102 | 1034 |
| 850 | 4436 | 88 | 2 | 102 | 977 |
| 910 | 4523 | 85 | 2 | 100 | 1127 |
| 980 | 4595 | 82 | 2 | 103 | 712 |
| 1059 | 4659 | 78 | 2 | 101 | 563 |
| 1142 | 4719 | 74 | 2 | 103 | 533 |
| 1230 | 4777 | 69 | 2 | 105 | 565 |
| 1319 | 4827 | 65 | 2 | 103 | 661 |
| 1417 | 4865 | 59 | 2 | 105 | 661 |
| 1519 | 4892 | 54 | 2 | 106 | 599 |
| 1619 | 4912 | 48 | 2 | 101 | 504 |

becomes increasingly difficult for the motion controller to reach each via point within a small tolerance. The result would be very choppy motion. By selecting tolerances suitable to the intended maximum speed smooth motion is obtained under all path modes.

From this discussion and Table III it is clear that when highest accuracy is required, for example, when maneuvering in tightly confined space or when approaching a docking station, path mode 1 is best suited because it provides the most accurate path following (within 30 mm from each via point). In contrast, when traveling through large open areas, typically a higher speed and less position accuracy are appropriate.

Decisions on what path mode is most appropriate for the local environment are best made during lead-through teaching. That is why the path mode is selected by the operator at that time. It should also be noted that during pathfile execution the maximum speed is always determined by the relationships defined in Table III. The benefit of this approach is that intermitted stopping, operator hesitation, or other causes for inconsistency in speed are not repeated during pathfile execution. The disadvantage is that the operator can specify only three different speed levels by selected the respective path modes during lead-through teaching. Nonetheless, we found that in practice this implementation works very well and is highly efficient. Furthermore, if necessary, path modes (and thus, speed levels) can be changed easily by editing the pathfile manually.

Table III: Relationship between path modes, motion modes, maximum speed, and pass_abs tolerances.

| Path mode | Motion mode | Max. speed [mm/s] | Tolerance [mm] |
|-----------|-------------|-------------------|----------------|
| 1 | Crab | 240 | 30 |
| 2 | Crab | 360 | 80 |
| 3 | FTL | 480 | 120 |

8. CONCLUSIONS AND FUTURE WORK

This paper presents an overview over the design of a new, commercially available mobile platform called *OmniMate*. The *OmniMate* provides true omnidirectional motion and its kinematic design eliminates the excessive wheel-slippage often associated with other omnidirectional platforms. One of the *OmniMate*'s most unique features is its gyro-enhanced *Internal Position Error Correction* (IPEC) that provides hitherto unachieved dead-reckoning accuracy. This accuracy is almost completely insensitive to wheel slippage or even severe irregularities of the floor.

Because of its unique dead-reckoning accuracy the *OmniMate* lends itself to guidewire- and beacon-free AGV applications. A novel lead-through teaching and path execution feature allows new paths of 100 m length or more to be programmed within minutes and with no installation cost.

For longer paths we envisage a sonar-based correction system that would use permanent stationary landmarks, such as building support columns or doorways to correct position information on-the-fly as follows. In lead-through teach mode the operator would command a side-facing ultrasonic range sensor to measure the distance to the landmark that is being passed at that moment. Then, during path execu-

tion, the OmniMate would automatically repeat that measurement and correct its lateral position estimate. We are planning to implement this feature in the future.

Another feature developed at our lab is a fully autonomous obstacle avoidance system. This system uses 32 ultrasonic range sensors mounted on the periphery of the platform (underneath the loading deck). The obstacle avoidance system allows the OmniMate to detect unexpected obstacles in the vehicle's path and to safely circumnavigate them.

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9. REFERENCES

1. Borenstein, J., 1995a, "Control and Kinematic Design for Multi-degree-of-freedom Mobile Robots With Compliant Linkage." *IEEE Transactions on Robotics and Automation*, February, Vol. 11, No. 1, pp. 21-35.
2. Borenstein, J., 1995b, "Internal Correction of Dead-reckoning Errors with the Compliant Linkage Vehicle." *Journal of Robotic Systems*, Vol. 12, No. 4, April, pp. 257-273.
3. Borenstein, J., 1995V, "The CLAPPER: A Dual-drive Mobile Robot with Internal Correction of Dead-reckoning Errors." *Video Proceedings of the 1995 IEEE International Conference on Robotics and Automation*, Nagoya, Japan, May 21-27.
4. Borenstein, J. and Feng, L., 1996, "Measurement and Correction of Systematic Odometry Errors in Mobile Robots." *IEEE Transactions on Robotics and Automation*, Vol 12, No 5, October
5. Borenstein, J., Everett, B., and Feng, L., 1996, "Navigating Mobile Robots: Systems and Techniques." A. K. Peters, Ltd., Wellesley, MA, ISBN 1-56881-058-X, Publication Date: February 1996.
6. Crowley, J. L., 1989, "Asynchronous Control of Orientation and Displacement in a Robot Vehicle." *Proceedings of the 1989 IEEE International Conference on Robotics and Automation*. Scottsdale, Arizona, May 14-19, pp. 1277-1282.
7. Crowley, J. L. and Reignier, P., 1992, "Asynchronous Control of Rotation and Translation for a Robot Vehicle." *Robotics and Autonomous Systems*, Vol. 10, 1992, pp. 243-251.
8. Everett, H.R., 1995, "Sensors for Mobile Robots," A K Peters, Ltd., Wellesley, MA, 1995.

9. Feng, L, Koren, Y., and Borenstein, J., 1993, "A Cross-Coupling Motion Controller for Mobile Robots." *IEEE Journal of Control Systems*. December, pp. 35-43.
10. Hirose, S., and Amano, S., 1993, "The VUTON: High Payload Efficiency Holonomic Omnidirectional Vehicle." *Proceedings of the Sixth International Symposium on Robotics Research (ISRR-93)*, Hidden Valley, PA, Oct. 2-5.
11. HRI — Helpmate Robotics Inc., (formerly TRC - Transitions Research Corp.) Shelter Rock Lane, Danbury, CT 06810, 203-798-8988.
12. Killough, S. M. and Pin, F. G., 1992, "Design of an Omnidirectional Holonomic Wheeled Platform Prototype." *Proceedings of the 1992 IEEE Conference on Robotics and Automation*, Nice, France, May 1992, pp. 84-90.
13. KVH – KVH Industries, Inc. KVH Industries, Inc. Middletown, RI 02842, Ph.: 401-847-3327.
14. Pin, F. G. and Killough, M., 1994, "A New Family of Omnidirectional and Holonomic Wheeled Platforms for Mobile Robots." *IEEE Transactions on Robotics and Automation*, Vol. 10, No. 4, August 1994, pp. 480-489.
15. Reister, D. B., 1991, "A New Wheel Control System for the Omnidirectional HERMIES-III Robot." *Proceedings of the 1991 IEEE Conference on Robotics and Automation*, Sacramento, California, April 7-12, pp. 2322-2327.
16. West, M. and Asada, H., 1992, "Design of a Holonomic Omnidirectional Vehicle." *Proceedings of the 1992 IEEE International Conference on Robotics and Automation*. Nice, France, May, pp. 97-103.